**The phenomena of gas formation in the foundations of concrete dams**

Kuznetsov, A. M.; National Research Council of Canada. Division of Building Research



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# PREFACE

## THE DANGER OF METHANE IN EXCAVATIONS

In the hope that it will provide a helpful warning to Canadian civil engineers and contractors, the Division of Building Research is glad to publish this translation from the Russian in the National Research Council's Technical Translation Series. The translation was prepared by Mr. S.H. Bayley of George Wimpey and Co. Ltd., and is included in this series with the kind permission of this British Company through the kindness of Dr. W.M. MacGregor.

Dr. MacGregor is the joint author (with F.H. Lyra) of a notable paper on the "Furnas hydro-electric scheme, Brazil; closure of diversion tunnels" that was published in the Proceedings of the Institution of Civil Engineers for January 1967 (Vol. 36, p. 21-46). A lengthy and interesting discussion of the paper appears in the August 1967 issue of the same journal on pages 751 to 773. The paper deals with a serious explosion that took place during the closure of the diversion tunnels of this Brazilian water power project and describes the remarkable construction operations required to effect the final closure.

Of special significance, however, is the fact that the explosion is believed to have occurred through the seepage into the tunnels of methane gas from decomposed organic material at the bottom of the reservoir, newly flooded, from which the tunnels led to the outlet. Correspondence between Dr. MacGregor and the writer on this matter revealed the existence of this translation which so clearly shows that the phenomenon of this occurrence of methane is not unknown elsewhere. The matter is so vital to the safety of men engaged on such work that publication of this translation in Canada appeared to be desirable.

In the discussion of the paper, an account is given of another very serious accident, involving serious loss of life, apparently from the same cause, on the Akosombo Dam on the Volta River in Ghana. References are made to other similar cases, even in ordinary excavations when the source of the methane might have been shale. And a Canadian engineer is quoted as having experienced trouble with a pontoon used for removal of closure gates on a hydro-electric scheme which was swamped by a huge bubble of air escaping when the first lift occurred.

Here is clearly a real danger on heavy construction work which occurs so rarely that it has received little attention in the technical press. It is so serious when it does develop that the warning provided by this Translation may be useful in Canadian construction practice. The Division is greatly indebted to Dr. MacGregor for his ready agreement to have this use made of an internal paper of his well-known Company.

Ottawa
October 1967

R. F. Legget
Director, DBR/NRC

NATIONAL RESEARCH COUNCIL OF CANADA

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(O gazovykh yavleniykh v osnovanii betonnykh plotin)

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Translator: S.H. Bayley, George Wimpey and Co. Ltd., Central Laboratory, Hayes, Middlesex, England

# THE PHENOMENA OF GAS FORMATION IN THE FOUNDATIONS OF CONCRETE DAMS

In recent years at the many hydro-electric stations erected on the Dnieper, the Volga and the Kama, emissions of combustible gases were detected in the concrete foundations of the structures, during the second and third year after the filling of the reservoirs. In the gas formation, methane and nitrogen predominate and more rarely, hydrogen. This phenomenon had not been investigated (1). In this article the results of research into the occurrence of gas in the foundations of the Kama hydro-electric station are explained, also some information is given on the chemical composition of the gases at the V. I. Lenin hydro-electric station on the Dnieper, the V. I. Lenin hydro-electric station on the Volga, and the 22nd KPSS Convention station on the Volga, where the author became acquainted with the phenomenon under natural conditions.

As a general rule, the gases occurring in the foundations are subject to considerable variation in chemical composition. In the initial stage of the investigation no discharge of gas is noticed. Later, often violent gas discharges are observed in piezometers in underground galleries, either in the form of water bubbling with gas or in the form of a stream of dry gas. The flows of dry gas are not usually prolonged, but they recur with a definite periodicity. The gases are diffused locally under the structures, and the waters in the stratum beneath the foundation emit different amounts of gases Generally, the amount of gas in the water increases in the direction of the seepage flow. Immediately below the concrete foundation the underground waters become supersaturated with gas.

