ELECTROFORMING

Harold J. Read*

Of the many methods by which raw metals can be shaped into useful objects, electroforming is one of the least generally known—in spite of some remarkable things that can be done with it. One of the four major divisions of electrometallurgy (the others are electrowinning, electrorefining, and electroplating), electroforming is distinctive from the others in that it is the only one in which a finished, salable product is produced principally by electrolytic means.

Electrolytically, electroforming does not differ significantly from other electrometallurgical processes. All that is involved is the building up of a metallic body at the cathode of a cell containing a suitable electrolyte. The anodes may or may not be soluble. If they are, they comprise the source of cations for continued deposition of metal at the cathode; if not, cations must be supplied by frequent addition of a suitable compound—for example, the addition of chromium trioxide to a chromium plating bath. The important point of distinction is the nature of the cathode on which deposition occurs. This electrode must be a mandrel, mold, core, or other object whose shape is to be reproduced—either as an intaglio or an exact duplicate.

Although it is difficult to classify all of the possible uses of electroforming in a few categories, the following will encompass the principal applications.

(a) The reproduction in metal of objects having minute details of configuration which much be reproduced as exactly as possible. Examples: electrotypes and phonograph-record stampers.

(b) The reproduction in metal of objects having irregular shapes that cannot be produced by machining—even with jig borers or profilers. Example: synthetic-textile molds.

(c) The production of objects that could be made in some other way but can be made better and cheaper by electroforming. Examples: radar wave guides, fuel-distribution grids, wind-tunnel nozzles, fountain-pen caps, copper foil, and Micro-Mesh sieves.

The following discussion of electroforming techniques is based upon the examples mentioned above. In addition, some of the metallurgical properties of electroformed metal will be examined, and the limitations of the technique will be indicated.

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Electrotyping

For large press runs of printed matter something harder and more wear-resistant than type metal is required; and, in the case of tremendous runs which must be done quickly, several sets of type are required for the simultaneous operation of several presses. Electrotyping provides a means of solving both problems. Only the original set of type and of halftones or other cuts is required. An intaglio replica is made by pressing a heated plastic sheet into intimate contact with the type and allowing it to cool and harden. When it is carefully pulled away from the type, it will bear a reversed or negative impression (an intaglio) of the original type. The replica or mandrel is made electrically conductive on its surface by silvering it chemically, and then it is hung as a cathode in a copper-plating solution. Copper is deposited slowly at first on the very thin film of silver, but the rate is increased as the metal film becomes thicker and can carry the current required for rapid plating. When the copper is about 0.01 inch thick, deposition is stopped and the plated replica is removed from the tank. Flexure of the plastic mandrel will release it from the shell of copper. Too flimsy for printing purposes, the electroformed copper shell is strengthened and brought to type height by backing it with type metal. Often the face of the resulting printing plate is thinly chromium plated to increase wear resistance. There is no difficulty whatever in routinely reproducing every detail of well-cast type as well as photoengravings having more than 17,000 dots per square inch.

Electrotyping is not only one of the oldest applications of electroforming, it is also one of the major uses with respect to volume of business. Although exact data cannot be obtained, it is known that more than 6,000,000 pounds of copper are plated annually in producing electrotypes and that more than 350,000 gallons of solution are involved.

Phonograph Record Stampers

The most spectacular application of electroforming that comes daily in one way or another to the attention of hundreds of millions of people is the phonograph record. A modern, long-playing record requires the reproduction in a vinyl plastic of grooves where-in the details of configuration (that may

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MARCH 1960

CONTRIBUTIONS

The papers listed below are among the contributions by members of the staff of the College of Mineral Industries appearing in recent journal issues. A complete list of publications of the College for the year July 1, 1957, to June 30, 1958, has been released as Mineral Industries Experiment Station Circular No. 52. It is available free on request to the Experiment Station:


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represent anything in the way of audible sound) must be reproduced to less than 0.1 microinch. This makes the ideal condition for common reality. For example, one would have to slice a sheet of ordinary bond typing paper into 40,000 sheets in order to reduce its thickness to 0.1 microinch. Good modern records have a surface noise of about —50 db, representing elements of roughness in the groove having amplitudes of about 0.03 microinches at 1,000 cycles per second. Consider also that the deepness of the recording can be more than 20,000,000 microinches long. One bump a microinch high will provide a click when the record is played that will send any high-fidelity enthusiast screaming to his dealer for a replacement.

In addition to the problems of making even one die, or stamper as it is called in the industry, several identical dies must be made for runs that exceed a few thousand records because the dies deteriorate in use and must be replaced. This is a problem dependent on the quality required—perhaps every 500 records for transcriptions used in radio broadcasting or every 10,000 records for cheap "popular" discs (which are, for the most part, abominable). In a few dozen microinches of bumps and scratches would probably do more to improve the sound than to ruin it.

Electroforming is the only technique which has come close to solving this problem of making dies and other objects. Indeed, until the electrolytic method of stamper production was perfected, the mass reproduction of phonograph records seemed hopeless. In principle, the technique is quite simple, but great care and skill are required in its execution.

