MANAGEMENT PRESCRIPTIONS FOR THE DEVELOPMENT OF LAKE KIVU GAS RESOURCES

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PREPARED FOR:

Ministry of Infrastructure
Republic of Rwanda

and

Ministry of Hydrocarbons
Democratic Republic of the Congo

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List of Acronyms

BP	Basic Principle
GoR	Government of the Republic of Rwanda
GoC	Government of the Democratic Republic of Congo
IZ	Intermediate Zone
LRZ	Lower Resource Zone
MAR	Mandatory Administrative Requirement
MTR	Mandatory Technical Requirement
MWe	Megawatt of electrical power
PRZ	Potential Resource Zone
RZ	Resource Zone
URZ	Upper Resource Zone

1 Background

1.1 Origin and Purpose of this Document

To support initiatives to extract methane dissolved deep in Lake Kivu, a Workshop on Lake Kivu Monitoring was held in Gisenyi from March 25 to March 28, 2007. The main topic of the workshop was the monitoring of the lake necessary for maintaining public safety and the integrity of the lake's stability, ecology and gas resource while undertaking gas extraction operations. At the workshop it was realised that, to achieve these objectives, scientific-technical guidance was required for the concessioning, design and operation of gas extraction plants.

Thus, an Expert Working Group on Lake Kivu Gas Extraction was asked by the governments of the Republic of Rwanda and the Democratic Republic of the Congo to prepare the scientific-technical guidance contained in this document. The initial group was comprised of Klaus Tietze (PDT GmbH / Germany), Finn Hirslund (COWI A/S / Denmark) and Philip Morkel (MMR Gas Technologies Ltd / South Africa), with John Boyle (World Bank / USA) as coordinator. The group grew to include Alfred Wüest and Martin Schmid (both Eawag / Switzerland), and received important inputs from others along the way.

The working group started drafting this document based on initial proposals by Klaus Tietze, developed from his pioneering research on Lake Kivu. The group's work was supported by modelling work by Eawag, detailed technical analyses by COWI, and workshops in Kastanienbaum (October 2007) and Copenhagen (May 2008) hosted by Eawag and COWI, respectively. Group members have contributed their time *pro bono* to the development of this document, while the World Bank contributed the expenses for the Kastanienbaum and Copenhagen workshops.

The primary purpose of this document is to delineate basic principles for determining the size, number, location and design of extraction operations, and then to prescribe mandatory requirements and guidelines for any gas extraction operation. Before doing so, the document also outlines, in chapter 2, some larger considerations that need to be taken into account in the overall management of Lake Kivu gas resources. They provide a context for understanding the balance of the document. Overall, the document is intended for use by the governments of the Republic of Rwanda and the Democratic Republic of the Congo in ensuring the safe and environmentally sound extraction of methane from Lake Kivu for the benefit of their citizens.

This document is a consensus product of the Expert Working Group on Lake Kivu Gas Extraction that has gone through several iterations as new issues were raised, analyses were undertaken, and thinking has evolved. The working group believes it has defined a robust and supportable response to the scientific/technical challenges of harvesting Lake Kivu's gas resources, and input from others with substantial knowledge of the subject matter was then solicited in a peer review. This document has now been updated and finalised at a conference held in Copenhagen from May 13 to May 15, 2009. English was the working language when this document was established; and after completion it was translated into French. Although much effort has been spent on assuring a proper translation, in case of any doubt, the English version should be consulted.

1.2 Nature of the Basic Principles, Mandatory Requirements and Guidelines

The scientific understanding of the nature and behaviour of the lake and its gas resources will further develop with the commencement of methane extraction and the accompanying lake monitoring. Thus, the Basic Principles, mandatory requirements, and guidelines are intentionally conservative to ensure that the initial gas extraction operations cannot jeopardize public safety, the ecological integrity and stability of the lake, and the gas resource.

Adherence to the Basic Principles (BPs, chapter 3) is considered essential to safe gas extraction in the long term. The Mandatory Technical and Mandatory Administrative Requirements (MTRs and MARs, chapter 4), and Guidelines (chapter 5), applicable to individual extraction operations may require updating as knowledge and experience grow with continuing extraction and monitoring of the gas resource. As an example, Klaus Tietze is researching a concept for the removal of nutrients from the re-injection water to allow such re-injection into the upper zones of the lake. Should this research prove successful there may then be an opportunity to allow such partial re-injection as an environmentally safer response, if needed, to prevent the pushing-up of gradients.

While significant changes to the Mandatory Requirements and Guidelines are not expected, there may be the need to adjust the regulated depths for the extraction of gas-rich water, and the re-injection of degassed water, as well as densities of the re-injected water, over the decades.

A companion document "Methane from Lake Kivu - How to extract the gas and avert the dangers" provides reference technical information to assist with an appreciation of the nature of Lake Kivu and its gas resource, and the rationale for the basic principles, mandatory requirements, and guidelines.

1.3 Definition of Terms

<u>Lake Zones</u>

The four major depth zones in Lake Kivu are roughly depicted in *Figure 1: Vertical density profile in Lake Kivu (excluding pressure effect) and the associated definition of zones and of density gradients.*

Adjacent zones are separated by significant density gradients in which water parameters such as conductivity, density and gas concentrations change rather rapidly with depth. The depths specified in the definitions below are as measured in 2004.

Biozone:

This is the upper, oxygenated part of the lake water body, about 60 m deep, where algal biomass provides food for zooplankton and fish. This zone becomes practically homogenised during the dry season, and is strongly stratified during the rainy season when usually only the top 40 m contain oxygen. The lower limit of the Biozone is the top of a density gradient from 60 m depth to 120 m depth, with its centre at about 85 m depth.

At the top of the gradient below, the concentration of hydrogen sulphide is zero, while the concentrations of methane and carbon dioxide are very low, as in the Biozone. The concentrations of these gases increase with depth into the Resource Zone.

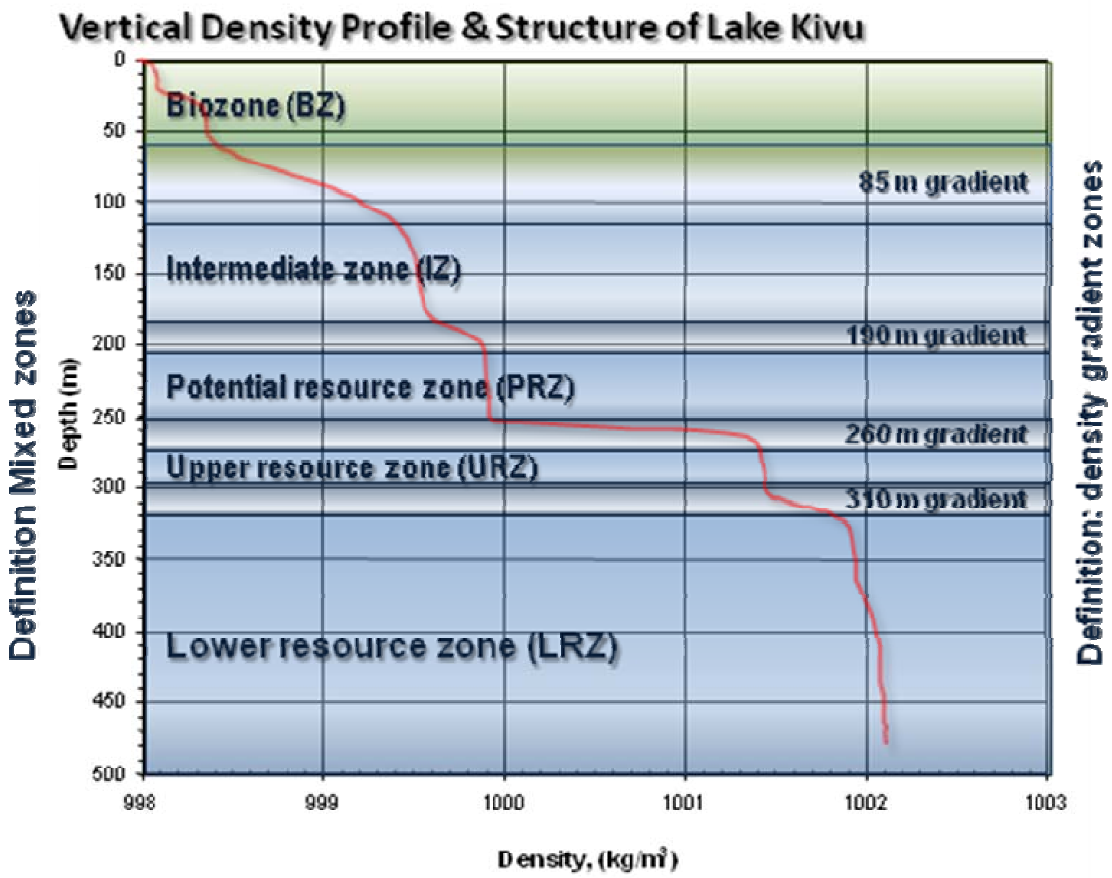

Figure 1 Vertical density profile in Lake Kivu (excluding pressure effect) and the associated definition of zones and of density gradients

Intermediate Zone (IZ):

The Intermediate Zone ranges from about 120 m depth to 180 m depth. Below it is a density gradient from 180 m depth to 200 m depth, with its centre at 190 m depth. The methane resources of this zone are not expected to be exploitable for many decades into the future, perhaps never.

