Republic of Rwanda
Energy, Water and Sanitation Authority

REPUBLIC OF RWANDA

DATA COLLECTION SURVEY ON GEOTHERMAL DEVELOPMENT IN RWANDA

FINAL REPORT

August 2013

JAPAN INTERNATIONAL COOPETATION AGENCY (JICA)

NIPPON KOEI CO., LTD.

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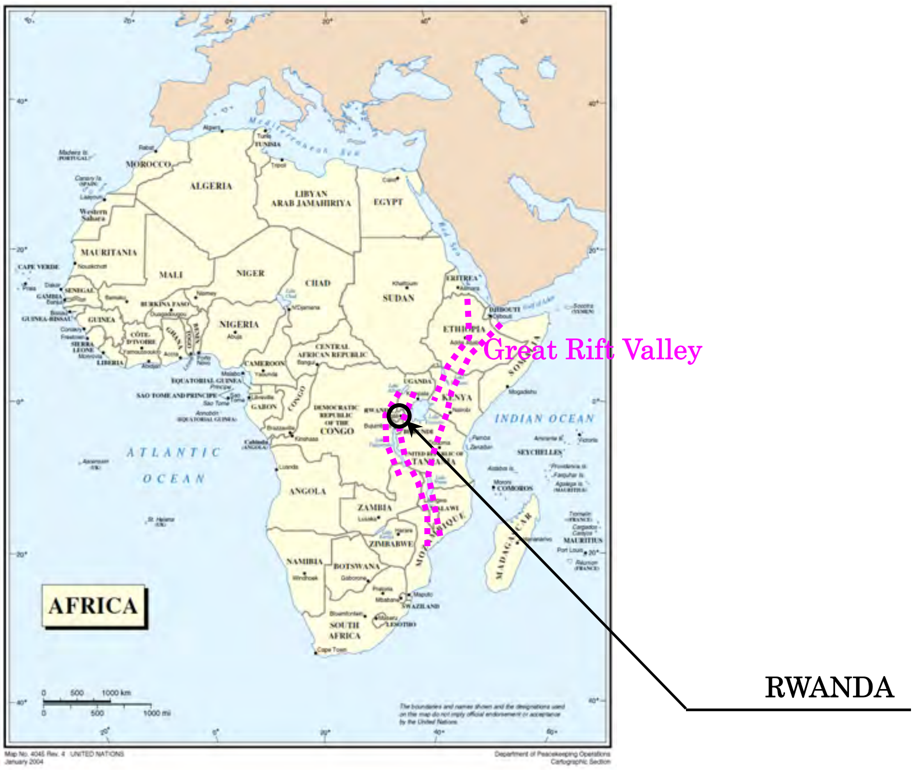


Location Map

General View of the Drilling Site

Water Supply Tank (4,000m^3 x 3 tanks), Two tanks were ready to use.

Tank No.3 under construction

Pipe lines around tanks

Water intake at Karago Lake

Submersible pumps at Karago Lake
(Q=150m^3, H=25m) x 2 pumps

Pump station at Karago Lake
(Q=155m^3, V=536m) x 2 pumps

Pump Station at Karago Lake

Valve arrangement
at Karago lake pump station

Delivery pipe near Karago Lake (8")

	
Booster pumps (Q=155m3, H= 268m) x 2 pumps	Booster pump station
	
Valve arrangement at the booster pump station	Pipe arrangement to the tank at the booster pump station
	
Pipe arrangement along a main road	Pipe arrangement along a street in front of houses

Pipe arrangement at a bend point

Pipe bend arrangement
without pipe support

Pipe on a rock support

Pipe arrangement along a rural road

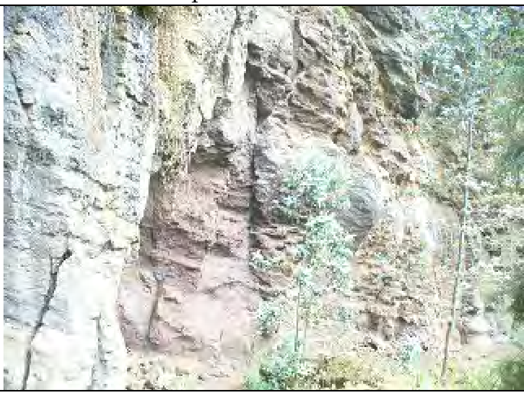
Delivery pine near Karago Lake

Water supply by water tracks

	
Drilling bit	Operation stage
	
BOP	Drilling (kelly in the middle)
	
Rock sampling location	Silencer

Bondi Caldera - Water disappeared in 1950th
Crops on the bottom

Bondi Caldera – Basalt out crop

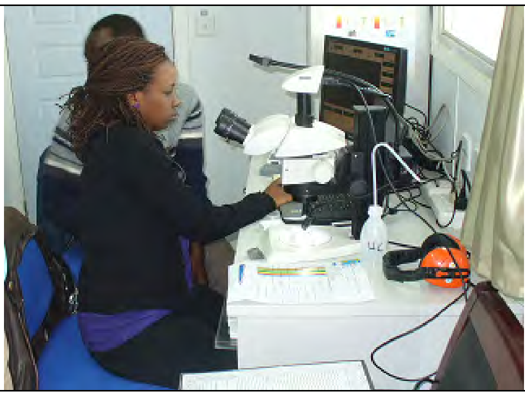


Bondi Caldera – Basalt out crop

Bondi Caldera – Calcite vain

EWSA Geologist at the outcrop

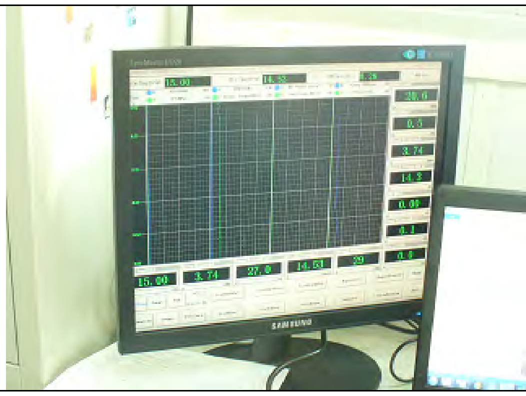
Granit behind, lava in front



Stereoscope procured by ICEIDA-ISOR

Sampling vessels supplied by ICEIDA-ISOR

Geologist from ISOR on lecture



Drilling monitor in geologist room at site

Drilling program finalization

Drilling program finalization

Construction of water intake by the army

Low viscosity lava flow

Rubindi spring (dray season)

Rubindi spring (wet season)

Rwandan children at spring

EIA team at site (BTC support)

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Figures and Tables

Attachments

Abbreviations

AfDB	African Development Bank
ANSI	American National Standards Institute
API	American Petroleum Institute
BGR	Bundesanstalt für Geowissenschaften und Rohstoffe (Federal Institute for Geosciences and Natural Resources)
BOP	Blow-off Preventer
BRGM	Bureau de Recherches Géologiques et Minières (Bureau of Geological and Mining Research)
BTC	Belgian Development Agency　Belgian Technical Cooperation)
BTC	Buttress Thread Casing
CFO	Chief Financing Officer
DFID	Department for International Development
DRC	Democratic Republic of the Congo
EARP	Electricity Access Rollout Project
EGL	Energie des Grands Lacs (Great Lakes Energy)
EWSA	Energy, Water Supply Agency
FMO	Netherlands Development Finance Company
GDU	Geothermal Development Unit, EWSA
GoR	Government of Rwanda
GPS	Global Positioning System
GRMF	Geothermal Risk Mitigation Facility
GTZ	Deutsche Gesellschaft fur Internationale Zusammenarbeit GmbH (German Society for International Cooperation Co., Ltd)
ICEIDA	Iceland International Development Agency
IDA	International Development Association
IDDP	Iceland Deep Drilling Project
IPP	Independent Power Producer
ISOR	Íslenskar orkurannsóknir (Iceland Geo-Survey)
JICA	Japan International Cooperation Agency
KfW	Kreditanstalt für Wiederaufbau (Reconstruction Credit Institute)
LOC	Loss of Circulation
MT	Magnetotellurics
NBI	Nile Basin Initiative
NDF	Nordic Development Fund

NELSAP	Rwanda Nile Equatorial Lakes Subsidiary Action Programme
NZS	New Zealand Standard
ORC	Organic Rankine Cycle
PN	Pressure Numbers (Nominal Pressures)
PPP	Public Private Partnership
PTS	Pressure, Temperature and Spinner (logging)
RBF	Result Based Financing
REC	Rwanda Energy Company
RIG	Rwanda Investment Group
RNRA	Rwanda Natural Resources Authority
ROP	Rate of Penetration
TEM	Transient electromagnetics
UNU-GTP	United Nations University - Geothermal Tanning Programme

CHAPTER 1 INTRODUCTION

1.1 Background

The Republic of Rwanda has made its first priority to develop the social infrastructure in the country. In particular, improvement of energy supply both in the urban and rural areas has been emphasized. According to the Electricity Development Strategy: 2011-2017 (June, 2011), as of 2010, the total installed capacity was about 96.44 MW and available electric power generation was 86.84 MW, resulting to 14% of the electrification ratio in the country. Under this condition, the Government of Rwanda has formulated the Rwanda Vision 2020 (July 2020) under the national development plan, as well as the "Economic Development and Poverty Reduction Strategy 2008-2021 (September 2007)" and the "[DRAFT] National Energy Policy and Strategy (May 2011)" as the electricity sectoral development plan; therein these challenging plans address to achieve a total of 1000 MWe of installed capacity and 50% of the national electrification ratio by 2017.

In particular, Rwanda, as an inland state, intends to increase the electricity generation capacity through utilization of indigenous resources for diversity of energy sources. Rwanda is making as a top priority the development of geothermal energy resources, as clean and stable source for electricity generation. With this premise, geothermal energy may be available to Rwanda, located at the eastern edge of the West African Great Rift Valley. Several potential surveys have been conducted in the country and these showed that over 700 MWe of potential energy may be available in the country; and 300 MWe in Karisimbu - northwest part of Rwanda. Drilling of three exploratory wells in Karisimbi have been decided and the drilling commenced on 19th July 2013.

This Japan International Cooperation Agency (JICA) Survey (herein referred to as the Survey) has been implemented to mainly provide technical advisory services on geothermal exploratory well drilling and well testing to the institution competent for geothermal development for smooth implementation, as the work is the first-of-its-kind in Rwanda.

1.2 Purpose and Scope

1.2.1 Purpose

The purposes of the Survey are as follows:

- To collect data and information on present conditions and issues of geothermal development; and to determine the competency of the Energy, Water, and Sanitation Authority (EWSA) for geothermal development, through review of existing information, site survey, interview survey with relevant personnel and etc.;
- To provide technical advice on development policy of geothermal energy and on drilling and data acquisition from exploratory wells through review of the surface survey and plans of exploratory drilling and testing that were prepared based on the final report;
- To organize and summarize the information collected in order for JICA to consider its assistance approach for achieving geothermal development in Rwanda.

1.2.2 Study Area

The study area of the Survey is the Republic of Rwanda.

1.2.3 Terms of Reference

The Survey shall conduct the following activities to achieve the abovementioned purposes:

(1) To collect information on geothermal electricity development and analysis thereof,
(2) To review the final report of geothermal potential survey,
(3) To provide technical advice on exploratory drilling,
(4) To provide technical advice on well testing,
(5) To collect information that may be useful for assistance approach,
(6) To provide advisory services (preparation works, well drilling, data acquisition, and data analysis)
(7) Reporting
    a. Inception Report
    b. Progress Report
    c. Final Report

1.2.4 Survey Period

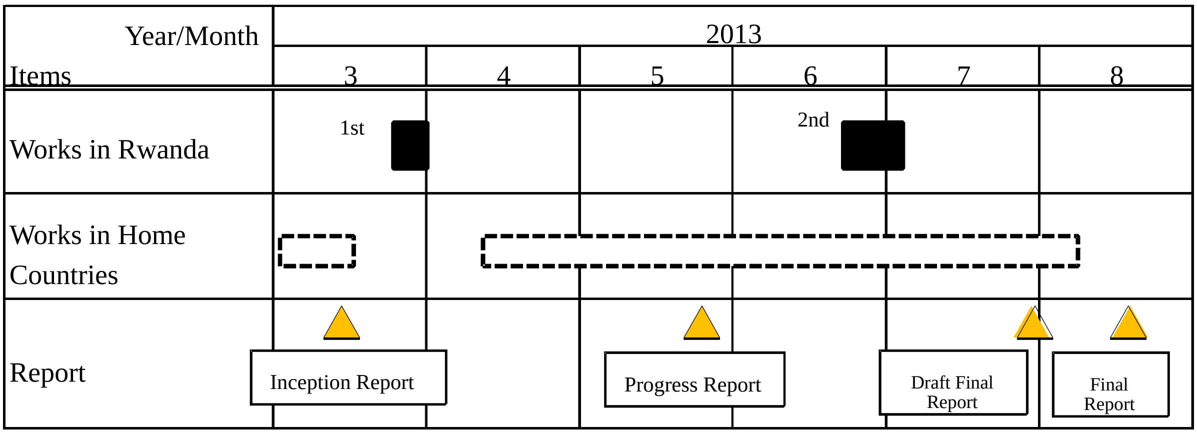
The Survey will begin from 1 March 2013 to 30August 2013.

1.2.5 Survey Schedule

The Survey schedule is presented as follows:

-Preparation in home countries	Intermittent in the beginning–middle of March 2013
-First assignment in Rwanda	End of March 2013
-Fist assignment in home countries	Intermittent in the beginning of April–Middle of June 2013
-Second assignment in Rwanda	Middle of June–beginning of July 2013
-Second assignment in home countries	Intermittent in the beginning of July until the end of August 2013

The Survey schedule is shown in Figure 1-1.



Note: Works in home countries are intermittent as necessary.

(Source: JICA Team)

Figure 1-1 Survey Schedule

1.2.6 JICA Team Members

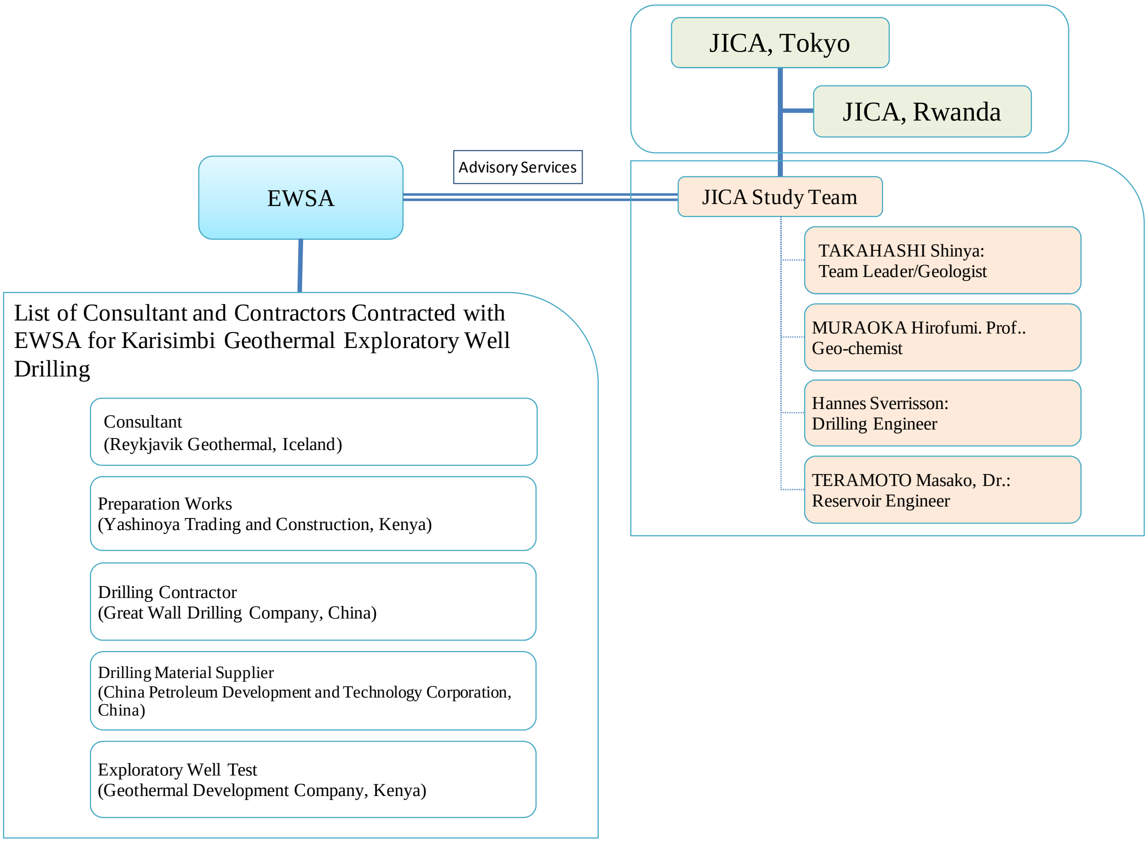
The JICA Team members (hereinafter referred to as the JICA Team) are listed in Table1-1 below:

Table 1-1 List of the JICA Team Members

Name		Position	Organization
1	Shinya Takahashi	Team Leader/Geologist	Nippon Koei Co., Ltd
2	Prof. Hirofumi Muraoka (PhD)	Geochemist	Nippon Koei Co., Ltd (Hirosaki University)
3	Hannes Sverrisson	Drilling, Well Testing Engineer	Nippon Koei Co., Ltd (Mannvit Engineering, Iceland)
4.	Masako Teramoto *(PhD)*	Reservoir Engineer	Nippon Koei Co., Ltd *(Nippon Koei Self-financed)*

(Source: JICA Team)

The organizational framework of the Survey is shown in Figure 1-2.



(Source: JICA Team)

Figure 1-2 Organizational Framework of the Survey

For the implementation of the geothermal exploratory well drilling, EWSA employed consultants and relevant contractors as shown in Figure 1-2. The JICA Team dispatched by JICA, apart from those institutions that have contractual obligation, is on a mission that technical advice shall be provided on preparation works, drilling works, data acquisition, and data analysis through observation and review of drilling works and well testing works that were conducted by the contractors.

CHAPTER 2 INFORMATION MADE AVAILABLE TO THE JICA TEAM

The JICA Team obtained various data and information mainly before commencement of the first assignment to Rwanda, owing to the great support of the JICA Rwanda Office. The data and information obtained are listed in Table 2-1.

The summaries of major information will be shown in the subsequent chapters.

Table 2-1 Data and Information Made Available to the JICA Team

Title	Publisher/Author	Month/Year
1. National Development Plan		
a. Rwanda Vision 2020	Ministry of Finance and Economic Planning	July 2000
b. Economic Development and Poverty Reduction Strategy 2008-2021	Ministry of Finance and Economic Planning	September 2007
2. Energy Electricity Development Plan		
a. [DRAFT] National Energy Policy and Strategy	Ministry of Infrastructure	May 2011
b. [DRAFT] Electricity Development Strategy (2011-2017)	Ministry of Infrastructure	June 2011
3. Geothermal Development Plan		
a. [DRAFT] Rwanda Geothermal Resources Exploration and Development for 2011-2017	Ministry of Infrastructure	December 2010
b. Rwanda Geothermal Resourced Potential	Ministry of Infrastructure	December 2011
4. Geothermal Potential Exploration		
a. Reconnaissance Geothermique de la Republique de Rwanda; in French	BRGM(1983)	1983
b. Preliminary Assessment of Rwanda's Geothermal Energy Development Potential	Chevron	November 2006
c. Geothermal Potential Assessment in the Virunga Geothermal Prospect, Northern Rwanda	Federal Institute for Geosciences and Natural Resources (BGR)	August 2009
d. Feasibility Design of an Integrated Single-Flash Binary Pilot Power Plant in NW-Rwanda	Theoneste Uhorakeye (Geothermal Training Programme, United Nations University)	2008
e. Assessing Generating Capacity of Rwanda Geothermal Field from Green Field Data Only	Uwera Rutagarama (Geothermal Training Programme, United Nations University)	2009
f. Geothermal Potential Appraisal of	Kenya Electricity	March

	Title	Publisher/Author	Month/Year
	Karisimbi Prospect, Rwanda (Combined Report)	Generating Company (KenGen)	2010
g.	Geoscientific Survey of the Rwandan Karisimbi, Gisenyi and Kinigi Geothermal Prospect	Institute of Earth Science and Engineering (IESE) of The University of Auckland	October 、 2012
h.	[DRAFT] Data and Final Report Validation Workshop (organized)	Coordinated by EWSA	09-10 January 2013
5.	Relevant Documents for Exploration Geothermal Wells		
a.	Tender Document for Provision of Drilling Services for Three Exploration Geothermal Wells at Karisimbi, EWSA	Ministry of Infrastructure	April 2011
b.	Tender Document for Provision of Drilling Materials for Three Exploratory Geothermal Wells at Karisimbi, EWSA	Ministry of Infrastructure	April 2011
c.	Review of Geothermal Development Schedule – Plan for Drilling of Three Geothermal Exploration Wells at Karisimbi, Rwanda	Iceland GeoSurvey (ISOR)	September 2011

(Source: JICA Team)

CHAPTER 3 OUTLINE OF THE NATIONAL ELECTRIC DEVELOPMENT PLAN

3.1 National Development Plan

3.1.1 Rwanda Vision 2020 (July 2000)

How do Rwandans envisage their future? What kind of society do they want to become? How can they construct a united and inclusive Rwandan identity? What are the transformations needed to emerge from a deeply unsatisfactory social and economic situation? These are the main questions Rwanda Vision 2020 addresses.

This vision is a result of a national consultative process that took place in Village Urugwiro in 1998-1999. There was broad consensus on the necessity for Rwandans to clearly define the future of the country. This process provided the basis upon which this vision was developed.

Today, Rwanda finds itself at a crossroads, moving from the humanitarian assistance phase associated with the 1994 genocide into one of sustainable development. Since 1994, the Government of Rwanda has stabilized the political situation, whilst putting the economy back on track with considerable assistance from development partners.

Given that the major aspiration of Rwanda Vision 2020 is to transform Rwanda's economy into a middle income country (per capita income of about USD 900 per year, from USD 290 today), this will require an annual growth rate of at least 7%. This will not be achieved unless the country transforms from a subsistence agriculture economy to a knowledge-based society, with high levels of savings and private investment, thereby reducing the country's dependence on external aid.

The main items are as follows:

- Reconstruction of the nation and its social capital anchored on good governance, undefined by a capable state;
- Transformation of agriculture into a productive, high value, market-oriented sector, with forward linkages to other sectors;
- Development of an efficient private sector spearheaded by competitiveness and entrepreneurship;
- Comprehensive human resources development, encompassing education, health, and information and communication technology (ICT) skills aimed at public sector, private sector, and civil society. To be integrated with demographic, health, and gender issues; and
- Promotion of regional economic integration and cooperation.

Key indicators of the Rwandan Vision 2020 are shown in Table 3-1.

Regarding infrastructure development, the Rwanda Vision 2020 has taken up the following six fields: (i) Land use management, (ii) Urban development, (iii) Transport, (iv) Communication and ICT, (v) Energy and (vi) Water. Among these, the description for energy is summarized as follows:

【Description of Energy】

Inadequate and expensive electricity supply constitutes a limiting factor to development. Wood is the source of energy for 99% of the population, which leads to massive deforestation and soil destruction. Imported petroleum products consume more than 40% of foreign exchange. Rwanda will therefore increase energy production and diversify into alternative energy sources.

Through the utilization of indigenous energy such as hydropower and/or methane gas, peat, solar energy, or photovoltaic energy; Rwanda projects that by 2020 at least 35% of the population will be connected to electricity (up from the current 6%) and the consumption of wood will decrease from the current 94% to 50% of the national energy consumption.

Table 3-1 Key Indicators of the Rwandan Vision 2020[1]

Indicators	Situation In 2000	Target in 2010	Target in 2020	Inter-national level
1. Rwandan population	7,700,000	10,200,000	13,000,000	
2. Literacy level	48	80	100	100
3. Life expectancy (years)	49	50	55	
4. Women fertility rate	6.5	5.5	4.5	
5. Infant mortality rate (0/00)	107	80	50	
6. Maternal mortality rate (0/00.000)	1070	600	200	
7. Child Malnutrition (Insufficiency in %)	30	20	10	
8. Population Growth rate (%)	2.9	2.3	2.2	
9. Net primary school enrolment (%)	72	100	100	100
10. Growth secondary school enrolment (%)		100	100	
11. Secondary school transitional rate (%)	42	60	80	
12. Growth Secondary school enrolment (%)	7	40	60	
13. Rate of qualification of teachers (%)	20	100	100	100
14. Professional and technical training centers		50	106	
15. The rate of admission in tertiary education. (0/00)	1	4	6	
16. Gender equality in tertiary education (F %)	30	40	50	50
17. Gender equality in decision-making positions (% of females)	10	30	40	
18. HIV/AIDS prevalence rate (%)	13	11	8	0
19. Malaria-related mortality (%)	51	30	25	
20. Doctors per 100,000 inhabitants	1.5	5	10	10
21. Population in a good hygienic condition (%)	20	40	60	
22. Nurses per 100,000 inhabitants	16	18	20	20
23. Laboratory technicians per 100,000 inhabitants	2	5	5	
24. Poverty (%< 1 US $/day)	64	40	30	
25. Average GDP growth rate (%)	6.2	8	8	
26. Growth rate of the agricultural sector (%)	9	8	6	
27. Growth rate of the industry sector (%)	7	9	12	
28. Growth rate of the service sector (%)	7	9	11	
29. Ginni Coefficient (income disparity)	0.454	0.400	0.350	
30. Growth national savings (% of GDP)	1	4	6	
31. Growth national investment (% of GDP)	18	23	30	30
32. GDP per capita in US $	220	400	900	
33. Urban population (%)	10	20	30	
34. Agricultural population (%)	90	75	50	
35. Modernized agricultural land (%)	3	20	50	
36. Use of fertilizers (Kg/ha/year)	0.5	8	15	
37. Financial credits to the agricultural sector (%)	1	15	20	
38. Access to clear water (%)	52	80	100	100
39. Agricultural production (kcal/day/person (% needs)	1612	2000	2200	
40. Availability of proteins/person/day (% of needs)	35	55	65	70
41. Road network (km/km2)	0.54	0.56	0.60	
42. Annual electricity consumption (Khw/inhabitants)	30	60	100	
43. Access to electric energy (% of population.)	2	25	35	
44. Land portion against soil erosion (%)	20	80	90	
45. Level of reforestation (ha)				
46. Wood energy in the national energy consumption (%)	94	50	50	
47. Non-agricultural jobs	200.000	500.000	1.400.000	

(Source: Rwanda Vision 2020, 2000)

[1] Explanation for "International level" shown as one of the "Indications" is not given in the text of Vision 2020. The Team interprets that the "international level" implies the levels of developed countries as the final target to be attained.

3.2 Energy and Electricity Development Plan

3.2.1 [DRAFT] National Energy Policy and Strategy (May 2011)

Energy is a key strategic sector for Rwanda because it is a basic requirement for the development of the national economy. The provision of adequate energy infrastructure is essential for the development of industries and businesses especially for the development of energy intensive industries such as mining and for ensuring a high quality service delivery from social institutions such as health facilities, schools, and administrative offices to the Rwandan population. In the future, Rwanda could also become a net exporter of electricity to the region if production exceeds local demand.

The target is to develop over 1000 MW additional generating capacity by 2017. The policy will therefore be reviewed periodically to align itself to Rwanda's strategic requirements.

Rwanda is committed to a sustainable and durable development path that will focus on a green and low carbon development with regard to electricity generation as well as biomass utilization. Rwanda will therefore focus on maximizing the use of its energy resources while at the same time encouraging and participating in the regional initiatives. While developing the energy resources, community involvement will be a priority.

In formulating this policy, the main issues of the energy sector in Rwanda and its linkages with the rest of the economy and the international scene were considered.

These issues include the following:

(a) Rwanda has significant local renewable energy resources, especially hydropower, geothermal, and methane gas that can be developed to improve energy supply.

(b) Planning for modern energy supply especially electricity had been limited in the past and a paradigm shift in energy planning is required to achieve equitable modern energy distribution.

(c) The sector needs large investment in generation, transmission, and distribution and prudent utility practices.

(d) Sustainable development is a big priority for the Rwandan government while also expanding access to sufficient, affordable, reliable, and adequate energy supply.

(e) The energy sector is directly linked to other sectors of the economy, and it is crucial for their functions. The policy framework provides for harmonization with the policies of other sectors of the economy.

(f) The policy shall provide a conducive environment to attract private financing and encourage energy trade and other aspects of partnerships. This is particularly required as the energy sector is currently constrained by inadequate financing.

(g) Competition as a principle to attain efficiency shall apply to the electricity market.

(h) Generation of electric power shall be fully open to public and private investors as independent power producers. Investment shall be fully based on social, economic, and financial criteria that support the development of Rwanda.

(i) Promote enhanced regional cooperation to accelerate development of shared energy resources mainly in hydropower, methane gas, and geothermal.

(j) Institutional and legal issues are addressed in this policy especially in the areas of renewable energy.

In line with the above basic policy, energy development policy was formulated with the prediction of the social index as shown in Table 3-2.

Table 3-2 Annual Average Growth Rates 2008-2020

Item	Units	2008	Annual Average Growth	2020
Population	people	9,886,767	2.3%	13,000,000
GDP	USD in millions	3,460	7.0%	7,800
Exports (goods and services)	USD in millions	405	10.5%	1,342
Imports (goods and services)	USD in millions	903	6.0%	1,817
Households with electricity	Number of households	92,000	21.0%	2,000,000
Biomass (net)	Toe	1,108,600	2.3%	1,453,700
Petroleum products	x1000 m^3/Ml	225	15%	1933
Electricity – energy	GWh	225	25%	3500
Electricity – capacity (incl. regional supplies)	MW	55	294%	1300
Primary energy (gross)	Toe	1,652,500	15%	14,119,945

Toe: tonne of oil equivalent

(Source: National Energy Policy and Strategy, 2011)

Among the various energy sectors, the present status of the electricity sector is summarized as shown in Table 3-3. This table shows that the present installed capacity is 96.44 MW and the available capacity is 86.84 MW. Hydropower shares 56.2% (including 15.5% of domestic facility) and petroleum thermal power occupies 39.2%. The cost for the petroleum thermal power generation is said to be the largest financial burden of Rwanda.

The power demand was predicted up to 2020 based on the social indicators as mentioned in Table 3-2 and others as shown in Table 3-4. The table shows that the power peak demand will reach 1300 MW by 2020.

To cope with the power demand in 2020, Rwanda has set up a target to increase the installed capacity up to 1200 MW by 2017 with diversified energy sources such as hydropower of 306.6 MW (25.6%), geothermal of 310 MW (25.8%), methane of 295.5 MW (24.6%), and peat of 200.0 MW (6.6%), thereby petroleum thermal power would be abolished.

The development plans of each energy resources are shown in Table 3-5 to Table 3-8, whereas the geothermal development plan is shown in Table 3-6. The table shows that a 10 MW power plant will be installed by 2012 and thereafter from 2013 to 2017 power plant of 75 MW will be installed in four steps. Thereby a total of 310 MW will be achieved by 2017.

Table 3-3 Current Electricity Generation Capacity

Category	Name	Installed Capacity (MW)	Available Capacity (MW)
In-house Hydropower	Ntaruka	11.25	11.25
	Mukungwa	12	12
	Gihira	1.8	0 (Rehabilitation)
	Gisenyi	1.2	0 (Rehabilitation)
	Rukarara	9.5	3-8 MW under commissioning
	Rugezi	2.2	Under commissioning
	Subtotal	37.95	
Imported Hydropower	Rusizi 1(SNEL)	3.5	3.5
	Rusizi 2 (SINELAC)	12	11
	Kabale (UETCL)	-	1
	Subtotal	15.5	
Micro Hydropower	Nyamyotsi I	0.1	0.1
	Mutobo	0.2	0.2
	Agatobwe	0.2	0.2
	Nyamyotsi II	0.1	0.1
	Murunda (REPRO)	0.1	0.1
	Rushaki	0.04	0.04
	Subtotal	0.74	
In-house Thermal Power	Jabana (Diesel)	7.8	7.8
	Jabana (Heavy Fuel Oil)	20	20
	Subtotal	27.8	
Rental Thermal Power	Aggreko (Gikondo)	10	10
Methane to Power	KP1	4.2	1.3
Solar Power	Kigali Solar	0.25	0.25
Total		**96.44**	**86.84**

(Source: National Energy Policy and Strategy, 2011)

Table 3-4 Energy Demand Projections 2008-2020

	2008	2012	2015	2020
Peak power demand (MW)	55	165	700	1,300
Energy demand after losses (GWh)	225	460	1,500	2,010
Percent (%) households with electricity	6%	16%	35%	60%
Percent (%) energy consumed by households	38%	64%	75%	83%

(Source: National Energy Policy and Strategy, 2011)

Table 3-5 Possible Additional Hydropower Capacity by 2017

Expected Commissioning	Responsible	Project	Status	Expected Capacity (MW)
2011	GTZ	2 micro hydros*	Under construction	1
	GOR	6 micro hydros**	Under construction	4
	BTC	3 micro hydros***	Under construction	3.2
2013	CTB/EU/GoR	Rukarara II	-	2
	GoR	Nyabarongo I Hydro	Under construction	28
2014	GoR	Ntaruka A	-	2
	GoR/IPP (REFAD)	Rukarara IV/ Mushishiro Hydro	-	5
	GoR/IPP (Rwanda Mountain Tea)	Giciye Micro Hydro	-	4.5
2015	GoR/Burundi	Akanyaru Hydro	-	3.9
2016	Rwanda/BR/DRC	Ruzizi III Hydro	F/S	48
	Rwanda/TZ/BR	Rusumo Hydro	F/S	21
2017	Nyabarongo II	Nyabarongo II Hydro multipurpose	-	17
	Rwanda/DRC/BR	Ruzizi IV Hydro	Pre F/S	96
	GoR/IPPs	Micro hydros	-	50
Total				**306.6**

* Mazimeru, Musarara; **Janja, MukungwaII, Nyabahanga,Nyrabuhombohombo, Gashashi, Nshili I; ***Nkora, Keya, Cyimbili;

(Source : Rwanda Vision 2020, 2000)

Table 3-6 Possible Geothermal Projects by 2017

Expected Commissioning	Responsible	Project	Status	Expected Capacity (MW)
2013	GoR/IPP	Karisimbi Early Well; Head Generation Unit	Drilling before end of 2011	10
2014	GoR/IPP	Geothermal I	-	75
2016	GoR/IPP	Geothermal II	-	75
2016	GoR/IPP	Geothermal III	-	75
2017	GoR/IPP	Geothermal IV	-	75
Total				**310**

(Source: National Energy Policy and Strategy, 2011)

Table 3-7 Possible Additional Methane to Power Project by 2017 [2]

Expected Commissioning	Responsible	Project	Status	Expected Capacity (MWe)
2012	Israel Africa	Lake Kivu methane project	-	3.5
	Kivu watt		-	25
2013	Israel Africa		-	30
	RIG/REC		-	25
2014	Kivu watt	-	-	75
2015	Israel Africa	-	-	15
	REC	-	-	22
	DRC & Rwanda	-	-	50
2016		-	-	50
Total				**295.5**

(Source: Electricity Development Strategy (2011-2017), 2011)

Table 3-8 Possible Peat to Power Project by 2017

Expected Commissioning	Responsible	Project	Status	Expected Capacity (MW)
2012	GoR/RIG/REC	Peat to power	Under negotiations	15
2013	PUNJ LLOYD	Peat to power	F/S	100
2016	IPP to be identified	Peat to power	-	85
Total				**200**

(Source: National Energy Policy and Strategy, 2011)

3.2.2 [DRAFT] Electricity Development Strategy (2011-2017)

This paper discusses the strategy to be adopted by the Government of Rwanda to develop its electricity sector through a strategic approach to planning and capacity building, and policy and regulatory reform, which will improve its ability to promote private sector participation and manage the delivery of new generation projects.

One of the key challenges in the electricity sector is the present low generation capacity, which is inadequate to meet the increasing demand and expand access to electricity. To overcome this challenge, the sector has to develop a mix of electricity generation resources including hydropower, methane gas-to-power, geothermal, peat-to-power, diesel, solar, biogas, and waste to energy projects.

The primary goal of the accelerated electricity development strategy for the period 2011 to 2017 is to generate the planned additional 1000 MW of electricity by developing least cost electricity generation options using indigenous energy resources and also from shared energy resources with the neighboring countries of DRC, Burundi, and

[2] Data from Electricity Development Strategy (2011-2017) are used for Possible Additional Methane.

Tanzania.

The “Electric Development Plan (2011-2017)” was formulated in line with the above basic policy entitled the “National Energy Policy and Strategy” with modifications, showing the “Action plan” as shown in Table 3-9.

Table 3-9 Compact Action Plan for 2011 to 2017 to Increase Generation Capacity from 96.44 MW to 1000 MW

Expected Commissioning	Plant Size and Configuration/ Length and Size of Transmission and Distribution Lines			Responsibility	Capital Cost (USD in millions)	Generation Option/ Transmission and Distribution Location	Added Capacity (MW)	Total Capacity Added (MW)
2011	1	x	20	GoR		Diesel	20	28.4
	3			GTZ	5	Micro hydro	1	
	7	x		GOR	0	6 Micro hydros	4	
	3	x		CTB	10	3 Micro hydros + MV &LV	3.2	
	50 solar PV installations in health centers			CTB	1.5	Solar PV	0.2	
	Transmission line- 100 km			CTB	10	Rutsiro-Rubavu and Nyaruguru		
2012	1	x	3.5	Israel Africa	14	Methane	3.5	53.98
	1	x	25	KivuWatt	75	Methane	25	
	1	x	10	GoR/IPP	35	Geothermal	10	
	1	x	15	GoR/PEC	25	Peat	15	
	Electrification of 300 rural schools			GoR/EU	7.5	Solar PV	0.48	
	Transmission line- 65 km			EWSA	20	Karisimbi to Musanze		
	Transmission line- 180 km			EWSA	54	Kibuye-Rubavu- Kigali		
	Distribution line (MV) 450 km			EWSA	27	Countrywide interconnections		
	Access – 300,000 connections			EWSA	360	Countrywide		
	Distribution substations 400 MVA+ 3 *220 /110 kV substations			EWSA	23	Countrywide		
2013	1	x	30	Israel Africa	90	Methane	30	260
	1	x	25	REC	75	Methane	25	
	1	x	75	GoR/IPP	225	Geothermal I	75	
	1	x	28	GOR	0	Nyabarongo I Hydro	28	
	1	x	2	CTB/EU/GoR	10	Rukarara II	2	
	2	x	50	PUNJ	300	Peat	100	
2014	1	x	75	KivuWatt	225	Methane	75	161.5
	1	x	75	GoR/IPP	225	Geothermal II	75	
	1	x	5	REFAD	18	RukararaIV/Mushishiro	5	
	1	x	4.5	GoR/RMT	16	Giciye Micro hydro	4.5	
	1	x	2	GoR	10	Ntaruka A	2	
	Distribution line (MV)- 450 km			EWSA	27	Countrywide		

Expected Commissioning	Plant Size and Configuration/ Length and Size of Transmission and Distribution Lines			Responsibility	Capital Cost (USD in millions)	Generation Option/ Transmission and Distribution Location	Added Capacity (MW)	Total Capacity Added (MW)
	Access – 325,000 connections			EWSA	390	Countrywide		
	Distribution substations 400 MVA+ 1*220 /110 kV substations			EWSA	13	Countrywide		
2015	1	x	15	Israel Africa	45	Methane	15	90.9
	1	x	22	REC	66	Methane	22	
	1	x	3.9	GoR/Burundi	35	Akanyaru	3.9	
	1	x	50	DRC & Rwanda	150	Methane	50	
	Transmission line- 130 km			EWSA	40	Countrywide interconnections		
2016	1	x	75	GoR/IPP	225	Geothermal III	75	229
	1	x	48	Rwanda/BR/DRC	150	Ruzizi III Hydro	48	
	1	x	21	GoR/Tz/Burundi	200	Rusumo Falls	21	
	1	x	85	IPP	225	Peat	85	
	Transmission line-15 km			EWSA	5	Geothermal III & IV to Gisenyi		
	Transmission line- 10 km			EWSA	3	Ruzizi III to Ruzizi IV		
	Transmission line- 85 km			EWSA	25	Ruzizi III to Kibuye		
2017	1	x	50	DRC & Rwanda	150	Methane	50	288
	1	x	75	GoR/IPP	225	Geothermal IV	75	
	1	x	17	Nyabarongo II	158	Hydro multipurpose	17	
	1	x	96	Rwanda/DRC/BR	240	Ruzizi IV Hydro	96	
			50	GoR/IPPs	200	Micro hydros	50	
	Transmission line- 85 km			EWSA	25	Rusumo to Kigali		
	Transmission line-180 km			EWSA	55	Countrywide Interconnections		
	Distribution line (MV)- 500 km			EWSA	30	Countrywide		
	Access- 400,000 connections			EWSA	480	Countrywide		
	Distribution substations 400 MVA+ 3*220 /110 kV substations			EWSA	23	Countrywide		
Total					5,046		1,111.78	

(Source: Electricity Development Strategy (2011-2017)

3.3 Geothermal Development Plan

3.3.1 [DRAFT] Rwanda Geothermal Resources Exploration and Development for 2011-2017 (December 2010)

This report is an overview of the activities required for accelerated development of the geothermal resources in Rwanda to contribute 310 MWe to the planned electricity generation mix of 1000 MWe by 2017. The outline of the report is presented below.

- Current status in geothermal exploration and development,
- Issues affecting geothermal development,
- Planned scope of work,
- Suggested strategy for exploration and development,
- Timelines,
- Indicative costs,
- Environmental considerations,
- Stakeholder's involvement especially the role of communities in geothermal development, and
- Required support from donors and investors.

【Current Status in Geothermal Exploration and Development】

Geothermal potential in Rwanda is estimated at over 700 MWe. The exploration has just started as shown in Table 3-10.

Table 3-10 Status of Geothermal Exploration and Development

Prospect	Inception Report	Surface Reconnaissance Studies	Detailed Surface Studies	Wells Sited	Wells Drilled
Western Region Karisimbi, Gisenyi, Kinigi	Yes	Yes	No	No	No
Southern Region (Bugarama)	No	No	No	No	No
Other areas	No	No	No	No	No

(Source: Rwanda Geothermal Resourced Exploration and Development for 2011-2017)

【Issues Affecting Geothermal Development】

Issues affecting geothermal development are grouped into five categories. Various types of issues are recognized as shown in Table 3-11.

Table 3-11 Issues Affecting Geothermal Development

Category	Issues
Institutional	• Inadequate facilities • Inadequate and well-motivated human resources • Inadequate and unpredictable funding • No local and regional collaboration with all stakeholders • Serious limitations in the implementation process due to lengthy bureaucratic–procedures • Unfavorable and sometimes unrealistic donor conditions
・Technical	• Do we have geothermal resources, how deep and what is the temperature and fluid chemistry?- Drill and test exploration wells • Inadequate data to conclusively determine the geothermal potential-Drilling + additional exploration • Where do we drill and where do we get water for drilling?
・Legal and Regulatory	• No existing legal and regulatory framework for geothermal exploration and development • No resource management act – Geothermal same area as oil and gas • Mechanism for giving out concessions
・Policy	• Incentives and tariffs – How to attract foreign investors? • Foreign exchange risk management • Local community, local governments, and local private investors participation • Indirect uses of geothermal resources
・Perception	• Geothermal perceived as risky and expensive

(Source: Rwanda Geothermal Resourced Exploration and Development for 2011-2017)

【Scope of Works】

The scope of works to cope with the issues mentioned above is shown in Table 3-12.

Table 3-12 Scope of Work

Category	Scope of Works for the Issues
Overall	• Discuss, involve, and seek concurrence of all stakeholders to have a shared commitment, vision and mission to achieve geothermal development.
Institutional	• Source for funding as well as for training, equipment, and geothermal development. • Recruit and train staff both locally and overseas (including on the-job-training).
Technical	• Carry out detailed surface studies and exploration drilling in all four geothermal prospects. ➢ Start with Karisimbi detailed surface studies and three exploration drilling wells. ➢ Carry out simultaneous studies in Karisimbi, Gisenyi, Bugarama, and Kinigi.

	➢ Formulate best and most economic development scenarios • Drill three exploration wells in each of the four prospects after detailed studies ➢ Locate drilling targets and water sources and environment impact assessment (EIA) ➢ Encourage use of wellhead generating units as proof of concept ➢ Well testing and reservoir modeling
Legal and Regulatory	• Legal and regulatory framework • Concession procedures- Do we give concessions only to Rwanda companies?
Policy	• Prepare expression of interests to gauge interest in exploration and development of geothermal resources • Put in place incentives and tariffs to attract foreign investors • Focus on indirect uses of geothermal resources
Perception	• Engage local communities, local governments, and local private investors participation • Showcase geothermal potential in Rwanda through workshops and conferences • Change perception- Share information through workshops, attending conferences for policy makers and opinion leaders.

(Source: Rwanda Geothermal Resourced Exploration and Development for 2011-2017, modified by the JICA Team)

【Strategy for Exploration and Development】

As a strategy for exploration and development, four steps are proposed as shown in Table 3-13. In order to achieve the target of 2017, a total of 20 wells will be drilled in three prospects in Step-3.

Table 3-13 Strategy for Exploration and Development

Step	Description
Step 1	• Data search and acquisition, desktop study, reconnaissance survey, and project plan
Step 2	• Detailed geoscientific studies to be carried in phases. • Specific objectives of exploration studies in a geothermal prospect.
Step 3	• Drill three exploration wells in each prospect, drill three field appraisal wells in each field, and drill a further 14 production wells, conceptual modeling, prefeasibility studies and review meetings. • If the exploration wells are successful, use wellhead generating units to generate 10 MWe. Where possible mobilize local resources for infrastructure development.
Step 4	• Production drilling and monitoring for 4 X 75 MWe plants. • EIA, feasibility studies, and power plant design construction.

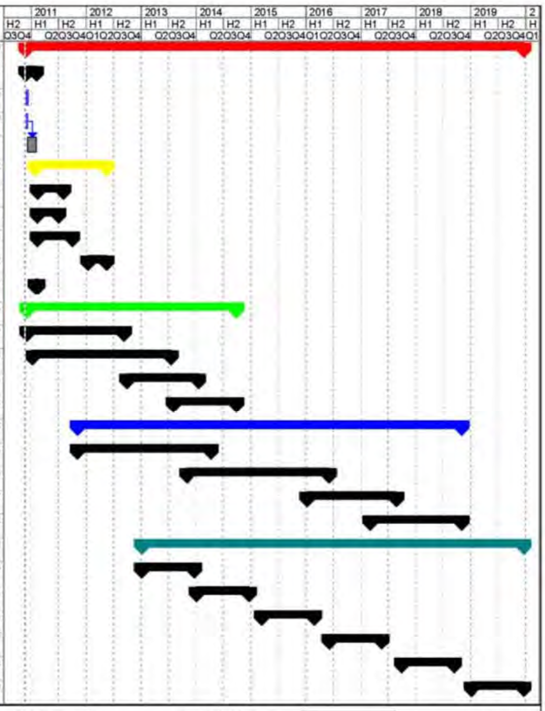
(Source: Rwanda Geothermal Resourced Exploration and Development for 2011-2017, modified by the JICA Team)

【Time Schedule】

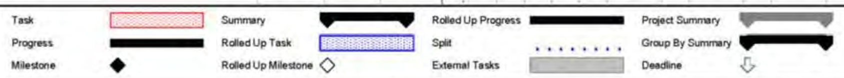
Table 3-14 shows the overall time schedule to 2019. By 2017, a total of 300 MWe of facilities will be built by installing 2 x 75 MWe each in Karisimbi and Gisenyi. By 2019, 1 x 75 MWe each for Kinigi and Bugarama will be installed.

Table 3-14 Time Schedule

ID	Task Name	Duration	Start	Finish
1	Rwanda Geothermal Resources Exploration and Development	2838 days	11/29/10	12/21/19
2	Exploration and Development Strategy	60 days	11/29/10	2/5/11
3	Draft Strategy	10 days	12/1/10	12/11/10
4	Preparation of inception reports	10 days	11/29/10	12/9/10
5	Draft legal and regulatory framework	50 days	12/10/10	2/5/11
6	Detailed Surface studies	406 days	2/1/11	5/18/12
7	Karisimbi Additional Surface Studies	148 days	2/14/11	8/4/11
15	Gisenyi Detailed surface studies	122 days	2/14/11	7/5/11
23	Bugarama surface studies	200 days	2/14/11	10/4/11
31	Kinigi surface studies	107 days	1/16/12	5/18/12
38	Other areas	14 days	2/1/11	2/16/11
43	Exploration & Appraisal Drilling	1194 days	12/6/10	9/27/14
44	Karisimbi Exploration & Appraisal Drilling & Well Heads	554 days	12/6/10	9/11/12
55	Gisenyi Exploration & Appraisal Drilling & well heads	792 days	1/10/11	7/20/13
65	Bugarama Exploration Drilling	408 days	10/1/12	1/18/14
75	Kinigi Exploration Drilling	360 days	8/5/13	9/27/14
85	production drilling	2190 days	11/7/11	11/3/18
86	Karisimbi Production drilling (150 Mwe)	762 days	11/7/11	4/12/14
95	Gisenyi Production drilling (150 Mwe)	810 days	11/4/13	6/4/16
104	Bugarama appraisal & production drilling	510 days	1/11/16	8/26/17
112	Kinigi appraisal & production drilling	522 days	3/6/17	11/3/18
120	Power plant construction & monitoring	2178 days	1/7/13	12/21/19
121	Karisimbi I (75MWe)	300 days	1/7/13	12/21/13
126	Karisimbi II (75MWe)	300 days	1/6/14	12/20/14
131	Gisenyi I (75 MWe)	300 days	3/16/15	2/27/16
136	Gisenyi II (75 Mwe)	300 days	6/6/16	5/20/17
141	Bugarama (75 Mwe)	300 days	10/2/17	9/15/18
146	Kinigi (75MWE)	300 days	1/7/19	12/21/19



Project: Exploration Strategy
Date: 11/18/10



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(Source: Rwanda Geothermal Resourced Exploration and Development for 2011-2017)

3.4 Development Partner Project Matrix-Energy Sector (January 2012)

The energy sector projects by donors are listed in Table 3-15

The following projects are also conducted by JICA.

- Data collection survey on geothermal development in 2013

To conduct data/information collection through review of existing data/information, site reconnaissance, interview with people concerned and etc.

To prepare a proposal on "geothermal development policy of Rwanda" and a technical proposals on test well drilling and data acquisition from the test wells.

To prepare/organize basic information in which JICA should consider/investigate directions/policies of assistance to Rwanda for geothermal development.

- **Study for the preparation of a detailed plan to proceed the project to aid designing of electric power development plan for the promotion of sustainable geothermal energy development in Rwanda**

The Rwandan government requested the Japanese government to help design the geothermal power development as well as upgrade the existing electric power development focusing on the design for geothermal development plan, which is consistent with the power development plan and capacity building for the ability to design.

While this project is being conducteded, the design for power development plan for promoting geothermal energy, the JICA Team is classifying, collecting, and analyzing the necessary information for the design of the electric power development and the detailed plan.

Table 3-15 Energy Sector Project by Donors

Donor	Stage	Detailed Specifications	Period	Fund
European Union	In preparation	Activities to be defined, most probably in cooperation with other development partners.	2014-2020	Possibly a focal point for the EU-Rwanda cooperation within the 11th European Development Fund
Belgium /BTC	Planned	Energy component of the indicative cooperation program	2011-2014	EUR 55 million grant EUR 27 million (Geothermal)
AFD	Planned	Development of a pilot-production geothermal unit at Karisimbi site		EUR 10 million soft loan
Japan/JICA	 Planned	Training courses (for about three weeks) geothermal energy development facilitation seminar geothermal master plan project short-term geothermal experts	in 2011 and 2012 14 December 2011 March 2013	

(Source: JICA Team)

3.5 Assistance from Donors for Geothermal Development

【Karisimbi Geothermal Prospect】

- UNU-GTP has implemented the six months technical training program for geothermal development since 24th June 2013 under ICEIDA contract for EWSA. The training is given by experts from ISOR to the staff of EWSA GDU (Geothermal Development Unit), covering such subjects as geothermal well and drilling technology, geological exploration of geothermal systems, chemical exploration of geothermal systems, and environmental impact assessment. Together with the training, a stereo-microscope and polarizing microscope; and vessels for cutting samples have been provided as tools for geological survey. The program was opened with a five days intensive course followed by On-the-Job training on site toward the end of the drilling. The program of the five days course is as attached as **Attachment- 6**.
- Nordic Development Fund has been made available for supervision of the exploratory drilling being conducted by a Chinese drilling contractor. An supervisory engineer has been deployed from an Iceland company – Reykjavik Geothermal. One engineer is assigned to the site for three weeks followed by a replacement engineer for the following three weeks, which will continue for 24 months.
- Belgian Technical Cooperation (BTC) assists EWSA in implementing of EIA. An British based consultants is conducting EIA activities.