The original recording is made on a metal disc coated with a relatively soft lacquer. Sound is electronically translated into mechanical motion of a stylus that cuts the grooves in the lacquer. By means of silverying processes similar to those used on mirrors, the lacquer surface can be made electrically conducting. The metallized recording is then electroplated with nickel to a thickness of about 0.0001 inch. The electroplate is transferred to a copper plating bath to build up a thickness of about 0.025 inch. Separation of the metal disc from the lacquer gives an intaglio of the original recording that could be used to stamp records. It is difficult, however, to make several stampers from a soft lacquer original. Instead, the original intaglio is used to make a "mold." The surface of the intaglio is treated to promote good adhesion during electrodeposition, and then a layer of metal is electroplated on it to 0.025-inch thickness.

When separated from the intaglio, the new electroform is an exact reproduction in metal of the original lacquer disc. It can be played as a phonograph record; in fact, it is at this stage that the audio quality of the recording is first determined. The mold can be used to produce any reasonable number of intaglio replicas for use as stampers in the record presses by a process similar to that employed in making the mold. Thus, three separate electroforming operations are involved in the over-all process, a point that should be remembered in assessing the accuracy of reproduction.

Although the consummate skill of the operator is a prime factor in the production of high-quality record stampers, scientific control of the electrodeposition operations is important. Composition of the plating solution is critical and must be controlled by frequent analyses and almost continuous additions to the baths. Tests for tensile strength and ductility of the deposited metal are made regularly, and particular attention is paid to measurements and control of stress in nickel deposits. An addition agent whose concentration amounts to only a few parts per million in the bath controls the stress.

Mold Making

Consider the plight of a tool-and-die maker who is asked to make a typical mold for the production of a synthetic upholstery material now in the business of producing molds by methods of this kind—though details may vary considerably.

Radar Wave Guides, Wind-Tunnel Nozzles and Fuel-Distribution Grids

The three products listed in the heading above have been chosen from among many to illustrate the use of electroforming to turn nasty machining jobs into relatively simple tasks. A radar wave guide seems like a simple gadget—merely a pipe with straight sections connected by fittings such as elbows and tees. The complication arises from the fact that the inner surface of the guide is square or rectangular in cross section—with very accurate dimensions and sharp corners. Metal drawing as a production technique is not accurate enough and cannot be applied to fittings. Internal machining is impractical because of the requirement for square corners. On the other hand, it is not at all difficult to machine a low-melting alloy to external shapes and dimensions that correspond to the wave guide opening. Used as a mandrel, such an alloy can be coated with the desired metal by electrodeposition to the necessary thickness for rigidity and strength. Then the alloy is melted and peeled off, leaving a hollow cavity.

A similar procedure can be followed in making nozzles for supersonic wind tunnels, although here the machining problem is quite different. The nozzle has an axis of circular symmetry; hence, it can be turned on a lathe. Complications arise, however, because internal turning of a complex curve is not easy in the first place and, secondly, the nozzle is long and slim, increasing the problems of internal turning. Add to this the complications of a mandrel, which is itself the machine, and some other way out begins to seem more attractive. Contour external turning of a fusible mandrel is not a difficult matter. Such a mandrel can be treated exactly as is done for radar wave guides.

Electroforming was used to solve a production problem in an early-model ram-jet engine. It required a fuel-distribution grid resembling a metallic spider web which was, in fact, a web of relatively small diameter tubing arranged around the barrel of the rocket engine supported by radial tubes. Fluid flowed through the web in both the circular and radial members and emerged from holes in the downstream face of the web. The resulting grid was mounted across the entrance end of the ram-jet engine. Webs could be constructed by welding pieces of tubing into the desired configuration, but this was both tedious and troublesome. It was almost impossible to prevent some of the weld metal from getting through one or more of the numerous joints. The resulting partial, or even complete, obstruction of a portion of the grid gave uneven fuel distribution to the feed holes and caused erratic engine performance.

The solution was quite simple. Wax rods or fusible-alloy wires whose external diameter was that of the hollows desired in the web were fabricated into a grid and plated with nickel to the necessary wall thickness. When the fusible core was melted out, the resulting grid was internally perfect.

Fountain-Pen Caps

A notable example of electroforming as a technique for overcoming fabrication difficulties involving the properties of a metal may be found in the making of caps for a popular fountain pen. Nickel is well suited for this application by virtue of its pleasant appearance, corrosion resistance, and hardness. Unfortunately, nickel work hardens very rapidly and the production of caps by traditional deep-drawing techniques becomes a very expensive operation because of the many draws and intermediate anneals that are required. It is difficult also to achieve the dimensional accuracy which is required in order to be a good friction fit on the pen barrel.

Production of such caps in quantity on automatic equipment has been attained. All that is involved is the provision of a nickel-plating tank and a number of stainless steel mandrels mounted on a conveyor mechanism. A cycle starts with the introduction of the mandrel by the conveyor mechanism, and its movement through the plating tank until the desired thickness of nickel is attained. On emerging from the tank, the mandrel is bumped free from the mandrel, to which it adheres but slightly. The electroformed cap is then trimmed, brushed to the desired finish, and the clip assembly pressed into place. The mandrel continues on its way to receive another de
Copper Foil

When one begins to consider electroforming as a technique to be combined with other electrometallurgical operations, some interesting possibilities appear. Electrowinning is the process of dissolving the metallic content of an ore in a suitable solvent (hydrometallurgy) and then electrolyzing the solution with insoluble anodes to recover the metal in the form of sheets or plates at the cathodes and to regenerate the solvent. Why not combine this with an electroforming process and produce finished products at the cathode? There are a number of difficult problems to be solved before this can become a reality, but none is greater than the inevitable circumstance that the solution changes composition as the process is carried out. This change markedly affects the properties of the metal being deposited, and the product would, therefore, not be uniform throughout its thickness.