Potential Resource Zone (PRZ):

This zone reaches from about 200 m depth to about 250 m depth. Below it, the main density gradient in the lake reaches from 250 m depth to 270 m depth with its centre at 260 m depth. Some of the methane in this zone may become exploitable within the next several decades if methane accumulation continues at the current rate, or increases further.

Resource Zone (RZ):

Below the main density gradient, the Resource Zone reaches from 270 m depth to the bottom of the lake, and contains the bulk of the methane which is commercially exploitable. In addition, it contains substantial amounts of carbon dioxide, nutrients and salts. Thus, Resource Zone waters are significantly denser (heavier) than the rest of the lake waters. The zone is differentiated into **Upper** and **Lower Resource Zones (URZ and LRZ)** by a secondary gradient between 300 m depth and 320 m depth with its centre at 310 m depth.

Technical Terms

The following technical terms are important to understanding and describing the structure and function of the lake:

Density Gradient:

In between the different relatively homogenous zones of the lake in which the water parameters do not change significantly with depth, there are transitional layers where parameters such as conductivity, density and gas concentrations change rather rapidly with depth. Dissolved gases (and nutrients and salts) largely remain trapped in the deeper lake below these density gradient layers thus building up an exploitable deposit. The different gradients may be named for their span from top to bottom (e.g. 60 m depth to 120 m depth) or by the depth of the centre of the gradient (e.g. 85 m gradient).

Partial Gas Pressure:

The pressure exerted by any single dissolved component gas. It is proportional to the concentration of the gas and is measured in bar or Pascal. The total gas pressure is thus the sum of the partial pressures exerted by all gases in solution. Since different gases have different solubility in water, the same concentration of different gases results in different partial pressures.

Total Relative Gas Pressure:

The total relative gas pressure is the total of the partial pressures of all gases at any given depth divided by the hydrostatic “in-situ” pressure at that same depth. It is most frequently expressed in percent or as percentage saturation.

Bilateral Regulatory Authority:

The institution to be established by the governments of the Republic of Rwanda and the Democratic Republic of the Congo to regulate the size, location, design, operation, and monitoring of gas extraction facilities.

2 Resource Management

A number of related matters concerning the overall management of the gas resources of Lake Kivu are outlined in this section. These matters are pertinent to how the Bilateral Regulatory Authority goes about concessioning gas extraction operations, to how individual operations are designed, and thus to the way the basic principles, mandatory requirements and guidelines are written.

2.1 Harvesting Strategy by Lake Zones

It is the consensus view of the Expert Working Group on Lake Kivu Gas Extraction that the development and behaviour of the density gradients in Lake Kivu are not sufficiently well-understood to confidently permit gas extraction operations that would deliberately cause substantial changes to the lake structure. Thus, a conservative or "safe side" harvesting strategy will, above all, avoid any actions that would predictably weaken or displace the existing density gradients and lake zones until knowledge about the lake is much better developed. See also the recommendations in Chapter 6.

Implementing such a strategy largely dictates the basic principles and mandatory requirements specified below. Overall, they prevent the transfer of lake waters between zones and, thus, (a) the transfer of salts upward across density gradients with a consequent weakening of lake stability, and (b) the transfer of nutrients into upper lake zones where they pose a risk to the ecology of the lake.

Resource Zone

An overall gas harvesting strategy must reduce the risk of uncontrollable gas outbursts, and thus target gas concentrations at depths where total gas pressures are closest to saturation. Currently, the main risk lies in the Resource Zone (RZ) just below the main density gradient at 270 m depth. Ideally, then, it would be best to extract gas-rich water from near the bottom of the lake and re-inject degassed water at 270 m depth and below the secondary gradient at 320 m depth, thus gradually depressing or "pushing down" the gas-rich waters to less risky depths.

However, since there is a secondary density gradient in the RZ between 300 m and 320 m depth, this approach risks over-diluting the methane in the Upper Resource Zone (URZ), now about one-third of all methane in the entire RZ. This dilution could reduce the methane concentration in the URZ to a level which cannot be extracted with present technology, and postpone gas recovery from the resource water currently in the URZ until it is pushed down to the intakes of the extraction plants. Even then, gas recovery from the diluted water may be problematic unless methane levels are replenished by natural recharge.

Thus, in order to maximize the initial gas production from the RZ while targeting the main risk area below the main density gradient, gas extraction should take place separately in the URZ and the LRZ. Because the URZ is relatively shallow, only smaller extraction facilities will be able to both extract gas-rich water from, and re-inject degassed water back into, the URZ while minimizing the possibility of short-circuiting between extraction and re-injection points. This approach is optimal for effective extraction, though it may turn out to be technically difficult to achieve. The following overall harvesting strategy is recommended for the initial harvest period.

Initial gas extraction operations of sufficiently small scale to avoid short-circuiting (say, about 5 MWe capacity each) should extract gas-rich water from, and re-inject degassed water back into, the URZ (Plan A1 as described in MTR3 below). These operations would thus harvest the methane in the URZ and gradually displace gas-rich water downwards with degassed water.

These small-scale operations would be complemented by potentially larger-scale operations that extract gas-rich water from the Lower Resource Zone (LRZ) and re-inject degassed water just below the secondary density gradient in the RZ (Plan A2, MTR4). These two approaches are complementary: Plan A2 operations must only be implemented if Plan A1 operations are working, and be limited to about half the total extraction rate of Plan A1 operations. Plan A2 operations may be built in larger modules than Plan A1 operations at locations where the lake is sufficiently deep. The complementary Plan A1/A2 operations would continue until the methane in the URZ has been reduced to below harvestable concentrations.

At a total gas production rate for the two countries that converts to about 500 MWe (at 40% efficiency), full implementation of Plan A1/A2 would take about 20 years. When the Plan A1/A2 strategy has run its course, or if it encounters severe technical limitations such as short-circuiting, gas extraction operations would change to extracting from the LRZ and re-injecting into the URZ (Plan B, MTR5).

It is expected that the maximum possible extraction of methane from the lake is achieved if Plan A1/A2 is fully implemented, and then Plan B is used for the rest of the high-rate extraction until the gas resource is depleted. When they are no longer useful for Plan A1 operations, some of the facilities may be able to be redeployed for gas extraction from the PRZ as this would be a relatively small piping modification to accomplish the change.

Concessionaires may apply to deploy variations to the above methods (such as the zone-mixing method) provided such a variation is initially tested at a limited capacity (nominally 5 MWe) and in relative isolation to other production plants.

<u>Potential Resource Zone</u>

At present, gas concentrations in the Potential Resource Zone (PRZ) are such that gas extraction is just about technically feasible, but not yet economically feasible. It is expected that gas concentrations in this zone will continue to rise and that gas extraction could be economically feasible, possibly within a couple of decades.

Provided that the uncertainty on the measurement and extent of rising density gradients, and the challenges they might pose are resolved (see Section 2.7 below), there remains ample time (around a century) before gas in this zone would accumulate to approach unacceptable levels of risk.

<u>Intermediate Zone</u>

With the presently known technology, gas extraction from this zone may never become economically viable. The limiting factor is the fraction of produced methane that would be required to operate an extraction facility. Nonetheless, present indications are that gas concentrations will eventually accumulate to such a level that concern for public safety will dictate the need to extract gas from this zone.

This matter must be studied further before the present round of concession agreements are up for renewal some 25 years from now. The Bilateral Regulatory Authority must coordinate the effort to establish technically and economically viable solutions to incorporate with the concession renewal requirements.

2.2 Density Control

In order to "push down" or downwardly displace the gas-rich waters as described above, degassed water must re-stratify quite accurately. Achieving this objective will require close density control, and this subject is therefore addressed in a number of the mandatory requirements and guidelines.

To avoid interfering with the density structure in the lake, the use of dilution water from a different zone to achieve density control is normally prohibited (BP1.2 below). The only remaining option is to control how much carbon dioxide is left in the degassed water before re-injection. When extracting gas separately from the LRZ, URZ and PRZ, such control is physically possible since around 40 to 50% of the carbon dioxide should be removed initially during separation. Over time, this removal rate must be reduced in order maintain the vital gas-lift that powers extraction operations.

The amount of carbon dioxide to be removed dictates the operating pressure of the (final) separator in gas extraction facilities. The carbon dioxide thus removed can be disposed of to the atmosphere in two ways: 1) with the produced gas, for capture as liquid or solid carbon dioxide or through the combustion engines that drive the power generators, and 2) with the washing water to the bottom of the Biozone from where it will diffuse into the atmosphere.

2.3 Location of Gas Extraction Operations

Locating gas extraction operations on Lake Kivu needs to take into account technical and logistical/economic factors and the geographic concessions granted. Ultimately, concessions should have access to the deepest water in order to be able to withdraw the maximum amount of the gas resource. Other factors affect design such as ensuring that the difference in the depths of extraction and re-injection are large enough to avoid short-circuiting the extraction/re-injection process. Pipeline costs and deep-water construction issues further condition decisions on plant locations, as does application of Plans A1/A2 and Plan B.

The gas extraction location in Rwandese waters that provides the deepest water access is an area at the north end of the lake adjacent to DRC waters and south-west of Cape Rubona where depths exceed 475 m. Concessions are each provided such access for their long-term viability (Plan A2 + Plan B).

A branch of the deep water basin extends southwards with depths over 400 m. A large volume of resource water lies in this branch, but the duration for harvesting methane as in Plan B is limited due to lack of depth. To the southern end of this branch, the width of the lake is constrained and dispersion of re-injected degassed water is more problematic. Further south in this branch, technical considerations will limit extraction to small-scale operations only, using Plan A1.

