Regulation ruling the methane gas exploitation at lake Kivu

Scientific and technical proposition

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(Modification regarding the PRZ exploitation on November 2011)

Foreword

This text is currently at a draft state and likely contains omissions and imperfections. We wrote it in an emergency context with a very short deadline of 3 weeks, whereas the « Management Prescriptions for the Development of Lake Kivu Gas Resources » (MPs) document has been written by a 6 member expert comity over a 2 year time frame. In that condition, we therefore apologize for any possible imperfections, omissions or even

This text was not written primarily for the purpose of criticizing the MPs. We were very cautious about that point: each of our comments are carefully documented and supported by an alternate solution. We then proposed the technical process of exploitation (extraction and water rejection), which we thought was best for safety, environmental protection and efficiency of the extraction of methane.

Concerning the MPs, the two main criticisms that we held are directed at:

errors.

- The water re-injection option after degassing. We propose a fully different approach (cf. YLec Report GMW292, September 2009).
- A crucial omission in the MPs, regarding the lack of an optimized efficiency criterion for the gas exploited in the resource. We describe an energetic yield definition that sets the limits an extraction station will have to absolutely reach, if not exceed.

Note: the MPs especially focus on the selection and geometry of the concessions. We think that this selection is not related to any documentation governing the gas exploitation at Lake Kivu and is therefore outside the comity boundaries. We think that the choice for the concessions locations is the sole responsibility of the states involved.

We thus wrote a separate document presenting our ideas about the selection criteria outlining favorable sites for implementing the extraction stations.

A Criticism of Water re-injection as proposed in the MPs

Almost all the discussions that were held in the board experts leading to the MPs focused on the process of rejecting into the deep waters the degassed water coming from the device for gas-liquid separation (separator).

We do not concur with the solution chosen by the board experts. We hold it as inadequate for resource preservation, and technically infeasible. Besides, that decision has not been consensual within the comity. It has been drawn after confronting two points of view and was only adopted because it gathered the majority of the experts (MPs, p.36).

A detailed analysis of MPs has been made by the consulting firm YLec Consultant in the document "Exploitation of Lake Kivu Gas Resource, Consequences of the re-injection of degassed water into the Resource Zone", GMW292 Report, September 2009.

The conclusions from this analysis, particularly argued on the basis of hydrodynamic, are clear:

1) It's absolutely impossible to reject the degassed waters in a way that they themselves form an individual layer inserted between the layers of the resource. By diffusion, rejected waters will immediately mix in water rich in dissolved gases and lead to an irreversible dilution phenomenon i.e. a decrease of dissolved methane content.

2) The dilution of a layer of the resource leads to a rapid decrease in the efficiency of the extraction device. The flow of extracted methane decreases, and the layer in question becomes permanently unusable, at first economically and then finally technically.

3) The proposal is based on the idea of adjusting the density of rejected water by limiting the concentration of dissolved CO_2 at levels of 40 to 50 %.

For us, the CO_2 concentration is set by the depth of the separator (as an example, at 25 m, the CO_2 concentration in the rejected waters is about 70 %). If some sophisticated technique is able to regulate that CO_2 concentration to levels under 70 %, then it should be clearly stated and explained in the MPs.

One can't impose to reject water with 40-50 % of CO₂ without clearly explaining how to achieve such concentrations and describing the methodology. It's possible that such a technique is very complex and costly.

In conclusion, in our opinion, the method of water rejection proposed in the MPs is unrealistic to implement, impossible to control and leads to a considerable waste of the amount of methane contained in the resource. In an optimistic scenario, 30 to 50 % of the methane quantity in the resource could be extracted, using techniques hard to manage (e.g. concerning the decreasing rate over time) and probably expensive.

Missing Efficiency Criterion concerning gas exploitation

The omission of an efficiency criterion is surprising in a text aiming to define a sound, optimal and sustainable technique for the extraction of methane from Kivu.

An operator who uses a technology wasting 80 % of methane in the rejected water is not penalized compared to one that returns only 20 % of methane.

Moreover, an operator who consumes to operate its facilities 25 % of the electricity generated from methane extraction from its station is not penalized compared to an operator who consumes only 1 %.

We propose in our text to define a parameter of "minimum efficiency" to be met by any operator.

Summary and main conclusions

A simplified description of the physico-chemical structure of Lake Kivu underlines five distinct layers:

- Biozone (BZ)
- Intermediate Resource Zone : IRZ
- Potential Resource Zone : PRZ
- Upper Resource Zone : URZ
- Lower Resource Zone : LRZ

The methane extraction is done by taking water from the resource zone (URZ, LRZ), separation of gas and liquid (in the device called a separator), and degassed water reinjection.

Problem with degassed water rejection

The MPs arbitrarily impose to reject degassed waters into the layers where they have been collected.

The report by YLec consultants categorically dismisses this solution, by proving that such a process would lead to a dilution of the layer, to a dramatic decrease of the extraction efficiency, and would transform the layer's properties. That layer, which would still contain most of the methane, could no longer, ever, be exploited. It would be a vast and unacceptable waste of the resource.

In our report, we bring additional arguments again the MPs' method. For instance, we explain on page 26 that:

- There are vertical oscillations within the deep waters of the lake (this is called internal waves). The oscillations amplitudes can reach 2 to 4 m and thus make it impossible for an individualized degassed layer less than 4 m thick to be formed. Nor can rejections be sustained in a laminar mode, no matter how complex the system put in place would be.

- Adjusting the water density as proposed in the MPs (by regulating the CO_2 concentration) is technically unrealistic: one should know density at a better than 10^{-4} precision. No instrument can directly measure density with such a precision, whereas calculation from a combination of parameters measured in the water and a few constants also results in an insufficient precision, due to combined uncertainties on factors.

To sum up, it would be impossible to prove that the degassed water would form an individualized layer.

- Finally, some parameters, such as the temperature, greatly vary over a few years, for example in the URZ layer (located between the main and secondary gradient limits). This phenomenon may much complicate a precise monitoring of densities.

Regardless of the conclusions detailed in the YLec Report, the elements just cited would be sufficient by themselves to eliminate the rejection solution proposed in the MPs.

Degassed water rejection methodology that we advocate

In order to clarify the explanation, let us simplify the lake structure by considering only three generic zones (instead of five):

- the biozone and the intermediate zone (BZ-IRZ),

- the potential resource zone (PRZ),
- the resource itself (URZ -LRZ).

A fundament of our method comes from simulations of the potential resource zone (PRZ) exploitation. These simulations have been backed up by onsite experiments returns. Today, exploiting this resource zone is impossible in practice (technically as well as economically). Worse, as shown on page 11, even a liberal evaluation of the methane natural enrichment rate in the future doesn't bring hope for any realistic exploitation before several centuries.

We conclude that exploiting the methane of the PRZ layer cannot be done, neither now nor in the future.

Also, we should consider the impact of rejecting the degassed waters into the biozone and the intermediate zone. Though not being experts in lake ecology, we tend to follow the recommendations from most expert scientists who have studied the problem: they advise against this kind of rejection. Directly rejecting deep waters that are enriched with salt and nutritive elements (such as phosphates, nitrates, silicates) into the oxygenated biozone would lead to a major increase in organic production that would have disastrous ecological consequences to the lake environment (bloom algae, eutrophication).

Furthermore, the EAWAG studies clearly establish that the continuous ascending flow of water carries a major amount of nutriments up to the biozone. That ascending flow is generated by deep advective water supplies, especially at the main gradient level as well as at the gradient located at depth 190 m (above the potential resource).

The EAWAG experts clearly insist on the environmental risk linked to an increase of that flow and its related yearly nutriment supply into the biozone.