【Kinigi Geothermal Prospect 】

- Kinigi is located on the southeast flank of Mt. Visoke, about 15km east Karisimbi drilling site. BTC is scheduled to provide financial assistance of EUR 27million for exploratory drillings in Kinigi, and this will have to be confirmed in the beginning of 2014; according to the interview to the head of EWSA-GDU.

CHAPTER 4 SUMMARY OF PREVIOUS STUDIES ON GEOTHERMAL POTENTIAL

4.1 Reconnaissance Geothermique de la Republique du Rwanda (in French) by the French Bureau of Geology and Mining Research (BRGM) (1983)

The original article was not made available to the JICA Team. The following summary was taken from an article by U. Ruragarama and R. Uhorakeye (2010)[3]:

Geothermal exploration started in 1982 with the BRGM. Reconnaissance missions and limited surface exploration works with a focus on hydrogeological data collection were carried out in the western, northern, and southern parts of the country. Eighteen hydrothermal springs of the country were identified and analyzed for the study. The hottest spring was located at the northeastern shores of Lake Kivu. The major areas which have been investigated in the country are the following:

- In the Western Province, Mashyuza (Rusizi District), Gisenyi (Rubanu District), and Kibuye (Karongi District);
- In the Southern Province, Ntaresi (Karaba District); and
- In the Northern Province (Musanze District).

Another article[4] describes, "In 1983, the BRGM identified Gisenyi and Bugarama as potential sites for geothermal with estimated reservoir temperatures of over 100 °C".

4.2 Preliminary Assessment of Rwanda's Geothermal Energy Development Potential by Chevron (27 November 2006)

In 2007, Chevron conducted a preliminary geothermal potential survey in Gisenyi in the northwestern area and Mashyuza in the southern area of Rwanda using geothermometer technique. A summary of the results is shown in Table 4-1. According to the geothermometers, the reservoir temperature is estimated to be between 150 and 210 °C. The quartz geothermometer yields a temperature of 110 to 141 °C, while the N-K-Ca geothermometer provides a temperature of 181 °C. When the magnesium correction is made for the N-K-Ca geothermometer the estimated reservoir temperature drops to 74 °C. The Giggenbach NKM geothermometer can also be applied to water in Gisenyi by assuming that the Gisenyi hot spring waters are a mixture of equilibrated

[3] Uwera Rutagarama and Theoneste Uhorakeye, 2010, "Geothermal Development in Rwanda: Proceeding an Alternative to the Energy Crisis". World Geothermal Congress 2010, Bali Indonesia, 25-29 April 2010

[4] Stephen Onacha, 2011, Rwanda Geothermal Resources Development Country Update: Proceedings, Kenya Geothermal Conference 2011

hot reservoir water with cooler magnesium enriched groundwater. This geothermometer suggests a reservoir temperature of 210 °C.

Table 4-1 Results of the Geothermometer Survey in Gisenyi and Mashyuza

Prospect	Measured Temp. (°C)	Na-K (°C)	Na-K-Ca (°C)	Na-K-Ca-Mg (°C)	Quartz (°C)	Sources
Gisenyi	70 to 75	161 to 212	181	74	141	1982 Samples
		161 to 212	181	72	110	2006 Samples
Mashyuza	42 to 54	241 to 272	204 to 205	21 to 23	122 to 128	1982 Samples
		241 to 272	202 to 205	21 to 27	101 to 102	2006 Samples

Note: Mashyuza is not included in the Karisimbi geothermal prospect.
(Source: Chevron, 27 November 2006)

If reservoir temperatures of 150 to 210 °C are confirmed through exploration drilling, then Gisenyi's resources could be economically exploited using binary technology.

The following two geothermal models are considered in the report:

- Model-1 : The most likely geologic model for the Gisenyi prospect is that the reservoir waters are rising vertically along a normal fault near the eastern boundary of the East African Rift Valley. The fluids could be mixing along their flow path from the reservoir with low temperature groundwater or water from Lake Kivu. The reservoir waters may also be degassing during their ascent as suggested by the relatively small amount of gas being vented from the hot springs. There is a risk that reservoir temperature will be too low for power generation.
- Model-2 : An alternative and less likely model is that the hot springs represent a distal outflow of fluid from a high temperature reservoir associated with the Virunga Volcanoes to the north. If this is the case, the potential would exist for finding a higher temperature resource than suggested by the chemical geothermometry. Also, it is conceivable that the prospective area extends westward toward the center of Lake Kivu. There is some weak evidence that higher temperature geothermal fluids are being released in the lake bottom.

Surface geological survey, geochemistry survey, geophysical survey, bathymetric survey, and exploratory well drilling of Lake Kivu, were recommended in the report.

4.3 Feasibility Design of an Integrated Single-Flash Binary Pilot Power Plant in NW-Rwanda by Theoneste Uhorakeye (2008)

The purpose of the report is to pre-design a pilot geothermal power plant intended to be used in the country with the assumption that the reservoir temperature and enthalpy are 210 °C and 900 kJ/kg, respectively, based on the results of preliminary potential surveys by BGRM (1983) and Chevron (2006). As a result, 85 kWe will be generated with a binary generation system from 1 kg/s geothermal fluid of 900 kJ/kg. The report does not deal with the geothermal potential itself.

4.4 Geothermal Potential Assessment in the Virunga Geothermal Prospect, Northern Rwanda by the Federal Institute for Geosciences and Natural Resources (BGR) (1 August 2009)

The BGR of Germany conducted a comprehensive surface geothermal potential assessment that included geological remote sensing, geochemical survey, geophysical survey, and soil gas survey. A summary of the potential assessment is as follows:

【Geology and Geological Structure】

- The western branch of the rift is characterized by paucity of volcanism comparative to the Kenyan and Ethiopian rifts. Whereas the volcanism and tectonic activity in the eastern branch commenced about 30 million years ago, volcanic activity in the western branch commenced about 12 megaannum (Ma) in the north near Lake Albert and about 7 Ma ago in the Tanganyika rift (Ebinger, 1989). The most recent ages of Karisimbi lavas vary between 240,000 and 90,000 years (Dancon et Demange, 1983).
- Geothermal potential is expected to be maximum in the eastern part of the accommodation zone bounding the Butare block, roughly southeast of Karisimbi Volcano.
- Surface and underground water are expected to flow in abundance; faulting is high; and heat sources are at proximity.

【Geochemistry】

- The springs emanated from the old basement rock and were more likely to have equilibrated with quartz than chalcedony. The possible temperatures of the six samples are shown in Table 4-2.

Table 4-2 Possible Subsurface Temperature

Location	Likely Temperature Range (°C)
Mbonyebyombi	110–130
Mpatsi	130–150
Karago	120–140
Giseny	105–130
Iriba	110–120
Nyakagen	110–140

(Source: BGR, 2009)

The readings of the hydrocarbon geothermometers are presented in Table 4-3. It is not certain that the temperature reflects upon equilibrium in geothermal systems. It is possible that they show some very old temperatures but the one from Ntango is still likely to be reflecting something different.

Table 4-3 Hydrocarbon Geothermometer Readings

Location	C1/C2 Temperature (°C)
Ntango	342
Mubona	232
Gisenyi	209
Karago	226

(Source: BGR, 2009)

Based from Table 4-2 and Table 4-3 the following are observed:

- Mbonyebyombi, Mpatsi, Karago, and Gisenyi suggest a geothermal system in which the temperature probably exceeds 100 °C. Two other locations, Iriba and Nyakageni, also suggest geothermal characteristics and have possibly similar temperature;
- Gisenyi and Karago are probably the most promising locations; and
- None of these locations suggests a high-temperature geothermal system but they might be suitable for the production of electricity in binary power plants.

【Geophysics（Magnetotelluric (MT) Survey and Time-domain Electromagnetic (TEM) Survey）】

- The results of the resistivity survey suggested that medium- to high-temperature geothermal system/s might exist in the southern slopes of Karisimbi Volcano.
- The heat source of the geothermal system/s is structurally controlled and associated with the latest phases of trachytic magmatism at Karisimbi.

【Gas Geochemistry】

- The main results of the surface geochemical survey showed that the spatial distribution of soil degassing suggests a structural control of the diffuse emissions.

- The results delineated two main diffuse degassing structures. The major one following a SW-NE direction along the main fault (Muhungwe Fault) between lava plains and Precambrian units, and the secondary one following a NW-SE direction and perpendicular to the SW-NE directions.
- Relatively high concentrations of different geochemical parameters were observed along these two main structures, suggesting an endogenous contribution to the surface degassing. The potential existence of an underlying volcanic-hydrothermal system and vertical permeable structures could be the cause of these observed surface anomalies.

【Conclusions】

From the above survey results, the report concluded the following points:

- The main geological structure, dominating the geothermal prospect, is the Muhungwe Fault with a strike direction of WSW-ENE.
- Geophysical studies detected a low resistivity anomaly along the SW flank of the Karisimbi Central Volcano passing through Mukamira to Lake Karago.
- Studies on diffuse soil degassing detected the same subsurface structures as indicated by the results of the geophysical measurements.
- Geothermometers suggest reservoir temperature in the range of 105 °C to 140 °C.

4.5 Assessing Generating Capacity of Rwanda Geothermal Field from Green Field Data Only by Uwera Rutagarama (2009)

This article assesses the geothermal potential of Rwanda as well as Karisimbi by using various methodologies along with existing data and information. The author, before describing the assessment results, pointed out that "resource assessment is of only transitory value and must be updated periodically".

"Resource assessment is a statement made at a given time using a given data set and a given set of assumptions concerning economics, technology, etc. Both data and the assumptions can change rapidly: the former primarily in response to exploration activities, the latter in response to technology development, economics, environmental constraints, social policy, …Consequently a resource assessment is of only transitory value and must be updated periodically" (Muffler, 1981).

Five methodologies were applied for the potential assessment. The results, as taken from the article, are shown in Table 4-4.

1. Counting of volcanoes;
2. Monte Carlo assessment of natural heat flux;
3. Surface thermal flux;
4. Soil CO_2 flux; and
5. Monte Carlo assessment with various parameters.

Table 4-4 Summary of Generating Capacity Estimates for Rwanda

Method	Most Likely (MWe)	Error (MWe)
Counting of volcanoes	100	
Surface heat flux	80	± 40
Surface gas flux	17	± 1
Monte Carlo assessment (country scale)	26	± 12
Monte Carlo assessment of Karisimbi	345	± 150
Average	120	± 50

(Source: U. Rutagarama, 2009)

Based on Table 4-4, the article concluded the following:

- In the case of the potential as a whole, results ranged from 100 MWe in the counting of volcanoes method to 26 MWe in the Monte Carlo method, by considering that the mineable heat is transferred by steady heat conduction only.
- In the case of the Karisimbi volcano field, results differed from 17 MWe in the surface CO_2 flux to 80±40 MWe in the surface thermal flux, and finally, 345 MWe in the Monte Carlo simulation, in which heat and mass reserves are aggressively mined.
- The average generation capacity from the methods is approximately 120 MWe, of which 50 MWe can be considered as a reasonable initial target for geothermal generation in Rwanda.

The maximum potential is obtained from the Monte Carlo assessment of Karisimbi. It may be useful to refer the parameters adopted for the assessment in order to interpret the outcome from the Monte Carlo assessment. The parameters adopted are shown in Table 4-5 and Table 4-6 .

Table 4-5 Parameters for the Monte Carlo Assessment of Natural Heat Flux

Parameter	Unit	Most Likely	Probability Distribution		
			Type of Distribution	Minimum Value	Maximum Value
Area	km^2	26,338	Constant	-	-
Thermal Conductivity	W/m °C	2.5	Triangular	2	3
Thermal Gradient	°C/km	40	Rectangular	20	60

(Source: U. Rutagarama, 2009)

Table 4-6 Parameters for the Monte Carlo Assessment with Various Parameters

Parameter	Unit	Most Likely	Probability Distribution		
			Type of Distribution	Minimum Value	Maximum Value
Area	km^2	40	Triangular	30	50
Thickness	m	1250	Triangular	1000	1500
Rock Density	kg/m^3	2750	Triangular	2500	3000
Rock Specific Heat	kJ/kg	0.84	Triangular	0.79	0.9
Porosity	%	0.1	Triangular	0.05	0.15
Temperature	°C	240	Triangular	200	300
Base Temperature	°C	155	Constant	-	-
Fluid Density	kg/m^3	814	Constant	-	-
Fluid Specific Heat	kJ/kg °C	4.78	Constant	-	-
Recovery Factor	%	0.2	Triangular	0.15	0.25
Conversion Efficiency	%	0.13	Triangular	0.1	0.15
Plant Life	year	30	Constant	-	-
Load Factor	%	0.95	Constant	-	-

(Source: U. Rutagarama, 2009)

It is noted that the assessment assumed that the reservoir temperature should range from 200 °C to 300 °C. Most likely the temperature would be 240 °C.

4.6 Geothermal Potential Appraisal of Karisimbi Prospect, Rwanda (Combined Report) by Kenya Electricity Generating Company (KenGen) (March 2010)

This survey was conducted mainly based on the recommendation of the report of BGR (2009). The surveys conducted are as follows:

- Geophysical survey: MT survey (60 points), TEM survey (55 points);
- Geochemical survey (soil gas survey: CO_2, Hg, and radon):140 samples;
- Environmental baseline survey; and
- Hydrogeological survey.

Summaries are described hereunder for the results of the surveys except for the environmental baseline survey.

【Geophysical Survey: MT Survey and TEM Survey】

- Low resistivity (<20 Ωm) zones are observed in the following areas;
  - The south of the Karisimbi summit and near Lake Karago. At shallow depths, these two are separate but merge at depth.
  - Northeast of the Karisimbi Massif.
- The low resistivity anomaly is attributed to higher subsurface temperature, higher degree of hydrothermal alteration, and higher permeability.
- The large low resistivity anomaly body observed at a location about 5 km deep to the south of Karisimbi Volcano was interpreted to be due to a conductive body, inferred to be magma intruded into the granitic basement rock which is believed to be the heat source of this geothermal system.
- The low resistivity areas are coincident with regional NE-NW trending faults that cut across the rift floor through the geothermal prospect. An interpretation is that these faults control fluid flow into the geothermal system and suggests that the recharge of the system along these, faults from the higher area.

【Geochemical Survey: CO_2, Hg, and Radon】

- Zones that indicate anomalous radon counts and high carbon dioxide value fall in the NE-SW and NW-SE directions, conceding with lineaments or fractured zones as indicated also in the BGR report in 2009.
- High values of $^{222}R/CO_2$ and $^{222}Rn/^{220}Rn$ are observed in Kabatwa, southwest of Karisimbi Volcano, suggesting upflow of gases in these areas.
- As for mercury, very low concentration of mercury was observed only at three points. No meaningful analysis is possible.

【Hydrogeological Survey】

- The main recharges from the highland are postulated to be the Karisimbi Massif and the other volcanoes nearby.
- The main recharge for deep aquifers would be a combination from the high areas and from the rift. The recharges from the highland into the prospect are expected to flow deep, tortuous, and long paths through the main rift fault.
- There are springs and swampy ground. The occurrence of the swamps is associated with an area where numerous faults are sealed by blanketing the

latest phases of trachytic lava flows from Karisimbi.

- It is postulated that the paucity of geothermal manifestation in the area could also be due to blanketing by the lava flows.
- The groundwater of Karisimbi area is classified as bicarbonate type. Values of magnesium content suggest that the area is adequately recharged by groundwater flow systems.
- The distribution of high concentrations of sulphate in the groundwater of Karago, Buserua, and Mbonyebyombihas suggests two discrete sources of magma chambers as the sources of heat in the area.

【Geothermal Potential】

- The potential area has been determined using the combined MT/TEM 20 Ohm0m resistivity distribution at 1,000 m below sea level (about 3.5 km from the surface) around the caldera, and at sea level for areas below Lake Karago where the reservoir appears shallower.
- Using the experience gained from the Olkaria geothermal field where about 15 MWe is generated per km^2, it was estimated that 300 MWe can be generated from the identified resource in Karisimbi.

【Conclusions】

- A geothermal system exists in Karisimbi Volcano. It is possibly restricted to the regions around the southern slopes and trends to the southeast through the town of Mukamira toward Lake Karago.
- The presence of Karisimbi Volcano would imply the availability of a reliable heat source.
- From geochemical data analysis (BGR report in 2009), it was postulated that the system is of medium temperature (100-200 °C).
- Such temperature is ideal for binary cycle electricity generation and direct uses.

【Recommendations】

- The first exploratory drilling, KW-1, will be in Kabatwa, southwest of Karisimbi Volcano.
- The second exploratory drilling, KW-2, will be at an area 2-3 km east of KW-1.
- If the potential would be confirmed from KW-1 and KW-2, a third exploration well should be located at a point 1 km south of Mukamira, southeast of Kabatwa.
- It is recommended that the three exploration wells be drilled directionally to

intersect as many structures as possible that are assumed to be conducting geothermal fluid. The reservoir is inferred to be deep, ranging between 2,000 and 3,000 m.

4.7 Rwanda Geothermal Resources Potential by the Ministry of Infrastructure, Republic of Rwanda (1 December 2011)

The geothermal potential of Rwanda based on the evaluation of surface geoscientific data was estimated to be more than 700 MW. This is only an estimate that needs to be confirmed by deep exploration drilling of at least three exploration wells in each prospect. The evaluation of the geothermal potential is based on the resistivity data which showed that there could be a geothermal field in the depths of Karisimbi Volcano, Gisenyi, and Kinigi. The heat source of the geothermal systems was estimated to be at a depth of more than 6 km. The summary of this report is shown in Table 4-7 below.

Table 4-7 List of Geothermal Areas, Potential Resources, and Required Work

Geothermal Prospect	Karisimbi	Gisenyi	Kinigi	Bugarama	Other Area	Total
Approximate Resource Area (km^2)	25	30	25	50	20	150
Estimated Development Resource Area (km^2)	8	5	4	2	2	
Number of Wells per km^2	10	10	10	10	10	
Average Well Productivity (MWe)	4	4	3	3	2	
Resource Potential (MWe)	320	200	120	60	40	740
Target Generation by 2017	160	150				310
Completed Work	Reconnaissance surface studies	Reconnaissance surface studies	Reconnaissance surface studies	No surface studies	No surface studies	
Required Work	Detailed geology and geophysics, infrastructure, exploration drilling, production drilling, and power plant construction.	Detailed geology and geophysics, infrastructure, exploration drilling, production drilling, and power plant construction.	Detailed geology and geophysics, infrastructure, exploration drilling, production drilling, and power plant construction.	Reconnaissance surface studies	Reconnaissance surface studies	

(Source: Ministry of Infrastructure, 2011)

4.8 Geoscientific Survey of the Rwandan Karisimbi, Gisenyi, and Kinigi Geothermal Prospects by the Institute of Earth Science and Engineering (IESE) of The University of Auckland, New Zealand (15 October 2012)

This geoscientific survey conducted the following field surveys:

- 160 MT and TEM field data of good quality were collected by conducting field measurements at about 300 points;
- Controlled source audio-frequency magnetotelluric (CSAMT) data were of poor quality; and covered only 10 km of the planned 20 km;
- Ground temperature and heat flow assessment at 62 three-meter deep wells and 52 one-meter deep wells;
- Collection and analysis of rock samples to ascertain possible heat source for any geothermal system; and
- Microseismic observations at 12 points.

This report dealt with the information obtained by this survey and reviewed existing data as well. A summary of the report is as follows:

【Geology】

- The Karisimbi geothermal area is underlain by volcanic rock that overlies Proterozoic granites with pegmatite lenses and spatially related gneisses. The volcanic rock is composed of lava and pyroclastic rock of tephrite-basanite and trachyandesites. This report analyzed the total alkalis vs. silica. The total akalis vs. silica diagram is shown in Figure 4-1. The figure shows that the SiO_2 of most rock samples taken from Karisimbi and the cones fall under 52%, classifying the samples as basic or ultrabasic rocks[5].

[5] Rock classification: SiO_2<45%: ultrabasic rock, SiO_2<52%: basic rock, SiO_2<63%: intermediate, SiO_2 >63%: acidic rock.

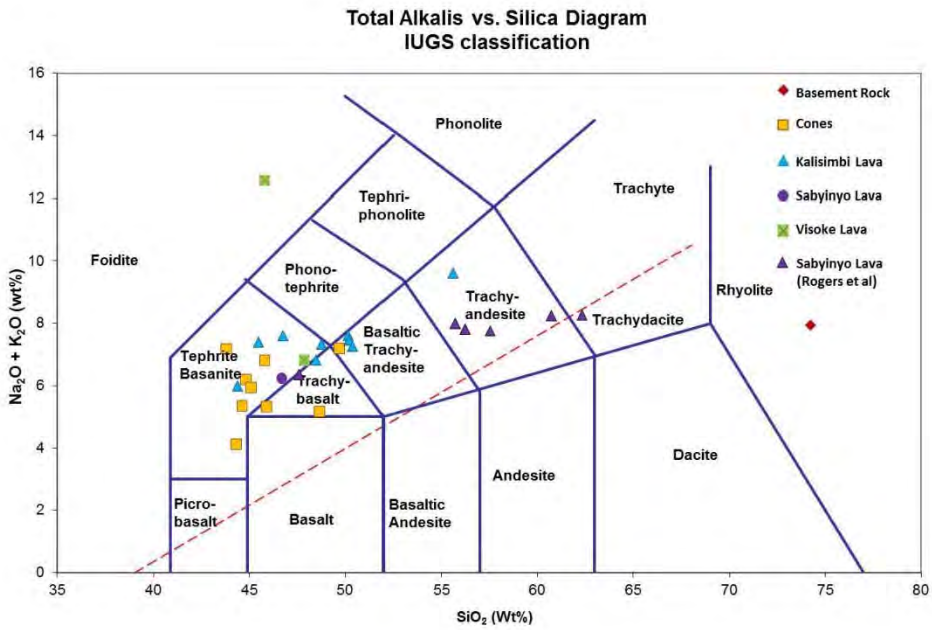


Figure 4.9: Compositional domains of volcanic rocks in Northwest Rwanda.

(Source: UniServices Report, 2012)

Figure 4-1 Total Alkalis vs. Silica Diagram of Karisimbi

- It is unlikely that the volcanic rocks host a usable geothermal reservoir; rather, interconnected joints in the granites and gneisses provide permeability;
- None of the rocks have been hydrothermally altered;
- Rock samples from Karisimbi Volcano and small basalt cones are derived, at least initially, from the same magma source (Figure 4-1). There is no evidence that they are presently heat sources for a convecting geothermal system.
- There is no geological evidence that reveals whether the Gisenyi Spring and Karago Spring are manifestations of a heat-sweep hydrology or are outflows from Karisimbi;
- Travertine near Musanze is a product of the loss of CO_2 from groundwater flowing away from the volcanoes; and
- Temperatures interpreted by silica and action geothermometry of thermal waters may be misleading as the volcanic rocks do not contain quartz. Fluid circulation in the plutonic rocks may have re-equilibrated as they slowly ascend and so do not now remember temperatures at greater depths.

【Hydrogeology and Geochemistry】

- Hot springs, tepid springs, and cold springs in the Karisimbi prospect were classified into four groups. The hot springs of Gisenyi and Karago were classified under Group-I, which cannot be interpreted in terms of deep concealed outflows from a geothermal system beneath one of the East Virunga Volcanoes. The springs appear to have discharge features of small advective, low temperature systems hosted entirely by the Proterozoic basement rocks.
- Geothermometry data were reviewed based on the existing data as shown in Table 4-8 below. The geothermometer readings of the areas ranges from 54 °C to 107 °C, and even the geothermometers of Gisenyi and Karago which yield hot springs of 69 °C and 64 °C, range from 96 °C to 109 °C.

Table 4-8 Geothermometer

Group	Site	Geothermometer (℃)		
		T (K/Mg)	T (Qtz)	T (Ch)
I	Gisenyi (2008)	101	107	*78*
	Gisenyi (2006)	102	109	*80*
	Karago	96	*127*	100
	Mbonyebyombi	90	*111*	81
II	Iriba	72	*109*	80
	Nyakaheni	95	*113*	84
III	Cyabararika	100	*117*	(89)
	Mubona	103	*120*	(91)
	Buseruka	103	*137*	110
	Rubindi	96	*134*	107
IV	Cyamabuye	80	*99*	70
	Mutera	54	*107*	(77)
	Kagohe	54	*93*	63
	Bukeri	*108*	*108*	*79*

The T (Qtz) and T (Ch) values in *italic* are not acceptable.
The T (CH) values in parentheses ( ) are anomalous.

(Source: IESE Report, 2010)

- The existing data on soil gas (CO_2, H_2S) and isotopes were also reviewed. Based on the results, the anomalous features pointed out by the BGR report in 2009 might be artifacts of extrapolation created in areas where data were not available.
- The widespread occurrence of CO_2 discharges over the prospect area together with the observed large influx of CO_2 at the bottom of adjacent Lake Kivu and the active discharge of mantle melts and gasses in the Democratic Republic of Congo

(DRC) sector of the Virunga volcanic chain, can be interpreted as part of the region affected by an upper mantle that covers an area of at least 4,000 km^2, including the Karisimbi prospect.

- The advective flow model can be constructed for the discharge. This conceptual models for the advective flow settings cannot be associated with any concealed thermal outflow derived from an inferred deep geothermal reservoir beneath Karisimbi Volcano.

【Ground Temperature and Heat Flow Assessment】

- The temperature gradient of Karisimbi is estimated at $\Delta T = +/- 0.1$ °C/3 m.
- There are anomalous points of ground temperatures near Gisenyi, whereas no such anomalies are observed in areas distant to Gisenyi. The results indicated that the thermal manifestations of Gisenyi are not part of an inferred larger and deeper upflow but discharge via a few localized permeable channels that are separated mainly by impermeable basement rocks.

【Geophysical Survey: MT survey and TEM survey】

- The previously inferred low resistivity structures of the 2008 and 2009 surveys at crustal depth levels of -2 km and -5 km beneath the southern and southwestern foothill region of Karisimbi Volcano cannot be confirmed.
- Instead, significant, previously unknown, low resistivity structures were found in the east (Kinigi) area at depths between 3 km and 5 km beneath the lower south flank of Sabyinyo Volcano.
- Low resistivity rocks (<20 Ohm-m) with plume characteristics from 3 km to 5 km depths may not be the manifestation of thermal alteration (associated with an active geothermal system) and/or (hot) intrusions, because of the observed fluid characteristics and the absence of characteristic surface manifestations; while the occurrence of deep low resistivity basement rocks may reflect some palaeo alteration of extinct thermal systems.
- The two cross-sections of the MT survey in Kabatwa are presented in Figure 4-2 below. The exploration wells are located in Kabatwa (the data were reanalyzed in 2013 as it will be explained in the next subchapter of this report).

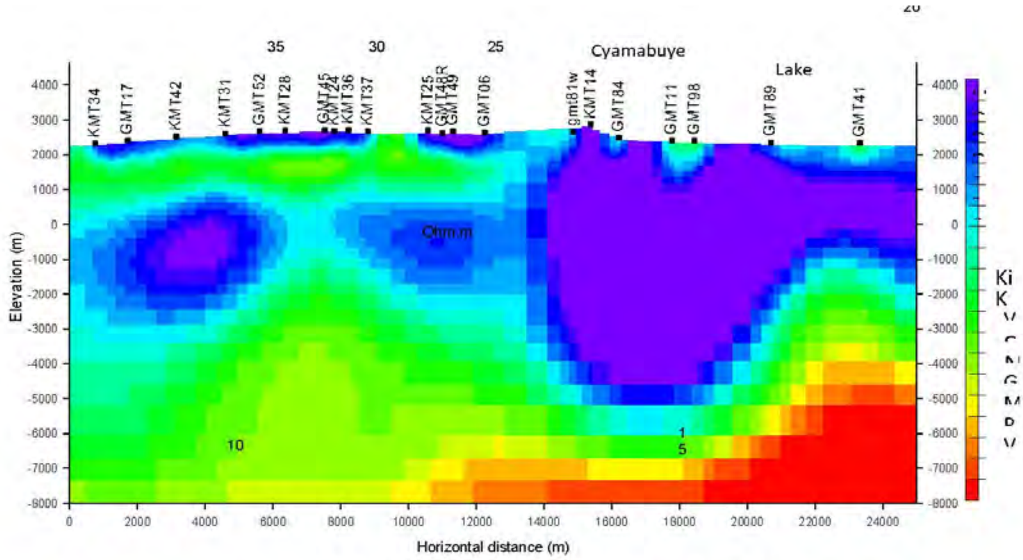


Figure 7.2.42: 2D MT Resistivity cross-section (K1)

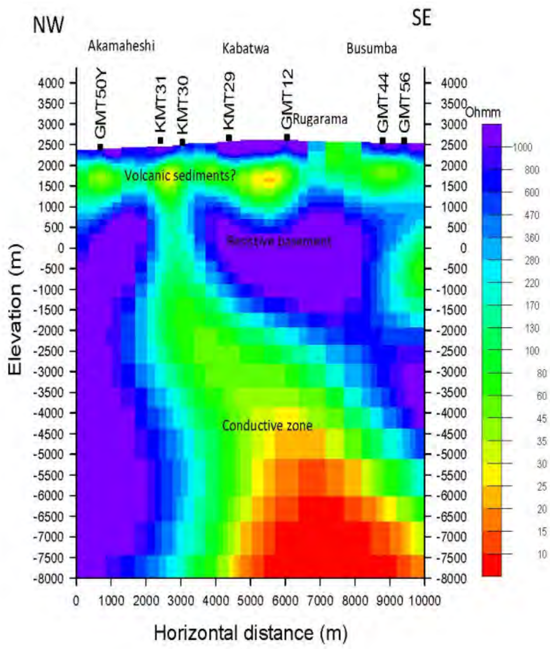


Figure 7.2.43: 2-D MT Resistivity cross-section (K2).

(Source: UniServices, 2012)

Figure 4-2 MT Resistivity Cross-sections along K1 and K2 (Kabatwa)

- UniServices (2012) presented a conceptual model, as shown in Figure 4-3, indicating that the hot springs of Gisenyi and Karago are water heated in the crustal zone, and evidence for possible clay cap was not observed, thereby a concealed geothermal reservoir might not be present in the Karisimbi prospect.

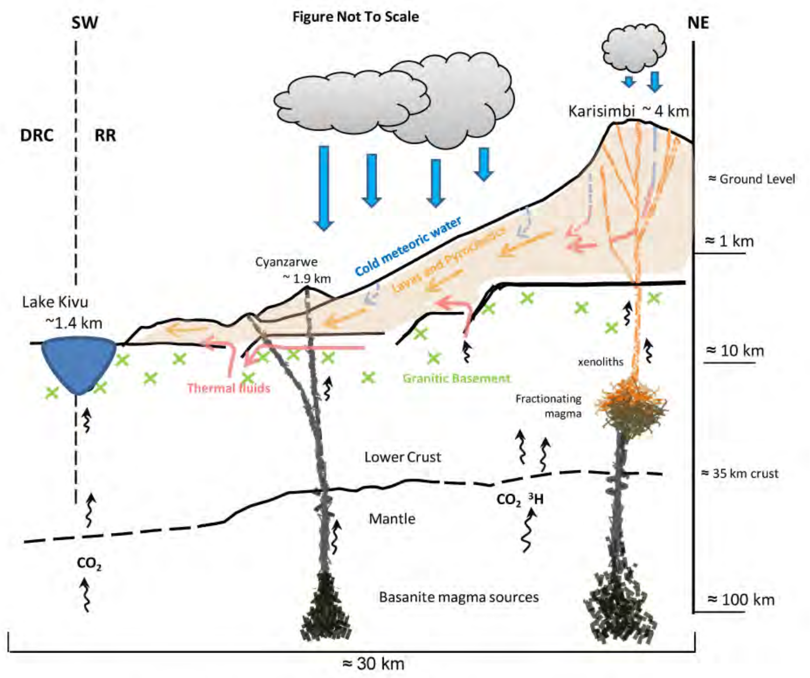


Figure 2.7.1: Conceptual Model - Geology and Volcanic Setting.

(Source: UniServices, 2012)

Figure 4-3 Conceptual Model–Geology and Volcanic Setting

4.9 [DRAFT] Data and Final Report Validation Workshop, Organized by the Energy, Water, and Sanitation Authority (EWSA) (9-10 January 2013)

The EWSA organized a workshop for data and final report validation to jointly review the results of past studies of BGR (2009), KenGen (2010), and UniServices (2012). The workshop was attended by participants from UniServices of New Zealand, the Geothermal Development Company of Kenya, Reykjavik Geothermal of Iceland, KenGen of Kenya, and EWSA. Most of the comprehensive discussions were made mainly on data correction and analysis of the geophysical survey. The summary of the workshop is as follows:

- Successful review of the results of additional studies carried out by KenGen and the recent studies carried out by Auckland UniServices Ltd;
- Harmonization of data analysis and interpretation protocols between KenGen and UniServices;
- Production of harmonized 1-D models by both KenGen and UniServices. As an output of the workshop, reanalyzed MT cross sections are presented, as shown in Figure 4-4 below; and

- Figure 4-2 before the reanalysis. The reanalyzed cross-sections are similar to the one for the K1 section that was analyzed by EWSA using Occam analysis, as shown in Figure 4-5.

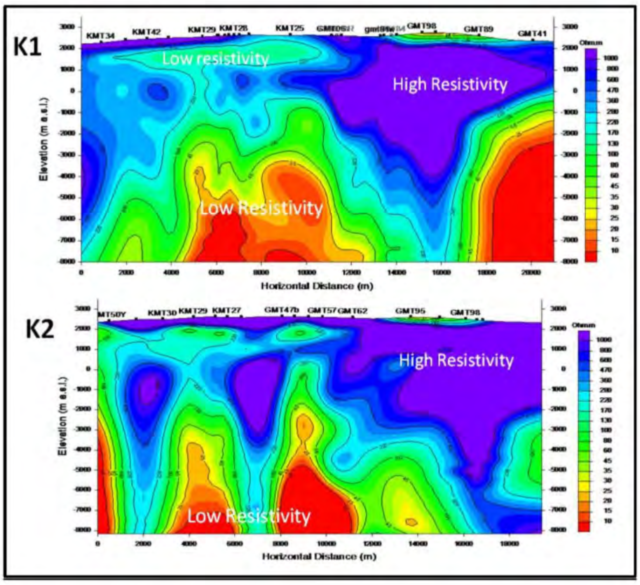


Figure 6: 1D resistivity models for profiles K1 and K2 after harmonization of the data quality checks and processing.

(Source: EWSA, 2013)

Figure 4-4 MT Cross-section of K1 and K2 after Data Harmonization

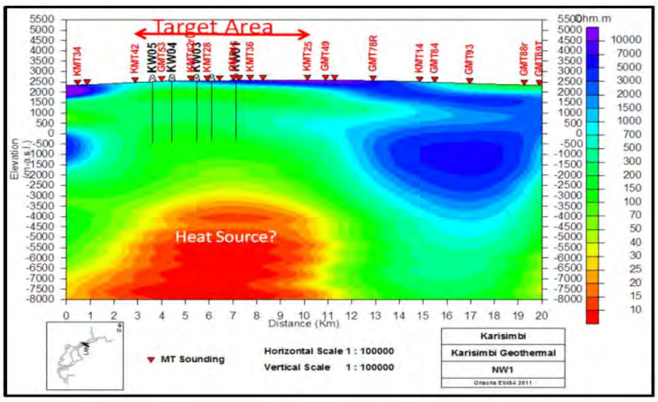


Figure 6: 1D Occam smooth by EWSA along profile K1 showing the target area between MT sites KMT 25 and KMT 42

(Source: EWSA, 2013)

Figure 4-5 EWAS 1-D Occam Analysis (K1 Section)

- Conceptual geothermal model: Development of a conceptual model indicating that the area of highest priority is toward Karisimbi Volcano, which hosts an interpreted heat source. The best study area is represented by a resistivity model which has a high resistivity layer (recent volcanic), a second low resistivity (may be the clay cap) due to hydrothermal alteration of low temperature clays, a third higher resistivity layer (reservoir) due to a higher degree of hydrothermal alteration, and a deeper low resistivity layer (heat source) which becomes shallower toward Karisimbi Volcano and dips sharply to the south.
- Confirmation of uniqueness: The geological, tectonic, and hydrogeological setting of Virunga is unique and different from other geothermal areas and should therefore not be compared with other areas.
- Confirmation of target for drilling: Future drilling should be directional toward Karisimbi Volcano targeting the NW and NE trending interpreted fractures.
- Confirmation of proposed sites, targets, and drilling strategy proposed by EWSA: KW-1 will be drilled first, and then the decision to move either to the KW-2 or KW-3 sites would depend on the initial results from KW-1.

Other discussions are as follows:

- The Karisimbi volcanic area shows evidence of a differentiated magma chamber suggesting a very positive indicator that this could sustain a convective geothermal system. There is a very big hydrogeological gradient (over 3,000 m) between Karisimbi Volcano (4,000 m) and the region. This hydrogeological gradient can easily flow away the geothermal fluid from the volcano through the active faults and fractures.
- The graphite can only be an explanation of low resistivity for an old crust. Graphite can also be related to high temperature.

As a conclusion, the exploratory wells should be located in an area between KMT 25 and KMT 42 of the K1 line of the MT survey, to a depth of 3,000 m (refer to Figure 4-5) .

CHAPTER 5 REVIEW OF DOCUMENTS PROVIDED ON EXPLORATORY WELL DRILLING

5.1 Technical Specifications (Tender Documents, April 2011)

The technical specifications (April 2011) were prepared as part of the tender documents. The following two sets of technical specifications were made available to the JICA Team:

- Tender document for provision of drilling services for three geothermal exploration wells in Karisimbi.
- Tender document for provision of drilling materials for geothermal exploration wells and Victaulic pipes in Karisimbi.

Based on these documents the contractor and supplier selected are Great Wall Drilling Company (GWDC), and China Petroleum Development and Technology Corporation (CPDT), respectively. The technical proposals submitted by the contractors were reviewed by Iceland GeoSurvey (ISOR), which was employed by the Energy, Water, and Sanitation Authority (EWSA), in September 2011. Although the technical proposals were not made available to the JICA Team, the review report of ISOR was given to the JICA Team.

The contractor for well testing, Geothermal Development Company of Kenya, was separately selected. The technical specifications prepared by EWSA and the technical proposal submitted by the contractor were not made available to the JICA Team.

5.1.1 Tender Document for Provision of Drilling Services for Three Geothermal Exploration Wells in Karisimbi, EWSA (April 2011)

Details of the tender document for provision of drilling services for three geothermal exploration wells in Karisimbi, EWSA (April 2011), include the following:

1. Well Names: KW-01, KW-02, and KW-03
2. Well Direction and Depth: Vertical, 3,000 m
3. Drilling Program: Diameter and casing program are shown in Table 5-1 below.

Table 5-1 Diameter and Drilling Program

Name of Casing	Drilling Diameter	Depth (m)	Casing					Cementing
			Diameter	Specifications			Stretch	
Surface	26”	60	20”	94 lb/ft	Weld-on mild steel	Blank	Up to surface	Up to surface
Anchor	17-1/2”	300	13-3/8”	54.5 lb/ft	K55 R-3	Blank	Up to surface	Up to surface
Production	12-1/4”	1,200	9-5/8”	47 lb/ft	K55 R-3	Blank	Up to surface	Up to surface
Open hole (Slotted liner)	8-1/2”	3,000	7”	26 lb/ft	K55 R-3	Slotted	Up to 1,200 m-a	

(Source: JICA Team)

4. Drilling Water: Mainly water-based bentonite mud, aerated water may be required below the production casing (slotted liner). Aerated water or soap foam may be required. A drilling fluid program shall be issued by the owner.
5. Coring: In addition to cutting sampling, rock core sampling up to 3-m long may be required.
6. Directional Drilling: Not required in principle.
7. Logging and Well Testing: Logging program shall be issued by the owner.
8. Drilling Program: Detailed drilling program shall be issued by the owner[6].
9. Blowout Prevention Equipment: Annular type blowout preventer and single (or double) ram type blowout preventer
10. Cementing Services: A cementing subcontractor is required. Bulk Portland cement and cement additives shall be supplied by the owner.
11. Others

5.1.2 Tender Document for Provision of Drilling Materials for Three Geothermal Exploration Wells in Karisimbi, EWSA (April 2011)

Details of the tender document for provision of drilling materials for three geothermal exploration wells in Karisimbi, EWSA (April 2011), include the following:

The document instructs the specifications and quantities of materials necessary for drilling. The main items specified in the document are as follows:

1. Casing

[6] The JICA Team was requested to prepare the drilling program in March 2012 when they visited Rwanda. The drilling program is attached to this progress report.

2. Casing Accessories
3. Rock Bits
4. Wellhead Equipment and Valves
5. Drilling Mud and Mud Additives (Bentonite, walnut shells, mica flaks, caustic soda)
6. Cement Additives[7] (Bentonite, mica flaks, retarder, friction reducer, dispersant, etc.)
7. Drilling Detergent
8. Cement (Portland Cement)
9. Automotive Oil (Diesel)
10. Victaulic Pipes and Flanges

5.2 Review of Geothermal Development Schedule – Plan for Drilling of Three Geothermal Exploration Wells in Karisimbi, Rwanda, ISOR (8 September 2011)

1. Strategy for rapid geothermal development;
2. Well design and drilling program;
3. Contract for drilling services; and
4. Contract for the supply of drilling materials.

Among those above, the following is a summary of the description on "well design and drilling program":

1. 10" master valve: One piece of ANSI 900 and three pieces of ANSI 600 are specified. All four pieces should be ANSI 900 taking consideration that the well depth temperature may reach above 300 °C as the depth is very deep at 3,000 m.
2. Adapter flange: ANSI 900 is recommended; the height should be 500 mm rather than the 266.6 mm specified.
3. Silica flour: Silica flour that is not specified from experiences in Olkaria is strongly recommended as cement additive.
4. Rubber plugs for casing cementing: Inner-string of stab-in method is recommended rather than the rubber plugs specified.
5. Cementing of 1,200-m long production casing is challenging. For the cement top-up, it is suggested to introduce two "one-inch macaroni" pipes down the

[7] Silica flour that is usually mixed with cement for geothermal well drilling is not specified in this document.

annulus to the top of the cement.

6. Flame cutting to have a slotting of 6 km of 7”-26l b/ft casing pipe is not the best for the material. Drilling of hoes is now the preferred method.

Before the preparation of this review report, the issues were summarized by ISOR and presented to the first meeting with EWSA. This may be useful as a checklist and therefore reproduced below.

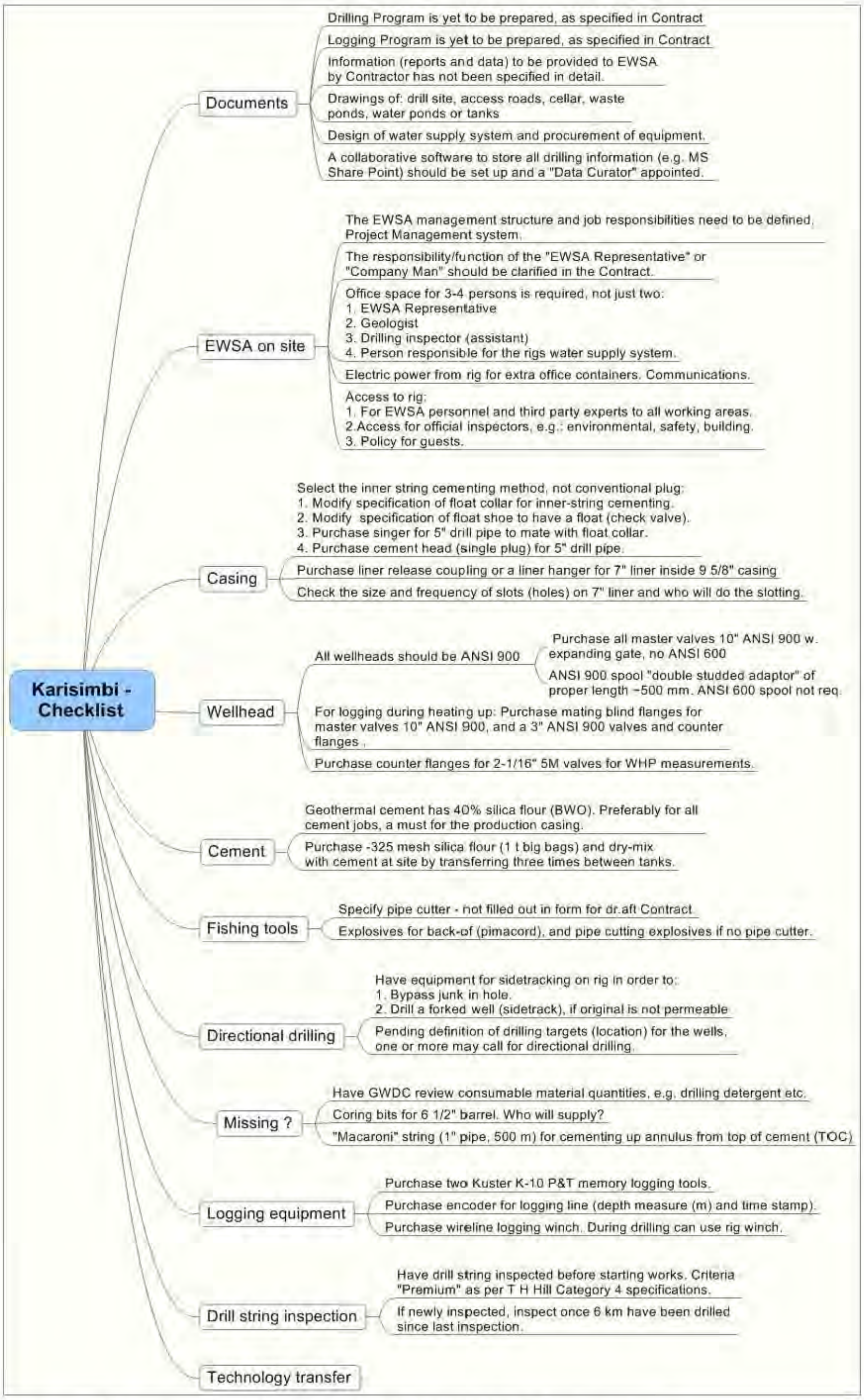


Figure 1. „Map" prepared for the first meeting at EWSA headquarters.

(Source: EWSA, ISOR, 2011)

Figure 5-1 Checklist for the Preparation of Well Drilling

CHAPTER 6 REPORT OF SITE RECONNAISSANCE

6.1 First Site Survey in Rwanda

6.1.1 Inception Meeting

The JICA Team explained to the Energy, Water, and Sanitation Authority (EWSA) the purpose of the survey and survey schedule in accordance with the explanatory slides (Attachment- 1).

In response to the presentation of the JICA Team, EWSA made an explanation on the history and present conditions of the geothermal potential survey, and issues on potential assessment based on the attached slide (Attachment- 1).

- Previous and ongoing studies showed good indications of viable geothermal resources in the Virunga area,
- Urgent need for a harmonized conceptual model to guide exploration drilling,
- Fulfill the commitment of the Government of Rwanda (GoR) to develop geothermal resources, and
- If exploration drilling is successful:
  - Use exploration wells to generate 10 MWe;
  - Carry out exploration drilling in other areas; and
  - Invite the private sector to drill production wells and develop over 300 MWe from geothermal resources.

Professor Muraoka made a presentation on the geothermal potential issues in Rwanda (Attachment- 1).

- Even if the given temperature is 70 °C at the ground surface, 250 °C can be expected at a 2,000 m depth in the upflow zone.
- A magma chamber could be deeper where the lateral stress is extensional as in the East African Great Rift Valley. If there is a magma chamber with density of 2.5 g/cm^3, the magma chamber would settle at a depth of 1 km in NE Japan in a contraction tectonic field and at a depth of 4 km in Kyushu in an extensional tectonic field in terms of neutral buoyancy depth.
- The composition of volcanic rocks and their magma sources in Rwanda do not provide optimistic expectations with regard to geothermal development.
- Although it is thought that there could be masking effects for geothermal manifestation by the wide lake water and wide groundwater along the west branch of the Great Rift Valley, there are still a lot of chances to detect high temperature geothermal reservoirs.

- The most important effort is to drill an initial geothermal exploration well.

The minutes of the inception meeting is also attached (Attachment- 1).

6.1.2 Site Reconnaissance Survey

The JICA Team, together with EWSA, conducted site reconnaissance surveys at the locations shown in Table 6-1. After the site reconnaissance survey, the report was explained to EWSA. The report submitted is attached as Attachment- 2.

Table 6-1 Locations Visited in the First Fieldwork

	Location Visited	Purpose
1.	Kinigi	Site inspection of geological and geomorphic conditions in the Kinigi prospect
2.	Karisimbi	Site inspection of geological and geomorphic conditions, and preparation works for drilling in the Karisimbi prospect
3.	Mufunba Volcanic Cone	Confirmation of calcite
4.	Gisenyi	Confirmation of hot spring and basement rock
5.	Karago Lake	Confirmation of hot spring, and preparation works for intake structure
6.	Rubindi Spring	Confirmation of HCO_3 – type, cold spring
	Others	Inspection of volcanic cones, and distant views of boundary of basement rock and volcanic rock.

(Source: JICA Team)

【Geological and Geomorphic Observations】

The JICA Team made the following observations:

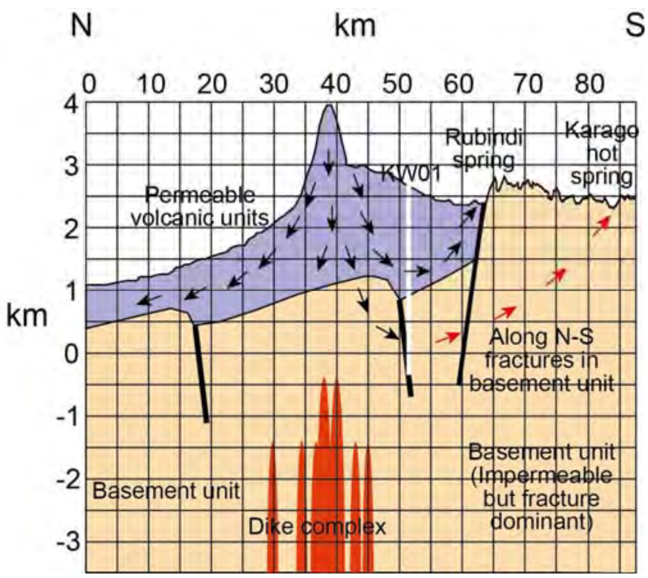
- Volcanic rocks in Kinigi and Karisimbi are fresh unaltered porous basaltic lava. No evidence of geothermal manifestation, such as clay mineral alteration, hydro-sulfate and so on, was observed.
- Calcite at the Mufunba volcanic cone was confirmed. Hardness seemed to be higher than expected.
- Massive granitic rock and micaceous phyllite as the basement rock were also observed. The apparent resistivity of granitic rock seems to be quite higher than that of phyllite. The magnetotelluric (MT) survey may give different resistivities for each type of basement rock.
- The hot spring of Gisenyi has a temperature of 73.6 °C and electrical conductivity (EC) of 3,100 μS/cm; whereas Karago has a temperature of 72.5 °C and EC = 1,100-1,200 μS/cm.
- The Rubindi Spring has a temperature of 18.8 °C and EC = 2,100 μS/cm,

discharging about 1-2 m^3/sec even after the water intake for drinking water. It was considered that this huge amount of water might mask geothermal manifestation.

【Interpretation of the Karisimbi Prospect】

The interpretation of Professor Muraoka is as follows:

- Contrary to the previous assumption that geothermal potential might not be so high because of the absence of a boiling spring, the masking effects by the cold meteoric water and groundwater are considered in Karisimbi Volcano.
- The hot springs of Gisenyi and Karago are probably outflows from Karisimbi Volcano along the N-S trending fractures of basement units, and they are very close to the boiling hot springs because of the easily diluting environment.
- Exploratory drilling of KW-01 is challenging but valuable. However, it should be kept in mind that the probability of successful geothermal drilling in green fields is only at 50%.
- Before drilling, the geological and geothermal cross-sections along KW-01 need to be drawn even if there still remain many unknown factors.