Extraction operations from the LRZ need to be located at the north end of the lake, with access to the deepest water. Extraction from the URZ could be over less deep water, but the uncertainties with the above Plan A1/A2 and Plan B indicate that concessions extracting from the URZ must have potential access to the deepest parts of the lake.

Gas extraction from the PRZ, maybe a few decades from now, can take place at any location where the 260 m density gradient is intact. PRZ extraction operations can take place concurrently with RZ extraction operations, and will depend upon available technology and gas concentrations. These operations can be located over a wider part of the lake covering a large part of the northern lake at some distance from the deeper water. Extraction from the IZ can take place at any location where the 190 m gradient is intact, and thus over a very wide part of the lake. In this case, the distance to shore may well govern the economics of a location decision.

In conclusion, the most efficient strategy for harvesting the gas resource will ensure that all concessions have access to all depths of the lake. This strategy gives each concessionaire the flexibility to propose the optimal location of his gas extraction facilities for approval by the Bilateral Regulatory Authority. This strategy is elaborated further in Section 2.4 below.

2.4 A Conceptual Framework for Concessioning Gas Development

The process of granting gas concessions on Lake Kivu in Rwanda has developed since 2000 without the benefit of the analyses contained in this document. It is now clear that the requirements for resource management are unique to Lake Kivu, and thus concessioning arrangements need to be purpose-designed to ensure (a) efficient and socially-beneficial harvesting of the gas resource while reducing the risks of uncontrolled gas outbursts, and (b) a clear, transparent and fair concession allocation process.

As discussed above, the nature of Lake Kivu’s bathymetry and methane resource indicates that for both public safety and economic reasons, all gas extraction concessions should have access to the deepest parts of the lake at its northern end. As technology and methane densities change over time, this approach provides operators with the flexibility to maximise economic returns by extracting gas from different depth zones (URZ, LRZ, PRZ, IZ) at various distances from shore. It also provides the Bilateral Regulatory Authority with the flexibility to manage the overall gas resource through licensing the deployment of individual extraction operations.

To achieve these flexibilities, it is recommended that the two governments concession gas extraction operations with the co-allocation of a geographic area of operation with shore access and a defined portion of the gas resource to each concession.

The **geographic allocation** would determine where on the lake operators can locate their equipment and, conceptually, would best be based on a “radial model” centred on the deepest part of the lake (see *Figure 2: Conceptual geographic arrangements of gas concessions per country*). This approach allows each operator access to all depths of the lake, and thus to the assigned gas resource in the different depth zones.

At the same time, the geographic concession size would be independent of the gas resource allocation described below. Governments would ensure that power plant sites, utilities, road access and transmission lines to evacuate the generated power are made available on the shore-line allocation for each concession.

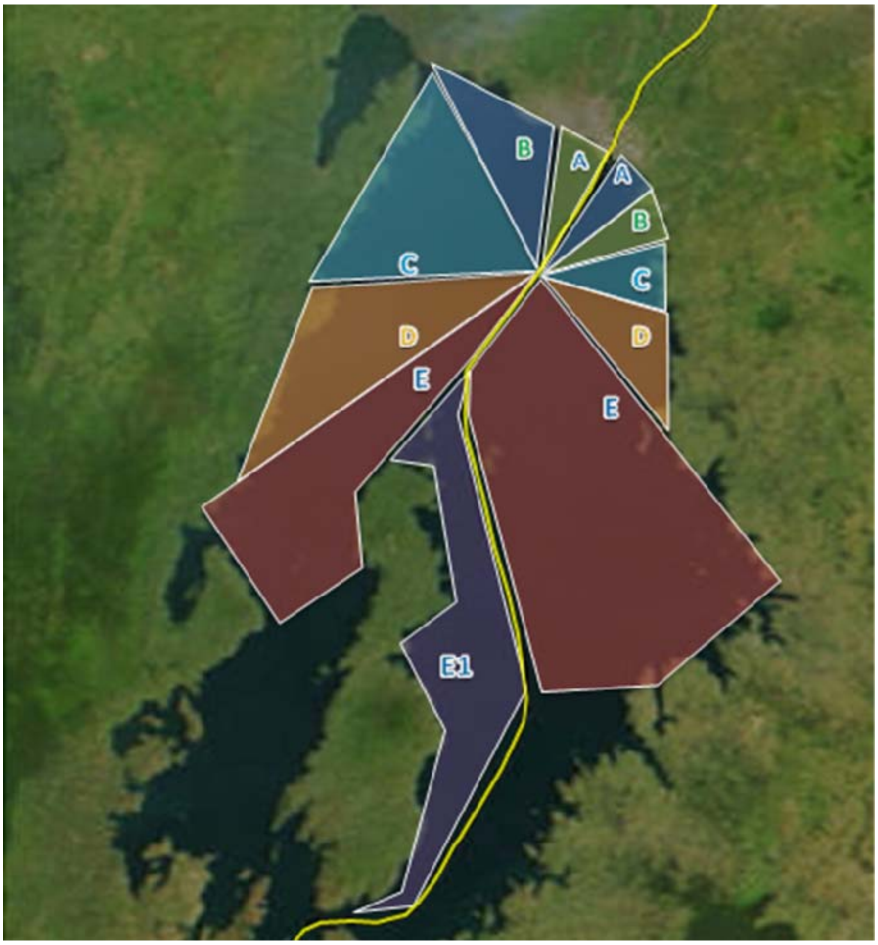

Figure 2 Conceptual geographic arrangement of gas concessions per country

The **gas resource allocation** to each concession would be a defined portion of each country's bilaterally-agreed share of the total gas resource, with quantities differentiated by depth zone (LRZ, URZ, PRZ, IZ)[1]. This second dimension of allocation is essential because gas-rich water in each depth zone will move laterally between concession areas in response to extraction operations. Individual operators must be limited in the total amount of gas they can extract in order to avoid

[1] This allocation is recommended over the MWe used to date since the latter does not value the gas resource, only the final output. For reference, an existing concession measured in MWe can be converted to extracted gas volume based on the best extraction and conversion efficiency available with known technology.

jeopardising the viability of other concessions. Moreover, concession agreements based on the volume of available gas are an important incentive for operators to optimise resource usage.

Resource allocations among concessions might be made equally (e.g. 20% of each country's share of the total resource if there are five concessions in each country) or on some other practical basis. An illustration of resource allocation is provided in *Figure 3: Concept distribution of resources and power potential by concession*. The potential power yield, based on a high-efficiency extraction and conversion basis is shown by zone. The quantum of projected methane yield over 50 years is shown in km^3 for each zone. The Bilateral Regulatory Authority will need to cooperate with both governments to formalise the resource allocation basis in concessions.

The most economically efficient, and profitable, way for the two governments to benefit from concessioning would be to solicit competing bids for each concession area and associated gas resource allocation. Logically, the highest bids would be received for the perceived best location, and lower bids would be received for less attractive concession areas. In bid adjudication, allocations should be made according to the bid values respecting the limitations also imposed on the number of concessions per bidder.

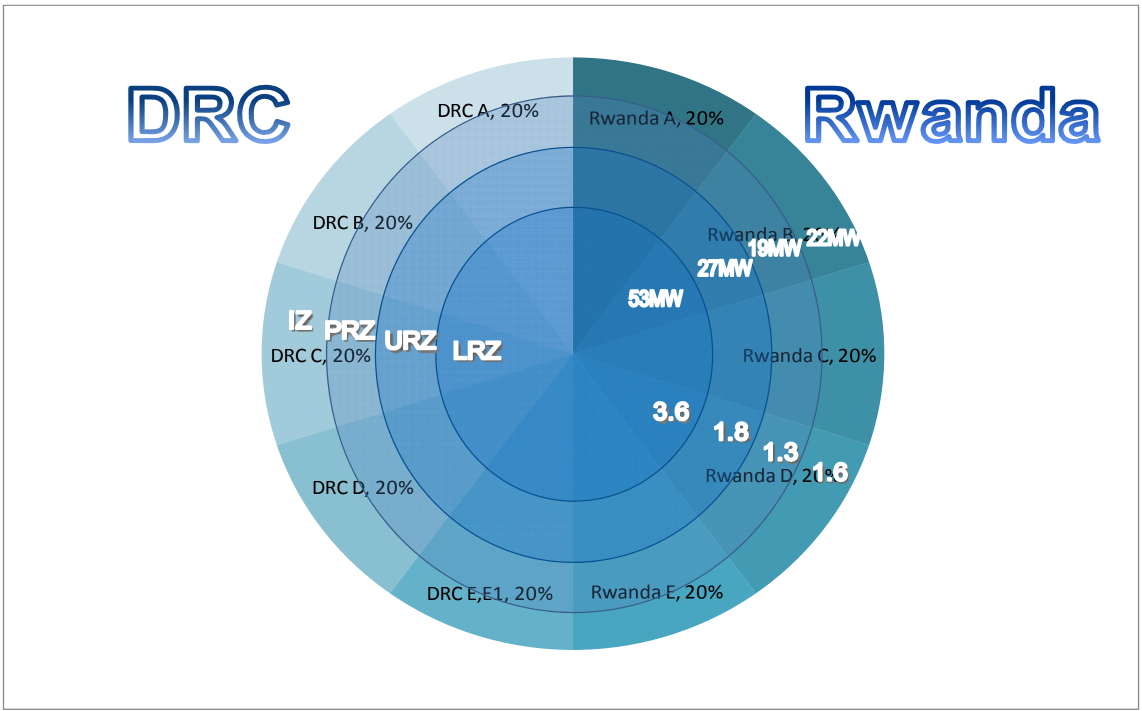

Figure 3: Concept distribution of resources and power potential by concession

Sale proceeds (and production royalties) should first go to financing and running the Bilateral Regulatory Authority and the lake monitoring programme. Public investments (roads, transmission lines, etc.) needed to support gas extraction and power production operations, may be funded from any surplus. A way would need to be defined for bringing the existing concessionaires granted into conformity with the concessioning framework described above. They should perhaps be required to at least bid for geographic allocations if the governments consider that any existing resource allocations will remain in force.