Although a one-step electrolytic process from ore to finished product has not been achieved on any significant commercial scale, at least one well-established operation involves a mutually helpful merger of electrorefining and electroforming. In electrorefining, an impure metal is dissolved anodically and deposited in pure form cathodically. Impurities may either fall to the bottom of the cell to form a slime which is removed mechanically from time to time, or they may dissolve in the electrolyte but not deposit on the cathode. Soluble impurities are removed by chemical treatment of the electrolyte on either a continuous or a batch basis. In the electrorefining of copper, a combination of chemical and electrochemical processes at the anodes leads to the solution of more copper than is deposited at the cathode by a given quantity of electricity. In most refineries some of the cells have insoluble anodes, and as the electrolyte is circulated through these the copper content of the solution is reduced. Such cells are called "liberator" cells.

One copper refiner has replaced many of the liberator cells with an ingenious method of using the excess copper in the refining electrolyte and making from it copper foil of good quality. Copper-rich refinery electrolyte is pumped to a separate building containing several electrolysis cells of unusual construction. The cathodes are large, lead-covered, cylindrical drums mounted so that they can be revolved a little less than half-submerged in the electrolyte. Banks of semicylindrical lead anodes are mounted opposite the submerged portion of the drum in such a manner that a uniform distance is maintained between the cathode and the anodes. The entire assembly is mounted in a tank through which the refinery electrolyte is circulated. In operation, the angular velocity of the drum and the current density are regulated to give a deposit of the desired thickness just as the periphery of the revolving drum emerges from the solution. Shortly after its emergence, the deposit is peeled from the drum, to which it adheres only superficially; and, as the operation continues, the thin copper is rolled into a coil. So long as there are no interruptions owing to failure of solution supply, electrical power, or mechanical breakdown, the product can be made to any desired length—many miles, if need be.

The rate of flow of solution is regulated so that, in passing through a cell, the solution is depleted of copper until the metal content is somewhat below the desired average concentration for refining electrolyte. Some of the liquor to the main body of refinery electrolyte restores the copper balance.

Can this process compete with traditional rolling operations for sheet metal production? The answer is a qualified "yes"—the qualification being based on the thickness of the sheet. The cost of mechanically rolling slabs into sheets increases exponentially with decreasing thickness. On the other hand, the cost of electrolytic sheet increases almost linearly with increasing thickness. Obviously, there is a division of fields of usefulness. In practice it appears that for thicknesses below about 0.003 inch, the electrolytic method is the cheaper.

Is there any difference in the quality of the product in the electrolytic vs. mechanical production of thin copper sheet or foil? From the standpoint of mechanical properties there seems to be little to choose between the two methods. Work done in the Department of Metallurgy at Penn State has yielded data to support this conclusion. Table I shows some typical results. It is interesting to note that the as-deposited copper is similar in properties to cold-rolled copper. This is not an unusual phenomenon in electrodeposited metal. Furthermore, the as-deposited copper corresponds to annealing treatments in about the same way as cold-rolled copper. From the viewpoint of appearance, the electrolytic foil is usually inferior to the rolled product. Happily for electrometallurgists, the major uses of copper foil involve concealed application, and appearance is of secondary importance.

### TABLE I

<table>
<thead>
<tr>
<th>Condition</th>
<th>Tensile Strength (PSI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rolled—50% Reduction</td>
<td>49,000</td>
</tr>
<tr>
<td>Electrolytic—As Plated</td>
<td>47,000</td>
</tr>
<tr>
<td>Rolled—Annealed</td>
<td>32,000</td>
</tr>
<tr>
<td>Electrolytic—Annealed</td>
<td>34,000</td>
</tr>
</tbody>
</table>

**Micro-Mesh Sieves**

Electroforming as a technique which makes possible the production of an object that could not be manufactured by traditional methods is well exemplified in the making of certain screens for both commercial and laboratory applications. Traditionally, screens are...
made either by weaving wire on a loom similar to those used in producing cloth or by punching holes in sheet metal. In the first instance, the size of the screen opening is determined by the diameter of the wire, the spacing of the warp, and the beating of the weft; in the second, the diameter and the spacing of the punches determine the character of the screen. The mesh size of wire is limited to about 300 openings to the inch and the product is deplorably nonuniform. Furthermore, the passing of wires over and under each other produces a nonplanar surface that is undesirable when a double-wire is used in conjunction with the screen—not an unusual circumstance. Punched screens are planar, but punches and punching are not practical for small hole sizes.

Two companies are producing screens by electroforming methods. The Micro-Mesh screen, but nickel of graphite at four magnifications reveal the per lineal inch. Tolerance can be held to plus ground in the accompanying photograph of a mechanical support when used in sieves. A metal—only 0.0001 inch in thickness, it required metal to give poor adhesion of an electrodeposit, was ruling. The nickel surface, having been treated to give poor adhesion of an electrodeposited, was plated with nickel to the desired thickness for the finished screen. Deposition took place, of course, only in the areas between the islands of nickel, and, when the deposit was pulled away from the plate, it contained a hole for each bead—on the plate.

