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Exploitation of bedded sulphur deposits by the hydrodynamic method

by B. Zakiewicz

Bohdan Zakiewicz has specialized in hydrogeological engineering for more than 25 years. In 1951 he graduated from the Academy of Mining and Metallurgy at Krakow, where he had specialized in mining and engineering geology. In 1953, he was appointed General Manager of State Mining and Geological Specialist Enterprises, a completely new position. During the 1950s Mr. Zakiewicz was mainly concerned with dewatering opencast lignite and sulphur mines, and with the problem of exploiting deeper bedded sulphur deposits, not amenable to opencast working. By 1957 he had formulated the hydrodynamic method of exploiting these deposits. During the next 10 years Mr. Zakiewicz continued to be involved in the application of hydraulic engineering to a variety of mine dewatering problems, at the same time supervising the development of a number of techniques for the emplacement of watertight underground screens. Following negotiations between Polish and Iraqi authorities, Mr. Zakiewicz was appointed General Manager of the Mishraq Sulphur Mining Project in Iraq. Throughout his career in management he has continued to lecture at the Academy in Krakow and to serve on three committees of the National Academy of Science, to publish papers and take out patents and registered designs. In 1968 he was awarded a State Prize for technology, a rare honour.

Mr. Bohdan Zakiewicz

Mr. Zakiewicz' purpose in writing the article presented here is to make the readers of Sulphur *more familiar with the hydrodynamic method of sulphur exploitation and with the criteria to be used in judging its applicability to specific deposits.*

PROBLEMS POSED BY BEDDED SULPHUR DEPOSITS

Polish deposits

By the mid-1950s the further expansion of the Polish sulphur industry was dependent on the exploitation of bedded sulphur deposits. Unfortunately these deposits on the one hand were too deep to be accessible to the opencast techniques already in use on shallower deposits within the same region, and on the other were of a geological nature which seemed to preclude the successful application of the method introduced by Frasch. This, it was known from the technical literature, had been devised for deposits with quite strictly defined characteristics, including finite entity and rather complete isolation from other pervious strata (hereafter referred to as spatial isolation). The Polish deposits, in contrast, were known not to be spatially isolated but to be relatively thinly bedded, widely dispersed and, frequently, underlain by pervious strata. Consequently, it was thought, while screening the mining area to make it watertight would be necessary to maintain the injected, superheated water at the pressure required to melt sulphur, the established method of screening – by injecting a mud suspension – would be too expensive. (This view was later confirmed by two prominent United States experts, Messrs. F. Wilson and D. E. Flint, who visited Poland in 1958.)

While this was the fundamental and initial problem to be solved, the Polish sulphur deposits had further surprises in store. Later examination revealed other characteristics which distinguish them from the deposits worked by the classic Frasch method. For instance, some of the occurrences, or parts of them, are very compact, with few pores, and are almost or completely impermeable, making it impossible to inject sufficient quantities of water without special prior preparation of the deposit.

