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Profiles of hydraulic-fill tailings beaches, and seepage through hydraulically sorted tailings

by G.E. BLIGHT[*], R.R. THOMSON[†], and K. VORSTER[‡]

SYNOPSIS

It is shown that the profiles of beaches of hydraulic-fill tailings dams can be predicted with good accuracy by the use of small-scale laboratory deposition tests on materials from a prototype tailings dam.

Although the slope of a tailings beach at any point is related to the shear strength of the settled slurry, there are severe practical difficulties in the prediction of beach profiles from shear strengths measured in the laboratory.

The hydraulic sorting of particle sizes that occurs on a tailings beach results in a gradient of permeability along the beach, and this gradient has the significant effect of lowering the phreatic surface in the tailings dam.

SAMEVATTING

Daar word getoon dat die profiele van die strande van hidroulies gevulde uitskotdamme baie akkuraat voorspel kan word deur die gebruik van kleinskaalse laboratoriumafsettingstoetse met materiaal afkomstig van 'n prototipe uitskotdam.

Hoewel die helling van 'n uitskotstrand op enige punt met die skuifsterkte van die afgesakte flodder verband hou, is daar verskeie praktiese probleme in verband met die voorspelling van strandprofiele aan die hand van skuifsterktes wat in die laboratorium gemeet is.

Die hidroulies gesorteerde partikelgroottes wat op 'n uitskotstrand voorkom, lei tot 'n deurlatenheidsgradiënt langs die strand en hierdie gradiënt het die belangrike uitwerking dat dit die grondwaterstand in die uitskotdam verlaag.

Introduction

In a recent paper[1], Blight and Bentel (following Melent'ev[2] *et al.*) showed that the profiles of a series of dam beaches of hydraulic-fill tailings can be represented by a single dimensionless 'master profile'. It followed from this, that the profile of any beach of a particular tailings can be predicted accurately from the elevation of the point at which the tailings are deposited, and the elevation and distance of the edge of the pool. Examples were given for beaches of copper, diamond, gold, and platinum tailings[1], and it was shown that the principle is also applicable to the profiles of cones of underflow material deposited by cyclone.

The prediction of the profile of a beach is important in the design of tailings dams because it allows the designer to predict the position of the pool, to assess the stormwater storage capacity of the top of the dam, and to assess the tailings storage capacity more accurately.

The principle of the dimensionless master profile is illustrated in this paper for a series of beach profiles measured on a uranium-tailings dam: Fig. 1 shows five profiles (numbered 1, 3, 4, 5, and 6) for beach lengths from 293 to 718 m, and for differences in elevation between the point of deposition and the pool from 17 to 24 m. In Fig. 2, the profiles were replotted on a dimensionless basis, in terms of the length ratios h/Y and H/X. It will be seen that all the measured data cluster about the master profile with equation

$$h/Y = (1-H/X)^n, \quad \ldots\ldots\ldots\ldots (1)$$

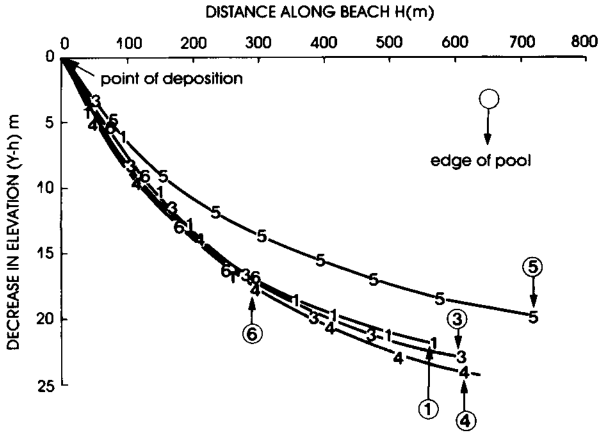

Fig. 1—Five beach profiles observed on a uranium-tailings dam

where $n = 2{,}0$ in this case[§].

The previous study left a number of questions unanswered.

(i) Can the exponent n in equation (1) be obtained from small-scale laboratory tests, or must it be determined from measurements of full-scale hydraulic beaches?

(ii) What factors affect the value of n? Is it unique for each type of tailings, or does it vary with the fineness of the material and the density or water content at which it is deposited?