Instructions to concession bidders will need to include this Management Prescriptions document to ensure that they are fully aware of the mandatory requirements to be met. To ensure maintenance of the long-term safety and integrity of the gas resource, bidders should be required to submit proof of either having developed, or having access to, proven technology acceptable to the Bilateral Regulatory Authority. New entrants proposing new technologies should be required to follow the established practice of proving their approach with approximately 4 MWe pilot facilities in order to qualify for the licensing of commercial-scale gas plant construction.

There will be many details to be worked out to implement the concessioning framework, including legal, commercial and financial arrangements. Among the technical details to be determined are:

a. the number of concessions in each country, and their geographic and gas resource allocations;

b. the rules of tenure (e.g. gas plant setback distances, perhaps 500 m, from concession boundaries to avoid conflict between anchoring systems; pipeline routings; the use of buoys and navigation lights to demarcate platform locations; and marker buoys for pipelines);

c. whether the royalties applicable to gas produced from different zones need to vary in order to provide incentives for gas removal from the different zones, especially the PRZ and IZ in the future;

d. the duration of concessions, renewal conditions[2], and the development and production milestones that must be met to retain a concession – in order to support gas extraction from all depth zones over time; and

e. the guarantees required to ensure that all facilities (e.g. extraction platforms, pipelines, power generation plants) are removed if required at the end of a concession period. The Bilateral Regulatory Authority may require a concessionaire to make available, modify or otherwise redeploy a gas extraction facility to assist with necessary degassing of the lake in the post-concession period. This requirement should be met by the concessionaire provided such costs are below the cost of removal.

[2] For example, concessions could be set at, say, 25 years, renewable for 25 years, and defaulting to government in 50 years. The availability of technology and the build-up of resource levels in the PRZ and IZ may not enable or permit gas production from these zones much before 25 years.

2.5 Rate of Gas Extraction

Lake Kivu contains very large quantities of accumulated methane that should be removed expeditiously to reduce the risks of uncontrolled gas outbursts. At the same time, methane is continuously produced in the lake, though the rate has only been estimated and will remain highly uncertain without years of monitoring. In the long-term, once methane levels are reduced to a safe level, gas production can be sustained at a long-term, reduced rate approximately 15-20% of the 50-year yield.

Figure 4 and Figure 5 represent conceptually some of the resource harvesting options available to the two governments, presented here in terms of total power available over different extraction periods. The first figure represents the total calculated power available over time from the Resource Zone in both the Rwandese and Congolese waters of the lake, assuming conservative recovery and power conversion efficiencies. These were estimated at 300 MW per km^3 of methane per year. The second figure includes production also from the Potential Resource Zone and at higher, but easily achievable, recovery and power conversion efficiencies (425 MW per km^3 per year). A maximum rate, up to 50% higher, can be achieved with >60% power conversion efficiency, such as is achievable with combined cycle gas turbines.

Detailed monitoring of the gas resource, and gas and power production, is required to confirm the position and shape of the curves in the two figures, especially when PRZ production is included. The power yields are based on assumed efficiencies in the conversion of the thermal energy in the produced gas to electrical power. The actual efficiencies of gas extraction and power conversion will be a function of the technologies employed, and will strongly influence the total power that can be produced.

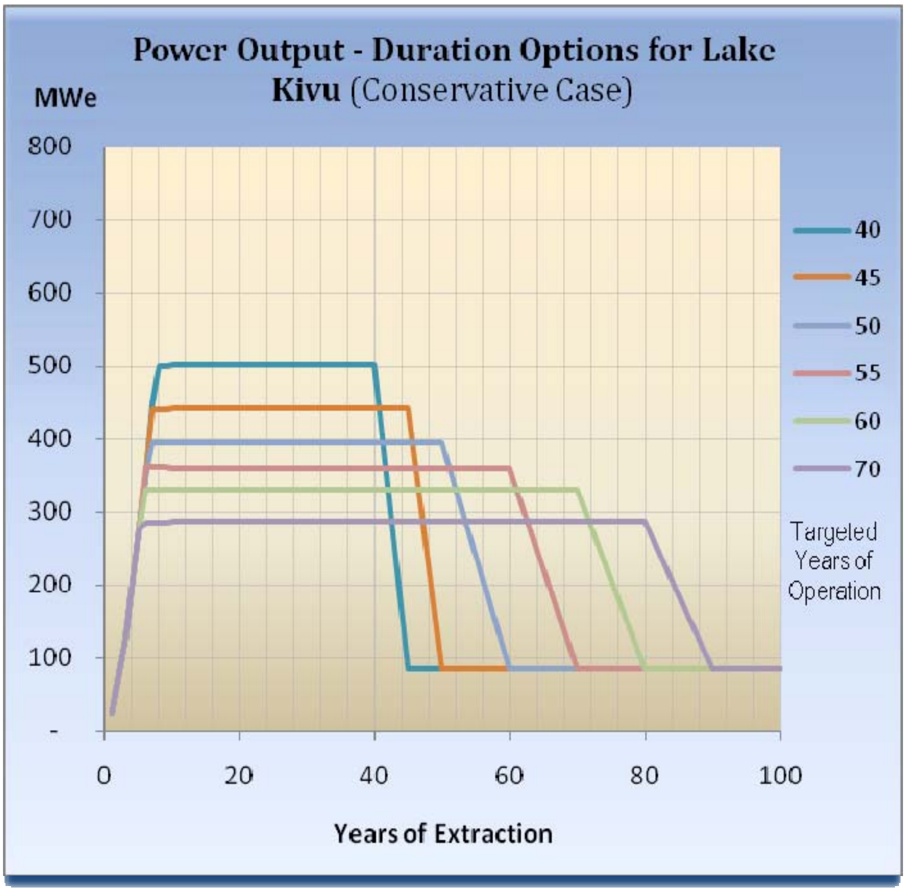

Figure 4 Approximate "conservative" power vs. lifetime options for RZ gas extraction from Lake Kivu

Analysis of the full range of possible energy yield from the lake provides a strong incentive to governments to require the deployment of both the most efficient gas extraction facilities (that also best preserve the integrity of the resource) combined with the most efficient gas-to-power (or other gas conversion) technologies.

Assessment of the best yielding combination compared to the worst available combined efficiencies indicates that the power potential of the lake can vary from the extremes of 160 MW_e to 960 MW_e total lake output. Measured in terms of 50-year economic yield, at a price of $100/MWh, the total lake yield could vary between $7 billion to $42 billion.

The power yield curves are illustrative only, and must not be taken as a prescriptive guide for concessioning gas production. Continuous assessment will better define the ultimate yield potential of the lake.

The figures illustrate that higher total power production rates to harvest the accumulated gas in the lake mean a shorter lifetime of the investments and, thus, reduced economic feasibility of establishing the power generation and transmission system. The upward sloping lines on the left represent the time needed to build up the power market and transmission system.

The lowest horizontal lines on the right, at up to 90 MWe and 130 MWe, indicate the highly uncertain rate of long-term methane production in the lake, and thus the kind of variability there may be in the long-term sustainable rate of power production.

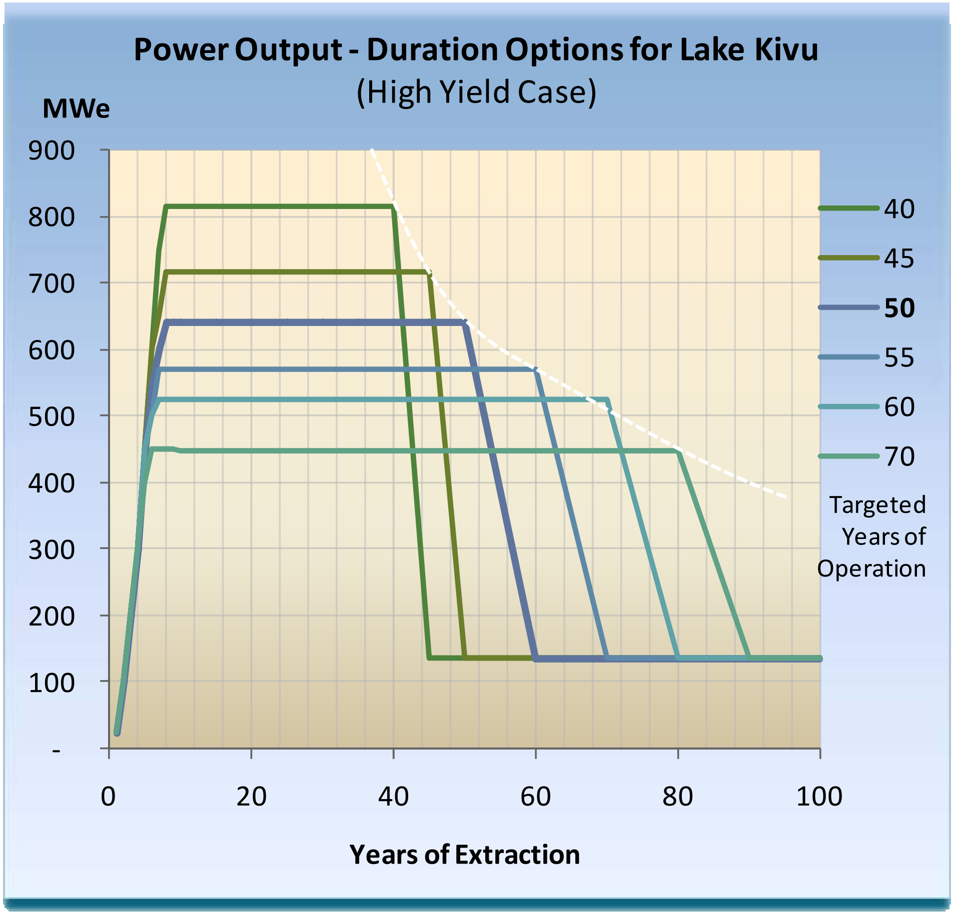

Figure 5 Approximate “high yield” power vs. lifetime options for RZ and PRZ gas extraction from Lake Kivu