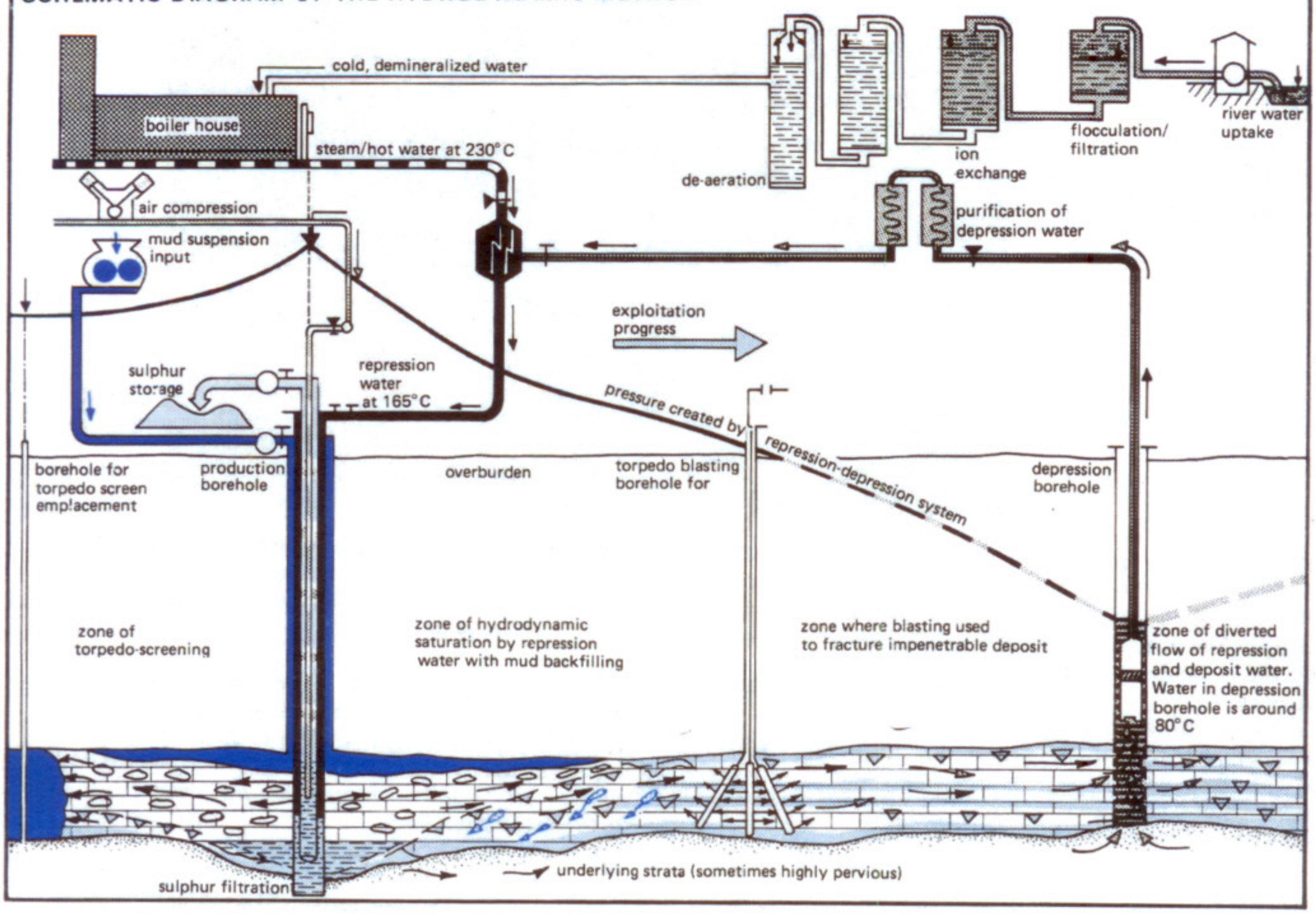
The Mishraq deposit, Iraq

Investigation of the bedded deposits in the Mishraq area revealed a new and quite different problem: Mishraq is so catastrophically cavernous and lacking in spatial isolation that, without preparatory treatment, injected water escapes through underground channels at such a velocity that acoustic hum can be detected in the boreholes. At one time an underground channel, about 200 m wide, was draining away approximately 60% of all the water injected into the deposit which the engineers were attempting to exploit!

DEVELOPMENT OF THE HYDRODYNAMIC METHOD

Conception

The task which faced Polish engineers in the mid-1950s was, then, to develop a method for extracting sulphur economically from deposits to which well-proven Frasch routines could not be applied.



SCHEMATIC DIAGRAM OF THE HYDRODYNAMIC METHOD

It was quickly decided that the basic Frasch concept of using superheated water to melt the sulphur must be retained and that a solution to the problem of economically maintaining the necessary pressure might be found by applying principles and techniques already developed in the field of applied mining hydrogeology.

The theoretical and practical basis for a new mining method was, in fact, found in design work already carried out for groundwater engineering projects. In 1950 the author had been called upon to design a large cooling system to a specification which required that the cold water input of 12.7 million U.S. gallons per day be drawn from an aquifer, used in cooling and recycled to the aquifer by injection at 9.5 million U.S. gallons per day. The heat absorbed during cooling would be dissipated to the rock between injection and re-extraction. In solving the hydrodynamic problems of cycling water through the aquifer means were developed for: (1) adjusting the degree of enthalpy concentration in a pressurized flow; (2) controlling the direction of this flow; (3) regulating the degree of heat loss in a pervious medium not spatially isolated; and (4) recirculating the water, following performance of the cooling function.

Subsequently the author was engaged in the design and supervision of dewatering operations in opencast lignite Patnów, Turów) and sulphur (Piaseczno, Machów) mines, work which involved the application and evaluation of the theories of unsteady underground water filtration, advanced by Theis and by Hantush.

Drawing on this experience, together with that gained in designing the cooling water system, the author was able, in 1957, to formulate a theory of unsteady filtration and flow which provided the basis of a method for exploiting the Polish sulphur deposits.