Consequently, rejecting those nutriment-rich waters into the intermediate zone is regarded as dangerous for the lake ecosystem.

To summarize, we face the following points to solve the degassed water rejection problem:

1- As mentioned before, it is practically and economically impossible to reject the degassed waters into the URZ and LRZ of the resource.

2- It is ecologically unwise and dangerous to reject those waters into the biozone, as well as into the intermediate zone.

3- The potential resource zone (PRZ) will never be exploited.

With those considerations at hand, the only viable, and in fact obvious, solution relies on rejecting the degassed waters into the potential resource zone (PRZ). This way, the resource will steadily be extracted during the exploitation process, while its characteristics will be maintained, and without affecting the upper zone of the lake (the biozone and the intermediate zone, BZ-IRZ).

Extraction process main principle

Water is rejected into the potential resource (PRZ) right under it's upper limit.

This salt-enriched water, due to it's higher density, will diffuse downwards through the PRZ and intimately mix with it. The layer formed by this mixture will thicken, and its density will increase, while remaining homogenous. This results in a subsidence of the waters above the collecting point.

As will be seen on page16, it is possible to start exploiting the methane

- either by the upper resource zone (scenario A),
- or by the lower zone (scenario B).

Choosing one scenario relies on several criteria, some in favour of A, others in favour of B. It is therefore difficult to strictly define the best one.

Criterion 1 – Gradients resistance during the exploitation.

This point is discussed in details on pages 20 and 21. Scenario A, which starts with the exploitation of the upper resource, is preferred, primarily to preserve gradient zones strong enough to isolate the resource zone from the zone resulting from the mixture of the PRZ and degassed waters.

Indeed, in scenario A, this gradient presents a minimum span of 0.9 kg/m³ at the final stage of the exploitation of methane. In scenario B, this gradient's span is only 0.4 kg/m³ at the final stage of the methane exploitation.

Nevertheless, the phenomenon of layers subsidence, which keeps unchanged the shape of the density gradients, has been validated in practice during the degassing of Lake Monoun (see page 24), where rejecting above a gradient the water collected below it did not trigger a de-stratification phenomenon.

Criterion 2 - Evolution of the gas explosion risk

This question is treated on page 23.

Scenario B, starting with the lower resource, is for this concern much more secure.

Criterion 3 - Economical Aspects

Scenario B is on the whole more interesting. Exploiting the LRZ is much more effective than the URZ, thanks to its high methane concentration. For a given geometry of the station, the extraction flow is about 1.5 times larger in the scenario B as compared to A. Moreover, the LRZ contains twice more methane than the URZ.

On the other hand, scenario A, which occurs at shallower depths than B, beneficiates by the proximity of the shore and thus requires a shorter pipeline.

Given that the exploitation of the resource will spread over several decades, a continuous follow-up of the impact along the different criteria mentioned above should allow to correct the original plans and possibly modulate the mode of extraction from scenario A or scenario B, by exploiting both the URZ and LRZ in such proportions as to still preserve strong gradients and also reduce the risk of explosion.

Energy efficiency of the resource

In order to maximize the exploitation efficiency of the latent energy in the resource, the energy waste has to be reduced as much as possible. As little as possible of methane must be returned with the rejected water.

For sure, the overall process must also minimize the electric power required to operate the plant/extraction station itself, but we particularly focus on reducing the methane loss in the rejected waters. We take this as the key point in the extraction process efficiency.

Methane loss through rejection occurs at two places during the liquid-gas separation, and during gas washing (methane enrichment step, achieved by preferential dilution of the CO₂ contained in the original gas mixture).

The methane loss during the wash phase can be calculated (within a given error margin) against the methane concentration we want to reach.

On the other hand, the methane loss taking place in the liquid-gas separation can't be easily determined: it is directly linked to the extraction process itself. We insist that techniques will have to be developed to measure the dissolved methane concentration in the rejected waters.

We consider vital, to ensure a sustainable exploitation of the resource, that the maximum concentration of methane tolerated in the rejected water should be clearly defined. This limit may depend on the operated zone, which may be more or less rich in methane, depending on whether the water is collected from the URZ or from the LRZ.

Logically, the use of any facility exceeding this limit should be prohibited or at a minimum be subject to penalties.

1 – Lake Kivu Structure

Water density

The water density profile is an essential consideration in maintaining the lake stability, picking the optimal gas enriched water rejection process and in estimating the gas explosion risk.

The Lake Kivu waters are clearly organized in stratifications according to variations of their physical and chemical parameters at different depths.

The reasons for this stratification phenomenon are complex. The various layers in the lake separate in homogenous strata - where mixing is easily achieved by convection – and are kept individualized thanks to the boundaries formed by the high gradient density levels. The physical and chemical structure of the lake follows a staircase schema as shown on the figure below where a density curve is displayed. We clearly distinguish the strong gradient zones separating the homogenous layers.

We will pay particular attention to the high gradient zone located around 260 m, which works as a trap for the dissolved gas in the deep layers.



The structure of the lake can be roughly divided into 5 more or less homogenous zones that are delimited by density gradients more or less marked.

The biozone (BZ) is formed by the shallow alive surface layer of the lake. Its oxygenated portion varies between a depth of 30 to 60 m, depending on the seasons.

The Intermediate Zone (IZ), between 90 and 190m, is not methane rich enough to be exploited in the future.

The Potential Resource Zone (PRZ), between 190 and 260 m, has a not-so-small content of methane, but we will see that its low concentration doesn't make it worth exploiting, even in the future.

A density gradient is clearly marked at a depth of 258m. It is called the main gradient and it delimits the lake into its methane exploitable zone, hereafter called the resource (below it) and the one that is not (above it).

In the resource, we distinguish the upper zone (URZ) between 260 and 310 m from the lower zone (LRZ), which stands between 310 m and the deepest point of the lake at 485 m. Those two layers are clearly separated by a gradient called the secondary gradient.

The water density varies accordingly to several physical and chemical parameters:

- it decreases when the temperature increases,

- it increases with salinity (ion concentration characterized by the electric conductivity parameter),

- it increases along with the dissolved CO₂ concentration,

- it decreases along with the dissolved methane concentration.

Fresh water is linked to the temperature T (between 23 and 26°) by the following expression:

$$D(T) = 1.00332 - 2.56 \times 10^{-4} T$$

Density is expressed as follows :

$$D(T, C, CO_2, CH_4) = D(T) \times (1 + \beta C + \beta_{CO2} CO_2 - \beta_{CH4}CH_4)$$

where

T is the temperature in degrees Celsius

C is the conductivity in mS/cm ; $\beta = 8.826 \ 10^{-4}$

CO₂ is the CO₂ dissolved concentration in L_{gas}/L_{water} ; $\beta_{CO2} = 5.576 \times 10^{-4}$

CH₄ is the dissolved methane concentration in L_{gas}/L_{water} ; $\beta_{CH4} = 8.945 \times 10^{-4}$

On the figure below, we plot the density dependence versus depth for several curves, to show separately the effects of each parameter.

D(T) is the density of fresh water at the lake temperature,

D(T,C) is the density of the water at the lake temperature and conductivity,

 $D(T,C,CO_2)$ is the density of the water at the lake temperature, conductivity and CO_2 concentration,

 $D(T,C,CO_2,CH_4)$ is the water density at the temperature, conductivity, CO_2 concentration and CH_4 concentration.

We clearly note that salinity (measured from electric conductivity) is a major actor over density.



Density profiles calculated from the physico-chemical parameters of the lake waters

2 - Methane extraction problem

Effect of the separator depth

We plotted (below, left) the curves of the methane flow vs. the separator's depth. The rate is expressed under a normalized form, i.e. as a percentage to the best obtainable flow, namely the one obtained when the water comes from the deepest layer and the separator is placed at depth zero.