Considering the uncertainties that can only be resolved through future lake monitoring, the two governments should agree to issue concessions for gas production from the lake with the following in mind:

1. Concession agreements should be based on rate of resource use, and total resource used, not power produced (see Section 2.4 above);

2. Notionally a gas resource usage target that converts to about 500 MWe, at 40% power conversion efficiency, can be recommended initially as the combined concessioned production rate for the two countries. Overall power yield may be boosted by 50% with 60% efficient power conversion plant;

3. It appears that a total gas production target, that extracts 1,9km^3/y of water from the resource zone, should be reached as quickly as possible in order to adequately reduce methane concentrations and the growing risk of an uncontrolled gas eruption triggered by a volcanic event; and

4. Initial gas production operations need to start entirely with Plan A1/A2.

The two countries will have to agree on how to share this production potential, with agreement on ramp-up as well as maximum production rates by country.

Before the first round of concessions expire and are up for renewal, it will be necessary – with the help of a model of the lake – to study and decide how best to transition from the relatively high, initial 50-year gas production regime to a long-term sustainable regime with lower gas production, limited by annual natural methane generation. The Bilateral Regulatory Authority will need to better establish the lake's long-term yield potential, and gas extraction practices to be employed over the transition, as it approaches the end of the resource bonanza period.

2.6 Managing Carbon Dioxide in the Lake

Carbon dioxide in Lake Kivu has a multi-faceted role. It represents a threat, but is also a resource. As a carrier gas, it enables the production of methane, but it contaminates produced gas as a fuel. It is a co-product of methane in the gas generation process, but has limited economic value. It can asphyxiate people in a gas eruption, but it also helps stabilise the density of deep water.

For the above reasons, the carbon dioxide inventory in the lake must be managed, zone-by-zone, to:

- reduce gas pressures and the risk of an uncontrolled outburst due to volcanic activity;
- maintain density for gas re-stratification control; and
- sustain the gas-lift needed for continued methane production over the productive life of the lake.

Until recently, it was considered essential to remove carbon dioxide from the lake to improve lake safety and stability. Thus, initial extraction methods were designed to remove and vent 80% or more of the CO_2. Opposition to CO_2 venting was based solely on its role as a greenhouse gas in the atmosphere.

More recent and precise analysis of the density control and gas-lift requirements of the lake leads to a policy of more balanced and precise measures to control lake stability and production. These methods are discussed in Section 2.2 above on density control.

The methodologies used for methane production will determine the balance of CO_2 displaced to, or retained within the zones. Indications are that the required density control regime would need about 50-60% of CO_2 to remain in the re-injected water to the Resource Zone, while the balance is removed with the product gas or rejected at the bottom of the Biozone with wash water. In the long term, as much carbon dioxide must be removed as is accumulated.

It is believed that the need to control the density of the degassed water will automatically ensure a satisfactory removal rate for CO_2 so as to maintain long term public safety.

2.7 Additional Uncertainties

Dynamics of Density Gradients

The density gradients are not at steady-state and are changing due to natural inflows of dense water to the lake, causing apparent upward flux of the gradients. Some less dense inflows appear to counteract the rise of certain gradients by diluting and trimming the gradient upper margins. Should this effect be confirmed, it would explain the apparent depth-stability of the affected gradients.

Monitoring over the next few decades will resolve these uncertainties. The future technical and economic viability of gas extraction, including that for the PRZ, depends on the maintenance of the position of key gradients at or near their present levels to ensure a safe-side approach.

Moreover, especially if the gradient between the IZ and PRZ rises, total relative gas pressure below this gradient may gradually increase towards saturation. If this situation begins to develop, the Bilateral Regulatory Authority will need to ensure sufficient gas harvesting from the PRZ to reduce the risk of an uncontrolled outburst to acceptable levels. Rising gradients would reduce the capacity of the lake to trap and retain newly-generated methane at concentrations sufficient to support the commercial gas extraction operations.

If the gradients are rising, and the Bilateral Regulatory Authority establishes a proven need to limit their rise or stop them rising, the only apparent solution would seem to be to displace some salt- and nutrient-laden degassed water elsewhere. At present, two methods seem possible: discharging the degassed water to the Biozone with potentially severe environmental impact, or discharging it directly to the Ruzizi River. This latter option transfers the nutrients and salts problem to Lake Tanganyika sooner than would have otherwise been the case.

Proximity of Location of Gas Extraction Facilities

When gas extraction facilities are sited too close together, the dispersing lens of degassed water is expected to superimpose with other lenses from neighbouring facilities discharged at the same level. The spreading, and thus the thickness, of the lenses or merging lenses depend on mechanisms difficult to predict. This spreading/ merging should be monitored from the very beginning of gas extraction from the lake. Depending on actually measured spreading rates there may be an additional risk of short-circuiting and a need for distributing gas extraction plants over a larger area of the lake.

3 Basic Principles

The governments of the Republic of Rwanda and the Democratic Republic of Congo should adhere to the following basic principles in determining the number, location and design of extraction operations.

3.1 First: Public Safety

In developing the gas resources of Lake Kivu, ensuring public safety is the primary concern. (Depths referenced are as measured in 2004.)

BP1.1 The total relative gas pressure must be controlled at all levels in the lake to reduce the risk of dangerous, uncontrolled gas outbursts. To address this concern:

a) In the long term, the total rate of methane extraction from all operations should equal the rate of estimated natural increase. The natural generation rate in the Resource Zone needs to be better quantified through monitoring over the next decades.

b) In the short to medium term, the total rate of methane extraction from all operations should be greater than the natural generation rate in order to reduce the public safety risk.

c) Operations should focus on reducing total gas pressures at depths where the relative saturation levels are highest.

d) Development of the gas resource needs to be done incrementally to test extraction locations, technologies and their ability to adapt to the structure and behaviour of the resource. Thus, extraction operations must be able to be deployed modularly to reach the concession total, and to be demonstrably able and willing to readily adjust the depths of extraction of gas-rich water and re-injection (level of re-stratification) of degassed water.

BP1.2 The overall density gradient of the lake, mainly determined by the salt content, must not be significantly weakened. Thus:

a) The overall density stability[3] of the lake must not be reduced by more than 25 %.

[3] Schmidt stability – the energy needed to completely homogenise a water body, expressed in Joules per square metre.

b) The main density gradient, at approximately 260 m depth, must remain strong enough to prevent the upward movement of dissolved methane from the Resource Zone.

c) There must be no dilution of the Resource Zone and the Potential Resource Zone with water that did not originate in that zone.

d) Deliberate redistribution of salts between zones is to be avoided.

BP1.3 The management of the amount of carbon dioxide in the lake must balance the need to remove it for safety reasons with the need to maintain sufficient concentrations for sustaining lake stratification and gas lift forces for extraction operations.

BP1.4 Water extraction methods shall be sustainable, preserving for society the future ability to maintain safety while economically extracting gas.

BP1.5 Lake-wide Monitoring must be carried out on a regular basis under the direction of the Bilateral Regulatory Authority to detect any unacceptable gas concentrations or accumulations that require intervention.

3.2 Second: Environmental Protection

The second priority concern is for the protection of the lake environment, especially the Biozone.

BP2.1 There must be no release of water into the Biozone that did not originate in that zone. In particular, there must be no release of nutrient-bearing water from deep in the lake into the Biozone.

BP2.2 Deliberate changes to the vertical nutrient fluxes into the biozone must be kept to less than 25 % of the natural fluxes with no gas extraction operations.

BP2.3 Gas extraction plants must be designed for no emissions of methane and hydrogen sulphide to the atmosphere during regular operations. Limited, short-term emissions are acceptable when plant safety considerations are paramount.

BP2.4 Washing water containing hydrogen sulphide shall be released at the base of the Biozone.

3.3 Third: Maximum Social Benefit

The third priority concern is to obtain the maximum social benefit from the development of the gas resource by minimizing any losses of recoverable methane.

BP3.1 Methane returned with degassed water to the zone from which it was extracted is not considered to be lost. Methane should be minimized in washing water discharged to the Biozone.

BP3.2 Concessions should be granted, and concession royalties should be based, on the amount of methane in the extracted resource-bearing water in order to encourage concessionaires to make optimal use of the methane resource. Concessions should be granted providing access to the deepest water and to shore locations. Concessions granted confer rights to the concessionaire but simultaneously confer responsibility of care to the area of the concession.

BP3.3 The Bilateral Regulatory Authority, in conjunction with interested parties and experts, should develop a gas harvesting plan for the lake that minimizes the risk of uncontrolled gas outbursts to acceptable levels, and thus the rate, location and extent of gas removal.