Design and application in Poland

It was now necessary to design and test the special techniques of fracturing and screening which would be necessary to work the deposits according to the new method. In 1958/59 the deposit at Grzybów was investigated, the first torpedo fracturing tests were carried out, and the hot water flow within the fractured strata was analysed. The techniques for creating screens – underground dams, effectively – developed in the period 1958-1966 are covered by 33 foreign and a number of Polish patents. They considerably extend the scope of the underground melting method and can, moreover, be used to so change the hydrogeological conditions in a deposit that the classical Frasch method can be applied. From 196[illegible] to 1965 detailed planning of the first projects was carried out and construction of the pilot mine at Grzybów was completed by June 1966, when the first sulphur was obtained. In 1967, Jeziorko yielded its first sulphur.

Over a period of more than 15 years, the author and his team have developed a body of hydrogeological techniques which includes:

The author and two colleagues discuss plans for a test-run of the boiler house at Mishraq.

1. The use of explosives to increase the permeability of impermeable zones and bring about the controlled homogenization of the permeability of a given deposit.
2. The use of explosives in the creation of vertical screens to seal off and separate individual deposits and old, worked out areas.
3. Co-exploitational, horizontal, dynamic backfilling in the hanging wall of the deposit to permit the deeper penetration of the injected superheated repression water* in the sulphur-bearing zone.
4. The pre-exploitational total testing of the hydrodynamic properties of each deposit in relation to those of its host aquifer as a whole, in order to define the optimum recovery factor in a mine situated on the deposit.
5. The optimization of the system of repression and depression boreholes and screening installations by mathematical calculations and the construction of models based on them, to obtain the proper degree of heat saturation required for optimum production and recovery.
6. The adaptation and modification of sundry conventional drilling, mining, pressure-relieving, screening, back-filling with mud suspension and blasting techniques to the special needs of underground sulphur mining.
7. The devising of water treatment procedures for the processing and re-circulation of water bled from the deposit at high temperatures.

The scope of these techniques, taken as a group, is sufficiently comprehensive, the author considers, to constitute a new, exclusively Polish means of mining sulphur, *the hydrodynamic method for the exploitation of bedded sulphur deposits.* This status is confirmed by the fact that the method is now being used economically to exploit deposits of the following types, which were previously considered unworkable.

- Thin deposits, not spatially isolated, sometimes with sub-outcrops almost in contact with the ground surface.
- Deposits underlain by pervious beds leading to spatially unlimited seepage zones.
- Deposits which are poorly permeable or even impermeable to super-heated water.
- Deposits which are catastrophically permeable.
- Deposits under overburden as thin as 40 m.
- Deposits adjoining zones of high seepage or old workings.
- Deposits situated in regions where water is scarce but essential for exploitation.
- Poorly mineralized deposits with small reserves of sulphur.

Experience at Mishraq

To illustrate the application of the hydrodynamic method to a specific deposit, developments at Mishraq may be briefly discussed: the operation has already been described in *Sulphur* No. 111, March/April 1974, pages 36-40, to which the reader is referred for a detailed study.

A number of factors contributed to the success of this, the first application of the hydrodynamic method outside Poland. Coincidentally, Polish army units, based in the area during 1943, had built a small chapel at Qayara, which the Iraqi authorities had maintained ever since. This simple symbol of friendship greatly assisted the establishment of friendly relations between Polish experts and the Iraqi staff. The involvement of Iraqi personnel from the earliest stage of the project, the efficiency of the National Iraqi Minerals Co. in expanding their own capability, and the priority granted to the project made very rapid progress possible.

The Mishraq installations are spread over an unusually wide area — 40 km^2 — for a number of reasons. Firstly, the terrain is difficult. The deposit underlies an area generally 80 m higher than the River Tigris, which flows between steep escarpments, themselves broken where tributary

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* The terms *repression, depression* and *decompression* used in this article refer respectively to the creation of pressure in the deposit by water injection; the relief of pressure in the deposit by pumping out hot water; and the decrease in pressure in the deposit which occurs when water flows out. Thus *repression water* is the superheated water injected into the deposit, *depression water* is water at not less than 80°C removed by pumping, and *decompression water* is hot water allowed to flow out of the deposit via decompression wells, without pumping.

streams have cut deep and boulder-strewn gorges. This rugged relief made it impossible to lay a railway line close to the mine. Furthermore, it was anticipated the area above the deposit itself would be affected by subsidences of 4-5 m during mining, so that no plant could be located in this area. Secondly, the contract with the Iraqi authorities obliged the Polish engineering team to guarantee, *a priori*, a capacity of 1 million t.p.a. of sulphur, with closely delimited operating variables. A 70% sulphur recovery rate was a prerequisite and so was purification to a level of 0.02% bitumen. These stipulations effectively permitted a margin of error of only 10-15% in drawing up the technical specifications for the operation. Yet the only basis for establishing these specifications was the initial project study plus the results of some drilling done by U.S.S.R. engineers in 1962, when an opencast operation was planned. Consequently the mine design had to be sufficiently flexible to permit the solution of unexpected problems while remaining within the limits imposed by the forecasted cost. There were, in fact, sufficient such problems to daunt even the most experienced mining man.