The two curves correspond to water coming respectively from the URZ and from the LRZ. We can see that the flow increases when the separator's depth decreases.

We also plotted (below, right) two curves showing the percentage of CH_4 (respectively CO_2) contained in the rejected water, while supposing that both water and gas are at equilibrium in the separator. More precisely, the percentage of CH_4 (respectively CO_2) is the quantity of CH_4 (resp. CO_2) dissolved in one unit of rejected water, divided by the quantity of CH_4 (respectively CO_2) dissolved in one unit of liquid arriving on top of the extraction column. We observe that the methane loss increases along with the depth of the separator.

Thus, two considerations tend to favor placing the separator at shallow depth.



Meanwhile, as shown by the third schema, placing the separator at shallow depth has some undesirable consequences:

- the methane richness (proportion of gaseous CH_4 over total gaseous mixture CH_4 plus CO_2) decreases when the separator is placed less deep,

- and the void fraction (gas flow divided by total flow of water plus gas) strongly increases, threatening to induce an inadequate flow regime, as described further.

Diphasic flow typology



On the above chart, we have represented the results obtained during many experimental surveys on lakes Nyos, Monoun, Kivu and the gulf of Kabuno.

Depending on the void fraction level in the diphasic flow, different modes may appear:

1 - bubbles flow: bubbles are scattered in the liquid (we distinguish finely scattered bubbles from simple bubble modes)

2 - and 3 - intermittent flows: the gas pockets are coalesced into bigger churns which are separated by liquid corks.

4 - annular flow: The liquid phase is then preferably released on the walls, the heart of the gas flow vehicle liquid droplets.

Intermittent flows happen when the void fraction is greater than approximately 25 %. They appear suddenly, without warning, and are dangerous since they generate vibrations and even shocks in the structure. Also, they prevent the component exchanges (CO_2 and CH_4) between the liquid and gaseous phases, and therefore harm at reaching an equilibrium state. Finally, they penalize the efficiency of the liquid flow conveyed by the gas bubbles.

That void fraction level of 25 % also corresponds to the limit before bubble coalescence takes place which can be observed in semi-industrial bubble columns.

To conclude, the depth of the separator should be set in order to circumvent unstable flow modes.

Taking this into account along with what has been described in the previous pages advises to position the separator at a depth of 20-30 m.

Quality factor of a layer versus its methane concentration

Layers	Water (km ³)	Average density	CH₄ (km³)	Concentration CH ₄ (L _{meth} /L _{liq})	
0 m - 60 m	133	998,352	0	0	biozone
60 m - 190 m	219	999,435	10,5	0,045	Intermediate zone
190 m – 260 m	84	1000,175	9,5	0,10	potential ressource
260 m – 310 m	49	1001,447	16	0,34	ressource : upper layer
310 m – 480 m	74	1001,882	30	0,414	ressource : lower layer
Total	559		65,7		

The table below summarizes the capacities and concentrations of the methane in each layer.

Each layer of the resource (potential, upper, lower) is determined by two parameters, one quantitative, and the other qualitative.

- The quantitative parameter consists in the whole quantity of methane in the layer,

- The qualitative one consists in the ability of the layer's water to activate the self-maintained siphon process.

Using a computer code on the two-phase flow has shown that it is essentially the concentration of methane which acts as the main factor in the self-siphon process efficiency, and therefore on the flow of extracted gas. In fact, it is the methane itself that triggers the gas ex-solution in the column, due to its low solubility in water. The CO_2 has only a relative marginal role in the process.

This factor has an important consequence when considering the potential resource PRZ. The quantity of methane contained in the PRZ is not negligible (9.5 / 65.7 = 14 % of the overall resource), but the low methane concentration there (0.10 L_{gas}/L_{water}) makes the layer non-exploitable.

The same law on un-ability to extract low concentrated methane holds when diluting a layer. This important topic is developed in the YLec Report.

Exploitability of the potential resource layer (PRZ)?

In the figure below, we plotted methane concentration (relative to the maximum concentration of dissolved methane at 350 m, inside the LRZ, rated 100 %) versus the flow of methane (relative to the maximum possible flow, rated 100 %). Each curve corresponds to a specific depth for the separator location.

As a first example of the effect of methane concentration on the available flow, let's extract from the URZ, the methane concentration in which is 0.34 $L_{methane}/L_{water}$, that is 82 % of the concentration in the LRZ (0.414 $L_{methane}/L_{water}$), and let's place the separator at a 20 m depth. Using the 20 m chart curve, an 82 % on the bottom axis leads to a 68 % on the left axis, meaning that the flow of methane would reach 68 % of the maximal possible flow.

Now consider the extraction from the potential resource layer PRZ, the methane concentration in which is 0.10 $L_{methane}/L_{water}$, that is 25 % of the concentration in the LRZ (0.414 $L_{methane}/L_{water}$). With such a low concentration of methane, the requirement that the void fraction level should be less than 25 % can still be met, provided one places the separator at depth 0.

The curve for depth 0 associates to a 25 % on the bottom axis a poor 12 % on the left axis. That's the best flow we may hope for from the PRZ.



Even if we assume that the methane concentration could be multiplied by 1.5 for some natural reasons over the next century (which is very unlikely, since the present estimations rather consider this multiplicative factor to be 1.3), the fraction of flow delivered would increase from 12 % to only 18 %.

Clearly, the idea of exploiting the PRZ must be definitely abandoned.

Water density variation taking place in the gas separation phase

We recall that the density, according to those parameters, is defined by:

$D(T, C, CO_2, CH_4) = D(T) \times (1 + \beta C + \beta_{CO2}CO_2 - \beta_{CH4}CH_4)$

During the gas separation from water, the temperature and the salinity stay constant (we can ignore the cooling factor of the gas expansion in the extracting column, as it almost remains at an isotherm).

If we only consider the influence of the $\beta_{CO2}CO_2$ and the $\beta_{CH4}CH_4$ terms, we notice that whatever takes place during the liquid-gas separation, at depths greater than 20-25 m the $\beta_{CO2}CO_2$ term wins over the subtracted $\beta_{CH4}CH_4$ term. The water rejected by the separator retains the majority of its CO_2 whereas it releases almost the entire methane. A crucial consequence is that the water exiting the extraction column has a higher density than the entering one.

We have already mentioned that the separator is located between 20 and 25 m. In examining the adjacent figure, we can therefore consider that the water outlet of the separator will present a density almost equal to that of the water taken from the resource.



3 - Strategy to reject the degassed water

The water rejected into the lake after being degassed causes a few tricky problems:

- environmental protection of the lake (especially of the oxygenated layer, called biozone),
- resource protection (protecting its integrity, especially its dissolved gas composition),
- reduction of the gas explosion hazard,
- efficiency of the technology used in order to maximize the methane extraction against the maximum capacity of the resource,
- stability of the lake stratification,
- cost efficiency of the extraction process, concerning installation and energetic consumption while operating.

Extraction Requirements

The requirements have been graded by importance (in our opinion).

1) Preserve the biozone integrity for a depth of 0 to 60 m.

2) Reduce as much as possible the rise speed of salts-loaded water in order to reduce the impact that these nutriments would have on the biotope.

3) Reduce the loss of methane rejected at the separator and scrubber levels in order to increase the efficiency of the plant exploitation.

4) Preserve the role of high density gradient zones as barriers to water mixing and «methane traps», in order to take advantage of the natural methane enrichment process (the importance of which is, to date, not accurately known).

5) Fully avoid gas rejection into the atmosphere during normal extraction operations.

