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Exploitation of Lake Kivu Gas Resource

Consequences of the re-injection of degassed water into the Resource Zone

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GMW292

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А	m^2	Surface.
С	kg/m ³	Concentration.
C_{g}	kg/m ³	Concentration of dissolved gas g.
C _{CO2}	kg/m ³	Concentration of dissolved CO2.
C _{CH4}	kg/m ³	Concentration of dissolved methane.
D	m	Diameter.
D	m^2/s	Diffusivity of methane in water.
e ₀	m	Initial jet width.
g	m/s^2	Gravity acceleration.
h	m	Height.
Н	kg/m ³ /Pa	Henry constant.
H_{i}	kg/m ³ /Pa	Henry constant of gas i.
Kz	m^2/s	Vertical diffusivity.
L	m	Length.
L_d	m	Diffusion length.
m	kg	Mass.
M_{i}	kg/mol	Molar mass for gas i.
N^2	s ⁻²	Stability of density stratification.
р	Ра	Pressure.
p_{g}	Pa	Gas pressure.
p _a	Ра	Atmospheric pressure.
Q	m ³ /s	Volume flow rate.
Q_G	m ³ /s	Volume gas flow rate.
Q_L	m ³ /s	Volume liquid flow rate.
Q _{tot}	m ³ /s	Total extracted liquid flow rate.
R	J/mol/K	Perfect gases constant.
R _e		Reynolds number.
Т	S	Time.
Т	°C	Temperature.
U	m/s	Velocity.

U_0	m/s	Initial jet velocity.
U _G	m/s	Mean velocity of gas.
U_{H}	m/s	Homogeneous velocity.
U_L	m/s	Mean velocity of liquid.
V	m ³	Volume.
V_{G}	m ³	Volume of gas.
V_{L}	m ³	Volume of liquid.
Z	m	Depth.
Zsep	m	Separation depth.
Zextr	m	Extraction depth.

$\alpha = \frac{V_G}{V}$	-	Void fraction.
δ		Volumetric dilution ratio.
3	W/kg	Energy dissipation rate.
ý		Head loss coefficient.
μ	Pa.s	Dynamic viscosity.
ν	m^2/s	Kinematic viscosity.
ρ	kg/m ³	Specific mass.
$ ho_{\rm H}$	kg/m ³	Specific mass of homogeneous two-phase mixture.
$ ho_{\rm L}$	kg/m ³	Specific mass of liquid.
$ ho_G$	kg/m ³	Specific mass of gas.
τ_{perf}		Perforation rate.

Some notations are defined in the text. Units are generally MKSA. Pressures are absolute pressures.

SUMMARY AND MAIN CONCLUSIONS.

The present report is related to the analysis of some possible scenarios for the exploitation of methane dissolved in the depths of Lake Kivu. The objective is to estimate the consequences of the reinjection of degassed water into the Resource Zone, as suggested in the exploitation scenarios recommended in the document *Management Prescriptions for the development of Lake Kivu Gas Resources* (plan A1, A2 and B).

Economy of production.

At first, we analyse the possible economic consequences of dilution of the resource which can be described as follows :

- First of all, experts consider that below a certain minimum dissolved methane concentration, the harvesting of the resource is not anymore economically viable. This limit concentration is, as suggested in the Management Prescriptions document, assumed to be approximately of 5 mol/m³ (0.11 Nl/l), which is possibly an optimistic value.

- Secondly, a diminution of the concentration of dissolved gas would result in a decrease of the gas flow rate possibly produced by each extraction facility. As a consequence, if the total methane gas flow rate delivered on shore has to be maintained constant, the total number of installations has to be increased when dilution of extracted water occurs.

The first part of the present report focuses on this second consequence of dilution of the resource.

Extracted gas flow rate versus methane content in extracted water.

The physical modelling of the degassing column functioning is described. This includes the modelling of degassing phenomenon and pressure drops in two-phase flow. The simplified model utilised is based on an equilibrium in concentration between the gas and liquid at any point of the column. This is a reasonable assumption since we are interested in performances of degassing facilities relatively to the maximum performances that could be reached if

dilution did not occur. An evaluation of absolute gas flow rate would require a more complex calculation taking into account so called ex-solution delays.

The calculation based on this modelling gives access to the influence of a decrease of the methane content in extracted water on :

- the extracted water flow rate,

- and thus the extracted gas flow rate.

Dilution of the resource would result in a significant decrease of extracted water flow rate and consequently of gas flow rate produced by each extraction facility. This influence of dilution on economic performances depends on the separation depth. The results of our calculations are illustrated on figure a for different separation depths.

 $Q_{CH4}/Q_{CH4,max}$ is the ratio of actual methane gas flow rate (Nm³/s) to maximum gas flow rate

that could be extracted if dilution did not occur.

 $C_{CH4}/C_{CH4,max}$ is the ratio of the methane concentration in diluted extracted water, to the initial methane concentration.



Figure a. Methane flow rate versus methane concentration in extracted water. GMX273.

One can conclude that, whatever the separation depth is, if the methane content in extracted water is reduced of 50%, the resulting diminution of extracted gas flow rate would, in the best case (separation at the surface) exceed 60%. For this same dilution ratio, if the separation depth is equal to 20 m, the extracted methane flow rate would fall to only 21% of its initial value.

As a conclusion, if the gas flow rate delivered on shore is to be maintained constant, the number of degassing units has to be multiplied by a factor 3 (separation at the surface of the lake), and more probably 5 (separation depth equal to 20 m), when the concentration of dissolved methane in extracted water is divided by a factor 2.

Possible causes for dilution of extracted water.

When degassed water is re-injected into the resource, in a zone of low density gradient, it tends to mix with surrounding water. The result is a dilution of the resource. Mixing can mainly results from energy dissipation, thus the main possible causes for dilution of the resource are :

- vertical diffusion induced by "natural" dissipation over the whole lake depth of the energy transmitted by wind at the lake surface,
- local spreading resulting from progressive slowing-down of the degassed reinjected flow caused by entrainment of initially quiescent surrounding water.

We mainly focus on the reinjection of degassed water into the Upper Resource Zone (plan A1 and plan B).

Influence of vertical diffusion.

We have evaluated the influence of vertical diffusion on the vertical spreading of a re-injected degassed water, which is then supposed to "gently" spread over whole lake surface, thus forming an initially separated degassed layer at the top the URZ. This supposes that :

- degassed water is uniformly distributed over the whole lake surface with zero velocity,
- rich water is uniformly extracted over the whole lake surface with zero velocity.

In such **ideal** conditions and for a total extracted water flow rate supposed equal to 70 m^3/s (300 to 350 MWe) :

- the exploitation of the URZ would remain constant for a period of 12 years,

- after this initial period, the production would progressively decrease and one fifth of the resource would be exploited with an average gas flow rate equal to 30% of the initial gas flow rate.

This estimation is function of the value of the so-called vertical diffusivity and of the total extracted water flow rate. Moreover, we have only considered the exploitation of the main volume of the URZ comprised between 270 m depth and 300 m depth, containing approximately 33 km3 of water and 11.5 Nkm³ of dissolved methane.

We can conclude that if vertical diffusion was the only phenomenon taken into account for the vertical spreading of degassed water re-injected at the top of the URZ, then the economic consequence for the exploitation of the resource would probably be limited.

Vertical spreading of re-injected flow.

Then we have analysed the theory of submerged jets so as to estimate the local vertical dispersion of the re-injected degassed water flow.

As mentioned in the *Management Prescriptions* document, water re-injection must be done horizontally and "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.".

A laminar reinjection suppresses intense local turbulent dissipation that occurs within the mixing layers produced by turbulent submerged jets. Thus a turbulent reinjection would probably results in a rapid mixing of the re-injected degassed water with the surrounding water. This would lead to a rapid local dilution of the resource.

On the basis of Reynolds numbers calculations, we have evaluated the minimum technical requirements to ensure an initially laminar re-injection. We concluded that the only solution

was to re-inject water through multiple small nozzles. As a consequence, the possible reinjection device would be very high and big (typically 10 m height, 4 m diameter).

Nevertheless, most of experimental studies on submerged laminar jet show that for reasonably low Reynolds number (500 to 1000) the jets do not remain laminar but become turbulent at a relatively short distance from the nozzle exit. Once turbulent the initially separated small jets will entrain large quantities of surrounding water, mixing with it and finally forming a large single turbulent radial jet.

Then we have calculated the velocity profiles and concentration profiles for dissolved species carried by such a submerged turbulent jet.

Our conclusion, based on the analysis of submerged jet theory, is that water re-injected at the top of the URZ would rapidly be spread over the whole depth of this resource. This vertical spreading is associated with unavoidable surrounding water entrainment. One consequence of the resulting unavoidable local dilution is that the density of reinjected water does not need to be adjusted since it will naturally tend to that of surrounding water.

The problem is more complex when water is re-injected a the top of the LRZ, because of the possible larger vertical interval between reinjection and intake (if rich water is extracted at the bottom of the LRZ).

Importance of horizontal mixing.

Once degassed water has reached the extraction depth the consequence for the performance of the extraction facility is greatly influenced by the efficiency of horizontal mixing which is linked to the presence of underwater currents.

If the velocity of underwater current is sufficiently high then re-injected degassed water is pushed away, thus "cleaning" the extraction zone. If horizontal mixing is very efficient then re-injected degassed water is simply mixed with the whole volume of the URZ.

It is a priori possible that the local velocity of underwater current fall to zero at least periodically. Then the degassed water would accumulate in the vicinity of the extraction facility. As a result the methane content in extracted water can rapidly decrease.