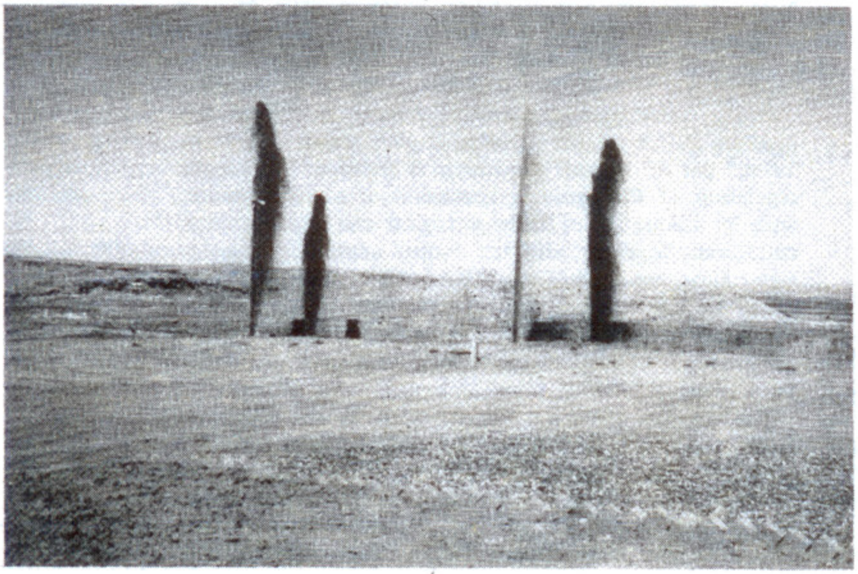
The most significant difficulties encountered were: a very steep natural hydraulic slope (I = 0.1%) with flow directed towards the River Tigris; an unmapped hydrodynamic parting between two sulphur-bearing layers (this had been irrelevant in terms of opencast mining); a marked reduction in sulphur reserve estimates following detailed drilling to determine the quantities which might be extracted by the hydrodynamic, rather than opencast method; the existence within the deposit of an extensive karst drainage system in which the three main aquifers were not only interconnected but also eroded to form extensive caverns (sometimes 7 m wide) and tunnels; and a bitumen content ten times greater than had been indicated by the 1962 research.

To solve the problem of the steep hydraulic slope it was necessary to match the injection of repression water into the mine to the drainage through the pervious layer and to correctly site and align the exploitation front. With this accomplished it was possible to harness the steep hydraulic slope as a directed belt-like groundwater flow, entirely eliminating the need for depression boreholes. This, in turn, meant that no hydrogen sulphide removal plant was required.

Because of the hydrodynamic separation of two sulphur-bearing beds it was necessary to exploit them separately, while the new data on the effective reserves within the deposit required fundamental changes in the delineation of mining areas. To determine the likely effects of the subterranean karst drainage pattern, gravimetric methods were used to map the major components. Three zones were identified, forming a network of underground rivers extending throughout the deposit. The course of one river lay along an axis perpendicular to the 1 km long exploitation front and the Tigris. To prevent a major loss of water, while maintaining a steady outlet from the exploitation foreland, it was necessary to divert this river by emplacing an underground watertight screen using the drilling-torpedoing technique patented by the author: a series of vertical boreholes, spaced at 5-7 m intervals, is drilled in the zone to be sealed; in each hole an explosive charge (torpedo) is placed at the appropriate depth; when the torpedoes are simultaneously detonated the rock fractures, caving along the screen line; the caved zone is filled with waterproof material to form the screen. In this case the screen, about 500 m long and 100 m deep, diverted the underground river as planned.

Overlying the second and third sulphur horizons there are thin limestones and other poorly plastic sediments totalling nearly 150 m in thickness; within the first aquifer there are large karst cavities. Consequently, exploitation caused subsidence and the resultant fracturing allowed repression water to escape from the second and third aquifers to the first, that is to the karst horizon. This unwonted increase of the exploitation area led to a marked rise in water consumption: over a 1 year period, consumption per tonne S (the deposit being completely dynamically saturated) rose from 11 m^3 to 13 m^3 (2,900 gals per tonne to 3,400 gals per tonne), and a further increase seemed likely. The co-exploitation mud suspension back-filling technique was considered the best way to counteract loss of repression water, since mud back-filling can be carried on without interrupting borehole operations.