6) Check that the deployed process increases the security of the lake by reducing the gas explosion hazard. To this end, favor the subsidence of the layers of water situated at or deeper than the main gradient zone, especially at levels 270 and 320 m, where dissolved gas is at its nearest (60 %) to saturation.

7) Return as much CO_2 as possible via the water rejected from the separator in order to avoid releasing this greenhouse gas into the atmosphere*.

8) Use an extraction process that is compatible with the economical and financial constraints (optimize the cost of the extraction system)

9) Maintain the lake stability by avoiding as much as possible to weaken the density differences between the deep and the shallow water layers.

^{*} Note: the estimated 300 km³ of CO₂ available represent, as a carbon credit, a total value of ≤ 2 billions (currently at ≤ 13 /ton). Moving from an efficiency of 40 % advocated by the MPs to 70 % with the method we promote would result in a gain of ≤ 600 millions.

Exhaust place for rejected water

Where to reject degassed water can be decided straight from the degassed water rejection methodology.

- We have outlined in the YLec Report what would be the consequences of degassed water rejection into the LRZ and URZ layers (that is, directly into the resource itself). The mixing of that water would automatically lead to methane dilution inside those layers and to a major waste of the resource (this is incompatible with the requirements 3 and 8). It is therefore not conceivable to reject into the layers forming the resource.

- We think it very important to keep the low density water cover formed by the biozone BZ and the intermediate zone IZ intact, this both to reduce explosion risk and limit the upward flow of nutrients. Note that the density gradient consisting of those two layers on a 190 m thickness represent 2.1 kg/m³, which is approximately one half of the full gradient between the bottom and the surface of the lake. This way, we comply with requirements 1, 2 and (partly) 4.

For economic reasons, the rejection of the degassed water cannot be performed in the resource.

For environmental reasons, it seems prudent that this rejection should not occur in the biozone, or even in the intermediate layer.

Furthermore, we pointed out earlier that the exploitation of PRZ was not economically viable, even in the long term.

<u>From the three previous comments, the rejection process follows naturally.</u> <u>Degassed water can only be rejected into the potential resource (PRZ):</u>

- either we collect the water in the LRZ and reject (and mix) it into the PRZ,
- or we collect the water in the URZ and reject (and mix) it into the PRZ.

The following figures show that the strong gradient zones shapes are preserved while using this process (requirements 4 and 9) and that the gas enriched layers subside in a satisfactory manner, including avoidance of deviating to hazardous conditions of gas explosion (requirement 6).

To conclude, the rejection procedure presented here fully respects all the requirements expressed before, as much for the lake environment protection as well as for the security, optimization of the economical efficiency and cost of extraction.



Generic extraction procedure

The procedure presented here is simple to put in place.

Step 1 – We start by exploiting the URZ layer (respectively: the LRZ) while rejecting the degassed water into the PRZ (via a simple system favoring the water mixing). During this process, the layer initially called PRZ deserves a more descriptive name such as {PRZ+URZ} (respectively: {PRZ+LRZ}), because all three of its total content, lower limit and density keep changing.

At the end of step 1, the volume of {PRZ+URZ} (resp.: {PRZ+LRZ}) is the sum of former PRZ and former URZ (resp.: LRZ) volumes; and its density is calculable from the densities of these former layers.

Note: we have already mentioned that the rejected water density at the separator is practically identical to the density of the water collected in the resource.

Step 2 – We exploit now the remaining other layer of the resource, that is the LRZ (resp.: URZ) and we start returning and mixing the degassed water into {PRZ+URZ} (resp.: {PRZ+LRZ}) which we'll from now call {PRZ+URZ+LRZ}, the volume of which keeps increasing, along with its density and lower limit depth.

After the exploitation completes, the final volume of {PRZ+URZ+LRZ} is the sum of the volumes of the initial PRZ, URZ and LRZ layers; its density can be calculated from the densities of these initial layers; and its lower limit is the lake's floor.



Hypsometric curve of Lake Kivu (10 m thickness steps) and today's occupation by distinguished water layers.

Green:	biozone (BZ)
Light blue:	intermediate zone (IZ)
Orange:	potential resource (PRZ)
Dark blue:	upper resource (URZ)
Red:	lower resource (LRZ)





Evolution of the gradient zones

(See pictures on precedent pages)

The main evolution mechanism between figure a (today's state) and figure d (stage at the end of the total exploitation) is pretty simple.

If we first exploit the URZ, the depth level of the main gradient (situated on top of the URZ, originally around 260 m) tends to get deeper.

If we first exploit the LRZ, then the depth levels of both gradients, main and secondary one (situated on top of the LRZ, originally around 310 m) get deeper.

In both cases, the density amplitude of the gradient zone situated and staying at depth 190 m increases and the density of the mixture layer increases.

> Scenario A : the taking is done at first in the URZ , then in the LRZ

Starting from Figure a, leading to Figure b: exploiting the URZ

During this phase, we can observe that:

- The main gradient level undergoes a subsidence, dropping from 260 m to 310 m, before disappearing when the URZ is exhausted. The main gradient-secondary gradient couple (which had a combined density ranging from 1000,0 kg/m³ to 1001,9 kg/m³) turns into a single gradient ranging from 1000.6 kg/m³ to 1001.9 kg/m³, situated at 310 m.

- The gradient zone situated at 190 m is reinforced: it used to range from 999.6 kg/m³ to 1000.0 kg/m³, and now it ranges from 999.6 kg/m³ to 1000.6 kg/m³.

-The evolving {PRZ+URZ} layer, originally constituted of the sole 70 m thick PRZ, turns into a 120 m thick layer, where the former PRZ content is mixed with the rejections of the former URZ. The density of {PRZ+URZ} increases from 1000.0 kg/m³ to 1000.6 kg/m³.

then from Figure b, leading to Figure d at end of total exploitation: exploiting the LRZ This phase induces the following transformations:

- The new gradient level (resulting from the disappearance of the URZ layer) drops from 310 m down to a final 485 m (bottom of the lake) when the LRZ is exhausted.

-The gradient at 190 m continues being reinforced. It ranged from 999.6 kg/m³ to 1000.6 kg/m³, while at end it ranges from 999.6 kg/m³ to 1001.0 kg/m³.

-The {PRZ+URZ } mixture layer, now called {PRZ+URZ+LRZ }, keeps on thickening. At end it is 290 m thick and lies between depth 190 m and the bottom of the lake. Meanwhile its density increases from 1000.6 kg/m³ to 1001.0 kg/m³.

> Scenario B : the taking is done at first in the LRZ, then in the URZ

Starting from Figure a, leading to Figure c: exploiting the LRZ

During this phase, we can observe that:

- The secondary gradient level undergoes a subsidence, dropping from 310 m to 350 m.

- The main gradient zone disappears.

- The gradient zone situated at 190 m is strongly reinforced: at start it ranges from 999.6 kg/m³ to 1000.0 kg/m³, at the end of the phase it ranges from 999.6 kg/m³ to 1000.9 kg/m³.

- The thickness of the evolving {PRZ+LRZ} mixture layer augments from 70 m to become 160 m, while the density in this layer increases from 1000.0 kg/m³ to 1000.9 kg/m³.

-The gradient situated at depth 350 m at the end of this phase ranges from 1000.9 kg/m³ to1001.4 kg/m³. This weak range makes the gradient not very apt to act as a trap. From this point of view, scenario B seems less appropriate than scenario A.

then from Figure c, leading to Figure d at end of total exploitation: exploiting the URZ This phase induces the following transformations:

- The gradient level resulting from the LZR layer disappearance drops from 350 m, down to 485 m (the bottom of the lake) when the content of the former URZ in its turn gets exhausted.

