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TECHNOLOGICAL INNOVATIONS IN SEPARATION OF PARTICULATES IN SOLID-LIQUID AND SOLID-SOLID-LIQUID SYSTEMS

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INTRODUCTION

The discipline of ore benefication is concerned with development and application of methods and processes in comminution, sorting, concentration and enrichment of primary and secondary raw materials. It encompasses a wide variety of basic processes, ranging from crushing and milling, through screening, sorting and classification to handling and separation of multiphase and multicomponent systems - solid-solid, solid-gas, or solid-liquid. Concentration and separation techniques are determined on the strength of definite techno-economical criteria, the basic consideration being location of dissimilarities (relative or differential) in physical, chemical and physicochemical properties of the set of minerals (desirable and useless) in a given ore[1]. Processes are selected in a dry or wet environment (organic, aqueous, or gaseous fluid) and applied in accordance with the feasibility of reliable and effective separation at optimal yields and efficiencies. The capacity of a mineral for enrichment is determined by its bulk and surface properties (whether natural or artificially modified) such as density, size, shape, porosity, colour, lustre and hardness, coefficient of friction, heat conductivity, radioactivity, dielectric con-

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stant, electric conductivity, magnetic susceptibility, surface polarity, water wettability and chemical stability.

Until the early '70's the art of ore benefication had been in a state of stagnation; but since then there has been rapid progress in three directions:

(a) introduction of innovative methods;
(b) improvement of existing methods;
(c) automatic process control.

What follows is an abridged survey of technological innovations in physical separation of solids and enrichment in the fields of mineral and chemical engineering, ceramics, refractories, fillers, pigments and building materials.

BASIC CONSIDERATIONS AND GENERAL BACKGROUND

The "case history" just described has several basic reasons, namely:

(i) Dissatisfaction with existing processes owing to low efficiency, limited yields, poor reliability, short life-span of equipment or prolonged residence of the material in it, high energy consumption, etc.

(ii) The need to reduce the number of stages in complex processes.

(iii) Unattainability of techno-economical targets under prevailing market conditions, due to high cost of treatment, maintenance and/or energy, high labour requirements (manual work!), etc.

(iv) Lack of processes or equipment suitable for dry or wet processing of certain ores (suitability as to type and quantity), or for their substitutes.

(v) New market demand for improved end concentrates or for new products in the market.

(vi) The need to utilize poor quality ores (low concentrations of desired elements) and increased throughputs in mining and benefication, i.e. difficult starting conditions.

(vii) The need for treatment processes for mining and other waste dumps, with a view to utilizing displaced resources (man-made ores).

(viii) Difficulties in tackling extra-fine particle systems, in the subsieve or colloidal range.

(ix) Ecological constraints and cross-pressures.

(x) The desire to slow down depletion of our natural mineral wealth.

The growing world-wide demand for basic raw materials, the rising prices of energy and production inputs, the need for substitutes, considerations of product quality, the need for recycling and re-use dictated by considerations of economy and ecology - all these facilitated the advent of new technologies, some of which are already in commercial exploitation and some still in the initial stages of development.

Availability of professional manpower, of a definite development policy, and of material resources and funds - made progress possible and bore the expected fruit. Besides these purely industrial R & D activities, there should be close links and mutual involvement between industry and the universities as illustrated in Figure 1.

For the long term, the mineral processing industry has a bright future in the design of new concentrators. For the short term, the most interesting new developments are those that allow existing operations to reduce costs.

The hallmark of the cost-effective, efficiently operated concentrator is the innovative manager or metallurgist. Most mill managers will agree that technology and equipment are only part of the ingredients for successful and profitable minerals processing today. The challenge for minerals-industry engineers today, faced with lower metal prices and higher capital and energy costs, is greater than ever before. At the same time, the tools - equipment

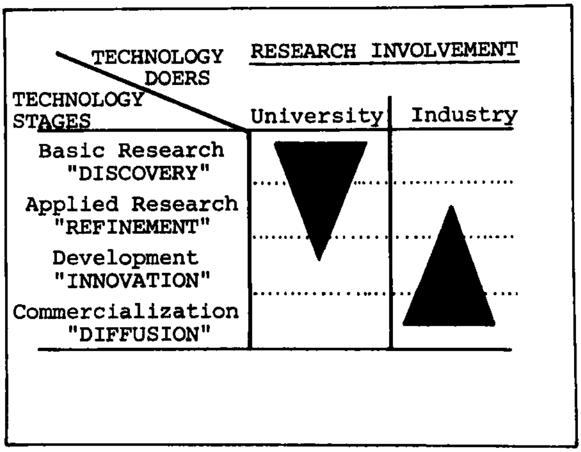

FIGURE 1
Universities and industries have separate roles to play in research.

and technology - are far superior today to those of the past. And as is clearly shown in the chapters that follow, the future holds more promise for better equipment and more efficient technology than ever before.

EXAMPLES OF INDUSTRIALLY-APPLIED NEW PROCESSES

The following list of examples of physical separation processes is by no means exhaustive, nor does it reflect their order of importance. Systematic and up-to-date documentation on them is available at the Mineral Engineering Research Centre (MERC) of the Technion.

(i) *High-Intensity Magnetic Separation.* Based on passage of a solid suspension through a ferromagnetic bed in a variety of geometries (spheres, grids, cylinders, etc.) under a magnetic field with constant high intensity. Specific sites on the bed medium become trapping zones for particles of high magnetic susceptibility, whereas those of low susceptibility pass unimpeded. Solid-solid or solid-liquid systems, batch-type or continuous, are commercially available.

This technique, WHIMS[2], is applied for ferromagnetic and paramagnetic particles (using a permanent magnet or an electromagnet, respectively). It is simple and reliable and is applied for aqueous and other liquid suspensions, and is being extended to air suspensions[3]. It is used for iron, chromium, uranium and tungsten ores, as well as for coal. It is also practicable for two additional purposes: (a) selective pre-implantation (seeding) of nonmagnetic particles in a ferromagnetic material (magnetite, ferrite, ferrosilicon) with a view to improved susceptibility, thereby rendering the aggregate trappable; (b) utilization of paramagnetic liquid medium (e.g. aqueous manganese chloride) for solid-solid separation of high-susceptibility components.

In the first case the treatment consists in selective adsorption, resulting in artificial increase of the susceptibility of one of the components, e.g. by means of iron carbonyl (MAGNEX process)[5]; in the second, the medium is chosen so as to fall between the susceptibilities of the two fractions[6], being used to selectively wash away captured particles. The MERC at the Technion and the Institute of Cryogenics at the University of Southampton are pioneering methods of using magnetic fluids as the medium for separation.

(ii) *High-Intensity, High-Gradient Magnetic Separation.* This method (HGMS) is mainly used for benefication of industrial minerals such as clays (Kaolin), and resembles WHIMS in principle[7]. The ferromagnetic bed consists of steel wool; the acting forces are of larger order (see Table I), permitting effective removal of fine and ultra-fine paramagnetic impurities. Commercial units up to 200 t/h capacity are available. The particle range is 100 to 0.1 micron. Glass sand, ball clay, silica flour, bentonite, tripoli, talc and bauxite are amongst those industrial minerals whose quality may be improved.

While the principles of magnetic separation remain relatively

TABLE I

Common Magnetic Separators and their Characteristics

Device	Competing Forces	--Approximate Values of Fffective Magnetic Parameters-- Force Range cm	Field Oersteds	Field Gradient Gauss/cm	Force*, dynes/cm^3 Fe_3O_4	CuO
Grate	Gravity	1	500	500	3×10^5	5
Drum	Gravity, hydrodynamic drag	5	500	500	3×10^5	5
Belt	Gravity	1-10	100-1,000	100-1,000	$5-50\times10^4$	0.2-20
Davis Tube	Gravity, hydrodynamic drag	1cm	4,000	4,000	2×10^6	3×10^2
Frantz-Isodynamic	Gravity	1	10,000	2,000	1×10^6	4×10^2
Frantz-Ferrofilter	Hydrodynamic drag	0.1	10,000	100,000	1×10^8	2×10^4
Jones	Hydrodynamic drag	0.1	20,000	200,000	1×10^8	8×10^4
Kolm-Marston	Hydrodynamic drag	0.01	20,000	2,000,000	1×10^9	8×10^5

* For a particle whose diameter is smaller than or equal to the range of the magnetic force.

simple, the unit operation continues to improve and new applications are found. To a large degree, developments in magnetics and magnetic separation equipment are jointly by equipment manufacturers and minerals-industry companies.

Applications for both HGMS and WHIMS are listed in Table II and compared with typical applications for conventional magnetic separators (Table III).

