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46. It is tempting to associate Kirov and Stephens' reaction 2 with the release of soluble matter; also, to associate its subsequent conversion to coke in absence of a donor solvent with the solidifcation of a fluid bituminous coal as it undergoes slow heating. Coals of lower rank are harder to liquefy, and this fact may reflect chemical disparities that also underlie differences in behavior of coals of low and high rank as they undergo pyrolysis (*37*).
47. Work on the fast fluidized bed and flash hydrogenation of coal at The City College is supported by grant AER-72-03426 A (formerly GI-34286) from the RANN Program (Research Applied to National Needs) of NSF. For informative discussions, I thank M. Sherwin of Chem Systems, Inc., L. Topper of the Office of Energy R & D Policy of the NSF, and S. B. Alpert, R. H. Wolk, and W. C. Rovesti of the Electric Power Research Institute.

World Changes and Chances: Some New Perspectives for Materials

Trends in use, world trade, and international politics define issues and research directions.

S. Victor Radcliffe

In a controversial revival or reexamination of Malthus's hypothesis, system dynamics models of the world economy have suggested that the resource constraints of a finite planet will not permit ongoing trends in population and industrial growth to continue far into the future. Shortages of materials are identified as one of the key limiting factors. Despite their uncertainties, such analyses, combined with recent world events, do affirm the significance of materials and the other natural or physical resources as part of the larger economic and social system. It is in these terms rather than solely technical ones that this article focuses attention on the role of materials over the transition period from now into the early part of the next century and beyond.

How are we to get from here to there without being more certain where *there* is? How can goals and policies involving materials be formulated to facilitate the transition, and how can science and technology assist in discerning better the most likely long-term demands on natural resources—for what and in what quantities—and the options for meeting them? In particular, how can we better assess what priorities appear appropriate for materials research? This article attempts a preliminary attack on such questions. It is based on the belief that we must better understand the present and how we got here before we are likely to be prescient as to the resource needs and opportunities of the transition period and the further future.

Materials and Natural Resources

Appropriate research for materials, if it is to be conducted in the manner now accepted for such other major resources as energy and food, should encompass the full spectrum of activities involved in the materials system, that is, the resources from which materials are derived, their processing and utilization, and the discharges and wastes to which such activities give rise. The interrelationships of materials and the other natural resources are shown in Fig. 1 in terms of the flow of resources, as means to attain given ends, through the successive production stages of "raw materials" and "processed materials" (both of which figure prominently in world trade as the "primary commodities") into industrial use and consumer use. These different types of derived resources have key common features: (i) their importance lies less in their being specific things or substances than in providing "the function or operation of attaining a given end such as satisfying a want" (*1*), and (ii) they are dynamic, in that they are created, and in some cases, destroyed, by man.

The delineation of function as a key

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characteristic of materials is essential for understanding the forces that will determine what mix of resources, including both substitutions and new resources, will be called upon to meet national and world needs in the future. Correspondingly, it is not necessarily wise to extrapolate from the historical changes in the physical quantities and makeup of the resource consumption of industrialized countries in order to predict their future needs, except for the near term. It is even less likely that the needs of developing countries as they proceed to higher levels of industrial activity can be forecast from this same experience because their development is occurring in a different technological era.