(Source: JICA Team)

Figure 6-1 Conceptual Cross-section of Karisimbi Volcano

【Observations on Site Preparation and Suggestions】

The JICA Team conducted site confirmation and information collection regarding the well drilling works. A summary of the observation is included in Attachment- 2. It was explained therein that the drilling works will commence in the middle of May 2013.

6.2 Second Field Survey in Rwanda

6.2.1 Kick-off Meeting

The JICA Team explained the contents of the Progress Report; and the purpose and schedule of the second field survey in Rwanda (**Attachment- 5**).

EWSA explained the progress of drilling works and schedule of the staff activity in relation to the training program provided by ICEIDA-ISOR. Discussions were made on the activity schedule among the parties concerned. Also, discussion was made regarding work allocation between the Team and Reykjavik Geothermal who is assigned with a Nordic Fund and is responsible for supervision of the drilling works.

6.2.2 Site Survey for Confirmation of Site Conditions

The site surveys conducted during the second visit in Rwanda, through coordinating with the schedules of EWSA, ICEIDA-ISOR and Raykjavik Geothermal, is shown in Table 6-3.

Table 6-2 Activity Record of the Second Visit in Rwanda

			TAKAHASHI S. Team Leader/ Geologist	Hannes S Drilling Engineer	*TERAMOTO M. (NK own fund)*
27-Jun	Thu	day		RKV->AMT, FI502(0740->1240)	
28-Jun	Fri	day		AMT->KGL, KL535(1100->1905)	HND->DXB,EK313(0130->0705)
29-Jun	Sat	day		off work	DXB->NBO,EK719(1045->1445)
30-Jun	Sun	day	NRT->DHA,QR805(2230->0330)	off work	NBO->KGL,KQ442(1055->1305)
1-Jul	Mon	a.m.	DHA->KGL,QR536(0730->1350)	public holiday	public holiday
		p.m	**Public holiday in Rwanda**		
2-Jul	Tue	a.m.	**9:30 Meeting with JICA Rwanda office**		
		p.m	**Preparation for the 1st meeting**		
3-Jul	Wed	a.m.	**8:00 Meeting with EWSA at GDU of EWSA, Joint Training Program with ISOR to EWSA**		
		p.m	**Continuation of Joint Training Program with ISOR to EWSA**		
4-Jul	Thu	a.m.	**Public holiday in Rwanda**		
		p.m			
5-Jul	Fri	a.m.	Site Inspection (Pumping sites and Karisimbi Drilling Site) for confirmation of preparation works for drilling		
		p.m			
6-Jul	Sat	a.m.	off work	off work	off work
		p.m			
7-Jul	Sun	a.m.	off work	off work	off work
		p.m			
8-Jul	Mon	a.m.	Explanation of Geological Survey while Drilling with	Explanation of Drilling Program and Drilling Technology	Explanation of Geo-chemical survey
		p.m	Discussions	Discussions	Discussions
9-Jul	Tue	a.m.	Additional explanation of Geological Aspect	Discussion on Drilling Program with EWSA and RG on site	Site survey
		p.m	Preparation for site visit		
10-Jul	Wed	a.m.	Site Visit with Equipment provided by ISOR	Joint Discusstion with iSOR and EWSA	Discussions on Geo-chemical survey
		p.m			
11-Jul	Thu	a.m.	Joint meeting for the finalization of the Drilling Program among EWSA, RG, GWDC and JICA Team on site		
		p.m			
12-Jul	Fri	a.m.	Site survey (Karago Spring)	Preparation of Site Reports and Materials for wrap-up meeting	Site survey (Karago Spring)
		p.m			
13-Jul	Sat	a.m.	Site visit of Springs: Buseka, Cyabararika, Rubindi and Cyamabuye; and Bondi volcanic cone	Home work	Site visit of Springs: Buseka, Cyabararika, Rubindi and Cyamabuye; and Bondi volcanic cone
		p.m			
14-Jul	Sun	a.m.	Site visit of Gyseni spring	Home work	Site visit of Gyseni spring
		p.m			
15-Jul	Mon	a.m.	Site visits: Karago and Sashwara pump station; Drilling site; Moving to Kigali	Preparation of Site Reports and Materials for wrap-up meeting	Site visits: Karago and Sashwara pump station; Drilling site; Moving to Kigali
		p.m			
16-Jul	Tue	a.m.	**Collecting of additional inforamtion and discsuution with EWSA**		
		p.m	**Prparation for wrap-up meeting**		
17-Jul	Wed	a.m.	**Prparation for wrap-up meeting**		
		afternoon	**14:00 Wrap-up meeting**		
		evening		KGL->AST, KL535(2020->0645)	
18-Jul	Thu	a.m.	Report preparation	AMT->RKV,FI503(1400->1510)	Report preparation
		p.m			
19-Jul	Fri	a.m.	Report preparation		KGL->NBO,KQ471(0900->1130)
		p.m			
20-Jul	Sat		KGL->DHA, QR539(0950->1805)		NBO->ICN,KE960(1030->0450)
21-Jul	Sun		DHA->NRT,QR804(0150->1750)		ICN->NRT,KE701(0910->1130)

(Source: JICA Team)

Out of the activities shown in Table 6-2, summery of the main activities in location visited is shown in Table 6-3.

Table 6-3 Summary of Site Observation of the Second Site Survey in Rwanda

	Site Visited	Purpose
a.	Karisimbi drilling site , Stock yard	Confirmation of progress and site conditions, discussions on drilling program
b.	Karago Lake and others	Confirmation of progress and site conditions
c.	Rubindi and others	Hydro-geological survey as geothermal manifestation, water usage survey
d.	Bondi volcanic cone	Confirmation of geological conditions of a volcanic cone, confirmation of alteration mineral, others

(Source: JICA Team)

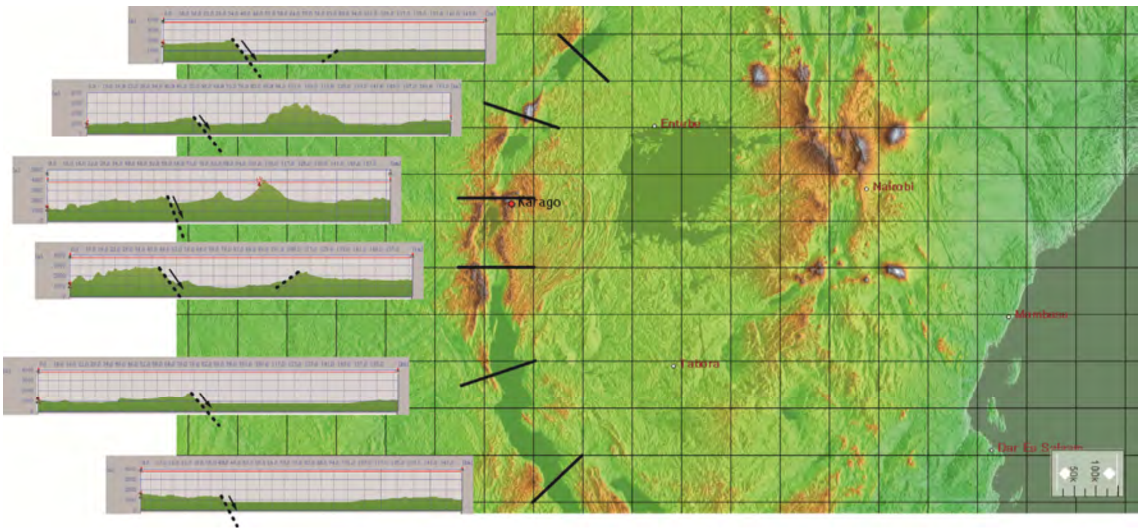
The observation and recommendations were summarized in the presentation materials for the wrap-up meeting as **Attachment- 9**; and descriptions are made in the following chapters or sub-chapters.

a. Explanation of the activities in Karisimbi is as described in 8.2 and 8.3; and the summarized description on the drilling program is in 8.6.1. The drilling program finalized by EWSA is attached as Attachment- 8 and the presentation material for the meeting is included as Attachment- 9.
b. Explanation on water supply facilities is as described in 8.5.
c. Additional and updated explanation on springs based on the observation made in the second visit is as described in 7.3.
d. Explanation on the additional geological observations made at Bondi volcanic cone and the other rock outcrops are as described in 7.2.
e. Our observations and recommendations regarding the way forwards for the geothermal development is as described in Chapter-9 based on the interview survey to the head of EWSA-GDU and our review of the existing information available to the Team.

CHAPTER 7 OBSERVATIONS ON GEOTHERMAL POTENTIAL ASSESSMENT

7.1 Consideration of Regional Tectonic Geology

Figure 7-1 shows the regional relief map including cross-sections the JICA Team produced with 3D data of SRTM-3[8] from the website of the U.S. Geological Survey (USGS) using KASHMIR 3D, a 3D relief drawing computer program. The cross-sections in the figure show that the western branch of the East African Rift Valley (EARV) forms asymmetric rims at the western rim of the western branch which forms clear fault cliffs; whereas the eastern rim does not always show clear cliffs. The geomorphologic characteristics of the western branch correspond to such other characteristics as less active volcanism and tensional tectonics compared with those of the eastern branch of EARV. The asymmetry also explains the reason why the western boundary of the basement is irregular. It should be noted that the western branch is also characterized by the fact that there are many large lakes along rift valleys. Accordingly, it is possible that the lakes mask geothermal manifestation by dilution of geothermal fluid.



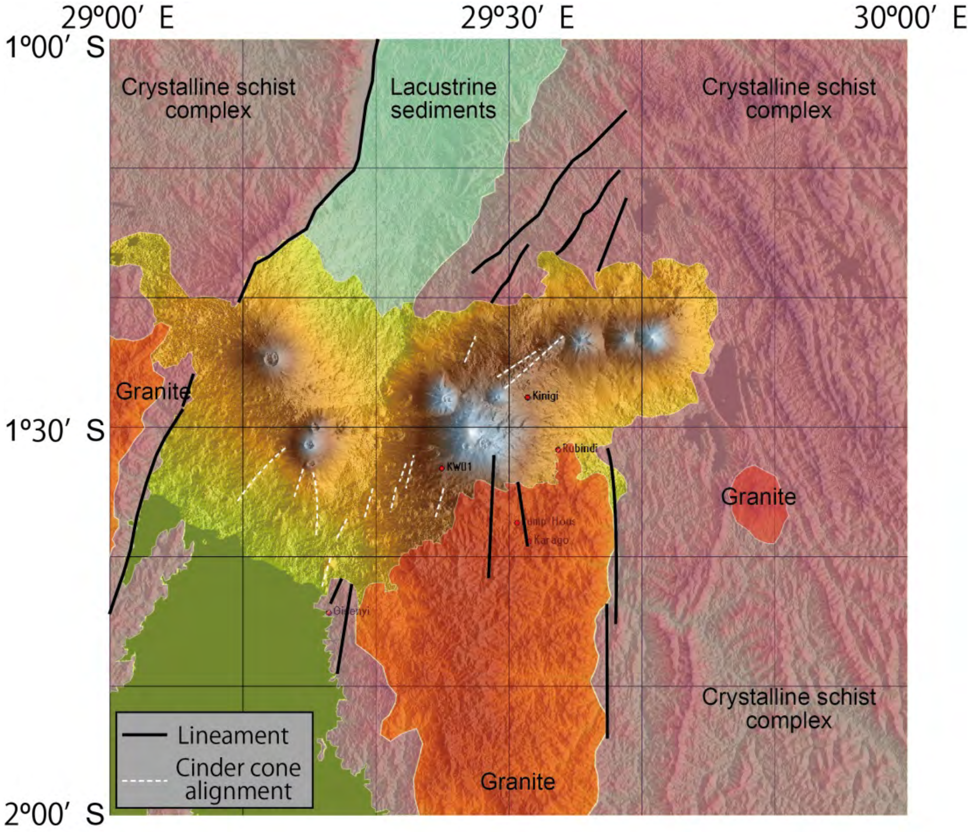
(V/H=5; 1-mesh=1 degree)

(Source: JICA Team)

Figure 7-1 Geomorphic Characteristics of the Western Branch of EARV

[8] SRTM: Shuttle Rader Topography Mission

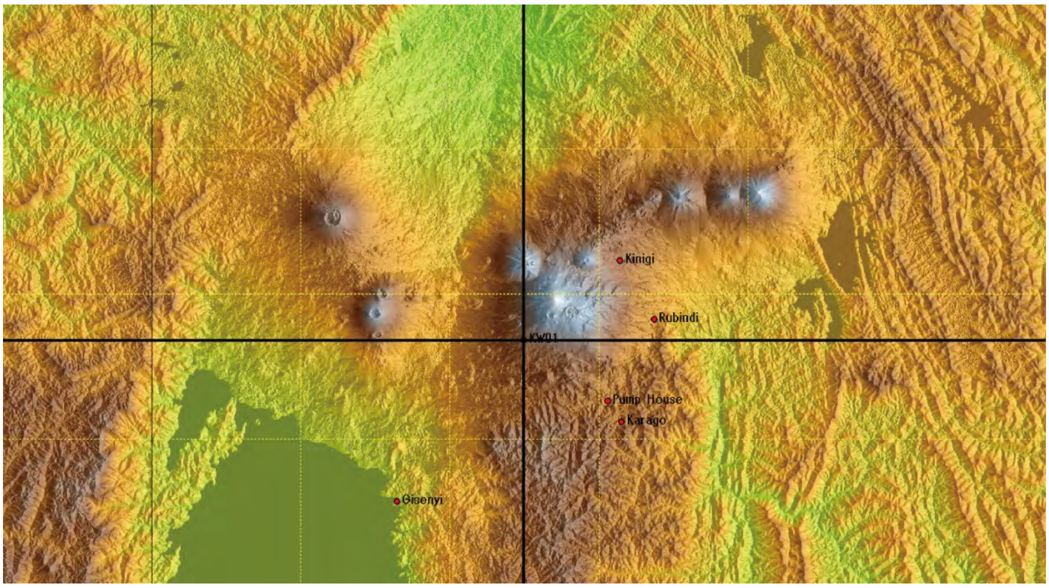
As explained later, the Virunga Volcanoes are poor in felsic rocks and mainly consist of alkaline basaltic magma. The neutral buoyancy depth is thus considered to be deeper. An analogy with Mt. Fuji of Japan may be recalled that there is no hot springs around the active Mt. Fuji. In other words, volcanoes with deeper magma chambers such as Mt. Fuji do not necessarily possess favorable conditions to form geothermal reservoirs.



(Source: JICA Team)

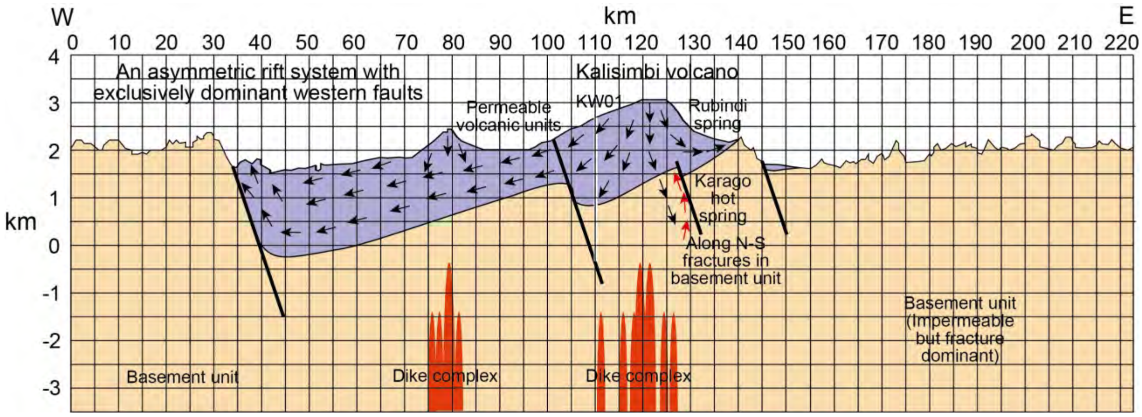
Figure 7-2 Geotectonic Sketch Map of the Virunga Volcanoes

However, there are three points that should be addressed that are different from the case of Mt. Fuji. Firstly, the hot springs of Gisenyi (73.5 °C) and Karago (72.5°C), which are considered to be related to Karisimbi Volcano, are observed. Secondly, the Virunga Volcanoes are in an extensional tectonic stress field and not in a compression tectonic stress field as is the case of Mt. Fuji. Thirdly, there are series of cinder cones or scoria cones that are arranged in lines (refer to Figure 7-2). This implies that magmatic dikes might have intruded in to the upper part of the crust (see Figure 7-3). On the other hand, Figure 7-4 shows that groundwater flowing in high-permeable volcanoes reaches the range of low-permeable basement rock at Rubindi, and therefore emerges to the surface.



(Source: JICA Team)

Figure 7-3 Relief Map Showing E-W Cross-section Line



(Source: JICA Team)

Figure 7-4 E-W Geological Cross-section

According to past experiences from a practical and academic point of view, the JICA Team considers that the geothermal potential in Karisimbi Volcano might not be as large as expected due to the possibility of a large neutral buoyancy depth. However, the linear alignments of cinder cones or scoria cones indicate, at least, that magmatic dikes might have reached shallower depths (see Figure 7-3 and Figure 7-4), and such magmatic dikes sometimes take important roles as heat sources in an extensional tectonic stress field. The above consideration implies that exploratory drilling for geothermal development in Karisimbi will be challenging.

7.2 Rock Classification and Implication

The KenGen Report (2010) estimated the potential of the Karisimbi prospect at about 300 MWe with reference to the experience in Olkaria, Kenya. To get an overview of the geological setting, the diagram for classification of rocks in Olkaria is presented in Figure 7-5. This figure shows that most of rock samples were classified as trachyte and rhyolite, falling in the zone of SiO_2 over 63%. Such may be classified as felsic rocks.

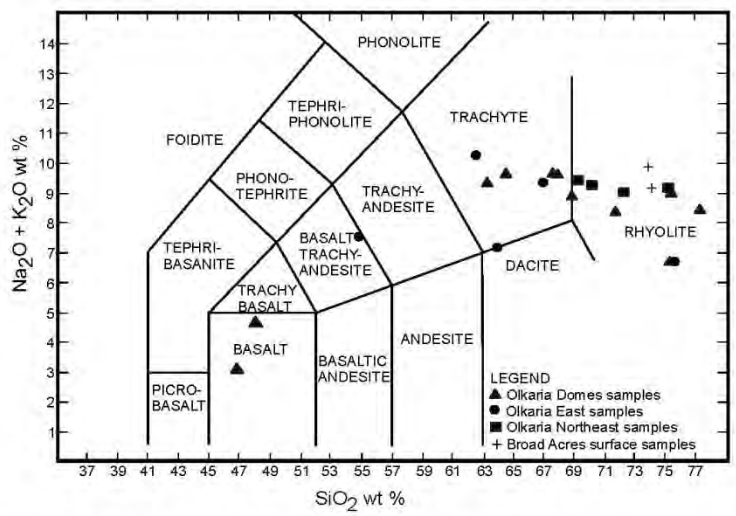


FIGURE 7: Total alkalis silica (TAS) diagram for classification of volcanic rocks using chemical analysis (Les Bas et al., 1989). Data from Olkaria Domes is from the present study, Olkaria East data is from Browne (1984), Olkaria Northeast data are from Omenda (2000), MacDonald et al., (1987) and Black et al (1997), Broad Acres data is from McDonald et al (1987)

(Source : J K Lagat (2004) [9])

Figure 7-5 Total Alkalis Silica Diagram, Olkaria in Kenya

On the other hand, the rock samples from Karisimbi fall in the area of SiO_2 under 52% when plotted in the total alkalis silica diagram (refer to Figure 4-1). This rock group may be classified as “mafic” or even “ultra-mafic”. The above comparison indicates that geological conditions are different between Olkaria and Karisimbi.

Table 7-1 simplifies a general comparison of magma characteristics in terms of “mafic” and “felsic”. This simple comparison indicates that the mafic magma chamber where Karisimbi Volcano may have originated: (i) may stay a deeper part of the crust because of larger specific weight, (ii) may form a smaller-sized magma chamber because of low

[9] UN-Univ. Geothermal Training Program Geology, hydrothermal Alteration and Fluid Inclusion Studies of Olkaria Dome Geothermal Field, Kenya, J K Lagat (2004)

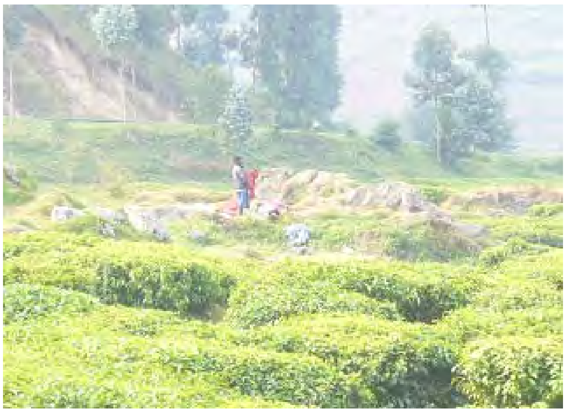
viscosity; and (iii) may possess less self-heating characteristics because of lesser content of radio isotopes in the magma chamber. Items (ii) and (iii) above may lead to quicker cooling of the magma chamber.

It may be prudent to make a comparison for potential assessment between Olkaria and Karisimbi.

Table 7-1 General Characteristics of Magma in the Chamber

	Classification		
	Mafic (Basic)	←→	Felsic (Silicic)
1. Specific Weight	Larger	←→	Smaller
→Depth in Crust	Deeper	←→	Shallower
2. Viscosity	Smaller	←→	Larger
→Flowability	Larger	←→	Smaller
→Size of Magma Chamber	Smaller	←→	Larger
→Cooling	Quicker	←→	Slower
3. Radioactive Element	Releasing	←→	Condensing
→Self-heating Ability	Smaller	←→	Higher
General comparison by constituents with many exceptions in according to outer conditions.			

(Source: JICA Team)



Lava in the center, granite behind. Lave flew flat in a granite valley, indicating very low viscosity of the Lava flow.

Lava with smooth flow surfaces, also indicating very low viscosity of the Lava flow.

(Source: JICA Team)

Figure 7-6 Characteristic

【Geomorphology and Geology of Bondi Volcanic cone】

It is recorded by a British church person that the caldera of the Bondi volcanic cone was once filled with water, but the water disappeared to the bottom in 1950th. The caldera has now been highly cultivated (Figure 7-7), indicating that workers even at the bottom of the caldera have not been affected by such gasses as CO_2 and/or H_2S. This may be an indication that the volcanic activities have become very weak or even dormant.

	
Bondi Caldera once filled with water but disappeared in 1950. The land has since been cultivated	Basalt outcrop in the Bondi Caldera. Thin calcite veins are seen in the outcrop.

(Source: JICA Team)

Figure 7-7 Bondi Volcanic Caldera

On the basalt outcrop in the Bondi Caldera, many thin white calcite veins are seen. This may be rather digenetic effects than an indication of magma differentiation but digenetic effects.

7.3 Geochemical and Hydrogeological Considerations

7.3.1 Chemistry of Hot and Cold Springs

Diagrams of major ions of sample water from the hot and cold springs (Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-}, HCO_3^-) are useful to qualitatively and quantitatively compare the characteristics of each water sample.

【Trilinear Diagram (Piper Diagram)】

A trilinear diagram (piper diagram) is a graph which shows the chemical characteristics of water samples, such as the percentages of cations and anions. If some samples are plotted closely, it indicates that those samples are from the same or of similar origin.

The hot and cold spring samples taken from the project area are shown in Figure 7-8. Water samples of each group (I to IV classified by IESE, 2012) are closely plotted, thus it is estimated that the process to create the water quality of each sample is similar in each group.

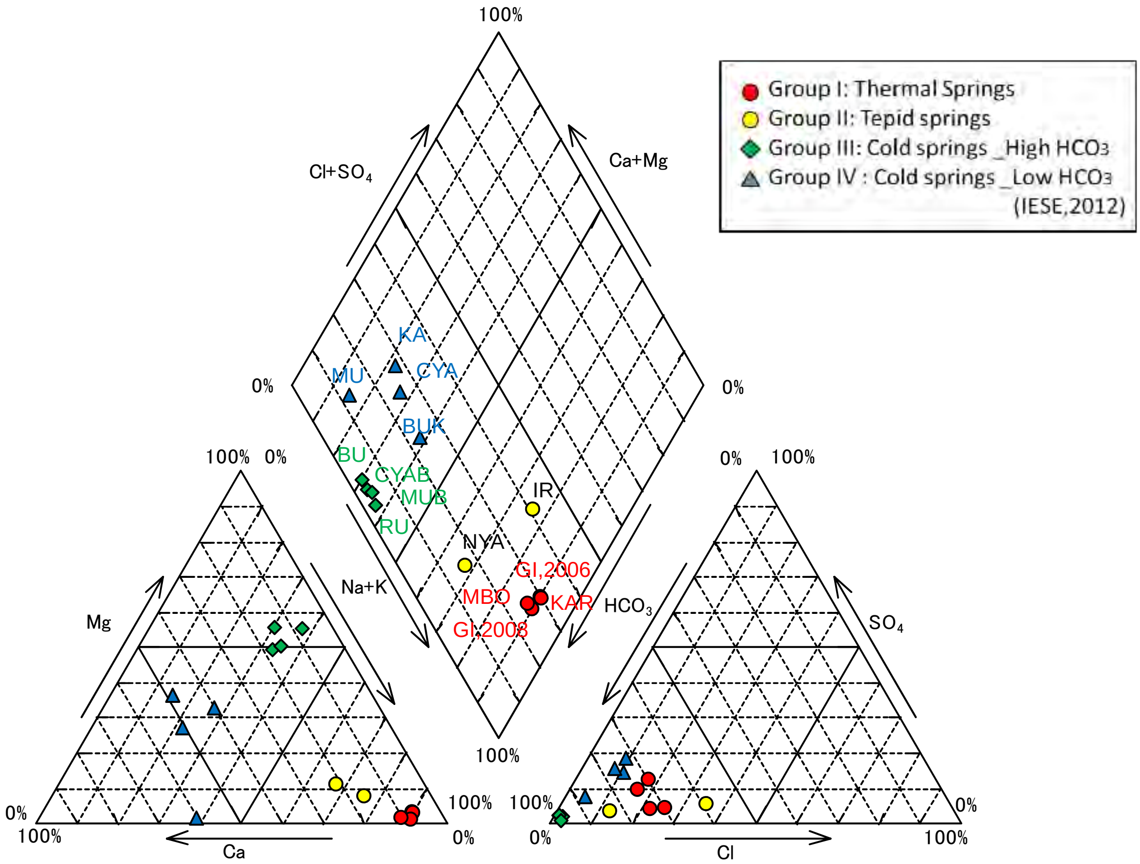
Figure 7-9 shows the typical classification of water quality using the trilinear diagram. The hot and cold spring samples were classified into the following four groups according to their position in the trilinear diagram:

Table 7-2 Water Quality Types

Group	Samples(Abbreviation: Temperature(degree-C))	Water Type	Origin
Group I	Gisenyi (GI: 69), Karago (KAR: 64), Mbonyebyombi (MBO: 37)	[B] NaHCO3 Type	Deep groundwater, non active flow system
Group II	Iriba (IR: 22.3) , Nyakageri (NYA: 20.5)	[B~mix] NaHCO3 Type to Mixture Type	Mixture of deep and shallow groundwater
Group III	Cyabararika (CYAB: 18.5), Mubona (MUB: 19.5), Buseruka (BU: 17.4), Rubindo (RU18.0)	[B~mix] MgHCO3Type to Mixture Type	Shallow groundwater, active flow system
Group IV	Bukeri (BUK18.9), Cyamabuye (CYA: 16.0), Kagohe (KA18.8), Mutera (MU: 17.4)	[A] CaHCO3 Type	Shallow groundwater, active flow system

(Source: UniService (2012))

None of the samples fell under the SO_4 [C domain] or Cl [D domain] domains. This implies that thermal systems showing similar characteristics with those in Japan may not exist in the Karisimbi prospect.

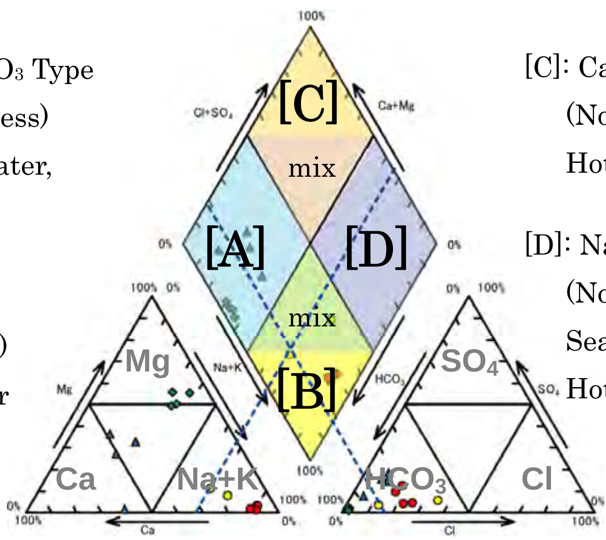


(Source: JICA Team, Data from UniServices(2012))

Figure 7-8 Trilinear Diagram of Hot and Cold Spring Samples from the Study Area

[A]: $CaHCO_3$, $MgHCO_3$ Type
(Carbonate hardness)
Shallow groundwater,
River water

[B]: $NaHCO_3$ Type
(Carbonate Alkali)
Deep groundwater



[C]: $CaSO_4$, $CaCl_2$ Type
(Non-carbonate hardness)
Hot spring, Mineral spring

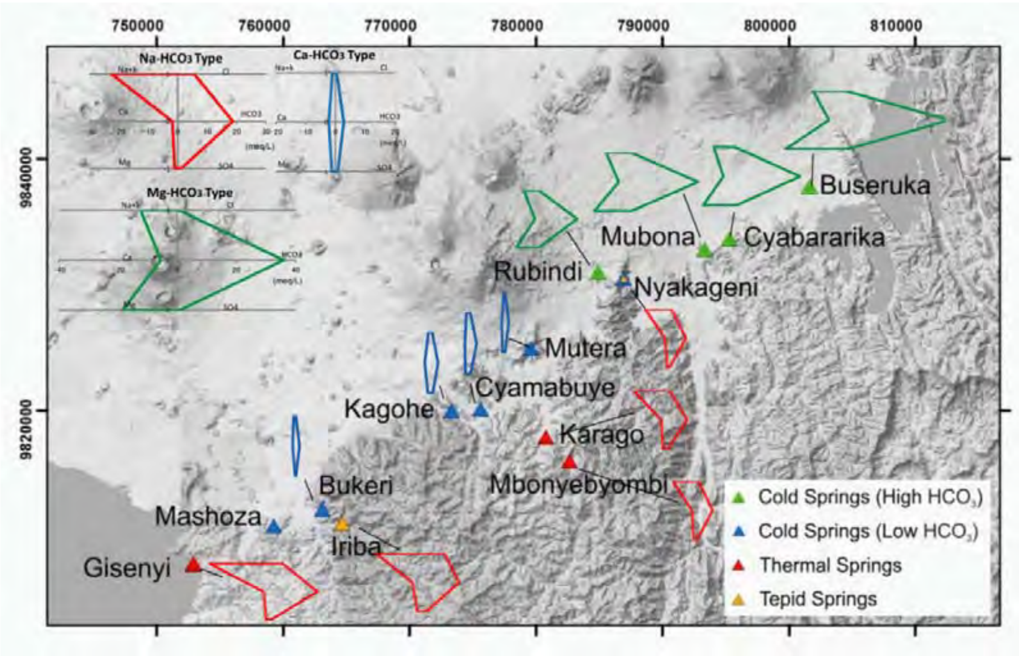
[D]: $NaSO_4$, NaCl Type
(Non-carbonate, Alkali)
Seawater, Fossil water,
Hot spring

(Source: JICA Team)

Figure 7-9 Water Quality Classification by Trilinear Diagram (Legend)

【Stiff Diagram】

A stiff diagram is a graphical representation of chemical analyses displaying the major ions in a polygonal shape, which is created by plotting equivalent concentration of cations to the left of the center axis, and anions to the right. This diagram is useful to classify the ion pattern through the diagram's shape, and the dissolved amount through the diagram's size.



(Source: JICA Team, Data from UniServices(2012))

Figure 7-10 Distribution Map of Stiff Diagrams

As shown in (Source: JICA Team, Data from UniServices(2012))

Figure 7-10, Group I and II springs from basement rock have similar ion type, and spring water in the west area (Gisenyi and Iriba) have a higher concentration of dissolved ions than the central area (Nyakageni, Karago, and Mbonyebyombi).

Groups III and IV have been classified according to the trilinear diagram as active flow systems; however, these groups seem to have different flow systems because of the significant difference in the amount of dissolved ions.

- Groups I and II have similar chemical compositions, which indicate similar flow process.
- Gisenyi and Iriba in the west area have chloride ion content and higher ion concentrations.
- Group IV seems to have a short travel time due to the low ion concentration.
- Group III has a longer travel time than Group IV.

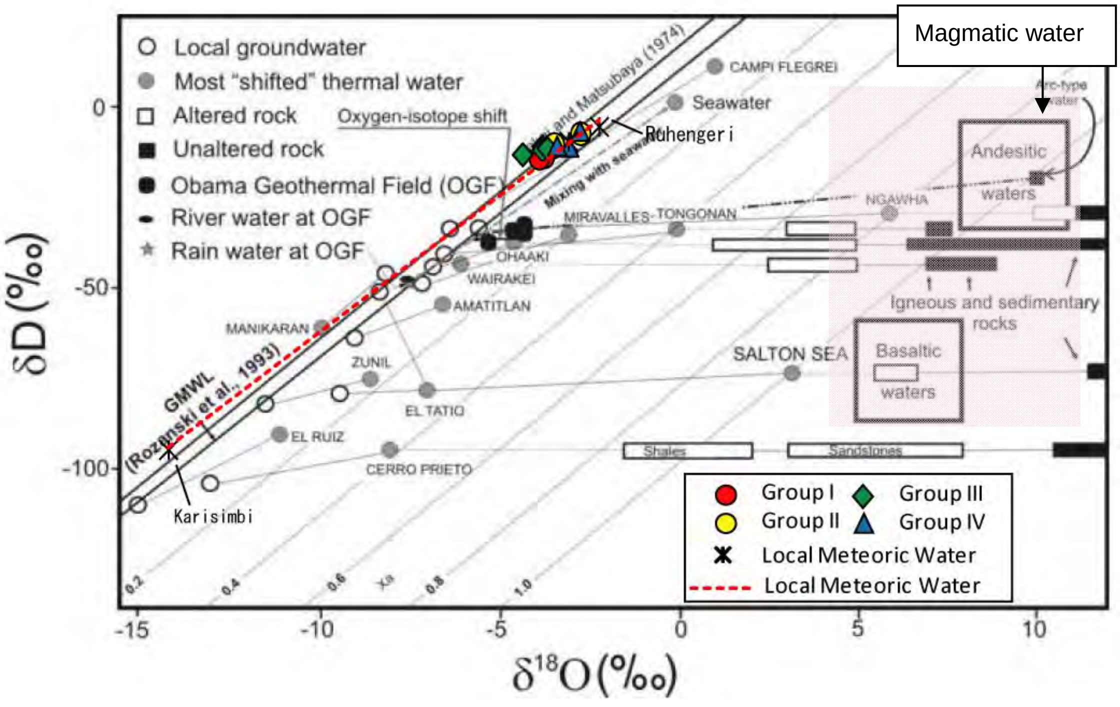
7.3.2 Isotopes of Hot and Cold Water

【Stable Isotope】

Stable isotope data of hydrogen and oxygen are useful in investigating the origin of water. Figure 7-11 shows a delta diagram representing the composition of hydrogen and oxygen stable isotopes in water samples. The data plotted in the delta diagram are taken from the study area, and the Obama geothermal area in southwest Japan.

The Delta-^{18}O and Delta-D values decrease with increasing latitude (latitude effect) and decrease with increasing altitude (altitude effect). The isotopes in the hot and cold spring samples taken from the study area are relatively heavy because they are located at low latitude.

It is known that magmatic waters are plotted at the area with heavy δ^{18}O value (pink-colored area in Figure 7-11). If water of magmatic origin is mixed with groundwater recharge through precipitation, the isotope plots on the local meteoric water line (LMWL) will shift toward the right side (see the lines of samples from the Obama geothermal field in the delta diagram).



(Source: Saibi, 2010[10] modified by the JICA Team)

Figure 7-11 Delta Diagram of Geothermal Water

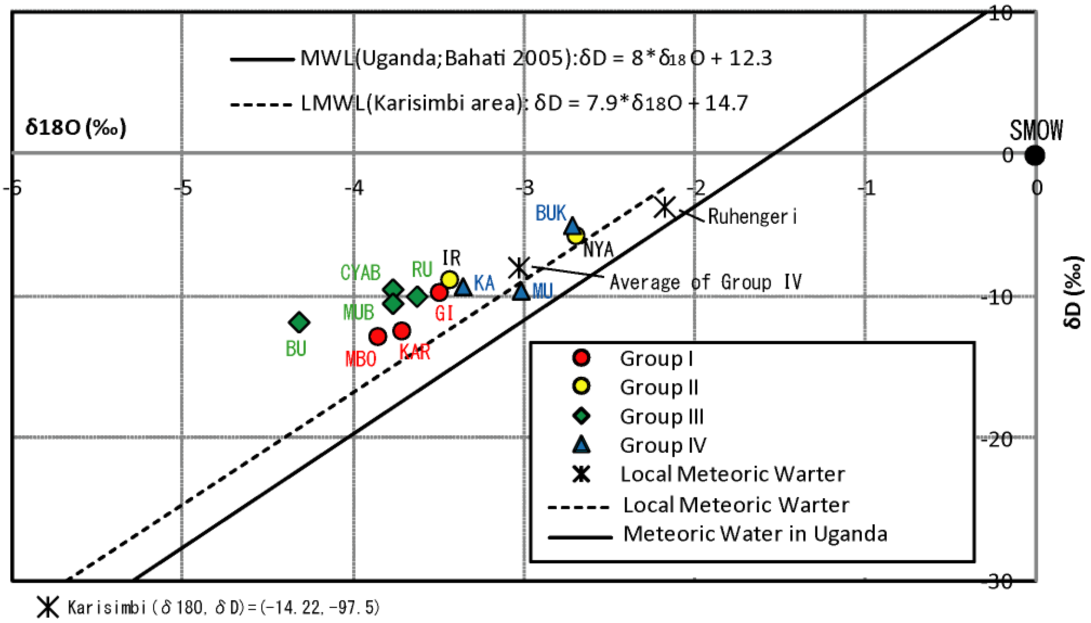
10 Saibi et al.(2010): Temperature and chemical changes in the fluids of the Obama geothermal field (SW Japan) in response to field utilization, *Geothermics*, 39 (3) pp228-241.Elsevier

This kind of shift is not clearly shown in the samples from the study area in Rwanda. Therefore, it can be concluded that there is no evidence that water in the hot and cold springs in the study area have been mixed with magmatic water.

In the previous studies, isotope data do not seem to be well used because of 'unexplained disturbance' and 'all isotope values have been negatively and upward shifted' (IESE, 2012). The LMWL should be made using the local data; however, the LMWL in the previous study has been made using data from the Ugandan study of Bahati in 2005. It is always better to use local precipitation data to make the LMWL because isotope values are controlled by several geographic factors such as latitude effect, altitude effect, and continental effect.

For this reason, the local data of precipitation in Ruhengeri (1,830 m) and in Karisimbi (4,516 m), and the average value of shallow groundwater were used in creating the LMWL of the study area. As shown in Figure 7-12, the new LMWL is drawn nearer the water samples from the study area.

It was also known that an intercept of the meteoric water line (called "d-excess") varies seasonally. Therefore, it would be better to collect and analyze the isotopes in annual precipitation samples in order to create the LMWL.

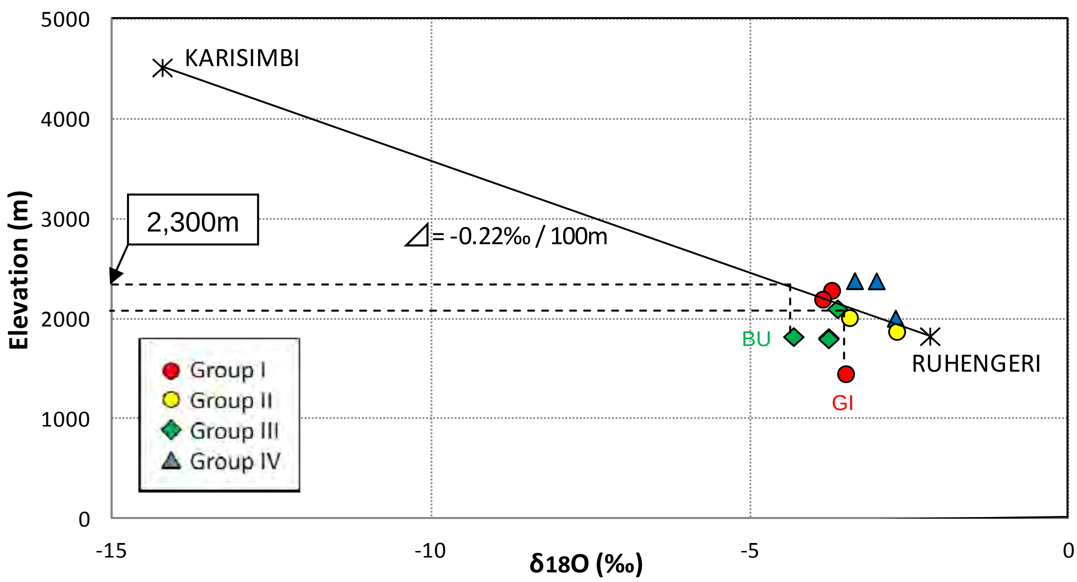


(Source: JICA Team)

Figure 7-12 Stable Isotopes in the Hot and Cold Springs in the Study Area

Using the altitude effect[11] of isotopes, it is possible to estimate the recharged elevation of groundwater. The regression line will be defined as Delta-^{18}O:-0.22‰/100 m, as shown in Figure 7-13, using precipitation data in Ruhengeri and Karisimbi.

For example, the recharged level of Gisenyi (GI) is estimated approximately 2,100 m, and Buseruka (BU) is 2,100 m where the Delta-^{18}O values cross the regression line. Therefore, the original recharge level of the hot and cold springs is estimated from around 2,000 m to 2,300 m.



(Source: JICA Team)

Figure 7-13 Estimation of Recharge Level using Stable Isotopes

【Tritium Concentration】

Tritium is a radioactive isotope of hydrogen whose half-life period is approximately 12.32 years. It can be used to estimate the travel time of groundwater by taking into consideration the decay of tritium concentrations. Since there are no tritium data of precipitation at the project site, the average tritium concentration of river water, which is 2.5 tritium unit (TU) in Uganda from the study of Bahati in 2005, was used as the natural level of tritium value for this evaluation.

It is known that the tritium concentration of precipitation has a tendency to decrease with increasing latitude, and increase with decreasing latitude. This tendency refers to the latitude effect. The tritium value in mid-latitude regions, such as in Japan, is about 5 to 10 TU.

The travel time of recharged water, T, (year) is calculated by the following equation:

[11] The δ^{18}O and δD values of precipitation decrease with increasing altitude.

$$T_{(year)} = 1/\lambda In[N_0]/[N]$$

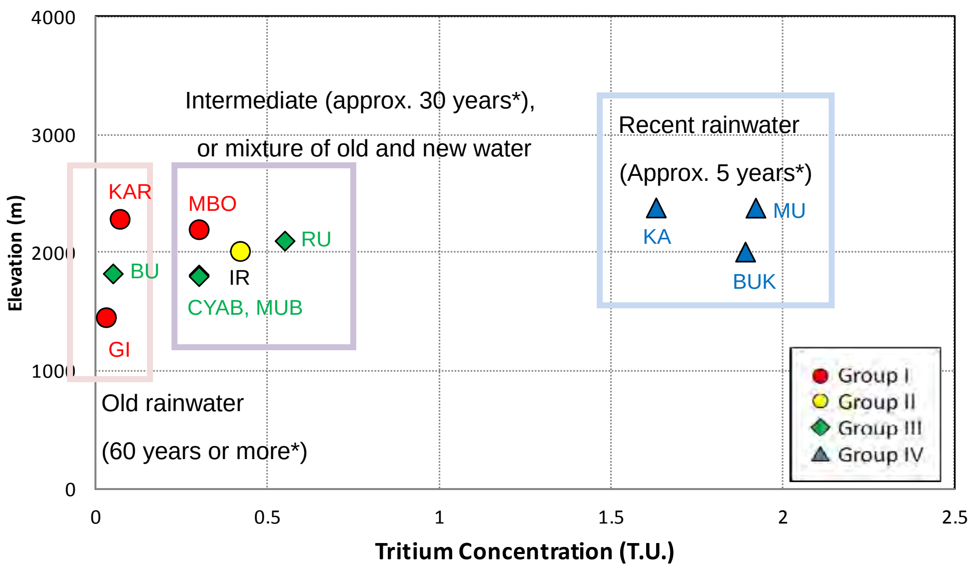
Where,

λ = In 2/12.3

$[N_0]$ = Tritium concentration of original precipitation

[N] = Tritium concentration at sampling

The calculated residence times of hot and cold springs are shown in Figure 7-14. There are three groups: 1) relatively new water about five years (Group IV - Kagohe (KA), Bukeri (BUK), Mutera(MU)); 2) Old water more than 60 years (Group I – Gihenyi (GI), Karago (KAR), Group III – Buseruka (BU)); and 3) Intermediate water (Group I – Mbonyebyombi (MBO), Group II – Iriba (IR), Group III- Rubindi (RU), Cyabararika (CYAB), Mubona(MUB)). Intermediate water is about 30 years or the mixture of new and old water.



(Note*: The natural level of tritium concentration used is 2.5 TU)

(Source: JICA Team)

Figure 7-14 Estimation of Residence Time by Tritium Concentration

7.3.3 Summary of Geochemical Considerations

By analyzing the geochemical data, the detailed information about the source of hot and cold springs have been evaluated for better understanding of the regional fluid circulation system. A summary of the geochemical considerations is shown in

Table 7-2 below. The red-colored items in the table indicate newly added information from this analysis.

Temperatures of reservoir fluid estimated by geothermometry are summarized in the table. Group IV springs are outflow from shallow groundwater flow system. It is not applicable for the geothermometry analysis because they are unequilibrated waters.

Table 7-3 Result of Reconsideration of the Origin of the Hot and Cold Springs in the Study Area

	Group-I	Group-II	Group-III	Group-IV
Location	Gisenyi (GI), Karago (KAR), Mbonyebyombi (MBO)	Iriba (IR) , Nyakageri (NYA)	Cyabararika (CYAB), Mubona (MUB), Buseruka (BU), Rubindo (RU)	Bukeri (BUK), Cyamabuye (CYA), Kagohe (KA), Mutera (MU), Mushoza
Type of Spring	Hot	Tepid	Cold	Cold
	$Na\text{-}HCO_3$	$Na\text{-}HCO_3$	$Mg\text{-}HCO_3$	Ca-HCO3
	Deep groundwater,		Shallow groundwater, circulated water	
	Recharged by meteoric water from 2,000-2,500m a.s.l., no influence by magmatic water			
Tritium (short half-time, 12.3 yr)	Deep, long flow path	Deep, long flow path	Deep, long flow path	Less deep flow path, mixed with groundwater
	Residence time is more than 60yr	approx. 30 yr or mixture of old and new water	approx. 30 yr or mixture of old and new water	approx.5 yr
Temperature from Geothermometry (UniService, 2010)	81 - 109 deg.C	72 - 95 deg.C	96 - 110 deg.C	(54 - 80 deg.C)

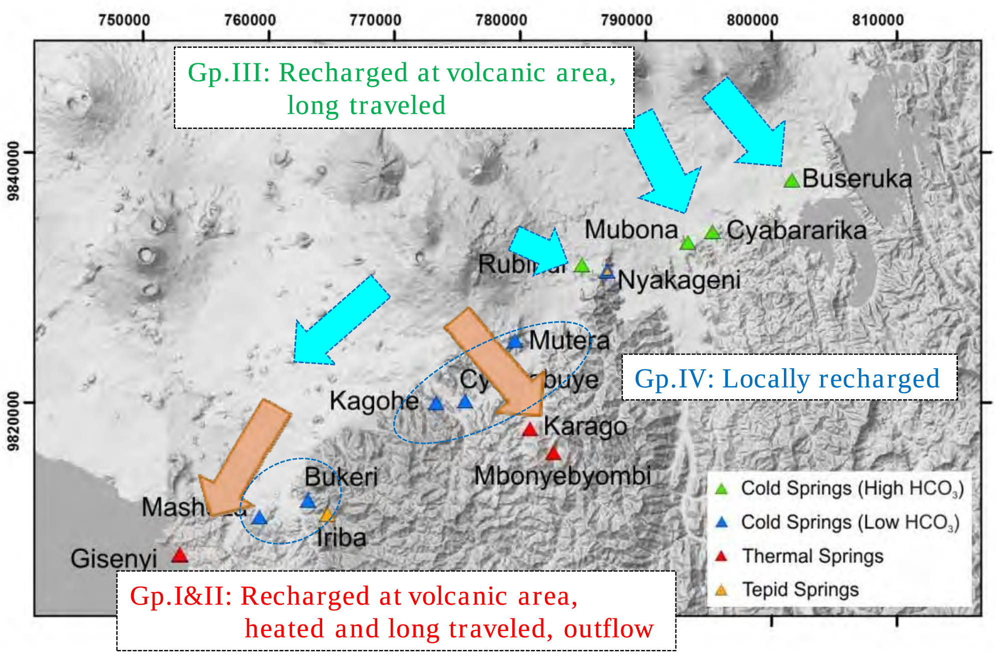
(Source: JICA Team)

7.3.4 Groundwater Flow in the Study Area

The groundwater flow path of hot and cold springs in Karisinbi area can be estimated by geochemical data and hydraulic condition as shown in Figure 7-15. It is considered that Group I and II are recharged in the volcanic area and infiltrated into deep ground, then heated by the heat source and outflow. Group III is also recharged in the volcanic area, migrate toward south, and carbon dioxide gets mixed into groundwater. While Group IV is a shallow groundwater locally recharged at the granite basement area.

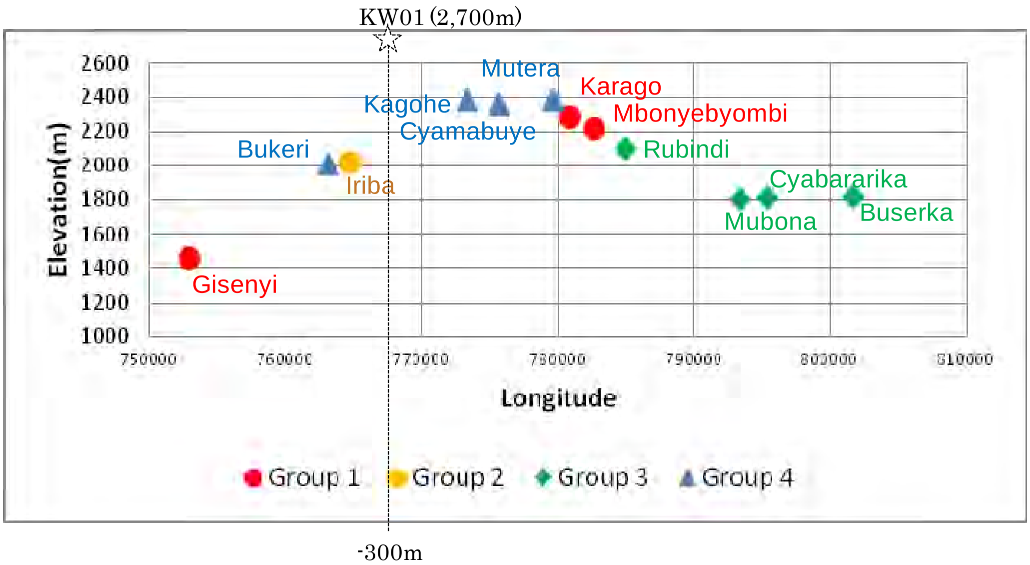
Figure 7-16 shows the E-W cross section with the elevation of hot and cold springs. All springs are located above 1,800m except one spring in Gisenyi. It is remarkable that Mubona, Cyabararika and Buseruka from Group III are located at the almost same level.

Table 7-4 provides the geological information at each spring. Most of springs are found near the geological boundary of the volcanic rock and the basement rock. However, only Group III is found in the volcanic (lava) rock, while others are in the basement rock. It is considered that lava flow which once deposited in the valley of granite area forms the paths of groundwater of Group III.