Use of extraneous ore-treatment agents with a view to enhancing mineral properties and generating areas of higher magnetic susceptibility, might possibly extend the range of this technique.

Use of superconducting magnets is another area of potential development. In a separation process based on such a magnet the matrix would be replaced by a stream splitter, thereby

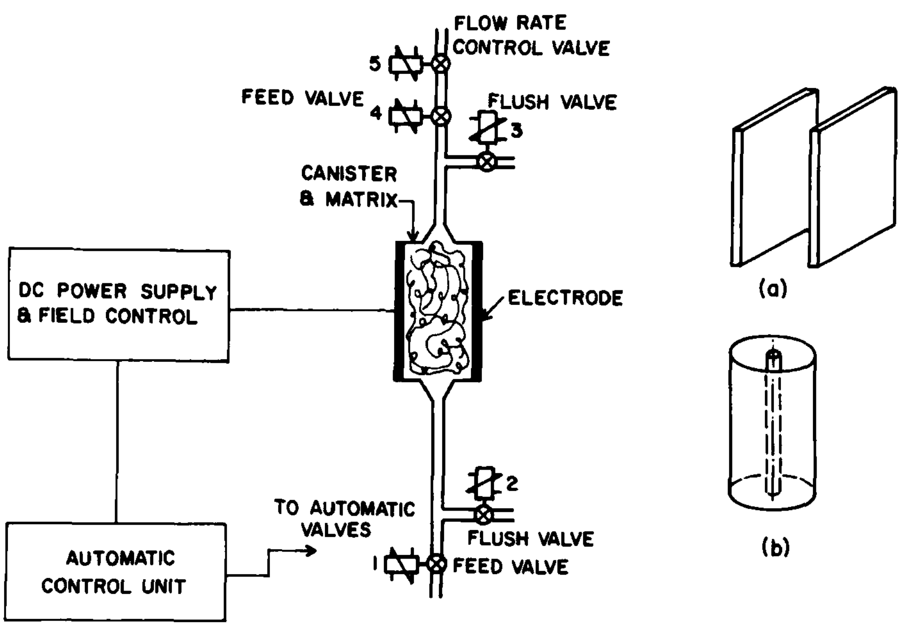

FIGURE 2
Laboratory batch-type HGES unit

TABLE II

Applications for High-Gradient Magnetic Separators

Mineral Beneficiation

Coal	Beryllium	Magnesium	Thallium
Thorium	Bismuth	Mercury	Zinc
Uranium	Cadmium	Platinum-group metals	Zirconium
Cobalt	Copper	Radium	Asbestos
Silicon	Gallium	Scandium	Feldspar
Vanadium	Gold	Silver	Graphite
Antimony	Indium	Tellurium	Lithium
Arsenic	Lead	Sulphur	Mica

Water Treatment for Removal of:

Magnetic suspended solids

Nonmagnetic suspended solids*

Dissolved solids*

Oils

Waste Treatment for Recovery of Magnetic Materials from:

Smelter and furnace dusts

Coal- and oil ash

Ore tailings

Removal of Paramagnetic Particulate Impurities

Chemicals

Minerals

Pharmaceuticals

Fluids

Chemical Processing

Recovery of weakly magnetic fine precipitates

Deposition and recovery of substances on magnetic particles

* By magnetic seeding and flocculation.

TABLE III

Typical Applications for Conventional Magnetic Separators

(Dry or Wet)

Tramp Iron Removal

Food processing	Cooling fluids
Chemicals	Scrap metals
Minerals	Water, glass, cork, textiles, miscellaneous materials
Pharmaceuticals	

Mineral Beneficiation

Chromium	Rhenium	Rare earths	Diamond
Columbium	Tantalum	Tin	Garnet
Iron	Tungsten	Titanium	Kyanite
Manganese	Aluminium	Yttrium	Talc
Molybdenum	Germanium	Barium	
Nickel	Hafnium	Clay	

Iron Recovery

Solid waste

Heavy media (e.g., ferrosilicon, magnetite)

obviating the maintenance problem of the former (the need for intermittent washing while the magnet is kept switched on). Such a unit would be capable of high throughput without use of moving parts (e.g. Oxford Instruments, U.K.).

(iii) *Dielectric Filtration and Separation.* Dielectric separation is a new technology that appears to hold great promise for processing material fines. Used in the metal, petrochemical and oil (lubricant and edible) industries, with potentialities in other areas, such as liquefaction of coal. Based in principle on passage of a suspension of solids (nonconducting medium with lower dielectric constant) through a ceramic bed under a constant high electric field, particles being trapped while the liquid passes unimpeded (see Fig. 2). The field is periodically switched off (in cyclic-type units) or alternatively the matrix is taken out of the field (in continuous units) and the captured particles are washed off. Analogical to WHIMS and HGMS, highly effective, suitable for particle sizes down to the sub-micron range, and competes with mechanical filtration for suspensions in nonconducting liquids[8]. Applied at the MERC for solid-solid separation and for clarification of liquids. Commercial batch-type and cyclic-action equipment available for a range of capacities, comprising a series of modular elements in parallel. Continuous units are in development[9].

Use of air instead of liquid as the fluid medium has been suggested, to minimize the problem of fluid-drag forces in the fine size range.

(iv) *Gravity Separation*. Several refinements and modifications have recently been introduced in conventional equipment: vibrating (shaking) table, pneumatic table, Humphry spiral, and heavy-medium cyclones; new solid-separation methods, based on the inclined-plane principle, have also been developed[10], such as the Reichert cone, the GEC Duplex Concentrator and the Bartles-Mozley concentrator. Throughputs have been increased, efficiencies improved, and ranges extended to cover additional raw materials.

The recently marketed Knelson concentrator for fine gold recovery from placer deposits outperforms other gravity methods as regards recovery for minus ¼" particles down to a few microns[11]. The upgrading ratio is typically 1000 to 1 or better, in a single pass through the separator at high capacity (40 t/hr).

The basic reasons for the failure of gravity concentrators in the ultra-fine size range are not currently known. It has been suggested that in this size range, particles begin to lose their identity and act as fluids. Under such conditions, separation based solely on differences in specific gravity becomes almost impossible.

(v) *Magnetohydrostatics.* The MHS technique is based on imparting, by means of a nonhomogeneous external magnetic field[12], a suitable artificial density profile to a para- or ferromagnetic fluid. (Examples of the former are: aqueous solutions of the chlorides and sulphates of manganese, chromium, iron, nickel, holmium, etc.; of the latter - ferrofluid, which is a stable suspension of magnetite or ferrite particles in the 75-150 Å range in an aqueous or hydrocarbon medium). The smooth vertical density gradient thus created permits selective multifraction separation according to density and magnetic susceptibility. The process (either batch-type or continuous) is suitable for diamonds[13], precious-metal concentrates, nonmetals, etc.

A modification of the ferrofluid technique, currently under study, is based on the screening effect of a series of thin films of the medium (dispensing with a container) at different levels between the poles of a permanent magnet. The process is also multifractional.

(vi) *Eddy Currents*[14]. Based on application of a time-varying magnetic field to particulate metals. The relative motion of the latter causes time-variation of the magnetic flux and induces eddy currents in the conductors, thus permitting separation of non-magnetic components. Differential displacement of the components controlled in direction and in intensity (Lenz's electromagnetic law!) permits continuous concentration. The technique (only suitable for extra-coarse materials) served initially for removal of non-magnetic metallic components from municipal and industrial waste, and may find application for semi-conducting minerals.

(vii) *New Hydrocyclones.* There are approximately 20 major manufacturers of cyclones in the world today, supplying units with diameters ranging from 10mm to 50". In the last 10 years, attempts have been made to increase their capacity and efficiency to develop new designs with minimised operating difficulties or for specialised applications, and to develop mathematical models for simulating cyclone performance. Several design modifications have been applied to conventional hydrocyclones with a view to an extended range and improved performance[15]. Examples: A small unit[16] used for classification or for clarification of solid suspensions, resolving power down to 5 micron (Mozley type), was developed in the U.K.; a self-cleaning device ensures against choking of the narrow inlet and outlets. A new device of the spiral cone hydrocyclone type was developed in Sweden. A high-throughput choking-free cyclone was developed in Japan[17], with the concentrate fraction (under flow) removed continuously through the bottom of the cone by means of a spiral (worm). A different example is the lock-bottom hydrocyclone, with a single inlet and outlet, for solid-liquid separation processes or filtration-thickening unit operation, with the solids bin serving as thickener; it is used for concentration and enrichment, for classification, or for clarification with a view to reducing the load on filters and centrifuges. (These units, single or in battery form, are used for removal of suspended solids from well water, gas and crude oil; for prefiltration in sprinkler- and drip irrigation; for protection of liquid pipelines in industry and of domestic water piping, etc. (see Fig. 3). Cleaning in special cases is effected by means of a flexible wire installed along the hydrocyclone axis).