Finally, the gas concentration profiles, induced by degassed water reinjection, in the vicinity of the extraction facility, will be influenced by :

- The "rapidity" of vertical spreading,
- The ability of horizontal mixing to push degassed water away from the extraction facility.

The main possible scenarios, illustrated on figure b, are the following ones :

- 1. Rapid vertical spreading and low horizontal mixing (most pessimistic scenario),
- 2. Rapid vertical spreading and high horizontal mixing,
- 3. Slow vertical spreading and low horizontal mixing,
- 4. Slow vertical spreading and high horizontal mixing (most optimistic scenario).



Figure b. Schematic possible horizontal and vertical spreading of degassed water after a relatively short period of exploitation.

Figure c shows the calculated evolution of dissolved methane concentration in the vicinity of the extraction facility in absence of underwater current and for vertical spreading estimated from analysis of submerged jet theory. The re-injected degassed water flow rate is supposed equal to 1.3 m^3 /s, which correspond to one 6MWe facility.



Figure c. Dilution of the resource in the vicinity of the extraction facility. Plan A1. No underwater currents. $Q = 1.3 \text{ m}^3/\text{s}$ (6 MWe).

We can conclude that, in absence of horizontal mixing, the concentration of dissolved gasses in the vicinity of the reinjection device will rapidly decrease on the whole depth of the URZ. Within a period of 15 days the concentration of dissolved gas would almost be equal to zero and thus the extracted flow rate would also rapidly fall to zero.

Calculated evolutions of extracted flow rate.

We have calculated the evolutions of methane flow rate extracted from the URZ in case of plan A1, and plan A1 and B together, supposing rapid horizontal mixing (most optimistic scenario). This assumption implies that the whole volume of the URZ is instantaneously mixed with re-injected degassed water. The results are illustrated on figures d and e for various separation depths.



Figure d. Evolution of the methane flow rate extracted from the Upper Resource Zone. Instantaneous horizontal and vertical mixing. Plan A1. Initial water flow rate 70 m^3/s .

With plan A1 the extracted gas flow rate would rapidly decrease an fall to zero within a period comprised between 20 and 50 years depending on the separation depth. The decrease of production would be even more rapid with plan A1 and B together since the re-injected degassed water flow rate is more important.



Figure e. Evolution of the methane flow rate extracted from the Upper Resource Zone. Instantaneous horizontal and vertical mixing. Plan A1 and B together. Initial water flow rate extracted from the URZ : 70 m^3 /s. Constant re-injected flow rate from the LRZ : 70 m^3 /s.

Because of the larger possible vertical interval between re-injection and intakes (if rich water is extracted at the bottom of the LRZ), the evaluation of plan A2 is a much a more complex problem.

It is possible that water extracted at the bottom the LRZ is not diluted before a relatively long exploitation time, since the re-injected submerged jet will probably not spread over a 100 m depth.

Nevertheless we can consider that water re-injected at the top of the LRZ will rapidly spread over a 30 m depth layer. The progressive dilution of this diluted layer could considerably compromise the harvesting of the methane resource initially dissolved in this layer. The concerned resource is approximately of 13 Nkm³.

Final conclusions.

The main possible scenarios, resulting from reinjection of degassed water into the URZ, their probability and consequences on the resource exploitation rate are summarized on figure f below.

Possi	ble sc	Probabillity	Consequence on exploitation rate	
No vertical dispersion : Re-injected water spreads gently over the whole lake surface so as to form a separated degazed layer at the top of the URZ			Technically impossible	Limited : constant production during 12 years then progressive decrease of production
Rapid vertical dispersion : Re-injected water spreads	and	No underwater current (no horizontal mixing) : degassed water accumulates in the vicinity of the degassing facility	Probable at least for short periods	Catastrophic : extracted gas flow rate could fall to zero within a few days
vertically over the whole URZ depth		Intense horizontal mixing : the whole volume of URZ is instantaneously diluted with the re-injected degassed water	Most probable	Significant : production would decrease of 50% within a few years of exploitation

Figure f. Possible consequences of reinjection into the URZ.

Finally, the probable rapid decrease of methane content in extracted water can greatly damage the economic performances of the extraction facilities.

Because the involved physical phenomena are very complex, and since many technical solution can be imagined for water reinjection, including multiple nozzles, we recommend to evaluate experimentally the actual spreading of re-injected degassed flow.

Such an experimental study must be carried out with water flow rates comparable to that extracted and re-injected by industrial facilities.

1. INTRODUCTION.

1.1. Lake Kivu Methane Resource.

The methane resource dissolved in the depths of Lake Kivu can be exploited with different operation conditions namely concerning rich water extraction depth and degassed water reinjection depth.

The exploitable resource is mainly distributed within the two following zones :

- the Upper Resource Zone (URZ) ranging from 270 m depth to 300 m depth,
- the Lower Resource Zone (LRZ) ranging from 320 m depth to the bottom of the lake at 485 m depth.

Name	Location	Main Density	Water Volume	Mean methane concentration	Methane Resource
Upper Resource zone	-270 m to -300 m	1001,40 kg/m3	50 km3	0,34 l/l	17 Nkm3
Lower Resource Zone	-320 m to -485 m	1001,91 kg/m3	65 km3	0,41 l/l	27 Nkm3

Figure 1. Main characteristics of the Upper and Lower Resource Zones.

These two resources (URZ and LRZ) are separated by the so-called Secondary Density Gradient, ranging from 300 m depth to 320 m depth.

The Upper Resource Zone is separated from the upper layers by the so-called Main density gradient ranging from 260 m to 270 m.

Because of the sharpness of these two density gradients one can assume that there is no water exchange between the URZ and the upper layers, and between the URZ and the LRZ.

The current vertical density profile in the lake is illustrated on figure 1.



Figure 2. Vertical density profile in Lake Kivu. GMX265.

1.2. Proposed extraction scenarios.

The document *Management Prescriptions for the Development of Lake Kivu Gas Resources* recommends three scenarios considered as the most favourable ones for the exploitation of the URZ and the LRZ. These scenarios referenced as plan A1, plan A2 and plan B are described below.

Plan A1.

The so-called plan A1 concerns the exploitation of the Upper Resource Zone. The suggested operating conditions are :

- gas-rich water is extracted at the bottom of the URZ (300 m depth),

- degassed water is re-injected and must remain at the lower margin of the main density gradient (270 m depth).

This scenario implies a precise control of the density of degassed water which must be equal to the density of surrounding waters at the top of the URZ.



Figure 3. Suggested scenario for the exploitation of the Upper Resource Zone. Plan A1.

Plan A2.

Plan A2 deals with the exploitation of the LRZ. The suggested scenario is :

- gas-rich water is extracted at the bottom of the LRZ,

- degassed water is re-injected and must remain at the lower margin of the Secondary Density Gradient (325 m depth).



Figure 4. Suggested scenario for the exploitation of the Lower Resource Zone. Plan A2.

Plan B concerns the exploitation of both URZ and LRZ under the following operating conditions :

- gas-rich water is extracted from the LRZ,

- degassed water is re-injected and must remain at the lower margin of the Main Density Gradient (270 m depth).



Figure 5. Suggested scenario for simultaneous exploitation of the Upper Resource Zone and Lower Resource Zone. Plan B.

1.3. Possible consequences of these scenarios.

The above scenarios suggest that the degassed water must re-stratify at the top of the URZ (plans A1 and B) or at the top of the LRZ (plan A2). This supposes that the re-injected water is uniformly distributed over the whole lake surface.

Under such "ideal" conditions the degassed water could only mix with the rest of the resource under the effect of vertical diffusion. As described below, this natural diffusion is probably a slow phenomenon in the resource zones. As a conclusion, exploitation could be optimized, since most of the rich water contained in the resource would not be diluted before it is extracted. Nevertheless, degassed water is re-injected from a finite number of dispersed outlets. For that reason, the reinjection procedure must ensure that degassed water can spreads very gently over a long distance, probably several kilometres, away from each reinjection column.

This is a technical challenge, particularly if we consider the fact that the density gradient is close to zero at reinjection depth, which means that gravity has almost no effect on re-injected water spreading.

2. INFLUENCE OF DILUTION ON DISSOLVED GAS EXPLOITATION.

2.1. Influence of dilution on economic benefit.

The main possible economic consequences of dilution of the resource which can be described as follows :

- First of all, experts consider that below a certain minimum dissolved methane concentration, the harvesting of the resource is not anymore economically viable. This limit concentration is, as suggested in the Management Prescription document, assumed to be approximately of 5 mol/m³ (0.11 Nl/l), which is possibly an optimistic value.

- Secondly, a diminution of the concentration of dissolved gas in extracted water would result in a decrease of the gas flow rate possibly produced by each extraction facility. As a consequence, if the total methane gas flow rate delivered on shore has to be maintained constant, the total number of installations has to be increased when dilution of extracted water occurs.

The first consequence has been evaluated by Wuest and al¹ for different extraction scenario.

We would like to focus on the influence of dilution of the extracted water on the gas extracted flow-rate. The method proposed consists in modelling the physical phenomenon influencing

¹ Wüest A., Jarc L., Schmid M.. Modelling the reinjection of deep-water after methane extraction in Lake Kivu. June 2009.

the degassing column operation, this involves the analysis of liquid – gas equilibrium and pressure drop modelling.

2.2. Principle of the degassing column.

Ex-solution is the phenomenon of the formation of gas bubbles in a liquid that has reached saturation. The saturation limit of a gas in a liquid depends on two factors - the total quantity of dissolved gas and the pressure of the liquid (that is to say the depth, in the case of a lake).

The formation of bubbles can occur either by increasing the quantity of dissolved gas in the water or by lowering the pressure (that is to say, the depth). If one of these two conditions is fulfilled, and if the saturation curve is reached, then small bubbles of gas will form in the water and rise to the surface. These little bubbles entrain the liquid which is already over-saturated with gas. New bubbles will appear in this liquid. On the way up to the surface the size of the bubbles increases. A chain reaction is triggered off.