Inasmuch as the electroformed screen was only 0.0001 inch in thickness, it required mechanical support when used in sieves. A metallic grid was combined with the delicate screen, and the completed product is shown as a background in the accompanying photograph of a stack of Micro-Mesh sieves. The photomicrographs at four magnifications reveal the precision and detail in a screen having 450 holes per lineal inch. Tolerance can be held to plus or minus 0.00001 inch with no difficulty whatever on a production basis. Holes of other shapes could be provided. It is only necessary to draw the pattern at any convenient scale and reduce it by well-known techniques of microphotography and photoengraving to the desired dimensions. Metals other than nickel and several alloys could have been used in making the Micro-Mesh screen, but nickel offers a good combination of corrosion resistance, strength, and toughness.

A company producing copper screening with square holes in mesh sizes from about 10 to 200 to the lineal inch and in thicknesses of several thousandths of an inch has been doing so for at least two decades—proving that the product has a measure of commercial acceptance. The screen produced this way is more expensive than woven screen; it must command a market on quality rather than price. Micro-Mesh sieves, on the other hand, simply could not be made by any present-day weaving technique.

Problems in Electroforming

If electroforming can be used to accomplish so many technological triumphs, why is it not a leading method of metal fabrication instead of a rather raggle-taggle “also ran” in terms of tonnage? There are several waps in the electrolytic jam pot, but one king-sized bumble bee causes more trouble than all the minor problems put together. The distressing fact is that electroforming is a turtleneck process—and the turtleneck in this instance has just the good fortune to be pitted against an irresponsible hare!

Electrodeposition of comparatively thin shells of copper or nickel takes several hours; a thick object like a wind-tunnel nozzle requires several weeks. Under special circumstances the time requirement may be tolerated, but it is never an unimportant factor—time is money. Theoretically, time requirements could be greatly reduced by markedly increasing the current density, for the amount of metal deposited per unit time is a function of the current (Faraday’s Law). In practice, it has not yet proved practical to exceed certain rather limited current densities, ranging from about 10 to 100 amperes per square foot, depending on the metal involved and on some operating variables. Usually current densities of 25 to 50 amperes per square foot pose fewest difficulties with uneven metal distribution and surface roughness—two other problems which plague the practical electroformer. It is beyond the scope of this discussion to explore the reasons for limiting current density. Suffice it to say that electrolyte composition, temperature, and agitation are important operating variables which have been studied in connection with means of increasing current density. Much remains to be done with agitation, for some composition and temperature relationships have been studied enough to know that not much more progress is likely in those directions. Several thousand amperes per square foot have been used in jet plating, where agitation is tremendous, but this technique is not yet practical in general electroforming work.

Rough external surfaces are almost inevitable on any electroform and the thicker the deposit the rougher the surface. Where only the surface next to the mandrel is of importance, external roughness is of no consequence, but it is a severe limitation to general applications of electroforming. Although much progress has been made in the last few years in roughness control by means of addition agents in the bath, periodic current reversal, and bath cleanliness, there is still room for much improvement before the problem becomes inconsequential.

The uniform build-up of metal on a cathode is extremely difficult for objects of irregular contour. Particularly troublesome are deep re-entrant angles and crevices. Usually metal can be deposited fairly uniformly on almost any cathode, but often only at the expense of elaborate conforming anodes, current “thieves,” masks, or other contrivances. Costs soar when such expedients must be employed.

Mechanical Properties of Electroformed Metal

Although the mechanical properties of electroformed copper were referred to briefly above, this aspect of the general problem requires more discussion for some of the anomalies which are encountered. It is probable that many of the uses of electroforming which have been proposed and then abandoned were failures because of lack of knowledge of the effects of some operating variables on mechanical properties.

Copper has been much used in electroforming, and good mechanical properties can be easily attained—providing that the electroplater is aware of what can be done by changing solutions and other variables. Solution composition is tremendously important. The summary data in Table II emphasize this point. All four solutions are in common use for depositing copper, although only the first three are useful for thick electroforms. Notice the tremendous variation in tensile strength and ductility with relatively little change in hardness. Most impressive, however, is the fact that hardness and tensile strength do not have to be tied rigidly to ductility. One has remarkable control over ductility in that it is not tied rigidly to tensile strength, as is the usual metallurgical rule.

That copper is no unusual metal so far as variety of properties in electroforms is concerned is proven by the data in Table III for a few samples of typical nickel deposits. Here again the departures from the usual relationships that prevail between tensile strength, ductility, and hardness are notable. They emphasize the care, knowledge, and experience that are required to obtain the desired properties in an electroform in the first place and to continue to obtain them for extended production runs.

The work which has been done in our laboratory at Penn State has been devoted principally to studies of mechanical properties and particularly to the devising and evaluation of testing techniques. We are now in a position to proceed with confidence so far as methods are concerned, and further work will be directed to that relationship between properties, structures, and solutions in an effort to learn more about the mechanisms which govern the electrodeposition processes.