(iii) There is a theoretical relationship between the shear strength of settled tailings and the beach angle at that point. Can beach profiles be predicted on the basis of laboratory measurements of shear strength?

This paper sets out to provide answers to these questions.

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[*] Professor of Construction Materials, University of the Witwatersrand, P.O. Box 1176, Johannesburg 2000.

[†] Engineer, Steffen, Robertson & Kirsten, P.O. Box 8856, Johannesburg 2000.

[‡] Lecturer in Civil Engineering, Technikon Pretoria, 420 Church Street, Pretoria 0002.

[§] Equation (1) was given incorrectly in the earlier paper[1], where it appeared as Equation (17).

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Blight and Bentel[1] also showed that the hydraulic sorting of particles that occurs on a tailings beach can be predicted from the relationship

$$AH/X = M, \ldots\ldots (2a)$$

$$\text{in which } A = \frac{D_{50}\ (\text{at } H \text{ down the beach})}{D_{50}\ (\text{of the total product})} \ldots\ldots (2b)$$

X is as defined in Fig. 2,
M is a characteristic of the tailings, and
D_{50} is the particle size at which 50 per cent by mass of the solids at any point is finer than D_{50}.

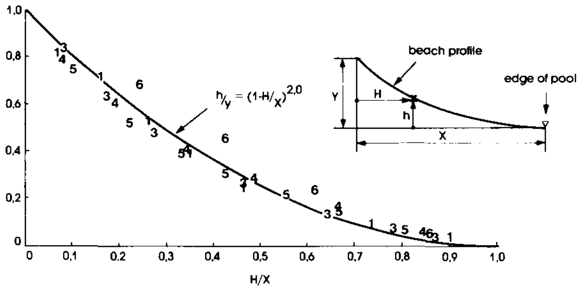

Fig. 2—Dimensionless master profile derived from the data of Fig. 1

The permeability, k, of a granular material can be related to a characteristic particle size by an equation such as that due to Hazen[3]. Hazen's formula is

$$k = D_{10}^{2} \text{ cm/s}, \ldots\ldots (3)$$

in which D_{10} has a similar definition to D_{50} and is measured in millimetres.

Hence, the gradient of particle sizes along a beach, which is predicted by equations (2a) and (2b), can be translated into a gradient of permeability. This paper explores the effect of the permeability gradient on the position of the phreatic surface in a tailings dam. It shows that a significant lowering of the phreatic surface occurs because of the progressive increase in permeability from the edge of the pool towards the wall of the dam.

Model Tests for the Prediction of Beach Profiles

Observations on full-scale tailings dams had indicated that the master profile is applicable regardless of the length of the beach. However, it seemed likely that the profile would not apply once the beach length became less than a certain minimum value. It would, naturally, be most useful if a very short beach length, say 1½ to 3 m, could be used in the laboratory to establish the master profile for the beaches of a projected full-scale dam.

The beach of an active gold-tailings dam was selected as the prototype, and its profile was surveyed. Material was collected from the dam for the laboratory model to represent the total tailings, the fine material from close to the pool, and the coarse material from close to the point of deposition. The particle-size distributions for these three materials are shown in Fig. 3.

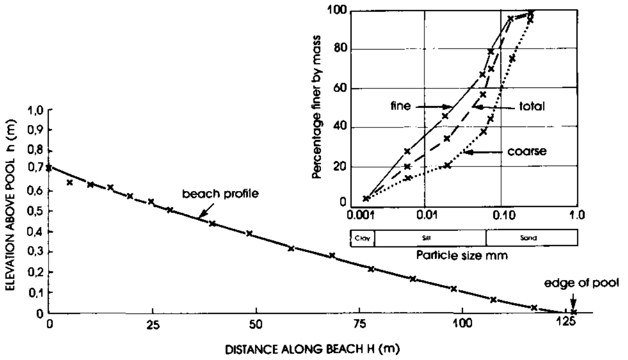

Fig. 3—Prototype beach profile to be modelled in the laboratory Inset: Particle-size distribution curves for total tailings, coarse tailings from near the deposition point, and fine tailings from near the pool

The arrangement for the formation of the model beach in the laboratory is illustrated in Fig. 4. As the diagram shows, it was very simple, consisting merely of a Perspex-sided tank or short flume with a facility for the charging of tailings slurry into the tank at one end and the decanting of water from the other. In falling into the tank, the slurry formed a plunge pool that overflowed to form the model beach, which had an effective length of only 1500 mm.