This phenomenon is the driving force, that counterbalances pressure drops induced by friction of the flow on pipe wall, and that enables the degassing column to extract rich water. Moreover the maximum extractable gas flow rate is the product of water flow rate and methane concentration dissolved in extracted water.

As a conclusion a diminution of the concentration of dissolved gas in the extracted water, caused by dilution with re-injected degassed water, would result in a decrease of both extracted water flow rate and gas flow. Thus dilution could be catastrophic for the rate of exploitation of the resource.

2.3. Mass transfer phenomena : equilibrium.

Simplifying assumption.

The simplified following analysis of the degassing column supposes equilibrium in concentration between the gas and liquid at any point of the column.

This is a reasonable assumption since we are here interested in performances of degassing facilities relatively to the maximum performances that could be reached if dilution did not occur. An evaluation of actual absolute gas flow rate would require a more complex calculation taking into account so called ex-solution delays.

The Henry's law.

Pure gas.

When a pure gas g and a liquid are put in contact in a vessel at constant pressure and temperature, the concentration of gas dissolved in the liquid tends to reach an asymptotic value which is called the equilibrium concentration C_g (kg/m³).

It has been shown that this concentration is dependent on temperature and is proportional to the gas pressure. The corresponding law is the so-called Henry law which states that :

$$C_g = H_g p_g$$

With

 C_g the concentration of dissolved gas in kg/m³,

 H_g the Henry constant, in kg/m³/Pa, for the gas g at the temperature T, p_g the pressure of the gas in the atmosphere surrounding the liquid in Pa.



Figure 6. The Henry's law.

The value of equilibrium concentration in water depends on the nature of the gas and on the temperature. Figure 7 and 8 gives the Henry's constant of respectively CO_2 and CH_4 at low temperature. In this simplified analysis we neglect the variations of Henry's constant with pressure and salinity.



Figure 7. Henry's constant of CO_2 in water versus temperature.



Figure 8. Henry's constant of CH₄ in water versus temperature.

If we now consider a volume of water containing a initial concentration of dissolved gas C_{g0} . Degassing can occur as soon as the pressure is below the so-called saturation pressure which is :

$$p_{crit} = \frac{C_{g0}}{H_g}$$

Gas mixture.

In the case of gas mixtures at low pressure, the equilibrium concentration in the water is the product of the Henry's constant of each gas by the partial pressure of this gas.

$$C_{gi} = H_{gi} p_{gi}$$

And the total pressure p_g is the sum of the partial pressure of each gas :

$$p_g = \sum_{1}^{n} p_{gi}$$

For a gas mixture the critical pressure p_{crit} , at which the first bubbles appear, is the sum of the saturation pressure of each gas, which can be written :

$$p_{crit} = \sum_{1}^{n} p_{sati}$$

Where the saturation pressure of each gas is defined as :

$$p_{sati} = \frac{C_{g0i}}{H_g}$$

Where C_{g0i} is the initial concentration of dissolved gas i in water.

Mixture composition.

Let us now consider an initial volume V of water containing two dissolved gases noted 1 and 2. This initial volume is described as state 0 on figure 9.

If the surrounding pressure becomes lower than the sum of the two saturation pressures, degassing occurs. Both freed gases are supposed to be in an atmosphere in equilibrium with the surrounding liquid. This state is referred as state 1 on figure 9.





Before degassing, both species are dissolved and they respective mass are :

$$m_{10} = C_{10} V_L$$

and

$$m_{20} = C_{20} V_{I}$$

After degassing under a surrounding pressure p, these masses are divided into dissolved and gaseous phases. We have :

$$m_{10} = C_1 V_L + \rho_{G1} V_G$$

and

$$m_{20} = C_2 V_L + \rho_{G2} V_G$$

We now write the Mariotte's law, which is the equation of state for gases :

$$p_{g1} V_G = \frac{m_{12}}{M_1} R T = \frac{\rho_{g1} V_G}{M_1} R T$$

and

$$p_{g2} V_G = \frac{m_{22}}{M_2} R T = \frac{\rho_{g2} V_G}{M_2} R T$$

 p_{g1} and p_{g2} are the partial pressures of each gas. The total pressure p is the sum of these two partial pressures :

$$\mathbf{p} = \mathbf{p}_{g1} + \mathbf{p}_{g2}$$

Finally, we write the equilibrium equations linking partial pressures and concentrations. These are the Henry laws for each gas :

$$\mathbf{C}_1 = \mathbf{H}_1 \mathbf{p}_{g1}$$

and

$$C_2 = H_2 p_{g2}$$

 H_1 and H_2 are the Henry constant, in kg/m³/Pa, for each gas at the temperature T.

The combination of mass conservation and Mariotte's law leads to :

$$V_{L} (C_{10} - C_{1}) = p_{g1} \frac{M_{1}}{R T} V_{G}$$

and

$$V_{L} (C_{20} - C_{2}) = p_{g2} \frac{M_{2}}{R T} V_{G}$$

And using the Henry laws we obtain :

$$V_{L} (C_{10} - C_{1}) = \frac{C_{1}}{H_{1}} \frac{M_{1}}{R T} V_{G}$$

and

$$V_{L} (C_{20} - C_{2}) = \frac{C_{2}}{H_{2}} \frac{M_{2}}{R T} V_{G}$$

Dividing these two expressions we find :

$$\frac{C_{10} - C_1}{C_{20} - C_2} = \frac{C_1 H_2}{C_2 H_1} \frac{M_1}{M_2}$$

With :

$$\mathbf{A} = \frac{\mathbf{H}_2}{\mathbf{H}_1} \frac{\mathbf{M}_1}{\mathbf{M}_2}$$

Moreover, the total pressure is the sum of partial pressures, then we have :

$$\mathbf{p} = \frac{\mathbf{C}_1}{\mathbf{H}_1} + \frac{\mathbf{C}_2}{\mathbf{H}_2}$$

Or :

$$C_1 = pH_1 - \frac{C_2 H_1}{H_2}$$

Finally C₁ can be determined by solving the following equation :

$$H_{2}(A-1)C_{1}^{2} + [H_{2}C_{10} + AH_{1}C_{20} - pH_{1}H_{2}(A-1)]C_{1} - pH_{1}H_{2}C_{10} = 0$$

Knowing C_1 and p, we can calculate successively the values of p_1 , p_2 and C_2 and other values characterizing the degassing column, such as the local gas flow rate.

The ratio of gas to liquid volume can be deduced from previous relationships which yield to :

$$\frac{V_{G}}{V_{L}} = \frac{C_{10} - C_{1}}{\frac{C_{1}}{H_{1}} \frac{M_{1}}{R T}}$$

The previous calculation can be applied to the degassing column to evaluate for each specie the maximum gas flow rate at each depth. This implies to determine the local static pressure p(z) along the degassing column.



Figure 10. Schematic representation of the degassing column.

At the bottom of the column, the static pressure is :

$$p_{A} = p_{a} + \rho_{L} g z_{extr} - \frac{1}{2} \rho_{L} U_{L}^{2}$$

p_a is the atmospheric pressure equal to 87 500 Pa at the lake altitude.

 ρ_L is the liquid specific mass.

g is the gravity acceleration.

 z_{extr} is the extraction depth.

If we neglect, in this first order analysis, the pressure drops in the separator or in the reinjection column, the pressure in the separator is equal to the local hydrostatic pressure at separation depth :

$$p_{\rm B} \approx p_{\rm a} + \rho_{\rm L} g z_{\rm sep}$$

Pressure gradient.

In this first order analysis, we assume homogeneous two-phase flow in the degassing column, which means that there is no slip between liquid and gas phases. This homogeneous two-phase flow is characterised by :

- a local homogeneous specific mass :

$$\rho_{\rm H} = \frac{\rho_{\rm L} \ Q_{\rm L} + \rho_{\rm G} \ Q_{\rm G}}{Q_{\rm L} + Q_{\rm G}}$$

 ρ_L is the liquid specific mass.

 ρ_G is the total gas specific mass which is the sum of contribution of methane and CO₂ :

$$\rho_{\rm G} = \rho_{\rm CH4} + \rho_{\rm CO2}$$

Local values for ρ_{CH4} and ρ_{C02} can be evaluate from the equilibrium degassing calculation and by application of the Mariotte's law, as described above.

 Q_G is the volumetric gas flow rate. It can be deduced from the equilibrium theory described above. We have indeed for an homogeneous two-phase flow :

$$\frac{Q_G}{Q_L} = \frac{V_G}{V_L}$$

 Q_L is the volumetric liquid flow rate which is constant along the column and which is simply equal to the extracted liquid flow rate.

- a local homogeneous velocity :

$$U_{\rm H} = \frac{Q_{\rm L} + Q_{\rm G}}{A}$$

A is the pipe internal cross section.

The application of the energy conservation law yields to the following pressure gradient along the degassing column :

$$\frac{dp}{dz} = g \frac{d}{dz} (\rho_{\rm H} z) - \frac{1}{2} \frac{d}{dz} (\rho_{\rm H} U_{\rm H}^2) - \frac{dp_{\rm f}}{dz}$$

 $\frac{dp_{f}}{dz}$ is the pressure gradient due to friction on the pipe wall.

Pressure drop.

In a first order analysis we can neglect pressure drops due to singularities such as elbows, valves or contraction for instance. We only take into account the pressure drop resulting from friction of fluids on the pipe wall.

Liquid flow.