Cyclones of a new type are used for processing iron ore, diamonds and coal by the "heavy-medium" technique (with ferrosilicon or magnetite), again with a view to improved efficiency and product quality[18].

(viii) *New Adsorbents and Ion Exchangers.* New types of adsorbents, catalysts and resins with implanted magnetic components[19] are being developed with a view to magnetic handling and separa-

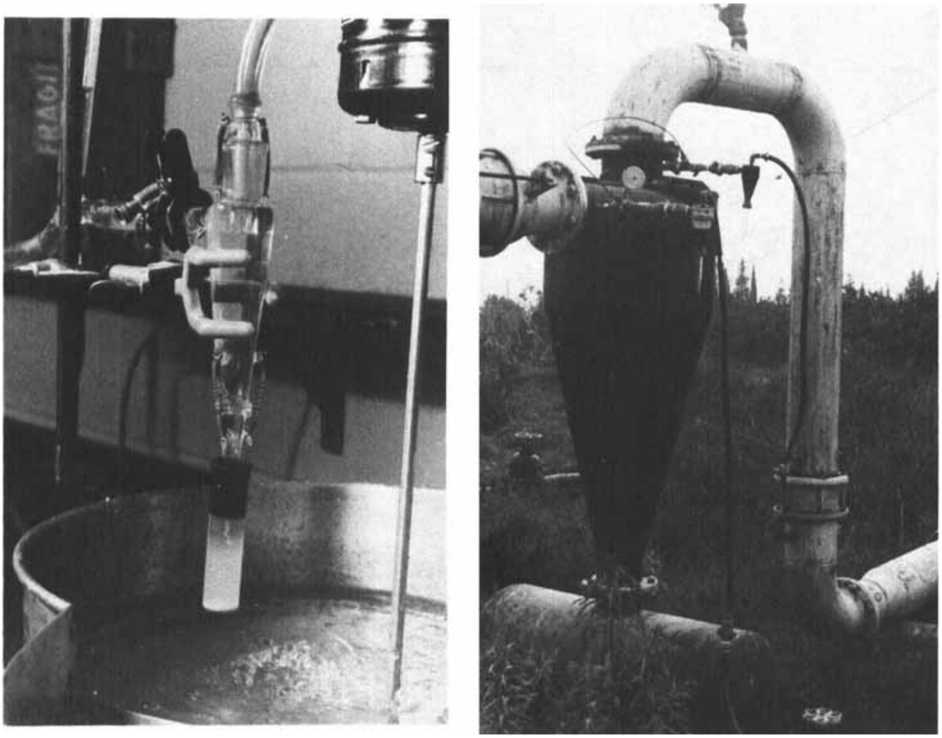

FIGURE 3
Lock-bottom hydrocyclone with a single inlet and outlet; (left) laboratory test unit; (right) industrial unit used for removal of suspended solids from well water.

tion (dry or wet). The carbon-in-pulp technique for extracting gold from solutions through adsorption on activated carbon[20] is a revolutionary development in beneficiation of auriferous ores; it has displaced more costly techniques and increased recovery to 99.9%. The magnetic adsorption medium called "magchar"[21] merits consideration in new CIP circuits (see Fig. 4).

(ix) *Sorting Techniques.* The stages of the comminution process - crushing and grinding - are heavily energy-consuming, so that pre-concentration (by sorting or heavy-medium separation) saves energy in any case. Manual sorting (based on colour

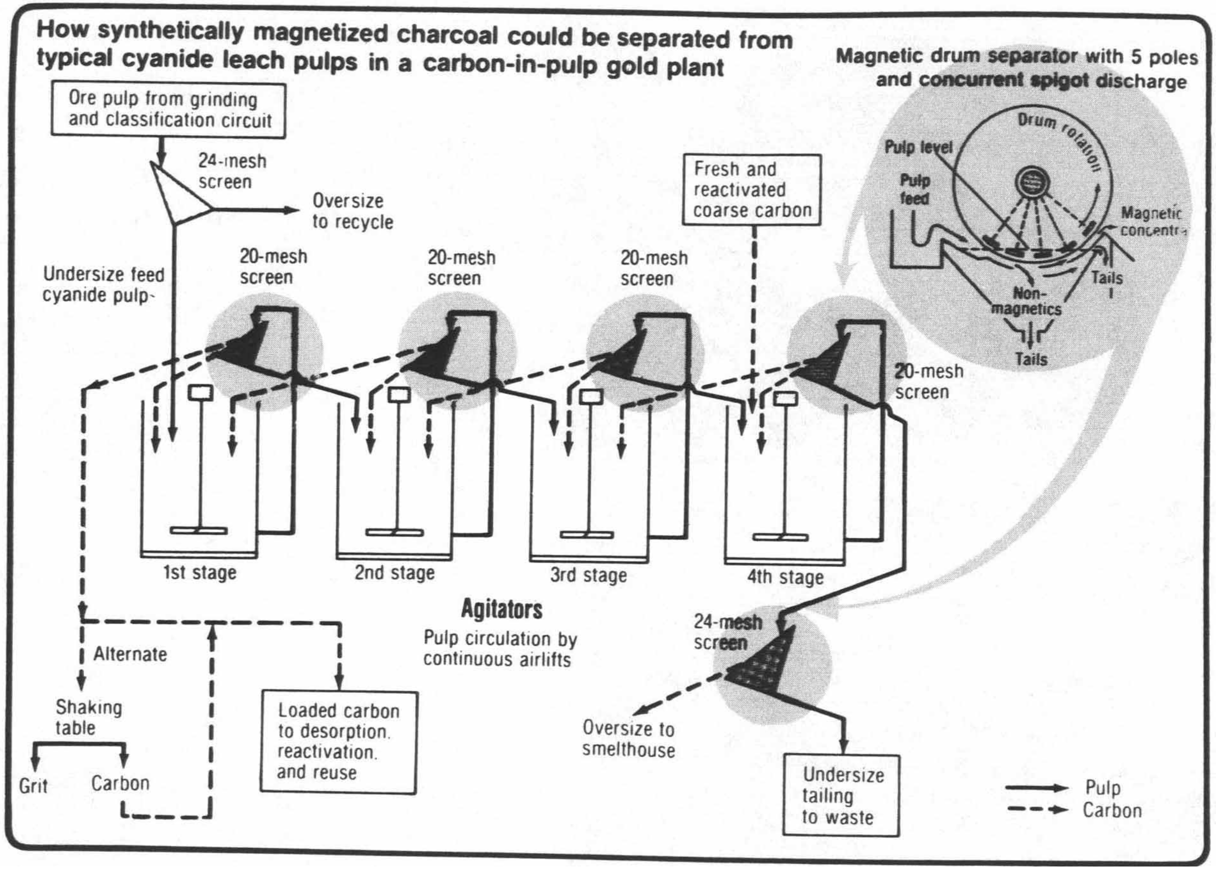

FIGURE 4
Synthetically magnetized charcoal in CIP process.

and lustre difference between ore components) is still common in regions with cheap labour, but is being supplanted by advanced automatic techniques with each fragment examined separately and with perfect operational synchronization (as shown in Fig. 5). Photometric sorting is suitable for ores with differently coloured minerals (gypsum, magnesite, talc, chalk, barite, flint, glass scrap, argenti- and auriferous ores, etc.), and where coarse constituents are unlocked. Electronic sorting with the aid of various radiations (x-ray, gamma, fluorescence, IR, etc.) is used for diamonds and for uranium, tungsten, gold, sulphide ores etc.[22]. Installations for the 10-200mm size range, with capacities up to 150 t/h, are available; (examples: Model 19 Conductivity/ magnetic response Q-sorter; RTZ ore sorters). Possible