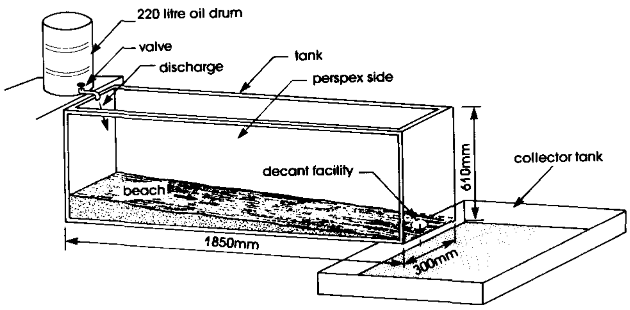

Fig. 4—Experimental arrangements for the modelling of tailings beaches

Model beaches were formed from each of the three materials (total, fine, and coarse). Each material was deposited at three solids contents (50, 60, and 70 per cent), which corresponded to water contents on a dry basis of 100, 67, and 43 per cent and slurry relative densities of 1,47, 1,62, and 1,81.

Profiles of the Model Beach

Fig. 5 compares the observed dimensionless profiles of the model beaches with the dimensionless profile of the prototype beach.

It will be seen from Fig. 5(a) that the field profile is in excellent agreement with the laboratory profile for the total material deposited at 50 per cent solids, which corresponds approximately to the conditions for field deposition. As the solids content increases and the shear strength of the slurry correspondingly rises (see later), the beach profile becomes steeper at small values of H/X and flatter at larger values.

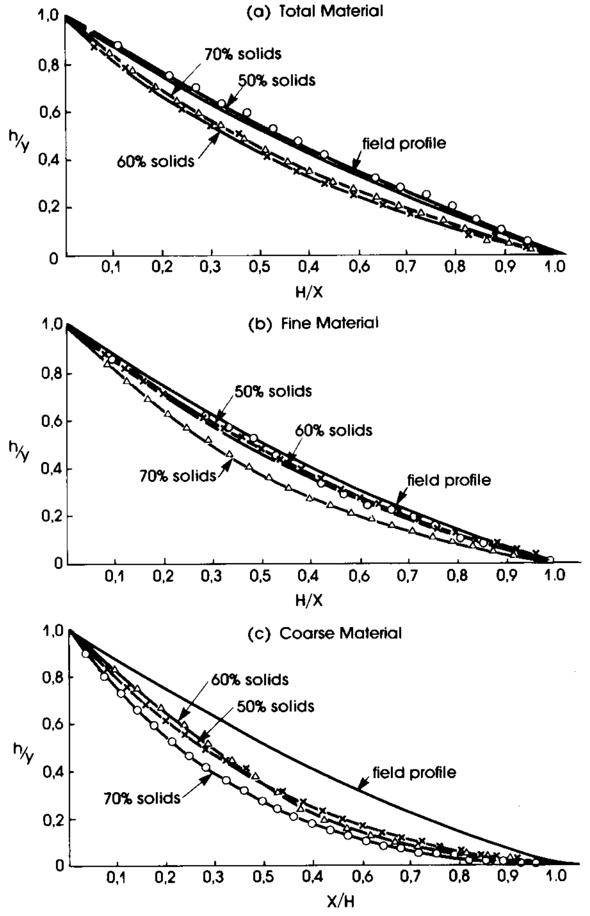

Fig. 5—Comparison of the field beach profile (Fig. 3) with beach profiles modelled in the laboratory

Fig. 5(b) shows profiles for model beaches of the fine material. Here again, good agreement was obtained between the field profiles and the laboratory profile for a solids content of 50 per cent. The profile for 60 per cent solids differed little from that for 50 per cent solids, but the profile for 70 per cent solids was very similar to the 70 per cent solids profile for the total material.

As shown by Fig. 5(c), the profiles for the model beaches of coarse material all fell below the profile for the prototype beach. As for the fine material, profiles for 50 per cent and 60 per cent solids contents were very similar, but the profile for 70 per cent solids was steeper at small values of H/X.

Hence, somewhat to the surprise of the writers, it appears that the profile of a full-scale hydraulic-fill tailings beach can be predicted by the use of a small-scale model in the laboratory. Agreement between model and prototype appears excellent, provided the same material is used and it is deposited at a similar solids content.

