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GEOLOGICAL SURVEY CIRCULAR 698

Mineral Resources: Potentials and Problems

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By Walden P. Pratt and Donald A. Brobst

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A summary of United States resources of 27 major mineral commodities, and the problems involved in their utilization

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CONTENTS

ILLUSTRATION

TABLES

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ABSTRACT

The encyclopedic nature of "United States Mineral Resources" (U.S. Geological Survey Professional Paper 820) seems to have inhibited its widespread use by people other than professional geologists. A summary of the principal findings and conclusions of Professional Paper 820 is presented with special regard to the resources of 27 mineral commodities of major importance to our industrial civilization (based on dollar value) and the problems involved in the utilization of these resources of the 10 most important nonferrous metals, the 11 principal ferrous metals, and the 6 principal fossil and nuclear fuels.

INTRODUCTION

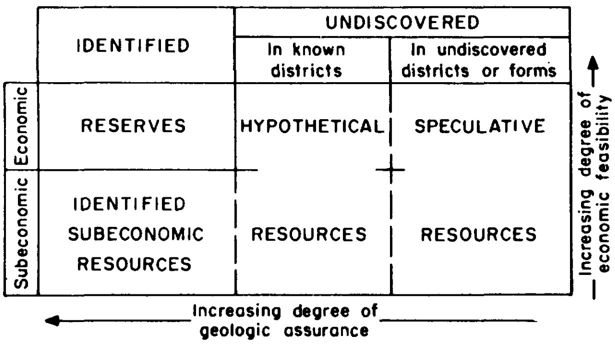
"United States Mineral Resources" (Brobst and Pratt, 1973) reviewed the long-term United States position for potential resources of 65 mineral commodities or commodity groups. One of the main purposes of the report was to provide people other than geologists with easily understandable factual data on the resources of the many mineral commodities that are important to our daily lives. However, the comprehensive encyclopedic nature of the volume seriously inhibits its effective use for this purpose; the 722 pages of scientific and technical prose does not make for great popular consumption.

We have, therefore, condensed a great mass of information into a form more readily usable by other writers and the general public. The present report summarizes the principal findings and conclusions of the larger report with regard to 27 mineral commodities of major importance to our industrial civilization: the 10 most important nonferrous metals, the 11 principal ferrous metals, and the principal fossil and nuclear fuels—petroleum and natural gas, coal, uranium, thorium, and oil shales. A separate companion article (W. P. Pratt and D. A. Brobst, written commun., 1974) has emphasized the importance of undiscovered high-grade resources in contrast to known resources that are not recoverable because of economic or technologic factors. The lesson to be drawn from both articles is the same. Our large resources of many minerals are at this point only a potential, not a reality. To bring them into the category of available reserves is not a simple matter of raising the price; it will require enormous research efforts, with long lead times. Crash programs responding to the shortage of the moment will not suffice. We hope that these two articles together may enlighten a larger segment of the American public to the problems that confront us if we are to overcome our present complacency and avert many future crises of mineral supply.

We acknowledge once again the efforts of our many colleagues without whose experience and continuing cooperation neither the large report nor the present one would have been possible.

RESOURCES AND RESERVES

Mineral *reserves* are materials from which a usable mineral or energy commodity can be extracted profitably by using existing technology and under present economic and legal conditions. They represent only a part of the broad field of mineral *resources*. In a long-range assessment of resources, reserves must be distinguished from other mineral deposits that may eventually become available: (1) Known deposits that cannot be profitably mined at present because of economics, technology, or legal restraints and (2) unknown deposits, rich or lean, that may be inferred to exist on the basis of geological reasoning but that have not yet been discovered. In order to make this distinction useful for all the commodities discussed in "United States Mineral Resources" we adapted a classification of mineral resources previously suggested by McKelvey (1972), which differentiated reserves and other resources on the basis of two factors: feasibility of economic recovery and geologic assurance or certainty of existence. This classification, with minor changes, has been accepted for formal use by the U.S. Geological Survey and U.S. Bureau of Mines, and is shown in figure 1.



Reserves: Identified resources from which a usable mineral or energy commodity can be economically and legally extracted at the time of determination.

Identified-subeconomic resources: Materials that are not reserves, but that may become reserves as a result of changes in economic and legal conditions. (Referred to as "conditional resources" in Brobst and Pratt, 1973.)

Hypothetical resources: Undiscovered materials that may reasonably be expected to exist in a known mining district under known geologic conditions.

Speculative resources: Undiscovered materials that may occur either in known types of deposits in a favorable geologic setting where no discoveries have been made, or in as-yet-unknown types of deposits that remain to be recognized.

FIGURE 1.—Classification of mineral resources.

FOCUS OF THIS REPORT

Our known reserves of most minerals are relatively small in relation to long-term demand, and the deficit can be made up only through a combination of four actions:

1. Reducing the demand, through substitution of other minerals, reduction of waste, or elimination of some uses.
2. Supplementing the raw (primary) mineral supply, through recovery and recycling of scrap and used materials.
3. Importing raw or refined minerals from foreign sources.
4. Increasing our reserves, through discovery of new mineral deposits (hypothetical and speculative resources) and through development of technology for the feasible recovery of low-grade deposits (identified subeconomic resources).

Probably no one of these actions alone will be enough to solve our long-range supply problems, but each one is important. The first two, which deal with processing of minerals and use of the products, are beyond the scope of this report, and the third is an increasingly sensitive question of international economics and politics. This report deals with the potential impact of the fourth action, by attempting to evaluate our resources that may eventually be converted into reserves.

We emphasize that the resource figures presented here are estimates, and obviously those that relate to undiscovered resources must be very rough estimates indeed. They will undergo constant revision in future years, probably for both better and worse, as new deposits are found, new theories are evolved, and old ideas discarded. However, they have been made by geologists who have spent a significant part of their careers studying the geology of their respective commodities, and they may probably be regarded as the most reliable resource estimates now publicly available. (Readers who have questions may refer to Brobst and Pratt (1973) or directly to the authors for more details.) We hope that a continuing resource appraisal program now being implemented in the Geological Survey may make possible the periodic refinement of these estimates and also may eventually be extended to include appraisal of the impact of the first three actions listed above on our domestic mineral supply.

Estimates of reserves are made by the U.S. Bureau of Mines, largely on the basis of data supplied annually by the mineral industries. Because of the competitive nature of the free enterprise system, and further because some States levy taxes on mineral reserves in the ground, mining companies, understandably, may be less than candid in reporting known reserves long in advance of their exploitation. We believe that many such known but unreported reserves are accounted for in our estimates of undiscovered (hypothetical and speculative) resources; they are still "undiscovered" from the standpoint of being public information. Although reserve data are reported to the Bureau of Mines in strict confidence, it seems likely that modification of the tax laws in some States would increase the reliability of total reserve estimates.

RESOURCE SUMMARIES

The rest of this report consists of summary information on the resources of three groups of minerals: nonferrous metals, ferrous metals, and mineral fuels. The text summarizes for each commodity the principal uses; the extent to which the United States depended on imports in 1972 (see below), and the principal sources of these imports; the extent of domestic reserves; the resource potential (identified subeconomic, hypothetical, and speculative resources); and the particular problems of discovery or technology that hamper our ability to convert the potential resources into reserves. Tables 1–3 summarize three factors for each mineral: (1) The dollar value of U.S. primary demand for 1968 (the latest year for which these data are readily available), as a means of ranking the minerals in relative importance, (2) the approximate 1972 U.S. consumption, and (3) the minimum projected cumulative U.S. demand to the year 2000.

The nonmetallic mineral commodities are not included in this review because the most important ones, in terms of the criterion used to rank the metallic minerals, are nearly all in long supply, and their reserves are adequate for the long term.

Data on imports in 1972, as reported here, may be misleading for several minerals of which we have little or no reserves. For example, the statement that we imported 67 percent of our 1972 consumption of niobium seems to imply that the remaining 33 percent came from domestic production—yet domestic reserves are reported to be nil. In this and similar cases, the difference between imports and consumption is accounted for by supply from domestic stocks (inventories) already on hand, including Government stockpile release—not by domestic production from very small or nonexistent reserves.