Samples of gas were collected by passing the water from the piezometers through a rubber hose into a bottle filled with the underseepage water, and immersed in a vessel of water. Depending on the composition of the gas, and the yield of water in the well, the collection of one litre of gas could take seconds, minutes or hours. Because the temperature of the underground water (7-8°C) differed only slightly from the temperature of the air in the gallery where the measurements were made, the release of gas from the water flowing through the bottle was brought about solely by a reduction in pressure. Complete degassification of the solution did not take place, but a large amount of gas remained in it, due to the solubility of the gas at atmospheric pressure and the temperature of the formation (2). In this connection, it often happens that a flight of little bubbles in a thin aqueous film is observed above the surface of the water in the vessel. The bubbles lose gas in their flight through the air and drops of water fall on the surface, which is clearly evident in the illumination from a slanting ray of light. The gas is released from the underground water sample and later, when the bottle is opened and a flame held to its neck, the emerging methane ignites and burns for some time.

The phenomenon of natural gas at the Kama dam was noticed in the fourth year after the filling of the reservoir and it has been observed there for a period of six years. As a rule the gas enters from the slightly fissured marls and dolomites of the Solikamsk formation (3), which is about 20 m thick (Fig. 1). During all the years of observation, accumulations of dry gas were detected in the piezometers at 15-30 day intervals, and at longer intervals after previous collection. In recent years the prolonged flow of dry gas has increased from a few minutes to 15 minutes and longer, and the nitrogen content in the composition of the gas has also increased.

At piezometer No. 199, fixed 16 m into the rock stratum of the foundation, dry gas was first detected in 1958 in a sample of water. After an emission of water, the stream of gas flowed in a small volume for 3 minutes and then the water poured out with a mass of little gas bubbles. The flame of the burning jet reached 40 cm. At this period, the emission of dry gas was repeatedly detected. A similar occurrence was found in the neighbouring piezometer No. 200, the filter of which was constructed under the waterproofed covering of the fore apron in the sandstone-clay strata of the Urzhum formation. At this point the discharge of gas it just as violent, but without the discharge of water. The gas appears every 10 - 15 days; the total quantity emitted during one hour's observation, is more than that given out in the first stage. Similar phenomena were also detected in thirteen other piezometers, fixed at depths of up to 20 m. They were arranged in a strip 150 m wide and 170 m long extending diagonally from the grout curtain to the foundation slab. The strip is aligned in the direction of seepage. It is characteristic that in the centre of the strip the gases detected are rich in methane, but along the edges nitrogen occurs. The volume of the free gas discharged from solution was not a constant proportion of the volume of water that emerged from the piezometer. In piezometer No. 199, measurements made at different times showed 9, 19, 30 and 70 ml. of gas present per litre of water. In the first measurements the water was not saturated with gas and flowed quietly from the well; in the last measurement it was supersaturated and came intermittently with emissions of dry gas.

Supersaturation of the water with gas was observed at different seasons of the year and increased with the fall in the hydrostatic pressure of the seepage flow beneath the dam. Supersaturation is eliminated to some extent at the point of contact of the water with the hard surface of the filter in the observation hole. Bubbles of gas forming on this surface come up to the mouths of piezometer tubes which appear to act as traps for the freely discharging gas. The gas probably accumulates both under the waterproofing of the fore apron and the foundation of the structure, forming a local gas accumulation in the fissured rock strata. Its volume changes with the variation in the head of water in the reservoir, hence the emissions of gas are more significant in winter than in summer. In the piezometer system, the lowering of the pressure caused by the falling reservoir leads to the expansion of the gas accumulation, and as a result of this, to a relatively large seepage of the gas through the rock fissures to the piezometer tubes. With the filling of the reservoir and the increase of hydrostatic head in the rock stratum, the gas accumulation contracts and is squeezed towards the waterproof covering on the fore apron and towards the foundation of the structure, so that the inflow of gas diminishes towards the deeper piezometers; this corresponds with the change in the duration of the gas outflow at different times of the year. The increase in the duration of dry gas outflow signifies an increase in the volume of gas above the water in the hole. The largest volume of gas in piezometer No. 199 reached 80 litres on the 20th March 1964, but in piezometer No. 200, where the foundation rock is in contact with the fore apron, it consisted of 55 litres. From the data it was found that the volume of the piezometer tube filled with gas at the pressure of the formation varied from 0.37 to 1.0 volume (Table 1).