- The gradient at 190m (which ranged from 999.6 kg/m³ to 1000.9 kg/m³) is slightly reinforced and now ranges from 999.6 kg/m³ to 1001.0 kg/m³.

- The {PRZ+LRZ+URZ} layer thickens and at end resides from depth 190m down to the bottom of the lake. Meanwhile, its density increases from 1000,9 kg/m³ to 1001.0 kg/m³.

In both scenarios, by the end of the exploitation the overall stability of the lake would be slightly diminished, due to the fact that the density at the bottom of the lake decreases from 1001,9 to 1001.0 kg/m³.

Discussing both scenarios

In this discussion, we mainly focus on what characterizes the density gradients separating the resource zone from the PRZ (more precisely: from the zone the content of which is the mixture of the initial PRZ content and the degassed rejected waters). Those gradients will act as a methane trap as usual, but should also prevent the two zones from mixing by diffusion.

Comparing both scenarios will specifically be focused on their ability to constantly maintain the presence of "strong enough" gradient zones.

Recall that the density gradient is a function of depth z synonymous to the derivative function (or slope) of the density vs. depth function.

A "strong" gradient zone is such that the density gradient has a high (ideally infinite) value for z in that zone. There is in the zone a depth z_M for which the gradient function shows a (local) maximum (which might at extreme be infinite). Before and after z_M the gradient is less than for z_M .

This corresponds to an inflexion point in the density vs. depth curve.

Given the way axes are disposed on our drawings: a strong density gradient shows concretely as an almost horizontal portion of the density curve around z_M . This is what mostly characterizes a good ability to act as a boundary preventing mixing the methane-rich zones with the poor ones.

Of course, this "strong enough" quality is somewhat subjective and not quantifiable but we will favor any solution tending to reinforce those barriers against mixing.

Scenario A is more secure since it always maintains a gradient strong enough to play the barrier purpose against mixing: from the case shown on Figure b to the one on Figure d, the span of the barrier gradient decreases from 1.4 kg/m^3 down to 0.9 kg/m^3 in the very last phase of the exploitation (as a reminder, the main gradient has a current span of 1.4 kg/m^3).

Concerning scenario B, the barrier gradient is only 0.5 kg/m³ at mid-exploitation on Figure c, and slightly decreases down to 0.4 kg/m³ while moving from Figure c to Figure d.

4 – Misc. fundamental and technical facts

Gas explosion risk evolution during the exploitation

A gaseous phase that can trigger an explosion (limnic eruption) appears when the sum of the partial pressures of the various dissolved gas equals the hydrostatic pressure. We see on the following figure that two zones are actually concerned, at depths 270 m and 330 m, where the cumulated gas pressure is around 55-60 % of the hydrostatic pressure.



Calculation results from our measurements of the levels of CO₂ and CH₄, November 2003 survey

The degassed water rejection method that we recommend must insure a risk decrease at all depths and all times. We won't detail the optimization of the water collection/rejection process that is explained on pp. 18-19 of the document.

We will just underline a major difference whether we begin the extraction from the lower zone (fig. b, p.18) or the upper zone (fig. c, p.19)

We easily can figure the case where the extraction first starts with the upper zone. We suppress the layer between 260 and 310 m, without touching the lower resource.

Concerning risk, we eliminate all threats between 260 and 310 m, and thus, the zone close to 270 m is secured. Note that the risk remains unchanged at 310 m.

On the opposite, if we first start the extraction in the lower zone, it is the entire layer between 260 m and the collection point (for example, the bed of the lake) that gradually disappears. In that particular case, all the layers above the collecting point are subjected to the subsidence during the exploitation. In particular, the zones around 270 and 310 m will subside to a more secure context.

It is obvious that first starting with the lower zone extraction presents a major advantage in terms of safety.

Structure of the lake after total degassing (in the distant future)

If you look at figure d on page 18, the final structure of the lake is divided into three parts: From surface to depth 190 m, one finds the biozone and the intermediate layer, which remain unchanged; Between 190 m and the bottom, there is a mixture of the rejected degassed waters.

In today's initial state of the lake (figure a, page 18) the main gradient located at depth 260 m, with a span of 1.4 kg/m³, constitutes the trap for methane.

In the final state (figure d, page 19), there is a new gradient, with roughly the same span (1.4 kg/m³), but located at 190 m, that is 70 m higher than in today's state. It is quite possible to predict that the new gradient will constitute an efficient trap for methane.

In the centuries (millennia?) to come, it is possible that the methane concentration at 190 m will reach such intensity that a new exploitation could be envisaged, including the ability to balance the extraction rate of recharge of the lake with gas. At depth 190 m, the saturation concentration of methane is 0.57 $L_{methane}/L_{water}$: with such gas content, the extraction of methane would be particularly easy.

Gradients sensitivity resistance to the gas extraction

An important point, the issue of which was not evident, is the possibility of a destratification of one gradient when collecting the water under it and rejecting it above it.

That point has been handled during degassing Lake Monoun, which has a structure relatively close to that of Lake Kivu.

Before degassing Monoun in 2003, we clearly noticed a density gradient at depth 25 m that was caused by a high salinity, followed by a second gradient at depth 55 m, caused by the presence of CO_2 . During the degassing from 2003 to 2007, the water was collected at the bottom of the lake and rejected at surface level. The subsidence of the layers has been monitored by following the conductivity parameter.

On the chart presented below, we note that the conductivity curves all show a clear subsidence, without distortion and without any de-stratification phenomena. Both gradients have been moved down but remained perfectly individualized until the gradient related to the dissolved gas presence fully disappeared once degassing was over (between July and November 2007).

In parallel to Monoun, Lake Nyos degassing began with installing a column in 2001. In March 2011 two extra columns with a greater diameter were added, hence multiplying by 8 the total degassing rate. Observations rather similar to those from Monoun were made, as to what concerns the subsidence of the strong density gradient level which laid at first at depth 185 m. The level simply moved down. However, a slight de-stratification could be observed, before the level finally disappeared in 2007.

We're reassured by these results about the density gradients staying strong and surviving during the extraction.



Studies conducted by EAWAG have shown that density gradients are linked to sources supplying the lake (coming from the North coast of the lake, made of the Virunga volcanic natural dams).

Without getting into details, the total underwater water supply has been estimated (Wuëst, 2011) to 1.3 km³/year. As a reminder: the Ruzizi river, the only exit for water from the lake, has a flow of 3.2 km³/year.

According to a model made by EAWAG, the water flow coming from the sources at depth 260 m is about 0.47 km³/year, when the sources at 190 m supply the lake at 0.69 km³/year.

According to the exploitation method that we propose, the gradient should undergo a subsidence whose speed will depend on the flow of water taken from the resource. It is difficult to predict what will be the influence of advective water flows on the main subsidence gradient. On an area of 1000 km², the layer of water produced each year by the advective sources reached a substantial thickness of about 50 cm. The depth and overall appearance of the main gradient must be followed experimentally.

We believe however, without absolute certainty, that the source water should run along the coast and spread over the main gradient, while diluting at the same time. We do not believe that stratification of the main gradient would be significantly modified by the addition of water.

Hindrances to the rejection method advocated by the MPs

The degassed water rejection process advocated by the MPs relies on the hypothesis that it is possible to pick a density gradient zone and use a sophisticated – and poorly detailed - rejection system, to form a degassed layer that is totally individualized from the surrounding methane bearing waters. That layer would supposedly spread on the entire lake's area at the rejection depth. This assumption seems unrealistic.