The friction pressure gradient in the portion of the pipe submitted to single phase flow can be written :

$$\frac{dp_{\rm f}}{dz} = \frac{1}{2} \rho_{\rm L} \left(\frac{Q}{S}\right)^2 \frac{\lambda}{D}$$

D being the pipe internal diameter.

 λ is the head loss coefficient, it depends on the Reynolds number and the pipe roughness. The Reynolds number is :

$$Re = \frac{\rho_L U_L D}{\mu_L}$$

 μ_L is the water dynamic viscosity equal to 0.001 Pa.s.

The value of λ , for a smooth pipe in turbulent flow (Re > 2000) is given by the Blasius correlation :

$$\lambda = \frac{0.3164}{\sqrt[4]{\text{Re}}}$$

Two phase flow.

In the case of two phase flows, the problem is made complex because the following parameters are to be taken into account :

- Liquid viscosity,
- Gas viscosity,
- Surface tension
- Coalescence characteristics,
- Density of liquid,

- Density of gas (variable),
- Inclination of tubes,
- Fluid flow rates,
- Roughness of pipes.

Amongst the possible methods to determine the friction pressure drop are the following :

- the use of homogeneous flow theory,
- the use of Lockard-Martinelli correlations,
- the C coefficient method.

The simplest method is the use of homogeneous flow theory². This theory states that the pressure drops in two phase flow can be estimated by applying equations presented for single phase flow to an equivalent homogenous flow. Then we have :

$$\frac{\mathrm{d} \mathrm{p}_{\mathrm{f}}}{\mathrm{d} z} = \frac{\mathrm{\rho}_{\mathrm{H}} \mathrm{U}_{\mathrm{H}}^{2}}{2} \frac{\lambda}{\mathrm{D}}$$

The pressure drop coefficient λ being calculated using the Blasius equation with the Reynolds number in homogeneous two-phase flow defined by :

$$Re_{\rm H} = \frac{\rho_{\rm H} U_{\rm H} D}{\mu_{\rm H}}$$

We can apply the following relationship to determine the homogeneous two-phase flow dynamic viscosity :

$$\mu_{\rm H} = \left[\frac{x}{\mu_{\rm G}} + \frac{(1-x)}{\mu_{\rm L}}\right]^{-1}$$

with :

$$x = \frac{\rho_G Q_G}{\rho_G Q_G + \rho_L Q_L}$$

² D. Chisholm. Two-phase flow in pipelines and heat exchangers. George Godwin.

Extracted flow rate.

The objective of this calculation is to determine the extracted liquid flow rate Q_L which satisfies :

$$\int_{zextr}^{z \text{ deg}} \frac{dp}{dz} \, dz = p_{\text{A}} - p_{\text{B}}$$

From the hydrostatic law, we have :

$$p_{\rm A} - p_{\rm B} = \rho_{\rm L} g \left(z_{\rm extr} - z_{\rm sep} \right)$$

Finally this modelling give access to the decrease of extracted water flow rate, and thus gas flow rate, induced by dilution.

2.5. Calculations.

Gas concentration in extracted water.

It is interesting to evaluate the evolution of the extracted gas flow rate as a function of the concentration of dissolved methane in the extracted water. Nevertheless the concentration in dissolved CO_2 also has an impact on the extracted water flow rates, specially for shallow separation depth. Thus it is necessary to determine the evolution of CO_2 concentration as a function of methane dilution. This dependency is imposed by the extraction scenario.

Let us consider a control volume V_0 of water, equal to the volume of one of the two main resource zones (URZ or LRZ). Initially this volume of water contains the following masses of dissolved gases :

$$m_{CH4,0} = C_{CH4,0} V_0$$

and

$$m_{C02,0} = C_{C02,0} V_0$$

 $C_{CH4,0}$ and $C_{CO2,0}$ are the initial concentrations for each dissolved gas.



Figure 11. Mixing of the resource with degassed water. Notation.

We now suppose that this initial volume is mixed with an additional volume V_{rej} of partially degassed water. Then the amount of dissolved gases are :

$$m_{CH4} = C_{CH4,0} V_0 + C_{CH4,rej} V_{rej}$$

and

$$m_{C02} = C_{C02,0} V_0 + C_{C02,rej} V_{rej}$$

And the mean concentrations in state 1 are :

$$C_{CH4} = \frac{m_{CH4}}{V_0 + V_{rej}}$$

and

$$C_{C02} = \frac{m_{C02}}{V_0 + V_{rej}}$$

or :

$$\frac{C_{CH4}}{C_{CH4,0}} = \frac{1 + \frac{C_{CH4,rej}}{C_{CH4,0}} \frac{V_{rej}}{V_0}}{1 + \frac{V_{rej}}{V_0}}$$

$$\frac{C_{\text{C02}}}{C_{\text{C02,0}}} = \frac{1 + \frac{C_{\text{C02,rej}}}{C_{\text{C02,0}}} \frac{V_{\text{rej}}}{V_0}}{1 + \frac{V_{\text{rej}}}{V_0}}$$

We define the volumetric dilution ratio $\boldsymbol{\delta}$ as :

$$\delta = \frac{V_{rej}}{V_0}$$

Finally we found that the ratio of dilution for each dissolved gas is :

$$\frac{\frac{C_{C02}}{C_{C02,0}}}{\frac{C_{CH4}}{C_{CH4,0}}} = \frac{1 + \frac{C_{C02,rej}}{C_{C02,0}} \delta}{1 + \frac{C_{C02,0}}{C_{CH4,rej}} \delta}$$

Results.

Plan A1.

For the exploitation of the Upper Resource Zone, the extraction depth is set equal to 300 m. At this depth the initial (no dilution) concentration of dissolved gases is :

$$C_{CH4,0} \approx 0.345 \, 1/1$$

and

$$C_{C02,0} \approx 1.57 \, 1/1$$

The scenario proposed in the Management Prescription document for the exploitation of URZ (plan A1) suggests that the concentrations of dissolved gases in re-injected water are :

$$C_{CH4,rej} = 0.05 C_{CH4,0}$$

and

$$C_{C02,rej} = 0.6 C_{C02,0}$$

YLec Consultants.
This adjustment of residual $C0_2$ concentration is such that the density of re-injected water is equal to the density of surrounding water at the top of URZ.

Then we calculate :

$$\frac{C_{CH4}}{C_{CH4,0}} = \frac{1 + 0.05 \,\delta}{1 + \delta}$$

and

$$\frac{\frac{C_{C02}}{C_{C02,0}}}{\frac{C_{CH4}}{C_{CH4,0}}} = \frac{1+0.6 \,\delta}{1+0.05 \,\delta}$$

 \mathbf{C}

For a volumetric dilution $\delta = \frac{V_{rej}}{V_0} = 0.5$, we calculate :

$$\frac{C_{CH4}}{C_{CH4,0}} \approx 0.68$$

and

$$\frac{\frac{C_{C02}}{C_{C02,0}}}{\frac{C_{CH4}}{C_{CH4,0}}} \approx 1.27$$

For the scenario suggest in plan A1, a dilution ratio of dissolved methane concentration of 0.68 would lead to a dilution ratio for the concentration of dissolved CO_2 of 0.87.

The results of our calculations are illustrated on figure 12 in the case of plan A1.



Figure 12. *Methane flow rate versus methane concentration in extracted water. Plan A1. GMX273.*

One can conclude that, whatever the separation depth, if the concentration in methane of the extracted water is less than 50% of its initial concentration then the extracted methane flow rate will be approximately no more than 37% of the initial flow rate. For this dilution the extracted methane flow rate would be only 21% of its initial value, if the separation depth is equal to 20 m.

As a conclusion, if the gas flow rate delivered on shore is to be maintained constant, the number of degassing units has to be multiplied by a factor 3 (separation at the surface of the lake), and more probably 5 (separation depth equal to 20 m) when the rate of dilution of the methane resource reaches 50%.

Plan A2.

For the exploitation of the Lower Resource Zone, the extraction depth is set equal to 350 m. At this depth the initial (no dilution) concentration of dissolved gases is :

$$C_{CH4.0} \approx 0.412 \, 1/1$$

and

$$C_{C02,0} \approx 2.0151/1$$

The scenario proposed in the Management Prescription document for the exploitation of LRZ (plan A2) suggests that the concentrations of dissolved gases in re-injected water are :

$$C_{CH4,rej} = 0.05 C_{CH4,0}$$

and

$$C_{C02,rej} = 0.55 C_{C02,0}$$

This adjustment of residual CO_2 concentration is such that the density of re-injected water is equal to the density of surrounding water at the top of LRZ.



Figure 13. *Methane flow rate versus methane concentration in extracted water. Plan A2. GMX273.*

We can note that the impact of dilution on the exploitation rate with plan A2 would be approximately the same as for plan A1. For a dilution of 50% of the dissolved methane resource, the decrease in extracted gas flow rate would be of :

60% for a separation at the surface,70% if the separation depth is equal to 10 m.

Plan A1 and B together.

As illustrated on figure 14, the adjustment of CO_2 content for a re-stratification at 270 m depth would require to remove 80% of CO_2 content from the water extracted at 350 m. This is not practically possible even with separation at the surface.

That's probably the reason why it is suggested, in the Prescription Management document, to remove only 50% of $C0_2$ content and to achieve water density equilibrium by local dilution using so-called "diffuser nozzles on the injectors".



Figure 14. Water density profiles for various CO₂ content removing.