(Source: JICA Team)

Figure 7-15 Groundwater Recharge Area and Flow Pattern



(Source: JICA Team)

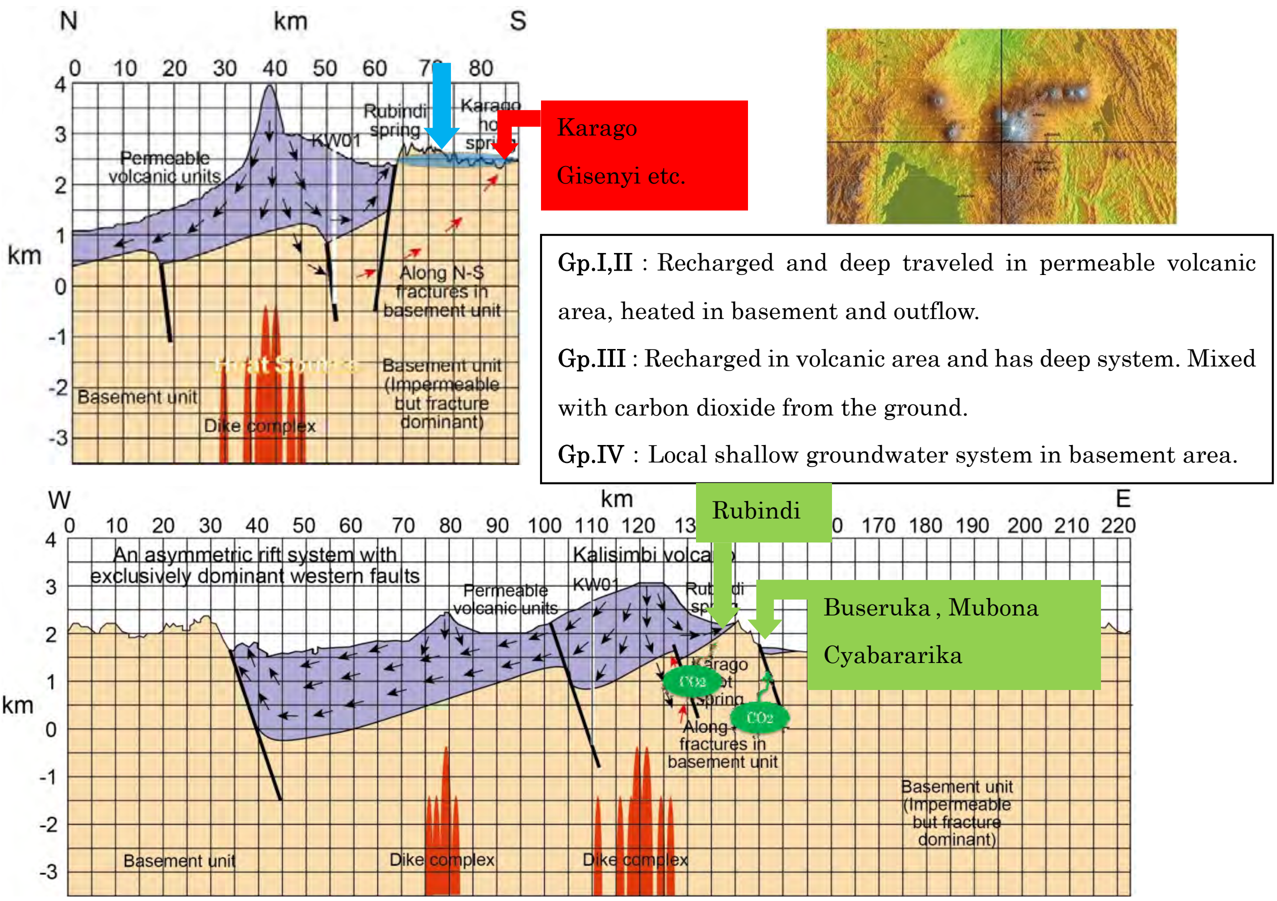
Figure 7-16 Elevation of Hot and Cold Springs (E-W)

Table 7-4 Host Rock of Hot and Cold Springs

Group	Name	Elevation	Host Rock
1	Karago	2288	basement rock
	Gisenyi	1455	basement rock
	Mbonyebyombi	2220	basement rock
2	Iriba	2016	basement rock
3	Rubindi	2104	volcanic rock
	Mubona	1803	volcanic rock
	Cyabararika	1816	volcanic rock
	Buseruka	1823	volcanic rock
4	Kagohe	2385	basement rock
	Cyamabuye	2361	volcanic rock
	Bukeri	2010	basement rock
	Mutera	2383	basement rock

(Source: JICA Team)

From the examinations above, conceptual groundwater flow model is determined as shown in Figure 7-17. Group I,II and IV are described in the NS cross section, and Group III in the EW cross section.



(Source: JICA Team)

Figure 7-17 Schematic Groundwater Flow Model

7.3.5 Summary of Geochemical Considerations

Study team has visited several springs and investigated the usages of springs as water resources by the local people (Table 7-5).

The hot spring in Gisenyi of Group I is not much used as water resources but it seems very important as tourist attractions. Springs of Group III are highly used as water resources not only by the local residents but also by public water supply. There is a water treatment plant in Rubindi, and the source area is managed by EWSA. Springs of Group IV are also important water resources for the local people.

The possible influence from geothermal development project on those water resources have been evaluated in Table 7-5.

It is considered that the risk on Group I and II is not big, because of the distance from the project site and minor usage as water resources.

The risk of the interaction from the geothermal project on the groundwater system of Group III might be small, because the catchment area of Group III is located at east volcanic mountain flank which is different from the reservoir targeted by the project. However, water quality and quantity monitoring are recommended, as the springs on Group III are very important water resource.

The influence on Group IV might be very small, because the groundwater system of these springs is different from that of geothermal resources.

Table 7-5 Summary of Interaction on Water Resources from the Project

Group	Name	Water Type	Main Usage	Interaction from project
I , II	Gisenyi Karago	Hot Deep water	Washing, Bath Tourism	Medium •Possibly same reservoir as geothermal resource •But not very big influence because of the long distance from drilling area
III	Rubindi Buseruka Cyabararika Mubona	Cold High HCO3 Deep water	Main water resources for public	Small-Medium •Different catchment area and different reservoir •Need assessment
IV	Mutera Cyamabuye Kagohe	Cold Low HCO3 Shallow	Water resources	Small •Different reservoir and groundwater system

(Source: JICA Team)

CHAPTER 8 ADVISORY SERVICE CONDUCTED

8.1 Preparation of Application for Geothermal Risk Mitigation Facility

During the second site survey in Rwanda it was noted that EWSA intends to continue the geothermal potential survey in Kinigi with financial assistance from BTC.

When the JICA Team was in Rwanda for the first site survey, it was informed that EWSA intended to conduct the geothermal potential survey in Kinigi with financial assistance from the Geothermal Risk Mitigation Facility (GRMF). The JICA Team was then requested to update the application to GRMF.

An outline of the GRMF is as follows[12]:

[About GRMF]

The African Union Commission (AUC) on one side and the German Federal Ministry for Economic Cooperation and Development and the EU-Africa Infrastructure Trust Fund via KfW (*Entwicklungsbank*) on the other side have agreed to establish the GRMF to fund geothermal development in East Africa. The GRMF was launched in April 2012 and will consist of a series of application rounds.

The GRMF program currently comprises EUR 50 million available for funding.

[Objectives]

The objective of the GRMF is to encourage public and private investors, as well as public-private partnerships, to develop geothermal prospects for power generation in East Africa by providing grants for two types of activity:

- Surface studies to determine the optimal location of reservoir confirmation wells at the most promising geothermal prospects.
- Drilling and testing of reservoir confirmation wells at the most promising geothermal prospects to assist developers secure financing for subsequent reservoir confirmation and/or field development wells.

[Financial Support]

The upper limits for financial support of the allowable field expenditure (AFE) at the time of proposal submission, in the form of a grant agreement, to winning applicants for surface studies and exploration drilling and testing program, are as follows:

12 http://www.grmf-eastafrica.org/

- Infrastructure grants: 20% of approved allowable costs for infrastructure required for eligible surface studies and eligible drilling program (e.g., access roads, water, power).
- Surface studies grants: 80% of approved allowable costs (excluding infrastructure costs).
- Drilling grants: 40% of approved allowable costs for the exploration drilling and testing program for reservoir confirmation wells (excluding infrastructure costs).
- Continuation premium: 30% of the developer's share of the approved allowable and expended costs for the drilling and testing program.

[Countries]

Initially, the GRMF will only support geothermal activities in the following countries:

- Ethiopia,
- Kenya,
- Rwanda,
- Tanzania, and
- Uganda.

Further countries may be eligible at a later phase, if funds are available.

8.2 Preparation of Drilling Program

The JICA Team was requested by EWSA to prepare the drilling program in March 2013 during their first visit in Rwanda. Preparation of the drilling program by the owner is stipulated in the technical specifications (April 2011), and the Iceland GeoSurvey's (ISOR) review report (September 2011) also pointed out that it should be prepared.

The JICA Team prepared the Drilling Program (Draft) and sent the digital file to EWSA with the covering letter dated 5th June, 2013 (**Attachment- 4**).

During the second field survey in Rwanda, the JICA team was requested for comments on the drilling program drafted by EWSA followed by discussions among the parties; and the Drilling Program was finalized at the finalization meeting held at the drilling site on 11th July, 2013. The final version of the Drilling Program finalized by EWSA is as attached as **Attachment- 8**.

8.3 Advice on Cement Slurry

The cement material ordered is generally Portland cement, but no silica flour additives were ordered. This has already been pointed out to EWSA during meetings and in previous communication with them. This is very essential that the JICA Team issued a separate letter, “Advice on Cement Slurry”, dated 15 April 2013, which is attached as Attachment- 3.

8.4 Advice on Geological Observation during Drilling

The ICEIDA-ISOR training course includes training for geological observation during drilling works; in particular for sampling, rock mineral identification under microscope provided by ICEIDA-ISOR, creation of geological logs on a computer soft ware and etc.

The JICA Team provided seminars and discussions to EWSA GDU mainly on the following subjects with the explanation materials (Attachment- 5) with attention to avoiding overlapping with the program of ICEIDA-ISOR; (1) X-ray diffraction analysis, (2) identification of alteration minerals and its significance and so on.

8.5 Advice on Water Supply Facility for Drilling Water

The JICA Team inspected the water supply facility for the drilling works soon after the arrival in Rwanda for the second field survey and obtained such approximate information as （1）Water source: Karago Lake, Height difference: 430m, total pipe line: 18km, (3) a booster pump station at Sashwara. The JICA Team conducted approximate calculation with more detail information obtained to review the design of the water supply facility.

Table 8-1 Key Information of the Water Supply Facility

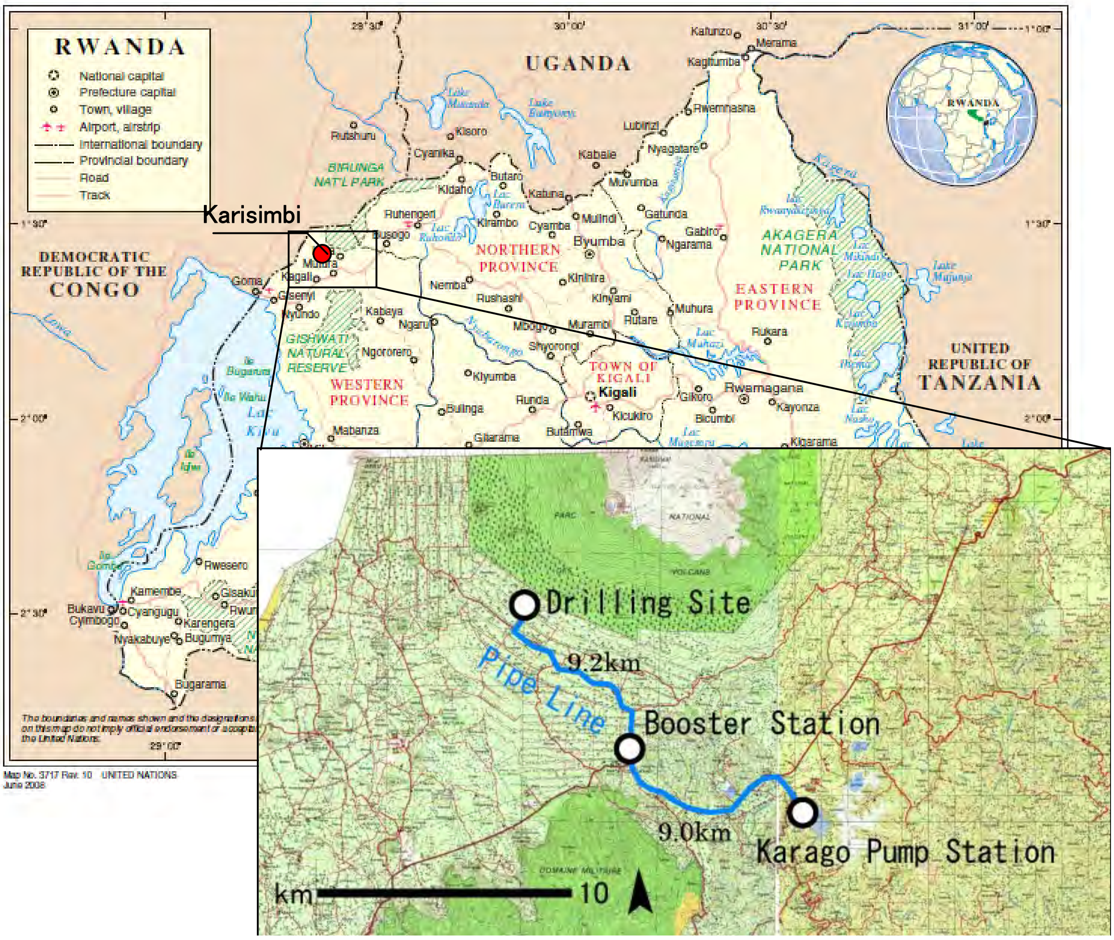
<table>
<tr><th></th><th>Altitude (masl)</th><th>Relative height (m)</th><th>Pipe Length (m)</th><th>Pipe diameter (inch)</th></tr>
<tr><td>Drilling Site (Kabatwa)</td><td>2718.8</td><td rowspan="2">219.3</td><td rowspan="2">9200</td><td rowspan="2">8</td></tr>
<tr><td rowspan="2">Booster Station (Sashwara)</td><td rowspan="2">2499.5</td></tr>
<tr><td rowspan="2">211.7</td><td rowspan="2">9000</td><td rowspan="2">8</td></tr>
<tr><td>Water Intake (Karago Lake)</td><td>2287.8</td></tr>
</table>

（Source : JICA Team）

Table 8-2 Key Information of Water Pumps

	Designed Capacity		Rated Capacity			Comments
	Volume (m³/hour)	Height (m)	Volume (m³/hour)	Height (m)	Notes	
Booster Station (Sashwara)	120	265 or more	155	268	2 pumps (one for stand-by)	Actual pumping volume may not reach the designed volume
Water Intake (Karago Lake)	120	257or more	155	532	2 pumps (one for stand-by	Excessive pressure may be imposed to the pipe line
Head loss calculation : Hazen-Williams equation for straight pipe line						
Pumping height for pumping rate of 120(m³/hour) is not available; Rated curves for the pump are not available.						

(Source : JICA Team)



(Source: JICA Team, Base Map: Service de cartographie du Rwanda 1988, Gisenyi and Ruhengeri)

Figure 8-1 Location Map of Water Supply Facilities

Based on the above approximate calculation, the JICA Team pointed out the followings:

- The capacity of the pump at the Karago intake site may be of over capacity; excessive pressure may be imposed to the pipe line. A piping arrangement to release such excessive pressure may be required at the Karago pumping station.
- The capacity of the pump at Sashwara may be marginal for the designed pumping volume. The designed pumping volume (120 m^3/hour) may not be achieved.

In addition, the JICA Team recommended the followings based on the site observations:

- There were not air-valves observed that are inevitably required for the water pipe placed on undulating ground.
- Mud flash valves may be required because the water in Karago lake is muddy.
- Proper pipe supports will be required particularly at bending portions, because joints may be loosened due to micro-vibration.

It was informed that water was being pumped up on 29th July 2013 with pressures of 30 bar-g (306 m) at Karago and 26.9 bar-g (274 m) at Sashwara after temporary arrangement to release air. Information on pumping volume, though, was not made available.

8.6 Advisory for Well Design and Drilling Program

This Chapter presents an introduction of well design and drilling. Emphasis is placed on subjects applicable to the Karisimbi exploration area. A shorter version of this material was presented by the JICA team during the final wrap–up meeting in Kigali, 17 July, 2013 (**Attachment- 5**).

8.6.1 Design

(1) References for Well Design

The following documents are necessary for a proper well design:

1. *Code of Practice for Deep Geothermal Wells:*
   - NZS 2403:1991, New Zealand Standard (NZS).
2. *API and ANSI Standards and Recommended Procedures:*
   - API Standards for casings, BOP, valves, and material.

- Line Pipe material grade used for surface casings.
- Pipe Valves and Flanges ANSI or PN standards.

3. *Other:*
   - Drilling Data Handbook (“The Green Book”), 8th Edition, Éditions Technip, Paris 2006.
   - International Steam Tables: http://www.international-steam-tables.com/
   - Xsteam: http://xsteam.sourceforge.net/

(2) Understanding Fluid Properties

[General]

The design of geothermal wells is dependent on the expected enthalpy of the produced fluid from the reservoir, because the enthalpy of the fluid determines the temperature and flow characteristics of the fluid, which has to be considered for the well design.

[Definition of high or low enthalpy]

An Explanation given by the IGA (International Geothermal Association) is quoted[13].
“The most common criterion for classifying geothermal resources is, however, that based on the enthalpy of the geothermal fluids that act as the carrier transporting heat from the deep hot rocks to the surface. *Enthalpy*, which can be considered more or less proportional to temperature, is used to express the heat (thermal energy) content of the fluids, and gives a rough idea of their 'value'. The resources are divided into low, medium and high enthalpy (or temperature) resources, according to criteria that are generally based on the energy content of the fluids and their potential forms of utilization. Table 8-3 reports the classifications proposed by a number of authors. A standard method of classification, as with terminology, would avoid confusion and ambiguity but, until such a method exists, we must indicate the temperature values or ranges involved case by case, since terms such as low, intermediate and high are meaningless at best, and frequently misleading.”

[13] IGA web site, accessed in July 2013

Table 8-3 Classification of Geothermal Resources

Resources	(a)	(b)	(c)	(d)	(e)
Low enthalpy	< 90	< 125	< 100	≤ 150	≤ 190
Intermediate enthalpy	90 - 150	125 - 225	100 - 200	-	-
High enthalpy	> 150	> 225	> 200	> 150	> 190

(a) Muffler and Cataldi (1978)
(b) Hochstein (1990)
(c) Benderitter and Corny (1990)
(d) Nicholson (1993)
(e) Axelsson and Gunnlaugsson (2000)
(Unit: °C)

(Source: International Geothermal Association (IGA))

For this discussion, we refer to (e) in Table 8-3, where enthalpy below 190°C is considered *low* enthalpy and above that *high* enthalpy.

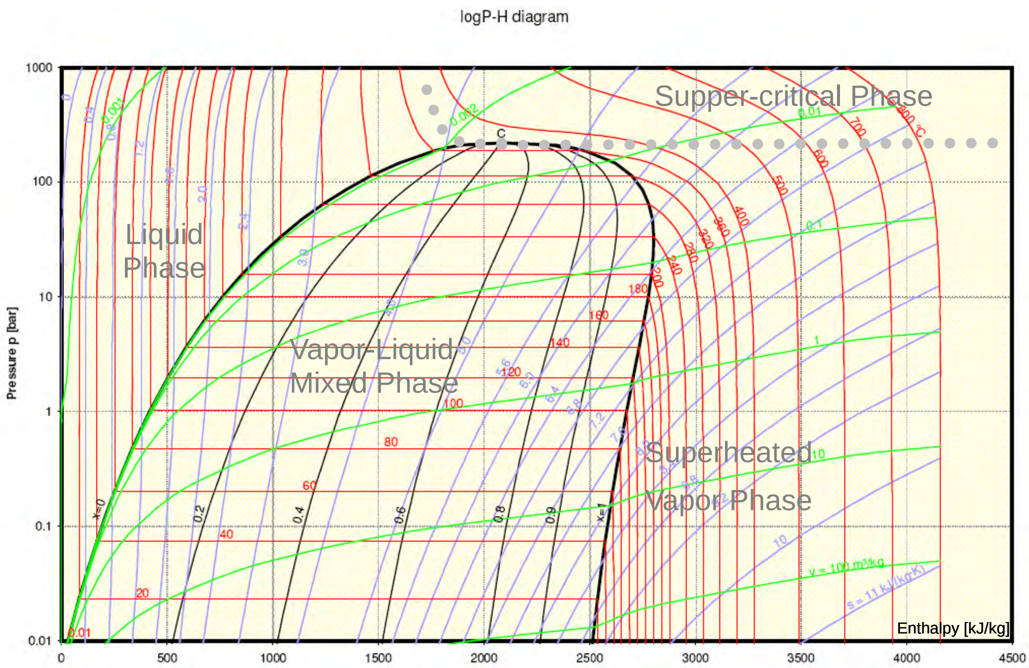
[For the case of Karisimbi]

At this time, the temperature of the Karisimbi reservoir fluid are expected to be 130 – 150 °C and would thus be characterized as *low* enthalpy fluid, though the information from the exploratory well is yet to be obtained.

The maximum pressure at 3000 m vertical depth is expected to be at around 30 MPa (300 bar_a), and if the temperature at this depth is around 150°C as expected; then this would be a low enthalpy well and this type of fluid would generally be utilized for binary power plants, i.e. Organic Rankine Cycle (ORC).

The current well design is ANSI Cl. 900 which allows up to 330°C at 10 bar_a (1MPa) fluid to be produced. This fluid would be classified as *high* enthalpy. If this type of fluid were produced, the fluid should flash (boil) in the reservoir rock surrounding the well and high quality dry steam would be produced.

When the properties of the reservoir fluid are known, the well diameter and design shall be revised.



(Source: Steam Tables).

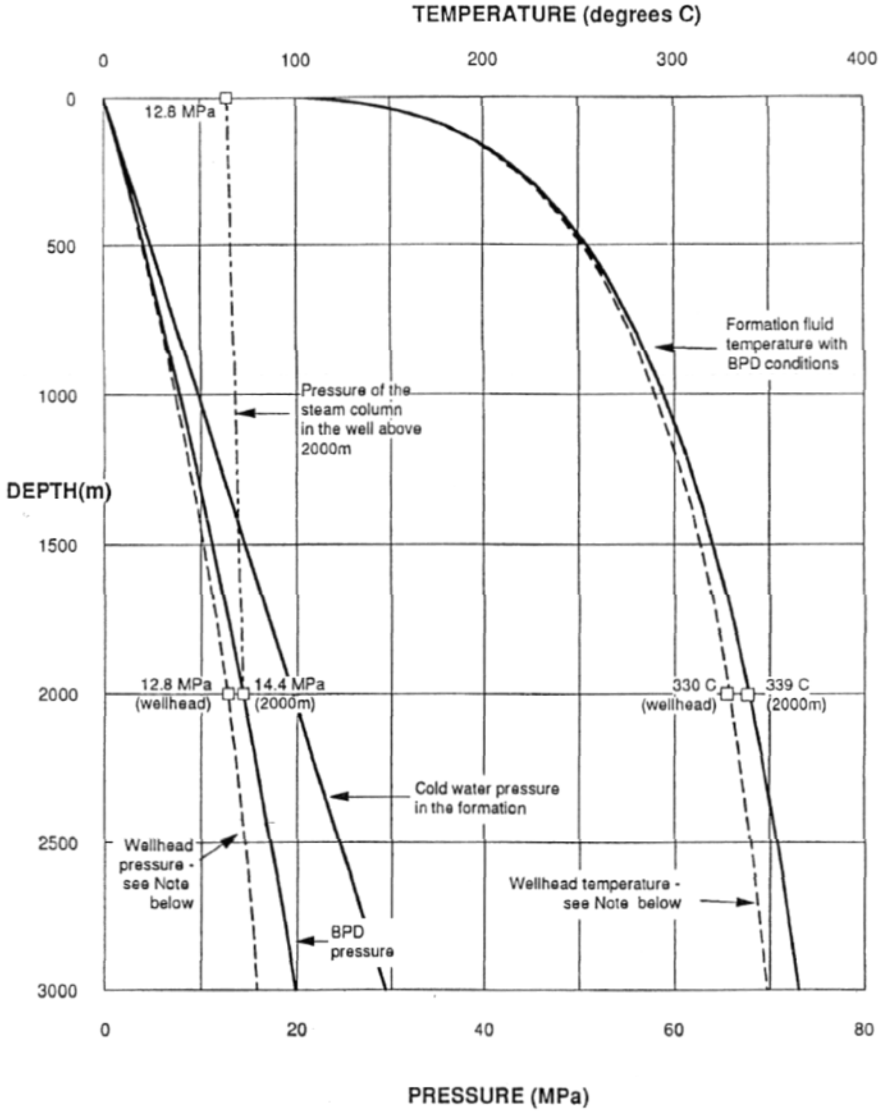
Figure 8-2 Logarithmic Pressure – Enthalpy Diagram

(3) Well Pressure

The design of geothermal wells focuses on extreme cases, when the well is empty of fluid but only a steam column to the surface. This is similar to a well design for oil production where the extreme case would be a well empty of oil but full of gas. This results in a well head pressure equal to the pressure at the well bottom subtracted by the weight of the steam column. This is explained schematically in (Source: NZS 2403:1991)
Figure 8-3.

The column of BPD fluid[14] at depth of 2000 m has a pressure of 144 bar_g (14.4 MPa), while a cold water column of fluid would have a bottom hole pressure of 196 bar_g (19.6 MPa) at 2000m depth. If the well fluid would flash and the well fill with steam to the surface, the well head pressure will be equal to the pressure of bottom hole pressure subtracted by the weight of the steam column, 16 bar_g (1.6 MPa_g); resulting in the well head pressure of 128 bar_g (12.8 MPa_g). Thus, the well head has to withstand a pressure of 128 bar_g (12.8 MPa_g). Correspondingly, the casing has to withstand this same pressure.

[14] Fluid at boiling point for the relevant pressure (BPD: Boiling Point Depth)



(Source: NZS 2403:1991)

Figure 8-3 Pressure of Boiling Water and Steam Column with Depth

Another extreme case is when the casing is being cemented with an inner string; where the casing may be empty, but the annulus full of high density cement slurry (though this is not likely to happen and usually the casing would be full of drilling fluid or water). Then, the casing has to withstand this outer pressure to prevent a collapse.

Other extreme cases to be considered are the tension or compression stresses imposed to the casing, caused by self–weight when it is being lowered into the empty well, or caused by thermal expansion or cooling contraption.

(4) Casing Steel

Geothermal fluids are usually hot and acidic, which is a corrosive environment. When choosing the steel for casing, this has to be taken into account, together with the consideration for the compression and tension in thermal and cooling contraction.

Steel material of more ductile (not brittle) is commonly selected in geothermal wells, which is low cost, corrosion resistive. Steel with low yield strength but high tension strength is more suiteable because it will become ductile in high temperatures, which exceed the yield strength without breaking, and thus adapting to the hot environment.

Thus, the steel of this type will minimize the risks of rupturing caused by stresses due to high temperature. The risk is that thermal cycles with warm–up and cooling will deteriote the casing strength and they should be minimized as possible as they can.
The common steel to be used is Grade K55 (API) or sometimes N80, which is low in cost. It is possible that casing manufacturers would supply higher grade steel than K55 (API) and thus, the material properties should be specified for very hot or acidic wells.

For surface casing a line pipe material of steel grade X56 is often used due to good welding characteristics.

(5) Casing Design

The casing steel properties have to be adjusted for temperature according to Table 8-4. The relevant design factors to be used for the casing design are given in Table 8-5. For further details in the casing calculations, refer to the NZS and API standards.

Table 8-4 Adjustment to Casing Steel Properties due to Temperature

Grade	Temperature (°C) 20	100	200	300
API Yield Strength (Factor):				
J/K-55	1.00	0.95	0.95	0.95
N-80	1.00	0.96	0.92	0.88
Tensile Strength (Factor):				
J/K-55	1.00	0.97	1.02	1.07
N-80	1.00	0.97	0.99	0.99
Modulus of Elasticity (10^3 MPa):				
J-55	178	172	168	160
K-55	208	208	200	192
N-80	206	206	200	192

(Source: NZS 2403:1991)

Table 8-5 Design Factors to Use in Casing Design

Design factors					
Axial		***Use***	Hoop		***Use***
Tensile	1.5-1.8	***1,5***	Internal yield (burst)	1.5-1.8	***1,5***
Compressive	1,2	***1,2***	Collapse	1,2	***1,2***
Wellhead anchorage	1,5	***1,5***	Inner collapse (outer burst)	1,2	***1,2***

(Source: NZS 2403:1991 for the range values, JICA Team for *Use*)

(6) Casing Threads

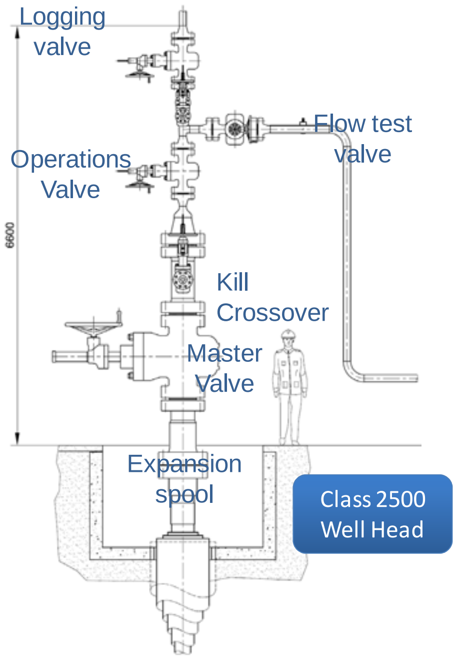
The casing threads chosen for geothermal casings have to withstand compression just as tension. The recommended threads are buttress (BTC: Buttress Thread Casing) and some Hydril threads that have high compression strength. Usually we use the buttress thread or simply weld the connections, which results in same compression and tension strength (note that the steel grade has to be suitable for welding).

The casing thread shall be protected with suitable thread compound ("casing dope") that can resist the temperature. It is recommended to use glue the joints to prevent them from loosing. If welded, "spot welding" at three points at a joint may be acceptable.

(7) Well Head

Every geothermal well shall have a master valve, which has to be operational when a leak or other emergency demands the closing of the well. Usually an "expanding gate valve" is used because the valve housing is sealed when the valve is fully open and thereby the housing is protected from scale accumulation. Another valve is then installed after the master valve for opening and closing the well during operations. This valve may be of lower quality and is sacrificed for the operation of the well. An example of well head is as shown in (Source: JICA Team)

Figure 8-4Figure 8-4) .

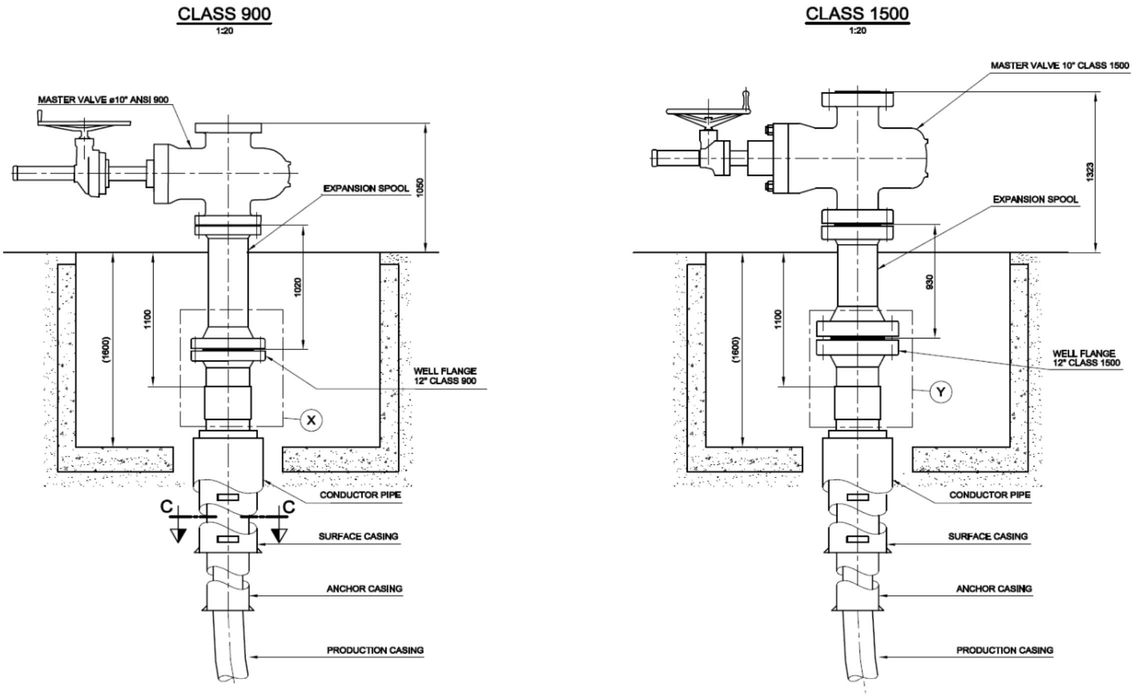


(Source: JICA Team)

Figure 8-4 Example of Well Head (Class 2500)

An expansion spool of appropriate length is to allow the production casing to move with thermal expansion. Examples of well heads are shown in (Source: JICA Team)

Figure 8-5, for Cl. 900 and 1500. Kill lines are installed on the expansion spool or on a cross above the master valve. Typical sizes for the well heads and casing programs are shown in Table 8-6.



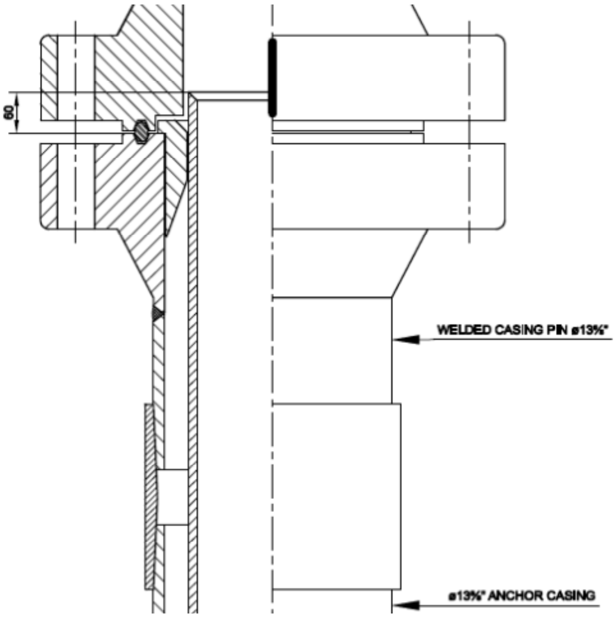
(Source: JICA Team)

Figure 8-5 Typical Well Heads for Cl. 900 and 1500 Wells

All well head flanges shall be of proper ANSI Class or PN number with steel gaskets. When assembled, it is important to follow the recommended assembly procedure for torquing, to prevent leakage.

The well head flange can be welded onto the casing in–situ. It is recommended to use a pre–welded flange onto a casing pin (Figure 8-6), which can be welded in a welding shop at ideal conditions and the weld tested before being installed. This well head flange can then be simply screwed into the top casing collar in the field.

Refer to NZS for further well head design.



(Source: JICA Team)

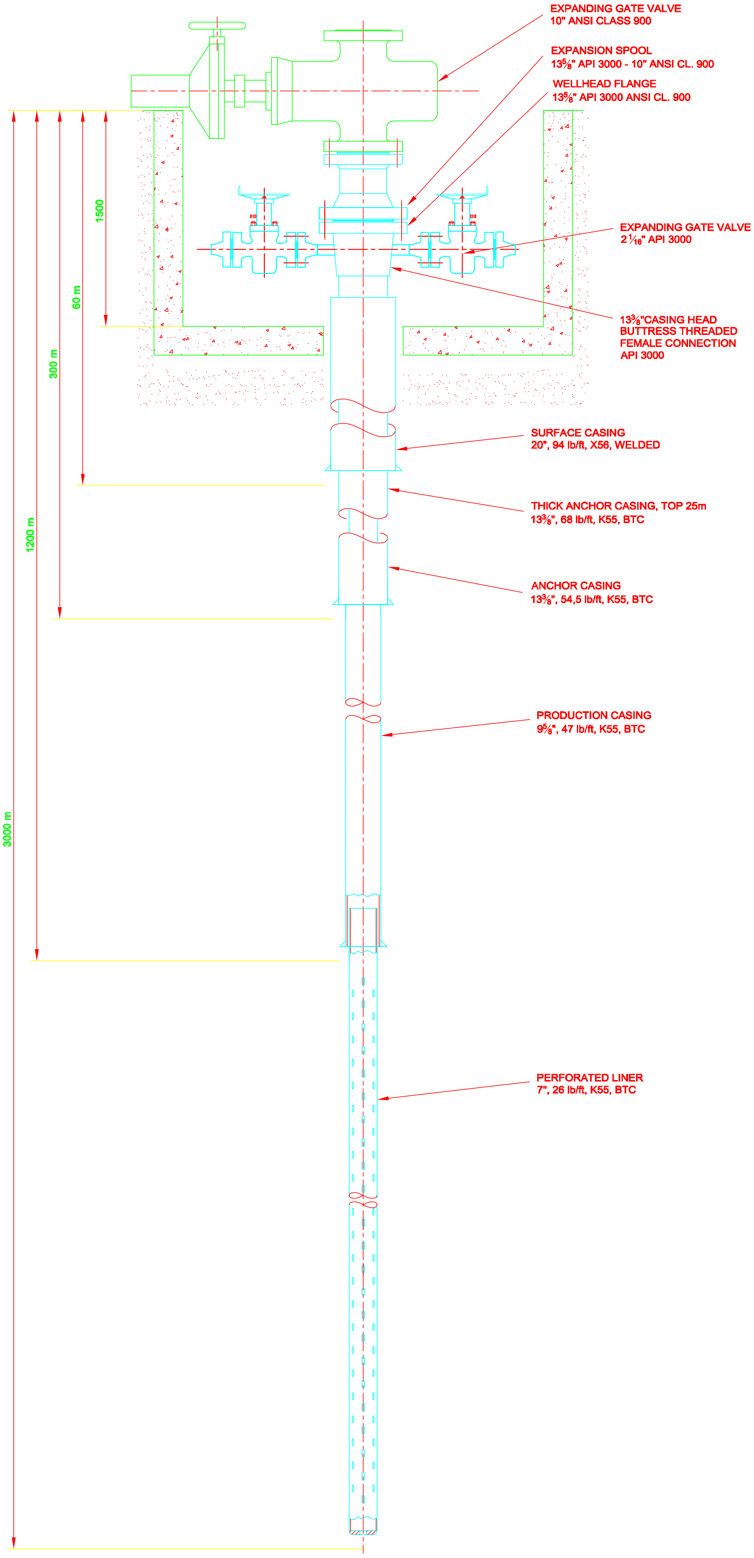
Figure 8-6 Well Head Flange

8.6.2 Drilling Program

The JICA team spent considerable time in assisting with information and drawings for the KW–01 drilling program. There were also detailed recommendations as to the cement slurry (**Attachment- 3**).

(1) KW–01

The drilling program for the first exploration well in the Kabatwa area (Karisimbi Volcano) KW–01 is shown in Attachment- 8. The well drawing is shown in Figure 8-7. The design for this first exploration well is ANSI Cl. 900.



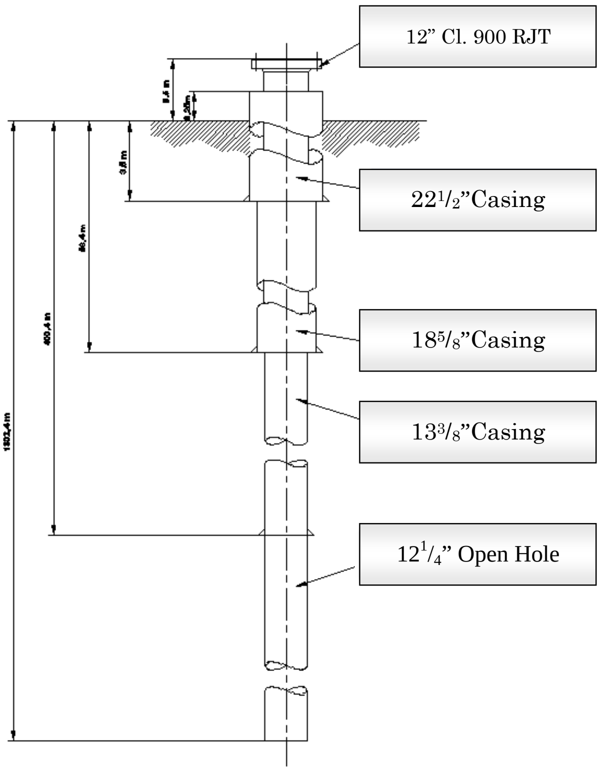
(Source: JICA Team)

Figure 8-7 Well Drawing for KW-01, Kabatwa Area

(2) Low Enthalpy Well

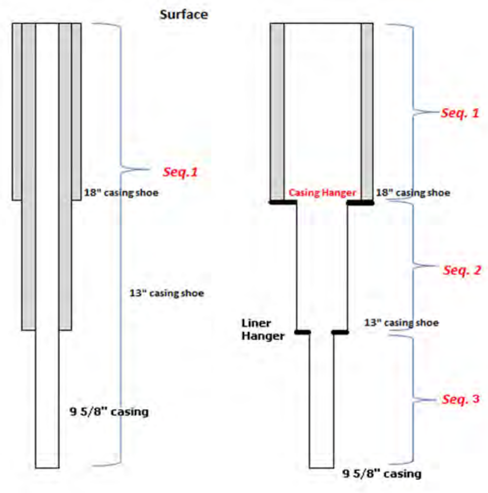
As discussed previously the next wells may possibly be low enthalpy wells, depending on the actual reservoir properties to be confirmed by the first well.

The main difference to consider for low enthalpy wells is larger casing diameters. Figure 8-8 shows a low enthalpy well with Ø13⅜″ casing to allow well pumps to be installed. Sometimes they have a Ø9⅝″ production casing that is telescopic to allow a well pump to be installed at around a few hundred meter depths (Figure 8-9). Electric Submersible well Pumps (ESP), of suitable size for the required volume and pressure head, usually require a casing size of Ø13⅜″.



(Source: JICA Team)

Figure 8-8 Low Enthalpy Well with Ø13⅜″ Casing



(Left: Basic Design; Right: Telescopic Design)

(Source: JICA Team)

Figure 8-9 Casing Design

As mentioned above a wider casing diameters are used for low enthalpy geothermal wells mainly to allow a submersible pump to be installed. Table 8-6 shows typical sizes used for wide casing programs and comparable sizes used for narrow casing programs.

Table 8-6 Typical Bit and Casing Sizes for Wide and Narrow Geothermal Casing Programs

Wide		Narrow	
Ø12¼″ Production Hole Ø12″ Master Valve ø18″ Well Flange Ø18″ – ø12″ Expansion Spool		Ø8½″ Production Hole Ø10″ Master Valve ø12″ Well Flange Ø12″ – ø10″ Expansion Spool	
Bit	***Casing***	***Bit***	***Casing***
Ø26″	ø24½″	Ø21″	ø18⅝″
Ø21″	ø18⅝″	Ø17½ ″	Ø13⅜″
Ø17½″	Ø13⅜″	Ø12¼″	Ø9⅝″
Ø12¼″	Ø9⅝″	Ø8½″	Ø7″

(Source: JICA Team).

8.6.3 Drilling

There are special cases that are frequently encountered in geothermal drilling; these are extreme Loss Of Circulation (LOC), and blind drilling, i.e. drilling without getting returns to surface.

In addition to these cases, a special care shall be taken at all times to prevent flashing (boiling) from occurring in the well. This may usually be prevented by keeping the well full of drilling fluid or water, with a careful monitoring the water level.

(1) Extreme Loss of Circulation (LOC)

"Extreme LOC" is the LOC of about 15 l/s or more of drilling fluid that is being lost to the formation. Small scale of LOC may sometimes cease or mitigate while further drilling. If the extreme LOC does not cease or mitigate, it should be addressed by loss circulation material (LCM), cement or chemical agent. When an extreme LOC should occur, further 20m – 50 m shall be drilled to observe any change of LOC and geological conditions on whether any more fractures exist or not. Cementing is effective against LOC if other procedure should be unsuccessful, though the cementing is costly. Thus a light weight drilling fluid such as "aerated mud" may be used, or drilling fluid mixed with fibrous material or particle may also used.

If those options should not be successful, cementing or chemical agent will be used to plug off the fractures that cause the extreme LOC. Type of cements and/or additives shall be selected to suit the LOC conditions and/or well temperatures, thereafter cement slurry of appropriate characteristic and volume shall be sent to the appropriate part or the well. If several trial of such cementing should be failed, alternative methods shall be considered. One of those is that pieces of crushed lightweight cement shall be put into the well, followed by normal cementing. Chemical agent may sometimes be used before cementing.

When cementing the fractured zones, proper care has to be taken to these cemented fractured zones as they may open up during the cementing procedure.

Blind drilling may sometimes applied when the cementing should be difficult. However, extreme LOC before/above the geothermal reservoir shall be mitigated or treated so that succeeding casing cementing could successfully be complted.

(2) Blind Drilling

"Blind drilling" is the drilling when drilling is continued even though the drilling fluid and cuttings are not returning to the surface, i.e. total LOC. When blind drilling, the build–up (accumulation) of cuttings in the well are unknown and thus care shall be taken to measure the cuttings build–up (accumulation) in the well by pulling a few stands up off the bottom of the well and circulating fluid; thereby the cuttings in the open hole are allowed to fall to the bottom. The speed of the cuttings falling to the bottom and the waiting time depends on the fluid properties (refer to the Green Book).

The drilling string is then lowered until the top of the cuttings is felt. The cuttings are then slowly grinded and blind drilling may resume. Blind drilling is usually conducted only for a short period because the geothermal target has been reached when total LOC is encountered in the reservoir rock.

8.6.4 Well Testing

After completion of drilling geothermal wells and the wells have been shut closed for some time, a gas usually accumulates in the top section of the casing. This gas should be allowed to escape by bleeding through a Ø2 mm orifice.

After bleeding the gas from the well, the well may be allowed to flow. The flow will usually be self flow if it is a high enthalpy fluid. For low enthalpy wells the flow may be induced by air–lift (pumping air down into the well to lower the fluid density) or by pumping up water out of the well.

The geothermal fluid in the reservoir is contaminated by the drilling fluid used during the drilling. Thus, enough time shall be allocated to release the drilling fluids from the geothermal reservoir to obtain a sample of the virgin reservoir fluid. About 1–2 months may be sufficient to release the drilling fluid and then further 2–6 months for sampling and testing to obtain reliable well data including production curves.

After the testing, the well shall be shut off or allowed to bleed, to prevent the well from "killing" or from allowing cooling down. This is to prevent thermal cycles as discussed in relation to the casing steel material.

CHAPTER 9 OTHER ISSUES OBSERVED AND RECOMMENDATION

9.1 Preparation for Master Plan Study on National Power Development

It is intended that a master plan study on national power development in Rwanda would be implemented with consideration of geothermal development, before conducting a feasibility study for Karisimbi geothermal development. To conduct the master plan study, reliable data and information is required.

Electric power development is of national importance to sustain the national economic development and therefore the demand forecasting will be closely linked with national development plan. It is thus essential for EWSA to obtain such relevant information on the national economic development plan, industrial development plan and/or etc.

On the other hand, the Rwanda has planned to increase the installed capacity up to 1000MWe consisting of 25.6% of hydro-power, 25.5% of geothermal power, 32.0% of methane gas power and 16.6 % of peat generated power by 2017; thereby to abolish oil generated power plants. In order to formulate a reliable power development master plan, reliable data and information will be inevitable on the natural resources for the power development; thus the master plan study could propose the best mix of energy. It is also essential that EWSA should obtain those information before commencement of the master plan study.

9.2 Observations and Recommendation on National Power Development Plan

9.2.1 General

(Draft) National Energy Policy and Strategy (May 2011) describes that the installed capacity of 1000 MWe should be added by 2017 to the present installed capacity of 96.44 MWe as of 2011. Of those, a well head geothermal power plant of 10MWe was scheduled to install in 2012 and thereafter, a geothermal power plant of 75MWe was to be installed each in 2014, 2016 and 2017, which totals to 310 MWe by 2017 ((Draft) Electricity Development Strategy (2011-2017)).

When formulating the master plan, the remarkable gap between the present installed capacity and the planed installed capacity in 2017 should be noted and a practical plan has to be recommended

9.2.2 Observations and Recommendations on Geothermal Potential Evaluation

The geothermal potential was evaluated to 310 MWe based on the experience of Olkaria in Kenya. However, the review of the previous documents and reports identified that Olkaria geothermal field is underlain by felsic magma whereas the Karisimbi site by mafic magma. The heat properties of these magmas are fundamentally different (Chapter-7). It should be prudently required that the geothermal potential should be reviewed based on the results of the fist exploratory drilling.

Further, 740MWe of geothermal potential has been estimated in Rwanda (Table 4-6). This evaluation seems to have been made also based on the experience of Olkaria.

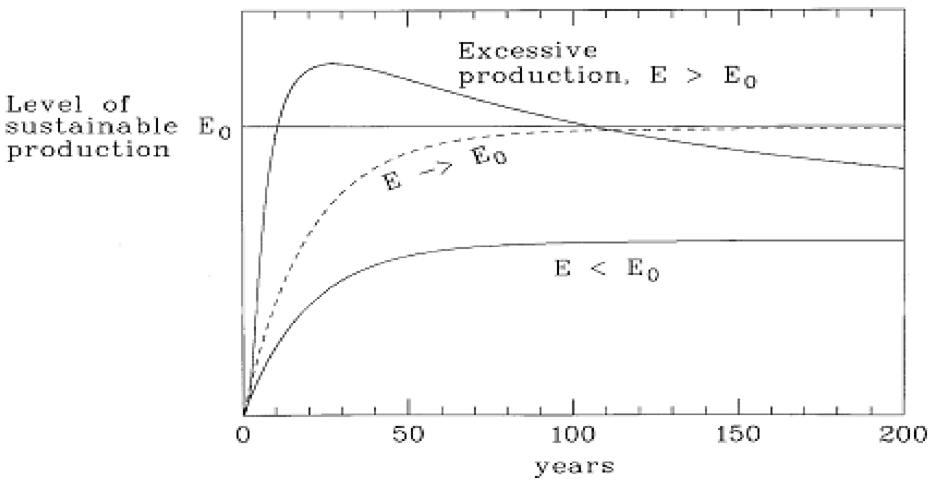
The master plan study will have to review the geothermal potential all in Rwanda.

In addition, well evaluation will have to be conducted after releasing sufficient fluid from the reservoir because the geothermal reservoir may have been contaminated and cooled with the drilling fluid during drilling. A half year or may be required to release sufficient fluid until the reservoir resumes its original characteristics.

9.2.3 Observations and Recommendation on Karisimbi Geothermal Development – Step by Step Approach

As described above, 310 MWe was to be developed in Karisimbi by 2017. However, this target seems to be very challenging at this moment when the first drilling has just started.

Because geothermal development includes various uncertainties such as potential evaluation, environmental assessment and/or others, a step-by-step approach will have to be adopted with a progressive assessment of those uncertainties. Excessively large or small investment at initial stages will not be preferable from effective utilization of the geothermal energy (Figure 9-1).