At a depth of more than 30 m in the underlying rock strata, which are equally fissured and water-bearing, no accumulation of gas was detected. After a long period of sampling and testing, small volumes of gas were obtained for analysis. The gas dissolved in the water of this part of the strata is discharged at the rate of 1-2 ml per litre of water. The gas is rich in helium and contains nitrogen and a small quantity of methane. These features point to the segregation of the gas concentrations in the foundations and to the different nature of the gas in the upper and lower parts of the Solikamsk strata.

The data in Table 2 concerning the composition of the gases in the foundations of the Kama hydro-electric station[1], shows that their chemical composition is different and varies with each individual piezometer. The largest methane content was 87% in piezometer No. 200 situated in the middle of the strip previously mentioned (see Fig. 1). The hydrogen content of the gases in the holes did not exceed 5%. Hydrogen sulphide, carbon dioxide, and small amounts of heavy hydrocarbons were present. There was practically no helium, quantities measured were less than 0.001%.

From the time that the emissions of gas were first observed in the foundations of the structures, changes began to take place in the chemical composition of the seepage waters where these carried methane. There was a decrease in sulphates amounting almost to their entire disappearance, and a five-fold increase in bicarbonates. This relation is illustrated in Figure 2.

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[1] The analyses were made in the gas laboratory of the Kama branch of VNIGNI under the direction of N.A. Piankov and T.A. Kariakin and in the VNIGNI gas laboratory in Leningrad under the direction of Z.M. Nesmelov.

The compositions of the gas discharges observed since 1957 (4) at the V. I. Lenin hydro-electric station on the Volga appeared to be even more irregular. The volumes of the gas discharges here are considerable, and they measure hundreds of litres, and even tens of cubic metres in 24 hours (5). The outflow of gas is exceedingly violent. It enters from the many piezometers, fixed at the area of contact of the fore apron and the concrete with the Tertiary Clays (6, 7). Observations made over a few years showed a diffusion of nitrogenous gas with a maximum nitrogen content of 90%, a diffusion of methaneous gas with a methane content of 74%, and a diffusion of hydrogeneous gas with a hydrogen content of 97% by volume. Very large concentrations of hydrogen were determined beneath the lower part of the foundation of the overflow weir. Some data on the composition of the gases is included in Table 3, in which data is also given about the gases detected in the foundation of the Dnieper hydro-electric station at the point of contact of the concrete with the granite formation (8). Below the foundation structures of the Dnieper hydro-electric station the methane content reached 89%; the volumes of the gas were small, the streams of free gas were weak, and the outflows were not prolonged. In these gas discharges, the underground waters also lost sulphates and were enriched with bicarbonates.

The discharge of combustible gases in the foundations of the 22nd KPSS (9) Convention hydro-electric station on the Volga was observed by us in November 1962. In one of the piezometers placed in the left bank termination of a gallery, a jet of dry gas flowed out after the emission of a small quantity of water. The gas was not analysed. Judging, however, from the burning flame of the jet, it consisted mainly of methane.

The gas discharges at the Kremenchug hydro-electric station, methane content about 45% and carbon dioxide content about 1.2%, are well known, and so too are those at the Kohkov, Irkutsk and Ribin hydro-electric stations.