Let us suppose that water is extracted from LRZ at a depth of 350 m then we have for water re-injected into the URZ :

$$C_{CH4 rei} = 0.05 \times 0.412 \approx 0.0211/1$$

and

$$C_{C02.rei} = 0.5 \times 2.015 \approx 1.008 \, 1/1$$

We now consider plan A1 and plan B running together. We suppose that dilution of the URZ mainly results from the re-injection of partially degassed water previously extracted from the LRZ (Plan B). Then we propose to evaluate the consequence of this dilution on the gas flow

rate that could be extracted from the URZ (Plan A1). Thus for plan A1 and B running together we consider the following scenario :

- extraction depth : 350 m,
- initial CH₄ content in the URZ (no dilution) : 0.345 l/l,
- initial CO₂ content in the URZ (no dilution) : 1.57 l/l,
- CH₄ content in re-injected water : 0.02 l/l,
- CO_2 content in re-injected water : 1.01 l/l.



Figure 15. *Methane flow rate versus methane concentration in extracted water. Plan B. GMX273.*

Once again we can conclude that methane resource dilution in plan B would result in a considerable decrease, around 70%, of the gas flow rate extractable by each degassing unit.

3. VERTICAL MIXING.

We have determined above the influence of dilution of the resource on the performances of degassing units, for plan A1, A2 and B suggested in the Management Prescription document.

The conclusion is that if the concentration of dissolved methane in extracted water is divided by a factor 2, then the decrease of extracted gas flow rate would be typically of 70%.

As a consequence, the total number of degassing units should be multiplied by 3 if the total gas flow rate delivered on shore has to be maintained constant.

At this stage it seems necessary to evaluate the actual methane concentration evolution that would result from degassed water re-injection into the resource.

In this paragraph we mainly focus on the plan A1 scenario which is the most critical regarding dilution of the resource because of the narrow vertical interval between intake and re-injection.

3.1. Possible causes for dilution.

The mixing of re-injected water with the surrounding gas-rich water may result from two main phenomenon :

- vertical diffusion induced by "natural" turbulence in the lake, which mainly results from the effect of wind on the surface of the lake.

- turbulent dissipation induced by local relative velocity between re-injected water and surrounding water and resulting in the development of shear layers.

3.2. Re-injection at zero velocity.

If the re-injection of degassed water is achieved with zero velocity then the mixing of reinjected water with surrounding water can only be caused by dissolved gases diffusion.

Diffusion length.

If we consider two regions with different dissolved gas concentration initially separated, as illustrated on figure 5, and suddenly put into contact, then dissolved gas will diffuse from the rich region to the low concentrated region. As a result, the transition region between rich and low concentrated regions, will progressively spread over a length L_d , called diffusion length, which after a time t is such that :

$$L_d \approx \sqrt{D t}$$

D is the diffusion coefficient in m^2/s .



Figure 16. Illustration of the diffusion length.

If the liquid is perfectly quiescent, then the diffusion coefficient that has to be taken into account is the molecular diffusion D_m which is typically of 10^{-9} m²/s.

Vertical diffusivity.

We consider the vertical diffusion of dissolved gases from a supposed upper degassed layer to a supposed lower gas rich layer. We suppose that these two layers are initially separated and suddenly put into contact.

Then the dissolved gases diffusion is mainly driven by the vertical diffusivity which is caused by turbulent kinetic energy dissipation. According to Wüest & al¹ if we consider the vertical diffusion of dissolved gases, and if double diffusion (induced by temperature microstratification) is taken into account, the vertical diffusivity K_z can be estimated applying the following formula :

$$K_z = \frac{0.15}{10} \frac{\varepsilon}{N^2}$$

Where N^2 is the stability of density stratification, which tend to moderate vertical mixing, and ϵ is the energy dissipation rate.



Figure 17. Diffusion of dissolved gas from a rich layer to a degassed layer.

In the resource zone, we can consider :

$$\epsilon = 3 \, 10^{-11} \, \mathrm{W} / \mathrm{kg}$$

and :

$$N^2 = 4\,10^{-6}\ s^{-2}$$

Then we calculate :

$$K_z \approx 1.110^{-7} \text{ m}^2 / \text{s}$$

The vertical diffusivity K_z induced by turbulent energy dissipation is approximately 100 times higher than the molecular diffusion coefficient D_m . According to Wüest & al¹, in absence of thermal micro-stratification vertical diffusivity would reach 10^{-6} m²/s.

First order analysis.

We assume that degassed water is re-injected with a velocity close to zero. What's more, we suppose that :

- degassed water is uniformly re-injected over the whole surface of the lake,
- rich water is uniformly extracted over the whole surface of the lake.

These assumptions imply that the structure of the lake is kept perfectly horizontally stratified. This supposes in practice that the horizontal spreading is "rapid" enough.



Figure 18. Vertical growth of the degassed layer and dilution of the resource.

Then we can be interested in evaluating the time needed for dilution to reach the extraction depth. Notations are illustrated on figure 18.

Diffusion time.

If a degassed layer is formed at the top of the Upper Resource Zone, and if vertical diffusion is the only mixing process, then water located at the bottom of the URZ would start to be diluted within within a characteristic time Δt_{diff} such that :

$$\Delta t_{diff} = \frac{h_{URZ}^2}{K_z}$$

 h_{URZ} is the height of the URZ equal to 30 m.

We calculate :

$$\Delta t_{\rm diff} = \frac{30^2}{1.110^{-7}} \approx 8.210^9 \,\, {\rm s}$$

or

$$\Delta t_{diff} \approx 260$$
 years

In absence of thermal micro-stratification ($K_z \sim 10^{-6} \text{ m}^2/\text{s}$), we would calculate :

$$\Delta t_{diff} \approx 26$$
 years

Degassed layer vertical growth.

If we assume that degassed water re-injection is uniformly distributed over the whole lake surface and if vertical diffusion is neglected, then the width of the degassed layer at a time t is such that :

$$\Delta h_{deg} = \frac{Q_{tot}}{A} t$$

A is the average section of the lake in the Upper Resource Zone. A is approximately equal to $1.1 \ 10^9 \ m^2$.

Q_{tot} is the total extraction flow-rate.

The time needed for a complete exploitation of the Upper Resource Zone is such that :

$$\Delta t = \frac{A \ h_{\mbox{\tiny URZ}}}{Q_{\mbox{\tiny tot}}}$$

For $Q_{tot} = 70 \text{ m}^3/\text{s}$, we calculate :

$$\Delta t = \frac{1.110^9 \ 30}{70} \approx 15 \ \text{years}$$

We can conclude that if thermal micro-stratification is to be taken into account then vertical diffusion would be a relatively slow phenomenon for a total exploitation rate of the URZ of $70 \text{ m}^3/\text{s}$.

Coupled calculation.

We suggest to complete the previous analysis taking into account both phenomena (vertical diffusion and degassed layer growth) at he same time. Notations are illustrated on figure 19.

In a first stage of exploitation of the URZ the quality of extracted water is not modified. Thus the extracted flow rate is constant. The duration of this first stage is noted Δt_0 . At the end of top of the URZ is filled with degassed water over a depth Δh_{deg} , below which the concentration profile is spread over a depth h_{diff} , as a result of vertical diffusion.

At that time we can write the following relationships :

$$\Delta t_0 = \frac{h_{dil}}{K_z}$$

and

$$h_{\rm diff} = h_{\rm URZ} - \frac{Q_{\rm tot}}{A} \Delta t_0$$



Figure 19. Concentration profile at the end of the first stage of exploitation.

Which yields to the following relationship :

$$K_z \Delta t_0 = h_{URZ}^2 - 2 \frac{Q_{tot}}{A} h_{URZ} \Delta t_0 + \left(\frac{Q_{tot}}{A}\right)^2 \Delta t_0^2$$

or

$$\left(\frac{Q_{tot}}{A}\right)^2 \Delta t_0^2 - \left(K_z + 2\frac{Q_{tot}}{A}h_{URZ}\right)\Delta t_0 + h_{URZ}^2 = 0$$

We have calculated the evolution of the duration of the first stage of exploitation Δt_0 as a function of K_z for different values of the total extraction flow rate. The results of these calculations are illustrated on figure 20.

We only consider the exploitation of the main volume of the URZ comprised between 270 m depth and 300 m depth, containing approximately 33 km³ of water and 11.5 Nkm³ of dissolved methane.

For $Q_{tot} = 70 \text{ m}^3/\text{s}$ and assuming $K_z = 1 \ 10^{-7} \text{ m}^2/\text{s}$, the duration of the first stage of exploitation (constant extracted flow rate) would be of some 12 years. We can note on figure 21 that, at that time, the depth h_{diff} would be of some 6 meters (one fifth of the URZ depth).

For $Q_{tot} = 35 \text{ m}^3/\text{s}$ and assuming $K_z = 1 \ 10^{-6} \ \text{m}^2/\text{s}$, the duration of the first stage of exploitation would also be of some 12 years, but the depth h_{diff} would be of some 20 meters (two third of the URZ depth).

The average methane concentration over the depth h_{diff} is :

$$\overline{C} \approx \frac{C_0}{2}$$

C₀ being the initial methane concentration in the resource.

From the results of previous calculation (see figure 12), we can conclude that the average gas flow rate extracted from this diluted layer would approximately be no more than 30% of the maximum gas flow rate which could be extracted if dilution did not occur.



Figure 20. Diffusion time versus vertical diffusivity. GMX281.



Figure 21. Depth of the diluted layer versus vertical diffusivity.

For this calculation we assumed that the concentrations of dissolved gas in the lake are uniform in each horizontal cross section. This supposes that :

- degassed water is uniformly distributed over the whole lake surface with zero velocity,
- rich water is uniformly extracted over the whole lake surface with zero velocity.

The validity of these assumptions has to be evaluated.

In such ideal conditions :

- the exploitation of the URZ would remain constant for a period of 12 years $(Q_{tot} = 70 \text{ m}^3/\text{s}),$

- after this initial period, the production would progressively decrease and one fifth of the resource would be exploited with an average gas flow rate equal to 30% of the initial gas flow rate.