From the MPs, the area of the lake at those depths reaches about 1000 km². That would mean that such a water layer would spread over distances up to 18 km without showing any sign of diffusion process into the surrounding waters. And even if such a layer was fully formed, it would mix anyway over time and lose its individuality.

Also, the MPs mention a system that would allow a laminar flow of rejected waters. At first, each flow is laminar, but it always turns into turbulences. In addition we also have to consider the mechanical oscillations taking place in the lake depth that are generated by the wind. This phenomenon, called internal waves, can show significant amplitudes. At Lake Kivu, the following figure describes the internal waves mechanism where experimental observations have revealed vertical amplitudes in the range of 2 to 3 m at depth 315 m. That would suffice by itself to cause the rejected waters to mix, no matter what system would be put in place.

A further problem comes from internal waves:

The MPs insist that the density of rejected water should be equal to the water density at the point of rejection. For the rejected water to remain as an individual layer, rejection should be done at a depth where the density gradient is strong enough. The depths proposed by the MPs correspond to the lower margin of the main density gradient zone (plans A1 and B) or of the secondary one (plan A2). But the necessary precision of the reinjection level will be defeated by internal waves, which will provoke an equivalent of 4 m ample oscillations in the reinjection point depth. This movement in a zone of high density gradient will certainly impact its integrity, and possibly cause a de-stratification.



Schematic mechanism of internal waves in Lake Kivu provided by EAWAG

Finally, variations occur in the physical parameters of the layers affected by discharges proposed by MPs. The variations occur at time scales that are small (few years) and it is difficult to imagine how an adjustment of the densities of discharged water requiring precision in the order of 10⁻⁴ in the measurements will be able to follow such changes in time. One can even imagine, given the rapid temporal evolution that occurs in layers on both upper and lower face of the secondary gradient, that this gradient will one day be brought to disappear naturally.



Stratification variation over time (Martin Schmid, EAWAG, personal communication): mixed layers from Lorke (2002) have vanished, temperatures increased significantly between 2002 and 2006 at depths 270 to 300 m and 320 to 370 m.

5 – Energy efficiency of the resource exploitation

The goal of methane extraction at Lake Kivu is to exploit as much as possible of the latent energy lying in the resource. It's thus obvious that the extraction process has to be optimized according to economical efficiency criteria.

We won't mention the energetic efficiency achieved when transforming the thermal energy from the gas mixture combustion. It takes place in the engines of the generators providing electricity to the local network.

In order to draw a simplistic energy balance sheet of a methane extraction station, we will highlight the following parameters:

- 1) The electric power produced by the station, to be called α .
- 2) The electric power consumption of the station (notably for pumps and compressors), to be called β .

The electric power delivered to the network will be $\alpha - \beta$.

We can already estimate the electric efficiency $\eta_{electric}$ by dividing the power delivered to the network by the power produced by the station:

$\eta_{\text{electric}} = (\alpha - \beta) / \alpha$

To simplify, we will chose a common unit to express the energy carried by the methane: it will be the volumetric flow rate of the pure methane (at $0 \,^{\circ}$ under 1 atm when the methane is in its gaseous state).

- o The energy received at the station comes from the methane dissolved in the resource water. The methane flow rate received by the station is defined by the liquid flow in the column multiplied by the methane concentration in the collected water. The methane flow in the column will be called ε .
- o The energy wasted by the station can be split into two parts:
 - methane returned with the separator's rejected waters, called y,

- methane returned with the scrubber's rejected waters during the gas enrichment, called $\boldsymbol{\delta}.$

The total methane flow that is wasted would then be $(\gamma + \delta)$.

The gaseous methane flow available at the output of the station is expressed by the difference between the methane collected and the methane lost during the separation and washing: $\lambda = \varepsilon - (\gamma + \delta)$

The station efficiency in terms of methane recovery can be defined by simply dividing the flow of available methane at the exit by the flow of methane collected at the station:

$\eta_{\text{methane}} = \lambda / \epsilon$

Put in another way involving the wastes γ et δ :

$\eta_{\text{methane}} = 1 - (\gamma + \delta) / \epsilon$

The total efficiency of the station, including the electric efficiency, writes:

$η_{total} = [(α - β) / α)] x [1 - (γ + δ) / ε]$

Examples of some energy efficiencies versus technology put in place

Let's imagine four (realistic) stations and determine their related energy efficiencies. We assume that we collect the water in the LRZ and that the separator is located at depth 20 m. We also assume that we aim at a 65 % methane concentration.

i) Ideal station:

It doesn't consume electricity: $\beta = 0$; electric efficiency = 1.

It rejects 7 % of the methane flow ϵ at the separator's level (gas-liquid equilibrium at depth 20 m): $\gamma = 0.07 \epsilon$.

It produces a gaseous mix enriched at 65 % of methane. In those conditions, the formulas predict a 6 % methane loss at the scrubber level: $\delta = 0.06 \epsilon$.

Applying the formula box above leads to: $\eta_{total} = 0.87$.

The energy efficiency is 87 %.

ii) Realistic station of good execution:

This station consumes 1 % of electricity: $\beta = 0,01 \ \alpha$; electric efficiency = 0.99. It rejects 13 % of the methane flow ϵ at the separator's level: $\gamma = 0.13 \ \epsilon$. The loss at the scrubber level is still 6 % of methane: $\delta = 0.06 \ \epsilon$. The formula box above will give $\eta_{total} = 0.80$. The energy efficiency is 80 %.

iii) Realistic station of average execution:

This kind of station consumes 15 % of electricity: $\beta = 0,15 \alpha$; electric efficiency = 0.85. It rejects 35 % of the methane flow ϵ at the separator's level: $\gamma = 0.35 \epsilon$; The loss at the scrubber level is still 6 % of methane: $\delta = 0.06 \epsilon$; Then, applying our formula will result in a $\eta_{total} = 0.50$ The energy efficiency is 50 %.

iv) Realistic station of poor execution:

This station consumes 25 % of electricity: $\beta = 0,25 \alpha$; electric efficiency = 0.75. It rejects 60 % of the methane flow ϵ at the separator's level: $\gamma = 0.60 \epsilon$. The loss at the scrubber level is again 6 % of methane: $\delta = 0.06 \epsilon$. The formula presented before in the box above will give $\eta_{total} = 0.255$. The energy efficiency is 25.5 %.

SUMMARY	ideal η	Good η	Avg. η	Poor η
% electric waste = β/α	0 %	1 %	15 %	25 %
$\eta_{\text{electric}} = (\alpha - \beta) / \alpha$	100 %	99 %	85 %	75 %
% methane loss at separator = γ / ϵ	7 %	13 %	35 %	60 %
% methane loss at washer = δ / ϵ	6%	6 %	6 %	6 %
% methane loss = $\gamma / \epsilon + \delta / \epsilon$	13 %	19 %	41 %	66 %
$η_{methane} = 1 - (γ + δ) / ε$	87 %	81 %	59 %	34 %
$\eta_{\text{total}} = \eta_{\text{elec}} \times \eta_{\text{methane}}$	87 %	80 %	50 %	25.5 %

These considerations, summarized in the table above, lead to a (somewhat expected) conclusion: putting a station in place and in production by using a straightforward, at hand technique has little chances to reach a satisfying efficiency. Only a clever, specifically adapted technology may succeed.

6 – A proposal for exploiting the PRZ (or even the IRZ)

In this section, let us simplify the lake's structure one step further. As far as methane extraction is concerned, the lake's waters can roughly be separated in two layers :

- A lower layer, called "the resource", situated between 260 m and the bottom of the lake, where dissolved gases are in strong concentration;

- An upper layer, called "the potential resource", between 60 m and 260 m, with weakly concentrated dissolved gases.