The models also show that, as the solids content of the tailings increases, the beach profile becomes steeper close to the point of deposition, while the same applies if the coarseness of the material is increased at a fixed solids content.

Relationship between Shear Strength and Beach Angle

The factors that tend to increase the initial steepness of a beach profile, namely increasing solids content and increasing coarseness, could be expected to result in increases in the shear strength of the settled slurry. Blight and Bentel[1] suggested that the slope of a beach at any point could, in principle, be predicted from the expression

$$2i = \sin^{-1} \tau_0/\rho g\delta, \qquad (4)^*$$

where i is the slope angle of the beach,
τ_0 is the shear strength of the settled slurry,
ρ is the density of the settled slurry, and
δ is the depth of the settled slurry layer.

The shear strength of slurries is difficult to measure and the results tend to be erratic, as shown in Fig. 6, which represents the variation of shear strength measured along the length of a model beach by means of a co-axial cylinder viscometer. The diagram illustrates the tendency for the shear strength to decrease with distance along the beach, i.e. to decrease as the slope angle decreases. However, the slope angle, i, cannot be calculated because δ, the thickness of slurry appropriate to equation (4), is not known. The effective value of δ is not easily determined, and seems to vary far more than would be expected. This is illustrated by Fig. 7, which shows observed relationships between the inclination of the slurry surface in the model beach-profile tests and the corresponding shear strength measured over a depth of 25 mm. Again, this diagram demonstrates how erratic measurements of shear strength on slurries tend to be. Lines of best fit were drawn through the experimental data, and the corresponding values of δ were calculated. It will be seen that δ increased from 11 mm for the coarse slurry, to 17 mm for the total material, to 33 m for the fine slurry. These are all perfectly reasonable values, but they cannot be predicted.

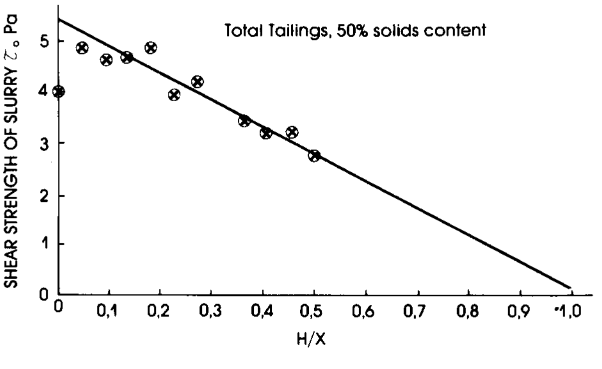

Fig. 6—Variation of the shear strength of settled slurry along the length of a model beach

One is forced to the reluctant conclusion that it is not possible for beach profiles to be predicted from laboratory measurements of the shear strength of slurries.

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*Equation (4) appeared as equation (9) in reference 1, where it was incorrectly given as
$i = \sin^{-1} \tau_0/\rho g\delta$.

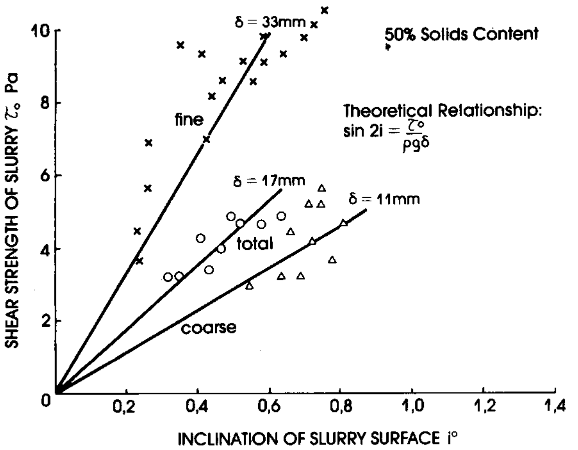

Fig. 7—Observed relationship between the inclination of a slurry surface on a model beach and the shear strength of the slurry

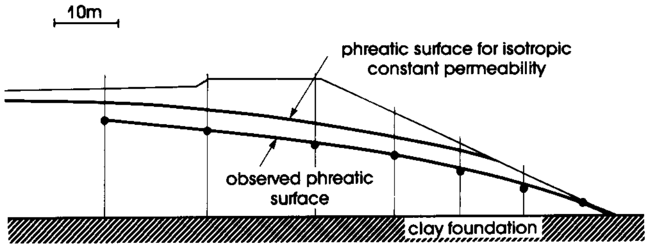

Fig. 8—Comparison of an observed phreatic surface in a gold-tailings dam with the phreatic surface predicted on the assumption of isotropic constant permeability