(Axelsson et al., 2003)

1. E > E_0: Excessive initial investment, geothermal resources may decrease
2. E < E_0: Underestimated initial investment: geothermal resources may not be sufficiently utilized
3. E → E_0: preferable step-by-step approach

(Source: Explanation by JICA Team)

Figure 9-1 Sustainable Development of Geothermal Energy

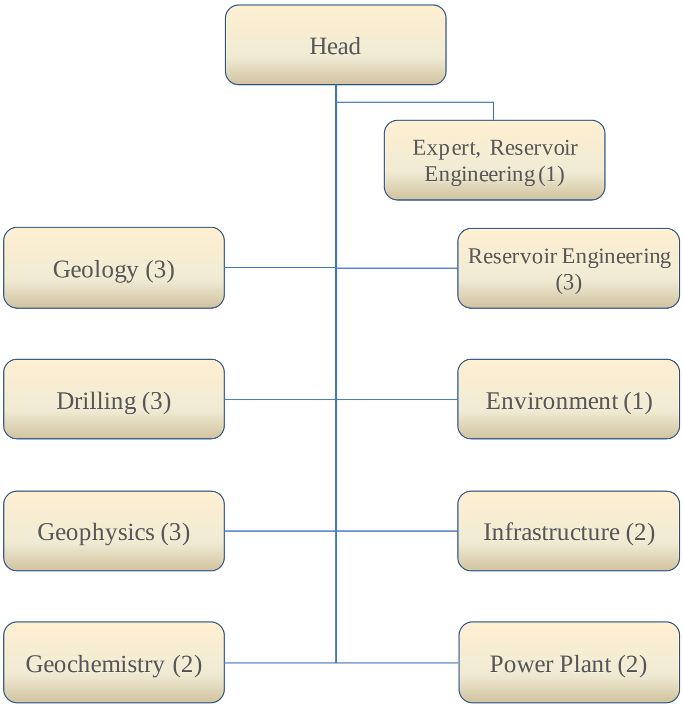
An example of geothermal development schedule will be as follows: (1) Regional and local surface investigation: 0.5 – 2.0 yr, (2) Exploratory drilling and evaluation: 1.0-3.0 yr, (3) EIA: 0.5-1.0 yr, (4) F/S: 0.5 – 1.0 yr, (5) Basic design and Detail design: 1.0-1.5 yr, (6) Procurement, construction and commissioning test: 3.0-4.0yr, (7) commercial operation. As a summary, approximate six years or more are required for a project; and at least five years will be for Karisimbi where the first exploratory drilling has now been commenced in 2013.

Not only Karisimbi prospect but for other prospect, the above time schedule should be considered when the master plan is to be formulated.

9.3 GDU: Geothermal Development Unit

9.3.1 Present Status

Geothermal Development Unit of EWSA is in charge of geothermal development in Rwanda. The organization of GDU is as shown in Figure 9-2.



1. All staff, except Head, are contract basis.
2. All are re-newed after the contact period.

(Source: JICA Team)

Figure 9-2 Organization of the Geothermal Development Unit

The GDU consists of 21 staff including the head and Ethiopian Expert. A Kenyan expert who was leading the geothermal development in Rwanda resigned GDU in June 2013. All staff except for the unit head are contract basis employees and they will be replaced or renewed once the contract period has reached.

9.3.2 Issues for Strengthening the GDU

(1) Organization and Staff

EWSA, a company that distributes power and water in Rwanda, was established in 1976 as a national utility. The mission of EWSA is "to provide sufficient and quality water and electricity to our customers at affordable and sustainable rates that support the socio-economic development of the country"; one of the key objectives is to "Achieve financial solvency for the company"; and one of the obligations is for "Coordination of all activities related with programmers aimed at development and exploitation of energy sources[15]". It seems that EWSA is not a competent agency for geothermal potential exploration with necessary technology within EWSA, rather than this; EWSA seems to be defined as coordinating body.

The issue noted is the employment mode where all staff except the unit head is contract basis employees with limited time periods. All staff having reached the end of the contract periods will have to be renewed with new employees. Increasing skills, experiences and knowledge of the technical staff cannot be expected under this current employment system.

As mentioned above, construction of geothermal station will require a longer time period for about six years and therefore a long term employment period may be required. In addition, the Kinigi prospect is scheduled to be explored, Bugarama near the Burundi border is considered to have geothermal potential of 60 MWe. In order to develop that geothermal prospect, accumulation of knowledge and experiences will be required.

From the above point of view, it will be necessary that the section chiefs at least should be re-employed depending on the performance in the previous contract periods. In addition, donors should identify appropriate targets for training so that the knowledge and experiences will be accumulated in EWSA.

(2) Equipment and Material

ICEIDA-ISOR has provided a stereo-microscope and a polarizing microscope. Other than those, the equipment as shown in Table 9-1 may be required for geothermal exploration. However, careful assessment may be necessary on organizational plan, employment plan and technical development plan before introducing equipments that

[15] EWSA web-site accessed in July 2013

needs skill and experience for operation.

Table 9-1 Necessary Equipment for Geothermal Development

Basic	Geological Analysis	Geo-physics	Geo-Chemistry	Chemical Analysis
GPS	X-RDA	MT Survey	Digital thermometer	ICP-AES
-	Micro-scope with heating and cooling stage (Fluid Inclusion)	TEM Survey	pH meter	Atomic Absorption Spectrometer
-	-	Gravity meter	Electric Resistivity Meter	Gas Chromatography
-	-	-	Ground water dip meter	Photoelectric Spectrophoto-meter
Underlined: Equipments needs experiences and skills				

(Source: JICA Team)

PTS logging and well testing is scheduled to be conducted by a Kenyan company (Kenya Geothermal Development Company). It was suggested to the JICA Team to procure those equipments for PTS logging and well testing to EWSA. However, the JICA Team is of opinion that those equipments shall be procured after careful assessment on the present conditions and future development plan of GDU as mentioned above.

(3) Technical Assistance (Technical Advisors)

As the Kenyan expert who had lead the geothermal development in Rwanda resigned EWSA, the following type of experts of advisors will be required to EWSA

- Geothermal Development Advisor
  - Karisimbi Geothermal Prospect
  - Rwanda Geothermal Development

The head of GDU mentioned that an advisor for reservoir evaluation or well test evaluation is required for the potential assessment of the first exploratory well, in addition to the drilling advisor from Reykjavík Geothermal and geological adviser from ICEIDA-ISOR.

The JICA Team considers that an advisor for construction management or supervisor for integrated supervision of the project.

9.4 About Binary Power Plant

Reports on Karisimbi geothermal prospects suggested that a binary power plan would be suitable because the geothermal fluid would be around 150°C according to geochemistry. Although a geothermal development plan has to be formulated based on the results to be obtained from the exploratory drilling presently implemented, a reconnaissance type consideration may be useful to for a consideration of a future plan.

Binary type power plant is classified into two types in Table 9-2 below. According to the table, Karisimbi may be of a Rankine cycle type due to its possible fluid temperature of 150°C.

Table 9-2 Types of Binary Power Plant

Binary Power Plant	Media	Temperature of Geothermal Fluid (°C)
Rankine Cycle	Inactive gases such as Pentane, Butane, replacing halon (chlorofluorocarbon)	150-100
Kalina Cycle	Mixture of water and ammonium	100-70

(Source: JICA Team)

Table 9-3 summarized the binary power plants that were newly constructed between 2005 and 2010. This shows the total capacity of the power plants vary from 0.2 to 50MW. However, one unit will have a capacity not larger than 20 MW[16].

[16] There are some plants that unit capacity exceeds 20MW. It is necessary to confirm such information individually.

Table 9-3 Binary Power Plants newly Constructed in 2005 - 2010

Country	Plant Name	Unit	COD	Installed Capacity (MW)
Turkey	Dora	2	2010	9.5
USA	Chena	3	2009	0.3
Germany	Bruchsal	1	2009	0.5
USA	North Brawley	1-7	2009	7
USA	Faulkner	1	2009	50
USA	Salt Wells	1-2	2009	12
USA	Stillwater	1-4	2009	12
USA	OIT	1	2009	0.3
Austria	Simbach Braunau	1	2009	0.2
USA	Thermo Hot Spring	1-50	2009	0.2
USA	Rocky Mountain	1	2009	0.2
El Salvador	Berlin	4	2008	9.4
USA	Herber South	1	2008	10
Turkey	Kizildere Binary	1	2008	6.8
USA	Raft River	1	2008	15.8
New Zealand	KA24	1	2008	8.3
Germany	Landau	1	2008	3
USA	Lightening Dock	1	2008	0.2
New Zealand	Ngawha2	1	2008	15
USA	Galena III	1	2008	27.5
France	Soultz-sous-Forets	1	2008	1.5
Germany	Unterhaching	1	2008	3.4
Guatemala	Amatitlan	1	2007	24
New Zealand	Mokai 1A	1	2007	17
USA	Galena II	1	2007	15
USA	Blundell I	2	2007	11
USA	Chena	1-2	2006	0.2
Turkey	Dora	1	2006	7.4
USA	Gould	1-2	2006	5
Japan	Kirishima Geotherma	1	2006	0.2
USA	Desert Peak II	1	2006	23
Japan	Hachobaru	3	2006	2
New Zealand	Mokai 2	2-5	2005	5
USA	Richard Burdett	1-2	2005	15
New Zealand	Binary	15-16	2005	8

(Source: from Table 10 in R.Bertani, 2012[17])

[17] Ruggero Bertani (2012): Geothermal power generation in the world 2005-2010 update report, Geothermics

Efforts are being continued to manufacture binary power plants of high efficiencies. An example is given below using geothermal fluid of 250 °C, that is an organic rankine cycle power plant producing 10.5MW (Source: Kapkan, 2007[18]).

Project:	Pico- Vermelho, Sao Miguel
Steam Inlet Temperature (°C) :	151
Steam Flow Rate (t/h):	74.86
Brine Inlet Temperature (°C):	161.3
Brine Flow Rate (t/h):	346.74
Plant Net Power (MW):	10.5

In this system, geothermal fluid is separated into vapor and liquid, thereafter the vapor is delivered to the vaporizer to vaporize the media whereas the liquid is delivered to the pre-heater where the media is pre-heated by the separated liquid.

When compared with the case of Karisimbi, the geothermal fluid of Karisimbi may be of 60% enthalpy of this example, and therefore a simplified calculation indicates that approximate 700t/h (195kg/s) of geothermal fluid from wells in Karisimbi may be required to produce a similar amount of power (10.5MW). Just for comparison, the required fluid is in a range of the water volume six times as the planed water volume (120m^3/hour) for the drilling

[18] Uri Kaplan (2007): Organic Rankine Cycle Configurations, Proceedings European Geothermal Congress 2007

Attachment-1

Presentations and Minutes of Meeting of Inception Meeting

The Data Collection Survey on Geothermal Development in Rwanda

Inception Report Meeting

On 21st March, 2013

At the board room, EWSA Head Quarters, Kigali, Rwanda

Participants: as attached

1. The chairperson, Ms. Uwera Rutagrama, Head of Geothermal Development Unit, opened the meeting by inviting the self-introduction of the participants.

2. The chairperson welcome the team and she made a brief explanation of Geothermal Development Unit of EWSA including the recent various activities of the geothermal development in Rwanda, and finally she addressed on how this meeting should proceed for useful cooperation for smooth implementation of the exploratory well drilling. She, then, invited the Team for the presentation.

3. Mr. Takahashi thanked for her introduction and made his presentation with the slide prepared (Appendix-I). The confirmation and/or discussions during his presentation were as follows:
   (a) Three 3000m wells are to be drilled in Karisimbi.
   (b) BGR Report 2009 includes a lot of information; the previous reports include the data that are not included in the other report; therefore the Team is requested to go through all the reports.
   (c) The study report WGC 2012 (written by Ms. Uwera) should also be referred to, because it is helpful to understand the project.
   (d) Work plan is still changing because the drilling (commencement) date is not fixed yet. Once other procurement schedule is fixed, the work plan will be ready, probably within a week.
   (e) Timely decisions are required if something happens on site. Real time communication, such as using skype, should be made for timely decision.
   (f) Reporting formats will be discussed with Reykjavik Geothermal and/or drilling contractor. Such format will be made available to the Team by the time of the next visit.
   (g) The reports will be uploaded to an internet common server so that parties concerned can access the information with a password to be set.
   (h) A question was made on the timing of the reports from the Team, if the drilling

progress should be delayed. At this moment the contract period of the Team with JICA will end at the beginning of August, 2013. The team informed that the team is not in the position to decide the change of the contract period.

(i) Fault locations are important to decide the well position. Gravity data is available slightly outside of the target area.

(j) The site visit schedule made through the coordination of Ms. Nishigori of JICA was confirmed among the parties participated.

4. Presentation was given by EWSA regarding geological settings and geothermal potential (Appendix-II).

5. Prof. Muraoka made a presentation (Appendix-III).

   (a) Empirically speaking, thick sinter deposits and boiling water should be observed in geothermal prospecting areas, as a case of Peru shown in his slide.

   (b) If an up-flow should be expected, the spring of 76 C still gives a hope that 250 C may be obtainable below 2000m deep.

   (c) There are many lakes along the west branch of the rift valley. The water may mask the evidence of the geothermal potential in that area, by a kind of cooling effect.

   (d) Regarding neutral buoyancy depth of magmatic heat sources, empirically in a contraction tectonic field the heat body is shallower that that in a extensional tectonic field, because the host rock is compacted to a higher density in the contraction tectonic field; as is observed in the geothermal field in northeast Japan (under contraction tectonic field) and south west Japan (under extensional field). Here in this volcanic zone of Rwanda, the magma is basaltic of high density in the extensional rift valley tectonic field; which render the magma chamber could be deeper in this region. EWSA pointed out that there are evidences of differentiation that may indicate that the magma is not a primitive basaltic magma; that could resulted in shallower magma body in the reason.

   (e) The Professor pointed out that a reliable logging tool should be used to obtain reliable field data.

   (f) As conclusions, the geothermal potential in Rwanda is not so optimistic, but possibly due to the mask effect of the lakes along the rift valley, there could be possibilities that the exploratory wells may encounter geothermal sources.

   (g) Discussions made after the presentation are as follows:

① EWAS informed that there are a lot of boiling points in Cong side. In Uganda, there are hot springs on the surface, but drilling wells did not encounter geothermal fluid sources. Things are complicated.

② There is a hot spring of 76C near Lake Kivu in Gisenyi. The temperature of 0.75 m below the ground is almost 100 C. But, the heat source is not known. Gisenyi hot spring is far from Karisimbi where the heat source is known.

③ The top of Karisimbi is 4500m and Gisenyi 1500; the elevation difference is about 3000m.

④ Surface water flow one direction whereas the groundwater flows the other direction in Karisimbi area; hydrogeology is so complicated.

⑤ Shallow wells were not drilled because those wells provide information of shallow depth only; they do not provide information of deep depth as experienced in Uganda. Mobilization cost for drilling of some shallow wells will be similar to the cost of a deep well; and the information from the shallow well may not be helpful.

⑥ By logging, EWSA wants to know temperature, pressure and fluid composition only; fancy thing come later. We should know where we are in middle of Africa. Drilling and testing equipment so far available in Africa is in Kenya. This stage is not a time to bring fancy things from other European countries of Japan. EWSA now want to decide they should go ahead or not by conducting initial exploration. Complicated things should come later.

(h) At the end of the meeting the team informed that they should be responsible for confidentiality of any information obtained through the work they undertake; and the team would use the data and information only for the purposes of this project.

(i) The meeting set the time of the meeting of the next day from 9:00 am, at the geothermal development unit.

(j) The chairperson closed the meeting.

List of Participants

No.

Date

DATA COLLECTION SURVEY
ON GEOTHERMAL DEVELOPMENT
IN RWANDA
IC/R Meeting 21-March-2013

	NAME	Organization	Position
1	Shinya TAKAHASHI	Study Team	Team Leader
2	Hirofumi MURAOKA	~~Hirofumi~~ Hirosaki Univ.	Prof.
	Hannes SVERRISSON	(Mannvit) Study Team	Drilling Engineer
	Eugene KARANGWA	EWSA	Reservoir Scientist
5	Satoko NISHIGORI	JICA	Program Manager
	UWERA RUTAGARAMA	EWSA	Head GDU
	Toshiyuki Hayashi	EWSA/JICA	Senior Advisor
	Placide NKUNZWENIMANA	JICA RWANDA	Program officer
	Stephen A. Onacha	EWSA	Geothermal Consultant
10	SAKINDI Gaëtan	EWSA	Geophysicist/GDU
	UWASE Alice	EWSA	Environment Section.
	Yiheyis AMDEBRHAN	EWSA	Reservoir engineer
	NGARUYE Claude	EWSA	Geologist
	HAGANJE Gilbert	EWSA	Geochemist
15	Aimable Hasinshuti	EWSA	Drilling Eng

End of Doc.

DATA COLLECTION SURVEY ON GEOTHERMAL DEVELOPMENT IN RWANDA

APPENDIX-I

1

INCEPTION REPORT

MARCH, 2013

JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)

NIPPON KOEI CO., LTD

*** Location ***

2

00. Introduction of the Survey Team

3

	Name	Position/Assignment	Organization
1	Mr. Shinya TAKAHASHI	Team Leader/Geologist	Nippon Koei Co., Ltd.
2	Dr. Hirofumi MURAOKA	Geochemist	Nippon Koei Co., Ltd. (Prof. , Hirosaki Univ, Japan)
3	Mr. Hannes SVERRISSON	Well Drilling Engineer	Nippon Koei Co., Ltd. (Mannvit Engineering, Iceland)
4.	Dr. Masako TERAMOTO	Geothermal Reservoir Engineer	Nippon Koei Co., Ltd (Self-financed by NK)

01. Contents of Presentation

4

Location
00. Introduction of the Survey Team
01. Contents of Presentation
02. Background – Our Understanding
03. Geothermal Potential – Our Understanding
04. Purpose of the Survey
05. 1. Overall Work Schedule
. 2. Revised overall schedule to be discussed
06. Information to be required
1. General Information
2. Information on Geothermal Potential
3. Information on Exploratory Well Drilling
4. Discussions
07. Communication through e-mail
08. Report Preparation
09. Proposed Activities of the Fist Visit in Rwanda
1. Time Table
2. Request
3. Activities

02. Background - Our Understanding

5

- Insufficient electricity power supply, i.e. installed capacity of 96.44 MW, only 14% of household are connected to the grid;
- Planned electricity generation of 1000MWe by 2017;
- Estimated 740MWe geothermal potential available in Rwanda;
- Accelerated development of geothermal resources of 310 MWe in Karisimbi and Kinigi by 2017;
- Data and Final Report Validation Workshop in January 2013 ➔three 3000m exploration wells to be drilled in Karisimbi prospect

03. Geothermal Potential – Our Understanding

6

1. **Rwanda Geothermal Resources Potential** (MININFRA, 1/12/2011)

	Karisimbi	Gisenyi	Kinigi	Bugarama	Others	Total
Resource Potential (MWe)	320	200	120	60	40	740
Target Generation by 2017	160	150	-	-	-	310

2. **Final Report (UniServices, 15 October, 2012)**

   The area (Karisimbi, Gisenyi and Kinigi) does not show the characteristics of a high temperature convective geothermal system.

3. **Data and Final Report Validation Workshop (9-10 January, 2013)**

   The Karisimbi Volcanic area shows evidence of a differential magma chamber which is a very positive indicator that could sustain a convective geothermal system.

   The models generally show 1st high resistivity zone, 2nd lower resistivity zone (alteration), a 3rd higher resistivity zone (reservoir) and a deep low resistivity zone (heat source), in descending order.

Three3000m exploration wells are to be drilled in Karisimbi.

04. Purpose of the Survey

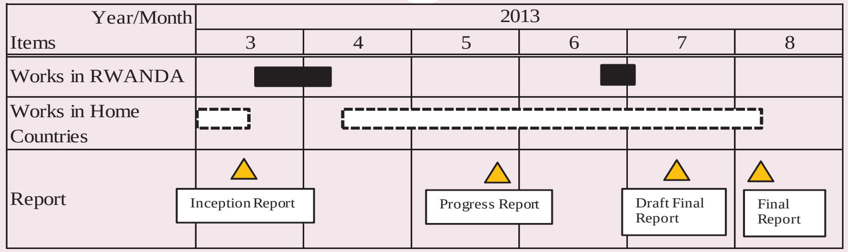
7

1. To review/update information on national energy and geothermal resources;
2. To review technical issues on exploration well drilling and well testing, based on the existing documents, and technical reports to be prepared during the drilling;
3. To review the geothermal development approached in Rwanda;
4. To prepare/organize basic information with which JICA could work out strategy of assistance to Rwanda in geothermal development;

05. Overall Work Schedule

1. Original

8



Note: Works in home countries are intermittent as necessary.

- Work in Rwanda:
  - First: from 20th March, 2013 to 7th April, 2013;
  - Second: from 24th June, 2013 to 3rd July, 2013.

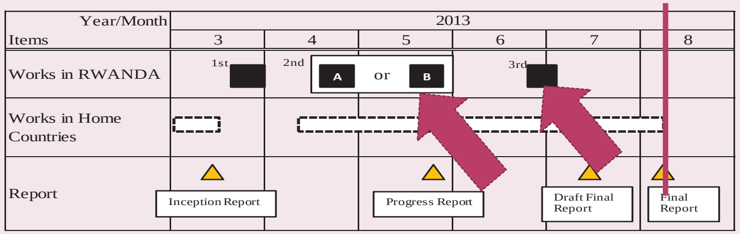
➔

05. Revised overall schedule

2. To be discussed

9

- Our Present Contractual Conditions
  - Period: 1st March – 30th August, 2013
  - Final Report: by 16th August, 2013
- Please Discuss on the timing of 2nd and 3rd visit within the above conditions, subject to the final approval by JICA-H/O.



Note: Works in home countries are intermittent as necessary.

- Requests beyond the above conditions need approval from JICA head office.

06. Information to be required (1/4)

10

1. General information;
   1. National development plan
      1. Vision2020 (July, 200) ➔ already made available
   2. Poverty Reduction Strategy Paper;
      1. Economic Development & Poverty Reduction Strategy 2008-2012 ➔ already made available
   3. National Electric Development Plan;
      1. National Energy Policy and Strategy (May, 2011) ➔ already made available
      2. [DRAFT]Electricity Development Strategy 2011-2017 (June, 2011) ➔ already made available
   4. Geothermal Development plan;
      1. Rwanda Geothermal Resources Exploration and Development for 2011-2017 ➔ already made available
      2. Rwanda Geothermal Resources Potential (1/12/2011) ➔ already made available
   5. Project lists for electric development; ➔ yet to be available

➔ Please provide others that may be useful for understanding electric energy development in Rwanda.

06. Information to be required (2/4)

11

2. Information on Geothermal Potential
   1. Geoscientific Survey of the Rwandan Kalisimbi, Gisenyi and Kinigi Geothermal Prospects (UniServices, 15-October, 2012)➔already made available
   2. Data and Final Report Validation Workshop (9-10, January 2013)➔already made available

➔ Please provide others that may be useful for reviewing exploration well drilling and well testing

06. Information to be required (3/4)

12

3. Information on Exploratory Well Drilling (Chap. 4.2 of IC/R)

Please provide, but not limited to, the following information

1. The technical specification given to the contractor/s;
2. The work plan/s submitted by the contractor/s;
3. Progress reports to be submitted by the contractor/s;
   1. Weekly (technical) report,
   2. Monthly (technical) report,
4. Other technical reports already submitted and/or to be submitted by the contractor/s ;
5. Others as necessary

Discussion:

➔Formats, Timing

06. Information to be required (4/4)

13

- Discussion is necessary for:
  - Format:
    - To maintain speedy communication, the formats already proposed by the SV-consultants/ contractors should be utilized;
    - We would like to review the formats.
  - Timing:
    - Weekly (report) as regular basis;
    - Monthly (report) as regular basis;
    - Any time as required.

7. Communication through e-mail

14

- As the Team will not be continuously present in Rwanda, communication will have to be made through e-mail:
- Please nominate persons in charge (one directly in charge, other 2-3)
  - Address to :
  - CC (1) to :
  - CC (2) to :
- The Team:
  - Address to: TAKAHASHI Shinya : a2604@n-koei.co.jp
  - CC (1) to : Hannes SVERRISSON : hannes@mannvit.is
  - CC (2) to : TERAMOTO Masako : a6643@n-koie.co.jp

08. Report Preparation

15

Report	Contents	Submission Schedule
Inception Report (IC/R)	· Review results of recent reports on geothermal potential · Approach of the Study	To be delivered directory to EWSA when the Survey Team is in Rwanda, in the middle of March 2013.
Progress Report (P/R)	· Technical recommendation of well drilling and well tests · Strategy/direction of the well drilling/testing to be agreed upon with the counterpart	To be delivered through e-mail followed by a courier service, toward the end of May 2013.
Draft Final Report (DF/R)	· All outputs of the Study	To be delivered through e-mail followed by a courier service, in the Middle of July 2013
Final Report (F/R)	· All outputs of the Study (comments are in cooperated)	To be submitted to JICA Head office, at the beginning of August 2013

09. Proposed Activities of the First Visit in Rwanda (1/3)
1. Schedule

16

Nos of days	Date 2013		TAKAHASHI S. (Team Leader/Geologist)	Dr. MURAOKA H. (Geo-Chemist)	H. SVERRISSON (Well Drilling Advisor)	Accommodation at
1	3/19	Tue	NRT-DHA (QR805,2230-04:30)		Reykjavik(KEF)-AMS (FI502, 07:40-08:05)	Flight
2	3/20	Wed	DOH-KGL (QR536, 07:30-1355)		AMS-KGL(KL535, 10:05-1910)	Kigali
3	3/21	Thu	Meeting With JICA, EoJ, EWSA (if required), Reykjavik Geothermal Co.,			Kigali
4	3/22	Fri	Meeting/data collection as necessary			Kigali
5	3/23	Sat	Data review, planning of site inspection, etc			Kigali
6	3/24	Sun	Data review, Planning of site inspection, etc			Kigali
7	3/25	Mon	1. Moving to Karisimbi (2.5 rs); 2. Site inspection in Karisimbi; 3. Checking in the Hotel in Ruhengeri.			Ruhengeri
8	3/26	Tue	1. Site inspection in Karisimbi, Kinigi (and/or Gisenyi)			Ruhengeri
9	3/27	Wed	Morning: 1. Checking out; 2. Moving to Kigari (2.5hrs); Afternoon: 1. Meeting with EWSA, RG (Brief Reporting); 2. Reporting to JICA (Brief Reporting)			Kigali
			Evening		KGL-AMS(KL 535, 20:20-06:45)	
10	3/28	Thu	(no good connection flight)		AMS-Reykjavik (FI503, 14:00-15:10)	Kigali
11	3/29	Fri	KGL-DOH (QR537, 1450-23:05)	KGL-DOH (QR537, 1450-23:05)		
12	3/30	Sat	DOH-NRT(QR804, 01:50-1750)	DOH-NRT(QR804, 01:50-1750)		

09. Proposed Activities of the First Visit in Rwanda (2/3)
2. Request

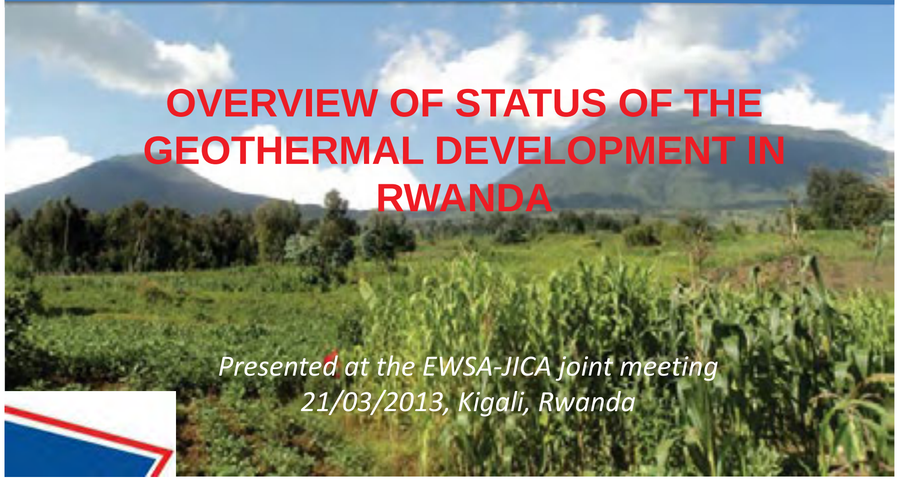
1. The Team would like to conduct a reconnaissance site survey is to familiarize ourselves with site conditions.
2. The Survey Team would like to request an engineer who is familiar with the site conditions to accompany the Survey Team for the site reconnaissance survey.

The Survey Team will conduct such activities on site as, but not limited to, the followings:

09. Proposed Activities of the First Visit in Rwanda (3/3)
3. Activities

1. To confirm geographical conditions on site;
2. To observe typical rock types and fractures (volcanic, granitic/gneissose rocks);
3. To observe typical geothermal manifestations such as:-
    1. Hot springs, gas
    2. Calcite at Mufambo,
    3. Travertine near Musanze,
    4. Other evidence of hydro-thermal alteration,
    5. Others as recommended by EWSA,
    6. (Temperature, EC, pH may be measured at spring sites. No other specific detailed field testing will be conducted on site)
4. To observe drilling site conditions (working condition, environmental conditions)

APPENDIX-II



OVERVIEW OF STATUS OF THE GEOTHERMAL DEVELOPMENT IN RWANDA

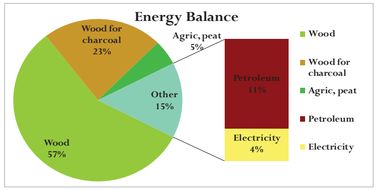
Presented at the EWSA-JICA joint meeting
21/03/2013, Kigali, Rwanda

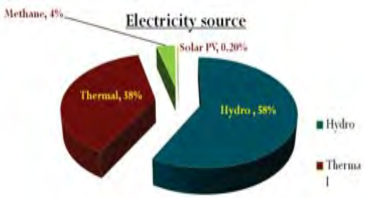
Outline

1. Why Focus on geothermal?
2. Geological & Structural settings
3. Surface manifestations
4. Previous studies
5. Current & future plans
6. Challenges
7. Conclusion

Why Focus on Geothermal

- Low access to electricity (needs to be increased to over 70% by 2017)
- Low electricity generation capacity of approx. 100MW
- Highest electricity costs in the region
- Over 300 M We expected from geothermal resources by 2017
- Commitment of the GoR to diversify the sources of energy & to lower the risks of geothermal exploration
- Ready market for base load generation

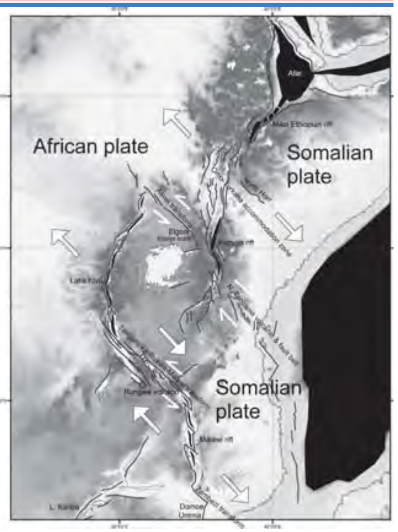




Geological settings

Virunga massif: explosive volcanism

- Pyroclastics (volcanic ash, lapilli & bombs), lahars;
- Recent to active volcanoes ; adventive cones/craters;
- Active NW-SE extension due to movement of African and Somalia plates that creates faults
- NS, NW-SE and NE-SW normal faults that control fluid flow (springs)
- 2 potential zones: Bugarama graben & Virunga massif



Geothermal manifestations

Gisenyi (74˚C)

Mashyuza (54˚C)

Geothermal manifestations

- ❑Hot Springs,
- ❑Warm Springs,
- ❑Cold and mineralized springs,
- ❑No fumaroles, no mud pools,no hot grounds

Geothermal manifestations

Qz and Na/K geothermometry temperatures for selected springs in Virunga geothermal prospect, Rwanda (Egbert, 2009)

Location	Quartz ^{0}C	Sodium- Potassium Na/K	Likely temperature
Mbonyebyombi	110	152	110-130
Mpatsi	129	213	130-150
Karago	126	147	120-140
Gisenyi	107	175	105-130
Iriba	109	123	110-120
Nyakageni	113	262	110-140

Previous studies

EWSA

1982: BRGM identified Gisenyi and Bugarama as potential sites for geothermal resources with temperatures over 100 ^{0}C.

2006: Chevron indicated that Reservoir T in Bugarama & Gisenyi to be in excess of 150 ^{0}C & concluded that Gisenyi most promising prospect

2007-2009: Reconnaissance studies in the range of volcanoes (BGR, MININFRA, MINIRENA, KenGen, Icelandic Geosurvey (ISOR) & the Spanish Institute for Technology and Renewable Energies (ITER)

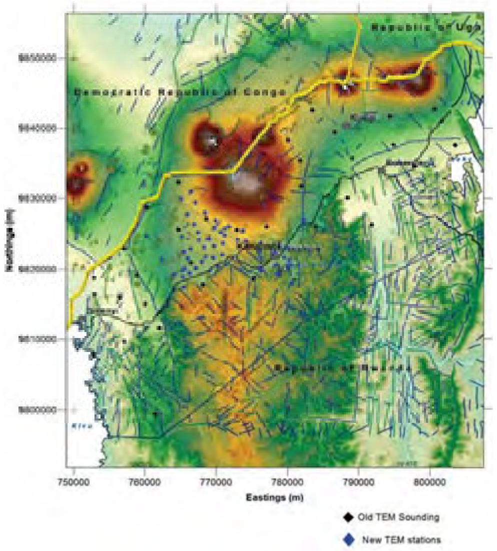
2009: **Additional geoscientific surveys & baseline EIA in the Karisimbi Prospect (KenGen)** Recommendations: EIA, Detailed geology, micro-earthquake data collection & 3 exploratory drilling wells.

Previous Studies

2007 & 2010:

Geo-scientific data acquisition in Gisenyi, Karisimbi & Kinigi Geothermal prospect

- ❑ Outcome: the most promising site is the southern slopes of Karisimbi volcano

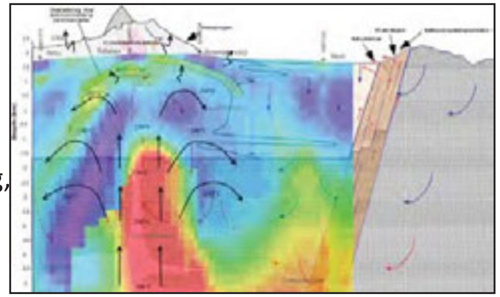


Previous Studies

2010: BGR & KenGen Concluded that a HT geothermal system may exist on the southern slopes of Karisimbi volcano &3 potential sites for drilling of exploration wells were identified;

2011-2012: Surface exploration by Uniservices- 3 drilling sites were proposed

2012: Camps & drill areas sitting, access road and water supply assessment by EWSA Staff



9-10/1/2013: 3 drilling sites were decided

Ongoing Activities and future plans

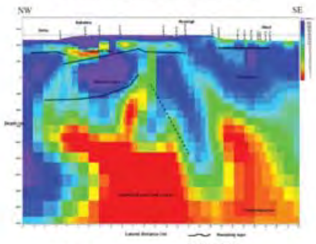
- ❑ Continuous data acquisition & evaluation (upgrade of conceptual model)
- ❑ Detailed ESIA & Environment Management Plan (EMP)
- ❑ Development of legal & regulatory framework;
- ❑ Development of geothermal development policy;
- ❑ Preparation of the required infrastructure before exploration drilling – access roads, water system & drilling pads
- ❑ Drill 3 exploration wells in each of the geothermal prospects starting with Karisimbi in April 2013
- ❑ If exploration drilling is successful, production drilling in Karisimbi & other prospects (4x75 MWe power plants)
- ❑ Design & construction of 10 MWe well head generating units in Karisimbi and Kinigi;
- ❑ Surface exploration for the Bugarama prospect.

Challenges

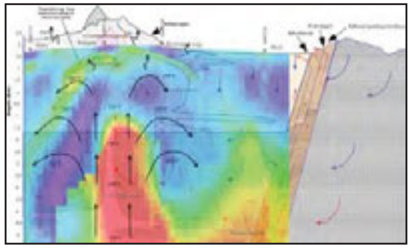
- ❑ Results of studies depend on who & when. This creates confusion among decision makers
- ❑ Harmonized conceptual models
- ❑ What are the targets for drilling exploration wells

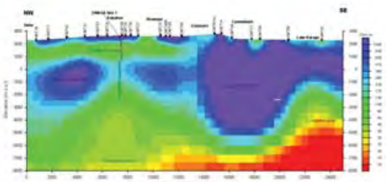
Sometimes results depend on who & when ?

Appendix D2 - 2D MT Resistivity cross-sections



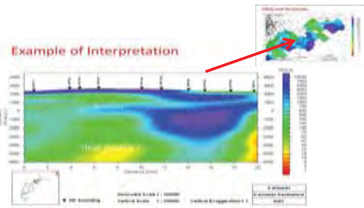
2D MT Resistivity cross-section (Figure 2.14 in the 2010 KenGen report)



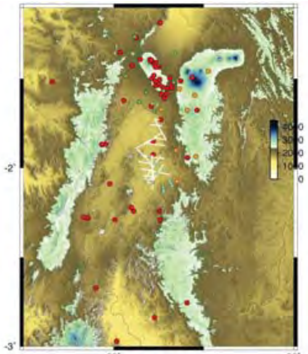


2D MT Resistivity cross-section (K1)

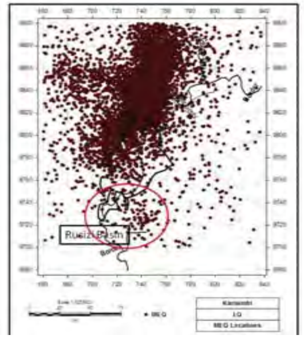
Example of Interpretation



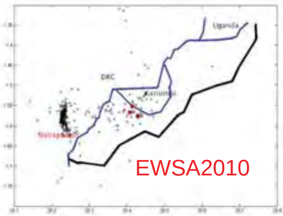
Seismic studies



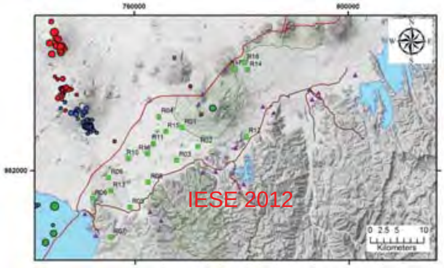
Ebinger 2012



Goma Observatory

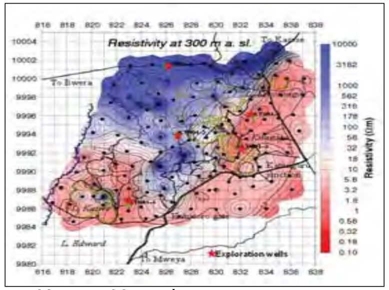


EWSA2010

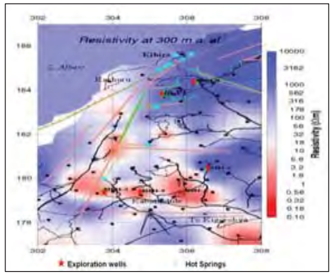


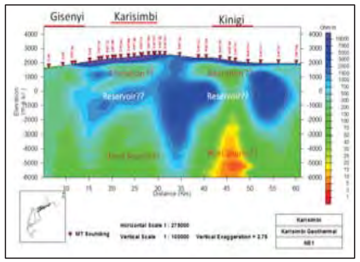
IESE 2012

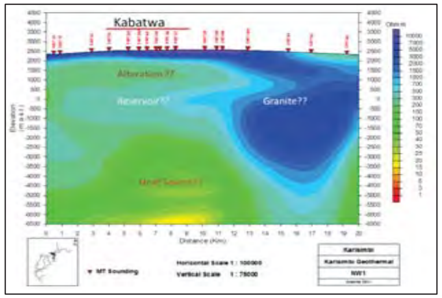
What should we target for drilling??



Katwe, Uganda







Conclusions

- ❑ Previous & ongoing studies show good indications of viable geothermal resources in the Virunga area
- ❑ Urgent need for a harmonized conceptual model to guide exploration drilling
- ❑ Full commitment by the GoR to develop geothermal resources
- ❑ If exploration drilling is successful;
  - ✓ Use exploration wells to generate 10 Mwe
  - ✓ Carry out exploration drilling in other areas
  - ✓ Invite private sector to drill production wells and develop over 300 MWe from geothermal resources

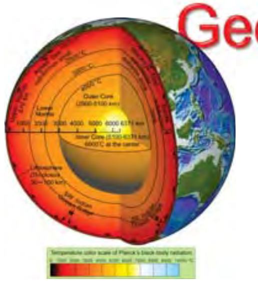
Thank you

JICA Rwanda-EWSA Geothermal Mission

APPENDIX-III

21 March 2013
Kigali, Rwanda

Short Comments to Meeting of JICA Rwanda-EWSA Geothermal Mission



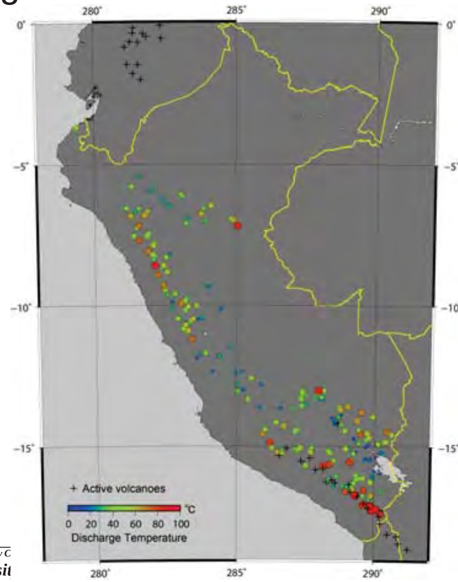
Hirofumi Muraoka
Nippon Koei Co., Ltd.
Hirosaki University

Potential geothermal fields have boiling hot springs

Potential geothermal fields have boiling hot springs

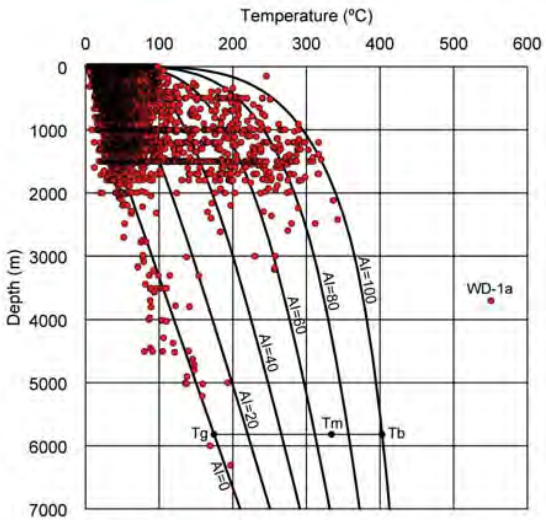
Borateras geothermal field, Peru at 4700 m altitude, 30 November 2008.

Potential geothermal fields have boiling hot springs



There are so many boiling hot springs in Peru, and the geothermal power potential is estimated to be 3000 MW.

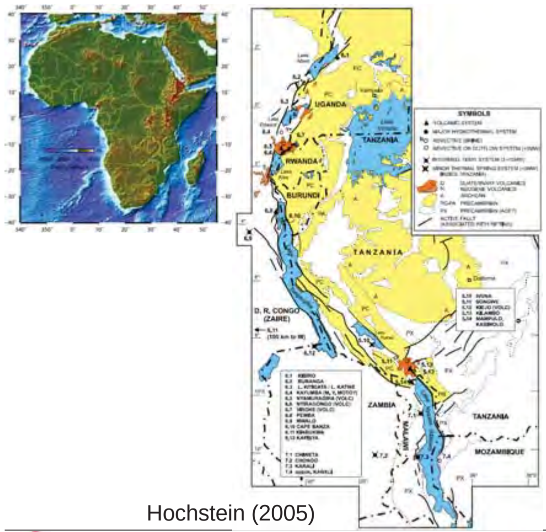
Potential geothermal fields have boiling hot springs



If you have a boiling hot spring at the surface, a profile close to the boiling temperature curve can be highly expected.

However, even if a given temperature is 70 ºC, 250 ºC can be expected at a 2000 m depth on the up-flow zone.

Potential geothermal fields have boiling hot springs



Hochstein (2005)

- The west branch of the Great Rift Valley is widely filled with lake water.
- One possibility is that the discharge of high-temperature water on the up-flow zones may be masked by the lake water and groundwater.

Neutral buoyancy depth of magmatic heat sources

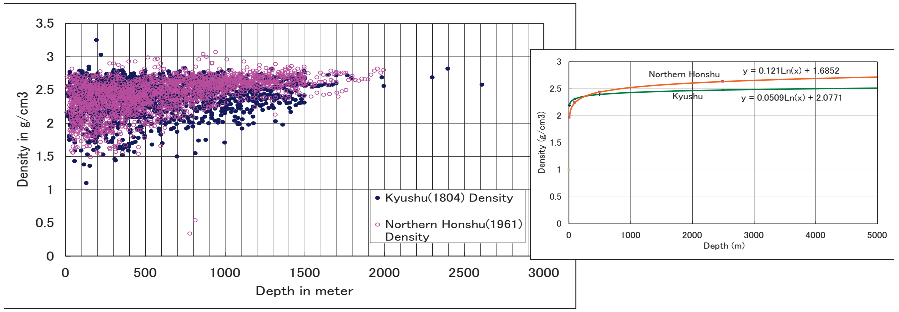
Extension vs contraction tectonic zones

Table 1. Depth of the magmatic intrusions acquired in the geothermal fields.

Regional field	Representative field	Tectonic settings	Major fault type	Magma pluton	Depth of top of pluton
Iceland	Nesjavellir	Extension tectonics Speading ridge	Normal fault	Lack (dike complex)	
Salton Trough	Cerro Prieto	Extension tectonics Speading ridge	Normal fault	Lack (dike complex)	
Tuscany	Monteverdi	Extension tectonics Subduction zone	Normal fault	Low velocity body	7 km?
Taupo	Ohaaki	Extension tectonics Subduction zone	Normal fault	Magnetized body	4 km?
Kyushu	Hachobaru	Extension tectonics Subduction zone	Normal fault	Heat body	4 km?
The Geysers	The Geysers	Contraction tectonics Slab windows	Strike-slip fault	The Geysers felsite	1.20 km
Philippines	Tongonan	Contraction tectonics Subduction zone	Reverse fault	Mahiao diorite	1.60 km
Kamchatka	Mutnovsky	Contraction tectonics Subduction zone	Reverse fault	Mutnovsky diorite	1.00 km
Northeast Japan	Nyuto	Contraction tectonics Subduction zone	Reverse fault	Nyuto diorite	1.34 km
	Kakkonda			Kakkonda granite	1.95 km

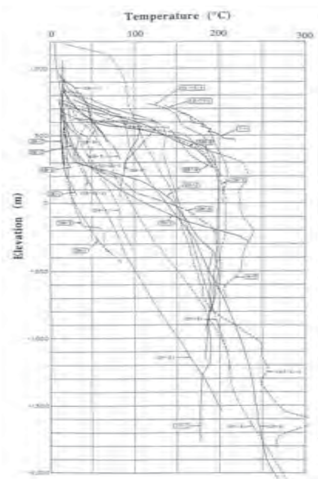
As shown in this table, empirically geothermal wells often penetrated magmatic intrusions in contraction tectonic fields rather than in the extension tectonic fields. Magmatic intrusions seem shallower in the contraction tectonic fields.

Extension vs contraction tectonic zones

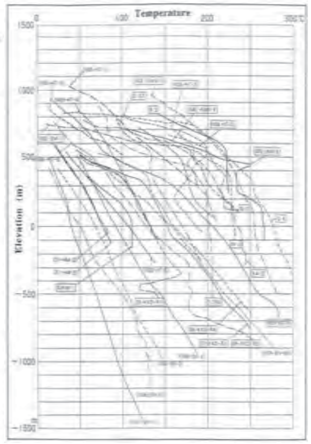


The relation is explained by fact that the lateral stress at the same depth is 3 or 5 times larger in the contraction tectonic fields than in the extension tectonic fields as known in the Byerlee's law. Actually the density of rocks reflect this relation. If you have a magma chamber with the density of 2.5 g/cm^3, the magma chamber will be settled at a depth of 1 km in NE Japan and will be settled at a depth of 4 km in Kyushu in terms of the neutral buoyancy depth. This explains the empirical difference in the extension and contraction tectonic zones (Muraoka and Yano, 1998).

Extension vs contraction tectonic zones



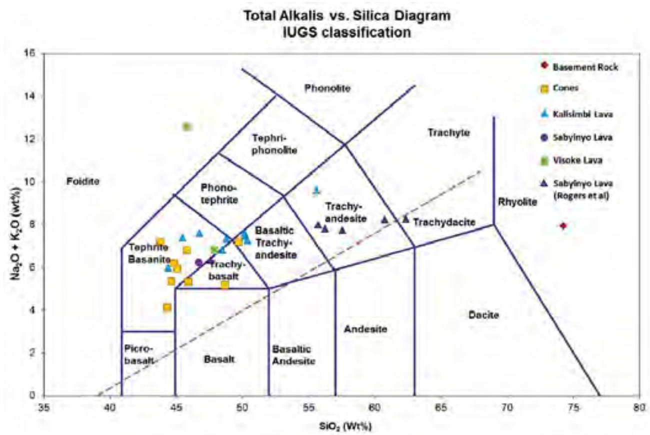
Geothermal wells in Kyushu (Tamanyu, 1994)



Geothermal wells in NE Japan (Tamanyu, 1994)

The temperature of geothermal wells at the same depth is higher in NE Japan than in Kyushu. This is because that the neutral buoyancy depth of magmatic intrusions is shallower in NE Japan than in Kyushu.

Virunga volcanoes are basaltic



The Virunga volcanoes are mainly composed of basalt and small amounts of andesite (UniService, 2012). It implies deeper heat sources in terms of the neutral buoyancy depth of magma chambers.

Exploration drilling is for logging data acquisition

Exploration drilling is for logging data acquisition

- Drilling requires very high costs.
- Therefore, you should take high quality logging data.
- For the purpose, preparation of logging tools is important.

Estimated cost for a full-scale JBBP

6000 m long armored cable with the survival temperature at 316 ºC in JMC Engineering in Japan.

PTS tool with the survival temperature at 316 ºC in JMC Engineering in Japan.

What we need is just challenge

- The discharge temperatures of hot water in Rwanda are not optimistic.
- Compositions of volcanic rocks and their magma sources in Rwanda are not optimistic.
- However, we should also think mask effects by the wide lake water and wide groundwater along the west branch of the Great Rift Valley.
- We still have plenty of chances to detect high-temperature geothermal reservoirs in Rwanda.
- The most important effort is to drill an initial geothermal exploration well in Rwanda.

Attachment-2

Presentation and Minutes of Meeting of Wrap-Up Meeting of the first field Survey in Rwanda

The Data Collection Survey on Geothermal Development in Rwanda

A Wrap-up Meeting

On 27th March, 2013

At JICA Meeting Room, Kigali, Rwanda

-----------------Preliminary----------------------

A. Participants:

EWSA

01. Ms.Uwera Rutagarama (Head of Geothermal Unit)
02. Dr. Stephen A. Onacha (Reservoir Enginerr)
03. Mr. Aimable Habinshuti (Drilling Engineer)
04. Mr. Yiheyis Amdebrhan (Reservior Engineer)
05. Mr. Hagahje Gilbert (Geochemist)
06. Mr. AGAROYE Jean Claude (Geologist)

JICA Rwanda Office

07. Mr. KOBAYASHI Hiroyuki (Chief Representative)
08. Ms. NISHIGORI Satoki (Program Manager)

JICA Head Office

09. Mr. KODAMA Akihiko (Officer, Africa Department, Africa Division I, JICA Head Office)

JICA Study Team

10. Mr. TAKAHASHI Shinya (Team Leader/Geologist, the Study Team)
11. Prof. MURAOKA Hirofumi (Geo-Chemist, the Study Team)
12. Mr. Hannes Svennisson (Drilling Engineer)

B. Presentation and Discussion

The Presentation and Discussions were made in the following order. The materials used are attached to this document.

a. A brief report on observation and interpretation: TAKAHASHI Shinya
b. Short comments after the field trip to the Virunga geothermal field: Prof. MURAOKA Hirofumi
c. Observation on Preparation works for drilling site KW01

1. Mr. Takahashi explained his observation and interpretation using photos he took on site. His explanation note is as attached (Appendix-A). He stated that the his images were getting clear after visiting site and he could confirm that the hot springs were emerging from the basement rock while cold springs were from the

volcanic rock near the boundary of the basement rock. He was very much impressed by the huge amount of cold spring at Rubindi site, amounting more than 1 cum per sec approximately, except of water captured for drinking. Also he reported that the basement rock consists of at least two rock types; one is massive granite and the other micaceous schist. He pointed out those might have quite different resistivity.