Each layer can be characterized by two parameters:

- A quantitative parameter, representing the total quantity of methane in the layer;

- A qualitative one, representing the possibility for a siphon process to be self-maintained.

In the "potential resource", the gas concentration is not sufficient to maintain a siphon process. On the contrary, waters from the "resource" allow a self-maintained siphon; moreover, the process provides extra-energy which can usefully be exploited as detailed below.

A self-maintained siphon process is based on the natural exsolution process. Once booted, it keeps a sustained activity without a need for energy from the outside. The process takes its energy from the emergence of a gaseous phase in the water when the depth, and hence the pressure, is less than required for the gases to remain dissolved. The density of the diphasic liquid-gas mixture being lower than the density of the liquid phase, archimedian forces continuously push the internal column's content upwards. It can be shown that the siphon's efficiency, and consequently the extracted gas flow, essentially depends on the methane concentration. This element is the main ally for triggering and maintaining the gas ex-solution in the extraction column, whereas the CO_2 only plays a marginal role in the process.

When booting a column with its lower mouth inside the resource zone, the methane concentration is more than sufficient to maintain a siphon process in the column. An extra energy is developed which causes an acceleration in the column.

The internal friction loss causes the internal liquid to be in a depression relatively to the external hydrostatic pressure.

Our proposal is to put this extra energy at work and make it carry water from the potential resource for free.

Let's equip the column with a lateral valve, at the level of the PRZ. When opening the valve, the internal depression will cause water from the potential resource, to get into the column and be carried upstream.

Of course, the opening of the valve must be judiciously controlled. The "dilution" (the rate of the lateral flow to the main flow) must lead to an optimal gas flow. The whole process must stay alive and economically efficient.



An outlined extraction process including the potential resource.

To sum up :

- Profit by the depression in the column to let some lateral water in at some level, and rule the lateral inwards flow through an adjustable friction loss valve;

- Adjust the dilution such as the dissolved gases concentration is sufficient for the siphon process to stay self-sustained, in its optimal conditions.

A simulation shows that this process would in theory allow extracting the whole of the gas from the potential resource. This gas was till now considered lost.

To compensate for the lesser capacity of the diluted water at sustaining the siphon process, and in order to keep a sufficient methane flow, the column, the separator and the pipes for rejected water should be increased in diameter. These costs, of course, impact on the economical balance of the project.

Considering that the resource and the potential resource respectively contain 46 km³ tpn ($0 \,$ °C, 1 atmosphere) and 20 km³ of methane, the proposed process in theory multiplies by almost 1,5 the quantity of energy extractable from lake Kivu's waters.

It should be stressed that each homogeneous layer in the resource

- not only makes available its own quantity of dissolved methane,

- but also brings for free - through the self-sustained siphon process - the possibility of methane extraction from OTHER layers, situated in the potential resource, which otherwise would remain unexploited.

To summarize, while it was generally admitted that one third of the total amount of methane contained in Lake Kivu was impossible to extract (the potential resource zone), we show that, at the cost of a more complex and bigger installation, extracting the whole of the methane is in theory technically feasible.

7 - Regulation texts

Fundamental rules

FR1 - It is prohibited to re-inject degassed water output from the separator into the Biozone (BZ).

FR2 - It is prohibited to re-inject degassed water output from the separator into the Intermediate Zone (IZ).

FR3 - It is prohibited to re-inject degassed water output from the separator into the Resource layers (URZ and LRZ).

FR4 - <u>The total energetic efficiency (as described beneath) of a station must be</u> <u>superior or equal to 80 %.</u>

The total energetic efficiency η_{total} is defined as the product of the electric efficiency $\eta_{electric}$ by the methane efficiency $\eta_{methane}$:

$\eta_{\text{total}} = \eta_{\text{electric}} \times \eta_{\text{methane}}$

- The electric efficiency $\eta_{electric}$ is defined by

$\eta_{\text{electric}} = (\alpha - \beta) / \alpha$

where α is the electric power produced by the station and β is the electric power consumed by the station.

- The methane efficiency $\eta_{methane}$ qualifies which proportion of the input flow ϵ of methane (coming through the extraction column) is delivered as an output flow λ of methane (from the station to the electrical plant). It accounts for methane loss due to the separation and the washing processes rejecting some methane with the rejected water.

$\eta_{\text{methane}} = \lambda / \epsilon$

Both flows are expressed in a common unit which conveniently conveys the energetic power of methane, namely the volumetric equivalent flow of pure methane at 0 % and 1 atm.

A detailed account for these quantities can be found in the document (paragraph 5).

Appendix 1 – Energy efficiency

Practical Estimate of the energy efficiency

The electric efficiency involves the electric power produced α and the one consumed β . They sum up the interactions with the electric plant operator.

The methane efficiency can be determined by processing through two different ways.

- the methane flow ε , that comes from the water collecting point through the column, can be calculated from the liquid flow in the column and the concentration of dissolved methane (which is accurately known, as we saw, by the depth of water collection).

- the methane flow λ output from the station should be measured by some flow meter which should be part of the station's design (introducing both temperature and pressure corrections).

The overall methane efficiency is obtained by dividing the output flow by the flow at the collection point: $\eta_{methane} = \lambda / \epsilon$.

We are convinced that it is important to set up a secondary method to evaluate this efficiency, by measuring the methane loss at the separator as well as at the scrubber levels.

On one hand, the waste evaluation will confirm (redundantly) and specify the methane efficiency obtained by the overall method just expressed before.

On the other hand, measuring the γ and δ terms will provide important information on the station operations, and could reveal some anomalies and warn us about corrective actions to be taken.

Loss in the washing column (term δ)

The scrubber case is a bit peculiar since the waste of methane will directly be bound to the methane richness that we want to obtain at the station's output.

Generally speaking, getting richer methane at the output involves losing more methane in the waters rejected from the scrubber.

Increasing the desired richness from 65 % to 80 % strongly (something like twice) increases the loss of methane at washing.

In order to estimate the loss in the scrubber, we will need to know the washing water flow and the methane concentration dissolved in the rejected waters. Sensors must be installed in the washing column to measure the liquid flow as well as the concentration of the dissolved methane.

Nevertheless, we can mention that it is actually possible to get a good estimate of the methane loss by using the formulas existing for washing columns, while taking some hypothesis regarding the offset from the liquid-gas equilibrium.

Loss in the separator column (term γ)

Estimating the methane loss γ at the separator stage is crucial and definitely the hardest goal to achieve with some precision.

The rejected liquid flow is of course the same as inside the column, but the uncertainty resides in the methane concentration in the rejected waters.

It's almost impossible to predict or calculate by formulas which would be the proportion of methane released as gas, and which part will remain dissolved and trapped in the rejected water. It would require diphasic dynamic calculation, integrating parameters such as the flow typology, the bubble sizes, the kinetic involved in the equilibrium between the liquid and gaseous phases, etc.

Certainly, determining the concentration of the methane dissolved in the rejected waters is essential. In our opinion, the loss of methane in the separator is the hardest parameter to quantify in order to estimate the global energy efficiency of an extraction station.

This parameter is also the one likely to penalize the most the said efficiency: It can show broad variations depending on the extraction technology, ranging from 0.1 ϵ to 0.6 ϵ (10 % to 60 % of methane in the rejected waters). One can see how severe the waste of methane at this stage may be.

Examples of poorly efficient stations:

The simplest methane extraction process can be described as follows.

We induce a powerful driving energy force in the extraction column, using the gas-lift method (by injecting either air or gas collected from the separator or the scrubber). The water flow increases with the gas lift flow. We can thus obtain an important gaseous methane flow from the separator.