The accumulations of methane detected in the foundations of concrete dams, erected on sites differing geologically, do not depend on the lithology nor on the age of the rock. No data has been acquired concerning entry of the gas from the depths. A study of the dynamics of gas phenomena has led to the conclusion that gaseous products are formed biologically in the fissured stratum of the foundation and at the points of contact with the concrete structures. The following facts point to a biological origin; the local diffusion of gas in the foundations of concrete dams; the periodical supersaturation of the underground waters with gas; the outflow of dry gas from the observation holes; the presence of hydrogen sulphide and carbon dioxide, the appearance of hydrogen, and the absence of, or an insignificant content of helium; the variation in the composition of the gaseous products at any time; the loss of sulphate and the increase in bicarbonate content of the subterranean waters carrying gas rich in methane.

Organic material dispersed in the rocks, wood submerged upstream of the dam, organic matter in the surface water passing from the reservoir into the rock strata, the waterproof membrane in the form of hessian saturated with bitumen, and cellulose from the wooden materials of the contiguous piezometers, all appear to act as a focus of micro-biological activity and of methane gas formation. In the silts of the reservoir, micro-organisms of many physiological groups have been found (10). They can be carried by infiltration into the fissured rocks of the foundation, and in anaerobic conditions they can set up processes which lead to the accumulation of gaseous products.

The loss of sulphates from the underseepage waters and the increase of bicarbonates are typical proofs of bacteriological activity in the rock stratum of the foundation. Sulphuric salts are lost as a result of the reduction of sulphate ions to hydrogen sulphide. The spontaneous reduction of $SO_4''$ ions to $S''$ ions in conditions of low temperature is impossible because the transition to $S''$ ions only takes place with an increase in the energy level (12). The biological reduction of sulphates in anaerobic environments is widespread in nature and has been proved experimentally (12, 13, 14). In this process organic matter and oxygen from sulphates are utilised. The facts of the breakdown of sulphuric salts in subterranean waters by sulphate reducing bacteria with the formation of calcite were well known previously and have been confirmed by new investigations and experiments. Similar phenomena are also well known from the practice of pumping water into oil-bearing rock strata for displacement of the oil from them; in this way a considerable increase of hydrogen sulphide is found in the water and in the oil. For example, during a ten-year period of oil-well operations (15), the hydrogen sulphide content in the emerging gas increased from 2.2% to 10%. Also described in the literature is onyx-like calcite filling the cracks and cavities in the limestones and dolomites, and assessed as a secondary formation. At the Kama hydro-electric station, we detected calcite in the form of a suspension of microscopic cross-shaped concretions a few microns in size, in water containing methane, issuing from one of the piezometers.

On the anaerobic breakdown of an organic substance, the bacteria form small quantities of methane, carbon dioxide and heavy hydrocarbons. Hydrogen can be produced biologically or chemically. In the chemical method, it is formed by the reaction of hydrogen sulphide with metal in an aqueous environment (16). A reaction takes place with the metal of the pipes of the numerous wells and with the metal of sheet piling driven into the rocks of the foundations as a barrier to seepage. Steel sheet piles were driven into the 600 m long bases of the V.I. Lenin hydro-electric station on the Volga and into the foundations of the 1600 m long spillway dam. The steel piles had a total weight of 30,000 tons and they occupied an area of 0.4 $km^2$. The steel piles were in contact with the underseepage waters which pass through the interlocks and beneath the toes of the piling, where the latter does not penetrate into the impermeable rocks. Water containing hydrogen sulphide is in contact with the piles, and interaction with the hydrogen sulphide takes place on the surface of the metal. As a result, hydrogen is able to accumulate both in solution and in the gaseous phase. This probably accounts for the large hydrogen content of the gases, amounting to 97%, and also the considerable variation in its concentration. Such an explanation finds confirmation both in the facts of the phenomena and in the accumulation of hydrogen in the salt waters of the holes. At first, hydrogen was not detected in the deep holes with salt water, but a year later its content in the water soluble gas reached 40% (17).