3.3. Local mixing induced by relative velocities.

Laminar and turbulent jets.

As mentioned in the Management Prescriptions document, water re-injection must be done horizontally and "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.".

A laminar reinjection suppress intense local turbulent dissipation that occurs within the mixing layers produced by turbulent submerged jets. Thus a turbulent reinjection would probably results in a rapid mixing of the re-injected degassed water with the surrounding water. This would lead to a rapid local dilution of the resource.

We would like to evaluate the technical feasibility of a laminar re-injection.



Figure 22. Initial conditions for a submerged jet.

The flow characteristics at the reinjection point is a function of the so called Reynolds number which can be written as follows :

$$R_{e} = \frac{U_{0} D_{0}}{v}$$

 U_0 is the flow velocity at nozzle exit, D_0 the dimension of the reinjection orifice and v is the kinematic viscosity of water equal to 10^{-6} m²/s.

It is generally assumed that for Reynolds number below 1000, the submerged jet exiting the nozzle is initially laminar. For Reynolds number above 3000, the flow emerging the nozzle is said turbulent. We give theoretical illustration of this two kinds of flow regime on figures 23 and 24.



Figure 23. Streamline pattern for an round laminar jet. Blevins³.



Figure 24. *Submerged turbulent jet. Blevins*¹.

Laminar re-injection.

Single round jet.

If a volumetric flow rate Q₀ is injected through a unique round orifice, the initial velocity is :

$$U_0 = \frac{Q_0}{\pi \frac{D_0^2}{4}}$$

³ Blevins R. D. Applied Fluid Dynamics Handbook. Krieger.

And the Reynolds number is :

$$R_e = \frac{4 Q_0}{\pi D_0 v}$$



Figure 25. Single round jet.

For each degassing unit, the degassed water flow rate is approximately equal to $1.3 \text{ m}^3/\text{s}$. Thus we have :

$$R_e = \frac{1.66\,10^6}{D_0}$$

We can note on figure 26 that it is practically impossible to generate a laminar re-injection through a unique round jet.



Figure 26. Reinjection through a unique round jet. Reynolds number versus nozzle diameter. $Q0 = 1.3 \text{ m}^3/\text{s}$. GMX271.

Radial jet.

In the case of reinjection through a radial plane jet, the reinjection velocity is :

$$\mathbf{U}_0 = \frac{\mathbf{Q}_0}{\boldsymbol{\pi}_0 \ \mathbf{D}_0 \ \mathbf{h}_0}$$

and the Reynolds number can be written :

$$R_{e} = \frac{U_{0} h_{0}}{v}$$

or

$$R_e = \frac{Q_0}{\pi D_0 v}$$

Finally the Reynolds number does not depend on the reinjection thickness h_0 . For $Q_0 = 1.3$ m³/s, we calculate :



Figure 27. Radial jet.

As well as for a unique round jet we can conclude from figure 28 that it is practically impossible to generate a laminar reinjection through a single radial jet.



Figure 28. Reinjection through a radial jet. Reynolds number versus nozzle diameter. $Q0 = 1.3 \text{ m}^3/\text{s. GMX271}.$

Multiple nozzles.

The best way to generate a laminar flow is probably to re-inject degassed water trough multiple small round nozzles. In this case the reinjection velocity is :

$$U_0 = \frac{Q_0}{N \pi \frac{d_0^2}{4}}$$

N is the number of nozzles and d_0 their exit diameter.

The Reynolds number for each individual jet can be written :

$$R_e = \frac{U_0 d_0}{v}$$

or

$$R_e = \frac{4 Q_0}{N \pi d_0 v}$$

For $Q_0 = 1.3 \text{ m}^3/\text{s}$, we calculate :

$$R_{e} = \frac{1.6610^{6}}{N d_{0}}$$

We can conclude from figure 29 that the minimum number of nozzles necessary for a laminar reinjection depends on the nozzles diameter. We find :

$$N \approx 80000$$
 for $d_0 = 20$ mm

and

 $N \approx 160000$ for $d_0 = 10$ mm



Figure 29. Reinjection through multiple round jets. Reynolds number versus number of nozzles. $Q0 = 1.3 \text{ m}^3/\text{s}$. GMX271.

Actually, the minimum number of nozzles necessary to produce an initially laminar reinjection is such that :

$$R_e = \frac{1.6610^6}{N d_0} = 1000$$

Or :

$$N = \frac{1.66 \, 10^3}{d_0}$$

Reinjection through a large number of nozzles imposes the use of a large device for water reinjection. For instance, the nozzles can be installed on a large cylindrical box, as illustrated on figure 30.

The total surface of the box is :

$$A_{b} = \pi D_{b} H_{b}$$

The total surface of nozzles or orifices exits is :

$$A_{perf} = N \pi \frac{d_0^2}{4}$$

Thus the perforation of the reinjection box is :

$$\tau_{perf} = \frac{A_{perf}}{A_{b}}$$

or :

$$\tau_{\text{perf}} = \frac{N d_0^2}{4 D_b H_b}$$

And for a laminar reinjection the perforation rate is such that :

$$\tau_{perf} = 4.14 \, 10^2 \, \frac{d_0}{D_b \, H_b}$$



Figure 30. Reinjection through multiple round jets.

Practically, it seems reasonable to limit to 10% the perforation rate of this box. What's more, the diameter of the reinjection box has to be limited for instance to 4 meters. Then we calculate :

$$\tau_{\rm perf} = 4.14\,10^2\,\,\frac{\rm d_0}{\rm H_b} = 0.1$$

or :

$$H_b \approx 1000 d_0$$

For instance, for $d_0 = 10$ mm, the minimum height of the reinjection box would be of 10 m.



Figure 31. Reinjection through multiple round jets. Perforation rate versus number of nozzles. $Q0 = 1.3 \text{ m}^3/\text{s}$. GMX271.

The typical device to produce a laminar reinjection of the degassed water would be a cylindrical box with the following characteristics :

- Box diameter : $D_b = 4 m$,
- Box height : $H_b = 10 m$,
- Number of orifices : $N_0 = 160000$,
- Orifices diameter : $d_0 = 10 \text{ mm}$,
- Perforation rate : $\tau_{perf} = 10 \%$.

With this configuration, the initial velocity of each individual jet would be of 0.1 m/s.



Figure 32. Laminar reinjection at the top of the Upper Resource Zone. Plan A1. Technical solution.

This is a relatively high device compared to the Upper Resource Zone height.

At this stage, we consider that in plan A1 reinjection must not occur in the main density gradient and that water must not be extracted in the secondary density gradient. What's more

it seems necessary to impose safety margins, regarding the amplitude of seiches, for the implantation of extraction and reinjection.

Finally, as illustrated on figure 32, the difference of depth between extraction and reinjection would be no more than 15 m.

Actual behaviour of initially laminar submerged jets.

Even if the Reynolds number of a submerged water jet is below 1000, in practice the jet becomes progressively turbulent. The development of turbulence results from the growing of unavoidable initial small disturbances. This growing can be emphasised by the natural turbulence in the lake.

This means that, in practice, the flow stream in a initially laminar submerged jet can't remain parallel to the jet axis. At a certain length downward the exit section, the flow is destabilized and vortices develop at the boundary between the jet and the surrounding fluid.

We give on figure 33 and 34 visualisations of different submerged jet for Reynolds values respectively equal to 340, 830 and 1800. We can note that in this rang of Reynolds number the jet becomes rapidly turbulent.



mostly laminar

transition to turbulence



⁴ Geiger M?, Herrmann S., Peinke J., sch K.D. Analysis of free jet turbulence with cross-correlation light-inflight holography. Proc. Appl. Math. Mech. 1 (2002).



Figure 34. *Visualisation of submerged axisymetric water jet for different Reynolds number. Kechiche & al*⁵.

So as to maintain a laminar flow a long distance downstream from the nozzle exit, it would be necessary :

- to impose a very low Reynolds number (below 100),
- to ensure very low turbulence level in the flow before nozzle exit,
- to ensure zero disturbance in the surrounding liquid, which is practically impossible in a lake.

As a conclusion it is necessary to consider that the behaviour of any submerged jet in the lake is rapidly similar to that of a turbulent jet.

⁵ N. Kechiche, A. Abbassi, F. Filali & H. Ben Aissia. 2006. Congrès Francophone de Techniques Laser. *Etude expérimentale par ALD des instabilités d'un jet axisymétrique*.

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It is generally considered that the length L_{turb} after which the jet is turbulent is comprised between 10 and 20 times the nozzle diameter.

Energy dissipation.

The initial kinetic energy carried by each jet is :

$$e_{_0} = \frac{1}{2} \, \rho_{_{\rm L}} \, \, U_{_0}^2 \, \, q_{_0}$$

or :

$$e_0 = \frac{1}{2} \rho_L \ U_0^3 \ \pi \ d_0^2$$

One can evaluate the energy dissipation resulting from the turbulent dissipation of the round jets. Once it became turbulent, we can assume that each jet dissipates its initial energy within a length equal to 20 times its initial diameter. The corresponding dissipation volume is :

$$V_{diss} \approx 20 d_0 \pi d_0^2$$

Finally the average energy dissipation rate of round jets is :

$$\epsilon = \frac{e_0}{\rho_L \ V_{diss}}$$

or

$$\varepsilon = \frac{U_0^3}{40 d_0}$$

We calculate :

$$\varepsilon \approx \frac{0.1^3}{40 \times 0.01} \approx 2.5 \, 10^{-3} \, \mathrm{W/kg}$$

The dissipation rate of the round jets is much greater than the natural dissipation of the lake. We can conclude that, despite the reinjection velocity is quite low, the stratification of the lake as no significant limiting effect on the vertical dispersion of dissolved species induced by water reinjection.