This process is not forbidden by the MPs. It is not even mentioned and apparently has not been foreseen by the expert committee; however, it has two seriously harmful consequences:

1- Obviously, one needs to consume electricity in order to power the gas-lift compressor.

2- More pernicious since it's not visible: the water rejected by the separator will remain highly enriched in methane, because the stronger the gas-lift effect, the higher the water speed, and the more we drift from the equilibrium state of the diphasic flow. Therefore the rejected waters will contain a high density of methane kept out of the equilibrium.

A more realistic simplified example:

1/3 of the electric power produced by the station is self-consumed to activate the gas-lift; 2/3 of the methane flowing through the column remains in the rejected waters (we ignore here the loss taking place in the washing process).

The global efficiency of such a system would be $(2/3) \times (1/3) = 2/9$, i.e. 22 %.

This is substantially the example of a station with poor performance presented in the table on page 29 in paragraph 5. This type of operation seems obviously unacceptable in that it leads to a considerable waste of the resource.

Appendix 2 – Extracting methane from the PRZ : a tentative estimate of the energetic gain

We can't give here a precise estimation of the potential energetic capacities for each layer in the lake's structure, because we don't know precisely the vertical profile of methane concentration versus depth in the lake. Nor is taken into account the natural reload in methane.

We aim at comparing the two following techniques in terms of the quantity of methane they permit to recover:

- either performing extraction from the only resource layers;

- or extracting methane simultaneously from the resource layers and the PRZ situated above, as is sketched in section 6.

For this comparison, the following estimate of the methane capacities for each layer is sufficient:

	Depth (m)	Water volume* (km ³)	Methane volume (km ³)
IRZ**	60 – 160	176	7
PRZ ^{**}	160 – 260	138	13
URZ	260 – 310	49	16
LRZ	310 – 485	74	30
Total		426	66

*The water volumes have been computed from a precise hypsometric curve, which gives the surface as a function of depth. This hypsometric curve was itself computed from a numerical 3D terrain model from Lahmeyer and Osae, which gives the lake's depth for each point on a 10 m x 10 m grid.

**The IRZ is limited from 60 to 160 m; the PRZ thickness was increased from 190 - 260 m to 160 - 260 m.

Note that, in our estimation, 13 km³ are extracted from the 20 km³ methane content between 60 and 260 m. A remaining of 7 km³ (i.e. 10 % of all the methane of the lake) is unexploited.

Further quantities introduced in our computations are as follows:

The calorific value of methane is 36 MJ/m^3 ;

The extraction efficiency, as defined in section 5, is 85 % (a second evaluation will be done with an efficiency of 75 %);

The exploitation is supposed to be spread on 50 years;

Finally, the efficiency of the electrical plant, defined as the ratio of the output electrical power to the input thermal power (see section 5), is 38 %.

We will estimate below the available electrical power for various scenarios.

Ideal limit case: exploiting the full methane content in the lake

Available methane volume: 66 km³

Corresponding thermal energy: $66 \text{ km}^3 \times 36 \text{ MJ/m}^3 = 2,38 \text{ }10^{12} \text{ MJ}$

Available energy per year: 2,38 10^{12} MJ / 50 y = 47,5 10^{9} MJ/y

Available energy output from the extraction station: $(47,5 \ 10^9 \ \text{MJ/y}) \times 0.85 = 40 \ 10^9 \ \text{MJ/y}$

Thermal power entered into the generator: $40 \ 10^9/365/24/3600 = 1281 \ MW_{th}$

Electrical power delivered by the electrical plant: $1281 \times 0.38 = 487 \text{ MW}_{el}$

If the extraction efficiency is 75 % instead of 85 %, the electrical power is reduced to 430 MW_{el} .

Estimation 1 : exploiting the resource (URZ + LRZ)

Available methane volume: 46 km³

Corresponding thermal energy: $46 \text{ km}^3 \times 36 \text{ MJ/m}^3 = 1,656 \text{ }10^{12} \text{ MJ}$

Available energy per year: 1,656 10^{12} MJ / 50 y = 33 10^{9} MJ/y

Available energy output from the extraction station: ($33 \ 10^9 \ MJ/y$) x 0,85 = 28 $10^9 \ MJ/y$

Thermal power entered into the generator: 28 $10^9/365/24/3600 = 892 \text{ MW}_{th}$

Electrical power delivered by the electrical plant: $892 \times 0.38 = 339 \text{ MW}_{el}$

The proportion of this mode to the ideal case is 339/487 = 69,6 %.

If the extraction efficiency is 75 % instead of 85 %, the electrical power is reduced to $299 \ MW_{el}$.

Estimation 2 : exploiting the resource (URZ + LRZ) plus the potential resource PRZ

Available methane volume: 59 km³

Corresponding thermal energy: 59 km³ x 36 MJ/m³ = 2,1 10^{12} MJ

Available energy per year: 2,1 10^{12} MJ / 50 y = 42 10^{9} MJ/y

Available energy output from the extraction station: ($42 \ 10^9 \ \text{MJ/y}$) x 0,85 = 36 $10^9 \ \text{MJ/y}$

Thermal power entered into the generator: $36 \ 10^9/365/24/3600 = 1145 \ MW_{th}$

Electrical power delivered by the electrical plant: $1145 \times 0.38 = 435 \text{ MW}_{el}$

If the extraction efficiency is 75 % instead of 85 %, the electrical power is reduced to 384 MW_{el} .

This mode operates at 435/487 = 89,3 % of the ideal limit.

The method exploiting the potential resource yields a power of **435** MW_{el} instead of **339** MW_{el} . The gain is **96** MW_{el} .

Exploiting the potential resource PRZ in addition to the resource (URZ + LRZ) saves 28 % (435/339) energy capacity during the full methane exploitation from Lake Kivu and achieves 89.3 % of the ideal exploitation limit.

Technical and economical considerations

There is no particular technical difficulty in implementing the exploitation of the PRZ through the use of the depression prevailing in the column because of the pressure loss which occurs in the water taken from the resource.

The water volumes in the PRZ (138 km³) and in the resource (123 km³) being nearly equal, a rough simulation can be done, where the lateral input from the PRZ is equal to the main flow coming up from the resource.

Of course, the section of the column should be increased, in order to achieve a given methane flow.

Concerning the rejection of degassed waters, a different method from that of section 3 should be employed. Instead of mixing the rejected water with the water of the PRZ, we suggest to throw them out right above the main gradient (for example at about 245 m). Preliminary calculations show that the density of rejected waters is about 1000,7 kg/m³, an approximation of the mean density between the PRZ and the URZ. We believe that, with some technical precautions, the rejected waters would mix with the waters in the lower

part of the PRZ. After a long time lapse, they would form a distinct layer, which would mix neither with the PRZ nor with the URZ.

The study of the rejection of the degassed waters needs a sophisticated model of liquid mixtures and should be accompanied by a rigorous experimental monitoring in the discharge area

Finally, one should notice that the proposed process has no influence on the nutriments flow in the biozone. Indeed, the water taken from the potential resource is rejected into the potential resource itself; and the water taken from the resource, beneath the main gradient, is rejected right above the main gradient. Estimations by EAWAG indicate that these nutriment-rich waters would take about 350 years to reach the biozone.

<u>Summary</u>

The method of exploiting the PRZ should be considered as an amelioration of the method proposed in section 3.

It is workable and has been validated by our experiences in degassing Cameroonian lakes. Further studies are needed concerning the rejection method.

In conclusion, it is possible to exploit the whole of the gas contained in the potential zone, without using external energy.

This would bring a 28 % energy gain on the total history of the lake's exploitation.

This proposition also has some drawbacks: the cost of the equipment is increased, and questions remain concerning the rejection method.