V. I. Vernadskii's ideas (18) on the widespread occurrence of micro-biological processes in zones of high activity have received full recognition. Micro-organisms exist at various depths (up to 4 km), and at different temperatures - even less than 10° -, (19) setting up processes the speed of which is many times greater than that of chemical reactions. The active life of the micro-organisms in nature is not limited to the alteration and breakdown of organic substances. So-called chemically autotrophic micro-organisms can develop using energy from the oxidation of inorganic substances such as molecular hydrogen, methane, compounds of sulphur, and iron. Of special interest in the history of geochemical processes are the anaerobic micro-organisms capable of developing in the absence of oxygen at the expense of organic and mineral compounds. In different strata where such conditions exist, the biogenical processes can lead to an accumulation of gaseous products.

In this way, judging from the actual data, gas accumulations in the foundations of concrete dams are caused by a micro-biological decomposition of organic substances, the reduction of sulphates in underground waters, and the natural fall in hydrostatic pressure in the water-containing rock strata beneath the concrete structures. Hence, it follows that pronounced anaerobic conditions will more clearly exist in the foundations of high head dams and considerable accumulations of gas are possible. Considering the inertness of methane molecule, we do not expect it to have an adverse effect on concrete. However, its slight flammability requires the provision of ventilation in the galleries of the structures.

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| *AN | Academy of Sciences, USSR. |
| *DAN | Proceedings of the Academy of Sciences. |
| *NII | Scientific Research Institute. |
| VSEGINGEO. | All-Union Scientific Research Institute of hydrology and engineering geology. |

Table 1

Gas discharge in the foundations of the Kama hydro-electric station according to measurements made on 20th March 1964

| Piezometer number | Depth from the floor of the gallery, metres | Yield of water, litres/minute | Volume of piezometer tube, litres | Pressure in closed piezometer tube, metres head of water | Reduction of pressure in the closed piezometer tube, metres head of water | Volume of discharging gas, litres | Volume of the piezometer tube filled with gas at formation pressure |
|---|---|---|---|---|---|---|---|
| 200 | 1 | 18.6 | 20 | 16 | 14 | 55 | 1.00 |
| 199 | 16 | 0.8 | 52 | 31 | 14 | 80 | 0.37 |
| 205 | 38 | 6.0 | 92 | 69 | 20 | - | 0 |

Note. Temperature in gallery 7.2°

Temperature of subterranean water 7.4°.

Table 2

The chemical composition of the natural gases of the concrete dam of the Kama hydro-electric power station (In percentages)

| Piezometer number | Face mark metres | Date of sample tests | Methane | Heavy hydro-carbons | Nitrogen | Hydrogen sulphide + carbon dioxide | Hydrogen |
|---|---|---|---|---|---|---|---|
| 169 | 79. 35 | 15. 6. 1959 | 8. 9 | 0. 7 | 90. 1 | 0. 1 | 0. 2 |
| 172 | 77. 8 | 10. 6. 1963 | 3. 0 | 1. 0 | 95. 0 | 1. 0 | - |
| 203 | 77. 40 | 20. 4. 1962 | 72. 9 | Present | 23. 9 | 3. 2 | - |
| 200 | 77. 40 | 15. 6. 1959 | 79. 8 | 2. 1 | 15. 9 | 2. 0 | 0. 2 |
| | | 15. 7. 1960 | 47. 8 | 0. 5 | 48. 9 | 2. 5 | 0. 3 |
| | | 22. 4. 1964 | 87. 4 | Present | 8. 0 | 4. 6 | - |
| 194 | 58. 55 | 15. 6. 1959 | 80. 5 | 0 | 17. 2 | 0. 1 | 2. 3 |
| | | 20. 4. 1960 | 62. 3 | 1. 6 | 30. 7 | 0. 1 | 5. 3 |
| | | 5. 10. 1961 | 24. 5 | Present | 75. 1 | 0. 4 | - |
| | | 12. 4. 1962 | 18. 9 | 0 | 78. 9 | 1. 5 | 0. 6 |
| 199 | 62. 05 | 10. 10. 1958 | 70. 7 | 0 | 25. 2 | 4. 2 | - |
| | | 30. 8. 1961 | 57. 6 | Present | 23. 6 | 18. 2 | - |
| | | 19. 3. 1964 | 86. 3 | 0. 4 | 8. 0 | 5. 3 | - |
| 204 | 63. 55 | 20. 4. 1962 | 72. 4 | Present | 25. 9 | 1. 7 | - |
| 195 | 66. 55 | 6. 10. 1961 | 9. 4 | Present | 87. 9 | 2. 7 | - |
| 205 | 31. 55 | 7. 5. 1962 | 7. 7 | 0 | 91. 7 | 0. 6 | - |