2. Prof. Muraoka made his presentation using the material attached hereto. His presentation material is as attached as Appendix-II, and his conclusions at this stage are as follows (a quotation from his presentation).
    - Before the field excursion, I felt fairly negative impression on geothermal potentials in the Virunga geothermal field.
    - The main reason is that there are no boiling hot springs.
    - However, I realized that masking effects by cold meteoric and ground water are obvious in Kalisimbi volcano.
    - Hot springs, Gisenyi and Karago, are probably out-flows from Kalisimbi volcano along N-S trending fractures of basement units, and they are very close to the boiling hot springs because of the easily diluting environment.
    - Then, now I realized that drilling of KW01 is really worthy and challenging to reach the thermal regime beneath the cold water curtains.
    - However, we should keep in mind that the probability of geothermal drilling in green fields is only 50 percent.
    - Before drilling, we should draw a geological and geothermal cross section along the KW01 well, even if there still remain many unknown factors.

3. During the presentation of Prof. Muraoka, questions and discussions made were as follows:
    a. A question is whether there has been the systematic migration of volcanic activities westward, because Sabyinyo is older than Bisoke. The last volcanic episode around here is 1957. This other one in Congo is active. Dating may be helpful for a possible explanation of the westward of volcanic migration.
    b. Comment on the tectonic movement was made by Dr. Onacha.
    c. It was pointed out that the volcano masked the topography of basement where water is supposed to flow northward whereas the present water flow is otherwise. The surface water flow direction may not indicate direction of underground water flow. It is complicated.
    d. EWSA is now preparing prognosis combining surface geology, geophysics, magnetic, gravity, gas data (BGR and KenGen Report).
    e. Even so geological cross section is very important for consideration of the second well location/direction.

4. Mr. Hannes Sverrisson then made his explanation and confirmation on the

preparation works he observed. After this meeting, the team had a meeting with the drilling contractor, Great Wall Drilling, to obtain more detail information on drilling preparation works. His comprehensive report is as attached as Appendix-III. It was understand from various information he obtained that the drilling works would start from a middle part of May 2013, still depending on progress of preparation works.

5. JICA Rwanda office stated that:
   a. JICA Rwanda office is always flexible to meet the EWSA requirement, basically based on the contract with the Team. But, if necessary, JICA Rwanda office is also flexible in changing the contract with the team as judged to be required.
   b. JICA Rwanda office appreciates EWSA's input to the Team in updating them for their short visit this time. But, the next visit of the Team would be more fruitful and useful in assisting EWSA.
   c. JICA Rwanda office takes this Study practical, not research, to meet EWSA's requirement, and therefore EWASA is requested to let us know what is needed.
   d. Necessary information including the overall schedule (a bar chart) has been already been shared with the Team. The Team is requested to read all the document given and if the Team should need quantities information, the Team should find out them.

6. Discussion on the next visit
   a. It was proposed that the next visit should be from the middle of May, probably from 14th, for a short period about a week. If the drilling should start by that time, then the period should be extended to two weeks or so.
   b. It was agreed that the next visit of the Team should tentatively be decided from 14th May, 2013 for a week.
   c. EWSA questioned to the Team on what kind of activities the Team undertake during the next visit if the drilling works should really starts, practically or otherwise.
   d. JICA Rwanda office stated that even though the ToR states that the team should give EWSA advice on drilling works and well testing, JICA Rwanda office and the Team will flexibly response to the needs that might be arisen during the actual drilling works.
   e. EWSA stated that the Geothermal Development Unit (GDU) is a young unit and needs practical capacity buildings. EWSA wishes the people participating

in this meeting will become geothermal consultants in future and to assist other projects not only in Rwanda but other countries.

End of Doc.

APPENDIX-I

Data Collection Survey on Geothermal Development in Rwanda

Brief Report of Site Reconnaissance (25th – 26th March, 2013)

By Mr. TAKAHASHI Shinya

(Team Leader/Geplogist)

1. Observation

(a) Visited at the junction to Kinigi site on the flunk of Mt. Visoke (the sign board to Kwamukecuru Parking);

- Fresh, porous basaltic lava was observed.
- A volcanic cone was observed.

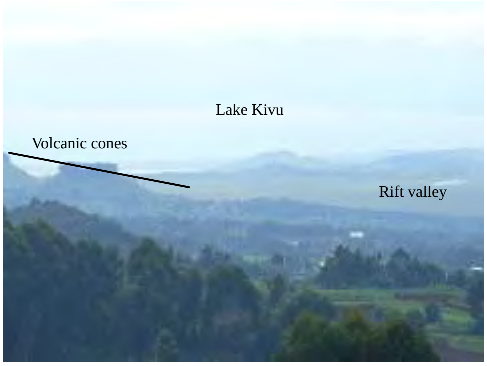
	
Porous, basaltic rock pieces everywhere were observed behind the sign board, at some 2km to Kinigi site; no clear geothermal manifestation was observed.	A volcanic cone some 2 km NE of the junction with porous basaltic rock pieces on the flunk, no clear geothermal manifestation was observed.

(b) Visited at Karisimbi site

- On the way to Karisimbi site, massive granite was observed along the main road.
- In the Karisimbi site, fresh, porous basaltic lave was observed.

	
A massive granite outcrop was observed along the main road between Mukingo and Nkuli, the rock will have high resistivity.	At the Karisimbi site, porous, fresh basaltic rock pieces were observed. Evidences of alteration were hardly observed.

- From the Karisimbi site, a series of volcanic cones were observed in the distance. It was confirmed that they are aligned in the direction of NEN-SWS, which could be a direction of faulting.

	
Flow structure was observed on a fresh porous basaltic rock pieces at Karisimbi well site.	A series of cone were aligned in NEN-SWS direction with the lake Kivu and rift valley behind.

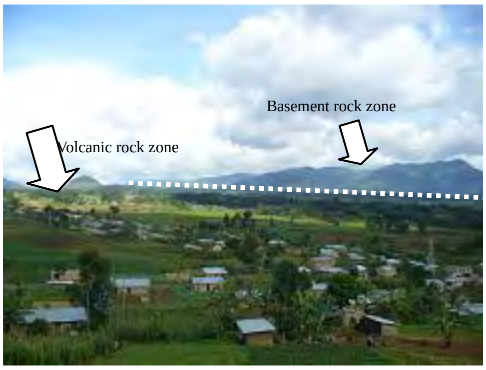
(c) Moving from Karisimbi to Gisenyi

- The Team moved from Karisimbi site to Gisenyi along the road near the Congo border.
- Observed the volcanic cores and Kivu Lake in the distance. The Team confirmed the topographic characteristics of rift valley and the cones.

 	
A distance view of volcanic cones, lake Kivu and the rift valley	A pair of volcanic cones

- The Team went up Mufunba cone, where the team confirmed the geological/topographical setting of basement rock area and the volcanic rock area.
- Also, the Team observed "calcite" in a volcanic rock peace. Though it is an indication of the existence of Carbone dioxide plus calcium, the team

considers that it may not be a positive evidence of “alteration”.

<table>
<tr><td>
</td><td>
</td></tr>
<tr><td>Porous, basaltic lava with calcite on the flunk of Mufunba cone, near Rwerere.</td><td>A distance view from Mufunba cone to eastward. A boundary between volcanic rock zone and basement rock zone was obvious.</td></tr>
</table>

- Observed a basement rock outcrop at a location 4-5 km north to Gisenyi. The basement rock was weathered micaceous (muscovite) schist with garnet. The Team came to know that the basement rock consists of at least two types of rock; granite and schist. Prof. Muraoka will explain the implication of this observation.

<table>
<tr><td></td><td></td></tr>
<tr><td>Micaceous schist, a type of basement rock, near Gisenyi city Schistosity is obvious.</td><td>The resistivity of the micaceous schist may be smaller than that of massive granite. Zoning of those rocks may be useful, if possible, for MT assessment</td></tr>
</table>

(d) Hot spring in Gisenyi

- One hot spring on the west side of the peninsular: 73.6 C, 3100 micro-S/cm. Travertine is formed.
- The other hot spring on the east side of the peninsular: 70.3 C. 2700 micro-S/cm.

- Both hot springs emerge from the basement rock (detail rock type not known)

	
A hot spring of Gisenyi (73.6 C, 3100 micro-S/cm), at the west side of the peninsular.	Calcareous-sinters (travertine) were seen in the lake side.

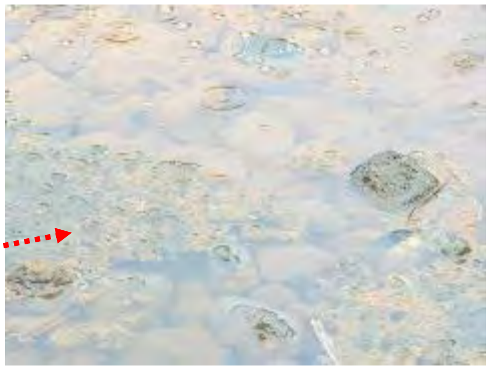
(e) Kargo hot spring

- On the way to the Kargo hot spring, a granite out crop with a Qz vein was observed, the vein is of N-S direction that is harmony with the structural direction of the basement rock.
- The Kargo spring: 72.5 C, 1100-1200 micro-S/cm, emerges from basement rock

	
Massive granitic rock (basement) on the way to Kargo spring, no obvious alterations were observed.	Qz vain of N-S direction in massive granitic rock (basement)
	←A spring area at shore of Kargo lake. 72.5C, 1100 -1200 micro-S/cm

(f) Rubindi Spring (cold)

- Water overflowing from the capping structure was of 17.8 C and 200 micro-S/cm. The water is used for drinking after treated at Mutubo water treatment facility.
- A spring with babbling was of 18.8 C and 2100 micro-S/cm.
- Huge amounts of water (500-1000 L/sec) are emerging from lava. The area is located near the boundary of the basement rock and the volcanic rock.

	
A spring with bubble in front and water capture structure behind for water supply (Mutobo Water Supply)	The spring with bubble (18.8C, 2100 micro-S/cm)
	
Springs are emerging out from many points in this area.	Huge amount of spring water flows down, in addition to the captured water for the water supply

2. Brief interpretation

- The Team hardly confirmed any of strong geothermal manifestation.
- The team, however, consider some kind of heating mechanism will exist in the basement rock, because the hot springs emerged from the basement rock area.
- Similar to the hot springs observed in the basement rock area, hot springs

are also considered to be emerging from the basement rock to the bottom of the volcanic rock below the volcanoes. However, because the huge amounts of water are recharged from rain to the very pervious volcanic rocks , the hot springs are diluted by the metric water and emerge from volcanic rock near the boundary of the basement rock as seen in Rubindi. This is because the basement rock is much impermeable than the volcanic rock. This may be a reason why not much geothermal manifestation are not observed in the volcanic rock areas.

- There are two types of basement rocks; one is granite and the other is micaceous schist. Resistivity of these rock may be different, which may affect the interpretation of the MT survey.

3. Observation of preparation construction works

Three water tanks (4,000 m3 each) were being constructed. Basement re-baring for the first (the above two picture), gravel placing for the second, excavation for the others were conducted.

Water supply for the Karisimbi drilling site: Six inches, steel pipes were placed along the some 2-3 km stretch of the main road, photos at the junction of the access road.

Construction of the pump house at the intake near Kargo lake. Placement of foundation was under way.

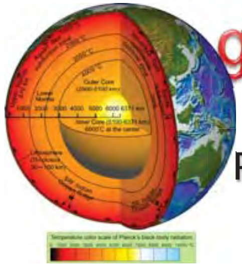
An intake structure on the lake and a water tank will be constructed behind the pump house.

APPENDIX-II

JICA: Data Collection Survey on Geothermal Development in Rwanda

27 March 2013
Kigali, Rwanda

Short comments after the field trip to the Virunga geothermal field

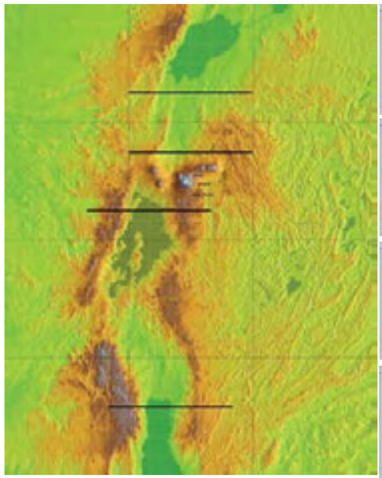


Prof. Hirofumi Muraoka
Nippon Koei Co., Ltd.
(Hirosaki University)

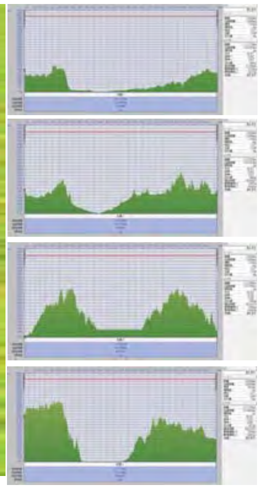
Observed facts

- The west branch of the Great Rift Valley is asymmetric, and the graben faults are exclusively obvious in the western side.
- The eastern graben faults are sometimes lack, and therefore, the rift locally widened to the eastern side.
- Relatively high temperature hot springs (>70 ºC) such as Gisenyi and Karago are always discharging from the fractures of basement units.
- Instead, huge amounts of cold water is discharging from the foot of the Karisimbi volcano.

Western Branch of the Great Rift Valley



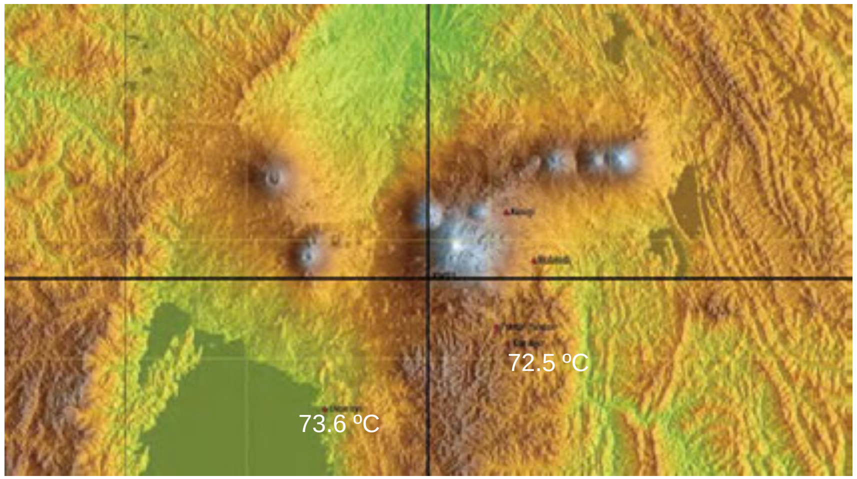
Data Source: USGS SRTM-3
Drawn with KASHMIR 3D



20 times vertical exaggeration

- The west branch of the Great Rift Valley is asymmetric.
- Graben faults are relatively clear in the western wall.
- Graben faults are unclear in the eastern wall.
- As a result, a width of the rift valley dramatically varies along the eastern wall.

Main observation points



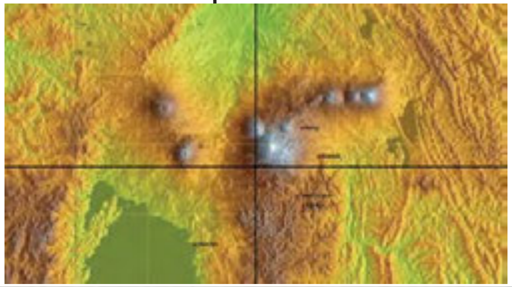
Data Source: USGS SRTM-3
Drawn with KASHMIR 3D

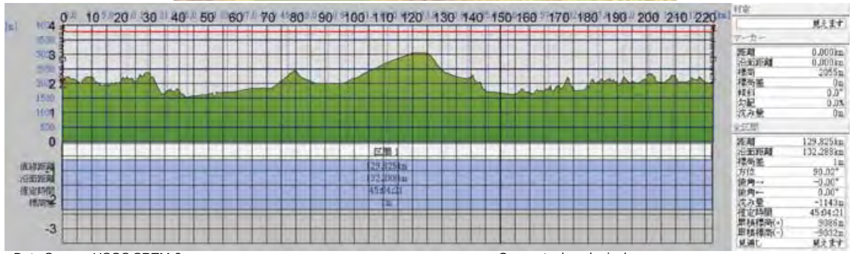
Main observation points

North-south trending quartz vein near the Karago hot spring

Huge volume of the Rubindi cold spring

Interpretation1

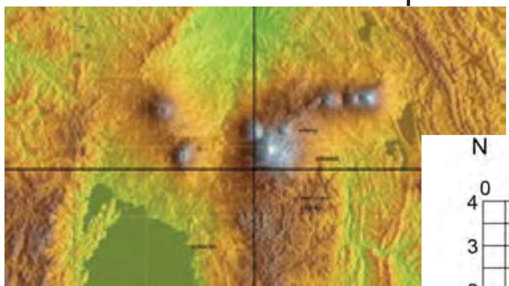




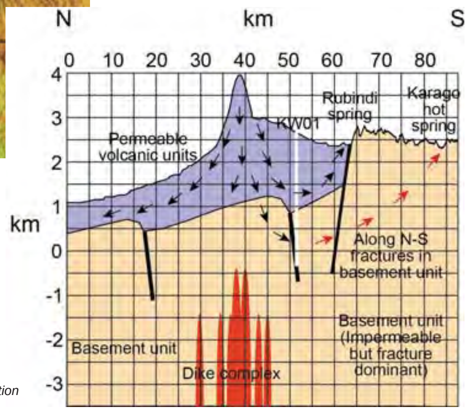
Data Source: USGS SRTM-3
Drawn with KASHMIR 3D

Conceptual geological cross section :Under Construction

Interpretation2



Data Source: USGS SRTM-3
Drawn with KASHMIR 3D



Conceptual geological cross section

Conclusions

- Before the field excursion, I felt fairly negative impression on geothermal potentials in the Virunga geothermal field.
- The main reason is that there are no boiling hot springs.
- However, I realized that masking effects by cold meteoric and ground water is obvious in Kalisimbi volcano.
- Hot springs, Gisenyi and Karago, are probably out-flow from Kalisimbi volcano along N-S trending fractures of basement units, and they are very close to the boiling hot springs because of the easily diluting environment.
- Then, now I realized that drilling of KW01 is really worthy and challenging.
- However, we should keep in mind that the probability of geothermal drilling in green fields is only 50 percent.
- Before drilling, we should draw a geological and geothermal cross section along the KW01 well, even if there still remain many unknown factors.

Data Collection Survey on Geothermal Development in Rwanda
Brief Report of Site Reconnaissance (25^{th} – 26^{th} March, 2013)
By Mr. Hannes Sverrisson

Drilling Preparations of KW-01

The following are observations and comments of the team regarding drilling preparations and related constructions. They were obtained by visiting the construction and drill sites and speaking with the EWSA representatives. The Great Wall Drilling Company (GWD), the drilling contractor, was also visited and the minutes of that meeting are in a separate Memo; "Meeting with the Drilling Contractor", some of the findings here are from that meeting.

Following are the main findings and observations of the team:

Drilling

➔Material

The material supplied by EWSA for the well drilling is expected to arrive on site after 1-2 weeks. We did not observe any storage area for the material, but it should be close to the drilling pad and security should be on-site due to valuable material being stored.

➔Estimated Drilling Progress

According to the drilling contract the drilling time is 53 days per well and then 5 days for moving the rig between wells, although the drilling contractor (GWD) expects the first well to take about 2 months with coring and then 2 weeks for moving between wells.

➔Well Head

The well head and the well master valve are ANSI Class 900, which is sufficient for the planned well.

➔Drilling Fluid

The well is drilled with drilling fluid in the upper sections where loose rock material may be encountered. The production section will be air-foam drilled.

➔Cementing

EWSA is currently in the process of trying to locate silica flour for mixing the Portland cement. Other options are also being looked into by GWD and they will give us the reason for why they had problems with using the silica flour mix in a previous project. Silica flour (particle size of 15 μm) mixed in Portland cements (35% silica BWOC[1]) are usually used for all geothermal wells. Other options of material to prolong the lifetime of the cementing are: Silica sand (particle size of 175 - 200 μm) and fly ash. But these are much less desirable options than using silica flour. We recommend strongly to use silica flour. The well will be cemented with a plug method, where the cement slurry is pumped into the casing and pushed down with a plug. The contractor does not have a caliper for hole-enlargement measurements, thus a minimum safety factor is at least 50% excess over the bit size, for the cement slurry estimates. If excessive caving or difficult drilling conditions are expected the excess should be increased appropriately to

[1] BWOC: by weight of cement

allow the cementing to be to the surface. Also if the leak off tests shows a week formation the density of the cement slurry should be adjusted to prevent losses from the annulus into the formation through cracks. If exceptional drilling conditions such as cave-ins, hole-enlargement or excessive Loss of Circulation (LOC) is encountered it should be considered to cement the leakage to prevent further drilling fluid losses and cementing problems.

➔Well Prognosis

A well prognosis is expected to be finished in the next weeks.

➔Coring

A 3 m core may be taken at several intervals if needed and decided by EWSA.

➔Well Logging

Wire-line logging will only be for temperature and pressure measurement. Which gives a lot of information for a geothermal well, but if funds were available we would recommend further wire-line logging measurements as; Gamma Ray (GR), Spontaneous Potential Logging (SPL), Resistivity (RES) to measure the rock layer characteristics, Caliper to monitor the well diameter; and Cement Bond Logging (CBL) to check the results of cementing operations.

➔Flow Testing

Flow testing will be performed by Geothermal Development Company (GDC) of Kenya. They will provide piping, separator, silencer and water flow tank. They also provide measuring equipment for steam and water flow and will take fluid samples.

➔Health, Safety and Environment

Health, Safety and Environment (HSE) will be done by Reykjavik Geothermal; it will be done with the drilling plan.

Drilling Site

➔Access Road

The access road to the side is still unfinished as may be seen in Figure 1. These are about 1.2 km for all the well sites, but finishing the access road construction is critical for the tank construction work and construction of the drilling pad.

➔Drilling Pad

The drilling pad was currently being leveled by moving the ground at the site and then a 40 cm layer of gravel will be placed for support and then impermeable material above it for compaction. The footprint of the rig is critical and the support gravel layer has to support the whole drilling unit without subsidence.

The team recommends that the gravel and the impermeable material layer shall be well compacted to prevent ground subsidence due to the load of drilling unit, as well as oil seepage in to the soil of the drilling pad.

➔Cellar

The BOP stack of the drilling rig needs a 3 m deep cemented cellar that is constructed after the drilling pad is finished. Drainage needs to be laid from the cellar to the edge of the drilling pad for drainage.

➔Fencing around the Drilling Pad

We also recommended fencing the drilling pad to prevent locals from entering the dangerous work area, although the site will be guarded by armed guards.

➔Progress of the Access Road and Drilling Pad Construction

The drilling pad and the access road may take up to 4 weeks to finish depending on the progress. The gravel mine is close to the drill site so the construction of it may be quickened if contractor allocates resources for it. The drilling contractor does not expect to start moving the drilling rig from Mombasa of Kenya until the drilling pad is finalized. It is important to finish the drilling pad so that the drilling contractor will start mobilizing the drilling unit as soon as possible.

➔Expected Spud Day

He expects 20 – 25 days for initial rig-up after arriving at the site. Thus, all delays in the drilling pad will be critical for the spud date. As progress is now the team expects that spud date will be in the middle of May.

Camp Site

The contractor is currently moving the housing units about 13 truckloads to the camp site that is being constructed. The sewer system has not been started on, but the housing units are containers that will be setup quickly when the camp site ground has been prepared. The camp site will be fenced off for security.

The total Great Wall Drilling Company crew is 44 persons. The campsite is expected to be ready for the housing units in 2 weeks (Figure 2).

Drilling Water

➔Water Intake

The water intake pump station is currently under construction (Figure 3 and 4) and will be finalized in a month according to the construction contractor, Yashinoya Trading and Construction.

➔Pipeline

We don´t have a status on the pipeline but the same contractor expressed his opinion on that the pipeline and the booster station would finish in about a month. EWSA intends to ask the contractor to put more resources into the project because some of the construction can be done in parallel.

The team expressed some concern on that the pipeline was above ground on the edge of the road and thus accidents are likely to happen if a truck drives into the pipe. A lot of heavy traffic will be in the area due to the drilling operations.

➔Water Tanks near the Drilling Site

Preparation of water tanks on the first drilling location (close to KW-01) are progressing. The steel bar construction of the first tank has started but all three tanks may take up to 3 weeks or more to finish (Figure 5).

The tanks will be 4000 m^3 each with total water capacity of 12 000 m^3. The diameter of the tanks is 28 m and the height 7 m.

The water will be supplied to the drill site by gravity from the tanks above the drill sites.

➔Pump Capacity

Pumping capacity is designed to be 2000 l/min (33 l/s) which would fill all tanks in 5 days, but delivered water capacity will be less and the plan is not to run the pumps at full capacity from the beginning, but at half capacity. Thus all the tanks may be filled in about 2 weeks. But the well may be spud (drilling started) before all the tanks have been filled.

➔Overflow and Water Path

There is currently no planned path for the water overflow, although the plan is to shut off the pumps when full capacity is reached. It is recommended to design a proper overflow and water path for safety, because shutting of water in a 19 km line is not instantaneous.

29. March, 2013.
Hannes Sverrisson

Figures:

Figure 1 Drilling site construction

Figure 2 Camp site construction

Figure 3 Water intake pump station construction, foundation preparations.

Figure 4 Water intake pump station construction, cement slurry mixing.

Figure 5 Water tank construction

Attachment-3

Letter on "Advice on Cement Slurry" dated on 15th April, 2013

JICA TECHNICAL ASSISTANCE
DATA COLLECTION SURVEY ON GEOTHERMAL DEVELOPMENT IN RWANDA

Date: 15 April, 2013

To: Geothermal Unit, Energy,
Water and Sanitation Authority (EWSA), Rwanda

Your ref. *Our ref.* *JA12G1014-0415-01*

Sub. Advice on Cement Slurry

Dear Head of Geothermal Unit,

During our visit to Rwanda we had a meeting with the drilling contractor GWDC together with your Drilling Engineer. One of the major issues discussed was on the use of silica flour. We have examined the page of his work plan the GWDC sent to us, the page that describes the reason he would not use silica flour.
As the conclusion, we strongly recommend mixing silica flour to Portland cement for geothermal well cementing as explained in the explanation note attached hereto.

It would be our pleasure should this advice assist you in successful completion of the exploratory well construction.

Sincerely yours,

TAKAHASHI Shinya
Team Leader,
Data Collection Survey on Geothermal Development in Rwanda

Enclosure:
1. Advice on Cement Slurry – Mixing Silica Flour

CC: JICA Rwanda Office

NIPPON KOEI CO.,LTD.

NIPPON KOEI CO., LTD
4, Kojimachi 5-chome, Chiyoda-ku, Tokyo, 102-8539, JAPAN
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http://www.n-koei.co.jp

Advice on Cement Slurry – Mixing Silica Flour

JICA Team (11 April. 2013)

The GWDC informed the Team that the GWDC would not add silica flour to the Portland cement mixture because "GWDC does not recommend mixing any silica flour to the Portland cement because Portland cement's compressive strength is too low", quoted from the work plan of GWDC.

However, the Team would like to recommend strongly of using silica flour as already recommended at the wrap-up meeting (please refer to the minutes of meeting of 27th March 2013). The main reasons are as follows:

1. Cement designs for high-temperature geothermal applications have typically included 35 to 45 % additional crystalline silica to help prevent loss of compressive strength and increase the permeability. This is based on research performed on cement systems, which indicated that at temperatures above 110°C (230°F), additional silica flour is required to provide a high-strength stable crystalline structure that does not regress in high temperature environment. This mixture has been used for many years, both in geothermal-well applications, high-temperature oil- and gas-well application[1].
2. Successful applications of silica flour in geothermal well drilling have been experienced all over the world and well documented in articles that could be read in web-sites. One example is the article written by Evans Kiprotich Bett, KenGen (2010)[2], describing "Silica flour is included in the design of cement slurry to prevent strength retrogression that occurs as a result of elevated temperatures encountered in geothermal wells.

The Team strongly advices the GWDC contractor to reconsider their procedures regarding usage of silica flour and mix it with the Portland cement. The recommended amount is 40% BWOC.

End of Document

[1] Mainly based on "B. Iverson and J. Maxson, Halliburton; and D Bour, AltaRock Energy, Inc: Strength retrogression in Cements Under High-Temperature Conditions; Proceeding, Thirty-Fifth Workshop on Geothermal Reservoir Engineering Stanford University, February 1 – 3, 2010 (attached hereto)", with some modifications by the Team.

[2] E K Bett: Geothermal Well Cementing. Materials and Placement Techniques, UNU Geothermal Training Programme, 2010 (attached hereto)

PROCEEDINGS, Thirty-Fifth Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 1-3, 2010
SGP-TR-188

STRENGTH RETROGRESSION IN CEMENTS UNDER HIGH-TEMPERATURE CONDITIONS

Benjamin Iverson and Joe Maxson, Halliburton; and Daniel Bour, AltaRock Energy, Inc.

Halliburton
2600 S. 2nd St.
Duncan, Oklahoma, 73536, USA
e-mail: benjamin.iverson@halliburton.com

ABSTRACT

Cement designs for high-temperature geothermal applications have typically included 35 to 40% additional crystalline silica to help prevent loss of compressive strength and an increase in permeability. This was based on research performed on Portland-cement systems, which indicated that at temperatures above 230°F, additional silica was required to provide a high-strength stable crystalline structure. This standard has been used by the industry for many years, both in geothermal-well applications and high-temperature oil- and gas-well applications. New research, however, has shown that 40% additional silica can be inadequate to provide a high-strength, low-permeability cement at temperatures typical for geothermal-well conditions of around 500°F or higher. This research also indicates that larger amounts of silica might be required to provide long-term strength stability in cements that are typically used in geothermal-well applications.

Preliminary results of this research are provided, including strength- and permeability-test results on cements cured at temperatures from 500 to 650°F, as well as a discussion on the associated crystalline phases found in these samples. In addition, a discussion of the practical ramifications, ongoing research, and additional research needed in this area is included.

INTRODUCTION

Geothermal wells incorporate some of the most extreme downhole conditions that a Portland-cement system will have to withstand. These conditions include hard and corrosive formations, lost-circulation zones, CO_2 and other toxic-gas intrusion, and extremely high temperatures. Of these issues, high temperature is the most common. In Portland cements, a phenomenon known as strength retrogression occurs when the cement is exposed to elevated temperatures. Strength retrogression in cements describes a cement with lower compressive strength and higher permeability. The detrimental properties of the cement are caused by the formation of lime-rich crystalline phases, such as alpha-dicalcium-silicate hydrate, which are known to weaken the mechanical strength of cements and cement-based materials (Hu et al. 2006; Patchen 1960; Eilers and Root 1976). The exact temperature under which strength retrogression occurs is dependent on the type and purity level of the cement used; however, typically at temperatures greater than 230˚F, strength retrogression becomes an issue.

To combat strength retrogression in Portland cements, crystalline silica is added to the cement blend (Hewlett 1998). The addition of the silica allows for the formation of silica-rich cement phases, such as tobermorite and xonotlite, which do not result in strength retrogression in the cement. Historically, the amount of silica added to the cement was 35 to 40% by weight of cement (bwoc) (Patchen 1960). This amount was based on research conducted at temperatures at or near 230˚F, or at higher temperatures for relatively short periods of time. In geothermal and other high-temperature applications, temperatures can easily reach levels of 600˚F or higher. While some previous studies have examined the long-term effects of exposure to temperatures as high as 600˚F, the total information available is lacking (Stiles 2006). Whether a 35 to 40% addition of silica remains adequate to avoid strength retrogression as the temperature increases has not been conclusively answered. However, advances in the ability to analyze cement samples cured over extended periods of time allow for the reexamination of the baseline amount of silica required to stabilize cements at high temperatures.

In this study, a systematic approach was undertaken to better answer the question of how much crystalline silica is required to avoid strength retrogression in Portland cements exposed to elevated temperatures. Mechanical properties, permeability, and chemical-phase development were examined at regular time intervals to determine any links between the crystalline structure and properties of the cement.

This paper will focus only on the short-term behavior, consisting of curing times of 14 and 30 days.

EXPERIMENTAL DATA

Class G (Dyckeroff) cement was selected for this study. Five separate cement designs were used in which the concentration of crystalline silica (SSA-1™ agent) was increased from 40 to 80% bwoc in 10% increments. The water concentration in each case was held at 55.073% bwoc. This resulted in a density variation between samples ranging from 16.0 to 16.7 lbm/gal. A small amount of dispersant (0.25 and 0.5% bwoc, respectively) was used in the 70 and 80% range to improve mixability of the cement slurry. Samples were poured into 2-in. by 1-in. diameter brass molds and allowed to set up for 24 hours in a room-temperature water bath. After the initial set, the samples were removed from their molds and placed into a high-temperature, high-pressure autoclave. Samples were then cured at the respective temperatures while water pressure in the autoclaves was held above the steam pressure at the respective temperature. The temperatures used for this study were 500, 550, 600, and 650˚F. While time intervals of 14, 30, 90, and 180 days are being investigated, the focus of this paper will be on the 14-day data for all samples and 30-day data for the 500 and 550˚F cured samples. At the required time intervals, the autoclaves were ramped back to ambient temperature and pressure over a 24-hour period and samples of each cement slurry were removed for study. Afterwards, the remaining cement samples were returned to the autoclave and taken back to temperature and pressure for additional curing.

Mechanical properties, permeability, and chemical-phase analysis were conducted on all samples. The Young's modulus, unconfined compressive strength, Poisson's ratio, and splitting tensile strength (Brazilian) were collected following the procedures outlined in their respective ASTM standards (ASTM D2664–95a 2000; ASTM D3148–02 2002; ASTM D3967-08 2005). Permeability was calculated using a Hassler sleeve permeameter. Powder X-ray diffraction (XRD) was conducted on all samples using a PANalytical X'Pert Pro Cu Kα diffractometer with accompanying Rietveld refinement (Jade version 9.0). When cured at elevated temperatures, multiple phases that are structurally analogous to mineralogical calcium silicates are known to form in cement systems (Richardson 2008). Rietveld refinement of the XRD patterns was used to identify and quantify the relative amounts of phases in the cured cement samples. A typical XRD pattern contains crystallographic information relative to the sample examined, such as lattice parameters, atomic positions, phase fractions, and preferred orientation, as well as information related to the type of diffraction experiment conducted (Young 1993). The Rietveld method minimizes the difference between a hypothetical diffraction pattern created from the theoretical crystal structures identified in the sample and the experimental diffraction pattern obtained. During the Rietveld refinement, experimental parameters, such as the background, X-ray wavelength, diffraction geometry, and peak-shape functions were refined. A fourth-order background function was utilized, simultaneously refining the Caglioti shape parameters, X-ray wavelength, and experimental geometry. The theoretical structures used in this study are listed in the reference section. For each theoretical structure, the lattice parameters, atomic positions, site occupancy, and phase fractions were refined. The refinement was continued until the weighted residual, R, was minimized (McCusker et al. 1999).

RESULTS AND DISCUSSION

For mechanical properties, the average values over three or four samples, depending on the number of samples recovered, are reported in Tables 1 and 2. The most-commonly associated effect observed when cements have undergone strength retrogression is a loss of compressive strength. The compressive-strength values obtained range from just over 4,500 psi to just under 10,000 psi. The Young's modulus, Poisson's ratio, and tensile strength for these samples were all in line with what is typically associated with a neat cement. When cured for longer time periods, no major trends in terms of loss of mechanical properties were observed. However, when tracked from 14 to 30 days for the 500 and 550°F cures, the mechanical properties changed. This indicated that the timeframe examined in this study might not be long enough to fully quantify strength retrogression at these temperatures, from a mechanical-property standpoint.

Table 1: 14-day Ultimate Compressive Strength (UCS), Young's Modulus (YM), Poisson's Ratio (PR), and Ultimate Tensile Strength (UTS).

Temp., °F	Silica %, bwoc	UCS, psi	YM, psi	PR, psi	UTS, psi
500	40	8,065	1,780,000	0.141	1,039
500	50	7,599	1,740,000	0.132	877
500	60	6,185	1,587,500	0.130	923
500	70	5,522	1,427,500	0.133	773
500	80	7,071	1,860,000	0.132	924
550	40	5,099	1,822,500	0.150	764
550	50	4,540	1,490,000	0.136	532
550	60	6,117	1,703,333	0.107	615
550	70	6,441	1,955,000	0.130	640
550	80	6,670	1,837,500	0.111	872
600	60	9,691	1,912,500	0.134	1,279
600	70	8,861	1,827,500	0.138	1,386
600	80	6,849	1,765,000	0.136	701
650	60	7,676	1,752,500	0.148	865
650	70	7,522	1,667,500	0.138	1,049
650	80	7,227	1,920,000	0.136	1,295

Table 2: 30-day Ultimate Compressive Strength (UCS), Young's Modulus (YM), Poisson's Ratio (PR) and Ultimate Tensile Strength (UTS).

Temp., °F	Silica %, bwoc	UCS, psi	YM, psi	PR, psi	UTS, psi
500	40	9,313	1,850,000	0.1268	923
500	50	7,689	1,832,500	0.134	800
500	60	4,467	1,682,500	0.127	806
500	70	6,247	1,542,500	0.1155	965
500	80	7,787	1,857,500	0.126	1,115
550	40	6,996	1,980,000	0.1473	1,261
550	50	5,792	1,935,000	0.129	738
550	60	5,686	1,677,500	0.1185	820
550	70	6,642	1,800,000	0.1125	750
550	80	7,512	1,865,000	0.1195	978

An increase in permeability is also an indication of strength retrogression in cements. For oilwell applications, cements with permeabilities less than 0.1 millidarcies (md) are typically deemed adequate. Values higher than this, especially if they are associated with either a change in temperature or a change in examined timeframe, can indicate strength retrogression. The Hassler sleeve permeameter was used for this test to prevent fluid flow around the sides of the sample. A confining pressure of 450 psi was used in conjunction with a 150-psi differential pressure with water flowing through the samples at room temperature. Figure 1 shows the complete collection of 14-day permeability data collected.

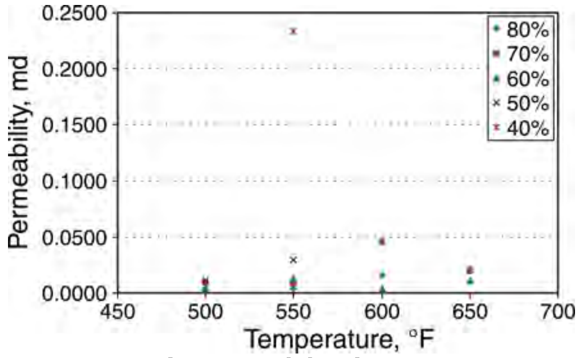

Figure 1: 14-day permeability data.

The 40% silica slurry cured at 550˚F was the only slurry that had a higher permeability than 0.1 md. Furthermore, if the 500 and 550°F cures are examined over time (Figures 2 and 3, respectively), the 40% silica slurry appeared to increase in permeability from 14 days to 30 days in the 500°F cured sample.

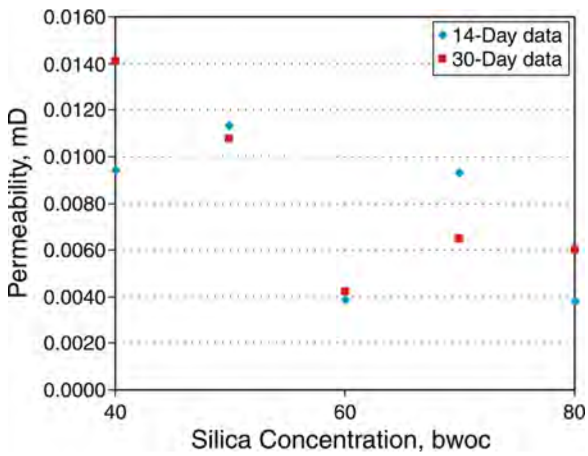

Figure 2: 14- and 30-day permeability data collected at a curing temperature of 500°F.

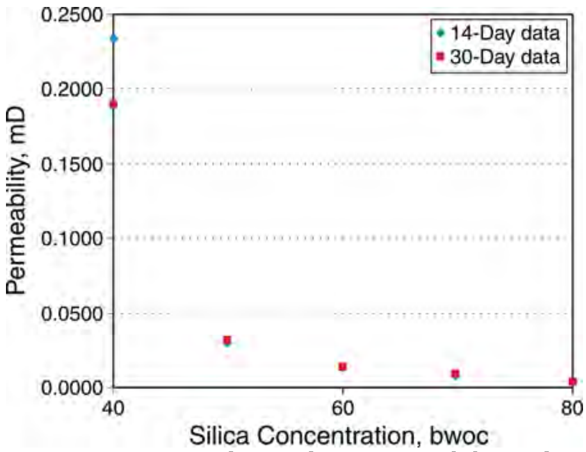

Figure 3: 14- and 30-day permeability data collected at a curing temperature of 550°F.

However, the values obtained were still below 0.1 md. At a temperature of 500˚F, the five slurries tested did not differentiate themselves, other than they are all less than 0.1 md. This did not hold true for the 550˚F cures in Figure 3. Here, the permeability tended to decrease as the silica concentration increased. The 600 and 650˚F cures were limited only to the 14-day cures with the 60, 70, and 80% silica slurries. For the samples examined, the permeability data looks adequate, but more information will have to be collected over a longer time period of curing.

Historically, crystalline silica, or quartz, is added to a cement slurry to stave off strength retrogression. The added silica stabilizes the formation of crystalline phases, such as xonotlite and tobermorite, which have a high silicon-to-calcium ratio. Phases that have a low silicon-to-calcium ratio can be an indication of silica deficiency or the start of strength retrogression in a slurry. Quartz is a crystalline form of silica and can be identified using XRD. Figure 4 shows the characteristic peak for quartz highlighted in the XRD patterns for the 550˚F samples cured for 14 days.

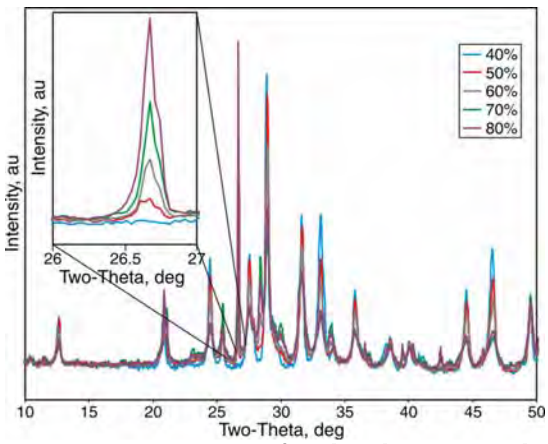

Figure 4: XRD patterns for the slurries cured at 550°F for 14 days.

Little to no intensity is found in the 40% silica sample after 14 days of curing. This indicates that the silica has been consumed. The relative intensity of this diffraction peak is directly proportional to the starting amount of silica in the sample. Hence, the more silica in the sample to begin with, the more quartz present after two weeks. Figure 5 shows the diffraction patterns for the same slurries cured at 30 days with the characteristic quartz peak highlighted.

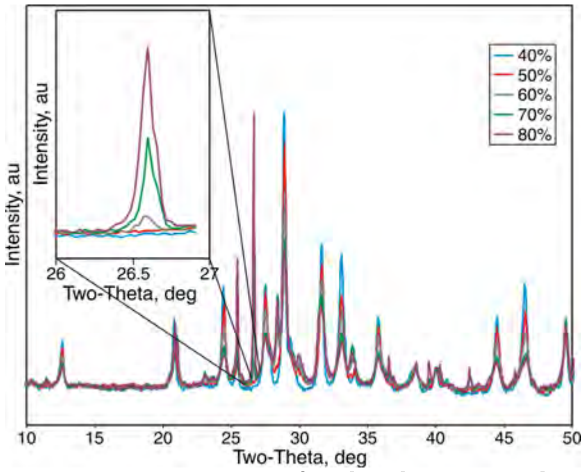

Figure 5: XRD patterns for the slurries cured at 550°F for 30 days.

While there is still no evidence of quartz remaining in the 40% silica sample, the 50% silica sample shows little to no presence of quartz remaining in the sample. Furthermore, the relative intensity of the quartz peak in the 60, 70, and 80% silica samples all appear to be decreasing relative to the 14-day cures.

This behavior indicates that the reactions that occurred in the cement did not reach equilibrium and that the remaining silica in the sample was being consumed over time. This type of conclusion is similar to some of the conclusions found in earlier works on the high-temperature behavior of cements (Speakman 1968). To quantify the amount of silica remaining in the samples over time, Rietveld analysis was conducted on all of the samples examined. The diffraction pattern for the 60% silica slurry cured at 500˚F for 14 days is shown in Figure 6.

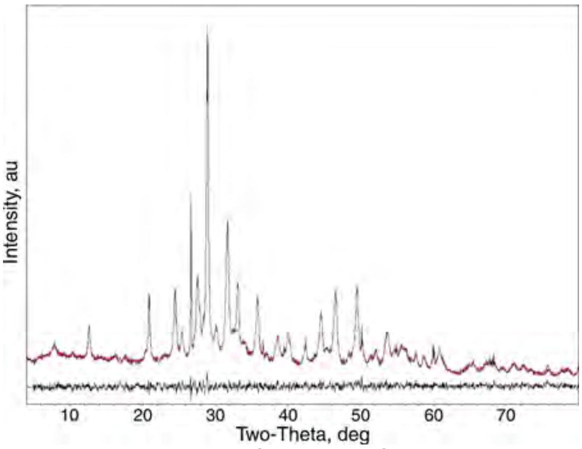

Figure 6: Rietveld refinement of the 60% silica slurry cured at 500°F for 14 days. The redline is the experimental diffraction pattern, the black line is the theoretical diffraction pattern, and the difference line (the graphical representation of the R value) is shown underneath.

All of the diffraction patterns collected in this study were examined in a similar manner. Rietveld refinement was deemed necessary for quantifying the phase fractions in cement because many of the crystalline phases that are present have complex structures that often overlap in their diffraction patterns. Tables 3 through 8 contain the phase fractions in wt% for the slurries studied. Across all of the samples examined, xonotlite, in both a triclinic and monoclinic polymorph (designated t and m, respectively), was the most abundant phase formed. All other phases that were identified in the samples were calcium-silicate hydrates of varying composition and structure. With the limited amount of data collected to date, conclusions based on the phases that form during hydration are difficult.

Table 3: Rietveld Refinement Results for the 14-day, 500˚F Cured Samples.

Phases	40%	50%	60%	70%	80%
Xonotlite t	32.3	41.8	26.9	20.1	15.4
Xonotlite m	31.1	37.6	35.1	31.7	30.8
Scawtite	3.1	0	0	0	0
Killalaite	4.9	4.7	5.8	4.8	2.6
Kilchoanite	9.3	0	0	0	0
Katoite	3.1	7.7	6.5	7.4	7.5
Hibschite	5.1	0	0	0	0
Dellaite	11.1	0	0	0	0
Tobermorite 11Å	0	5.8	7.1	8.8	7
Quartz	0	2.4	3.8	10.8	14.6
Reyerite	0	0	7.3	10	15.7
Hillebrandite	0	0	7.5	6.4	6.4
R	4.25	4.95	4.55	4.86	4.65

Table 4: Rietveld Refinement Results for the 30-day, 500˚F Cured Samples.

Phases	40%	50%	60%	70%	80%
Xonotlite t	26.7	40.1	24.9	20.5	14.5
Xonotlite m	33.4	39.7	25.2	30.8	31.5
Scawtite	3.1	0	0	0	0
Killalaite	6	5.3	4	0.2	2.3
Kilchoanite	8.9	0	0	0	0
Katoite	0	7.8	5.6	8.9	8.5
Hibschite	9.8	0	0	0	0
Dellaite	12.1	0	0	0	0
Tobermorite 11Å	0	5.5	10.7	12.5	8.2
Quartz	0	1.6	1.3	9.9	11.7
Reyerite	0	0	23.4	17.2	18
Hillebrandite	0	0	4.9	0	5.3
R	4.48	4.85	4.71	4.52	4.48

Table 5: Rietveld Refinement Results for the 14-day, 550˚F Cured Samples.

Phases	40%	50%	60%	70%	80%
Xonotlite m	38.1	40.7	37.6	27.5	34.6
Xonotlite t	24.4	33.9	26.9	16.8	21
Scawtite	3.6	3.5	5	5.5	3.3
Poldervaartite	10.3	7.8	7.7	11.1	0
Killalaite	3.3	3	4	4.7	9.1
Katoite	9.1	0	0	0	0
Hibschite	11.2	7.3	5.3	6	8.1
Tilleyite	0	2.4	4.4	7.8	4.7
Reyerite	0	0	6.2	15.8	11.4
Quartz	0	1.4	2.9	4.8	7.8
R	4.93	4.8	3.94	4.4	4.17

Table 6: Rietveld Refinement Results for the 30-day, 550˚F Cured Samples.

Phases	40%	50%	60%	70%	80%
Xonotlite m	41.1	40.8	33.3	32.1	33.2
Xonotlite t	25.8	26.6	26.8	15.4	20.5
Scawtite	3.6	3.1	5.4	6.1	3.9
Poldervaartite	7.7	8.2	7.3	9.9	0
Killalaite	4.1	7.3	4.6	5.6	6.2
Katoite	7.8	0	0	0	0
Hibschite	9.9	8.4	7.4	6.4	7.1
Tilleyite	0	5.6	4.6	5.4	4.5
Reyerite	0	0	10	15.7	16.3
Quartz	0	0	0.6	3.4	8.3
R	4.74	4.8	3.91	4.45	4.97

Table 7: Rietveld Refinement Results for the 14-day, 600˚F Cured Samples.

Phases	60%	70%	80%
Xonotlite t	40.9	34	31.3
Xonotlite m	27.4	28.7	27.8
Scawtite	5.3	7.3	7.9
Poldervaartite	6.7	7.1	6
Killalaite	4.9	5.9	5.6
Hibschite	4.8	3.7	4.9
quartz	10	13.3	16.5
R	4.75	4.73	4.28

Table 8: Rietveld Refinement Results for the 14-day, 650˚F Cured Samples.

Phases	60%	70%	80%
Xonotlite t	33.7	37	42.1
Xonotlite m	23.8	21.3	23.7
Scawtite	5.7	7	6.8
Poldervaartite	3.1	5.4	5.4
Killalaite	8.3	7.8	6
Hibschite	7.7	7.1	8.3
quartz	17.7	14.4	7.7
R	4.76	4.46	4.27

The phase-fraction analysis also quantifies the amount of crystalline silica remaining. This is essentially unreacted silica. As indicated previously, a general trend is observed that, as the initial quantity of quartz present increases, the more unreacted quartz is present. However, the amount of unreacted quartz tends to decrease as the samples are cured for longer periods of time at the same temperature. Outside of the 40% silica slurry cured at 550˚F, the loss of quartz with time has not shown any ill effects on the mechanical properties in the cement. While the 40% silica sample cured at 500˚F showed no presence of quartz, the permeability and mechanical properties showed no indication of strength retrogression. This is in contrast to the higher permeability observed in the 550˚F cured sample, which might negate its use at this temperature.

At the higher temperatures, quartz was still identified, although at 650˚F the amount of quartz remaining did not appear to be consistent relative to the amount that was initially present. The consumption of silica over time also indicates that equilibrium was not reached, meaning more time might be required to see any degradation in properties. With a longer timeframe for curing, the different silica concentrations might differentiate themselves further, both in properties of the cement and phases that are present. As the cement is allowed to cure for even longer periods of time after the silica has been consumed and examined in this manner, a better understanding of how the phase development in the cement relates to strength retrogression and long-term integrity is feasible.

CONCLUSIONS

A systematic approach was undertaken to examine strength retrogression in a Class G Portland cement containing silica additions ranging from 40 to 80% when subjected to elevated temperatures ranging from 500 to 650˚F. Mechanical properties and permeability were recorded for all samples studied. XRD with accompanying Rietveld refinement was utilized to identify and quantify the crystalline-phase fractions present in the cements. The amount of crystalline silica remaining in the cements studied was quantified. From this information, 40% silica was deemed to be too low of a starting point when curing temperatures reached 550˚F. While this is a preliminary study, this work highlights a methodology for analyzing strength retrogression in cements. Longer time frames for curing might be required to further differentiate the behavior of the cement.

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GEOTHERMAL WELL CEMENTING, MATERIALS AND PLACEMENT TECHNIQUES

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ABSTRACT

Geothermal wells are cemented using many of the same techniques as in the oil and gas industry. However, high temperatures, corrosive brines and carbon dioxide severely challenge the long-term durability of well cements. Well cementing is a critical part of well construction and requires a dedicated design and engineering process.