### Table II

<table>
<thead>
<tr>
<th>Type of Solution</th>
<th>Tensile Strength (PSI)</th>
<th>Ductility (25-g load)</th>
<th>Hardness (Knoop)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure Acid-Copper</td>
<td>19,000</td>
<td>0.035</td>
<td>150</td>
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<tr>
<td>Acid-Copper Proprietary A</td>
<td>57,000</td>
<td>0.013</td>
<td>70</td>
</tr>
<tr>
<td>Acid-Copper Proprietary B</td>
<td>38,000</td>
<td>0.009</td>
<td>190</td>
</tr>
<tr>
<td>Pure Cyanide-Copper</td>
<td>43,000</td>
<td>0.011</td>
<td>161</td>
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</tbody>
</table>

### Table III

<table>
<thead>
<tr>
<th>Type of Solution</th>
<th>Tensile Strength (PSI)</th>
<th>Ductility (25-g load)</th>
<th>Hardness (Knoop)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Watts (peroxide)</td>
<td>116,000</td>
<td>0.011</td>
<td>300</td>
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<tr>
<td>Watts (wetting agent)</td>
<td>46,000</td>
<td>0.011</td>
<td>290</td>
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<tr>
<td>Proprietary A</td>
<td>184,000</td>
<td>0.017</td>
<td>660</td>
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<tr>
<td>Proprietary B</td>
<td>198,000</td>
<td>0.025</td>
<td>650</td>
</tr>
<tr>
<td>Proprietary C (plus Zn ions)</td>
<td>97,000</td>
<td>0.009</td>
<td>540</td>
</tr>
</tbody>
</table>
In the past two years the United Kingdom has witnessed a growing struggle between oil and coal for the major segments of an industry that can burn either of these materials. Until 1957, the National Coal Board and the miners, faced with a demand for coal, were content to let the oil industry expand its share of the fuel market. The recent industrial recession and the consequent decline in the demand for coal, however, awakened the British coal industry to the fact that oil was not merely a substitute for coal that could be turned to in times of emergency, but was, in fact, an alternative fuel to coal which had, so to speak, come to stay. Such conclusions are strengthened by the figures in Table 1 which show that the percentage of the United Kingdom basic energy requirements supplied by oil rose from 9.1 per cent in 1947 to 17.3 per cent in 1958, while that supplied by coal declined from 90.6 to 82.0 per cent.

The steady decrease in demand for coal has led many members of Parliament representing mining constituencies to demand that the Minister of Power formulate a "National Fuel Policy," which would presumably guarantee the National Coal Board a certain share of the fuel market. Such requests have been rejected on several occasions, mainly on the grounds that a competitive fuel policy tends to keep down the price of fuels. The degree to which the current policy is unfortunate is clearly shown by the constant changes in plans for nuclear power output and the numerous revisions of the potential coal and coal reserves. A lack of foresight may, in the long run, lead to the loss of potentially recoverable coal reserves in exchange for short-term economic benefits.

The Areas of Fuel Competition

According to the Chairman of the National Coal Board, "about half the reduced demand for coal during 1958 was caused by its replacement by oil." Consumption of oil in fields where coal was previously king, according to his information, "increased from 19 million tons of coal equivalent in 1956 to 28.3 million tons in 1958." The coking coal market is now the only one in which coal is secure from competition by the oil industry.

The power generation industry is at present the largest consumer of fuel oil in the United Kingdom. This is due to Government policy inherited from 1955, when coal was in very short supply and the Government decided to encourage the use of oil in power plants. In 1958, the amount of coal equivalent of fuel oil burned at electricity power stations was approximately 4 million tons. The estimate for 1959 is 7 million tons of coal equivalent. Discussions have recently been taking place between the coal, oil, and electricity representative, however, with a view to reducing the quantity of fuel oil to be burned in power generation in the 1960s from 9 to 6 million tons of coal equivalent. Both the coal industry and the electricity boards are state-owned, and the degree to which this market is competitive is governed by defense considerations and national investment policies as well as by price. Thus the re-substitution of coal for fuel oil in the field of power generation will undoubtedly become a reality.

The United Kingdom gas industry is at present the scene of considerable competition between coal and oil. The struggle is taking place with a background of a falling demand for manufactured gas, and increasing costs for high-grade gas coal which has to be used in the conventional methods of gas manufacture.

The petroleum industry has found a natural market for its products in the South-Eastern and North Thames Gas Boards, which serve territories remote from the major United Kingdom coal fields. Traditionally supplied with sea-borne coal from Newcastle and Durham, these districts are now the sites of the new refineries in the Thames Estuary. The two gas boards in question have built large new works based solely on the gasification of refinery products, and it is estimated that these plants will consume some 390,000 tons of oil, or the equivalent of 1 million tons of coal a year.

In addition to the fuel derived from these gasification processes, "tail gas" from the refineries is now being used by the local gas boards, who have arranged to purchase 42 million therms, or the equivalent of 380,000 tons of coal, from the Shellhaven and Fawley refineries. The National Coal Board is also supplying small quantities of methane, derived from the air drained from the Point of Ayr Colliery in Wales, which is now being fed into the local gas grid in the principal coalfield.

By far the greatest threat to the coal industry's domination of the gas fuel market appears to lie in the proposed utilization of "foreign" methane by the gas boards. Vast quantities of natural gas are now wasted throughout the world due to the inability of the countries in whose terrains the crude oil and gas are found to make use of this additional source of fuel. Methane, a major component of natural gas, can be compressed to 1/600th of its natural volume when subjected to the appropriate conditions of temperature and pressure, and natural gas tankers have now been developed whose total transmission is fuel economically. The first 2,200 tons of methane under pressure were landed at Canvey Island in the Thames Estuary, by the Methane Pioneer in February, 1959. A few weeks ago the Gas Council sent plans for the construction of two 10,000-ton methane tankers to the Minister of Power, and the growth of this new phase of marine transportation seems to be assured, if the appropriate ministerial sanctions are obtained.

The Gas Council has also decided to use a German process, known as the Lurgi method, for the complete gasification of coal which will use low-grade material mined in West Central England and Scotland as its principal raw material. Butane and propane are added to the gas produced by this method. The new Lurgi plant at Coleshill, near Birmingham, is expected to have an annual consumption of some 400,000 tons of low-grade coal.