As a result of the unexpected geohydrologic regime, it seemed that the greatest problem at Mishraq was to determine the volume of water needed, in large scale production, to achieve proper dynamic saturation of the deposit.



Torpedo blasting was used to create a watertight screen at a depth of 100 m.

The first molten sulphur flows from Borehole No. 1 at Mishraq.

In fact, for Mishraq, as for other deposits which are not spatially isolated, there is a quite specific hydrodynamic saturation point. The identification of this point is critical for economic sulphur production: although sulphur can be melted without saturation reaching the critical level, neither the overall consumption of enthalpy nor the recovery rate will be adequate if it does not. For Mishraq the critical hydrodynamic saturation level was reached at about 500 m^3 water and about 77.5 Gcal enthalpy injected per hour. At these rates of injection, it was calculated, a production rate of 360,000 t.p.a. or more would be necessary for profitable operation. Even a quite small decrease in the quantities of water and enthalpy injected per hour into the Mishraq potentital field causes an enormous increase in water consumption per tonne sulphur output, up to 23 m^3 (6,000 gals) per tonne or more. Both the anticipated consequences of insufficient saturation and the calculations of the level actually necessary were fully confirmed, to within ± 1% during operation of the first industrial plant.

(Firstly, the ways in which the types of sulphur deposit susceptible to exploitation by the Frasch and hydrodynamic methods differ geologically, and in their response to the processes of sulphur melting and extraction, and, secondly, the differences in melting and extraction technology between the two methods, are noted, by way of a summary, at the end of this article.)

THE HYDRODYNAMIC METHOD IN PRODUCTION

During the period 1966-1974, some 17 million tonnes of sulphur – 80% of total output in Poland and Iraq during that period – were produced by three mines solely as a result of the development of the hydrodynamic method, and made available on the world market. Despite marked differences in geological conditions at each of the three mines, at no time was the development schedule at any one of them interrupted by unforeseen events. This experience with the method has made it possible now to plan both expansions at the existing mines and the exploitation of new deposits, without the threat of unexpected interruptions. In Poland, new refinements of technique are continuously being evolved and almost 75% of the proven reserves are now being recovered. Any further expansion of the Polish industry is likely to be based on the hydrodynamic method. In Iraq, 75% recovery has already been achieved at Mishraq, where the solutions outlined in the previous section have been applied and have enabled the mine to produce the quantities of sulphur stipulated by NIMCO (now the State Organization of Minerals). The operation is now in a position to increase production in accordance with world demand and the needs of Iraq's own chemical industry.

Initial development work and subsequent day-to-day operating experience at the three mines has defined basic operating parameters, established the most efficient and economic procedures, and has allowed the engineers to test a range of the equipment available, selecting the most suitable.

There are four fundamental operating requirements which must be met if production is to be efficient and economic:

- a continous movement of pressurized injection water through the deposit and toward the exploitation front must be maintained and the individual turbulent flows of injected water carefully directed toward and into the long, narrow belt which is mined at any given time. (This belt it will be recalled, is defined by the distance between the lines of injection boreholes and the line of depression boreholes 100-200 m distant).
- Pressurized water must be injected via the production boreholes at a temperature not less than 160°C.
- The water removed to relieve pressure must be at a temperature no lower than 70°C.

To ensure the dynamic saturation of thinly bedded deposits less than 20 m thick, it is necessary to provide a carefully calculated quantity of water: in Poland this quantity is 4.3 m^3 per m^3 deposit per annum, at Mishraq 4.8 m^3 per m^3 deposit per annum is required. The precise regulation of the dynamic saturation of a given deposit, with its unique set of hydrogeological and hydrodynamic conditions, together with the proper control of injected water flow, has a profound effect in determining the total production capacity of the mine. Careful management of the closed, cyclical water economy of the mine should permit a heat utilization per tonne of sulphur not exceeding 1 Gcal.

Considerable attention has been paid to the selection of the most efficient equipment for each unit operation. To heat injection water, gas-fired boilers have been found most effective. The WG-50 boiler, manufactured by Thermotics Inc. of Houston, Tex., proved particularly satisfactory in tests in Poland, was installed at the Mishraq operation, and has subsequently performed as required. In future, however, fuel economy being now of paramount importance, Poland will aim to make more efficient use of energy and to become increasingly self-sufficient through the greater use of indigenous coal. Thus, an increase in heating capacity, from the current 58 million Btu to about 150 million Btu, will be achieved through the use of pulverized coal or coal-dust/gas mixtures.