BP3.4 To minimize gas resource losses, concessionaires should design their plants with turn-down capabilities to be able to load-follow or respond to reductions in gas demand as is necessary. Continuous flaring or venting, for example for purpose of load sharing, is not permitted.

BP3.5 The Bilateral Regulatory Authority should ensure that the public are fully informed about the nature of the gas resource, the scope and results of the monitoring programme, and the location and gas production of the concessions.

4 Mandatory Requirements

In general, appropriate and recognized international codes and standards, and industrial practices, in the gas industry will apply to gas extraction operations on Lake Kivu. At the same time, the safety and environment in this unique lake require that the stipulations in this document will prevail over such codes, standards and practices in case of conflicts.

Force majeure can be instituted in unexpected developments such as major volcanic or seismic events, or significant changes in methane concentration in the resource body.

4.1 Mandatory Technical Requirements (MTR)

MTR1: Water extraction and re-injection must be done horizontally. Equipment must be designed to reliably prevent, for the design lifetime of a facility, the accidental deviation of re-injection flows away from the horizontal, and/or their redirection into vertical flows, at the point of re-injection.

The exit velocity at re-injection shall be so small that vertical displacement of the isopycnals (surfaces of equal density) shall be significantly smaller than the re-injection lens thickness. The design must be such as to prevent any accidental deviations from this throughout the lifetime of the facility.

The design as well as the choice of materials must ensure that corrosion or fatigue cannot cause premature failure of any parts of these points of re-injection. The design lifetime (materials as well as workmanship) must be 50 years. Fabrication of the re-injection pipe must be made to the highest standards.

MTR2: Using dilution water to adjust the density of degassed water before re-injection will normally be prohibited if taken from another zone. If required, dilution water must be taken from the zone into which the degassed water is re-injected.

MTR3: (Plan A1)

When extracting gas-rich water from the URZ, and re-injecting degassed water back into the same zone, the goal is to optimize harvesting gas from the URZ. Thus the degassed water must be re-injected and remain at the lower margin of the main density gradient (at 270 m depth in 2004). Meeting this objective will involve controlling the degassed water density through its CO_2 content (about 40 % removal), and sizing the plant to avoid short-circuiting between the re-injection and extraction points. Since this is both an essential and difficult objective to meet, a concessionaire must be able to thoroughly demonstrate his ability to meet it to the Bilateral Regulatory Authority prior to commencing any construction works.

MTR4: (Plan A2)

When extracting gas-rich water from the LRZ, and re-injecting degassed water back into the same zone, the goal is to optimize performance under Plan A1 while allowing additional gas harvesting from the LRZ. Thus, the degassed water must be re-injected to re-stratify at the lower margin of the secondary density gradient separating the URZ and LRZ (at 325 m depth in 2004). Meeting this objective will involve controlling the degassed water density through its CO_2 content (about 45% removal). Plan A2 (this MTR4) must only be implemented if Plan A1 (MTR3) operations are working, and then only at about 50% of the total water extraction rate of Plan A1 operations.

MTR5:(Plan B)

When extracting gas-rich water from the LRZ, and re-injecting degassed water into the URZ, the goal is to displace gas-rich water from the top of the upper zone and replace it with gas-poor water in order to reduce the risk of premature, uncontrolled gas eruption from the lake. Thus:

a) The re-injected water must re-stratify as close as possible to the lower margin of the main density gradient (at 270 m depth in 2004) and well above the upper margin of the 310 m gradient (at 300 m depth in 2004). Meeting this objective will involve, for example, using a combination of an appropriate depth of re-injection, controlling the degassed water density through its CO_2 content (minimum 50 % removal), and using diffuser nozzles on the injectors. Since this is both an essential and difficult objective to meet, a concessionaire must be able to thoroughly demonstrate his ability to meet it to the Bilateral Regulatory Authority prior to commencing any construction works.

b) The depth of extraction can be initially chosen to facilitate density control of re-injected water by abstracting less dense water. Over the course of a concession, an operator must be prepared to lower his extraction depth closer to the lake bottom as required to maintain production. In order to be able to control gas pressures at all levels, at least some of the gas extraction plants must extract from the very deepest parts of the lake.

MTR6: When extracting gas-rich water from the Potential Resource Zone, and re-injecting degassed water back into the same zone, the degassed water must be re-injected to re-stratify at the lower margin of the density gradient above (at 200 m depth in 2004). Meeting this objective will involve controlling the degassed water density through its

CO_2 content, and sizing the plant to avoid short-circuiting between the re-injection and extraction points.

MTR7: Methane gas produced offshore must not be transported to the shore in a way that might affect the surface use of the lake, or risk a gas outburst below the Biozone. Gas export pipelines must be located below -10 m depth. The Bilateral Regulatory Authority may approve shallower pipelines in special circumstances). Any pipeline must be designed and equipped to prevent, under any circumstances, an uncontrolled flow of gas through the pipeline, and the release of gas below the Biozone.

MTR8: The design of deep-water extraction systems must prevent any self-sustaining gas-lift effect should a pipe-break or rupture occur (e.g. in a riser pipe or return water line) and result in the following dangerous combination:

a) An open-ended pipe length remaining suspended or standing;

b) with the lower end in the Resource Zone; and

c) the upper end close enough to the surface to sustain gas-lift.

Gas concessionaires and their plant designers must make a convincing case that their underwater piping design will meet the objective of preventing this eventuality with sufficient reliability to ensure a fail-safe design. The designer must demonstrate that either the flow in the pipe will be completely arrested or that the pipe will naturally come to rest in an orientation that no longer connects the Resource Zone with the upper approximately 70 m of the lake in a manner that would support gas-lift.

MTR9: Gas extraction plant designs must ensure zero gaseous emissions during normal operations. Extraction facilities shall, as a minimum, be designed and operated to comply with the following regarding CH_4, CO_2 and H_2S releases during upset situations:

a) Offshore facilities: The amount of any gas released into the atmosphere must not be such as to result in atmospheric concentrations that would harm any person within the facility or nearby.

b) Onshore facilities: The amount of any gas released into the atmosphere must not be such as to result in atmospheric concentrations that would harm any person within the facility, or harm or cause a nuisance to any person nearby.

MTR10: Optimal use of the gas deposit while minimizing environmental impact requires that plant designs must be such as to minimize the loss of methane dissolved in the washing water.

MTR11: Washing water containing hydrogen sulphide and discharged into the Biozone must be injected below depths inhabited by fish to prevent fish-kill in the biozone (now down to about 60 m depth) and so as to restratify above the centre of the density gradient below (now at about 70 m depth).

MTR12: Gas production systems must be demonstrably designed to yield the maximum useful energy while minimizing the unrecoverable losses.

MTR13: In order to be able to react to changes, as set out in 2.7, the concessionaire must include in the design the capability to be able to adjust their extraction and re-injection levels from time to time, or to be able to re-inject at multiple levels, simultaneously if required.

MTR14: The location of gas extraction platforms and associated satellite facilities shall all be located at least 500 m inside the specific concession boundary. This margin shall allow sufficient distance for all anchor systems to remain fully within the concession boundaries.

4.2 Mandatory Administrative Requirements (MAR)

MAR1: Before applying for permission to proceed with the construction of gas extraction facilities, concessionaires must be able to thoroughly demonstrate that:

a) their plant designs and operational procedures will be in compliance with the provisions of this document; and

b) their Environmental Impact Assessments take these provisions into consideration.

Should existing facilities become non-compliant with an updated version of this document, the Bilateral Regulatory Authority will notify the operator of the non-compliance and the two parties will negotiate a mutually-agreed plan for bringing the facility into compliance.

MAR2: The locations of water intake and re-injection equipment will be approved by the Bilateral Regulatory Authority based on their depth, horizontal separation, and flow volumes.

MAR3: Prior to construction, design drawings must be submitted to the Bilateral Regulatory Authority for approval. This information will be kept confidential. Submitted designs must include at least all configurations of: underwater pipes, pumping systems, separators, gas lines, gas treatment facilities, gas buffer storage tanks, water mixing systems, compressors and blowers; power supply systems on off-shore barges; and gas flaring systems. All submerged materials of construction for underwater pipes and anchoring systems must be part of the documentation submitted.

Design drawings must include process flow diagrams (PFDs) and piping and instrumentation diagrams (P&IDs) prepared in accordance with ISO 10628. The design will have been subjected to the HAZOP process, and the HAZOP report must be submitted with the design drawings. This information will be kept confidential. The process flow diagrams (PFDs) shall as a minimum include the basic information as per section 4.2.1 plus items a (mass balance for all gases plus water), b, c, and d from section 4.2.2 of ISO 10628, and the P&IDs shall as a minimum contain the basic information as per section 4.3.1 plus items c, d, e, f and g from section 4.3.2.

MAR4: Relevant design data that will be reported at the design stage for all single extraction facilities, and that will be made public, include but are not limited to:

a) depth of all extraction and re-injection pipe openings;

b) design of the extraction and re-injection pipes: diameter, elasticity, heat conductivity, shape of pipe mouth to achieve internal mixing of re-injected water with surrounding water, ejector/diffuser, etc.;

c) design flow rates for all water extracted from or re-injected into the lake;

d) design flow rates including full mass balance, and expressed in SI Units (t/h or normal[4] m^3/h or km^3/h etc.) for all gas streams produced during the extraction process;

e) the concentrations of methane, carbon dioxide and hydrogen sulphide in said water and gas streams, showing the extraction efficiencies and gas losses;

f) detailed and verifiable calculations of expected re-stratification levels for degassed water and for washing water; and

g) amounts of sellable power and of all internal power consumption in gas extraction.