Nevertheless we can not that a low re-injection velocity reduces considerably the rate of energy dissipation since ε is proportional to U₀³.

Jets coalescence.

Because of their small diameter each individual jet will become turbulent at a short distance after its exit. We have :

$$L_{turb} \approx 20 d_0$$
,

Or :

$$L_{turb} \approx 0.2 \text{ m}$$

The average diverging angle of a turbulent submerged jet is equal to 10°. Because of this diverging angle the different individual round jets tend to coalesce with each others and to produce a large single radial jet, as illustrated on figure 35.



Figure 35. Coalescence of individual round jets to produce a radial jet.

Finally we can consider that the behaviour of the reinjection flow is rapidly equivalent to that of a radial jet characterised by :

Initial flow rate $Q_0 = 1.3 \text{ m}^3/\text{s}$, Initial thickness $e_0 = 10 \text{ m}$, Exit radius $R_0 = 2 \text{ m}$.

The virtual initial velocity of this radial jet would be :

$$U_0 = \frac{Q_0}{2 \pi R_0 e_0}$$

We calculate :

$$U_0 \approx 0.01 \, \text{m/s}$$

This is a relatively low velocity. Nevertheless the Reynolds number of the radial jet is :

$$R_e = \frac{U_0 e_0}{v}$$

We calculate :

$$R_e \approx 100000$$

This Reynolds number corresponds to a fully turbulent submerged jet.

Downstream characteristic of the submerged turbulent radial jet.

Velocity.

Blevins¹ proposes the following correlations for the main characteristics of a submerged radial turbulent jet :

- centre plane velocity :

$$U_{m} = 3.5 \frac{(R_{0} b_{0})^{1/2}}{r^{1/2} (r - R_{0})^{1/2}} U_{0}$$

 b_0 is the initial half width of the radial jet. R_0 is the radius of exit section of the radial jet.

- velocity profile :

$$\frac{\mathrm{u}}{\mathrm{U}_{\mathrm{m}}} = \exp\left(-57\left(\frac{\mathrm{y}}{\mathrm{r}}\right)^{2}\right)$$

y is the transversal distance to the jet centre plane.

We illustrated on figure 36 the ratio $\frac{u}{U_0}$ versus y at different distance from the radial jet axis. This illustrate the vertical spreading of the jet resulting from surrounding water entrainment through mixing layers.



Figure 36. Velocity profiles of the radial jet resulting from multiple round jets coalescence.

Species concentration.

It is possible to derive the theory of round jet dissipation to evaluate the evolution of species concentration within the radial jet. We can consider the following jet characteristics :

- centreline species concentration : C_m

$$\frac{C_0 - C_m}{C_0} = 3.5 \frac{\left(R_0 \ b_0\right)^{1/2}}{r^{1/2} \ \left(r - R_0\right)^{1/2}}$$

 C_0 is the initial species concentration of surrounding water. The species concentration in the surrounding liquid is supposed to be equal to zero.

- Species concentration profile : c(r,y)

$$\frac{C_0 - c}{C_m} = \exp\left(-35\left(\frac{y}{r}\right)^2\right)$$

From these correlations we have calculated the predicted concentration profiles along the radial jet. The results are illustrated on figure 37.



Figure 37. Vertical dispersion induced by turbulent mixing in a radial turbulent jet. *GMX279.*

We have also evaluated the jet width relatively to species concentration. This width $z_c(r)$ is such that :

$$\frac{c(z_c)}{C_m} = \exp\left(-35\left(\frac{z_c}{r}\right)^2\right) = 0.01$$



Figure 38. Radial jet vertical spreading regarding species concentration. GMX279.

We can conclude from this analysis that, in the case of plan A1 or plan B (reinjection into the URZ), dilution will significantly impact the extraction within a radius R_{max} approximately equal to 100 m.

At this downstream distance, the centreline concentration is approximately equal to 85% of initial concentration of surrounding water. We can suppose that for r > 100 m the species concentration is uniformly distributed across the whole URZ depth and is such that :

$$C \approx 0.9 C_0$$

From our calculations, we evaluated that the exploitation time after which this situation is reached is approximately equal to 12 hours. This time is very short compared to supposed overall exploitation period of the degassing unit.

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Figure 39. *Dissolved gas concentration profile close to the re-injection device.*

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3.4. Entrained water flow rate.

Evaluation.

One characteristic of submerged jets is that they entrain large volumetric flow rates from surrounding liquid. In the case of a radial jet the total flow rate increases linearly with radius r. The results of our calculations are illustrated on figure 40.



Figure 40. *Radial jet. Entrained volumetric flow rate versus radial distance to the jet axis. GMX279.*

Once dilution impact the bottom of the URZ ($R_{max} = 100$ m), the volumetric flow rate resulting from surrounding water entrainment is maximum and approximately equal to 17 m³/s, which is more than 10 times the initial flow rate $Q_0 = 1.3$ m³/s.

This phenomenon could be greatly emphasized because of the use of multiple reinjection nozzles. In this case the re-injected water would be rapidly diluted and its density will tend to that of the surrounding water. Therefore there is no need to adjust the density of degassed water through its CO_2 content.

Consequences.

Backflow and short-circuiting.

Water entrainment induced by the submerged jet results in a removal of the rich water initially located in the vicinity of the degassing facility. This removal is compensated by an inflow of surrounding water. Because of the presence of main density gradient and secondary density gradient, this inflow must be provided by the URZ. This results in the generation of a backflow as illustrated in figure 41.

For short term exploitation, the backflow carries rich water and the influence on the quality of extracted water is limited. Nevertheless the induced counter currents would lead to intensification of shearing stresses and thus to a more rapid vertical dispersion of re-injected water.

Once the diluted layer reaches the bottom of the URZ, the backflow carries diluted water, and the dissolved gas removal induced by water entrainment is not compensated anymore. The backflow results in a short-circuiting as illustrated on figure 41.

As a consequence, dissolved gas in the vicinity of the extraction facility will be drawn away because of water entrainment and the concentration of dissolved gas in extracted water will progressively decrease until reaching a value close to that of the re-injected water.

This effect would be catastrophic for the performances of the degassing unit since extracted gas flow rate would then fall to zero.
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Figure 41. Short term and long term exploitation. Water entrainment and backflow generation. Low horizontal mixing.

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Effect of horizontal mixing.

In the previous analysis of radial submerged jet dispersion, we have ignored the possible presence of underwater currents. These currents would tend to push re-injected water away from the extraction facility, thus limiting the risks of short-circuiting.

On the other hand underwater currents can increase relative velocity between re-injected water and surrounding water, thus resulting in an intensification of shearing stress and consequently in a more rapid vertical dispersion of degassed water.



Figure 42. Influence of underwater currents on degassed layer dispersion.

If horizontal mixing is very efficient then we can consider that the whole volume of URZ is instantaneously mixed. This corresponds to a virtual scenario for which degassed water reinjection would be uniformly distributed over the whole URZ volume.

The actual behaviour of re-injected water depends on underwater current velocity and on their possible evolution with time. Even if the time averaged horizontal mixing is very intense, if local underwater currents velocity fall to zero for sufficiently long period, then the gas flow rate extracted from the URZ could fall to zero.

For reinjection into the LRZ the problem is even more complex because the vertical interval between reinjection and intake is more important.

Conclusion on local dispersion of re-injected water.

If degassed water is re-injected into the resource, in a zone of low density gradient, its dilution with entrained surrounding water will be unavoidable, even if the outlet of the re-injection column produce an initially laminar flow.

This phenomenon is emphasized if water is re-injected through multiple nozzles, which is the only way to produce an initially laminar reinjection. In this case the density of re-injected water would rapidly tend to that of the surrounding water. Therefore it seems that there is no need to adjust the density of degassed water through its CO_2 content.

The evaluation of actual dispersion of re-injected water, influenced by permanent or non permanent under water currents is a very complex problem. Because of the possible catastrophic consequence of dilution on extracted gas flow rate (which could rapidly fall to zero in absence of underwater currents in the case of URZ exploitation) an experimental investigation of any reinjection technique seems absolutely necessary.

4. EVOLUTION OF EXTRACTED GAS FLOW RATE.

4.1. Plan A1.

Possible behaviours.

Because of the narrow vertical interval between intake and reinjection we have shown that the degassed water re-injected at the top of URZ would rapidly be distributed over the whole depth of this resource.

As a consequence, the re-injection of degassed water into the Upper Resource Zone could lead to one of the two following extreme behaviour, depending on the intensity of horizontal mixing :

- if horizontal mixing is permanently very efficient then we can consider that the whole volume of URZ is instantaneously mixed

- if local underwater currents velocity fall to zero, then the dissolved gas concentration in the vicinity of extraction facility would rapidly decrease because of water entrainment and short-circuiting.

Rapid horizontal mixing.

No limiting concentration.

This behaviour corresponds to a scenario for which degassed water re-injection would be uniformly distributed over the whole URZ volume. In this virtual scenario, the concentration C_i of dissolved gas i (CH₄ or CO₂) in the URZ would be such that :

$$\frac{\mathrm{dC}_{\mathrm{i}}}{\mathrm{dt}} = \frac{\left(\mathrm{C}_{\mathrm{i,rej}} - \mathrm{C}_{\mathrm{i}}\right)}{\mathrm{V}_{\mathrm{R}}}\mathrm{Q}_{\mathrm{L}}(\mathrm{t})$$

 V_R is the resource volume approximately equal to 33 km³ for the URZ.