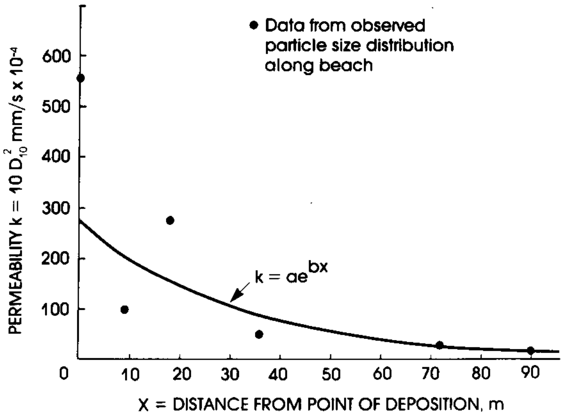

Fig. 9—Variation of permeability along a beach, based on the observed variation of particle sizes

The Effect of Particle Sorting

The unusually low position of the phreatic surface in tailings dams has been noted and commented on. Blight and Steffen[4], for example, were unable to account for the low phreatic surfaces observed in most tailings dams on the basis of the ratio of the permeability of the tailings to the permeability of the foundation, or the ratio of horizontal permeability to vertical permeability of the tailings. However, they appear to have paid insufficient attention to a paper by Abadjiev[5], which showed that, if the permeability of a tailings dam increases towards the toe of the dam, the phreatic surface is depressed. Mechanistically, the explanation of the depression is as follows. Continuity of flow requires that the flowrate should be the same through the low-permeability material near the pool as through the higher-permeability material near the outer slopes of the dam. It follows from d'Arcy's law that the flow gradient must decrease progressively from the pool outwards; that is, the phreatic surface must be steeply inclined close to the pool and then progressively flatten towards the outer slopes of the dam.

In a ring dyke dam (the type of most South African tailings dams), the fact that the flow is radial, from a relatively small pool to a much larger dam perimeter, also causes the phreatic surface to be depressed. Fig. 8 shows an example of a depressed phreatic surface in a gold-tailings dam. The upper curve in the diagram represents the phreatic surface that would be expected in an embankment of constant isotropically permeable material[6], and the lower curve shows the actual phreatic surface as observed in a series of stand-pipe piezometers. The depression amounts to nearly 4 m of water head, and would have a significant stabilizing effect on the outer slope of the dam.

Fig. 9 shows the variation of permeability along the beach of a platinum-tailings dam based on the application of the Hazen[3] formula to the observed variation of D_{10}. The point determinations are scattered, but a curve of the type

$$k = a\,e^{bH} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

fits the data reasonably well. In equation (5), a and b are characteristics of the beach, and H is the distance down the beach from the point of deposition (Fig. 2).

For this particular beach,

$a = 2{,}72\cdot10^{-5}$ m/s and
$b = 0{,}0315$/m.

The position of the phreatic surface was calculated by the application of a finite-element method to seepage through a dam with the above permeability profile. Full details of the method, which is suitable for use on a personal computer, are given by Vorster[7]. Only the result of the analysis, shown in Fig. 10, is considered here.

Fig. 10 shows the considerable difference between the phreatic surface calculated for values of permeability varying according to equation (5) and that based on the assumption of an isotropic constant permeability. In the case considered, the permeability of material upstream of the current point of deposition (A in Fig. 10), i.e. closer to the toe of the dam, was assumed to have a constant isotropic permeability equivalent to a in equation (5). From point A downstream, the permeability was assumed to be isotropic but to vary with distance according to equation (5). The depression of the water table for the example considered was no less than 15 m or 38 per cent of the maximum height of the dam.

This demonstrates the considerable influence that hydraulic particle sorting can have on the position of the phreatic surface in a dam. The method developed by Vorster[7] enables the depressed phreatic surface to be located and the depression to be taken into account when a dam is being designed for stability.