Portland cement manufactured to API specifications, classes A and G, is most commonly utilised in geothermal wells cementing. The cements and cement additives selected and the cementing practices utilised are an integral part of sound well design, construction and well integrity. Selected cements, additives and mixing fluids should be laboratory tested in advance to ensure they meet the requirements of the well design. Silica flour is included in the design of cement slurry to prevent strength retrogression that occurs as a result of elevated temperatures encountered in geothermal wells. Proper well conditioning before cementing ensures a sound cement sheath. There are four common techniques utilised in the primary cementing of geothermal wells. There are other techniques used to execute remedial cementing jobs when the need arises. During cementing operations, various parameters are recorded as part of the monitoring of the cementing execution job and for post-job analyses. In the post-job evaluation, it is important to carry out acoustic logs.

1. INTRODUCTION

Cementing is the process of mixing and pumping cement slurry down to fill the annular space behind the pipe. When setting, the cement will establish a bond between the pipe and the formation. Unlike oil and gas wells, the casings in geothermal wells are usually fully cemented back to the surface. Portland cement is the most commonly used cement. The American Petroleum Institute (API) classifies cement into eight types depending on required properties. Slurry is made by mixing cement with water and additives. Chemical additives are mixed into the cement slurry to alter the properties of both the slurry and the hardened cement.

The success and long life of well cementation requires the utilization of high-grade steel casing strings with special threaded couplings and temperature-stabilized cementing compositions. A hydraulic seal must be established between the cement and the casing and between the cement and the formation. This requirement makes the primary cementing operation important for the performance of the well. Geothermal wells are drilled in areas with hot water or steam and because of the hostile conditions, special planning is necessary to ensure the integrity of the well. When primary cementing is not well executed due to poor planning, despite using the right methods and materials, remedial cementing may have to be done in order to restore a well's operation.

In general, there are five steps in designing a successful cement placement:

a) Analysing the well conditions: reviewing objectives for the well before designing placement techniques and cement slurry to meet the needs for the life of the well;
b) Determining slurry composition and laboratory tests;
c) Determining slurry volume to be pumped, using the necessary equipment to blend, mix and pump slurry into the annulus, establishing backup and contingency procedures;
d) Monitoring the cement placement in real time: comparison is made with the first step and changes implemented where necessary;
e) Post-job evaluation of results.

Cementing operation is a continuous process as shown in Figure 1 (API, 2009).

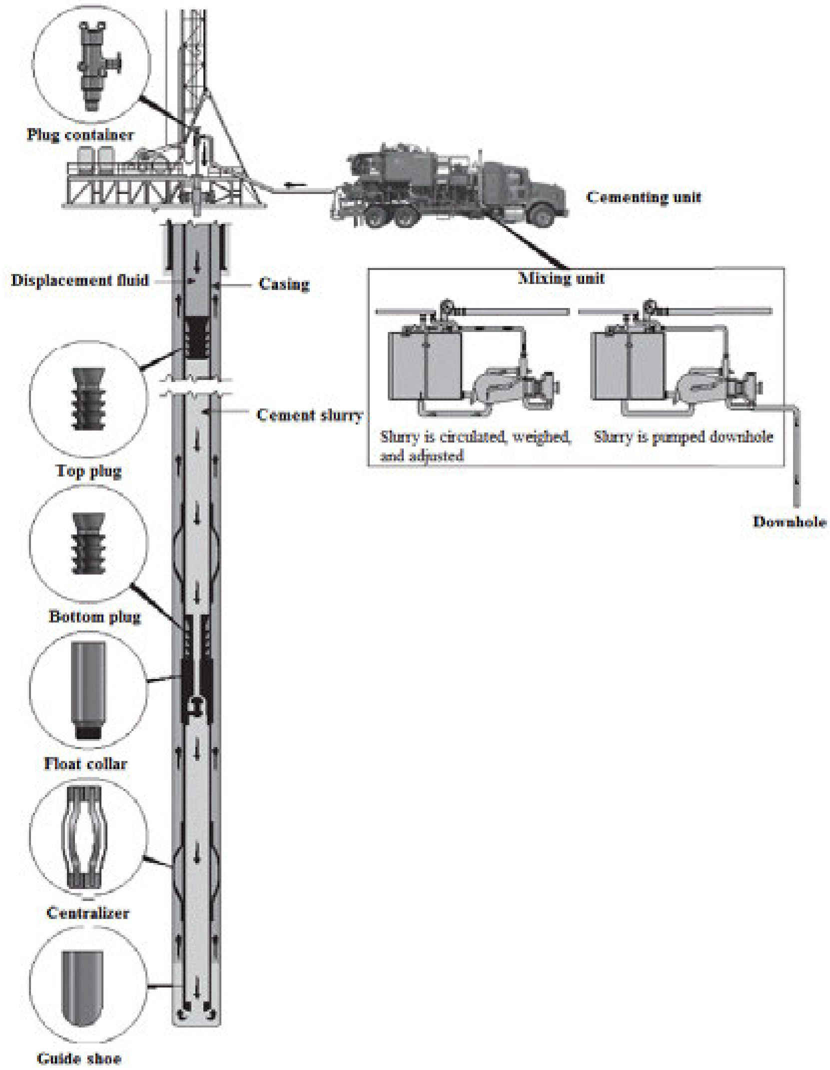

FIGURE 1: Typical cementing process (API, 2009)

2. OBJECTIVES OF CEMENTING

The objective of casing cementing is to ensure that the whole length of the annulus is completely filled with sound cement that can withstand long term exposure to geothermal fluids and temperatures (Hole, 2008). The most important functions of a cement sheath between the casing and the formation are (Rabia, 1985):

a) To prevent the movement (migration) of fluids from one formation to another or from the formations to the surface through the annulus;
b) To hold the casing string in the well;
c) To protect the casing from corrosive fluids in the formations and buckling;
d) To support the well-bore walls (in conjunction with the casing) to prevent collapse of formations;
e) To prevent blowouts by forming a seal in the annulus;
f) To protect the casing from shock loads when drilling deeper.

Cementing is also used to condition the well:

a) To seal loss of circulation zones;
b) To stabilize weak zones (washouts, collapses);
c) To plug a well for abandonment or for repair;
d) To kick-off side tracking in an open hole or past a junk;
e) To plug a well temporarily before being re-cased.

3. WELL CONDITIONS

It is important to get a clear picture of the conditions in the well to identify loss zones, losses, temperature, wellbore enlargements and other potentially useful information.

3.1 Mud conditioning

The top priority in achieving a successful cement job is to displace all the mud from the annular section to be cemented and the mud cake on the annular wall. Drilling mud is designed to help efficiently drill, transport cuttings to the surface and form a mud cake, but is not always conducive to good mud displacement during cementing operations. Therefore, prior to running the casing and cementing, the drilling fluid should be conditioned to exhibit ‘easy-to-remove’ properties including low fluid loss, thin rheological properties, and a flat gel profile (Bush and O'Donnell, 2007). Reducing the mud’s gel strength, yield stress and plastic viscosity is recognized as being beneficial, because the driving forces necessary to displace the mud are reduced, and its mobility is increased (Nelson, 1990). The addition of mud thinners and deflocculants will aid in this process. Prior to logging operations or the installation of casing, the bit should be short tripped to the previous casing shoe and then run back to bottom to be certain the well will remain open. Additionally, if there is a concern for mud losses while running casing or cementing, LCM (Lost Circulation Material) pill should be spotted on the bottom prior to POOH (Pull Out Of Hole) with the drill string.

Once the casing has been run, the mud should be further conditioned to remove gelled mud which will have formed beneath the casing in areas of poor centralization. After landing the casing, and the drilling mud has been conditioned, the cementing should begin as soon as possible, preferably within 15 minutes. Increased static times may cause the mud to gel significantly and make it difficult to remove from the annulus (Bush and O'Donnell, 2007).

3.2 Casing movement

If possible, the casing should be reciprocated. The pipe movement will both physically scrape mud from the wellbore, as well as keep fluid moving around all portions of the hole. Reciprocation is 5-15 m stroke length at 1 stroke per minute (Bush and O'Donnell, 2007).

3.3 Centralization

Good centralization is an important factor in achieving efficient mud displacement and cement placement. A poorly drilled hole may have several washed out zones which are difficult to clean out, regardless of the displacement rate. Crooked holes make casing centralization difficult. Consequently, the removal of the mud from the narrow side of the annulus is problematic. It is therefore necessary to ensure that the drilled hole is smooth without doglegs, in-gauge and stable (Nelson, 1990). A minimum casing stand-off of 70% through critical sections is a good rule-of-thumb. Stand-off can range from 0% (casing against the hole wall) to 100% (casing perfectly centred in the hole) (Bush and O'Donnell, 2007).

3.4 Bottomhole temperature

Accurate prediction of bottomhole circulation temperature (BHCT) and bottomhole static temperature (BHST) is important during drilling and completion of geothermal wells. The majority of borehole temperature measurements are obtained as maximum-reading values acquired during logging runs. Many methods and algorithms have been proposed to extrapolate bottomhole temperature values, measured during drilling or soon after circulation has ceased, in order to obtain static borehole or formation temperature.

To plan the cementing operations in high-temperature geothermal wells, accurate circulation temperatures are required. The BHCT typically used for cement slurry design are found in API Specification 10. It assumes 26°C surface formation temperature. One must know the average static temperature gradient to design cement-slurry thickening time with the current API bottomhole temperature circulation correlations. Many drilling operators have observed that the API method overestimates circulating mud temperatures for deep wells. A recently developed API equivalent well (API-EW) method allows one to use the API temperature correlations for any deep well, both onshore and offshore, and for any values of surface formation temperature. The API-EW method transforms a real wellbore into an API equivalent wellbore by treating the well's 26°C isotherm as the surface temperature (Kutasov and Kagan, 2002).

To calculate the average temperature gradient and determine the rate of cement strength development, BHST has to be known. Bottomhole shut-in temperature is used and an approximate analytical method. It is a function of drilling fluid circulation time, shut-in time, wellbore radius, circulation time, and formation thermal diffusivity.

A BHCT memory recorder was recently developed, capable of recording downhole temperatures during circulation before cementing, squeezing or plugback operations. The recorder can be tripped into the well with a pipe or wireline and can be dropped down the drill string. Temperature data obtained with BHCT recorders are representative of true bottomhole circulating temperatures and can provide an accurate assessment of downhole temperature conditions before critical cementing operations are performed (Kabinoff et al., 1992). Because of the uncertainty of actual BHCT, retardation and testing of the cement can be challenging.

3.5 Caliper log

A caliper log is used to measure the wellbore diameter. After the casing point is reached, caliper logs should be run, and the cement volume should be adjusted based upon the actual wellbore size. Even with the caliper log, it is common practice to use an excess volume to ensure fill-up by cement across all critical zones. The excess factor used is based on the experience obtained from the field being drilled. The volume obtained is added to the volume of cement that will remain between the float collar and the shoe, i.e. in the shoe track. The most commonly used caliper tools have 4 or more movable arms. The logging cable makes it possible to control the motor-operated arms. Caliper logs give the location of cavities in the well (Nelson, 1990). They are also used to assess the condition of the casing, i.e. to check for damage and deposition of calcite scales. If an excess factor has not been established, a rule of thumb may be to use 20% excess in the open hole section where the caliper is used and 50% otherwise.

4. PLACEMENT TECHNIQUES

Most primary cement jobs are performed by pumping the slurry down the casing and up the annulus. However, modified techniques can be used for special situations. A successful primary cement job is essential to allow further drilling operations to proceed. In geothermal wells, cement placement to the annulus is mostly done using one of the techniques explained below.

4.1 Single stage cementing

The single stage cementing operation is the most common type of cementing operation. The procedure is as outlined below and the operation is illustrated in Figure 2:

a) The casing string with all the required cementing accessories such as the float collar, guide/float shoe and centralizers (Figures 3, 4 and 5), is run in the hole until the shoe is just a few metres off bottom.

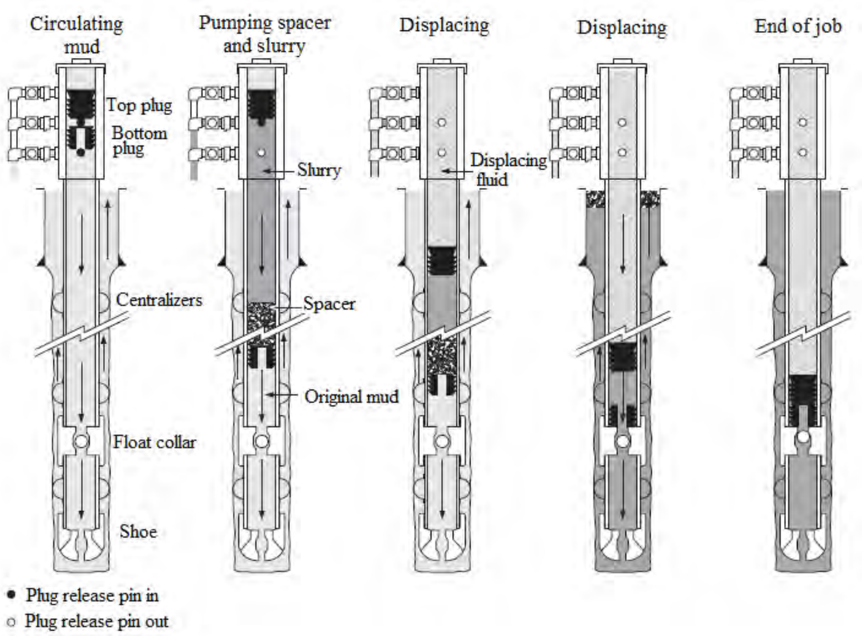

FIGURE 2: Single stage cementing operation (Nelson, 1990)

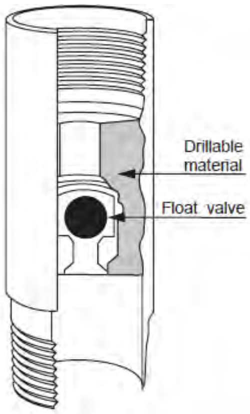

FIGURE 3: Float collar (Heriot-Watt University, 2010)

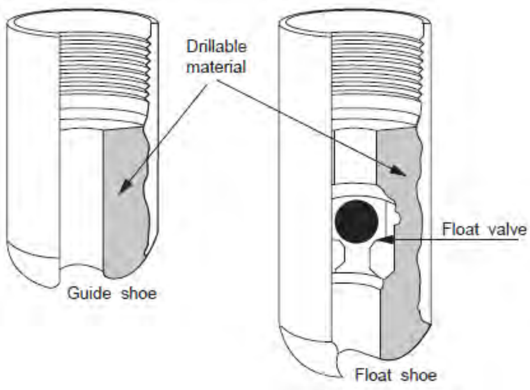

FIGURE 4: Guide/float shoe (Heriot-Watt University, 2010)

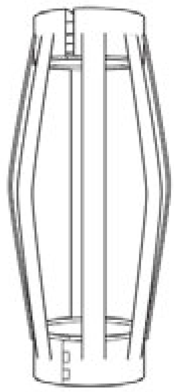

FIGURE 5: Casing centralizer (Heriot-Watt University, 2010)

b) The cementing head, shown in Figure 6, is then connected to the top of the casing string. It is essential that the cement plugs are correctly placed in the cementing head.
c) The casing is then circulated clean before the cement operation begins.
d) The bottom (wiper) plug, shown in Figure 7, is released and pumped down to wipe the inside of the casing clean. It is followed by a spacer, then cement slurry. A spacer is meant to provide a barrier to avoid cement slurry mixing with mud. When the plug reaches the float collar, its rubber diaphragm is ruptured, allowing the spacer and slurry to flow through the plug, around the shoe and up the annulus.
e) The top (shut-off) plug, shown in Figure 8, is then released and displacing fluid is pumped. When the plug reaches the float collar, it lands on the bottom plug and stops the displacement process.

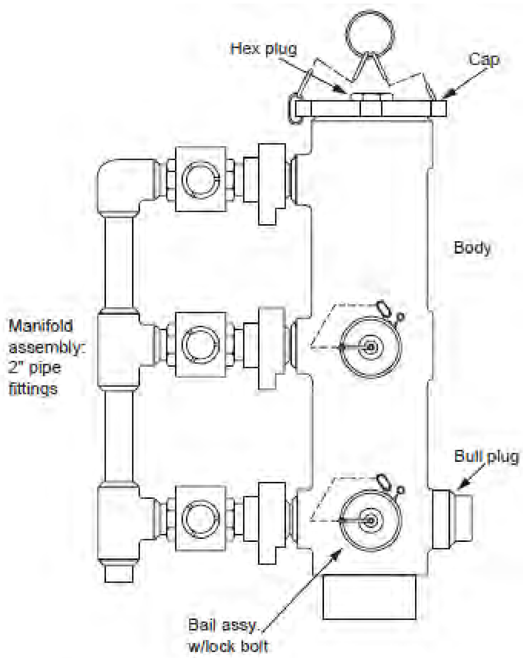

FIGURE 6: Cementing head (Nelson, 1990)

The pumping rate should be slowed down as the top plug approaches the float collar and the top plug should be gently ‘‘bumped’’ into the bottom, wiper plug. The displacement of the top plug is closely monitored. The volume of displacing fluid necessary to pump the plug should be calculated before the job begins. Throughout the cementing job, the mud returns from the annulus should be monitored to ensure that the formation has not been broken down. If formation breakdown does occur, then mud returns would slow down or stop during the displacement operation. Appropriate action should be taken if there are losses observed during cementing.

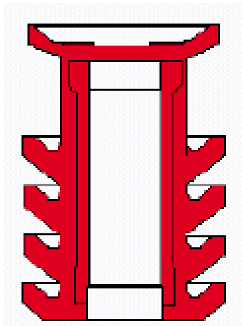
FIGURE 7: Bottom plug – hollow

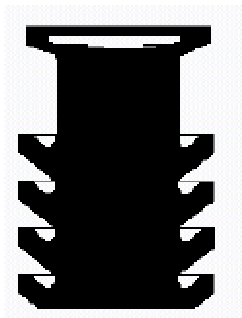
FIGURE 8: Top plug - solid

Upon displacement of cement in the casing and bumping of the plug, the positive seal in the float collar and shoe keeps the cement in place. Valves on the casing head should not be closed during the waiting-on-cement (WOC) period, because the temperature of the fluid left in the casing will increase and, thus, could cause pressure increase, which would expand the casing.

4.2 Inner string (stinger) cementing

Inner string cementing is also common in geothermal well cementing. It allows large-diameter casing strings to be cemented through the drill pipe or tubing that is inserted and sealed in floating equipment. Inner-string cementing has the following advantages:

a) Reduces the risk of cement slurry setting within the casing since cement reaches the annulus much faster than in conventional methods of cementing;
b) Does not require large-diameter cementing plugs;
c) Reduces cement contamination;
d) Reduces the amount of cement that has to be drilled out of large-diameter casing;
e) Decreases cementing displacement time;
f) Allows cement slurry to be pumped until returns are obtained on the surface.

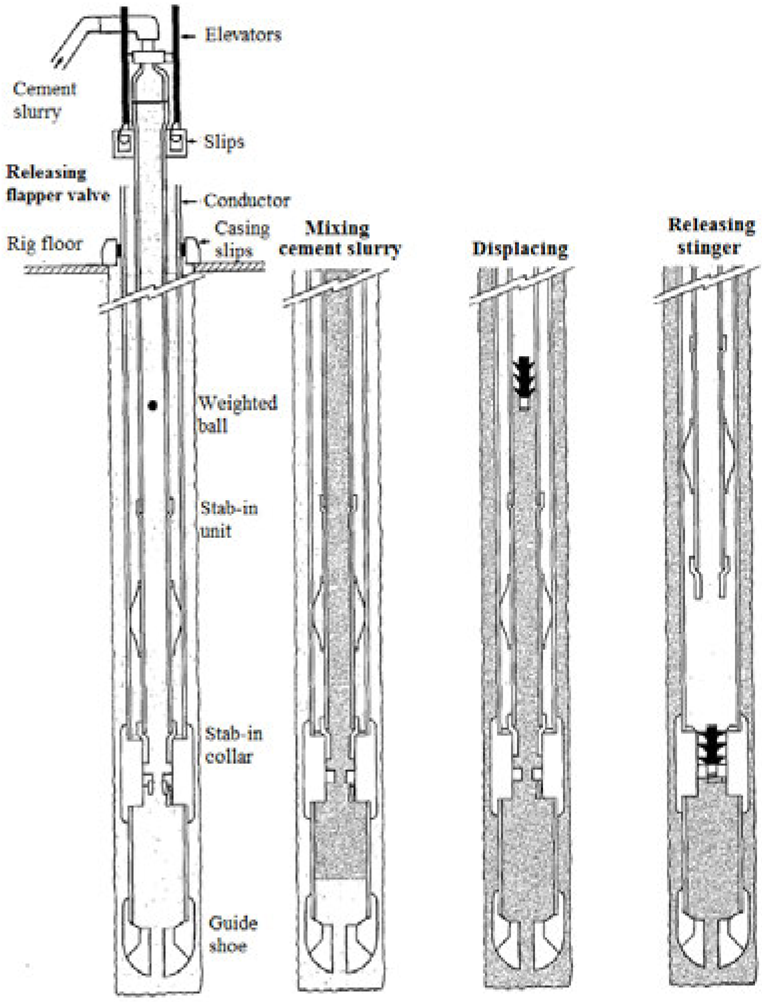

FIGURE 9: Inner string cementing operation (Nelson, 1990)

Inner-string cementing requires the installation of a stab-in float shoe or float collar in the casing string. The float collar with a sealing sleeve is usually installed two joints from the bottom in the casing string. The casing string is run into the well in the usual manner. The inner string is then run in, with the sealing adapter made up on the lower end and stabbed into the floating equipment sealing sleeve. The sealing sleeve is built into the floating equipment to provide a sealing-sleeve/bore receptacle for the inner-string sealing adapter. The float equipment top is also tapered to form a surface that helps guide the sealing-sleeve adapter into its sealing sleeve. Two centralizers should be run on the inner string, one centralizer directly above the sealing adapter and another one above the first centralizer. This arrangement will help the inner string enter the stab-in floating equipment. The inner string cementing operation is shown in Figure 9. Figure 10 shows the stab-in collar and drill pipe assembly.

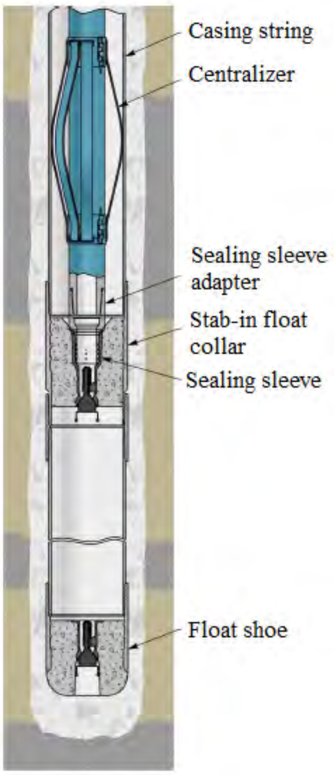

FIGURE 10: Stab-in collar and adapter assembly (CaseTech International, Inc., 2010)

After the inner string (usually drill pipe) has been stabbed into the floating equipment, water is circulated around the system to ensure that the stinger and annulus are clear of any debris. This is followed by a spacer (polymer). Cement slurry is then pumped through the stinger and floating equipment into the wellbore annulus.

Displacement on the inner string can be done with or without a plug. The diameter of the stinger is generally small so contamination of cement is unlikely if a large enough liquid spacer is used. The cement slurry is generally under-displaced so that when the sealing adapter on the stinger is pulled from the floating equipment, the excess cement falls down on top of the floating equipment. After cementing is completed, the check valve in the floating equipment prevents cement from re-entering the casing and the sealing adapter and inner string can be pulled from the casing. The main disadvantage of this method is that, for long casing strings, rig time is lost in running and retrieving the inner string.

4.3 Reverse circulation cementing

This is mainly used in wellbores where loss of circulation is encountered. The technique involves pumping the slurry down the annulus and displacing the drilling fluid back up through the casing; the cement slurry direction is opposite that of the conventional method as shown in Figure 11. The float equipment, differential fill-up equipment and wellhead assembly must be modified. This method is used when the cement slurry cannot be pumped in turbulent flow without breaking down the weak zones above the casing shoe. Reverse circulation allows for a wider range of slurry compositions, so heavier or more-retarded cement can be placed at the lower portion of the casing, and lighter or accelerated cement slurry can be placed at the top of the annulus. Calliper surveys should be made before the casing is run, to determine the necessary volume of cement and minimise over-placement (Crook, 2006).

Reverse circulation cementing can provide the following advantages:

a) Reduces hydraulic horsepower of the cement slurry pumping equipment since the gravitational force is working in favour of the slurry flow;
b) Reduces fluid pressure (often reported as an equivalent circulating density or ECD). ECD is normally calculated at the shoe by combining the effects of hydrostatic pressure and frictional fluid-induced pressures in the casing. Because the heavier and more viscous cement slurry is not circulated back to the surface through the casing, the ECDs can be significantly reduced in reverse cementing in comparison to conventional cementing as shown in Figure 12;
c) Enables shorter slurry thickening time since little or no retarders are used;
d) Takes a shorter time to execute since no displacement is done.

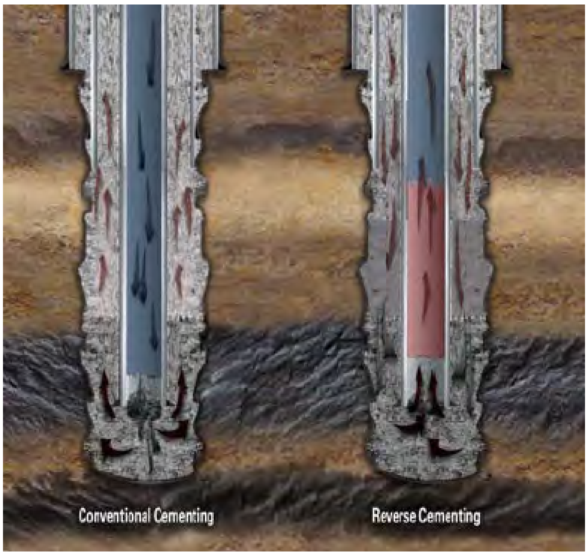

FIGURE 11: Conventional vs. reverse cementing (Hernández and Bour, 2010)

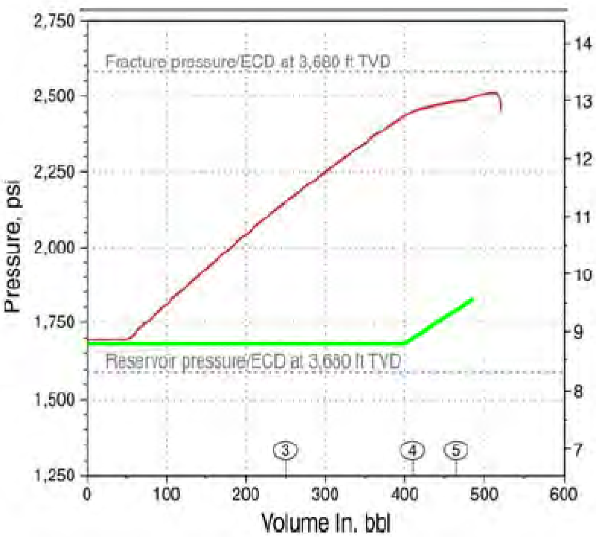

FIGURE 12: Conventional vs. reverse circulation ECDs (Hernández and Bour, 2010)

4.4 Two-stage cementing

This method is rarely used in geothermal well cementing because of the risk of having water pockets in the cement sheath. In geothermal wells, it is mostly used with tieback casing to minimise the risk of casing collapse caused by water pockets. In long casing strings and in particular where the formations are weak and may not be able to support the hydrostatic pressure generated by a very long column of cement slurry, the cement job may be carried out in two stages. The cement sheath in the annulus is split into two, with one sheath extending from the casing shoe to some point above the potentially troublesome formations at the bottom of the hole and the second sheath covers shallower troublesome formations. The placement of these cement sheaths is as shown in Figure 13. The reasons for using a two-stage operation are to reduce:

a) Collapse limit of casing;
b) Long pumping times;
c) High pump pressures;
d) Excessive hydrostatic pressure on weak formations due to the relatively high density of cement slurry.

The procedure for conducting a two-stage operation is as follows:

First stage
The procedure for the first stage is similar to that of single stage cementing, described in Section 4.1, except that a wiper plug is not used and only a liquid spacer is pumped ahead of the cement slurry. The conventional top (shut-off) plug is replaced by a plug with flexible blades to enable it to pass through the stage cementing collar (cementer), shown in Figure 14. The height of this cemented part of the annulus will depend on the fracture gradient of the formations which are exposed in the annulus.

Second stage
The second stage of the operation involves the use of a stage collar which is placed in the casing string at a pre-determined position. The position often corresponds to the depth of the previous casing shoe. The ports in the stage collar are initially sealed off by the inner sleeve. This sleeve is held in place by retaining pins. After the first stage is complete a special dart is released from the surface which lands in the inner sleeve of the stage collar. When a pressure of 69-100 bars is applied to the casing above the dart, and therefore to the dart, the retaining pins on the inner sleeve are sheared and the sleeve moves down, uncovering the ports in the outer mandrel. Circulation is established through the stage collar before the second stage slurry is pumped. The normal procedure for the second stage is as follows:

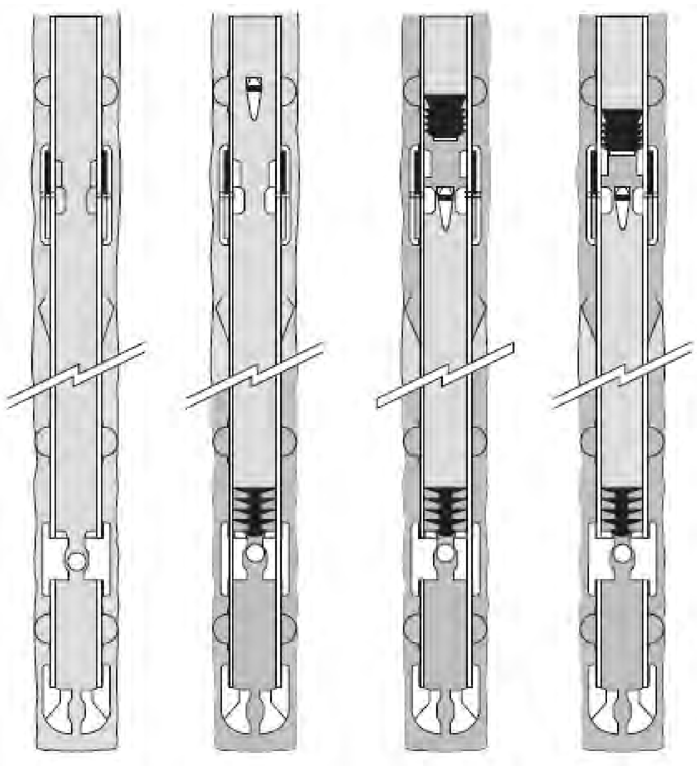

FIGURE 13: Two-stage cementing operation (Nelson, 1990)

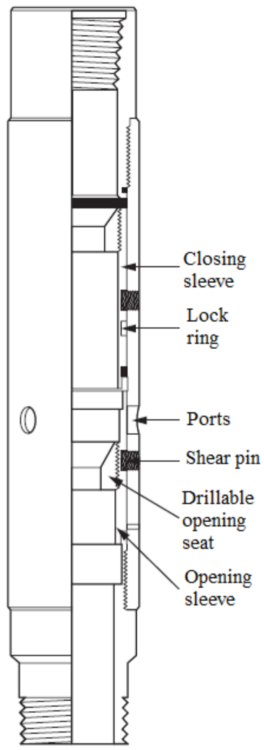

FIGURE 14: Stage cementing collar (Heriot-Watt University, 2010)

a) Drop opening dart;
b) Pressure up to shear retaining pins;
c) Circulate through stage collar whilst the first stage cement is setting;
d) Pump spacer;
e) Pump second stage slurry;
f) Release closing plug;
g) Displace plug and cement;
h) Pressure up on plug to close ports in stage collar.

The other accessories used in a two-stage cementing operation are shown in Figure 15. One disadvantage of stage cementing is that the casing cannot be moved after the first stage cement has set in the lower part of the annulus. This increases the risk of a poor cement bond.

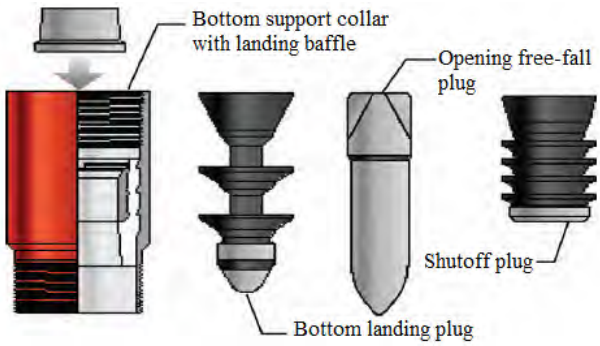

FIGURE 15: Two-stage cementing accessories (Crook, 2006)

5. SLURRY DESIGN

5.1 Cement and cement additives

Portland cement, manufactured to API specification, typically API Class A or API Class G cements, are now commonly utilised in geothermal well cementing. Portland cement is essentially a calcium silicate material, and the most abundant components are tricalcium silicate (C_3S), dicalcium silicate (C_2S) and tricalcium aluminate (C_3A). API Spec 10A classifies cement used in well cementing into the following classes and grades (Gabolde and Nguyen, 2006):

- *Class A* – intended for use when special properties are not required. It is available only in ordinary (O) grade.
- *Class B* – intended for use when conditions require moderate or high sulphate-resistance. It is available in both moderate sulphate-resistant (MSR) and high sulphate-resistant (HSR) grades.
- *Class C* – intended for use when conditions require high early strength. It is available in O, MSR and HSR grades.
- *Class D* – intended for use under conditions of moderately high temperatures and pressures. It is available in MSR and HSR grades.
- *Class E* – intended for use under conditions of high temperatures and pressures. It is available in MSR and HSR grades.
- *Class F* – intended for use under conditions of extremely high temperatures and pressures. It is available in MSR and HSR grades.
- *Class G* – intended for use as basic well cement. It is available in MSR and HSR grades. No additives other than calcium sulphate or water, or both, shall be inter-ground or blended with the clinker during the manufacture of class G well cement.
- *Class H* – intended for use as basic well cement. It is available in MSR grade. No additives other than calcium sulphate or water, or both, shall be inter-ground or blended with the clinker during the manufacture of class H well cement.

Planning for cementing operations and the design and specification of acceptable cement slurries must be performed based on specific well conditions. To adopt standardized cement slurry formulations is generally a recipe for disaster, since there will always be the one well that does not fit the standard specifications. Cementing temperature conditions are important because BHCT affects slurry thickening time, rheology, set time and compressive strength development.

Slurry design is affected by well depth, BHCT, BHST, type of drilling fluid, slurry density, pumping time, quality of mix water, fluid loss control, flow regime, settling and free water, quality of cement, dry or liquid additives, strength development, and the quality of lab cement testing and equipment. Cement system design for geothermal wells differs from those for conventional high temperature oil and gas wells in the exclusive use of silica flour (15 µm) instead of silica sand (175-200 µm) and the avoidance of fly ash as an extender (light weight additive) (Gaurina-Medimurec et al., 1994).

Usually the cement is mixed with 35-40% silica flour for heat resistance. This ensures longevity of the cement as it prevents strength retrogression and increasing porosity as is seen with neat cement slurries exposed to elevated temperatures. Strength retrogression in cement is a measure of decreased compressive strength and higher permeability as the curing time progresses as shown in Figure 16. Greater permeability of set cement due to a greater porosity makes it sensitive to corrosive formation fluids, which is an equally serious problem as losing strength. High temperatures in the range of 150 – 350°C are experienced in geothermal wells. Research studies that have been done on Portland cement have shown a need to add silica flour to the cement to avoid strength retrogression at temperatures above 120°C (Iverson et al., 2010).

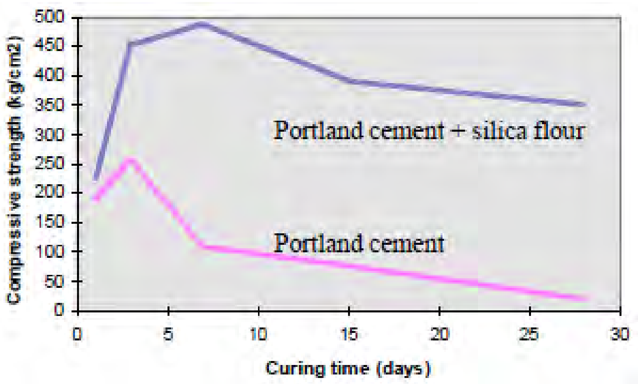

FIGURE 16: Cement strength retrogression (Thórhallsson, 2010)

Other additives besides silica flour used in the design of cement slurry for geothermal wells are:

Retarders – used to prolong the thickening time of cement slurry and avoid the risk of it setting in the casing prematurely by keeping it viscous and pumpable. They are used in deep wells where BHCT is expected to be high, i.e. above 38°C. They do not decrease the ultimate compressive strength of cement but do slow the rate of strength development. The most widely used retarder is calcium lignosulfonate – 0.1 to.5% BWOC. Circulation temperature should be carefully predicted so that the correct retarder concentration is used to avoid flash setting or very long setting up time due to over-retarded cement slurry. Other retarders include synthetic polymers, organic acids or borate salts.

Lightweight additives (extenders) – used to reduce the slurry density for jobs where the hydrostatic head of the cement slurry may exceed the fracture strength of the formation. In reducing slurry density the ultimate compressive strength is also reduced and the thickening time reduced. The most commonly used extender is Wyoming bentonite – 2 to 16% BWOC. It is able to hold water which is 16 times its volume and it therefore also ensures no free water evolves during cement set up.

Friction reducers (dispersants) **–** added to improve flow properties of slurry. Adding dispersants can lower friction and lower pressure during pumping, and enhances turbulent flow at reduced pumping rates.

Fluid loss control additives – used to prevent dehydration of cement slurry and premature setting. The requirement to cement the total length of each casing in under-pressured reservoirs results in a tendency of the water fraction of the cement slurry being lost to the formation. These additives help retain the key characteristics of their cement slurries, including viscosity, thickening time, rheology and comprehensive strength-development. The most common are Organic polymers – 0.5 to 1.5% BWOC and CMHEC – 0.3 to 1.0% BWOC.

Loss of circulation (LOC) additives – cement slurry can be lost to either natural or induced formation fractures. The additives help control the loss of slurry to the formation. The use of medium to finely ground *mica flakes,* which are completely inert and non-sensitive to temperature, dry blended into the cement has been found to be very effective. Organic LCM materials, traditionally utilised in drilling mud formulations, should not be used in cement slurry. Although they achieve the objective of sealing the permeable zones, after the well has been completed, the organic material is carbonised, leaving high porosity within the loss zones, thus providing a flow path for possibly corrosive formation fluids.

Antifoam additives – frequently used to decrease foaming and minimise air entrainment during mixing. Excessive foaming can result in an underestimation of the density downhole and cavitation of the mixing system. The additives modify the surface tension in the cement slurry so that foaming is prevented or the foam breaks up. The concentration required to be effective is very small, typically less than 0.1% BWOW. Polypropylene glycol is the most common.

Accelerators – added to cement slurry to shorten setting time. This is mostly used in surface casing where low temperatures are encountered. They are used when cement setting time is longer than that required to mix and pump cement, which in turn leads to reduced WOC time. Calcium chloride ($CaCl_2$) – 1.5 to 2.0% BWOC and Sodium Chloride (NaCl) – 2.0 to 2.5% BWOC are the most commonly used. It should be noted that higher concentrations act as retarders.

Identification colour or radioactive material – to identify the cement coming up when LOC or plug cementing is being done. During the course of numerous cementing jobs, it may be advantageous to see which cement is coming to the surface.

5.2 Cement mixing

On most rigs cement powder and additives are handled in bulk, which makes blending and mixing much easier. For large volume cement jobs, several bulk storage bins may be required on the rig. For any cement job, there must be sufficient water available to mix the slurry at the desired water/cement ratio when required. The mix-water must also be free of all contaminants. Figure 17 shows a typical schematic flow diagram of cement slurry preparation and indicates the steps performed at the central storage location and at the well site.

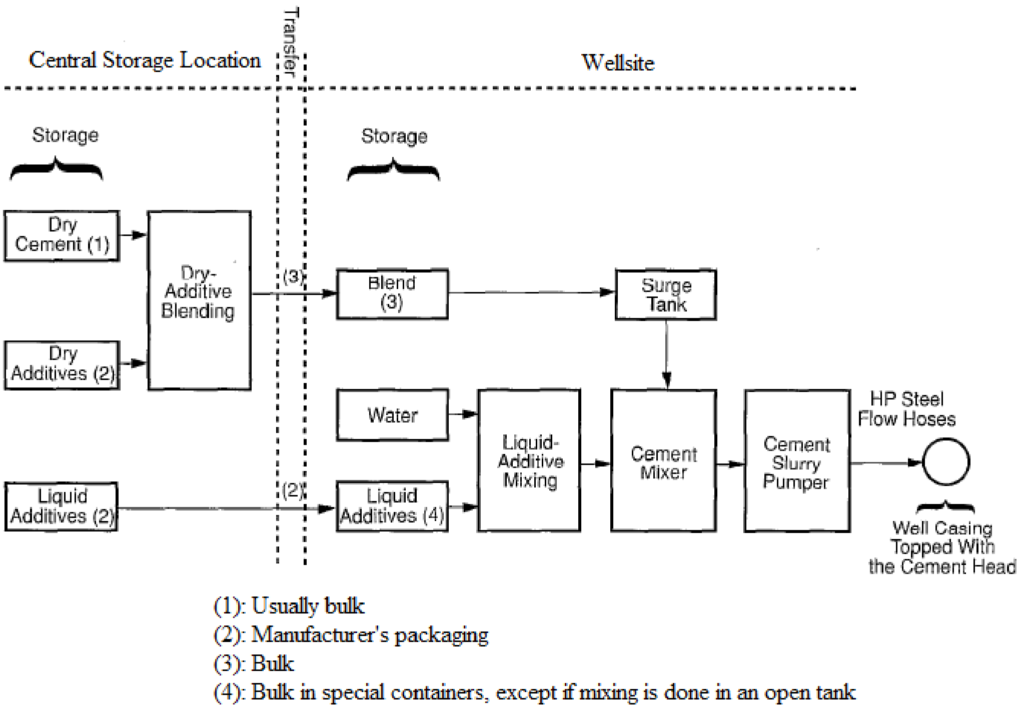

FIGURE 17: Typical cement mixing process (Nelson, 1990)

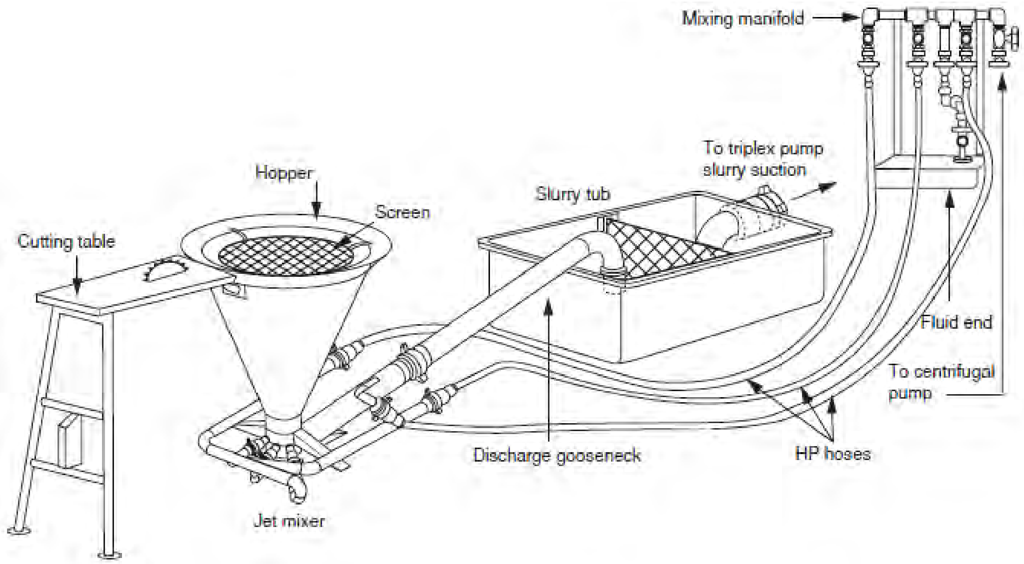

FIGURE 18: Jet mixer (Heriot-Watt University, 2010)

Cement mixing and pumping can be done either using a recirculation mixer, which is currently the most common, or conventional jet mixer units that may be truck, trailer or skid mounted.

Conventional jet mixer – it is an old method and no longer common. The mixer consists of a funnel shaped hopper, a mixing bowl, mixing tub, a water supply line and an outlet for the slurry as shown in Figure 18. Mix-water is pumped across the lower end of the flow and slurry is created. The slurry flows into a slurry tub where its density is measured. If the density of the slurry is correct then the correct amount of mix-water has been mixed with the cement powder. Samples can be taken directly from the mixer and weighed in a standard mud balance or automatic devices (densometers).

Recirculation mixer **–** the mixer can be mounted on a truck, as shown in Figure 1, or trailer, while a skid mounted unit is used mostly offshore and its configuration is as shown in Figure 19. The mixing system proportions and blends the dry cementing composition with predictable properties. The re-circulating mixer is designed for mixing more-uniform homogeneous slurries. It consists of the following (Nelson, 1990):

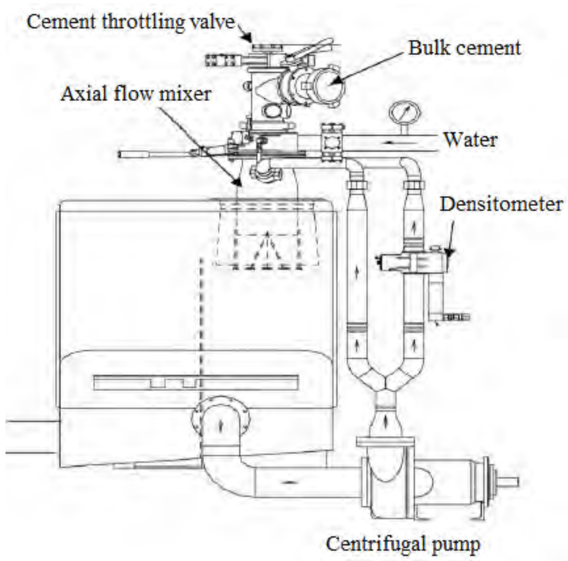

FIGURE 19: Recirculation mixer (Crook, 2006)

a) A sophisticated metering system to mix cement with water, and a device to mix the resulting slurry with previously mixed slurry from the mixing tub;
b) A re-circulating pump (centrifugal pump) at the bottom of the tub to improve the initial mixing by additional shearing;
c) A mixing tub which can be split into two sections. A film-like flow is created over the common partition which assists the release of entrapped air. Both sections can be equipped with agitation paddles (stirrers) to further improve the mixing.

The density is remotely controlled by metering cement and/or water, depending upon the model. Usually the water rate is kept constant, and the slurry density controlled by altering the rate at which cement is delivered to the mixer. Normally, the cement is transferred directly from a pressurized tank without passing through a surge tank.

5.3 Cement pumping

The cement pumping unit normally has twin displacement pumps (triplex, positive displacement) which may be diesel powered or driven by electric motors. The pump plungers have a diameter of between 76.2 and 152.4 mm. Their maximum hydraulic horsepower varies between 150 and 370 kW. The maximum pump flow rate is around 1.3 m^3 and the pumping pressure should not exceed 70 bars (1,030 psi).

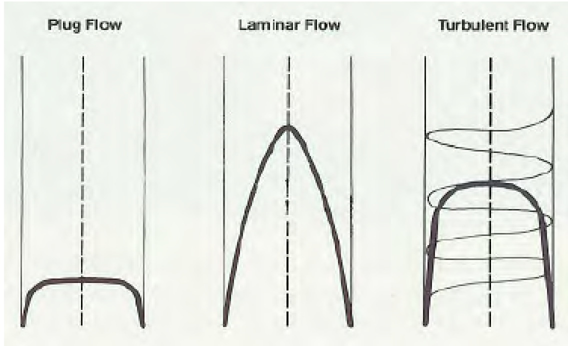

FIGURE 20: Flow regime (Weatherford ,1986)

Different flow regimes may be encountered, as shown in Figure 20, during cement pumping depending on conduit geometry, flow velocity and physical properties of slurry. Turbulent flow is desirable for good cementation, however it is difficult to attain due to limitations in eccentric annuli and irregular wellbores. Adding friction reducers to cement slurry helps achieve turbulent flow. Figure 21 shows different pumping rates necessary for turbulent flow related to casing/hole combination and slurry used. The annular displacement velocity should be at least 1.2 m/s and preferably 1.8 m/s for small casing sizes. The high displacements rates help attain high displacement efficiency, but if not possible, then a plug-flow type job should be carried out at low rates of 0.15 – 0.45 m/s. Laminar flow should be avoided whenever possible (Weatherford, 1986).

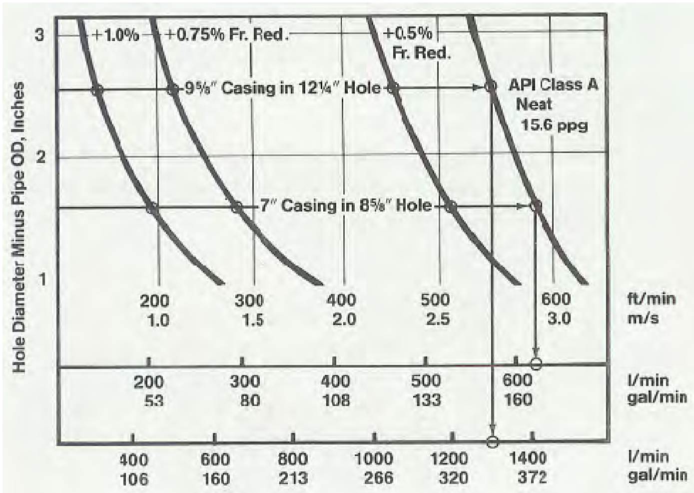

FIGURE 21: Pumping rates to achieve turbulent flow (Weatherford ,1986)

Cement jobs require the measurement of many parameters as explained below (Nelson, 1990):

- *Mix water* – the volume s of water is measured by means of the displacement tanks.
- *Cement (blend) and slurry* – the volumes of mixed slurry and dry cement are determined by combining the mix-water volume and slurry density.
- *Flow rate* – the slurry flow rate is observed at the downhole pump-stroke counter. A flow-meter is used if a continuous recording of job parameters is being made.
- *Pressure* – the pumping pressure is read at a gauge or display panel. An electronic pressure transducer is used if the various parameters are recorded by a central unit.
- *Slurry density* – is traditionally measured using a mud balance (Figure 22). More sophisticated systems are becoming common, e.g. continuous U-tube weighing balance and radioactive densitometer connected to a central recording unit.

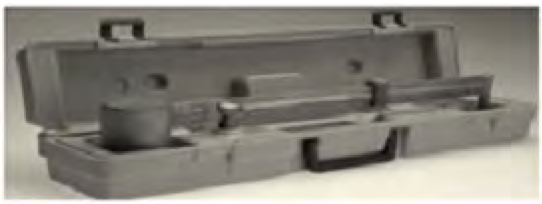

FIGURE 22: Mud balance

Central recording units are available which continuously record vital pumping parameters. The recorders significantly improve onsite job monitoring, while simultaneously storing data for post-job evaluation.

5.4 Cement slurry properties

There are six major slurry performance properties that are tested for each cement slurry design. These are: thickening time, slurry density, free water, fluid loss, compressive strength and rheology.

Thickening time – is designed to determine how long cement slurry remains pumpable under simulated down-hole temperature and pressure conditions. The pumpability, or consistency, is measured in Bearden consistency units (Bc). The test is performed in a HPHT (high pressure high temperature) consistometer. The test involves mixing cement slurry, placing it into the slurry cup, and then placing the slurry cup into the consistometer for testing. The testing pressure and temperature are controlled to simulate the conditions that the slurry will encounter in the well (Ogbonna, 2009). When the slurry reaches a consistency of 70 Bc, it is considered unpumpable in the well. The time is called thickening time or pumpable time. Also, the elapsed time to 40 and 100 Bc should be measured. The difference between the 100 and 40 Bc times is the transition time – used as an indication of the rate at which slurry changes from a pumpable to an unpumpable condition (Bush and O'Donnell, 2007). Normally, a contingency time of 1 hour is added to the pumping time to allow for possible equipment failure.