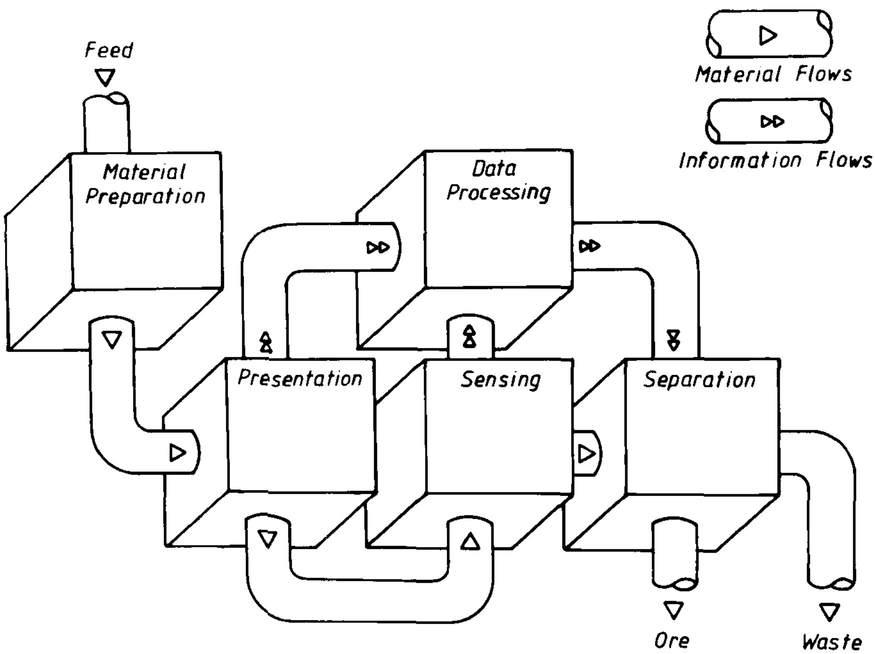

FIGURE 5
System block diagram.

local applications which should be examined are beneficiation of calcite and flint-clay (photometric) coarse fractions of phosphate (radiometric), and oil shale (fluorescence) scrap metal separation (conductivity/magnetic) as well as glass-scrap recycling (photometric). Automated ore-sorting machines are rapidly gaining worldwide acceptance in the mineral dressing industry as a practical alternative to other forms of sorting and beneficiation such as hand-picking, truck discrimination, selective mining, bulk milling of mixed ore and waste, and (in some instances) to heavy-medium separation. The effectiveness of preconcentration depends on the efficiency with which most of the valuable mineral can be reduced to as small a concentrate mass as possible.

In the field of energy storing minerals, presorting of oil shale by the above means into high- and low-grade fractions should prove useful in the surface or ex-situ retorting process[23] permitting exploitation of otherwise marginal or sub-economic deposits, at reduced operating- and waste-disposal costs.

(x) *High-Intensity, High-Gradient Cylindrical Magnet.* Originally invented in Scandinavia; consists of a drum with permanent (samarium-cobalt) magnets; used for separation (dry or wet) of magnetic particles; the magnetic circuit is suboptimal. A different model, developed in the early 80's in Israel and marketed commercially under the name "Perm Roll", permits processing of coarse material (see Fig. 6). It has a longer range of action than the IMR (where the magnetic force decays rapidly with distance, according to the induced-field principle), and was first applied in South Africa for processing andalusite (a ceramic) and diamonds[24].

(xi) *Surface Roughness-Based Techniques.* While there are no industrial techniques based on friction, there are a few utilizing surface roughness. Examples are separation of fibrous minerals (e.g. asbestos), and of agricultural seeds (e.g. clover

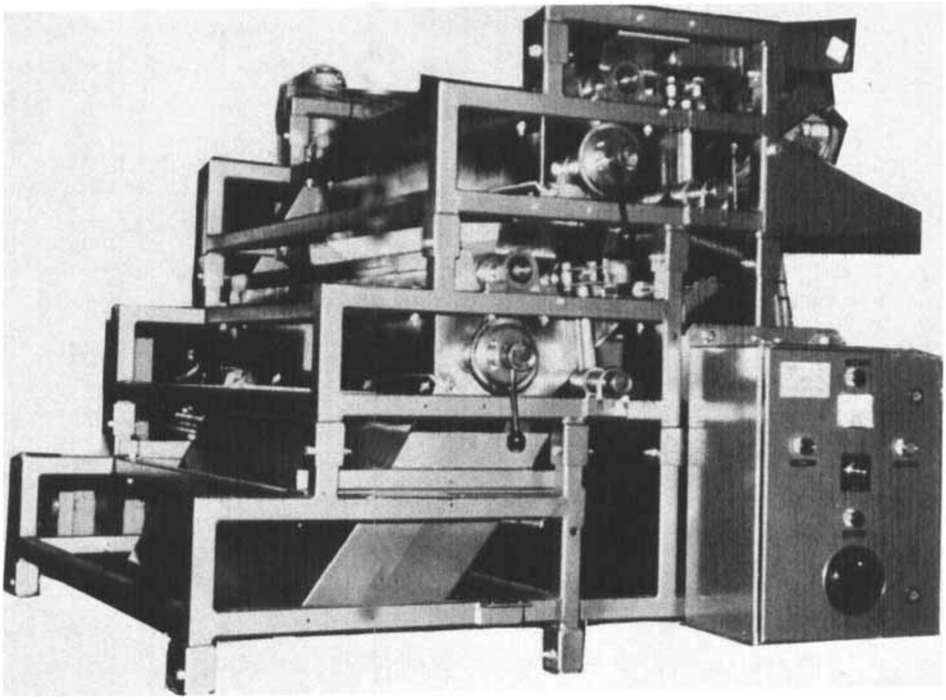

FIGURE 6
The Permroll separator.

and alfalfa) which have a smoother surface than the parasite impurities[25]. The mechanism is known as the "baby skin/ elephant hide" effect: when a fine-grained ferromagnetic powder (ferrite or iron) is admixed, it penetrates the creases of the "elephant hide" and permits dry separation in weak magnetic fields. The process was adopted at the "Hazera" plants in Israel.

(xii) *Grinding.* (a) Additives: This application is common mainly in the cement and mineral industries, and centers on the search for chemical aids in comminution, mostly in grinding[26]. These aids (whose mechanism of action consists in reducing agglomeration, weakening interparticle bonds, reducing suspension viscosity and preventing microcrack healing), accelerate the comminution process, improve the fineness profile (higher specific surface area!) and save energy. Examples are summarized in Table IV.

(b) "Orebed" magnetic lining in mills: A recently patented new concept. The device is based on a powerful ceramic magnet enclosed in rubber and attached to the mill shell, attracting ferromagnetics to its inner surface so as to form an orebed (see Fig. 7). The material in the mill thus grinds against the orebed, which while continuously renewing itself, protects the liner against wear and distortion. This in turn obviates the need for periodic replacement of the liner - as in conventional units presently in use - with correspondingly less down-time; it also permits reduced thickness of the liner.

(c) As the most expensive unit operation in a mineral dressing plant, the grinding circuit is naturally the object of a great deal of attention. The angular spiral lining (ASL) system developed by Waagner-Biro of Austria has been tested and evaluated for grate discharge ball mills[27] and found (through its modifying effect on the circular cross section) to reduce energy and grinding-medium consumption.

EXAMPLES OF NEW PROCESSES IN DEVELOPMENT

The processes reviewed below are at present at different stages of development. The examples refer to possible applications in mineral engineering.

(i) *Mechano-Chemistry*. A relatively new field, which comprises processes in which external mechanical action is applied to single or multi-component solids with a view to physical or chemical modification of the particles - polymorphic transformation, solid-state reactions, and surface coating[28]. The underlying principles, range of applications and scope of activity were described in detail at the 5th Mineral Engineering Meeting in Israel (1980)[29]. Recently, activity in this field at the MERC has been expanded to include: (1) new poly-