The Council has also developed a new process for the complete gasification of light distillate fuel stocks. The rise in consumption of "oilders" products" from "natural" tons in 1958 to 993,000 tons in 1959 (British Petroleum Information Bureau’s statistics for 1959) is believed to reflect this new consumption of light distillates.

Despite all the new schemes, gasified oil accounted for only some 2.5 per cent of the total output of the United Kingdom gas industry. Even if the figure for refinery tail gas combined with methane gas from the mines, 2.2 per cent, is added to the former amount, the total contribution of oil and natural gas industries amounted to only 4.5 per cent of the industry’s production of therms. However, the cost per B.T.U. produced is of vital significance to the gas industry in its struggle against the other domestic market fuels, and it may be expected to use all the means in its power to keep this down. This would appear to indicate an increase in consumption of petroleum products by the British gas industry.

British Railways are now engaged in a program of intense dieselization and electrification which will result in a heavy decrease in their use of coal over the next decade. The switch from oil to coal in this industry is expected to result in lower running costs and in greater over-all efficiency.

The principal factor in the marketing of any fuel in heavy industry is price per B.T.U. Because of this, the oil companies have been able to penetrate the iron and steel and other industries by means of a flexible pricing policy which permits them to give favorable prices for their less marketable products—particularly, fuel oil.

In light industry, convenience tends to be more important to the industrial consumer, and oil appears to be easier to handle than coal. Statistics show that in 1958, the consumption of oil in the iron and steel industry was 26.5 per cent greater than in 1957, and that it had increased by 52 per cent in engineering, 66.6 per cent in the paper and printing industry, 50 per cent in the food, drugs, and tobacco industries, and 35 per cent in other industry, over the corresponding figures for the previous year.

Another matter of considerable importance to British industrial and domestic fuel consumers is their choice of fuels is the Clean Air Act of 1956. Under the Act, compulsion may be applied to industry generally in order to prevent the discharge of excessive smoke, dust, and grit from furnaces. Local authorities are permitted to impose smoke control areas4 although the extent to which this power may be exercised is subject to regulation by the Minister of Power. The implementation of this Act has stimulated the use of oil in industry particularly since individual exemptions have to be sought for coal-burning furnaces in smokeless zones. Oil-burning appliances, on the other hand, have been granted widespread exemption, provided that they are operated and maintained so as to minimize emission of smoke.

A recent article in the Economist pointed out one way in which coal might still retain some of its former strength in industrial markets. "This is by signing selective long-term contracts at today's prices, with the possibility of

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there being subsequent downward revisions in price subject to economic conditions prevailing at the time." It was suggested that the prices now charged by oil companies for their fuel oil were already too low to permit them to cover the marketing and overhead costs that they may in due course wish to increase them after securing their footholds in these markets. Thus they would probably not be prepared to offer long-term contracts in a manner similar to that advocated for the coal industry.

The position of coal in the chemical industry is likely to be severely challenged by petrochemicals. The reaction of the coal industry will probably be to show greater flexibility than in the past. In July 1959, the Wilson Committee on Coal Derivatives was appointed by the Government to report on the possibilities of using coal as a source of chemicals and oil.

There has been an important increase in the use of liuid fuels for home heating in the British Isles. About 100,000 tons of fuel oils are now consumed by central heating units every year. Over a million tons of fuel oils, the amount used in 1956, were used to heat private houses and premises in 1958. It is felt that the introduction of block heating units in place of individual dwelling furnaces and that the greater sales consciousness of the public with their new metered trucks, will provide coal with greater competition in the domestic market than is currently allowed for in estimates of future fuel consumption. More people in the United Kingdom are disposed to pay for the ease of oil heat, and they are apparently prepared to abandon their traditional coal fires.

The coal industry is now counter-attacking with advice on furnace maintenance and cost estimates. It has also started to sell 28-pound and 56-pound bags of coal in the new supermarkets and other retail outlets. There is a problem in the retail sales of coal because the National Coal Board does not do its own retailing. If it is prepared to pay the ease of oil heat, and they are apparently prepared to abandon their traditional coal fires.

Future Fuel Requirements

Any estimates made as to the future fuel economy of the United Kingdom should bear in mind the nature of the country's fuel reserves. According to Parker, the total coal reserves of the United Kingdom are calculated to be of the order of 170,000 million tons of coal in seams not less than 1 foot thick and at depths not greater than 4,000 feet from the surface. Of this quantity probably no more than 50,000 million tons could economically be brought to the surface using present mining techniques. This is equivalent to a reserve of 250 million tons per annum for 200 years. United Kingdom peak reserves are estimated to be equivalent to 20,000,000 tons of bituminous coal, and the oil shales are assumed to be equivalent to 20,000,000 tons of oil. Natural oil reserves are estimated to be of the order of 1,000,000 tons. There are no significant reserves of natural gas in the British Isles.

Estimates as to the future fuel requirements of the United Kingdom are usually based on the assumption that the British standard of living will remain substantially as it is today. To achieve this, it is expected that, according to Evans, "be necessary to annually increase the total index of production by 3½ per cent cumulatively, which would be equivalent to an increase of 3 per cent in national income or 2 per cent in energy consumption."