Any subsequent changes to the above data must be submitted to the Bilateral Regulatory Authority for approval.

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[4] Normal conditions refer to 0 °C and standard atmospheric pressure (101,325 Pa).

MAR5: The Bilateral Regulatory Authority has the right of access to gas extraction facilities for inspection at any time, and will provide facility operators with sufficient notice of such inspections. The operator has overall responsibility for safety at the facilities, and thus for granting access. The Bilateral Regulatory Authority personnel will have all necessary safety training as required by the operator for access to the offshore facilities. The operator will provide such training.

MAR6: At start-up of a new or modified gas extraction facility, a concessionaire must engage a qualified third party to carry out monitoring in the lake (e.g. salinity and temperature profile measurements) around the point of re-injection. This monitoring will, with sufficient reliability and precision, demonstrate the shape of the plumes of any re-injected water (degassed and washing water). The purpose is to measure and report, from start-up until sufficient results have been reached, that there are no deviations from re-stratification levels as defined in this document. If necessary, adjustment of density control must take place followed by renewed monitoring until a satisfactory result has been obtained. The third party report will be submitted to the Bilateral Regulatory Authority.

MAR7: Operators of gas extraction facilities must report certain operation and monitoring data electronically to, and in a manner and frequency defined by, the Bilateral Regulatory Authority. Operators must be prepared to carry out automatic, online reporting if required by the Bilateral Regulatory Authority. These data will be made public and used together with other data to develop better scientific understanding of the lake and guidance of extraction concession design, safety and operations. Operator shall ensure that sample points for all major streams are installed, with suitable valving, for taking the necessary samples and for the Regulator's appointed third party to take samples on request. Facilities shall be designed to allow carrying out tests with injection of tracers (through sample points).

Data to be reported include the following parameters:

a) Hourly averages of flow rates for all water extracted from and re-injected to the lake, plus the rates of produced gas or electrical power (MW) and cumulative production. Flow meters shall be calibrated once a year and copies of the calibration reports submitted to the Bilateral Regulatory Authority;

b) Monthly average values of flow rates for all gas streams produced by the extraction process, including mass balances showing the methane extraction efficiency and the relative carbon dioxide removal rate; and

c) Monthly average values of water temperature, conductivity and salinity, as well as concentrations of methane and of carbon dioxide, hydrogen sulphide and nitrogen in said water and gas streams, as well as calculated and/or measured densities of the re-injection water.

Other data may be added if concerns for the lake so require.

Once a month, a full set of water parameter analyses shall be made in an agreed laboratory on samples of extracted and re-injected water.

MAR8: Concessions should be limited to a time frame considered appropriate by the Bilateral Regulatory Authority. In considering an application for the renewal of a concession, the Bilateral Regulatory Authority should consider, among other things:

a) the overall gas reservoir management plan for the lake;

b) the availability of more efficient and sustainable gas extraction methods;

c) the potential need to change the extraction or re-injection depth and/or location; and

d) the potential need to change the carbon dioxide removal rate.

The Bilateral Regulatory Authority has the right to determine what technical renewal conditions will be required.

MAR9: A precondition for permission to start operation of any gas extraction facility is that the Bilateral Competent Authority or its representative has been given the opportunity to inspect all underwater piping and their fittings (as well as the materials they are made of) when assembled onshore but prior to installing these under water.

5 Guidelines

These guidelines represent elements of good practice that should be followed by the designer of any gas extraction facility. Guidelines are numbered according to the applicable MTR. Depths are as measured in 2004.

G1: For maximum control over the level of re-stratification, water re-injection through vertical re-injection pipes should always be horizontal, such as through an inverted tee-piece. The design of the outlet should be such to produce as close to laminar flow as possible, having reduced to a minimum turbulence, vortexes, etc. Examples of options are: straightening vanes (to cut swirl) and bell-mouths or diffusers to reduce exit velocity.

G2: Active control of the density of re-injection water being a key element of design, density should be calculated based on water flow rates, plus temperature, salinity and concentrations of dissolved gases using the Chen and Millero density formula extended by Schmid et al (2004), as well as by Wüest et al (2008), for density calculations[5]. This model has been made on the best endeavour basis; all results should be verified through monitoring after start-up, and adjustments of density should be made, if necessary, to meet the re-stratification objective.

G3: Because the Upper Resource Zone is relatively shallow, the Plan A1 extraction methods employed for this zone need to be able to extract and return water relatively precisely. Design should address the issue of the shaping and distribution of re-injection water nozzles to obtain laminar, horizontal flow as much as possible, as well as precise control of re-injection density, to ensure re-stratification as specified in MTR3.

In order to avoid short-circuiting between intake and re-injection points, the size of the extraction facility should be carefully evaluated. The tendency for short circuiting and thus the risk of plant failure increases with plant size. A 4 MWe facility could function with these conditions of narrow vertical intervals between intake and re-injection, whereas a 20-25 MWe facility might not. At present, there is not enough operating experience to be more explicit. Any concessionaire starting with this MTR3 design is advised to begin with small-scale plants.

G4: The challenges of Plan A2 operations are the same as for Plan A1 operations with one exception. Because of the much larger vertical distances between extraction and re-injection, the risk of short-

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[5] Obtainable from the Bilateral Regulatory Authority.

circuiting is believed to minimal. For this reason, it should be technically and economically justifiable to build larger modules of gas extraction facilities for Plan A2 facilities.

G5: When concessionaires switch from Plan A1/A2 (MTR3/4) to Plan B (MTR5) operations, there will be a larger vertical distance between the point of extraction and the point of re-injection, including the 310 m gradient in between, allowing larger extraction units to operate while avoiding short-circuiting.

If transition to Plan B (MTR5) takes place because of failure of Plan A1 extraction facilities to drain the gas from the URZ then, in order to extract as much gas initially from the URZ as possible, the Plan A1 and A2 extraction plants should go into a transition extraction mode, probably lasting 1-2 decades, in which less dense water is extracted from 360 m depth while still re-injecting degassed water as described for Plan B, thus facilitating as high a level of re-stratification as possible of the degassed water. The purpose of this is to minimize as much as possible dilution of the now expanding URZ.

When the 310 m gradient has been drawn down, getting close to the interim point of extraction (360 m), the gas extraction level should then be shifted by extending risers to being as close as technically feasible to the bottom of the lake, at approximately 460 m depth. CO_2 removal must be adjusted so that degassed water density allows it to re-stratify as close as possible to the lowest part (270 m depth) of the 260 m gradient.

If transition to MTR5 (Plan B) takes place after harvesting all gas from the URZ, then concessionaires are free to choose their extraction depth, including whether to go directly into extraction from 460 m depth.

G6: The challenges with MTR6 operations are very similar to those of MTR3 operations. It is expected that when gas extraction from the PRZ commences, enough experience will be available from Plan A1 to understand the precise implications for MTR6. After a few decades, concessionaires should be prepared for an order from the Bilateral Regulatory Authority to start gas extraction from the PRZ in case this has not already started on a voluntary basis.

G7: Compliance with MTR7 may be achieved by one of the following two constraints:

a) The maximum allowable operating pressure of the gas transported to shore must not exceed 8 bar(g). In this case, there is no restriction on how deep the pipe may be installed within the Biozone.

b) A pipeline floating below the surface must be constructed in such a way that it may never sink (in case of the failure of construction elements). In this case there is no restriction on maximum operating pressure.

An instrumented solution to ensuring safe pipeline design and operation is not considered to be sufficiently reliable in the long run, and is thus not acceptable.

G8: Examples of acceptable technical solutions relevant to MTR8 are:

a) The top of the broken-off pipe falls to rest at more than 70 m depth.

b) An automatic fail-to-close shut-off valve mounted below the depth where degassing theoretically begins, preferably at about 180 m depth.

G9: Emissions to the atmosphere need to be minimised. This requirement also applies to the avoidable flaring of produced gas, such as during the maintenance of power generation facilities or in case of reduced power demand from the transmission grid. The gas extraction capacity needs to be able to follow any variations in power demand from the grid or otherwise store or beneficially use the gas.

G10: In order to minimize variations over the year in temperature (and thus in density and in re-stratification level), washing water should be extracted at approximately 40 m depth. This will also minimize potential problems with:

a) Forming an explosive atmosphere in the washing system (such as after stopping gas extraction but with washing water still flowing, or during start-ups or operational upsets).

b) Organic growth in the absorber.

Operators should measure the oxygen concentration in relevant parts of the degassing system, and ensure that it does not reach dangerous levels.

<u>Additional guidelines (not linked to MTRs)</u>:

G15: Water extraction pipes should be located and designed to minimize the intake of sediments.

G16: Safety precautions during construction and operation should consider and cater for the risks from rising bubbles from the sediments on the lake bottom in case of:

a) anything heavy such as an extraction pipe being dropped to the bottom;

b) placing of anchors for floating facilities; and

c) underwater sediment slides or similar causes of spontaneous release of gas bubbles.

G17: One way of complying with the requirement for carbon dioxide removal that follows from MTRs 3, 4, 5 and 6 is to produce gas with relatively low methane concentration (e.g. 40 % or 50 %) and use biogas-type of engines for power generation. This minimizes the use of power for washing water and, at the same time, minimizes the amount of methane lost to the Biozone with the washing water.

G18: The water from the deeper part of the lake is highly corrosive, and caution is recommended in the choice of construction materials. For example, the use of coated carbon steel for the gas pipe to shore is not recommended because the volcanic rock can easily tear a hole in the coating and lead to rapid corrosion piercing a hole in the pipe.