Table 3

Chemical composition of gases in the foundations of the structures of the Dnieper and Volga V. I. Lenin hydro-electric station

(In percentages)

| Year | Piezometer number | Methane | Nitrogen + rare gases | Hydrogen sulphide + carbon dioxide | Hydrogen |
|---|---|---|---|---|---|
| | Hydro-electric station on the Dnieper | | | | |
| 1959 | 232 | 89.2 | 10.3 | 0.3 | - |
| 1959 | 208 | 71.8 | 22.7 | 1.5 | - |
| | V. I. Lenin Hydro-electric station on the Volga | | | | |
| 1960 | 10; 5 | 74.5 | 25.5 | - | - |
| 1958 | 1; 1 | 30.5 | 63.6 | - | 5.1 |
| 1958 | 10; 6 | 5.3 | 29.4 | 0.6 | 61.7 |
| 1960 | 10; 6 | 1.8 | 6.4 | 1.3 | 90.8 |
| 1961 | 3; 3 | 1.9 | 95.1 | 1.5 | 1.2 |

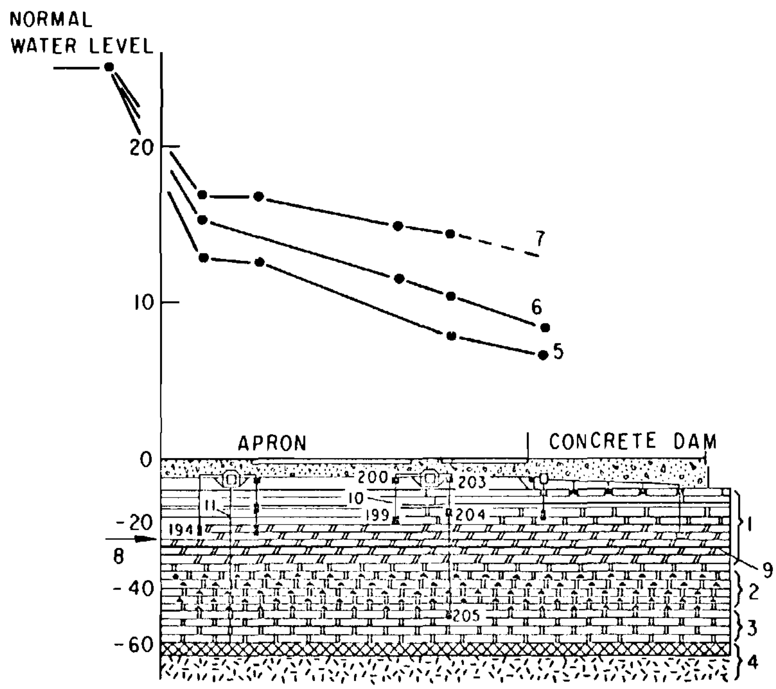


Fig. 1. Schematic hydro-geological profile of the foundation of the concrete dam of the Kama hydro-electric station in April, 1962.