Slurry density – should be specified to be as high as possible throughout the cemented interval without causing formation breakdown during placement. In general, the cement density should be a minimum of 0.12 kg/l (1.0 ppg) heavier than the drilling fluid density in the hole at the time of cementing (Bush and O'Donnell, 2007).

Free water – the purpose of this test is to help determine the amount of free water that will gather on top of the cement slurry between the time it is placed and the time it gels and sets up. The test involves preconditioning the slurry up to 88°C maximum temperature in an atmospheric consistometer. It is then transferred to a 250 ml graduated cylinder and allowed to set static for 2 hours. For deviated wells, a more critical test is to incline the cylinder at 45°. The slurry is then examined for any free fluid on the top of the cement column. This free fluid is decanted and measured to determine the percent of free water based on the 250 ml volume (Rabia, 2001). The maximum allowed is 0.5%. The separation of water from slurry, once it has been placed, can lead to channelling and formation of water pockets that can cause collapse of the casing once it is heated up.

Fluid loss – is designed to measure slurry dehydration during and immediately after cement placement. Under simulated wellbore conditions, the slurry is tested for filtrate loss across a standardized filter press at differential pressures of 69 bars (1000 psi). The test duration is 30 minutes and results are quoted as ml/30 min. API fluid-loss rate of 50-100 ml/30 min. (for 0.6 l of slurry) is satisfactory in most primary cementing (Gaurina-Medimurec et al., 1994).

Compressive strength – the pressure it takes to crush the set cement is measured in this test. This test indicates how the cement sheath will withstand the differential pressures in the well. In destructive testing, cement slurry is poured into two-inch cubical moulds. The cement cubes are then cured for 8, 12, 16 and 24 hours at bottom-hole temperatures and pressures. In destructive testing, the cement cubes are then crushed to determine their compressive strength in psi. In a non-destructive test, sonic speed is measured through the cement as it sets. This value is then converted into compressive strength (Ogbonna, 2009).

Rheology testing – to properly predict the frictional pressures that will occur while pumping the various fluids in the well, the rheological properties of the slurries should be known as a function of temperature. The slurry viscosity is measured using Fann viscometer. The slurry sample should be conditioned for 20 minutes in an atmospheric Consistometer before measurements are taken. Readings should be taken at ambient conditions and at BHCT when possible. Measurements should be limited to a maximum speed of 300 rpm. Readings should also be reported at 200, 100, 60, 30, 6 and 3 rpm (Ogbonna, 2009).

5.5 New slurry techniques

Fibre-reinforced cement slurry – has proved to be useful in geothermal wells. The fibres have been shown to improve cement toughness as a result of improved interfacial shear strength between the hydrated cement and fibre. It is important for the cement sheath placed in a well to maintain good structural performance and sealing capacity throughout the lifetime of the well. Fibre-reinforced cements are able to withstand higher tensile stresses than conventional cements. Experience from practical applications has shown that significant improvements in the mechanical properties of cementitious materials can readily be achieved by incorporation of fibres. Fibre reinforcement increases tensile strength and strain capacity, flexural and shear strength, ductility, toughness, and resistance to cracking induced by thermal effects, shrinkage or other causes. Furthermore, fibres act to arrest crack growth and transfer stresses across cracks. In general, the properties of fibre-reinforced materials are dependent on the physical and mechanical properties of the fibres, fibre length and volume fraction, interfacial bond strength, orientation of fibres and aspect ratio. In the case of geothermal cements, fibres added for reinforcement are also required to demonstrate durability and thermal compatibility in the well environment (Berndt and Philippacopoulos, 2002). In their studies of investigating different types of fibres, Berndt and Philippacopoulos evaluated different types of fibres with the objective of identifying systems offering the greatest improvement in cement tensile strength. The fibres investigated included steel, stainless steel, carbon, basalt and glass. The baseline cement matrix was standard Class G cement/40% silica flour. Variations on this were latex-modification and lightweight formulations incorporating either perlite or microspheres. The fibres that showed the best performance at low volume fraction were 13 mm brass-coated round steel fibres. Steel and carbon micro-fibres also improved the tensile strength, provided the volume fraction was high enough.

Hollow microspheres slurry – has a low specific gravity and can withstand high pressures. This allows the use of cement designs that can maintain low density at high pressures and still develop relatively high compressive strength over a broad temperature range. Density as low as 0.96 g/cm^3 can be obtained with microspheres (Nelson, 1990). However, the microspheres are expensive and when used in high enough concentrations, can require special bulk handling and mixing equipment to maintain a consistent slurry density. Also, the slurry rheology has to be carefully controlled to prevent the spheres from floating (Niggemann et al., 2010).

Foamed cement slurry – is a mixture of cement slurry, foaming agents and a gas. Foamed cement is created when a gas, usually nitrogen, is injected at high pressure into base slurry that incorporates a foaming agent and foam stabilizer. Nitrogen gas can be considered inert and does not react with or modify the cement-hydration product formation. Under special circumstances, compressed air can be used instead of nitrogen to create foamed cement (Crook, 2006). The small, fine foam bubbles are believed to promote stronger cement walls around the bubbles and to provide a set cement of increased integrity. It generates discrete, non-interconnected pore spaces in cement slurry as shown in Figure 23. Such integration of discrete pore spaces reduces the density of the cement slurry. When properly executed, the process creates stable lightweight slurry, with low permeability and relatively high compressive strength compared to conventional cements. Although the discrete pore spaces created by nitrogen will be compressed with pressure increases, they will not disappear like microspheres, which have a depth/pressure limitation; some spheres will crack and lose their ability to lighten the slurry when exposed to pressures higher than their pressure rating (Niggemann et al., 2010). Foamed cement is less expensive than microspheres and the slurries are easier to design. In addition, with foamed cement, densities as low as 0.42 kg/l can be obtained (Nelson, 1990).

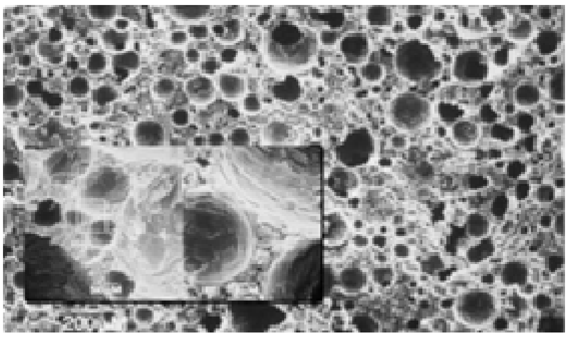

FIGURE 23: Foamed cement sample (Niggemann et al., 2010)

6. CEMENTING JOB

6.1 Pre-job preparation

To obtain a good cement job, it is important to be familiar with the wellbore conditions, design, materials and equipment available, try to think of unexpected LOC zones and how to react without delay. When cementing has started, there is not much time to do calculations, so be well prepared for unexpected events. The following are the preparations that need to be done before cementing job execution (Bush and O'Donnell, 2007; Drilling and Completion Committee, 1995):

1. Obtain the following information: hole depth, hole size with caliper data and required excess factor, casing information (length, size and weight), drill pipe information (length, size and weight), shoe track dimensions, length of rat hole, BHCT, BHST, any special well problem (lost circulation, salt sections, etc.) and any other pertinent information.
2. Determine the required amount of dry cement or blend, total mix water, liquid additives (if any), displacement volume and the resultant mix fluid volume.
3. Calculate the pump rates, surface and bottom-hole pressures during the job, mixing time, job time, and any other relevant information.
4. Calculate also the hydraulic lifting force that the casing string will experience just before the plug is pumped. This is the moment of maximum differential pressure.
5. Physically confirm that all the required equipment and materials (including mix water quantities) have been delivered to the location.
6. Sometimes, cement blowing and sieving between silos is required and should be done prior to the job.
7. Service company engineers and company representatives should independently recalculate the slurry volumes and displacements required. Changes to the original job program should be mutually agreed to and verified.
8. Service company engineers and company representatives should also review the laboratory blend results, paying special attention to the thickening time and the required WOC. Check whether the available pumping time as indicated by the lab thickening time test result is sufficient for the planned job.
9. Develop a pumping schedule based on the cement job simulator output.
10. Prepare a job plan that includes the following: rig up procedure, safety concerns, pressure testing procedure, spacer type, density and volumes to be pumped, wiper plug, dart/ball dropping sequence and procedure, conversion factors for calculating sacks per unit volume of slurry, and unit volume of slurry per unit volume of mix water, personnel requirements for the job, and contingency plans for the unexpected (float equipment failure, loss of returns while running in casing).
11. Rig up cementing equipment on location and discuss post job wash-up procedures and disposal.
12. The company representative should witness the installation of the float equipment and ensure that casing centralizers are placed according to the centralizer program.
13. The company representative should also witness the pre-loading of top and bottom plugs into the cementing head.
14. Complete the hook up of all equipment. As soon as the casing is landed, rig cementing head to casing and begin circulation to condition the well.

6.2 Cement job execution

It is important to have a clear and simple written plan and for all cementing personnel to know the procedure. During cementing, communication is often difficult due to noisy equipment and stress. The following is a general procedure to be followed during job execution (Bush and O'Donnell, 2007; Drilling and Completion Committee, 1995):

1. Conduct a safety meeting on the location with the cementing crew, company representative and the rig personnel who will be involved with the job; review the job procedures, safety procedures, and assign support responsibilities.
2. Pressure-test all high pressure lines and the cementing manifold with water or spacer prior to pumping any fluid into the casing and reconfirm the maximum allowable pressures. Test pressure should be at least 69 bars (1000 psi) above maximum anticipated pumping pressure during cementing operations. Note: the cementing head is usually the weakest link during a cementing operation and it should be noted that the cementing head maximum working pressure is often below the casing burst pressure.
3. Pressurize the bulk cement tanks.
4. Use a data acquisition system to record pumping rate, density and volumes pumped during the cementing job.
5. Start the pumping operation by establishing circulation from the cement equipment. Observe mud tanks or pits for returns.
6. Pump water (spacer) which is meant to minimise contamination of cement slurry by the mud in the annulus. The spacer should occupy 100 m of the annulus so as to provide sufficient separation of mud and cement in the annulus; 3-8 m^3 of spacer is common.
7. The water spacer is followed with either 1.5 m^3 of high density polymer (water mixed with viscosifying polyacrylamide polymer – 5-10 kg/m^3) or 4.0 m^3 of scavenge cement slurry with a density of 1.2 kg/l (10 ppg).
8. Mix and pump cement slurry as per design densities and rates. The pumping rate is 0.8-1.0 m^3. Measure and record the mix water and check electronic density measurements against the pressurized mud balance measurements.
9. Collect samples of the dry blended cement and mix water as mixing progresses. Samples must be taken in clean, well marked containers and stored securely at proper temperatures should they be required for post job evaluation.
10. Take slurry samples during the job. Do not use the setting of the surface samples as a guide to cement working time or drill out times. They do not accurately reflect the downhole condition of cement during or after placement.
11. Observe the well for returns during the entire cementing process. If possible, record the volume and densities of the returns.
12. Do not maintain the designed downhole rate at the expense of slurry density. If the density cannot be controlled within the acceptable limits (±25 kg/m^3 or ±0.25 ppg), the pump rate needs to be adjusted until the slurry density control is acceptable.
13. Switch to water without shutting down and try to maintain a steady pump rate throughout the displacement. Note:
    a) Depending on the pump rate, additional pressure may be required to overcome friction pressure. These pressures are calculated to determine the type of pump required, to ensure that the cementing head is adequate and that there is no danger of bursting the casing.
    b) To ensure the safety of the well, it is necessary to determine if it is likely that the well will flow or be fractured during or after the cement placement. This is done by calculating the hydrostatics at the critical points in the wellbore.
14. Bleed off the pressure. Check if the plug holds. If it does not, leave the casing valve closed to provide a hydraulic lock. Bleed off the pressure every two hours until the cement is set or fluid stops flowing out of the casing.
15. Apart from parameters recorded in 4 above, also record the following events: pressure test (psi) and time, start time for the job, start and stop time for each fluid pumped, start of displacement and any observed pressure.
16. Wait on cement for 20-24 hours before drilling. This is required in order that the cement anchors the pipe and withstands the shocks of subsequent operations.
17. Store two of the samples at hole temperature to see when they harden.

6.3 Post-job cement evaluation

To obtain a good cement bond, the annulus has to be filled to the surface by well designed cement slurry, based on wellbore conditions. There has to be an excellent bond between casing and cement and between the cement and the formation. A primary cement job can be considered a failure if the cement does not isolate undesirable zones. This will occur if:

- There are water pockets in between casings;
- The cement does not fully fill the annulus;
- The cement does not provide a good seal between the casing and borehole and fluid leaks through the cement sheath to the surface;
- The cement does not provide a good seal at the casing shoe or a poor leak-off test is achieved.

When any of the mentioned failures occur, a remedial job, such as squeeze cementing, may be carried out. The main method used to assess the effectiveness of the cement job is the acoustic log. Other methods like a temperature survey and a radioactive survey exist but are rarely used in geothermal wells.

6.3.1 Acoustic logs

There are two types of acoustic logs, namely: the cement bond log and the variable density log and they are usually done together. The acoustic properties of cemented casing are influenced by the quality of bond from casing to cement.

Cement bond log (CBL) **–** is a recording of the amplitude of the first arrival of energy on the 1 m (3 ft) receiver as shown on the CBL tool in Figure 24. They not only detect the top of the cement, but also indicate how good the cement bond is. The CBL tool is basically a sonic tool which is run on a wireline. The distance between transmitter and receiver is about 1 m.

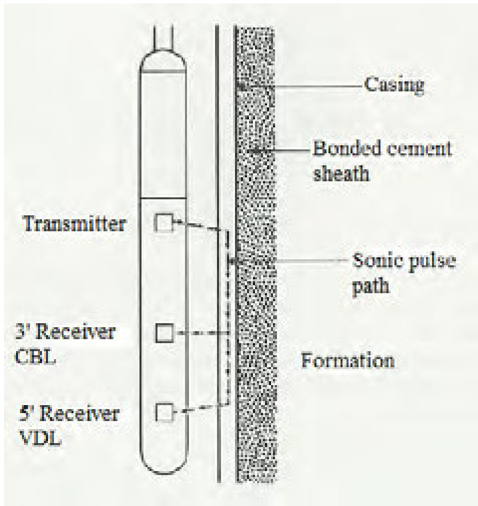

FIGURE 24: CBL tool (Weatherford, 1986)

The logging tool must be centralized in the hole to give accurate results. Both the time taken for the signal to reach the receiver, and the amplitude of the returning signal, give an indication of the cement bond. The speed of sound is greater in casing than in the formation or mud and therefore the first signals which are received at the receiver are those which travelled through the casing (Figure 25). If the amplitude (E1) is large (strong signal) this indicates that the pipe is free (poor bond). When cement is firmly bonded to the casing and the formation, the signal is attenuated, and is characteristic of the formation behind the casing.

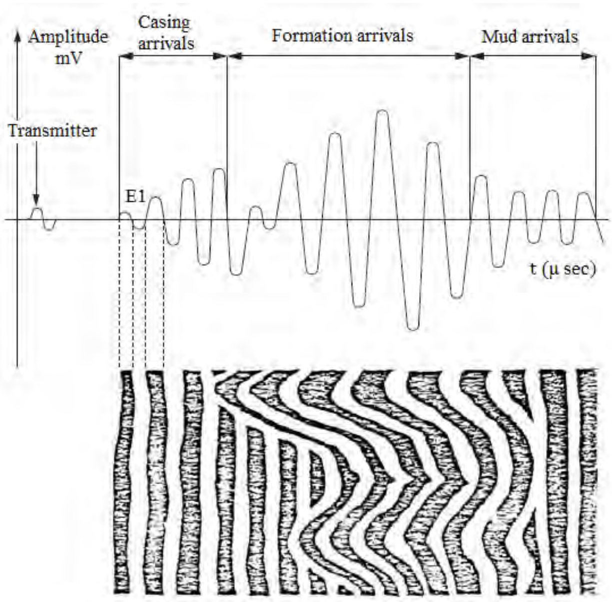

FIGURE 25: Receiver signals (Heriot-Watt University, 2010)

Variable density log (VDL) **–** is optional and supplements the information given by CBL. It is a full-wave display of the 5 feet receiver signal. The CBL log usually gives an

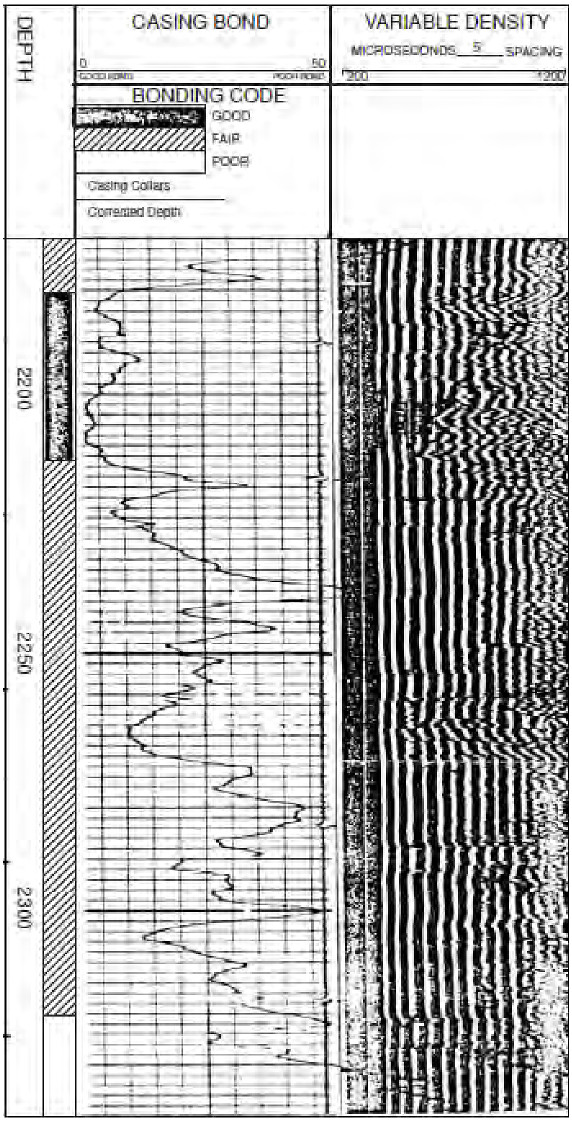

FIGURE 26: CBL/VDL plots (Heriot-Watt University, 2010)

amplitude curve and provides an indication of the quality of the bond between the casing and cement. On the other hand, VDL provides the wave train of the received signal and can indicate the quality of the cement bond between the casing and cement, and the cement and the formation. The signals which pass directly through the casing show up as parallel, straight lines to the left of the VDL plot. Figure 26 shows the difference in CBL and VDL logs. A good bond between the casing and cement and cement and formation is shown by wavy lines to the right of the VDL plot. The wavy lines correspond to those signals which have passed into and through the formation before passing back through the cement sheath and casing to the receiver. If the bonding is poor the signals will not reach the formation and parallel lines will be recorded all across the VDL plot.

It is recommended that a CBL log not be run until 24-36 hours after the cement job since cement setting affects velocity and amplitude signals.

6.3.2 Leak-off test

It is important to have competent rock at the shoe casing. A pressure test is done by drilling out the shoe into a new formation (usually 3 m of a new formation), then applying a pressure gradient above hydrostatic pressure to the wellbore. It evaluates the well's ability to withstand high pressures without breaking down the formation or the cement around the casing and is the basis of establishing the temperature to which the well can be drilled without setting another casing string. Clearly, if there is no competent rock around the shoe, the wellbore will not be able to withstand a high pressure gradient and the ability to advance the well to the desired depth/temperature will be compromised.

7. OTHER CEMENTING TECHNIQUES

7.1 Healing circulation losses during drilling by cementing

Many geothermal wells have to be drilled through fracture formations. Loss of drilling mud or any other fluid put into the hole usually occurs, creating problems which are expensive to eliminate. LOC during drilling can be obtained either by measuring the difference between the total drilling fluid pumping rate and the returns flow measured in the flow line, using magnetic or sonic flow-meters or by stopping the filling of the mud tanks and measuring the change in drilling fluid volume over a certain time interval (sometimes 15 min). Circulation losses measurement should be done after every 4 hours of drilling. It should be noted that it is not possible to measure losses during aerated drilling and if losses have to be measured, aerated drilling has to be stopped for a moment and measurement done.

LOC is the primary problem in geothermal drilling and cementing and it is common to deal with much higher LOC than in oil drilling. If the rate of returns becomes smaller and smaller until the mud loss approaches 5 l/s, the normal procedure is to add LCM to the mud and hope that full returns can be achieved. Quite often, this is unsuccessful. If circulation losses encountered cannot be regained with LCM, drill blind with water and high viscosity gel sweeps at every connection or more frequently depending on the hole conditions. When drilling blind, the build up of cuttings should be monitored. If the total loss of circulation is experienced and persists, drilling has to be stopped and the loss zone cemented after drilling a 30 m rat hole by placing a cement plug. Wait 4 hours before trying to fill the hole. This allows the cement slurry time to thicken and become more resistant to flow when subjected to an increased hydrostatic head. After waiting for 4 hours, an attempt is made to fill the hole, pumping 15% more than required without getting returns. The decision has to be made whether to wait longer or do a second job. Normal practice in geothermal well lost circulation cement plug jobs is to do a second job when unable to fill the hole following the first job. The second job is done similar to the first, only waiting longer for the cement to set. Eight hours following the second job, the hole is filled and the drill pipe lowered to tag on hard cement (Shyrock and Smith, 1980). Cementing LOC zones may often be unsuccessful if the cement cannot bond well with the walls and can shave off during further drilling. Thus, it is advantageous to put a colour identifier in the cement to identify different LOC cement jobs and know which one is breaking down.

When cement has proven unsuccessful as a cure for lost circulation during drilling, it is time to consider a new approach. This would involve pumping another material into the hole ahead of the cement. One such material is Halliburton's Flo-Chek chemical. It is a colourless liquid that instantly forms a stiff gel sealing off lost-circulation zones by blocking flow channels and fractures and also helps prevent slurry migration down away from the plug location. The procedure would then be to pump some water through the open-ended drill pipe as near the lost circulation zone as possible, following it with 4-8 m^3 of LCM material. A 0.8-1.5 m^3 spacer of fresh water should follow the LCM material, then 3-6 m^3 of cement slurry. Displace with water until the LCM material has been displaced from the drill pipe. Then pull the drill pipe above the cement and circulate at a low pressure to fill the hole. If returns are obtained, the cement needs 8-10 hours to harden (Shyrock and Smith, 1980).

7.2 Cement plugs

At some stage during the life of a well, a cement plug may have to be placed in the wellbore. It involves the placement of a relatively small amount of cement slurry inside an open hole or inside a casing. The main reasons for setting a cement plug are:

- To seal off lost circulation zones;
- To sidetrack above a fish or to initiate a sidetrack;
- To plug back a zone or abandon a well;
- To isolate a zone for formation testing.

The two common techniques for setting a cement plug are the balanced plug and the dump bailer.

7.2.1 Balanced plug technique

This method aims at achieving equal height of cement in both the drill pipe (stinger) and annulus. This is to ensure that the hydrostatic pressures inside the drill pipe and annulus are exactly the same. If the heights are not the same then a U-tube effect will take place and as a result, will lead to contamination of the cement slurry. The stinger length should be the plug length (150 m plugs are common) plus 30 m. The setting procedure, as illustrated in Figure 27, is as follows (Rabia, 2001):

a) Run the stinger to, say, 90 m below the bottom setting depth for the plug.
b) Spot a viscous mud pill having the same density as the mud in hole. The volume of the pill should be sufficient to cover the 90 m interval. A pill is not required if the cement plug is to be set on the bottom, or on top of a bridge plug (cement retainer).
c) Pull the stinger back to 90 m.
d) Pump a 1.5-3.0 m^3 spacer (pre-flush). The exact volume will depend on the hole size. Pump a sufficient volume of slurry for the 150 m plug or as specified in the drilling program. The slurry should be displaced at maximum rate. The rate should be slowed down to around 0.3 m^3/min when the cement is 1.5-3.0 m^3 away from the ported sub in the stinger and kept at this rate.
e) Pump sufficient spacer behind the cement to balance the pre-flush.
f) Displace the mud to the balanced position.
g) Pull back slowly to at least 150 m above the top of the plug and reverse circulate clean.
   Note: If a series of plugs are to be set on top of each other, then reverse circulate immediately above the bottom plug before attempting to set the next plug.
h) The drill pipe can then be pulled out of the hole.

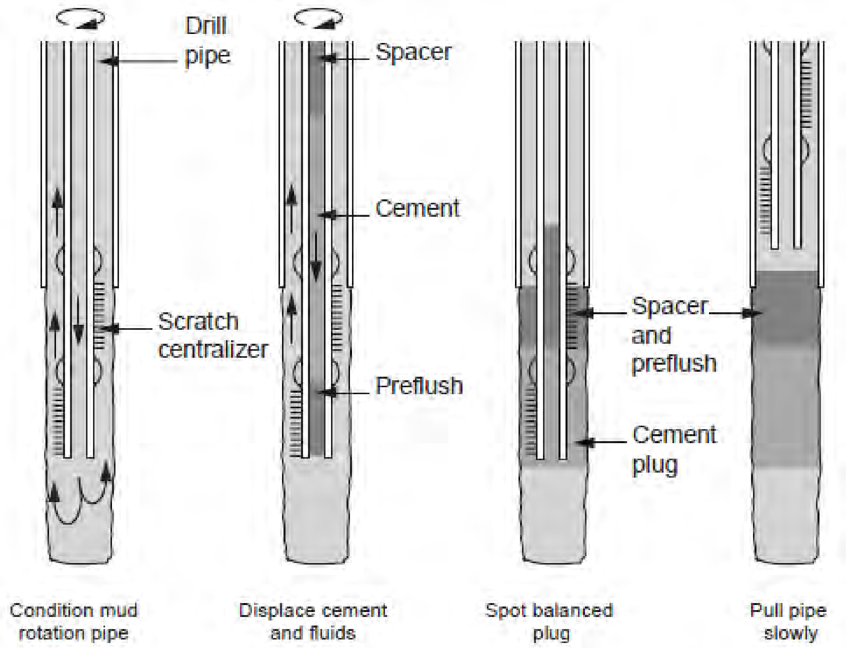

FIGURE 27: Balanced plug method (Rabia, 2001)

The calculation on plug balancing is shown in Section 8.4.

7.2.2 Dump bailer technique

The dump bailer technique, shown in Figure 28, allows the placement of a cement plug by wireline techniques. A permanent bridge plug is set below the required plug back depth. A cement bailer containing the slurry is then lowered down the well on wireline. When the bailer reaches the bridge plug, it is opened electrically or mechanically and the slurry is released and sits on top of the bridge plug. The advantages of this method are that the depth control is good; it reduces risk of slurry contamination and is a relatively fast and inexpensive means of setting a plug. The disadvantage is that only small volumes can be set due to the limited capacity of the bailer and it is also not suitable for deep wells unless retarders are used.

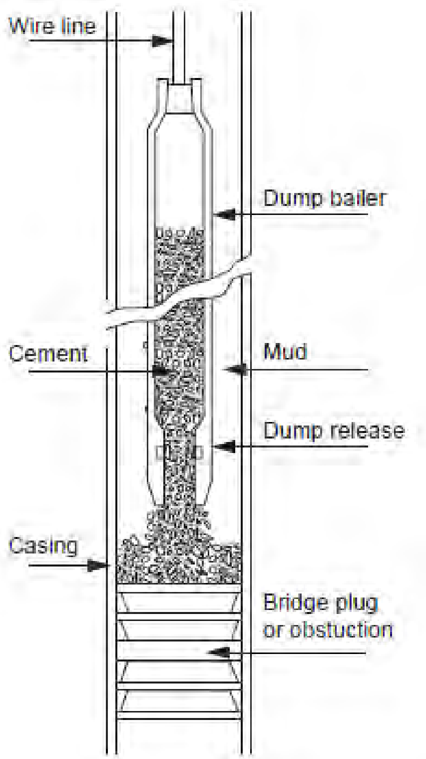

FIGURE 28: Dump bailer method (Heriot-Watt University, 2010)

8. CEMENTING CALCULATIONS

8.1 Case studies – single stage cementing and inner string cementing

In this section, two scenarios are shown in order to understand the calculations for both the single stage cementing technique used in Kenya and the inner string cementing technique commonly used in Iceland. Cementing of the anchor (intermediate) casing is shown for both methods.

8.1.1 Well OW-910 in Olkaria Domes field, Kenya – Single stage cementing

Well OW-910 anchor casing, 13⅜" was cemented in place with a single stage cementing operation. The details of the operation, as shown in Figure 29, are as follows:

Casing: 13⅜" 54.50 lb/ft, K-55 casing set at: 294.7 m
Drill bit: 17½" hole depth: 296.3 m
Previous casing: 20" 94 lb/ft
Previous casing shoe depth: 51.2 m

The casing was cemented with Portland class A cement with the following specifications and additives:

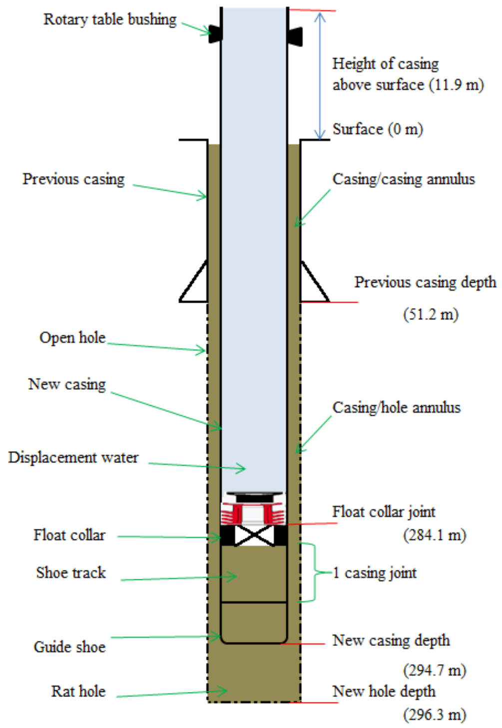

FIGURE 29: Well OW-910 anchor casing

Slurry density:	1.7 kg/l (14.4 ppg)
Slurry yield:	901 l/ton of cement
Water requirement:	550 l/ton of cement blend
Thickening time (70 Bc):	261 min

Additives (dry) BWOC: LCM – mica flakes (3.0%), lightweight – Wyoming bentonite (2.0%), fluid loss control (0.3%), friction reducer (0.3%) and retarder (0.3%).

A. Slurry volume calculation, V_s

The total slurry volume V_s needed is shown as brown in Figure 29. It is calculated by splitting the volume in few steps and then calculating an excess on the volume in the open hole section, where dimensions are not as well known due to hole enlargement:

$$V_s = V_{shoetrack} + V_{rathole} + V_{openhole} + V_{csg} + V_{excess} \quad (1)$$

where $V_{shoetrack}$ = The cement volume left inside the casing below the float collar;
$V_{rathole}$ = The cement volume in the open hole below the guide shoe;
$V_{openhole}$ = The cement volume in the annulus between the casing and the hole wall (up to the previous casing shoe).
V_{csg} = The cement volume in the annulus between the casing and the previous casing;
V_{excess} = The excess added for the uncertainity of the open hole volume.

The volume, V, in l/m of annular space may be calculated using (Gabolde and Nguyen, 2006):

$$V = 0.0007854\,(D_o^2 - D_i^2), \text{ where } D \text{ is in mm} \quad (2a)$$

or

$$V = 0.5067\,(D_o^2 - D_i^2), \text{ where } D \text{ is in inches} \quad (2b)$$

Capacities are as follows:

Casing capacity (13⅜"):	80.64 l/m;
Casing displacement (13⅜"):	90.65 l/m;
(Note: that the steel volume is equal to the difference in the numbers above)	
Capacity of open-hole (17½"):	155.18 l/m;
Annulus capacity - open hole and casing:	64.53 l/m.

$V_{shoetrack}$ = 80.64 l/m × (294.7 m – 284.1 m) × 1 m^3 / 1000 l = 0.9 m^3
$V_{rathole}$ = 155.18 l/m × (296.3 m – 294.7 m) × 1 m^3 / 1000 l = 0.2 m^3
$V_{openhole}$ = 64.53 l/m × (294.7 m - 51.2 m) × 1 m^3 / 1000 l = 15.7 m^3

Capacity of previous casing (20"):	185.32 l/m
Casing displacement (13⅜"):	90.65 l/m
Capacity of casing annulus:	94.7 l/m

V_{csg} = 94.67 l/m × 51.2 m × 1 m^3 / 1000 l = 4.9 m^3

Safety excess factor of 50% on an open hole is used (a rule of thumb where no caliper measurements are available), hence:

Calculated volume:	
Shoe track, $V_{shoetrack}$:	0.9 m^3
Rat hole, $V_{rathole}$:	0.2m^3
Open-hole annulus, $V_{openhole}$:	15.7 m^3
Casing annulus, V_{csg}:	4.9 m^3
Calculated volume:	21.7 m^3

V_{excess} = 16.8 m^3× 50% = 8.4 m^3

50% safety margin in open hole	8.4 m^3
Total slurry volume, V_s:	30.1 m^3

B. Displacement volume
This is the internal volume of casing between the cement head and the float collar (shown in blue in Figure 29):

Therefore displacement vol. = 80.64 l/m × (284.1 m + 11.9 m) × 1 m^3 / 1000 l = 23.9 m^3

C. Placement duration, T_p
Slurry pump rate used = 900 l/min
Displacement rate = 900 l/min

$$T_p = \frac{vol.of\ slurry}{pump\ rate} + \frac{displ.\ vol.}{displ.\ rate} + plugs\ drop\ time + contingency\ time \qquad (3)$$

Duration (min):	
Slurry mixing and pumping:	33
Displacement time:	27
Plugs dropping time:	15
Contingency time:	60
Total placement duration:	135 min

D. Pump pressure to land the plug, P_p

$$P_p = hydrostatic\ pressure\ outside\ casing - hydrostatic\ pressure\ inside\ casing \quad (4)$$

Density of cement slurry:	1.7 kg/l
Density of fluid inside the casing:	1.0 kg/l
Collapse pressure limit for casing:	7.8 MPa (78 bars)

Hydrostatic pressure (Pa):

$$P_h = \rho g H \quad (5)$$

Hydrostatic pressure outside the casing:	49.7 bars
Hydrostatic pressure inside the casing:	30.8 bars
Pressure to land plug (excluding friction pressure):	18.9 bars

E. Amount of cement blend and mix-water

$$Amount\ of\ cement\ blend = \frac{Slurry\ volume}{Slurry\ yield} \quad (6)$$

Therefore, the amount of cement blend = 33,074 kg

$$Mix\ water = water\ requirement\ per\ ton\ of\ blend \times amount\ of\ cement\ blend \quad (7)$$

Therefore, mix-water required = 18.2 m^3

8.1.2 Well HE-53 in Hverahlid field, Iceland – Inner string cementing

Well HE-53 anchor casing, 13⅜" was cemented in place with an inner-string cementing operation. The details of the operation, as shown in Figure 30, are as follows:

13⅜" 68.0 lb/ft casing set at:	302.5 m
17½" hole depth:	304.5 m
18⅝" 87.5 lb/ft previous casing shoe depth:	69.0 m
Cement. string (drill pipe) nominal size:	5", 19.5 lb/ft

The casing was cemented with class A cement with the following specifications and additives:

Slurry density:	1.67 kg/l
Silica (Sibron M-300):	40% BWOC
Lightweight agent, perlite:	2% BWOC
Bentonite (Wyoming):	2% BWOC
Retarder:	0.5% BWOC

A. Slurry volume calculation

Capacities are as follows:

Casing capacity:	78.1 l/m
Capacity of open hole:	155.2 l/m
Annulus capacity – open-hole and casing:	64.5 l/m
Capacity of casing/casing annulus:	69.1 l/m
Capacity of the drill pipe:	9.1 l/m

The volume of the hole was measured using a caliper log as shown in Figure 31. The volume obtained with the caliper log was 26.1 m^3. To get the open-hole volume, the volume between the casing string is subtracted from the caliper log volume.

A 20% safety excess factor is used in the open hole section with a caliper log measurement (a rule of thumb where a caliper measurement is available).

	Caliper vol. (m^3)	*Calculated vol. (m^3)*
Shoe track:	1.6	1.6
Rat hole & casing/open hole:	21.3	15.4
Casing/casing annulus:	4.9	4.9
Total volume:	27.8	21.9
20% and 50% excess respectively:	4.3	7.7
Total slurry volume:	32.1 m^3	29.6 m^3

In this case, the rule of thumb method works well comparing with and without a caliper log. Caliper logs should be used because the hole washout and caving can sometimes be excessive and thus an excess factor based on local and previous wells should be used if available.

B. Displacement volume
This is the internal volume of a drill pipe between the rig floor and the stab-in collar.

Therefore displacement vol. = 2.64 m^3

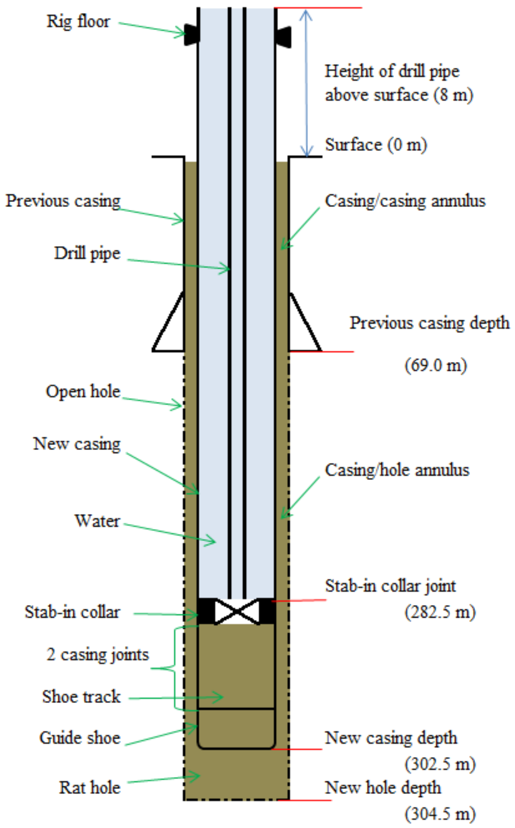

FIGURE 30: Well HE-53 anchor casing

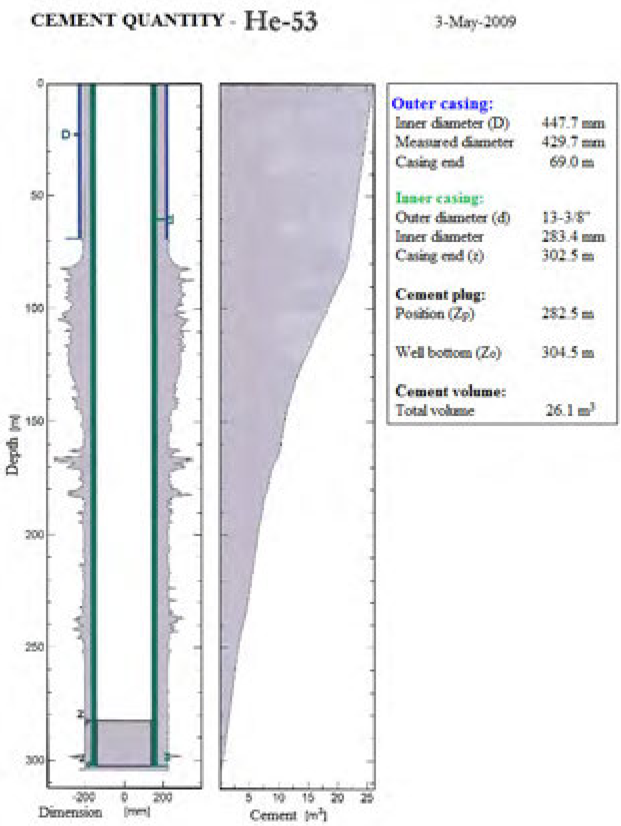

FIGURE 31: Well HE-53 caliper log

C. Placement duration, T_p

Slurry pump rate used = 1000 l/min
Displacement rate = 1000 l/min

$$Tp = \frac{vol.of\ slurry}{pump\ rate} + \frac{displacement\ vol.}{displacement\ rate} + contingency\ time \quad (8)$$

Duration (min)	
Slurry mixing and pumping:	32
Displacement time:	3
Contingency time:	60
Total placement duration:	95 min

Note: The displacement time is much shorter in inner string cementing compared to single stage cementing which in turn leads to reduced placement duration.

D. Maximum pump pressure at surface, P_a

$$P_a = casing\ collapse\ pressure\ limit - differential\ hydrostatic\ pressure\ at\ collar\ joint \quad (9)$$

Density of cement slurry:	1.67 kg/l
Density of fluid inside the casing:	1.0 kg/l
Collapse pressure limit for casing:	13.4 MPa (134 bars)

It is necessary to have the casing full of water/mud at all times during a cementing operation to minimise chances of collapsing the casing. The weakest point in the casing and the most susceptible to collapse is the stab-in collar joint. Using Equation 5:

Pressure (bars)	
Pressure from cement slurry at the collar joint:	46.3
Pressure from fluid inside casing at collar joint:	28.5
Differential pressure at collar joint:	17.8
Collapse strength of casing:	134.0
Maximum pump pressure at surface:	116 bars

*Note: D*ue to the friction in the drill pipe string, the downhole pressure will be lower.

8.2 Cement slurry design

Cement slurry is to be prepared using Class A cement and fresh water using the following dry-mixed additives BWOC: 40% silica flour, 2% bentonite, 2% perlite and 0.5% HR-12 retarder. The cement slurry density, water volume and slurry yield is calculated for 100 kg of cement.

Slurry density d is given by:

$$d = \frac{mass\ of\ (cement + water + bentonite + silica + perlite + retarder)}{volume\ of\ (cement + water + bentonite + silica + perlite + retarder)} \quad (10)$$

The specific gravities of cement, bentonite, silica flour, perlite and HR-12 retarder are 3.14, 2.65, 2.63, 2.2 and 1.22, respectively (Bourgoyne Jr. et al., 1991). Using the materials' specific gravities in Equation 10, slurry density, *d,* is then given by:

$$d = \frac{100 + e + (Z+1)b + (Y+1)s + (X+1)p + r}{\frac{100}{3.14} + \frac{e}{1} + \left(Z + \frac{1}{2.65}\right)b + \left(Y + \frac{1}{2.63}\right)s\ \left(X + \frac{1}{2.2}\right)p + \frac{r}{1.22}} \quad (11)$$

Water volume, *E* is given by:

$$E = e + Zb + Ys + Xp \quad (12)$$

Note: There is no water requirement for HR-12 retarder (Bourgoyne Jr. et al., 1991).

Slurry yield v is given by:

$$v = \frac{100}{3.14} + \frac{b}{2.65} + \frac{s}{2.63} + \frac{p}{2.2} + \frac{r}{1.22} + e + Zb + Ys + Xp \tag{13}$$

Data values are as follows:

e = 46 l for class A cement
Z = 5.3 l per kg of bentonite when dry mixed (Gabolde and Nguyen, 2006)
Y = 0.4 l per kg of silica
X = 7.8 l per kg of perlite (Bourgoyne Jr. et al., 1991).

Equations 11, 12 and 13 give the following solutions for 100 kg of cement:

Slurry density, d = 1.69 kg/l; Water volume, E = 88.2 l; Slurry yield, v = 137.3 l.

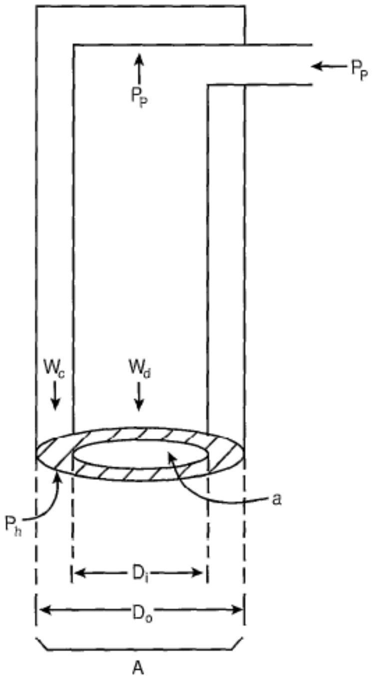

FIGURE 32: Forces acting on casing while cementing (Nelson, 1990)

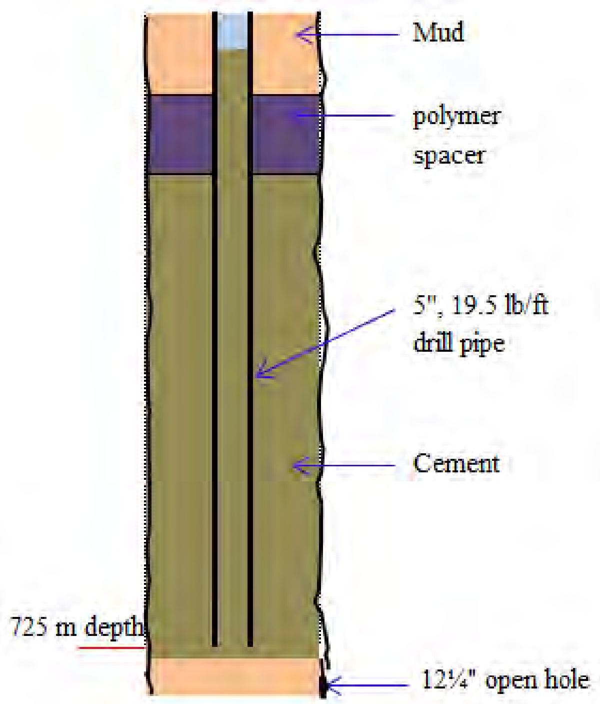

FIGURE 33: Balanced plug

8.3 Pressure to lift the casing

There may be danger of the casing being pumped out of the well, especially surface and intermediate (anchor) casing. Conditions which favour such an occurrence include: lightweight casing, short casing string length, large-diameter casing, high-density slurry, low-density displacement fluid and high annular friction pressures. The forces acting on the casing while cementing are as shown in Figure 32. Under static conditions, differential pressure ΔF is given by:

$$\Delta F = (P_h \times A) - (W_c + W_d) \tag{14}$$

When pumping, the pressure acting on the cross-sectional area internal diameter (ID) must be added to Equation 14 as shown below:

$$\Delta F = [(P_h \times A) + (P_p \times a)] - (W_c + W_d) \tag{15}$$

If ΔF is positive, the casing may come out of the well. The value of P_p giving a ΔF value of zero is the critical pump pressure above which the casing may be pumped from the well. The cementing service crew should ensure that the pump pressure during cement placement does not exceed this value unless the casing is restrained (Nelson, 1990).

The case study in Section 8.1.1 for well OW-910 is used to check if there is danger of floating the casing out of the well: 13⅜", 54.50 lb/ft (79.5 daN/m) anchor casing which was set at 294.7 m depth with 1.7 kg/l cement slurry and 1 kg/l water for displacement, the float was set at 284.1 m. Casing external diameter (D_o) is 339.7 mm and internal diameter (D_i) is 320.4 mm. Under static conditions:

$$\Delta F = [1.72 \times 10^3 \times 9.81 \times 294.68 \times \pi/4 \times (339.7/1000)^2] - [((294.68 + 11.9) \times 79.5) + (1.0 \times 10^3 \times 9.81 \times (284.12 + 11.9) \times \pi/4 \times (320.4/1000)^2) + (1.72 \times 10^3 \times 9.81 \times (294.68 - 284.12) \times \pi/4 \times (320.4/1000)^2)] = 178 \text{ kN}$$

From the above calculations, it can be seen that the casing will come out of the well even in static conditions.

The pump pressure, P_p, to pump the plug as calculated in sub-section D of section 8.1.1 is 18.9 bars. Apart from the positive upward-acting differential force, with the pump pressure acting on the inside of the casing, the additional force due to pump pressure F_p is:

$$F_p = 152 \text{ kN}$$

Therefore, the total force, F_T, acting on the casing is:

$$F_T = 330 \text{ kN}$$

In this case, the total force acting on the casing while cementing is acting upwards and unless the casing is restrained, it could be lifted out of the well. The rheology of the slurry also creates friction to prevent the casing from moving up.

8.4 Cement plug balancing

A cement plug is required in a 12¼" open hole, as shown in Figure 33, with a length L of 90 m by use of a 5", 19.5 lb/ft drill pipe. The plug is to be set at 725 m depth as shown in Figure 33 and 1.5 m^3 of polymer spacer V_{sp1} (1.0 m^3 polymer and 0.5 m^3 water) is to be used as pre-flush ahead of the cement slurry.

Open hole capacity C_h:	76 l/m
Drill pipe capacity C_{dp}:	9.1 l/m
Length of drill pipe being used D:	733 m
Annulus capacity between drill pipe and open hole C_{an}:	63.4 l/m

The required volume of cement (V_{cmt}) is given by:

$$V_{cmt} = L \times C_h \tag{16}$$

Thus:

$$V_{cmt} = 90 \times \frac{76}{1000} = 6.84\ m^3$$

The length of the balanced plug Lp (with work string in place) is given by:

$$Lp = \frac{V_{cmt}}{C_{an} + C_{dp}} \tag{17}$$

Thus:

$$L_p = \frac{6.84}{\left(\frac{63.4}{1000}\right) + \left(\frac{9.1}{1000}\right)} = 94.3\ m$$

The displacement volume (V_d) is given by:

$$V_d = C_{dp} \times (D - L_p) \quad (18)$$

Thus:

V_d = 5.7 m^3

The following should be noted when placing a cement plug:

1. In practice, the cement is frequently slightly under-displaced from the balance point to allow cement slurry to fall while the pipe is being pulled, filling the space that was occupied by the drill pipe.
2. High density spacer (polymer) is pumped ahead of slurry and water spacer is used for displacement.
3. It is good to rotate the drill string while setting the plug to monitor that it is free.
4. There is a risk of cementing tubing getting stuck, especially when the duration of placement is longer. The use of drill pipe wholly as a cementing tubing is not recommended. In Iceland, 3½" fibreglass cementing pipes are being used at the lower portion of the cementing string which can be drilled out.

9. CONCLUSIONS

The main conclusions of this work can be summarized as follows:

- A good and sound cement sheath is achieved when the wellbore is well conditioned before running the casing. It must be ensured that drilling mud cake is removed as much as possible as this ensures proper bonding between the casing and formation.
- The casing string should be well centralized in the wellbore to attain a good cement sheath all around the casing. This will be achieved by ensuring the minimum stand-off of 70% in critical sections of the well.
- Bottom hole circulation temperature is very critical in the design of cement slurry and accurate prediction is necessary as it affects the slurry thickening time and rheology.
- The inclusion of silica flour in the design of cement slurry for geothermal wells ensures longevity of the well since it helps prevent strength retrogression which occurs when cement sheath is exposed to elevated temperatures of more than 120°C.
- The conditions encountered in the wellbore vary from one well to another and therefore pilot tests of cement slurry should be conducted for each cement operation.
- Cementing calculations have to be done cautiously, taking into consideration the experience of the field being drilled, to ensure that correct volumes are pumped to avoid cases of wet shoe that come as a result of over-displacement of cement. This also ensures that pressure limits are not exceeded resulting in burst casings or fractured formations.

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NOMENCLATURE

A = Cross-sectional area (m^2);
a = Cross-sectional area for casing ID (m^2);
b = Weight of bentonite per 100 kg of cement (kg);
csg = Casing;
d = Slurry density (kg/l);
Di = Inside diameter (mm);
Do = Outside diameter (mm);
e = Volume of cement hydration water in relation to cement (l);
g = Acceleration due to gravity (9.81 m/s^2);
H = Fluid column height (m);
p = Weight of perlite per 100 kg of cement (kg);
P_p = Pumping pressure (N/m^2);
P_h = Hydrostatic pressure of cement slurry (N/m^2);
r = Weight of retarder per 100 kg of cement (kg);
s = Weight of silica flour per 100 kg of cement (kg);
v = Slurry yield (l);
$V_{shoetrack}$ = The cement volume left inside the casing below the float collar
$V_{rathole}$ = The cement volume in the open hole below the guide shoe
$V_{openhole}$ = The cement volume in the annulus between the casing and the hole wall (up to the previous casing shoe).
V_{csg} = The cement volume in the annulus between the casing and the previous casing
V_{excess} = The excess added for the uncertainity of the open hole volume
V_s = Total slurry volume,.
Wc = Casing weight (N);
W_d = Weight of fluid inside casing (N);
X = Amount of water per kg of silica (l);
Y = Amount of water per kg of silica (l);
Z = Amount of swelling water per kg of bentonite (l);
ρ = Fluid density (kg/m^3).

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