To meet Polish environmental protection standards for flue gas emission it was necessary to equip the boilers with dust and sulphur dioxide removal systems. An examination of the techniques and systems available led to choice of that marketed by Aeronetics, of Houston, Tex. The heart of the system is the mixing section, where water, piped in at approximately 204°C, is expanded across a two-phase jet nozzle into the gas stream. Addition of lime solution into the two-phase mixture of steam and ultra-fine water droplets ensures the low-cost removal of dust and 98% of the sulphur dioxide.

Trials designed to establish which currently available drilling machine was most suitable for exploration and development of sulphur deposits mineable by the hydrodynamic method led to the adoption of the Con-Cor drill, manufactured by Walker-Neer, in the United States. With its specified ability to produce continuous core, with 100% recovery, at the rate of around 20,000 m p.a., the drill, which is equipped with built-in compressor and pumps, was eminently suited to the purpose and the machine was rapidly gaining a world-wide reputation for efficiency. Production boreholes for injection, mudding and sulphur extraction have been drilled by Failing 1500XHD rigs, which have proved very reliable.

CONCLUSIONS

It is clear that the hydrodynamic method of sulphur melting is definably different from the established Frasch method in respect of the techniques employed and of the types of deposit to which it is best applied. The development of the method has significantly increased the number of presently unworked sulphur occurrences which could be economically exploited. At some of these Frasch processing has been tried without success.

There is also good reason to believe that the special techniques developed in Poland and Iraq could be applied to some sulphur deposits where the Frasch method, after a period of successful operation, has run into difficulties. From the little data available concerning such operations it appears that the conditions which best suit the Frasch process do not pertain throughout the deposits – in some parts there is only partial spatial isolation and water consumption is excessive. It is to work sulphur in such conditions that the hydrodynamic method was developed.

SUMMARY COMPARISON OF THE FRASCH AND HYDRODYNAMIC METHODS

FRASCH METHOD	*HYDRODYNAMIC METHOD*
A. GEOLOGICAL CHARACTER OF DEPOSITS TO WHICH METHOD IS BEST SUITED	
1. Form of the deposit	
1.1. Deposit concentrated in thick beds (20-100 m); within salt dome gypsum is most overlain by impervious clays and gypsum.	1.1. Deposit in flat, thin beds seldom more than 20 m thick, not hydrologically isolated. Hanging wall beds commonly only poorly impermeable or locally impermeable. Usually underlain by permeable sediments, also not isolated spatially from other pervious strata.
1.2. In vertical cross-section deposits most often have the shape of an upwardly convex lens with its margin some 100-300 m deeper than the base of the sulphur mineralization.	1.2. Deposits are often cross-bedded with dense, poorly permeable, graded beds.
2. Hydrogeological conditions	
2.1. Deposits contain stagnant relict water, which may partially or wholly fill the pores. There is no contact or interchange between deposit and meteoric waters.	2.1. Water flows through deposits in parallel streams, filtering through the whole bed profile. In some cases, hydraulic slope is so high as to cause turbulent flow. There is a continuous exchange between deposit and meteoric water.
2.2. Deposit permeability is usually medium to good, and quite homogeneous. K = 15 m per day. Anomalous conditions resulting from the presence of caverns or karst channels, which lead to wasteful leakage of the injected water, are seldom encountered. Pores and small channels are of geodal type and coated with crystalline sulphur.	2.2. Deposit permeability is heterogeneous for different deposits, ranging from totally impermeable to highly permeable and catastrophically caverned, with K at times varying locally from 0 to 150-200 m per day. Water rarely flows via pores or channels of geodal type, but migrates through micro-fractures, tectonic fractures or fractures created as a result of limestone ex-solution.
2.3. Deposit occurs as a large, isolated ore massif. The beds overlying the sulphur are mostly not sulphurized and are very porous.	2.3. Deposits are mostly sulphurized throughout the whole vertical profile, and do not have especially permeable overlying beds.

FRASCH METHOD	*HYDRODYNAMIC METHOD*
3. Sulphurization of ore	
3.1. Usually quite high, with most deposits carrying 28-32% S and sometimes including large concentrations with 35% S or more.	3.1. Usually medium, with most deposits lying within the range of 22-28% S. Rarely, concentrations with up to 30% S may occur.
4. Depth of deposit	
4.1. Average, 300-400 m.	4.1. Average, 10-250 m.
4.2. Minimum for underground melting purposes, 100 m.	4.2. Minimum for underground melting purposes, 40 m.