This does not take into account the potential savings to be made in fuel consumption through increases in fuel efficiency. These have been considerable in the past. Between 1947 and 1958, some 44 million tons of coal were saved by the introduction of new methods. The electricity industry accounted for 31½ million tons of these savings, and the gas industry for 2½ million tons. The amount of coke required to produce a ton of pig iron fell from 23 cwt. in 1945 to 19 cwt. in 1956, and is expected to decline to 18 cwt. in 1962. The distance traveled by a railway locomotive on a ton of coal increased from 35 miles to 37½ in the eight years ending with 1956.

Thus, the total United Kingdom energy requirements are expected to rise from 250 million tons of coal equivalent in 1955 to 300 million tons in 1965. According to Evans, coal production will decline from 214 to 196 million tons in this decade, while hydroelectric power output will double from 1 to 2 million tons of coal equivalent. Natural gas consumption will soar from 35 to 91 million tons of coal equivalent. In 1965, nuclear power stations are expected to produce power equivalent to some 11 million tons of coal.

Coal's greatest sales in 1965 will be made to electric power generation plants. Evans estimates that the Combined Electricity Boards will consume fuels equivalent to some 61.0 million tons of coal in that year, 6.0 of which will be supplied by the oil industry and 55.5 by coke, leaving a market of 54.5 million tons to coal. From this it can be seen that some of the base load of the electricity industry that might otherwise have been generated by oil-fired or coal-fired furnaces will already have been taken over by the atomic power stations in 1965.

The United Kingdom nuclear power plans have already been altered on several occasions. It is now almost safe to say, however, that, by the end of 1966, the generating capacity will amount to some 5,000 to 6,000 mw, producing the equivalent of 15 to 18 million tons of coal. The cost of the electricity so produced will be equivalent to that produced from conventional plants, provided that the atomic units are operated at base load.

Conclusions

The general rise in the standard of living in the United Kingdom will be accompanied by a growing demand for gasoline and lubricants, provided the highway structure can bear the traffic. The increased demands for these products will result in an extra output of refinery waste and fuel oils, which the oil industry will undoubtedly want to dispose of at such prices as it can obtain. The current policy of free competition is probably correct for the general industrial and domestic markets, but it is felt that the electricity generation market should be safeguarded for the coal industry, if only to pay off the investments that have now been made in the coal mines. The growth in the United Kingdom's consumption of fuel oil has been phenomenal. This will probably continue for the next few years until fuel oil has taken over most of the smaller industrial markets. After that the market will level off and stabilize. There is a large potential market for oil products in the gas industry; this should be more fully exploited, possibly to the benefit of all concerned. The railways are now committed to dieselization, and a continued increase in demand for diesel oils may be expected from this source. Thus the future role of the oil industry will be as a pace setter for coal. On a permanent basis it will never surpass the latter as the basic energy source for the United Kingdom.

References


| Table 1—Primary Fuel Consumption within the United Kingdom, 1947-1958 |
|-------------------------|--------|---------|-------------------------|--------|---------|-------------------------|--------|---------|
|                        | Coal   | Oil     | Hydro-electricity       | Total  |
|                        | T.C.   | %      | T.C.        | T.C.   | %      | T.C.        | T.C.   | %      |
| 1947                   | 184.4  | 90.6   | 18.5        | 91.1   | 0.7    | 0.3         | 203.6  |
| 1948                   | 191.9  | 90.5   | 19.3        | 91.8   | 0.9    | 0.4         | 212.1  |
| 1949                   | 195.4  | 90.0   | 20.5        | 96.0   | 0.8    | 0.4         | 214.7  |
| 1950                   | 201.0  | 89.5   | 22.7        | 101.7  | 0.9    | 0.4         | 224.6  |
| 1951                   | 206.5  | 88.8   | 25.0        | 108.0  | 1.0    | 0.4         | 228.2  |
| 1952                   | 204.8  | 88.3   | 26.1        | 113.1  | 1.0    | 0.4         | 231.9  |
| 1953                   | 218.4  | 87.6   | 28.3        | 126.0  | 1.0    | 0.4         | 238.7  |
| 1954                   | 213.1  | 88.7   | 31.4        | 128.1  | 1.2    | 0.5         | 245.8  |
| 1955                   | 213.8  | 85.6   | 35.0        | 140.0  | 1.0    | 0.4         | 249.8  |
| 1956                   | 214.5  | 84.0   | 38.0        | 142.0  | 1.2    | 0.4         | 253.7  |
| 1957                   | 207.7  | 84.2   | 37.2        | 131.5  | 1.7    | 0.7         | 246.6  |
|                        | 1958   | 199.3  | 82.0        | 24.0   | 1.7    | 0.7         | 245.0  |

Source of tons of coal equivalent data. S. I. Evans (9) p. 454.

The year 1958 is used as the base year.
College of Mineral Industries Activities

W. A. Weyl, research professor of the College of Mineral Industries, lectured on "The Kinetics of Melting and Nucleation" before the research scientists of the Experimental Station of E. I. duPont de Nemours & Company at Wilmington, Delaware, January 19.

The new theories developed by Dr. Weyl on the kinetics of melting and nucleation will also be published in a special issue of the German Ceramic Journal. Honoring the 70th birthday of Dr. H. Salmang, Professor Emeritus of the Technical University of Aachen, Germany, Dr. Salmang is a pioneer in the field of glass technology and ceramics and directed the Ph.D. thesis research work of Dr. Weyl.