Future demand is difficult to evaluate. To assume continued use at present rates, and no growth in either population or per capita use, would give a minimum figure that would be easy to project indefinitely; but the resulting projections would be unrealistically small, except for a few commodities whose consumption may be cut back drastically because of substitutes or environmental concerns. As an alternative, we use here figures estimated by the U.S. Bureau of Mines for the minimum anticipated cumulative demand (MACD) for the period 1968 to 2000—the total amount of each commodity we are expected to need, at the very least, from 1968 until the end of the century. (No attempt has been made to reduce the MACD to allow for the part already used from 1968 to 1973, but because demand for most commodities is projected to increase annually, this difference would amount to no more than a few percent of the total MACD.) These estimates are based on extrapolation of recent trends, modified by a number of contingencies assumed for technological, economic, social, environmental, and other relevant influences (U.S. Bureau of Mines, 1970). We believe these are the most reasonable projections available of probable minimum demand for each commodity over the next 26 years—a convenient minimum time span for assessment of "long-term" demand. The MACD for each commodity is shown in tables 1–3 and is used in the text.

Statistical data relating to production, consumption, imports, and reserves are taken from published reports of the U.S. Bureau of Mines (U.S. Bureau of Mines, 1970; U.S. Department of Interior, 1973, 1974). The estimates of identified subeconomic, hypothetical, and speculative resources, and discussions of their problems, are based on the commodity chapters of Brobst and Pratt (1973).

PRINCIPAL NONFERROUS METALS

ALUMINUM

Aluminum (S. H. Patterson and J. R. Dyni, in Brobst and Pratt, 1973, p. 35–43) is widely used in construction materials, aircraft and autos, electrical equipment, containers, and home consumer products. We import approximately 96 percent of our aluminum as bauxite, alumina (aluminum oxide derived from bauxite), and the metal, mainly from Jamaica, Surinam, and Australia. Virtually the only aluminum ore from which aluminum can be profitably recovered at present is bauxite, a complex impure mixture of aluminum hydroxides. Domestic bauxite *reserves* contain 13 million short tons of aluminum, less than 5 percent MACD. *Identified subeconomic resources* of bauxite in Hawaii, Washington, and Oregon amount to about 20 percent MACD, but for much of this material, a process of profitable extraction has not been devised. *Hypothetical and speculative resources* of bauxite in the United States are considered to be small, because the areas that have geologic environments in which bauxite commonly occurs are relatively small in extent and have been explored.

Potential resources of aluminum other than bauxite include a variety of minerals and rocks. An enormous amount of aluminum is involved, but few of these resources can be exploited without major technological or economic breakthroughs. High-alumina clays seem to be the most favorable of these potential sources because of their high aluminum content (25–35 percent alumina) and their widespread occurrence; the chief factors prohibiting their use at present are the lack of a method for profitable extraction of the alumina, and the greater value of the deposits for kaolin and for refractory and ceramic clays. Another major subeconomic resource of aluminum is dawsonite, a basic sodium-aluminum carbonate, soluble in acid. It occurs as crystals in the rich oil shales of the Green River Formation in northwestern Colorado, where one area of 250 square miles contains an estimated resource of some 3.5 billion tons of aluminum—more than 12× MACD. In addition, the rock contains an average of about 30 gallons of shale oil per ton; costs of mining and processing the rock would therefore be partly offset by coproduction of shale oil and nahcolite (soda ash) from the same rock. Processes for extraction of the aluminum are known, but utilization of this vast resource is largely dependent on solution of the technological, legal, and environmental problems of the oil shale.

Alunite (hydrous potassium aluminum sulfate) deposits near Cedar City, Utah, reportedly contain about 31 million tons of aluminum, or 11 percent MACD. Recovery of alumina from these deposits is now being tested by industry in a pilot plant at Golden, Colo. Alunite is a present source of aluminum in the U.S.S.R., and a plant for the recovery of alumina and fertilizers from alunite is planned in Mexico. Alumina and potassium sulfate were recovered experimentally from alunite in Utah during World War II (Parker, 1969).

Anorthosite, an igneous rock containing 23–28 percent alumina, occurs in large masses in Wyoming, California, New York, and elsewhere in the United States. A pilot plant operated by the U.S. Bureau of Mines in the early 1950's proved that alumina can be recovered from anorthosite, but not at currently competitive costs. Although United States anorthosite is not likely to become a source of aluminum in the near future, it constitutes an enormous low-grade resource.

In view of our present dependence on imports of bauxite and bauxite-derived alumina, it would appear that exploration for new bauxite deposits, especially in tropical areas, should be supplemented by research on methods for economical recovery of alumina from domestic nonbauxite resources. Any such methods, however, must deal with the large energy demands of conventional aluminum-reduction processes, a factor which a prominent consumer advocate recently highlighted by characterizing aluminum beverage cans as "congealed electricity."

TABLE 1.—*Principal nonferrous metals*

Commodity	Value (millions) of U.S. primary demand, 1968	Approximate 1972 consumption (short tons except as noted)	Minimum anticipated cumulative demand, 1968–2000 (short tons, except as noted)
Aluminum	$1,983	4,707,000	290,000,000
Copper	1,300	2,351,000	96,400,000
Titanium	414	440,000	21,100,000 (nonmetal) 1,000,000 (metal)
Zinc	380	1,535,000	57,000,000
Gold	259	9,400,000 troy oz	372,000,000 troy oz
Lead	243	1,435,000	37,000,000
Platinum group	202	1,430,000 troy oz	43,600,000 troy oz
Tin	196	67,000 long tons	6,200,000 long tons
Silver	193	137,000,000 troy oz	3,700,000,000 troy oz
Magnesium	144	1,100,000	40,900,000

COPPER

Copper (D. P. Cox and others, in Brobst and Pratt, 1973, p. 163–190) is used for electrical applications (53 percent of U.S. consumption in 1970), and in construction, industrial machinery, transportation, ordnance, and many other uses. Foreign sources, mainly Canada, Peru, and Chile, supplied about 18 percent of our needs in 1972. Most of current U.S. production comes from the porphyry copper deposits of the West—large bodies of igneous rock (typically porphyries) through which copper minerals are disseminated in such small amounts that they can be recovered only by mass-mining techniques. The cutoff grade, or minimum copper content for which these ores can be processed economically, is currently 0.2 to 0.4 percent.

The U.S. Bureau of Mines (Bennett and others, 1973) estimates domestic copper *reserves* on the basis of three different price levels, as follows: at 50 cents per pound, reserves are 83 million tons; at 75 cents, 114 million tons, and at $2.00 per pound, 180 million tons. Of this total, the strict definition of reserves limits us to a range of about 100–110 million tons (about 1.1× MACD) for reserves at the recent price range of 65–70 cents. The remaining 70 million to 80 million tons at prices as much as $2.00 is then, by definition, part of the *identified subeconomic resources* category; it includes deep deposits not now workable and known porphyry deposits averaging as little as 0.25 percent copper. It also includes an estimated 11 million tons in low-grade beds in Michigan. It does not, however, include an additional estimated 60 million tons in low-grade copper-nickel sulfide deposits in the Duluth Gabbro Complex of Minnesota, on which further research is needed on geology, mining methods, and technology of extracting the ore minerals, before mining will become economically and technologically feasible. It also does not include low-grade copper deposits in Precambrian sedimentary rocks in western Montana and adjacent parts of Idaho, which are currently being explored and evaluated; it seems clear that these deposits will eventually constitute a very large resource. Estimated *hypothetical resources* of as much as 150 million tons of copper (about 1.5× MACD) include resources in several areas but chiefly those in undiscovered deposits concealed under basin fill in the major porphyry copper regions of the Southwest. Whereas southeastern Arizona is the most favorable general target for discovery of hypothetical resources, most of the western Basin and Range province should be considered pristine exploration ground for *speculative resources* because of the generally favorable regional geology. In both places, even though these undiscovered resources are probably very large, discovering them will require an enormous amount of geologic and geophysical mapping, imaginative analysis of geologic data, and continued improvement of exploration techniques.