B. RESPONSES OF THE DIFFERENT DEPOSITS TO THE SULPHUR MELTING PROCESS

FRASCH METHOD	*HYDRODYNAMIC METHOD*
5. Heat retention	
5.1. Heat retention is excellent considering that there is little water movement in the deposit to effect heat transfer. In most cases it is possible to maintain the sulphur in the liquified state within the deposit for several months without adding heat. It was for this reason that serious consideration was at one time given to the possibility of large-scale industrial production by using an underground nuclear explosion to bring about the total melting of a deposit.	5.1. Heat retention minimal, considering the continous natural flow of deposit waters and the resultant heat exchange. Interruption of "steaming" for periods of as little as 5 to 50 hours is usually sufficient to bring about solidification of the sulphur and the permanent impregnation of the deposit by sulphur. Once impregnated, the reheating of a deposit is a very difficult operation necessitating special procedures to render it pervious again. If large masses of sulphur are totally melted (e.g. by nuclear explosion) but not immediately brought to surface rapid solidification of the sulphur and irreversible impregnation of the deposit ensues.
6. Response to pressurization	
6.1. Essentially, the melting process is dependent on the injection of sufficient quantities of heat in the preheated mine water. This becomes technically and economically possible after relieving over-pressure by means of bleed-water boreholes; these are located on the periphery of the orebody, in unsulphurized beds below the gypsum cap.	6.1. The essence of the melting process consists in maintaining the preheated water at the correct pressure and temperature to melt the sulphur, preventing the water from flashing into steam and minimizing losses due to the dispersion of heat and the wasteful exchange of enthalpy between the mining and deposit waters.
6.2. Pressure retention is excellent, considering the almost total isolation of the autoclave-like ore massif. In some cases, notably the Old Gulf mine, pressures of a few atmospheres may still be present in a deposit more than 30 years after production ceased and production and bleed wells were shut down.	6.2. Pressure retention is nearly nil. When repression occurs locally within the potential hydrodynamic field it can be maintained only by injection of the carefully calculated and measured amounts of superheated water needed to achieve dynamic flow equilibrium. Any interruption of or decrease in the intensity of water injection will result in a loss of repression and the return of the deposit to its natural state.
6.3. The degree of saturation of the deposit with superheated water is directly related to the planned rate of yield. As long as the proper temperature is maintained, a decrease in the level of saturation is unlikely to interrupt the melting process, and although there may be a decrease in the rate at which the sulphur melts, there should be no loss of heat.	6.3. To maintain the conditions referred to in (6.1.) above, it is essential that the proper degree of hydrodynamic saturation be maintained. Failure to maintain the correct degree of saturation leads to an interruption of the melting process, causing wasteful exploitation of the deposit and an inadequate recovery of the sulphur reserves.
7. Influence of super-heated water and saturation intensity on melting process	
7.1. These factors have a direct or technical significance. Usually, the most sensible procedure is to maintain very low velocities in the radial laminar flow outwards from the centre of these lens-like deposits, by bleeding off the mining water.	7.1. These factors have a direct bearing on the successful achievement of the conditions referred to in (6.1.) and (6.3.) above, and are fundamental to the efficient exploitation of bedded deposits which are not spatially isolated.
7.2. It is not normally necessary to control the flow of repression water.	7.2. It may be necessary to control the flow of repression water. To induce the injected water to flow in the desired direction, pressure-relieving wells are aligned ahead of and parallel to the injection wells. In some cases, it may be possible to use the natural direction of flow provided that the gradient, direction, and velocity conform with the flow pattern necessary for exploitation (e.g. Mishraq).

FRASCH METHOD

8. Extracting the molten sulphur

8.1. Optimum recovery of the sulphur from a given deposit can best be achieved by melting the sulphur in a large mass, which then acts in concert with the injected water in maintaining the deposit at the correct temperature. (This is the so-called "pre-heating" of a deposit.) The collection of the sulphur from the underground reservoir is performed at a steady rate in order not to disturb the determined level and constant high volume of melted sulphur, which flows steadily into the reservoir at about the same rate as it is extracted.

C. INJECTION AND EXTRACTION TECHNOLOGY

9. The influence of old gobs on exploitation

9.1. Old gobs have little or no influence on the consumption of heat, or on the economics of production in general. Within these lenticular deposits new production fields may be started up regardless of the proximity of old workings. The removal of sulphur from the pores by the melting process usually results in compaction by subsidence. Even if this does not occur, the amount of water conserved by these mined-out cavities in autoclave fashion does not constitute an exploitation problem; heat loss from water migration through them is insignificant.

10. Siting of repression, depression and decompression boreholes

10.1. Repression boreholes are normally sited in "nest-like" concentric clusters in the mining area. As each area is worked out the equipment is transferred to a new cluster of boreholes until the deposit is mined out.