1. The upper hydro-chemical complex in the rocks of the Upper Solikamsk and Urzhum formations with the periodic supersaturation of the underground water with methane.

2. The slightly fissured gypsum-bearing rocks containing salt waters.

3. The lower hydro-chemical complex of hydrogen sulphide waters with a small nitrogen content, rich in helium, and related to the dolomites of the Lower Solikamsk formation.

4. The dry, thick strata of gypsum and anhydrites of Kungur.

5. The levels of the underground water in the Urzhum aquifer.

6. The underground water levels of the Upper Solikamsk rock formation.

7. The underground water levels of the Lower Solikamsk rock formation.

8. The direction of seepage current.

9. The conjectured limit of the accumulations of underground waters supersaturated with gas in the foundations of the concrete dam.

10. Piezometers.

11. Grout curtain.

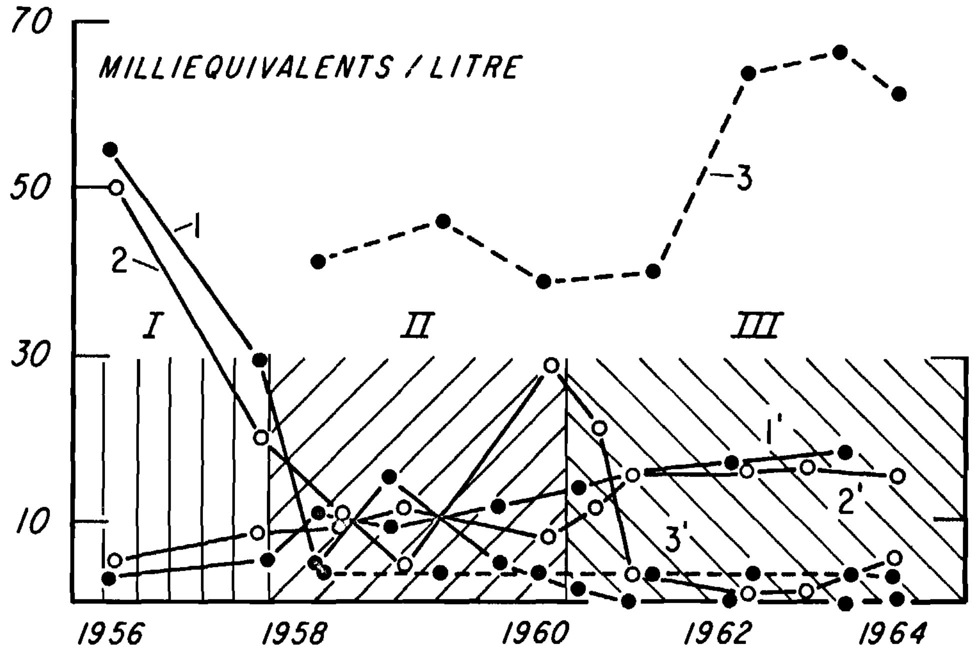


Fig. 2. The dynamics of the concentrations of sulphate and bicarbonate ions in the underseepage water, periodically saturated with gas, in the foundation of the concrete dam.

I. Period without marked discharges of gas.
II. Periodical gas discharges.
III. Considerable periodical supersaturations of the water with gas with a preponderance of methane.

Piezometer No. 199 set at 16 m from the floor of the gallery (underseepage waters contain methane): 1. Rate of reduction of concentration of sulphate ions. (1'). Increase in concentration of bicarbonate ions.

Piezometer No. 200 set at 1 m from the floor of the gallery (underground waters contain methane): 2. Rate of reduction of concentration of sulphate ions. (2'). Increase in concentration of bicarbonate ions.

Piezometer No. 115 set at 15.6 m from the floor of the gallery (no gas observed in water): 3. Curve for concentration of sulphate ions. (3'). Curve for concentration of bicarbonate ions.