TITANIUM

Titanium (Harry Klemic and others, in Brobst and Pratt, 1973, p. 653–665; J. W. Stamper, in U.S. Bureau of Mines, 1970, p. 773–794) is useful principally in the modern industrial technology of affluent societies. Only about 5 percent of titanium raw materials is used to produce titanium metal; the remaining 95 percent is used to make titania (titanium dioxide), which because of its whiteness, opacity, and chemical inertness, is especially suitable for use as a pigment in paints and other surface coatings and in plastics. Titanium metal and its alloys are used in the aerospace industry because of their favorable strength:weight ratio, and in the chemical industry because of their resistance to corrosion. The two principal mineral resources of titanium are ilmenite ($FeTiO_3$) and rutile (TiO_2). Metallic titanium is made from rutile and accounts for about 27 percent of the rutile used; the rest of the rutile and nearly all the ilmenite are used in making pigments. Although rutile is preferred as a source of titanium metal because the cost of processing ilmenite is so much higher, rutile is available in the United States only in deposits which at present are economically marginal or submarginal. Conversely, ilmenite is more abundant than rutile and is produced in many countries, including the United States. The United States in 1972 imported 86 percent of the rutile it consumed, mostly from Australia and Sierra Leone, but only 18 percent of its ilmenite needs, mainly from Canada and Australia; the ratio of ilmenite to rutile consumed was about 7:1.

Ilmenite is an accessory mineral in certain types of iron ores, and its greatest resources are in such iron ores, and in some modern or fossil beach sands. U.S. *reserves* of ilmenite are equivalent to about 1.4× MACD. Rutile reserves are here considered to be nil because of virtual cessation of rutile production. *Identified subeconomic resources* of titanium are estimated to be on the order of 147 million short tons, or 6.7× MACD. Nearly half this resource is in subeconomic titaniferous iron-ore deposits in Alaska, from which ilmenite would be produced as a byproduct. Other large identified subeconomic resources are in Hawaiian laterites; marginal resources are in both bedrock and sand deposits in the producing areas of the east coast of the United States (mostly ilmenite, minor rutile) and in magnetite-ilmenite deposits in the Duluth Gabbro Complex of Minnesota; all these resources are at present subeconomic because of economics or beneficiation problems or both. Identified subeconomic resources of rutile are estimated at 2.7–3.4 million short tons; this amount is only a fraction of MACD for titanium oxide, but as rutile is the preferred source material for metallic titanium, it is equivalent to about 1.6–2.0× the MACD of 1 million tons for titanium metal. Inasmuch as rutile has been produced in the past from most of the deposits that constitute the identified subeconomic resources, resumption of production will be largely a matter of economics. Estimated *hypothetical resources* are about 4× MACD, mostly in bedrock ilmenite deposits. *Speculative resources* are probably great in geologic environments common in regions such as Canada and South Africa but not in the United States.

ZINC

Zinc (Helmuth Wedow, Jr., and others, in Brobst and Pratt 1973, p. 697–711) is used chiefly in the automobile, household appliance, and hardware industries, for zinc-base alloy die castings, for galvanizing iron and steel products, and in the manufacture of brass. About 52 percent of domestic consumption in 1972 was imported from foreign sources, chiefly Canada, Mexico, Peru, and Australia. U.S. *reserves* amount to about 30 million short tons, or about 53 percent of MACD. *Identified subeconomic resources* estimated at more than 80 million tons (more than 1.4× MACD) occur chiefly in low-grade deposits in sedimentary carbonate rocks in the Mississippi Valley and Appalachian regions and in deep-lying deposits in Washington State. Some of these resources are in old mines that have been closed within the past few years because of short-term low metal prices. Such resources—formerly reserves until the price dropped below a certain level—now will require an even higher price to become enonomically recoverable because of the added cost of reopening mines that have filled up with water. *Hypothetical and speculative resources* of the same geologic type, elsewhere in North America, including both recoverable and subeconomic deposits, constitute a resource potential estimated at several hundred million tons of zinc, awaiting discovery through effective exploration techniques.

GOLD

Gold (F. S. Simons and W. C. Prinz, in Brobst and Pratt, 1973, p. 263–275) is used mainly in jewelry and the arts (60 percent of consumption in 1971), in electronic components (29 percent), and in dentistry (11 percent). Gold imports in 1972 were 61 percent of consumption, mostly from Canada and, through Switzerland, from South Africa. Although more excitement is popularly attached to gold mines proper, byproduct gold currently accounts for 40 percent of the total U.S. gold output, most of it from copper mines. Differentiation between gold reserves and resources is particularly sensitive to price fluctuations, which in the past 2 years (1972–73) have been extremely volatile; estimates given here are based on the price of $35 per troy ounce that obtained in 1968 when most of the detailed reserve estimates were made; consequently, some of the material considered identified subeconomic resources on that basis has now been moved into the reserve category, either theoretically or actually (Loehwing, 1973). With this in mind, estimated *reserves* as of 1970, including both primary and byproduct gold, were about 82 million troy ounces, or 22 percent MACD. *Identified subeconomic resources* estimated by the U.S. Bureau of Mines (1967) as potentially recoverable at prices up to $145 per oz were 244 million oz (66 percent MACD), including 30 million oz of byproduct gold. This does not include two other significant resources: an estimated several hundred million ounces dispersed in a volume of some 50 cubic miles of gold-bearing conglomerates (consolidated gravels) in northwestern Wyoming, and another estimated several hundred million ounces of potential byproduct gold in identified subeconomic resources of porphyry copper ores. Either of these identified subeconomic resources by itself is of the same order of magnitude as the MACD of 372 million oz. However, formidable technologic and legal problems militate against utilization of the resources in the Wyoming conglomerates, and the recovery of the gold in the identified subeconomic copper resources, as well as from copper reserves, will depend not only on conditions that govern the eventual mining of the copper, but also on the method used. In-place leaching methods recently introduced in Arizona, although they decrease the adverse impact of copper mining on the environment, leave all the byproduct metals (notably gold, silver, molybdenum, and selenium) behind. Recovery of gold from abundant materials in which it occurs in extremely low concentrations, such as sea-floor sediments in the Bering Sea and along parts of the Pacific Coast (concentrations of 10–390 parts per billion (ppb), or seawater itself (0.01–0.05 ppb), presents a potentially rewarding challenge to technology. (A median concentration of 0.03 ppb would be about 1 oz of gold per million cu m of seawater—enough water to flood two football fields to a depth of 100 m.)

The principal *hypothetical and speculative resources* of primary gold are probably to be found in deposits of the so-called Carlin type, in which the gold occurs as grains of submicroscopic size (less than 10 μ, or a hundredth of a millimeter, across), disseminated in dark-gray limestone beds—rocks so nondescript that neither gold nor anything else was normally sought in them 30 years ago. Two deposits of this type in Nevada together accounted for more than 20 percent of domestic gold production in 1969. Very likely, other deposits of this type have been overlooked. Large areas in the West are underlain by rocks now recognized as favorable hosts for this new type of gold deposit; these areas should be geologically mapped to outline the most favorable targets for exploration.

Another area that has strong possibilities for discovery of hypothetical resources is the northern Black Hills of South Dakota, site of the Homestake gold deposit, which is currently the most productive in the United States. The Homestake mine is in Precambrian rocks, less than 2 miles distant from the edge of an extensive cover of younger sedimentary rocks. This cover once extended over the area of the mine, but was eroded away in fairly recent geologic time. The same rocks and structures that contain the Homestake deposit continue underneath the younger rocks, and J. J. Norton (1974) has recently proposed testing of the hypothesis that another Homestake-type deposit might be discovered by carefully planned exploration of the buried Precambrian rocks. Total recorded production of the Homestake mine to date is more than 35 million oz.

LEAD

Lead (H. T. Morris and others, in Brobst and Pratt, 1973, p. 313–332) is used primarily in storage batteries (42 percent), from which it is recoverable, and in leaded gasoline (20 percent), from which it is not; other important uses are in the construction industry and in pigments, cable sheathing, type metal, and ammunition. About 26 percent of the lead used in the United States in 1972 came from foreign countries, principally Canada, Peru, Australia, and Mexico. Lead *reserves* are estimated at 56 million short tons, about 1.5× MACD. *Identified subeconomic resources* in low-grade deposits of conventional types in the United States have not been estimated quantitatively but may be of the same order of magnitude as the reserves; recovery of these resources is as much a matter of economics as of technology. As with zinc, however, some of these resources are in old mines that have been closed; their recovery now, even though metal prices have risen considerably, will be very costly and impractical because the mines have been allowed to fill with water. Quantitative estimates have not been made for *hypothetical and speculative resources* either;

the outlook for continuing discovery of additional resources at a rate that exceeds consumption will depend largely on continued research on regional geology and new methods of exploration to apply in geologically favorable areas.