10.2. Bleed-water boreholes tend to be sited on the periphery of the deposit, most often at the base of the mineralized strata, in a ring around the mining field. There is no need for regularity in borehole siting.

10.3. Bleed-water boreholes collect water from the deposit at temperatures not exceeding the ambient temperature by more than 4°-8°C. Collecting water at high temperatures close to the area being mined results in heat losses which detract from the efficiency of the process.

10.4. The following rule is binding: the relation between the area of the vertical cross-section of the quasi-cylindrical region being "steamed" and the area of the quasi-cylindrical region enclosed by the bleed wells should be not less than 1:5-1:10. This rule enables the temperature conditions described under (10.3) to be maintained. If decompression boreholes cannot be sited concentrically in relation to the mining field, then the distance between the closest holes and the mining field should be at least 1,500 m. The hydraulic gradient of flow across the radial cross-section is I = 0.1-0.05 for distances of 750-1,500 m.

HYDRODYNAMIC METHOD

8.1. Good recovery is best obtained by the rapid extraction of the sulphur immediately after it has been melted from the narrow belt being subjected to intensive injection of pre-heated water. Melting large masses of sulphur over wide areas and allowing molten sulphur to remain in the deposit leads to quick cooling on deposit fringes and irreversible impregnation of pores. Lack of directed and concentrated movement of injected water across narrow exploitation belt leads to wasteful partial peripheral melting; sulphur is unable to flow freely and is impossible to pump out.

9.1. Seepage of injected water into and through old gobs can have profound influence on exploitation, may even determine its economic viability. Even if subsidence and compaction do occur, the orebody still has much greater permeability than in the pre-melted state. Unless action is taken to reduce porosity, or to direct injected water away from gobs, large quantities of water may run to waste in and through them.

10.1. Optionally, repression boreholes are arranged in long rows forming a narrow belt at the exploitation front, such that the ratio of the belt's length to its width is at least 10:1, preferably approaching 15:1. The front is aligned perpendicular to the direction of repression water flow. As sulphur extraction from the front is completed so the line of boreholes moves over the deposit.

10.2. Depression wells must be aligned parallel and close to the exploitation front. To maintain continuous and effective extraction, the boreholes must be arranged regularly. The distance from the exploitation front to the line of depression wells should not exceed 100-200 m.

10.3. Water from depression wells, usually removed by pumping, should be extracted at not less than 70°-80°C, in order to maintain the enthalpy concentration of the repression water, as determined in tests and production practice. Collecting water at lower temperatures results in fundamental loss of enthalpy, diminishes efficiency of the decompression process, and prevents optimum recovery of the sulphur reserves. Decompression water is recirculated to the heating plant, raised to 170°C and reinjected.

10.4. The relation between the rectangular area being subjected to injection vertically beneath the line of production wells and the similar area delimited by the line of depression boreholes should be equivalent to 1:1. The hydraulic gradient of the flow from the repression boreholes to a line vertically below the depression boreholes is I = 2.5 to 1.5.

11. Ancillary processes and technical operations

FRASCH METHOD

11.1. The Frasch method was developed for diapir deposits with the characteristics described above. Apart from mudding, hardly any special technical operations are needed to secure production or improve effiency. The recovery factor, which is usually not lower than 70%, is accepted as an optimum.

HYDRODYNAMIC METHOD

11.1. The efficiency of the hydrodynamic method is defined by the heat consumption, which should not exceed 1.1 Gcal per tonne sulphur extracted. Recovery should be at least 70%, and to achieve this it may be necessary to employ one or more of a number of ancilliary techniques:

- **In poorly or impervious deposits torpedoing with explosive material will increase deposit permeability.**
- **For deposits strongly or heterogeneously permeable, in which wasteful loss of injected water occurs, the employment of a torpedo-injected diaphragm/screen is necessary.**
- **For mining fields adjacent to old gobs emplacement of surrounding underground diaphragms is advised.**
- **To increase the recovery factor, dynamic co-exploitation with mud suspension should be utilized.**
- **When the deposit being worked comprises relatively thinly bedded strata, at a depth below surface ranging from 40-100 m, those zones where substantial subsidence of the overburden would lead to dislocation of the deposit sufficient to interrupt the mining operation should be worked using dynamic, co-exploitational mud suspension filling.**
- **Where the deposit to be worked is both areally extensive and relatively thick, that is, over 20 m thick, then it may happen that, if an impervious screen is created which surrounds the deposit or the zone to be mined, exploitation conditions will be created that are essentially similar to those of the autoclave Frasch method.**