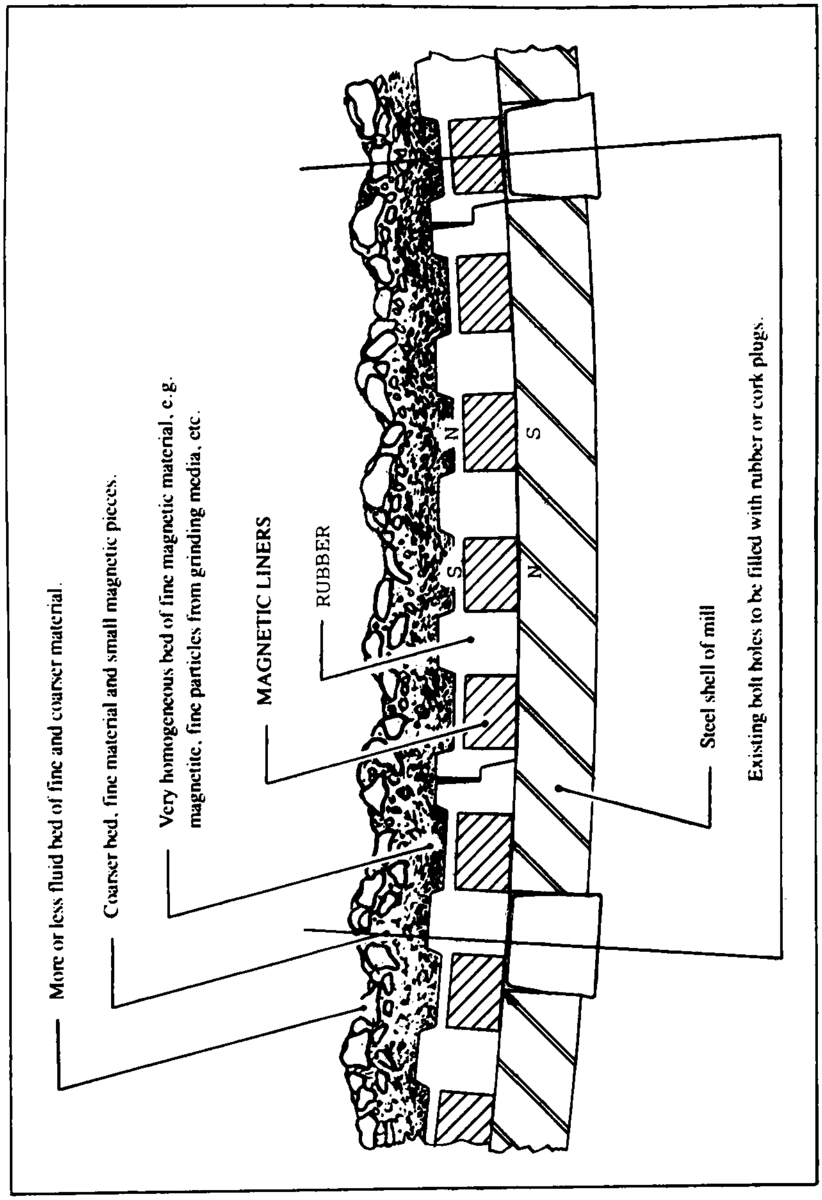

FIGURE 7
Schematic section illustrating principle of new "orebed" magnetic mill lining.

TABLE IV

Additives Used in Comminution

Additive	% Added	Material Ground	Wet or Dry	Grinding Rate Factor*
Water	0.06	Ceramic enamels	D	-
	0.06	Marble	D	1.6
	0.04	Cement clinker	D	1.3
Alcohols and phenols				
Methanol	-	Quartz		-
Isopentanol	-	Quartz		1.29
		Iron powder		20.0
s-Octanol	-	Quartz		1.4
Series normal alcohols	-	Soda lime glass	D	20.0
Glycerol	-	Iron powder		0.5
Phenols and polyphenols	0.01-0.25	Cement		-
	-	Gypsum		-
Ketones				
Acetone	0.2	Cement clinker	D	1.37
Amines				
Triethanolamine	-	-		
Flotigan (C_{12}-C_{14} amine ex coconut oil)	0.02	Quartzite		2.2
	0.02	Limestone		1.7
Sulphonic acids				
Arylalkyl sulphonic acid (RDA)	0.06	Graphite		-
	0.06	Cement		1.3
Fatty acids				
Oleic acid	0.003	Limestone		1.1
	-	Zinc blende		-
Butyric acid	-	Quartz		1.27
Stearic acid	1.0	Pumice		-
	-	Limestone		-
Sodium oleate	0.1	Quartz		2.0
	0.1	Limestone		2.0
Vinsol resin (calcium stearate)	0.05-0.10	Limestone		-
Sodium stearate	-	Dolomite		-
	0.15	Cement clinker		1.2
Aluminum stearate	-	Cement		-
Caprilic acid	0.5	Chrome ore-magnesite	D	1.2
Marine oil	0.5	Chrome ore-magnesite	D	1.1

Additive	% Added	Material Ground	Wet or Dry	Grinding Rate Factor*
Beef tallow	-			
Wool grease	5.0	Limestone		-
	-	Gypsum		-
Other carboxylic acids				
Napthenic acid	0.1	Cement clinker	D	1.33
Sodium napthenate	1.0	Quartzite	W	1.40
Sodium sulphonapthenate	1.0	Quartzite	W	1.80
Hydrocarbons				
n-alkanes, various	-	Soda lime glass	D	10.0
Esters				
Anylacetate	-	Quartz		1.23
Others				
Carbon black	0.08	Cement		1.3
	0.32	Cement		-
Sodium silicate	1.16	Clay slip		-
Sodium hydroxide	-	Magnesite		-
	0.008	Limestone		1.5
Sodium carbonate	0.02	Limestone		2.0
Sodium chloride	0.08	Quartzite		1.2
Carbon dioxide	-	Magnesite		-
	-	Dolomite		-
	0.03	Quartzite	W	1.55
Aluminum chloride	-	Carbon black		-
		Graphite		-
		Talc		-
Ammonium carbonate	-	Mica		-
		Vermiculite		-
Hardwood pitch	-	Pumice		-
Sodium polymetaphosphate (Calgon)	0.01-0.04	Lead-zinc ore		1.3
Kaolin	10.0	Sulphur	D	-
Thalium chloride	0.02	Quartzite	W	1.65

* Grinding rate factor = new surface produced with additive/new surface produced without additive.

Source: G.C. Lowrison, *Crushing and Grinding*, CRP Press, Cleveland, 1974.

morphic transformations in specific crystalline systems; cold chemical reactions for formation of ferrites and spinels and for decomposition of hydrates, carbonates, etc.: deeper insight into the mechanism, kinetics etc. of prolonged dry grinding processes under controlled conditions; (2) fluid mechano-chemistry, e.g. shearing of liquids.

(ii) *Magnetically-Controlled Fluidized Bed.* An innovative American invention (Exxon), based on admixture of ferromagnetic particles (controlled in size and quantity) to a fluidized bed and regulation of its physical and dynamic behaviour by means of an external magnetic field[30]; potentialities in sorting and separation of solids, in drying and combustion processes, etc.

In general, the technology centres on a magnetically stabilized bed (MSB) in which bubbles and turbulence normally found in conventional fluidized beds, are completely eliminated. A suitable magnetic field is imposed on a gas-solid bed, in which the solids have a magnetic component as well as other desired (i.e. catalytic) characteristics.

(iii) *Cyclone-Magnet Combination.* A hydrocyclone for aqueous suspensions containing a heavy medium (ferromagnetic particles), combined with an electromagnet with specific intensity and orientation, with a view to control of the particle trajectories. Sorting or separation are effected accordingly as the magnetic fraction is shifted towards the lower or upper outlet of the hydrocyclone. If successful, this technique may replace the standard magnetic-drum type separators used for recycling magnetite or ferrosilicon in HMS processing of diamonds, iron ore and coal, as well as for separation of magnetite or pyrrhotite in beneficiation processes. The simplicity and reliability of the technique promise rapid development and immediate applicability.

Boxmag-Rapid (U.K.) have developed a low-intensity magnetic hydrocyclone thickener[31] capable of inducing very fine magnetic particles to report to the cyclone underflow, while non-magnetic particles remain unaffected. The magnetic field is shaped so as to have a radial component - perpendicular to the axis of the cyclone - with an outward gradient, as a result, the net magnetic force acting on a particle is also radially outward. By this means the apparent specific gravity of the material is enhanced, so that the behaviour of a particle in the cyclone resembles that of one of somewhat larger diameter.

(iv) *Bio-Sorting.* Based on the feasibility of training animals for sorting and separation operations. Birds are used for location of printed circuits in the Japanese electronics industry, and for aerial photography and reconnaissance - in the U.S. Navy. The proven special characteristics of pigeons, in terms of vision and distinctive ability, may be put to use in ore sorting[32].

(v) *Cyclone as Flotation Cell.* A new system, based on a hydrocyclone with porous walls, operating under a centrifugal field (see Fig. 8). Special results were obtained in processing of coal[33-34].

(vi) *Thermal Separation.* This category comprises several new processes:

(1) *Dielectric Heating*[35] (familiarly used in bonding of vinyl plastic book bindings). On selective heating of a mixture of particulate plastics, the components acquire dissimilar dielectric properties and lend themselves to electrostatic or magnetic separation. When the process is applied to coal, the pyrite absorbs more electromagnetic energy and is heated more rapidly.

(2) *Differential IR Heating* (frequencies above the range of an electronic amplifier). When applied to a mixture of rock salt with dark gypsum grains, the latter acquire a higher temperature at which the picoplastic coating of the conveyor belt softens and traps them, thereby effecting complete separation.