PLATINUM

Platinum (N. J Page and others, in Brobst and Pratt, 1973, p. 537–545) and the related metals, ruthenium, rhodium, palladium, osmium, and iridium, which occur with platinum in nature, are used now much less in jewelry than in a variety of industrial applications, including production of high-octane fuels, vitamins and drugs, synthetic fibers, fertilizers, and manufacture of electrical components. Future demand could be greatly increased by the use of platinum in automotive emission-control mufflers. U.S. production is only about 1 percent of consumption; principal U.S. imports are from the U.S.S.R., the Republic of South Africa, and Canada. Domestic *reserves* of 3 million troy oz, almost entirely in copper ores, represent only 7 percent of MACD. *Identified subeconomic resources* are estimated at about 20.6 million oz, or 47 percent MACD. About a third of this is in low-grade placer and vein deposits in the Goodnews Bay area, Alaska, about half is in two titanium-bearing iron-ore deposits in Alaska, and about one-fifth is in currently unrecoverable chromite deposits in the Stillwater Complex, Montana. *Hypothetical resources* are very large, more than 4× MACD, but almost entirely subeconomic. *Speculative resources* are thought to be large, especially in the large areas of Alaska that have not yet been mapped geologically. Discovery of these resources would be aided by detailed mapping of geologically favorable belts that are known to exist and by improvement of analytical techniques for the platinum-group metals at very low concentrations.

TIN

Tin (C. L. Sainsbury and B. L. Reed, in Brobst and Pratt, 1973, p. 637–651; Sainsbury, 1969) is used in making tinplate (principally for "tin" cans), solders, bearing alloys, and bronze and brass. The United States imports virtually 100 percent of its primary tin requirements, of which about 90 percent comes from Malaysia and Thailand. In 1972, about 23 percent of its tin demand was met by secondary sources (reclaimed tin). A negligible amount of tin is recovered as a byproduct from the molybdenum mine at Climax, Colo. *Reserves* are estimated by the Geological Survey at about 38,000 long tons, or a scant 0.61 percent of MACD. Most of this is in fluorspar deposits on the Seward Peninsula, from which tin will be one of several byproducts. Figures on the production and reserves of tin in the Climax molybdenum mine are not available. *Identified subeconomic resources* are estimated to be just slightly greater than reserves; together with the reserves, they would provide only about 1¼ years' supply at the 1971 rate of consumption. *Hypothetical and speculative resources* in conventional types of deposits are each estimated to be of the same order of magnitude as the reserves.

Tin shows a well-marked geologic association with silicic granitic or volcanic rocks. Although most geologic environments of these types in the United States have been prospected, many have not been examined with their tin potential as a primary objective. Furthermore, the large gap between known tin resources and the resource potential suggested by the crustal abundance of tin (R. L. Erickson, in Brobst and Pratt, 1973, p. 21–25) at least suggests that additional promise for finding undiscovered resources may lie in unconventional speculative resources—that is, the possibility of a new geologic environment for tin concentrations.

SILVER

Silver (A. V. Heyl and others, in Brobst and Pratt, 1973, p. 581–603) has its greatest current use in photographic materials; this use alone accounts for nearly all our annual production of newly mined silver. Other important uses are in electrical and electronic products, sterling and plated ware, and brazing alloys. Imported silver supplied 44 percent of domestic needs in 1972, most of it coming from Canada, Peru, and Mexico. Byproduct silver from base-metal and gold ores accounts for roughly two-thirds of U.S. production and resources, the remainder being from ores in which silver is the principal metal. *Reserves* in currently operating mines are estimated to be about 1,300 million troy oz, or 35 percent MACD. *Identified* *subeconomic resources* that might become recoverable with a threefold to fourfold increase in the price of silver (over the October 1972 price of $1.80 per oz) are roughly estimated to be of the same order of magnitude as the reserves. Recovery of these subeconomic resources, however, is not entirely dependent on price increases; porphyry copper deposits supply about 20 percent of domestic silver production, which, like byproduct gold, is recoverable by mass (open-pit) mining but not by the new in-place copper-leaching techniques. A significant identified subeconomic resource is in the copper deposits disseminated in Precambrian sedimentary rocks of Idaho and Montana, which are still being evaluated. Estimated *hypothetical resources*, about 92 percent MACD, are largely potential byproduct resources in undiscovered but predicted sedimentary copper deposits (Precambrian) and porphyry copper deposits. Possibilities for discovery of *speculative resources* are highly favorable, in both primary and byproduct silver deposits.

Two recent developments are tending to increase U.S. dependence on foreign silver sources. First, increasing amounts of silver are being used in photography and other industrial applications from which it cannot be recovered and recycled. Second, as a byproduct or coproduct of copper, lead, zinc, and gold ores, the production of silver depends largely on the production of these other metals; therefore, because of the closure of one-third of our domestic lead and zinc smelters, domestic silver production has declined. As the consumption of silver is not likely to decrease in the foreseeable future, our growing dependence on foreign sources can be decreased only by the discovery of new domestic deposits and by more efficient mining methods and environmentally clean recovery methods.

MAGNESIUM

Magnesium (G. I. Smith and others, in Brobst and Pratt, 1973, p. 210) is the tenth most important nonferrous metal by virtue of its use as the metal, and as the oxide in preparing refractories and chemicals. Magnesium resources in brines, in widespread sedimentary rocks, and in seawater assure the United States a virtually inexhaustible supply.

PRINCIPAL FERROUS METALS

IRON

Iron (Harry Klemic and others, in Brobst and Pratt, 1973, p. 291–306) is the principal metal used in modern industrial civilization and is indispensable to everyday living. Iron and iron alloys (steel) are essential to the construction of buildings, bridges, and railroads, and the manufacture of industrial machinery, transportation equipment, pipelines, tools, containers, fasteners, pigments, and countless other items. Although other materials such as wood, aluminum, and plastics are used as substitutes for steel in some items of manufacture, there are no practical substitutes for iron and steel for a broad spectrum of purposes. The United States imported 28 percent of its iron ore in 1972, most of it from Canada and Venezuela. Domestic *reserves* are estimated at 2 billion short tons, or about equal to 60 percent MACD. *Identified subeconomic resources* of iron ore contain about 22.3 billion metric tons of iron, equal to about 7× MACD, but the bulk of these resources are of a mineralogical nature different from currently usable low grade deposits, and they will require development of a different technology. Enormous *hypothetical resources* of iron ore are predicated on the expectation that many identified iron-ore resources within half a mile of the surface are underlain by similar resources proportional in amount to the near-surface identified quantities. At present, however, physical limitations upon depths to which mining activities can be carried on in various types of rock impose limitations on not only the evaluation of hypothetical resources at great depths, but also the expectation of their recovery. *Speculative resources* in the United States are relatively low because the most promising regions for iron-ore discovery have largely been identified and at least part explored. The principal need is to obtain more detailed information concerning the geology of these regions. Because most of the major iron deposits or iron-bearing formations have associated magnetic anomalies, major programs of aeromagnetic surveying to delineate the zones of magnetic rocks and potential ore bodies should be continued. In some places, further geologic studies and interpretation of the magnetic and geologic data are needed.