G19: Facilities should be designed to permit the ready lifting and lowering of the extraction and re-injection pipes to enable inspection or to change the extraction or re-injection depths, as the Bilateral Competent Authority may require.

G20: Indications are that the existing Lahmeyer bathymetry curves are not accurate enough for construction purposes. Also, the sediment at the bottom of the lake is soft and anchors will sink some distance into it. Prior to detailed design, these factors should be further investigated.

6 Adoption of Extraction Methodology by the Expert Group

The Expert Working Group mainly discussed two principal but divergent methods for harvesting the methane from the lake, the Density Zone Preservation Method (ZPM) and the Density Gradient Draw-down Method (GDM).

The ZPM aims at maintaining the currently established density stratification of the lake. It is based on the idea that the density stratification is the main stabilizing force acting against a potential eruption of gases from the lake and forms a useful trap for the newly generated methane. It should thus be protected. Furthermore, it averts the transfer of nutrients and reduced substances, which are strongly enriched in the RZ (Pasche et al., 2009, Tassi et al., 2009), to a level above the major density gradient. From the re-injection level they would be slowly transported towards the surface by the lake-internal transport processes (Wüest et al., 2009, Schmid et al., 2005), with a barely predictable, but clearly negative range of effects on the lake ecosystem.

The GDM (Tietze, 2000, Tietze 2007b) aims at eliminating the gases from the lake as quickly and completely as possible. Gas-rich water is thus extracted from the RZ, and displaced above the RZ, by being re-injected above the main density gradient in order to draw down this gradient and removing all the gases dissolved in the RZ. The optimal re-injection depth for this method would have to be defined but is currently believed to be located as near as possible to the upper end of the PRZ. This re-injection level would enable the future harvest of the methane from the PRZ as well, while at the same time mitigating the upward transport of nutrients and other dissolved substances. The obvious advantage for extraction by this method is that it avoids any potential short-circuiting between the re-injection and the extraction points of the harvesting plants, as well as any dilution of the methane in the resource with re-injected water. The technical design of the harvesting plants in the GDM is simpler and therefore less prone to a short-circuiting failure than in the ZPM.

The simultaneous implementation of the ZPM and the GDM at a large scale would create incompatibilities. The lowering of the gradient by the GDM would require plants using the ZPM to continuously adjust their depths of extraction and re-injection to track the shifting gradients. The Expert Group therefore had to select a preferred option out of the two methods. After careful evaluation of the pros and cons of both methods, the majority of the Expert Group preferred the ZPM, while a minority preferred the GDM.

The Basic Principles and Technical Requirements described herein are therefore based on the assumption that the methane will be harvested using mainly the ZPM with the harvesting strategy as further outlined. It can be expected that the lake-wide monitoring as well as future research projects will improve our knowledge about the lake-internal processes. They will demonstrate the lake’s response to, as well as the efficacy of, the implemented harvesting strategy. Should these results ever indicate the need for changing the harvesting strategy, the present document would have to be reviewed and adapted accordingly.

The Expert Group, after being informed about the model for a Bilateral Authority including an Expert Advisory Group as was adopted in Copenhagen in May 2009, recommends to give this EAG an important role in this iterative adaptation process. The EAG should, among others, be charged with the continuous task of interpreting new insights and new data generated by the lake wide monitoring and by monitoring the ongoing operations.

7 Literature

The literature cited below provides more background information for understanding the basic principles, mandatory requirements and guidelines in this document. Inasmuch as the literature referenced has not examined the subject matter of gas extraction rules in the same detail as the expert working group herein, such references do not constitute a legitimate basis for objections to these prescriptions.

CHEN, C.T., and F.J. MILLERO (1986). Precise thermodynamic properties for natural waters covering only the limnological range. *Limnol. Oceanogr.* 31: 657-662.

HALBWACHS, M. (2007). Increasing Gas Content: Implications for Lake Kivu Monitoring and Extraction Strategies. Lecture at Workshop on Lake Kivu Monitoring, Ministry of Infrastructure, Republic of Rwanda, Gisenyi, 26 March 2007.[6]

HIRSLUND, F. (2007). Lake Monitoring and Design Constraints for floating gas extraction platforms. Lecture at Workshop on Lake Kivu Monitoring, Ministry of Infrastructure, Republic of Rwanda, Gisenyi, 26 March 2007.

KATAOKA, T., M. TSUTAHARA, and M. TANAKA (2000). Point sink flow in a linearly stratified fluid of finite depth. Physics of Fluids 12(11): 2775-2786

KLING, G., S. MacINTYRE, J.S. STEENFELT, and F. HIRSLUND (2006). Lake Kivu gas extraction, Report on lake stability, June 2006, 103 p.

LORKE, A., K. TIETZE, M. HALBWACHS, and A. WÜEST (2004). Response of Lake Kivu stratification to lava inflow and climate warming. Limnol. Oceanogr. 49(3):778-783

NYIRAHUKU, C. (2007). Ongoing methane gas Projects. Lecture at Workshop on Lake Kivu Monitoring, Ministry of Infrastructure, Republic of Rwanda, Gisenyi, 26 March 2007.

SCHMID M., K. TIETZE, M. HALBWACHS, A. LORKE, D. McGINNIS, and A. WÜEST (2003). How hazardous is the gas accumulation in Lake Kivu? Arguments for a risk assessment in light of the Nyiragongo volcano eruption of 2002. Acta Vulcanologica Vol14/15, No 1-2, p 115-122

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[6] Documents referenced may not be available in the public domain but shall be made available through the Bilateral Regulatory Authority or UPEGAZ in the Ministry of Energy, Rwanda.

SCHMID, M., M. HALBWACHS, and B. WEHRLI (2004). Report of the scientific expeditions to Lake Kivu in November 2003 and February 2004. Eawag

SCHMID, M., M. HALBWACHS, B. WEHRLI, and A. WÜEST (2005). Weak mixing in Lake Kivu: New insights indicate increasing risk of uncontrolled gas eruption. G3 Research Letter 6: Q07009, doi:10.1029/2004GC000892.

SCHMID, M. et. al (2007) Calculation sheet entitled Calculation of the optimal depth for the reinjection of deep-water after methane-extraction. Eawag.

SCHOELL, M, K. TIETZE, and S. SCHOBERTH (1988). Origin of the Methane in Lake Kivu (East-Central Africa). Chemical Geology, 71, 257-265

SOCIGAZ (1998). Textes réglementaires régissant le contrôle de l'exploitation industrielle du gaz méthane du lac Kivu. Société de contrôle de l'exploitation du gaz méthane du lac Kivu, Avril 1998.

TIETZE, K., and E. MAIER-REIMER (1977). Recherches Mathématiques–Physiques pour la Mise en Exploitation du Gisement de Gaz Méthane dans le Lac Kivu (Zaïre/Rwanda). Report No 76003, Bundesanstalt für Geowissenschaften und Rohstoffe, 2 Volumes, Hanover, 180 p.

TIETZE, K., M. GEYH, H. MÜLLER, L. SCHRÖDER, W. STAHL, and H. WEHNER (1980). The Genesis of the Methane in Lake Kivu (Central Africa). Geologische Rundschau, Vol 69, No 2, p 452-472

TIETZE, K. (1981). Direct Measurements of the In-Situ Density of Lake and Sea Water with a New Underwater Probe System. Geophysica, Vol 17, No 1-2, p.33-45.

TIETZE, K. (2000). Lake Kivu Gas Development and promotion-related issues: safe and environmentally sound exploitation. Report. Republic of Rwanda, Ministry of Energy, Water and Natural Resources, Kigali, 110 p.

TIETZE, K. (2005). Kibuye Stage 1 Project – Environmental Impact Assessment – Vol. II. Report. Elektrowatt-Ekono, Espoo, 157 p.

TIETZE, K. (2007a). Basic Plan for Monitoring, Regulating and Steering Exploitation of the unique Methane Gas Deposit in Lake Kivu: safely, environmentally soundly and with optimal yield”. P D T GmbH – Physik • Design • Technik, Celle, 180 p.

TIETZE, K. (2007b). Risk Assessment and Program for safe, environmentally sound and optimal Exploitation of the Lake Kivu Gas Deposit with the help of Monitoring, Regulating and Steering. Lecture at Workshop on Lake Kivu Monitoring, Ministry of Infrastructure, Republic of Rwanda, Gisenyi, 26 March 2007.

TIETZE, K. (2007c). How to organize Exploitation of the Lake Kivu Gas Deposit safely, environmentally soundly and optimally by harmonious cooperation between the Operating Companies and a Joint Rwandan-Congolese Supervising Institute. Lecture at Workshop on Lake Kivu Monitoring, Ministry of Infrastructure, Republic of Rwanda, Gisenyi, 27 March 2007.

WOOD, IR (2001). Extensions to the theory of selective withdrawal. Journal of Fluid Mechanics 448: 315-333.

WÜEST, A., G. PIEPKE and J. D. HALFMANN (1996). Combined Effects of Dissolved Solids and Temperature on the Density Stratification of Lake Malawi (East Africa). In Johnson and Odada [eds.] "The Limnology, Climatology and Paleoclimatology of the East African Lakes", *Gordon and Breach Scientific Publishers, New York*, p. 183-202.

WÜEST, A., JARC, L., SCHMID, M. (2009). Modelling the re-injection of deep water after methane extraction in Lake Kivu. EAWAG. Report to BTC, Govts. Of Rwanda and DR Congo