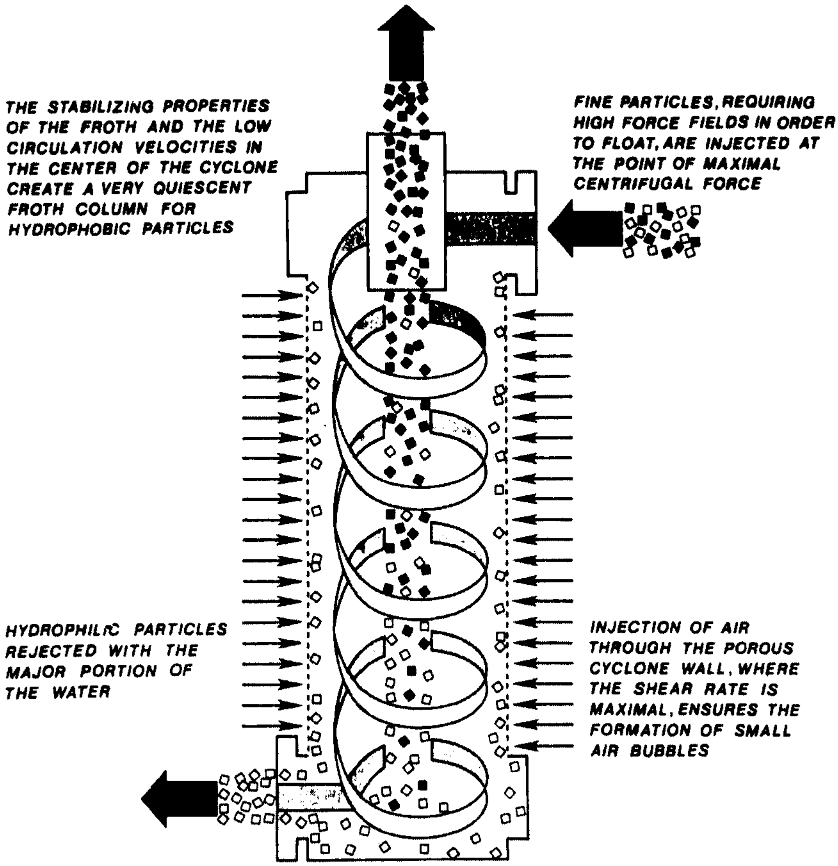

FIGURE 8
Sparged Hydrocyclone

(3) *Eddy-Current Heating.* Eddy currents are associated with selective heating, which can be used in flotation of sulphide ores, with improved separation of metallic particles.

(vii) *Integrated Processes.* Multistage processes are common practice in chemical and mineral engineering. Treatment of ores and other raw materials begins with comminution (crushing and grinding) combined with sorting, and proceeds through concentration and enrichment to the final "polishing". Addition of extra stages to a process entails increased cost and intermediate means of handling, while not necessarily ensuring improved efficiency. By contrast, integration (e.g. comminution combined with separation and concentration as an independent unit operation) opens the way for new technologies, such as:

- Jaw-crushing in a heavy liquid, releasing desired matrix-locked components with simultaneous "float/sink" separation.
- Electrical or mechanical crushing between the poles of a magnet (nonhomogeneous field) with a magnetic fluid as medium, thereby effecting simultaneous comminution and separation according to density and magnetic susceptibility.
- Ball-milling in a liquid solvent which simultaneously extracts (leaching or solvent extraction) one of the components. Kopper's Tower mill (capable of up to 60% power saving compared with ball mills in identical service) was first introduced in 1953 as an alternative to ball mills in regrind applications. Essentially a vertical ball mill with agitation of the medium provided by an internal screw flight, it has been used in Japan for a wide variety of minerals (silica, limestone, coal and copper). A unit intended for simultaneous grinding and leaching of gold tailings is being installed by the Langlea Mining Co. of Canada at Macassa, Ontario.
- Simultaneous grinding and flotation[36].
- Simultaneous grinding and sieving[37].

(viii) *Chemical Crushing.* Use of chemicals with a view to selective attack on part of the components, accompanied by comminution. The technique is under study for coal, using ammonia in concentrated aqueous solution or in gaseous form.

Biodegradation of rocks and minerals: some speculative work on the possibility of using microbes to promote biodegradation of rocks and minerals is under investigation at the Warren Spring Laboratory (U.K.). Survey work has shown that some minerals (for example, olivine and nepheline) are significantly more degradable than others, while certain microbial metabolites, in particular chelating agents like citric and oxalic acids, consistently more effective than others in the same context. Such a process, if economically viable, could materially reduce the energy requirement for liberation grinding of ores.

(ix) *New Methods Based on Deliberate Artificial Modification of Mineral Properties.*

- Implantation and/or seeding of ferromagnetic materials for trapping diamagnetic particles in suspension.
- Controlled heating so as to increase the magnetic susceptibility of weakly magnetic minerals (e.g. pyrite, chalcopyrite and other iron-bearing minerals), with a view to selective separation.
- Selective surface adsorption of a magnetic medium (ferrofluid) on minerals, again for increased magnetic susceptibility.
- Implantation and/or seeding of highly dielectric materials (e.g. titanates) with a view to dielectrophoretic filtration or separation.
- Low-temperature treatment for modification of physical properties with a view to improved grindability (applicable in production of rubber, plastics, foodstuffs, and explosive combustible substances).
- Selective colouring with a view to visual differentiation: e.g. spraying of boulders or quarry faces with methylene-blue solution, for distinction between flint and chalk in quarrying for the Portland cement industry.
- Selective colouring with a U.V. surface-active reagent with a view to application of electronic sorting[38].

(x) *Agglomeration*[39]. Agglomeration is useful in the context of heap or percolation leaching of ores containing clays and excessive fines, which has become a practical processing alternative over the last few years. Its importance is associated with the tendency of the fines to migrate into voids between larger rock fragments, and thus create impermeable barriers to solution flow. This "plugging effect" is minimized by the agglomeration process, whereby the ore is mixed and tumbled with water and a small amount of binder (Portland cement). The agglomerates are cured and piled into stable, porous heaps that do not disintegrate even when soaked in solution.

For an ore containing mostly fines, flow through an agglomerated heap may be 5000 times faster than through an unagglomerated one.

MINING USING SOLUTION-EXTRACTION TECHNIQUES

This novel form of mining (which may be categorized under the concept of unification of processes) is applicable in underground operations [sulphur, potash, gold, uranium, copper, salt (halite), trona, and boron minerals] as well as in in-situ leaching (heap- and dump leaching). Combining the functions of mining, transport, comminution, leaching and solid-liquid separation in a single operation it can be usefully applied in reassessing partially depleted mineral resources which are too uneconomic for traditional mining. Well technology (largely an area of petroleum industry expertise) is used to recover mineral values by injecting leaching solutions into the ore body via one set of bore holes and removing the pregnant solution containing the desired element via a second set. Some of its advantages and associated potential problems are summarized in Table V. Unlike the situation in solution mining, the ore for a heap-leach process must be mined, transported and sometimes comminuted before chemical extraction can begin (see Table VI).

On-site research into solution mining is being carried out by Conzinc Riotinto (CRA) at Eastville (Victoria) (see Fig. 9). In the case of gold, solution mining offers a systematic means of extraction with economic and environmental benefits. A prerequisite is a water-permeable alluvium lying below the water table (the groundwater must be virtually static) and overlying an impervious basement rock. Other prerequisites are a large, dependable supply

TABLE V

Advantages and Potential Problems in Solution Mining*

Parameter	Advantages	Problems
Economic	Treatment of lower grade ores. Lower capital and operating costs. Shorter lead time to production. Smaller financial participation. Little land restoration required.	Probable low recovery.
Environmental	Minimal surface disturbance Less exposure to dust and radiation. Less tailings generation.	State of flux of Federal and State environmental regulations with reference to solution mining in the U.S.A.
Technical	Less energy-intensive. Less equipment to maintain. Lower requirement for skilled personnel. Slow diffusion favours low grades (when good access is available) "Mill" located over "mine".	Decreasing permeability with time. Dissolution of feldspar, calcite, etc. Refractory minerals in the aquifer. Presence of organic carbon and pyrite. Adsorption of U_3O_8 by montmorillonite. Co-precipitation with other elements. Corrosion of non-plastic pipes. Strength limitation of plastic pipes. Presence of brines. High *Mo/U* ratios. Not applicable to all orebodies.
Safety	Absence of mining-related hazards.	Presence of high-pressure caustic/acid solutions. Use of high pressure oxygen.

* Simonsen, H.A., Boydell, D.W. and James, H.E., The Impact of New Technology on the Economics of Uranium Production from Low-Grade Ores, 5th Annual Symp. of the Uranium Inst., London, 2-4 Sept. (1980), 156 pp.