 $C_{i,rej}$ is the concentration of dissolved gas i in the re-injected water, we have set for the calculation :

$$C_{CH4,rej} = 0.05 C_{CH4,0}$$

and :

$$C_{CO2,rej} = 0.60 C_{C02,0i}$$

With the following initial concentrations :

$$C_{CH4,0} \approx 0.345 \, 1/1$$

and

$$C_{C02,0} \approx 1.57 \, 1/1$$

Because of the dilution of the resource, the extracted liquid flow rate Q_L decrease with time, as previously demonstrated. We have run a transient calculation with an initial total liquid flow rate equal to 70 m³/s. We have run transient calculations based on the modelling of the degassing column described above. We suppose that the number of extraction facility is constant during the calculation period.

The results of these calculations are illustrated on figures 43 to 44 in terms of extracted methane flow rate and of percentage of the initial resource exploited defined as :

%CH4 exploitation =
$$\frac{C_{CH4,ini} - C_{CH4}(t)}{C_{CH4,ini}}$$

For a complete exploitation of the resource ($C_{CH4}(t) = 0$) this parameter would be of 100%.

One can notice that, whatever the separator depth, the production of methane will rapidly decrease and finally the resource exploitation will reach a maximum comprised between 90% and 70% for separation depth respectively equal to 0 and 30 m.

The worst consequence concerns the rate of exploitation of the resource. In a scenario with no dilution, the total amount of gas dissolved in the URZ could be extracted within a period of

only 15 years ($Q_L = 70 \text{ m}^3/\text{s}$), whereas in the case of dilution with separation at 10 m depth, the time needed to extract the maximum value of 85% of the total methane resource is at least of 100.



Figure 43. Long term methane production from the Upper Resource Zone. Plan A1. Instantaneous horizontal and vertical mixing. Initial water flow rate 70 m^3/s . GMX275.



Figure 44. Evolution of the methane flow rate extracted from the Upper Resource Zone. Plan A1. Instantaneous horizontal and vertical mixing. Initial water flow rate 70 m^3/s . GMX275.

Economically viable methane concentration assumed as $5 \text{ mol/m}^3 (0.11 \text{ l/l})$.

In the previous calculations we supposed that the resource harvesting is not limiting when the concentration decrease. This analysis can be completed if we consider that below an economically viable methane concentration equal to 5 mol/m^3 the extracted liquid flow rate fall to zero. The results of this second calculation are illustrated on figures 45 and 46.



Figure 45. Long term methane production from the Upper Resource Zone. Plan A1. Instantaneous horizontal and vertical mixing. Initial water flow rate 70 m^3/s . GMX275b.



Figure 46. Evolution of the methane flow rate extracted from the Upper Resource Zone. Plan A1. Instantaneous horizontal and vertical mixing. Initial water flow rate 70 m^3/s . GMX275b.

Our feeling is that this results corresponds to the most optimistic possible behaviour. As soon as horizontal mixing is not efficient enough, the effect of dilution is emphasized because reinjected degassed water is not rapidly enough pushed away from the extraction facility. This results in an progressive accumulation of degassed water in the vicinity of intake.

Backflow : low horizontal mixing.

We consider that horizontal mixing results mainly from underwater currents. It has not been proven that theses currents are permanent everywhere in the lake. Therefore it has to be considered the velocity of underwater currents can be reduced to zero, at least periodically, in the vicinity of any extraction facility.

Notations are illustrated on figure 47. We can consider that the concentration of dissolved gas in the backflow zone is homogeneous. The evolution of this concentration can be deduced from mass balance analysis.



Figure 47. Local long term resource dilution. Mass balance analysis.

During a time step dt, the variation of the mass of dissolved gas contained in the backflow zone is :

$$dm_1 = dm_{in} - dm_{out}$$

with

$$dm_{in} = C_2 Q_2 dt$$

and :

$$dm_{out} = C_1 Q_1 dt$$

From the previous calculation we can consider :

$$Q_1 = Q_2 \approx 9 Q_0$$

and :

$$C_2 \approx 0.9 C_1$$

Thus we have :

$$\frac{\mathrm{dm}_1}{\mathrm{dt}} \approx -0.9 \mathrm{C}_1 \mathrm{Q}_0$$

What's more we can write :

$$\frac{\mathrm{d}\mathrm{C}_{1}}{\mathrm{d}\mathrm{t}} = \frac{\mathrm{d}\mathrm{m}_{1}}{\mathrm{V}_{1}}$$

 V_1 is the volume backflow zone, which can be considered as a cone of height $h_{cone} \approx h_{URZ} = 30 \text{ m}$ and radius $r_{cone} \approx R_{max} \approx 100 \text{ m}$. This volume is :

$$V_1 = \frac{\pi}{3} r_{\text{cone}}^2 h_{\text{cone}}$$

We calculate :

$$V_1 \approx 3.14 \, 10^6 \, m^3$$

Finally the evolution of concentration C_1 is such that :

$$\frac{dC_1}{dt} = -0.9 \frac{C_1 Q_0}{V_1}$$

Which can be integrated as follows :

$$\frac{\mathrm{C}_{1}(\mathrm{t})}{\mathrm{C}_{1,0}} = \exp\left(-0.9\,\frac{\mathrm{t}}{\mathrm{\tau}}\right)$$

With :

$$\tau = \frac{V_1}{Q_0} \approx \frac{3.14\,10^6}{1.3} \approx 2.42\,10^6 \text{ s}$$

Figure 48 shows the calculated concentration evolution that would result, in the vicinity of the extraction facility, from on accumulation of degassed water in absence of underwater currents. The re-injected degassed water flow rate Q_0 is supposed equal to 1.3 m³/s.



Figure 48. Dilution of the resource in the vicinity of the extraction facility. Plan A1. No underwater currents. GMX279.

We can conclude that, in absence of horizontal mixing, the concentration of dissolved gasses in the vicinity of the reinjection device will rapidly decrease on the whole depth of the URZ. Within a period of 15 days the concentration of dissolved gas would almost be equal to zero and thus the extracted flow rate would also rapidly fall to zero.

4.2. Plan A1 and B together.

Possible behaviours.

The scenario proposed in plan B would influence the exploitation of the URZ in a same way than the scenario proposed in plan A1. Nevertheless, the re-injected flow rates would be more important when plan A1 and B are run together.

Rapid horizontal mixing.

We consider the following scenario for the exploitation of the URZ with plan A1 and B together :

- initial extracted water flow rate : $70 \text{ m}^3/\text{s}$.
- initial re-injected water flow rate, previously extracted from the URZ : $70 \text{ m}^3/\text{s}$.
- re-injected water-flow rate, previously extracted from the LRZ : $70 \text{ m}^3/\text{s}$.

The extracted flow rate, and thus the first re-injected flow rate will progressively decrease because of dilution of extracted water.

The second re-injected flow rate is constant since dilution doesn't affect exploitation of the LRZ in this scenario.



Figure 49. Long term methane production from the Upper Resource Zone. Instantaneous horizontal and vertical mixing. Plan A1 and B together. Initial water flow rate extracted from the URZ : 70 m^3 /s. Constant re-injected flow rate from the LRZ : 70 m^3 /s. GMX275c.

The calculated evolution of the exploitation of the URZ is illustrated on figures 49 and 50. The exploitation of the URZ would rapidly decrease, within 15 years, and the percentage of exploitation would be limited to 35% of the total available resource.



Figure 50. Evolution of the methane flow rate extracted from the Upper Resource Zone. Instantaneous horizontal and vertical mixing. Plan A1 and B together. Initial water flow rate extracted from the URZ : 70 m^3/s . Constant re-injected flow rate from the LRZ : 70 m^3/s . GMX275c.

Backflow : low horizontal mixing.

The conclusions are the same as for plan A1.

4.3. Plan A2.

Because of the larger possible vertical interval between re-injection and intakes (if rich water is extracted at the bottom of the LRZ), the evaluation of plan A2 is a much a more complex problem.

It is possible that water extracted at the bottom the LRZ is not diluted before a relatively long exploitation time, since the re-injected submerged jet won't spread over a 100 m depth.

Nevertheless we can consider that water re-injected at the top of the LRZ will rapidly spread over a 30 m depth layer. The progressive dilution of this diluted layer could considerably compromise the harvesting of the methane resource initially dissolved in this layer. The concerned resource is approximately of 13 Nkm³.

5. RECOMMENDED EXPERIMENTAL STUDY.

5.1. Necessity.

Our opinion, based on the analysis of submerged jet theory, is that reinjection of degassed water into the URZ would rapidly result in dilution over the whole depth of this resource zone.

The possible rapid decrease of methane content in extracted water can greatly damage the economic performances of the extraction facilities.

Nevertheless, because the involved physical phenomena are very complex, and since many technical solution can be imagined for water reinjection, including multiple nozzles, we recommend to evaluate experimentally the actual spreading of re-injected degassed flow.

The experimental study must be carried out with water flow rates comparable to that extracted and re-injected by industrial facilities.

5.2. Objectives of experimental study.

The main objective of a such experimental investigation is to determine the modification of gas concentration profiles, induced by degassed water reinjection, in the vicinity of the extraction facility, so as to evaluate :

- The "rapidity" of vertical spreading,
- The ability of horizontal mixing to push degassed water away from the extraction facility.

The main possible scenarios, illustrated on figure 51, are the following ones :

- 5. Rapid vertical spreading and low horizontal mixing (most pessimistic scenario),
- 6. Rapid vertical spreading and high horizontal mixing,
- 7. Slow vertical spreading and low horizontal mixing,
- 8. Slow vertical spreading and high horizontal mixing (most optimistic scenario).



Figure 51. Schematic possible horizontal and vertical spreading of degassed water after a relatively short period of exploitation.

The extracted and thus re-injected water flow rate will possibly depend on the position of extraction relatively to underwater currents direction.