TABLE 2.—*Principal ferrous metals*

Commodity	Value (millions) of U.S. primary demand, 1968	Approximate 1972 consumption (short tons)	Minimum anticipated cumulative demand, 1968–2000 (short tons)
Iron	$1,294	86,000,000	3,280,000,000
Nickel	300	230,000	8,100,000
Silicon	148	470,000	22,900,000
Molybdenum	90	23,400	1,550,000
Manganese	64	1,260,000	47,000,000
Tungsten	43	6,600	550,000
Cobalt	26	7,000	260,000
Chromium	24	420,000	20,100,000
Vanadium	20	7,200	420,000
Tantalum	11	564	31,000
Niobium (Columbium)	6	2,135	138,000

NICKEL

Nickel (H. R. Cornwall, in Brobst and Pratt, 1973, p. 437–442) not only strengthens steel but also imparts corrosion resistance over a wide range of temperatures; hence, nickel steel is used widely in the chemical industries as well as in aircraft, motor vehicles, and electrical machinery. In 1972, the United States imported 74 percent of its nickel needs, principally from Canada and Norway (where some nickel ores of Canadian origin are refined). *Reserves* are about 200,000 short tons, a scant 2.5 percent of MACD. *Identified subeconomic resources* are estimated at 15.2 million tons (nearly 1.9× MACD); 90 percent of this resource is in low-grade copper-nickel sulfide deposits in the Duluth Gabbro Complex of Minnesota (see under Copper). Another 5 percent is in laterites, residual soils formed during long periods of intensive weathering and erosion over sparsely nickel-bearing rocks in the Pacific Northwest; these deposits are too small and remote to be mined profitably under current economic conditions. Deep-sea manganese oxide nodules could eventually contribute to U.S. nickel production, but technologic and legal problems preclude an estimate of this potential resource at present. Additional large identified subeconomic resources would be made available by the development of new metallurgical techniques to produce nickel from peridotite and serpentinite, rocks that occur in many areas of the United States and universally contain 0.2–0.4 percent nickel. Extraction of nickel from these resources, however, is likely to require so much energy that the process will not be feasible. *Hypothetical and speculative resurces* are not estimated, but discovery of a new type of nickel-sulfide deposit in the Thompson district, Manitoba, Canada, suggests a new type of geologic mechanism for the formation of nickel deposits. The greatest need therefore is for detailed geologic and geophysical mapping of geologic environments in the United States that are potentially favorable for either Thompson- or Duluth-type nickel deposits.

SILICON

Silicon (K. B. Ketner, in Brobst and Pratt, 1973, p. 577–580; F. E. Brantley, in U.S. Bureau of Mines, 1970, p. 369–384), in the form of high-purity silica (quartz) sand or its consolidated equivalents (sandstone and quartzite), is important not only for steelmaking and other metallurgical uses, but also in the manufacture of glass, ceramic ware, and chemicals. A possible future application of potentially great importance is the use of silica fibers in the manufacture of flywheels for energy-storage units, which could be used not only for large installations but for such small-scale items as automobile power sources (Post and Post, 1973).

Silica sand and sandstone are among the more common sedimentary formations cropping out in the United States, and, in general, their stratigraphic positions, extent, thicknesses, and the areas of outcrop are rather well known. It is unlikely that important units of high-purity silica sand and sandstone remain to be discovered. Therefore, almost all silica sand and sandstone units can be regarded as identified rather than undiscovered resources. Parts of these identified resources can be classed as *reserves*: such parts are where certain favorable geologic features are combined with favorable geographic circumstances so that the deposits are workable under present economic conditions.

Favorable geologic features include chemical purity, uniform grain size, friability (ease of crumbling), amenability to beneficiation, and proximity to the surface. The favorable geographic circumstances are proximity to markets and to transportation facilities.

Although U.S. silica-sand resources are so large that they are unlikely to be depleted by normal use, a large proportion of the most favorably located deposits may be precluded from exploitation by shortsighted public policies—either unconscious, as when residential developments are allowed to spread over valuable sand deposits, or deliberate, as when land-use laws are invoked to prohibit exploitation of known deposits in urban areas. The result is not that we will run out of silica sand, but that costs will increase because mining will be confined to areas remote from industrial users and the ultimate consumers. Sand and sandstone deposits capable of yielding high-quality silica sand should be identified and precisely delineated on geologic maps, especially on large-scale maps of urban regions. Geologic maps exist for many urban areas, but workable silica-sand deposits are specially designated on only a few of these. Precise location of all deposits in urban regions would permit orderly planning for the most beneficial use of land underlain by silica-sand deposits.

MOLYBDENUM

Molybdenum (R. U. King and others, in Brobst and Pratt, 1973, p. 425–435) is used principally in alloy, stainless, and tool steels. Other importance uses are in lubricants, agriculture, chemicals, and pigments. The element also has an assured future use as a principal material in nuclear and space applications. The United States is a net exporter of molybdenum, having *reserves* of approximately 3.15 million short tons (2× MACD) and estimated *identified subeconomic resources* of about 14.4 million short tons (more than 9× MACD); the subeconomic resources are in deposits having grades lower than the present cutoff, and the problem here is largely one of economics. *Hypothetical resources* in the United States are estimated to be on the order of half a billion tons (several hundred times MACD).

MANGANESE

Manganese (J. V. N. Dorr, II, and others, in Brobst and Pratt, 1973, p. 385–399) is essential in two ways to the manufacture of steel: (1) Used as a scavenger in the molten metal, it combines with sulfur and oxygen, which make steel brittle, and removes them as part of the slag; (2) used as an alloy, it makes steel more resistant to shock or abrasion. Manganese oxide is used in the chemical industry and in dry batteries. More than 90 percent of manganese consumption in the United States is by the steel industry, and no substitute has yet been found, despite much effort. About 13–20 pounds of manganese (as alloy or metal) is consumed per ton of steel manufactured in the United States; elsewhere in the world the amount of manganese needed per ton of steel may range from 13 to 50 pounds, owing to the wide range of efficiencies in its use. Clearly, the element is essential to the whole industrial capacity of the world. When we can do without steel, we can do without manganese. The United States in 1972 imported 95 percent of its manganese, mainly from Gabon, Brazil, the Republic of South Africa, and Zaïre. Although the United States has many small deposits of high-grade material, they cannot be considered reserves under present economic conditions, nor would they constitute significant reserves even at much higher prices (Brooks, 1966, p. 70–72).

Identified subeconomic resources contain an estimated 73 million short tons of manganese, or nearly 1.6× MACD. More than 80 percent of this resource is in deposits in Maine, Minnesota, and Arizona. Technologically feasible processes of extraction have been developed for much of this material, but they could be used only at 2–5× the present world price for manganese and would require great energy input. Of the remaining estimated identified subeconomic resources, about 16 percent (nearly 12 million short tons of manganese), plus an additional unmeasured but much larger resource in similar rocks at somewhat deeper levels, is contained in carbonate nodules and enclosing manganiferous shales of the Pierre Shale in South Dakota. This resource is essentially unworkable at present because of mining, ore-dressing, metallurgical, and pollution problems. Manganese oxide nodules known to occur over large areas of the sea floor at many localities have not been included in estimates of U.S. resources, but if the legal status of deep-sea mining can be favorably resolved, it appears likely that the nodules will eventually contribute to U.S. production. *Hypothetical resources* in the United States are nil, because the known districts are in general well enough known for most possibilities to have been identified. *Speculative resources* cannot be estimated, but geologic theory suggests several broad targets for research and exploration.

TUNGSTEN

Tungsten (S. W. Hobbs and J. E. Elliott, in Brobst and Pratt, 1973, p. 667–678) imparts to its compounds and alloys the properties of extreme hardness, ability to retain hardness and strength at high temperatures, high tensile strength, adequate electrical conductivity, and high wear resistance. Its principal uses, as tungsten carbide and in a variety of steels and nonferrous alloys, are in metalworking machinery, tool steel, construction and mining machinery, drill bits, turbines, rocket nozzles, structural material in nuclear and space applications, transportation equipment, electrical equipment, and many other items. Imports in 1971, mainly from Canada, Bolivia, Peru, and Australia, supplied 44 percent of domestic consumption. Domestic *reserves* are estimated by the Geological Survey at about 119,000 short tons, or about 22 percent MACD. *Identified subeconomic resources* of approximately 305,000 short tons (56 percent MACD) are mostly in deposits like those currently being mined, but of lower grade. The parts of the western United States from which most of our tungsten has been produced include vast areas, covered by surficial debris and by sedimentary or volcanic rocks geologically younger than those in which the tungsten is found, that undoubtedly conceal *hypothetical resources* of recoverable grade, at least equal in volume to, if not greatly exceeding, known deposits. Discovery of such deposits will require continued geologic mapping of exposed areas and imaginative and intensive application of various geophysical and other methods to identify favorable geologic situations in the intervening covered areas. An additional hypothetical resource lies in the possibility of byproduct recovery of tungsten from molybdenum deposits like the one at Climax, Colo., which is a significant source of our current domestic supply; as new molybdenum deposits of this type are discovered and developed, they will probably provide new tungsten reserves. *Speculative resources* may very likely be discovered in new districts in the known circum-Pacific tungsten belt, and a better understanding of small tungsten deposits in the Rocky Mountains might lead to the discovery of major new resources in that region.