TABLE VI

Advantages and Potential Problems in Heap Leaching

Parameter	Advantages	Problems
Economic	Can be applied to low grade ores. Can take advantage of bacterial action to produce low cost lixiviant. Low capital investment involved. Portable recovery plant can be employed.	Probable low recovery. Large quantities of pregnant solution tied up for long time periods. Large areas required for dump and sump accommodation.
Environmental	Reduction in permanent industrial equipment fixtures. Recovery plant can be skid-mounted for transportation to other sites.	Leach reaction may be difficult to terminate. Radon emission.
Technical	Savings in comminution facilities. Mechanical/air agitated leach tanks and ancilliary equipment not required. Liquid/solid separation avoided.	Large scale pilot testing required. Difficulty in contacting all ore with lixiviant. Poor control over leach conditions in large dumps. Adequate access of oxidant may be a problem. Precipitation can decrease permeability to a point where the dump becomes inactive.

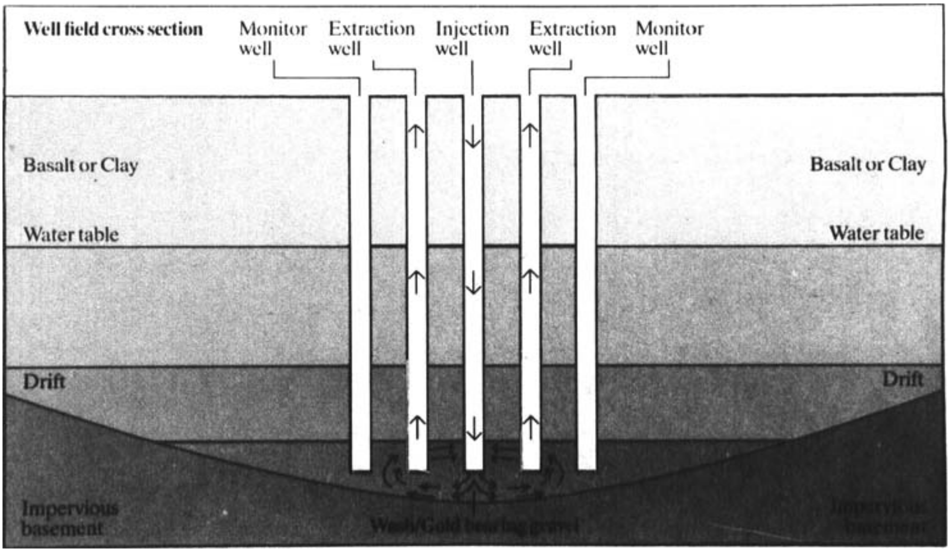

FIGURE 9
Mining by leaching techniques - well field cross section.

of solution and a cheap energy supply (solution may be preheated, air may be compressed for pumping the solution to the surface, etc.). Once position, depth and grade of the deposit have been determined by exploratory drilling, the pattern of injection and extraction wells can be drawn up and plant installed on the surface. The gold is dissolved by one of several types of solution (thiourea, thiosulphate, cyanide); recovery of the metal entails hydrometallurgical methods using either resins or active carbon (CIP, see p. 12 above). Precautions have to be taken to prevent contamination of the groundwater by the chemicals. Monitor wells on the periphery of the mining area should ensure that no leach solution escapes.

Another promising sector in this context is crude oil. As is well-known, the decline in production from primary oil stimulated the use of secondary recovery techniques such as water flooding and gas injection which increased the average amount of extractable oil by 17-38%; these were duly followed by tertiary techniques that have so far been only partially successful and would raise cumulative recovery expectation to 35-38%. The next step in gaining access to the untapped reserves suggested by Hutchins et al[40], involves petroleum mining. (Table VII indicates the areas of the world where oil mining may be practicable). The idea may cover a variety of processes such as:

(i) Mining below conventional reservoirs containing mobile oil, and recovery by gravity drainage.

(ii) Stripping exposure of shallow heavy oil deposits by viscosity modification, chemical treatment, surfactants or pressure.

(iii) Mining below heavy oil reservoirs.

(iv) Combined mining and cavern-jetting above or below heavy oil deposits.

(v) Mining above, below or into tar sand.

(vi) Extractive mining of conventional oil, heavy oil and tar sand deposits.

Figure 10 illustrates the proposed gravity-drainage technique. A shaft is sunk through the reservoir and horizontal tunnels are

TABLE VII

Potential Oil Mining Areas

Africa	North America	South America
Angola*	Canada (Alberta only)	Argentina
Algeria	U.S.	Bolivia
Congo		Brazil*
Egypt	**Central America**	Chile
	Mexico	Peru*
Asia		Venezuela
Burma	**Europe**	
India	Austria	
Indonesia	France	
U.S.S.R.	F.R.G.	

* Denotes countries with offshore prospects.

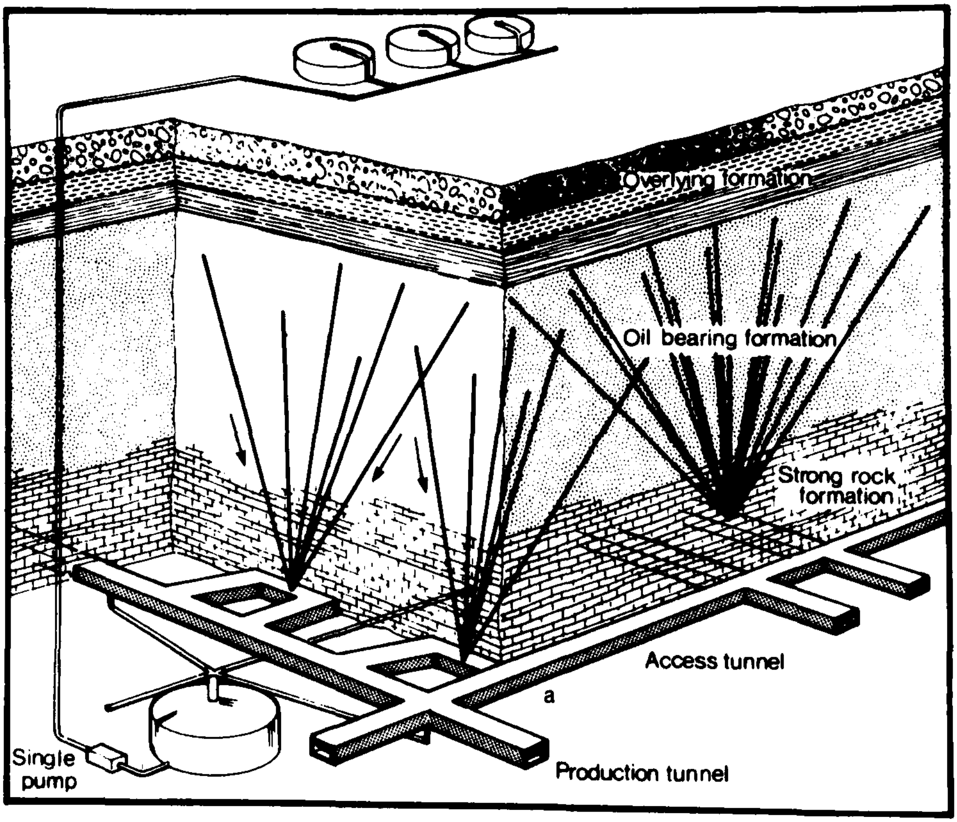

FIGURE 10
Proposed gravity drainage scheme to collect oil from wells driven upwards from underground workings.

driven underneath to the full lateral extent. Collection wells are driven from the workings up to the oil-bearing formation. These wells drain oil into a central collection system from which it is pumped to the surface. It may be necessary to protect the mine by pressure control devices. (Even "pressure-depleted" reservoirs may contain very high pressures in the range 172 kPa to 1.7 MPa).

The authors are at pains to point out some of the difficulties which would be encountered in implementing such techniques.

Another alternative is conventional underground mining of primarily- and secondarily-depleted petroleum deposits, using a method similar to oil shale mining (huge mining and materials handling).

It seems safe to predict that the future will see accelerated exploitation by oil mining both of unconventional hydrocarbon deposits and of the substantial supplies of petroleum still present in conventionally pumped-out reservoirs[41].

CONTROL AND MEASUREMENT

It has been stated that technology has been the main contributor to conservation of the world's economic reserves of most minerals. An important part of this technological advance lies in more sophisticated processes and more effective control. In fact, in the last 10 years no aspect of mining has advanced as much as process control. The objectives of the latter are: maintenance of product specifications while minimizing the consumption of energy, reagents and other materials used in the process, and maximized recovery (i.e. minimal waste) of the valuable elements.