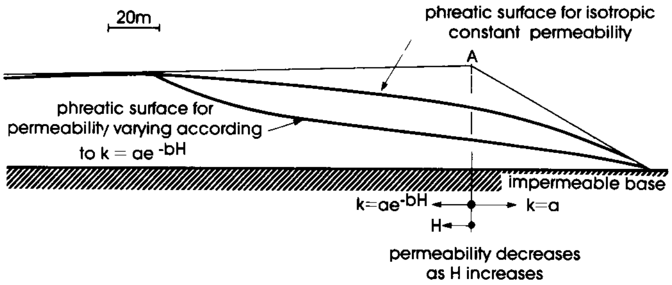

Fig. 10—Prediction of the phreatic surface for the variation of permeability shown in Fig. 9

Conclusion

Small-scale laboratory models of beaches of hydraulic-fill tailings provide an acceptably accurate method for the prediction of the beach profiles of full-scale tailings dams. However, laboratory measurements of the shear strength of settled slurries do not offer a practical means for this prediction.

Hydraulic particle sorting results in a gradient of permeability along a beach that, in turn, causes the phreatic surface in a dam to be significantly depressed.

Acknowledgements

The work described in this paper was undertaken by R.R. Thomson[8] and K. Vorster[7] in part fulfilment of the requirements for the M.Sc.(Eng.) degree at the University of the Witwatersrand, Johannesburg. The co-operation of their employers, Steffen, Robertson & Kirsten, Inc. and the Technikon Pretoria respectively, is gratefully acknowledged.

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Egyptian research institute

The Desert Research Institute is an arm of the Egyptian government whose activities are largely devoted to research in the deserts and newly reclaimed areas. It was officially inaugurated in 1951. The research work emphasizes water resources, soil resources, and plant and animal production.

Most of the work is performed in five geographical areas. The first of these is the northern part of the Sinai Peninsula, where there is an average rainfall of 100 mm each winter and there is adequate soil and range plant cover. Work is also done in the New Valley, a string of oases west of the Nile Valley in the Western Desert. A major artesian aquifer, the Nubian Sandstone, underlies the New Valley, which contains soil of lacustrine origin and is an area of planned agricultural development. A third area of interest is the marginal gravelly plains of the Nile delta, where there is a major groundwater basin. Work is also being done in the Mediterranean littoral zone, which has winter rainfall, extensive soils, and natural vegetation, and along the fringes of Lake Nasser behind the Aswan Dam to reclaim land in several valleys.

The Institute maintains an experimental station covering about 50 ha at Mariut, 30 km west of Alexandria in the Mediterranean sub-arid belt. The station specializes in animal husbandry, especially sheep breeding, range management, reclamation of saline soils, and utilization of saline water for irrigation.

A new research station of about 10 ha has been established in the arid belt of the Sinai peninsula, about 30 km southeast of the city of Suez.

The administrative offices, laboratories, and library are in El Mataria, a suburb of Cairo. The *Desert Research Bulletin* and special publications are published. They are not for sale but are given free on request to interested organizations. The Bulletin is exchanged with about 200 societies.

Research is carried out in collaboration with universities and includes post-doctoral as well as graduate research. In addition to work in Egypt, the Desert Research Institute has participated in studies of the Artesian Basin of North Africa with UNESCO, soil studies on the fringes of Lake Nasser with FAO, studies on the utilization of saline water for irrigation, and the preparation of the *Sheep Encyclopedia of the World* with ACSAD.

All the known Egyptian mineral deposits occur in extremely arid regions. Any consideration of the infrastructure associated with mineral development will involve detailed hydrological studies. These will be performed by the Desert Research Institute as part of the Minerals, Petroleum and Groundwater Assessment Programme. A heavy-duty mobile drill rig has been ordered. The rig will be especially designed for use in extremely hot dry regions, and will be able to drill hydrological test holes to a depth of 500 m. Shops capable of repairing and maintaining this and similar equipment in Cairo are in the advanced design stage, and construction should commence in the next few months.

The address of the Desert Research Institute is c/o Egyptian Geological Survey and Mining Authority, 3 Salah Salem, Abbassia, Cairo, Egypt. Telephone: 835617-31620-31644. Telex: 22695 GEOSU.

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Precious metals

This tenth anniversary year of the founding of the International Precious Metals Institute promises to be a 'gala celebration' according to Dr M. El Guindy, General Chairman of the 10th Conference, and President of Precious Metals Industries, Inc.