COBALT

Cobalt (J. S. Vhay and others, in Brobst and Pratt, 1973, p. 143–155) is used in high-temperature alloys (the "superalloys"), permanent-magnet alloys, cutting and wear-resistant alloys, tool steels, miscellaneous other alloys, and for a variety of other industrial and chemical purposes. The United States imported 98 percent of its apparent consumption in 1972, the major sources being Zaïre, Canada, Morocco, and Zambia. Most of the world's supply of cobalt reaches the market as a byproduct of mining copper, nickel, and silver ores; smaller amounts are byproducts of iron, chromium, lead, zinc, uranium, and manganese. U.S. *reserves* are estimated at 28,000 short tons, or 11 percent MACD. *Identified subeconomic resources*, most of which are available only as byproducts, are estimated at more than 800,000 short tons, or more than 3× MACD. About 60 percent of this estimated resource is in the copper-nickel sulfide ores of the Duluth Gabbro Complex in Minnesota, which are not yet economically or technologically minable (see under Copper). Probably the next largest single resource is in the lead ores of the Southeast Missouri district, where recovery of cobalt (as well as nickel) is more a problem of technology and economics than of geologic availability. *Hypothetical resources* are directly related to those of the major metals with whose ores cobalt is associated, most notably nickel, copper, iron, and lead. Possibilities seem favorable for the discovery of new cobalt-bearing ores of nickel and iron in eastern Pennsylvania, copper in Minnesota, Alaska, and the Appalachian region, and lead in the Mississippi Valley. As with the major metals, discovery of such resources depends on delineation of favorable exploration ground through careful geologic analysis and on the refinement of ore-finding techniques. A particular need in the case of cobalt is new and better technology for the recovery of cobalt (currently selling for about $3.15 per pound) from ores containing less valuable lead, zinc, and copper; loss of such valuable byproducts in mining, beneficiating, and smelting is not only a financial loss to the producer, but may be an irretrievable loss of the material itself.

CHROMIUM

Chromium (T. P. Thayer, in Brobst and Pratt, 1973, p. 111–121) is used to make stainless steel, tool steel, and various alloys and superalloys which are used mainly in construction, transportation, and machinery and equipment. The United States in 1972 imported 100 percent of its chromium consumption, mainly from the U.S.S.R., the Republic of South Africa, and Turkey. We have no *reserves* of chromium. *Identified subeconomic resources* amount to only about 1.67 million short tons, or 8 percent MACD; they would be difficult to mine and expensive to use. *Hypothetical and speculative resources* are even less, mainly because the geologic environments in which chromium occurs are of limited occurrence in the United States; moreover, the few postulated relatively large deposits could mitigate the national supply problem only temporarily and at very high cost. The nearest potential resources of significant size, both identified subeconomic and undiscovered, are in a deposit in Manitoba similar to the principal large U.S. resource (in the Stillwater Complex of Montana), and in very large low-grade deposits in Greenland; both metallurgical research and, for the Greenland deposits, more detailed geologic information, are needed.

VANADIUM

Vanadium (R. P. Fischer, in Brobst and Pratt, 1973, p. 679–688) is added to steel to toughen and strengthen it and to control its grain size; vanadium steels are used for construction, high-pressure pipelines, transportation equipment, and metal-working machinery. Vanadium-titanium alloys are used in the aerospace field, and vanadium alloyed with several other metals is a candidate for use in the nuclear industry as a fuel-cladding material for advanced fast-breeder reactors. In 1972, the United States imported 32 percent of its vanadium, mainly from the Republic of South Africa, Chile, and the U.S.S.R. U.S. *reserves* are 115,000 short tons, about 27 percent MACD; most of this quantity is contained in uranium and phosphate deposits from which vanadium would be recovered as a byproduct. *Identified subeconomic resources* are very large—probably on the order of a few million tons, or several times MACD; to extract the vanadium from some of these deposits would require modified metallurgical practices, and some deposits are in rocks such as carbonaceous shale that have not been mined previously and would require new technology altogether. Potentially recoverable vanadium is currently being lost from some operations that mine magnetite iron ores, others than mine phosphate rock, and others that burn or refine crude oil. *Hypothetical and speculative resources* have not been evaluated because the greatest potential for vanadium resources appears to be in byproduct recovery rather than in discovery of new deposits that would be mined primarily for vanadium.

TANTALUM

Tantalum (R. L. Parker and J. W. Adams, in Brobst and Pratt, 1973, p. 443–454) is still classed as a ferrous metal because of its earlier predominant use as an alloying element in steel, but its principal use now is in the electronics industry, largely in the manufacture of capacitors and rectifiers. The remainder goes into the production of superalloys for high-temperature corrosion-resistant applications, into tantalum carbide for high-temperature cutting tools, and into tantalum metal for a variety of corrosion-resistant uses. Imports in 1972 accounted for 97 percent of U.S. consumption; the principal sources were Nigeria, Malaysia, Australia, and Thailand.

The United States has no *reserves* of tantalum. *Identified subeconomic resources* are estimated at a scant 1,720 tons, less than 6 percent of MACD; recovery of the tantalum minerals in these resources, though technically feasible, is not profitable at present prices. The likelihood of discovering large new deposits of tantalum, of the type now exploitable commercially, is small. As is true of tin, the large gap between known tantalum resources and the resource potential suggested by the crustal abundance of tantalum (R. L. Erickson, in Brobst and Pratt, 1973, p. 21–25) indicates the need for geologic research on the possible existence of new types of deposits — unconventional speculative resources.

NIOBIUM

Niobium (R. L. Parker and J. W. Adams, in Brobst and Pratt, 1973, p. 443–454)—still referred to as columbium to some extent in metallurgy and mineral trades—is used chiefly in the form of ferrocolumbium as an alloying element in carbon and alloy steel, stainless steel, and superalloys. High-strength low-alloy niobium steels are used in the construction of large buildings, pipelines, and machinery and structures where savings in weight and increased durability and strength are important. Niobium alloys are used in aircraft and rocket engines, and unalloyed niobium is an important construction material in nuclear reactors. The United States in 1972 imported 67 percent of its consumption, principally from Brazil, Nigeria, Malaysia, and Thailand.

Domestic *reserves* at current prices are nil. *Identified subeconomic resources* total an estimated 121,000 tons of niobium, or about 88 percent MACD. More than half this resource is contained in a single body of carbonatite (an unusual igneous rock) near Powderhorn, Colo.; another third of the resource is a potential byproduct of bauxite (aluminum) deposits in Arkansas, from which recovery of the niobium is unprofitable under present market conditions. Improvements in technology could bring both these resources into the reserve category.

Hypothetical resources no doubt occur as blind ore bodies in known carbonatite masses, or as ore bodies in undiscovered carbonatites in known carbonatite provinces. These resources constitute probably several times the amount of currently known resources; their discovery will depend on continuing geologic and exploration activities. The outlook for *speculative resources* seems good, because of the probability that other carbonatite deposits, now concealed beneath younger rocks, remain to be discovered somewhere in the Rocky Mountains and the Midwest. Continued geologic mapping and development of new exploration methods will aid in the discovery of these resources.

MINERAL FUELS

A national energy crisis is now generally recognized, although there is still some debate whether it is temporary or long lived. Individual facets of the problem, and possible solutions, have become a matter of daily news. It would be presumptuous for us to attempt any kind of comprehensive statement on a problem of such magnitude and diversity, except to point out that to whatever extent any of the solutions involve mineral fuel resources, they are subject to the law of geologic availability. Thus, summaries are presented here to provide a brief appraisal of the geologic availability of the mineral fuels, rather than to offer an instant solution to the energy crisis.

TABLE 3.—*Mineral fuels*

Commodity	Value (millions) of U.S. primary demand, 1968	Approximate 1972 consumption	Minimum anticipated cumulative demand, 1968–2000
Petroleum / Shale oil	$13,769	[1] 5.96 billion bbls	[2] 195 billion bbls
Natural gas	3,109	22.6 trillion cu ft	860 trillion cu ft
Coal	2,147	510 million short tons	27 billion short tons
Uranium pentoxide	60	13,300 short tons	[3] 2,400,000 short tons
Thorium	1.5	132 short tons	27,500 short tons (*maximum*)

[1] One bbl (barrel) equals 42 gallons.
[2] This MACD, etsimated in 1968 for petroleum, can theoretically be satisfied equally well by shale oil. However, shale oil is not now being produced commercially and probably will not be produced in significant quantities before about 1978, so the extent to which MACD can be met by shale oil will depend on the speed with which, and the capacity to which, commercial production can be developed. It is estimated that a maximum production rate of 1 million bbls per day (0.3 billion bbls per year) is not likely to be reached before about 1985 at the earliest, so that total cumulative production by the year 2000 probably will not exceed 5 billion bbls.
[3] Revised estimate by the U.S. Atomic Energy Commission for approximate period 1972–2000.