Modern control techniques, based on chemical analysis, on radiometric size measurement, or on DP systems, yield real-time position readings and information, with everything this entails in terms of improvement[42]. Available equipment includes wet and dry systems yielding particle distributions at any desired stage; measuring control systems for density, pH, solids content (in suspension) and elementary composition; discharges; continuous dosage devices; power-reading instrumentation, fault location and advance-warning devices; power-reading instrumentation, fault location and advance-warning devices (safety aspect!). There is automatic instrumentation for simultaneous analysis of several elements in a given flowchart, and for dry analysis of carbon, moisture, ash, sulphur, etc. - in energy-storing minerals[43]. Further innovations are expected in short course, especially in the form of microprocessor applications[44].

The growing recourse to on-line (or in-plant) analysis in process control is a demonstration of the general principle that effective exploitation of resources is achieved through improved use of information rather than through energy consumption.

TRENDS AND TARGETS IN DEVELOPMENT

Ore benefication is defined as physical treatment of mineral raw materials, without altering their mineralogical identity, in the course of their conversion into marketable products.

Recent technological advances; the massive demand for effective treatment of new types of ores; increasingly rigorous requirements with regard to product standards; attempts to reduce production costs and improve process efficiencies; problems in tackling low-grade raw materials - in large masses - or fine fractions; and (last but not least) environmentalist pressures - all these have extended activity in ore beneficiation to its physical, chemical and physio-chemical areas.

As regards future developments in Israel, a report on local trends and targets in the field of industrial minerals has been published[45], encompassing a wide range of possibilities:

- While there are top-level plans for regular State support in such areas as water resources, agriculture, or the aviation and munitions industries, there are none for <u>intensified exploitation of natural resources</u> (terrestrial or marine); nor are there national development-planning facilities for this purpose.
- The possibility of <u>importing bulk ores or concentrates for local processing</u> (in both the civilian and military sectors) should be examined; for example - extraction of titanium oxide from ilmenite, or production of tungsten powder from scheelite or wolframite.
- <u>Local production in specific sectors</u> should be stimulated: lithium from Dead Sea brine, aluminium from clays, fillers from industrial minerals, iron from Manara ore, sophisticated ceramics from local clays, soluble salts from quartz sand, new phosphate derivatives and sophisticated fertilizers; maghemite and

ferrite (magnetics); synthetic zeolites; new building materials; treatment of energy-storing minerals.

- Greater economy in displaced resources: there is no national recycling scheme for re-use of industrial and material waste, coal ash, etc; information on recycling is generally incomplete, and the problem should be tackled.

- Development of new technologies: A field with high local potentialities, both with regard to export of know-how and to design and construction of sophisticated equipment for local and overseas use, ahead of other advanced countries[46]. Examples: new ion-exchangers; improved solvent-extraction techniques; extraction of precious metals and uranium from sea-water; new techniques for separation and enrichment (dry or wet) in fine-grained systems; dielectric filtration; processes with reduced energy consumption per unit product, and with reduced waste yields; processes for utilization of liquid and solid by-products; adaptation of radiometric pre-concentration/sorting techniques for enrichment of local phosphates; classifying devices utilizing an electromagnetic field; new synthetic products based on mechanochemical processes; separation processes based on ferrofluid (whose price is continuously dropping); new separators based on superconductores or on permanent magnets[47].

- Intensified processing of by-product suspensions from beneficiation plants and chemical industries, for improved recovery of valuable elements.

- Examination of upscaling problems in separation processes at the R & D or laboratory stage.

- Examination of basic problems still in their infancy, such as characterization and microprocessing of particle systems, tension-based comminution (utilizing low tensile strength), flow around particles in liquid media, etc.

- Institutionalization of problems of design and execution, at present tackled largely on a "rule of thumb" basis.

Interested circles and the government agencies concerned, in collaboration with local universities, should take positions on the above subjects.

CONCLUSION

In the above, the reader is introduced to a variety of innovations, some of them already applied industrially, others still on their way. They are obviously only a beginning, and further breakthroughs are expected - given initiative, motivation, imagination, inventiveness, creativeness, and access to current and up-to-date information.

The need to reduce costs, to tackle large bulks and high yields, to exploit low-quality resources, to convert from energy- and labour-intensive processes to alternative ones - in conjunction with the environmental aspect - is bound to accelerate these new developments. High mining costs due to poor ore quality, to geographical remoteness, to lack of an infrastructure, to depth of deposition, or to non-selective removal (resulting in large yields of superfluous materials) - all these, combined with the energy crisis, call for special solutions (such as pre-concentration) or for totally new approaches.

There are three main ways of reducing capital and production costs. The first is to eliminate one or more of the operational steps in the production sequence; the second is to transform or modify the techniques or equipment applied; the third is to raise the grade of the material treated at an early stage in the process. Examples of each of these methods are given in Table VIII.

Because mining and processing costs are proportional to the mass of raw material treated, the owners of high-grade deposits are in a more favourable position thanks to the lower unit production cost of their commodity. In the case of low-grade deposits, possible future trends may include greater emphasis on use of low-cost production routes such as: elimination of operating steps (e.g.,

TABLE VIII

Classification of Techniques for Reducing Treatment Costs

Elimination of Operating Steps	Modification of techniques or equipment	Preconcentration*
In-situ leaching	New magnetic separators	Automatic sorting
(i) Solution mining	New and modified sorting machines	HMS**
(ii) Heap leaching	Modified hydrocyclones	Magnetic scalping
Unification of processes***	New gravity separators	Differential classification
(i) Comminution/ sink-float	High-rate thickeners	Selective mining
(ii) Comminution/ leaching	Improved mixer-settlers	
(iii) Comminution/ flotation	Continuous ion exchange	
Resin-in-pulp	Modified flotation cells	
Solvent-in-pulp	New monitors	
Carbon-in-pulp	New filters	

* Addition of a preconcentration technique at the front end of a plant can be a cost-effective method of boosting plant capacity.

** Including an anhydrous heavy-liquid separation process for cleaning coal.

*** See (vii) on Integrated Processes in Examples of New Processes in Development (pp. 19/20 above).

in-situ leaching), modification of techniques (e.g., continuous ion exchange) and utilization of preconcentration methods (e.g., electronic sorting, selective screening, magnetic scalping, heavy media separation, etc.).

A certain amount of risk is incurred in a decision to make use of new technologies. This is particularly true for production from a low-grade ore which might depend for its profitability on successful application of a novel type of equipment or processing route.

Techniques proven on one site may not be transferable to another application because of unforeseen differences in the characteristics of the ore, or in environmental conditions. For years, one of the main ambitions of ore dressers and extractive metallurgists had been to develop continuous process because they give greater productivity, better materials efficiency and improved thermal economy.

Advanced separation theories, utilization of force combinations, and increase of intensities and gradients - are also bound to open the way for innovations. Advances in electric and magnetic separation techniques are in full swing; the latter are in fact being revolutionized, thanks to the advent of new magnetics and of improved circuits based on permanent magnets. There is also considerable progress in adaptation of ores to techniques, through controlled artificial changes.

There will be direct implications for various industries. Trans-application from one field of engineering to another is relatively easy; knowledge of the state of the art, understanding of the needs, and executive ability reinforced by steady and consistent efforts, will bear fruit in short course.

Larger mineral processing equipment, increased utilization of computer modelling, improved understanding of the basic processing principles, and much more careful analysis of the economic ramifications of operating strategies, reagent selection, and equipment utilization characterize recent trends in mineral processing.

The economic recession that has prevailed for the last two years has led to a severe slowdown in the expansion of the minerals industry, but has not precluded advances in processing technology. In fact, the lack of cheap capital has forced development of new equipment, processes, reagents, and operating techniques that may significantly lower operating costs, while minimizing capital investment. A sound R & D policy, training of professional cadres, and allocation of funds will make short-cuts possible. It should be noted that most of the research that brought about these improvements dates from before the recession, and the innovations are just now being tested on an industrial scale. As of now, there has been a significant reduction in research activity, which may manifest itself already in the near future.

Application of basic processes in mineral and chemical engineering will open the way for new processes in recycling municipal and industrial waste[48,49]. Re-use of secondary resources (man-made ores) is the order of the day.

Industry must deepen its involvement in innovative development, in middle- or long-term considerations. Collaboration with the academic world is essential for putting ideas into practice. Industry appears very reluctant to risk capital on "chancy" processes that are not commercially proven. Part of the problem may also be connected with the cyclical nature of metal prices. When they are too high, there is too much profit to be made with known technologies and no one is interested in "crazy ideas". When times are bad, no funds are available for research and development, and no new technologies can be created to help pull through the economic hardships. Mineral companies must show some foresight and encourage scientists to come up with totally new concepts, rather than with mere improvements on old ideas.

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