The dynamic characteristic of derived resources arises from the fact that they originate as useless or neutral "stuff" existing on or in the earth and are transformed into useful substances through human knowledge. Thus, it is the creation of technologies to better meet human wants that has "created" such resources throughout industrial history. Examples of this process are the transformation (i) in the 1840's of the sap of a wild tropical tree into a resource for a new material, vulcanized rubber, for industrial and consumer products; (ii) of atmospheric nitrogen in the early 1900's into a resource for fertilizer for agriculture; and (iii) of uranium in the 1950's into nuclear fuel for electric power. Conversely, human activity can also "destroy" certain resources either directly or physically as in the use of fossil minerals for fuels and in the "working out" of individual metallic ore deposits, or indirectly through technological obsolesence, such as in advances that provide an alternative resource that is more economic than or that overcomes the physical limitations of an existing resource, or both. Indirect destruction of a specific resource by reduction of usefulness also may be complete in that the resource is returned once again to being neutral "stuff." The changing pattern of resources for rubber illustrates these types of "destruction." The original resource for natural rubber—wild trees in the Amazon forests—was abandoned after superior, specially bred, high-yield trees were cultivated on plantations in Malaysia. This change of the resource for a given material was followed in turn by the creation of an alternative material—synthetic rubber—to better perform the same functions, a development which resulted in the substantial replacement of natural rubber by a technically and economically competitive material that is derived from entirely different resources—oil and natural gas. Most recently, shifts in the relative costs of the above-mentioned fuel-mineral and plant raw materials favor some slowdown or reversal of this replacement trend.

One indicator of the relative significance of the different materials required in a modern economy is the physical amount of each in use. Such an analysis is shown in Table 1 in terms of pounds of the different materials produced annually for use in the United States. Although this indicator is crude in that it reflects only indirectly the functional value of the materials, there is yet no accepted way of making more direct comparisons analogous with the type of comparison used for energy materials that translates their mass into common units of energy measure or coal equivalent. Nevertheless, Table 1 does illustrate the important point that large proportions of both nonmetallic minerals and natural polymers (such as wood, rubber, plant fibers, wool, and leather) are included, in addition to metals, in the current materials mix required for an advanced economy.

Table 1. Use intensity of new supply of materials in the United States (in pounds of material per capita for 1972).

Material	Amount (pounds per capita)*
Nonrenewable resources	
Nonmetallic minerals	
Sand and gravel	9,000
Stone	8,500
Cement	800
Clays	600
Total	18,900
Metals	
Iron and steel	1,200
Aluminum	50
Copper	25
Lead	15
Zinc	15
Other metals	35
Total	1,340
Polymers: (synthetics, mostly from oil and natural gas)	
Plastics and resins	100
Synthetic rubber	26
Noncellulosic fibers	22
Total	148
Renewable resources	
Wood and wood products (1971)	
Lumber	1,141
Plywood and veneer	224
Pulp product†	780
Other	77
Total	2,222
Natural rubber	8
Fibers	
Cotton	19
Other plant	1
Animal (wool, silk)	1
Synthetic (cellulosic)	8
Total	29
Leather	14

*Data include imports (*32*). The use intensity of the new supply of energy materials (which are not included in the definition of materials used here) totaled 17,800 pounds per capita (1 pound = 0.5 kg) as follows: petroleum, 7800; natural gas, 5000; and coal, 5000. Likewise excluded are minerals used for the chemical and agricultural (fertilizers) industries, which total some 1650 pounds per capita. †Including paper.

While the bulk construction minerals in most countries are derived predominantly from domestic resources—usually close to the construction itself to reduce otherwise high transportation costs—the other materials are all major items of world trade. It is the varying degrees to which the different countries of the world depend on trade for the sources or markets for these materials for their continued economic development that, in large part, has raised a "materials problem" as the focus of so much international attention over the past several years. Depending on the country involved, the "problem" is not necessarily one of metallic minerals, even though such a mineral problem often is prominent. For many developing countries, the "problem" is one of natural products, and these substances also figure significantly in the materials "problem" in some industrialized countries.

Changes and Chances: Issues and Policies

What are some of the principal changes that have brought materials into prominence as issues of national policy and international relations? What opportunities are implicit in these changes? Both of these aspects of change and chance are apparent in three interrelated forms—physical, economic, and political. All three forms have been influenced by dramatic developments, especially since the 1930's, in the science and technology of materials (*2*). These advances have led not only to improved performance and lower cost for existing materials, but also to new materials with unique and precisely controllable properties that have created entire new industries, such as those of electronics and synthetic polymers, which, in turn, have contributed to economic growth and the demand for materials in general.