The theme for the conference which is to be held from 8th to 13th June, 1986, at Lake Tahoe, will be 'Interactive Precious Metals Technology—Producer to User', according to Dr U.V. Rao, Technical Papers Chairman and Executive Vice President of Gemini Industries, Inc. A tour of the United Mining Company Mine in Virginia City, Nevada, will be a highlight of the Conference.

Members and non-members are invited to submit titles and abstracts pertaining to the use of precious metals in the categories outlined:

- Petroleum and Petrochemical
- Chemical and Pharmaceutical
- Human Health Care
- Environmental
- Advances in Analytical Techniques, Including Laboratory Computerization
- High Technology Areas, Including Microelectronics and Space
- Energy Applications—Fuel Cells, Fixation of Atmospheric Nitrogen, etc.
- Photographic
- Ceramic
- Glass.

In addition to the above categories, mining, metallurgical and economic aspects of precious metals will be included.

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Continuous casting

The Deutsche Gesellschaft für Metallkunde (Technical Committee—Continuous Casting) is organizing a Symposium on Continuous Casting in Bad Nauheim on 28th and 29th November, 1985.

Every year there are new improvements related to all areas of continuous casting that are aimed at improving the economics of the system, the quality of the product, and general working conditions. Practical experience still has to be gained in many of the new developments.

The Symposium will report on the present state-of-the-art from industry and on areas of research and development. The following main themes will be covered:

- Use of scrap and remelting techniques
- Melt treatments
- Continuous casting processes
- Process control
- Quality control.

The Symposium will deal primarily with industrial problems, and is intended for engineers and technicians connected with continuous casting, quality control, and research and planning operations. It is hoped that the Symposium will lead to in-depth discussions and intensify personal contacts between those engaged in the manufacture and testing of continuously cast products.

The programme will be available in September 1985 and can be obtained from the Conference Secretary, Deutsche Gesellschaft für Metallkunde e.V., Adenaueralee 21, D-6370 Oberursel, West Germany. Telephone: 06171/4081.

Photomicrograph competition

A photomicrograph competition will be held during the Metallography Conference 1985 from 9th to 11th October, 1985, in Trier. Black-and-white and coloured photomicrographs may be submitted for the following categories:

1. Optical microscopy—macro and microstructures
2. Electron microscopy—scanning
3. Electron microscopy—transmission
4. Information and teaching material
5. Failure analysis
6. Micrographs of outstanding artistic or aesthetic appeal.

The micrographs will be exhibited during the Conference and will be judged by the conference participants. In categories 1 to 5, the solution to the problem illustrated should be well documented metallographically and explained schematically or with an accompanying text.

In addition to the prizes for each category, a special prize will be presented for the best trainee entry. Trainee entries must be accompanied by a statement from their advisors that they are trainees.

How to enter:

All entries on white or coloured card.
On the face of the mount: Title and test, exposure, and magnification.
On the back of the mount: Name and address of entrant, and suggested category.
Each competitor may submit up to two entries.

Submit entries by 15th August, 1985, to Deutsche Gesellschaft für Metallkunde e.V., Adenauerallee 21, D-6370 Oberursel 1, West Germany. Telephone: 06171/4081.

Design and development of materials

The Technical Committee on the Constitution of the Deutsche Gesellschaft für Metallkunde is organizing a meeting on the above topic, which is to be held in Bad Nauheim on 5th and 6th December, 1985.

Knowledge of the constitution of metallic and nonmetallic materials is an important basis for understanding their properties and behaviour. In addition, it provides a basis for well-defined further development of these types of materials. New experimental methods, as well as improved and extended techniques covering theoretical procedures and calculations, lead to a rapidly increasing wealth of data covering a wide range of different groups of materials. Therefore the highest priority is given to data collection, processing, and applications.

This Symposium will be of particular interest to those involved in this field in research and development at universities, research institutes, and industry. The Symposium will deal with applications covering steels, ceramics, composite materials, wear-resistant materials, and coatings. The thermodynamics of the phases present, phase diagrams of multicomponent systems (computed and determined experimentally), and the documentation of data will be included.

The programme will be available in October 1985 from the Conference Secretary, Deutsche Gesellschaft für Metallkunde e.V., Adenauerallee 21, D-6370 Oberursel, West Germany. Telephone: 06171/4081.