H. MAUZEE DAVIS, professor of chemical metallurgy, addressed the local chapter of the Society of the Sigma Xi at a dinner meeting on the campus of Dennison University, Granville, Ohio. He spoke on the work he and his students have done on the failures in porcelain enamelled stoves owing to the effects of occluded gases, particularly hydrogen.

HAROLD J. READ, professor of physical metallurgy, was recently a Visiting Lecturer at the International Business Machines Research Laboratories in Poughkeepsie, N. Y. Dr. Read summarized the work which he and his students have been doing for the past several years on the topography and the mechanical properties of electrodeposited metals. One of the principal objectives of these investigations has been to determine the various causes of corrosion and other failures in the plated trim used on machines, automobiles, household appliances and plumbing goods.

FRIEDMANN FREUND, Ph.D. (cum laude) in mineralogy of the University of Marburg, Germany, has joined the Department of Ceramic Technology of The Pennsylvania State University as visiting research associate in solid state technology. Dr. Freund has been associated with Professor H. G. F. Winkler in an extensive study of metaplhases arising during the dehydration of layer silicate minerals. At Penn State, he will be associated with G. W. Brindley, head of the Department of Ceramic Technology, in studies of the kinetics of high-temperature reactions.

B. F. HOWELL, Jr., head of the Department of Geophysics and Geochemistry, has been elected a member of the Board of Directors of the Geosciences Society of America for 1960-61. G. W. BRINDLEY, head of the Department of Ceramic Technology, lectured to the Geology Division of the Jersey Production Research Company in Tulsa, on January 28th, on the subject of "The Clay-Water-Organic System."

HANS A. PANOFSKY, professor of meteorology, was invited to give a talk on knowledge of motions in the stratosphere at a meeting of the Scientific Committee of the United Nations which was held at the U. N. January 11-22. Dr. Panofsky also participated in several discussions of long-lasting fall-out. On January 25, Dr. Panofsky gave a summary talk, also on stratospheric circulation, before the annual joint session of the American Meteorology Society and the Institute for Aeronautical Sciences.

An Atlas of Pennsylvania Coal and Coal Mining, Part I, by George F. Deasy and Phyllis R. Gries of the Department of Geography has recently been released as a project of the Mineral Conservation Section. Published as Bulletin 73 of the Mineral Industries Experiment Station, the Atlas brings together selected data on the Commonwealth's bituminous coal resources and coal mining industry and presents them in graphic form. Included are maps dealing with geological, historical, engineering, economic, production, employment, safety, and transportation.

Part II of the Atlas, to be published later in the year, will cover the anthracite industry.

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CONTRIBUTIONS (Continued from page 2)


Papers Presented at AIME

Seven technical papers written by members of the College of Mineral Industries were presented at the annual meeting of the American Institute of Mining, Metallurgy, and Petroleum Engineers in New York, February 14-18.

John J. Schanz Jr., associate professor of mineral economics and W. Gibson Jaworek, graduate assistant, were co-authors of a paper, "Bituminous Coal Consumption—Estimating Its Long Term Growth and Annual Variation." John D. Ridge, professor and head of the department gave the results of a study entitled, "World Trade in Metal Raw Materials." Dr. Ridge also served as program chairman for the sessions of the Society's Council of Economics, and Dr. Schanz retired as secretary-treasurer of the Society's Council of Education.

Papers from the Department of Mining Engineering were: "Developments and Research in the Sawing of Dimension Stone" by Frank D. Hoyt, research assistant, and Howard L. Hartman, head of the department; "Portable Crusher in Quarries and Pits" by Boris J. Kochanovsky, associate professor; and "Underground Stress Instrumentation" by Robert Stefanko, instructor. Dr. Hartman also served at the meeting as co-chairman of the Industrial Stone and Aggregates Session of the Industrial Minerals Division.

The Department of Mineral Preparation was represented by the following authors: P. D. Rao, graduate assistant, H. B. Charmbury, head of the Department of Mineral Preparation, and D. R. Mitchell, chairman of the Division of Mineral Engineering, presented "Crushing of Anthracite for the Reduction of Domestic to Steam Sizes." J. C. Sun, professor of mineral preparation, spoke on "Reclamation of Coal from Plant Refuse by Flotation." Student co-authors of Dr. Sun were: J. L. Bayer, graduate student, R. C. Welch, and D. W. Kestner. Dr. Charmbury was invited to re-present education at the symposium on Fine Coal Recovery.

B. F. Howell, Jr. head of the Department of Geophysics and Geochemistry, served as co-chairman of the Geophysical session.

Professor Mitchell also attended the meeting in his capacity as chairman of the Percy Nicholls Award Committee and as a member of the Program and Executive Committees of the Coal Division as well as the Nominating Committee of the Society of Mining Engineers.

VAN ANDEL GUEST LECTURER

T. H. VAN ANDEL of the Scripps Institution of Oceanography spent the week of February 21 to 27 at the University as a guest lecturer in the College of Mineral Industries. He presented a series of lectures dealing with research on "Modern Marine Sediments." His current visit to universities in the eastern states is part of a lecture series arranged by the American Geological Institute.

Dr. Van Andel was born in the Netherlands and studied at the University of Neuchatel in Switzerland and at Groningen and Amsterdam Universities in the Netherlands. His principal contributions are in the fields of sedimentology, marine geology and stratigraphy, mainly in the oil fields of Venezuela and in the Gulf of Mexico. Dr. van Andel's work on modern marine sediments is of particular interest to geologists concerned with problems of the formation of sedimentary rocks and the origin and accumulation of petroleum.