OIL AND GAS

Oil and gas (T. H. McCulloh, in Brobst and Pratt, 1973, p. 477–496) are at once the most crucial and yet among the most difficult to evaluate of our energy resources. Estimates of oil and gas *reserves* ("proved reserves" in the parlance of the petroleum industry) are made periodically by the industry; the most recent estimates published are recoverable reserves of 36.3 billion barrels of oil (about 7 years' production at the present rate, or 19 percent MACD) and 266 trillion cubic feet of gas (about 13 years' production at the present rate, or 31 percent MACD) (U.S. Department of the Interior, 1974). Estimates of *resources*, however, are subject to the condition that no matter how they are made, they ultimately involve projections from the results of oil and gas exploration to date. Because very large areas of the earth have yet to be adequately explored geologically (especially parts of the seabed), and because our techniques for identifying oil and gas traps are very imperfect, the results of oil and gas exploration to date are an inadequate base on which to project results of future exploration. Thus, recent estimates of ultimate *producible* oil in the United States have ranged from 165 billion barrels (Arps and others, 1970) to 550 billion barrels (Schweinfurth, in McKelvey and others, 1973), and estimates of ultimate oil in place have ranged from 587 billion (Moore, 1970) to 2,900 billion barrels (Schweinfurth, in McKelvey and others, 1973). Perhaps more significant than the magnitudes of these estimates of resources (the most conservative of which is equivalent to 85 percent MACD) is their demonstration of the low recovery factor, the difference between producible oil and oil in place. When present techniques are used, for every gallon of oil pumped out of the ground, 2 gallons are left behind, locked in the poor spaces of the rocks by surface tension.

What are the principal problems to be solved in the effort to convert these potential resources of oil and gas into reserves? The distribution of fluid hydrocarbons in sedimentary rocks and basins is extremely uneven (although subject to certain broad general patterns), and a substantial understanding of the underlying physical and chemical reasons for their distribution is needed, particularly (1) the nature of the processes by which organic remains interred in sediment are transformed to protopetroleum and thence to fluid hydrocarbons capable of migration, and (2) the chemical and physical processes by which such mobilized hydrocarbons are expelled from source rocks and trapped during their migrations to form commercial accumulations. In general, the oil and gas fields that have been discovered are conspicuous (from the viewpoint of exploration techniques), very large, or in regions that have undergone thorough prospecting. Remaining to be discovered are innumerable small reservoirs, large reservoirs that are inconspicuous (again, from the viewpoint of the exploration techniques available), and traps of all sizes in regions that have not yet been prospected thoroughly or at all. Not all subsurface hydrocarbon accumulations are worth finding, however. For every accumulation that can be found and produced economically, doubtless many accumulations are so small that the volumes of hydrocarbons producible would be insufficient to repay the costs of finding them. Moreover, a very large percentage of the total oil (and gas) occurs in a very small percentage of all known accumulations. More than 85 percent of the world's hydrocarbon production plus reserves occurs in less than 5 percent (238 fields) of all producing accumulations. Even more remarkable, 65 percent occurs in slightly more than 1 percent of all fields—the 55 "supergiants" (a billion barrels of oil or a trillion cubic feet of gas, or more) (Halbouty and others, 1970; Klemme, 1971)—and an astounding 15 percent occurs in only two immense accumulations in the Middle East, the Ghawar field in Saudi Arabia and the Burgan field in Kuwait. In smaller areas, similar relations exist.

New oil-producing regions and areas have been discovered through combinations of business enterprise, economic pressures of many sorts, technologic advances, and exploitation effectiveness. There is considerable room for continuation of this evolutionary achievement. Much of the United States Continental Shelf is unexplored. The onshore-offshore region south of Cape Hatteras has much in common geologically with the onshore-offshore region of Saudi Arabia, including a very thick section of structurally simple sedimentary rocks of the same ages and similar compositions beneath a very large area. Prior to discovery by the drill, and subsequent development, the Ghawar field (the largest single oilfield known in the world) was not a particularly conspicuous prospect or structure, either from surface geologic mapping or from geophysical interpretation (Arabian American Oil Co., 1959). Another such inconspicuous "supergiant" might lie beneath the Blake Plateau, or somewhere else within the territorial limits of the United States. Discovery of new oil and gas fields and new provinces will require (1) research on the process of formation, migration, and entrapment, (2) detailed geologic mapping to outline potentially favorable geologic formations and structures, and (3) development and application of new and better geophysical exploration techniques. Last but far from least, although only the drill bit can finally prove the presence of oil, "oil must be sought first of all in our minds!" (Pratt, 1942, p. 49).

COAL

Of coal consumed in the United States (Paul Averitt, in Brobst and Pratt, 1973, p. 133–142), about 62 percent is used in the production of electric power, 20 percent is used by the steel industry, 16 percent in manufacturing, and 2 percent for all other purposes. Coal is also of great future value and importance as a subsidiary source of synthetic gas, liquid fuels, and lubricants.

Coal is widespread and abundant in the United States. Coal-bearing rocks underlie about 13 percent of the land area of the 50 States and are present in parts of 37 States. On any basis of analysis, U.S. resources of coal are larger than the combined resources of petroleum, natural gas, oil shale, and bituminous sandstone, but use of coal lags behind use of both petroleum and natural gas because they are cleaner and easier to handle. Recoverable coal *reserves* are estimated at 197 billion short tons, or about 7 MACD. Total *identified resources* in the ground, including reserves in thick accessible beds and subeconomic resources in thinner or less accessible beds, are estimated at 1,581 billion tons, or 58× MACD. Recoverability ranges from 40 to 90 percent, depending largely on the method of mining, but it is influenced by many other diverse factors such as the nature of the roof rock, joints, faults, and the need to protect oil and gas wells and fields. Average long-term recoverability, nationwide, is probably about 50 percent. Unmapped and unexplored areas in known coal fields contain substantial additional resources of an estimated 1,643 billion tons that must be classed as *hypothetical.* Although large, the hypothetical resources are, for the most part, relatively inaccessible for mining at present, and a more exact delineation of the magnitude, distribution, and future utility of such resources will require a substantial amount of detailed geologic mapping, exploration, and study over a long period. The major geologic features of the United States are known well enough to justify the statement that in all probability, no major coal fields remain to be discovered; hence there are no speculative resources.

Sulfur in coal is an undesirable element; it lowers the quality of coke and of the resulting iron and steel products; it contributes to corrosion, to the formation of boiler deposits, and to air pollution; its presence in spoil banks inhibits the growth of vegetation; and as sulfuric acid, it is the main deleterious compound in acid mine waters, which contribute to stream pollution. The sulfur content of coal in the United States ranges from 0.2 to about 7.0 percent; the average is 1.0–2.0 percent. Sulfur content is highest in bituminous coals of Pennsylvanian age in the Appalachian and Interior coal basins, which account for about 34 percent of the identified coal resources; it is low, generally less than 1 percent, in subbituminous coal and lignite of the Rocky Mountain and Northern Great Plains regions, which account for 56 percent of the identified resources.

Coal contains small but significant quantities of 25 metallic and nonmetallic elements, which are of considerable interest because some may become of future resource importance, and others may be pollutants. Five elements—uranium, germanium, arsenic, boron, and beryllium—occur locally in vastly greater concentrations than their estimated concentration in the earth's crust; others, including barium, bismuth, cobalt, copper, gallium, lanthanum, lead, lithium, mercury, molybdenum, nickel, scandium, selenium, silver, strontium, tin, vanadium, yttrium, zinc, and zirconium, occur locally in appreciably greater concentrations. When coal is burned, most of these elements are concentrated in the coal ash, but a few of the more volatile elements are emitted into the atmosphere.

URANIUM

Uranium (W. I. Finch and others, in Brobst and Pratt, 1973, p. 456–468) is well known as an important energy source. The readily fissionable isotope, U^{235}, constitutes only about 0.7 percent of natural uranium; U^{238}, which constitutes most of the remainder, is not readily fissionable, but under neutron bombardment converts to fissionable plutonium–239. Although the demand for electricity generated by nuclear energy is expected to increase significantly for many years, technological developments may ultimately permit a decrease in the amount of uranium required to generate the needed electricity. If fast breeder reactors are developed by the mid-1980's, annual domestic uranium requirements are expected to peak in about the year 2000 at about 150,000 short tons of U_3O_8, about 10 times the 1972 requirement, after which they will decline gradually to about the same level as in 1972, as the currently used nonbreeder reactors are phased out. If, on the other hand, fast breeder reactors are not successfully developed, uranium requirements will continue to increase. In this regard it is appropriate to quote from a 1969 report to the National Academy of Sciences by M. King Hubbert (1969, p. 227–228):

> The energy potentially obtainable by breeder reactors from rocks occurring at minable depths in the United States and containing 50 grams or more of uranium and thorium combined per metric ton is hundreds of thousands of times larger than that of all of the fossil fuels combined. It is clear, therefore, that by the transition to a complete breeder-reactor program before the initial supply of uranium-235 is exhausted, very much larger supplies of energy can be made available than now exist. Failure to make this transition would constitute one of the major disasters in human history.

Domestic *reserves* of uranium, about 273,000 short tons of U_3O_8 (at $8 per lb), can supply domestic requirements into the early 1980's. For *identified subeconomic resources,* the greatest promise is in low-grade resources in marine phosphate rocks in Idaho and adjacent States, in Florida, and in North Carolina. These deposits contain an estimated 6 million tons of U_3O_8, more than 20 times the uranium in present reserves, or more than 2× MACD, but to obtain significant supplies of uranium from them would require major technological changes. A very small amount of the total identified subeconomic resources in phosphate rock can be obtained at moderate cost as a byproduct of making fertilizer, but at present, most of the uranium in phosphorite that is used to make fertilizer by the wet process phosphoric acid method stays in the fertilizer and is lost as a resource when the fertilizer is used. (On April 10, 1974, a Florida subsidiary of Gulf Oil Corp. announced construction of a pilot plant to test a new process for extracting uranium from phosphate rock being converted to phosphoric acid.) To obtain more of this uranium would require mining and treating the rock principally for uranium; unit costs would be high, and vast quantities of rock would have to be moved—somewhat more than 25 billion tons of rock, or nearly a third of the total identified phosphorite resources, to obtain enough uranium to fulfill the MACD. Uranium in phosphate rock that is used to make elemental phosphorus by the electric furnace method goes mostly into the silicate slag. A process for recovering uranium from the slag has not been devised. Marine black shales, especially in Tennessee and adjacent States, also contain large identified subeconomic resources of uranium, but recovery would require mining vast areas by open-cut and underground methods, as well as development of an economic technology of extraction. *Recoverable hypothetical resources,* that is, new rich ore bodies in the known mining districts, are estimated at 500,000 tons U_3O_8; these resources, if discovered and mined, would satisfy estimated domestic requirements only until the early 1990's. Subeconomic hypothetical resources amount to somewhat less. The pressing need is for discovery of *speculative resources* in new districts; therefore, research on geologic guides to new districts is urgently needed.

THORIUM

Thorium (M. H. Staatz and J. C. Olson, in Brobst and Pratt, 1973, p. 468–476)) has a small current demand, mostly for use in making incandescent gas mantles and magnesium alloys, but it has considerable potential as a fuel for nuclear reactors, of which the farthest advanced at present is the high-temperature gas-cooled reactor. Because of this potential, we will here compare thorium reserves and resources to the maximum anticipated cumulative demand 1968–2000, which assumes commercial development of economically attractive thorium reactors by 1980. In that context, domestic *reserves*, producible as byproducts of titanium mining from Atlantic Coast beach placers, are equivalent to only 50 percent of the maximum anticipated cumulative demand. *Identified subeconomic resources* are substantial; the amount of thorium contained in relatively rich vein deposits, from which it would be the principal product, is more than 3× maximum anticipated cumulative demand and an even greater amount is contained in lower grade veins, in stream placer deposits, and in deposits from which it would be a byproduct. Still another resource is the Conway Granite of New Hampshire, a body of granite exposed over an area of 300 square miles and probably several miles deep. The Conway Granite contains an average of 2 ounces of thorium per short ton of rock. The energy released by nuclear fission of the thorium contained in just 1 cubic yard of this rock would be equivalent in fuel energy to about 300 short tons of coal, or 1,500 barrels of crude oil. If the entire area of 300 square miles were quarried to a depth of only 110 yards and the thorium used in nuclear reactors, the fuel equivalent of the energy produced would be about 30 trillion tons of coal, or 150 trillion barrels of crude oil (Hubbert, 1969, p. 227), about 165 times the coal reserves of the United States, or more than 3,900 times the proved recoverable reserves of crude oil! Utilization would, of course, depend on development of a technology for extracting the thorium and on minimizing the environmental impact. Nevertheless, the amount of available energy would be enormous. The outlook for discovery of *hypothetical* and *speculative resources* is good. Systematic geologic analysis should be made of known thorium regions to select favorable areas for prospecting, and geologic criteria should be applied to search for potentially favorable environments in less explored regions.

OIL SHALE

Oil shale (W. C. Culbertson and J. K. Pitman, in Brobst and Pratt, 1973, p. 497–503) is a fine-grained sedimentary rock containing organic matter that has the property of yielding substantial amounts of oil when heated in a closed retort (destructive distillation) but is mostly insoluble in ordinary petroleum solvents. The United States contains immense amounts of oil shale, but no oil-shale venture has been a commercial success in the last 100 years, principally because of the abundant supplies of lower cost oil, gas, and coal. The rising demand for energy, however, requires consideration of this abundant energy resource as a long-range supplement to the dwindling supplies of other fossil fuels. (See footnote 2 on table 3.)

In classifying public lands as valuable for oil shale, the U.S. Geological Survey specifies the minimum thickness and grade of oil shale as 15 feet of shale yielding an average of 15 gallons of oil per ton. On this basis, the *identified subeconomic resources* in the Green River Formation in Colorado, Utah, and Wyoming are estimated to total 1.8 trillion barrels of oil (one barrel contains 42 gallons). Nearly one-quarter of this amount (418 billion barrels, or about 2.1× MACD) is in oil shale yielding 30 or more gallons per ton. The recent increases in the price of oil mean that the more accessible of these higher grade deposits may soon be economically recoverable. Further increases in the price of crude oil, or major developments in the technology of recovering shale oil, or the value of coproducts such as aluminum or nahcolite (soda ash), locally present in the shale, may make less accessible or lower grade deposits economically recoverable in the near future. The *hypothetical resources* in the Green River Formation are estimated to total about 650 billion barrels, of which perhaps 50 billion barrels are in oil shale yielding 30 or more gallons per ton.

The possibility of heating the oil shale underground and pumping the oil to the surface has been investigated by private industry in western Colorado and by the U.S. Bureau of Mines in southwest Wyoming (L. W. Schramm, in U.S. Bureau of Mines, 1970, p. 188). Many technical problems remain to be solved, but this method holds promise as a way to obtain the oil with little harm to the environment.

The synthetic-gas potential of oil shale of the Green River Formation has been investigated by the Institute of Gas Technology. Their data indicate that high-quality synthetic gas could be produced at the rate of 100 cubic feet of gas for each gallon of shale oil that could be produced by a conventional retort, or 4,200 cubic feet for each barrel of shale oil. Thus the Green River Formation could be the source of an enormous amount of gas instead of oil, but at a relatively high price compared with present natural-gas prices.

Further *identified subeconomic resources* of an estimated 200 billion barrels of shale oil (using a minimum thickness and grade of 5 feet of shale yielding an average of 10 gallons of oil per ton) occur in marine black shales of the central and eastern United States. Oil shales in Alaska (not to be confused with the crude oil of the Prudhoe Bay fields) are incompletely known but are estimated to contain *hypothetical resources* of about 450 billion barrels of oil.

For *speculative resources*, it is unlikely that any other deposit of the magnitude of the Green River Formation exists in the United States; however, small high-grade deposits may be present in the many unexplored lacustrine deposits of Tertiary age in the western United States (Feth, 1963), particularly in Montana, Nevada, and Wyoming (Duncan and Swanson, 1965, p. 16).

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