The first of these forms relates to the sheer magnitude to which physical requirements for materials have grown with increasing industrialization and economic growth across the world. As a consequence, it has been contended that continued growth carries with it implications for a level of materials demand which perhaps cannot be met, and for an accompanying effect on the environment that will be unacceptable if the level of discharges and wastes associated with present-day materials production and use is sustained. The statistics for current world production of materials illustrate the point of large scale impressively enough. However, implications as to the size of future needs are better understood by analyzing the changes in materials production over the history of economic growth for the most advanced countries, together with the likely influence of technological and social factors on determining and meeting future demand.

The nature of such changes for some major materials in the United States from the early 19th century to the present is illustrated in Fig. 2. The U.S. population has grown consistently over the entire period, and the gross national product (GNP), as measured in constant dollars over the period from 1870, likewise has grown, although generally at a higher rate than that of the population. However, the growth of materials has a different pattern. In the 1820's when the population had reached 10 million persons, the GNP was about $2 billion, and the principal metal production, in the form of pig iron, was about 60,000 short tons per year (1 short ton = .9 metric ton). By the end of the century, the population reached 76 million, the GNP approached $17 billion, and iron and steel production was about 15 million tons per year. Thus, with a sevenfold increase in population and a slightly greater increase in GNP, iron and steel production increased by a factor of 250. However, by 1950, when the population had doubled to 152 million and the GNP had risen even more rapidly, iron and steel production had increased only sixfold. In the subsequent period, the growth rate of iron and steel production was approximately that of the U.S. population. The curves for two other major metals, lead and copper, in Fig. 2 show similar indications of the tendency for materials production to grow more rapidly than population over a period of years and then to decline to a rate close to that for the population (*3*). The rapid growth period, which was some 80 years for iron and steel, lasted only some 40 years for copper and lead. Aluminum, which was not produced in significant quantities until more than 50 years later than lead and copper, is still in a period of rapid growth compared with that of population, although the period of highest growth rate appears to have been passed.

An even newer material—plastic or synthetic organic polymer—is likewise still in a stage of much higher growth rate than that for population. In contrast, the principal natural polymer in terms of tonnage use—wood—reached a maximum in its annual growth rate shortly after the turn of the century, and the rate has fallen since then to approximately that of the population growth. Nevertheless, over the entire period since the early 19th century, wood has had the largest production and use of all the materials other than the nonmetallic minerals (Table 1).

Wood provides a particularly good illustration of the apparent tendency of a material in a given economy to reach steady-state levels in per capita consumption rate with time. In addition, wood is an instructive example of the dangers inherent in trying to predict future consumption for a given material by extrapolation from its historical behavior without considering the principal functional applications and the factors that might give rise to new ones (Fig. 3). In 1900, when per capita total use (or use intensity) of wood was still rising, the principal applications were in the form of fuel (the larger part of the "other" category) and lumber for construction. After 1910, these two applications declined in use intensity and absolutely. Over this same period, two newer applications—pulpwood (for paper products), and plywood and veneers—grew at rates much higher than that of the population. By 1940, their combined effect became sufficient to reverse the absolute decline in total wood use. Since then, the declining applications have been balanced by the increasing ones, with the result that the use intensity for wood as a whole appears to have become "saturated"—with corresponding implications for future demand for timber supplies, and for the intensity of environmental impacts resulting from wood production and use.

However, it is clear from Fig. 3 that this state of affairs is more apparent than real. What actually occurs to total wood use in the future will depend to a large extent on the character of the technological and social changes that develop outside the wood industry, as well as on the strength of the U.S. economy. An example is the rapid growth in the proportion of mobile homes in new housing construction over the past 25 years—homes that have tended to draw on a different mix of materials than the more traditional designs. Such changes demand functions that developments in wood technology can only attempt to provide

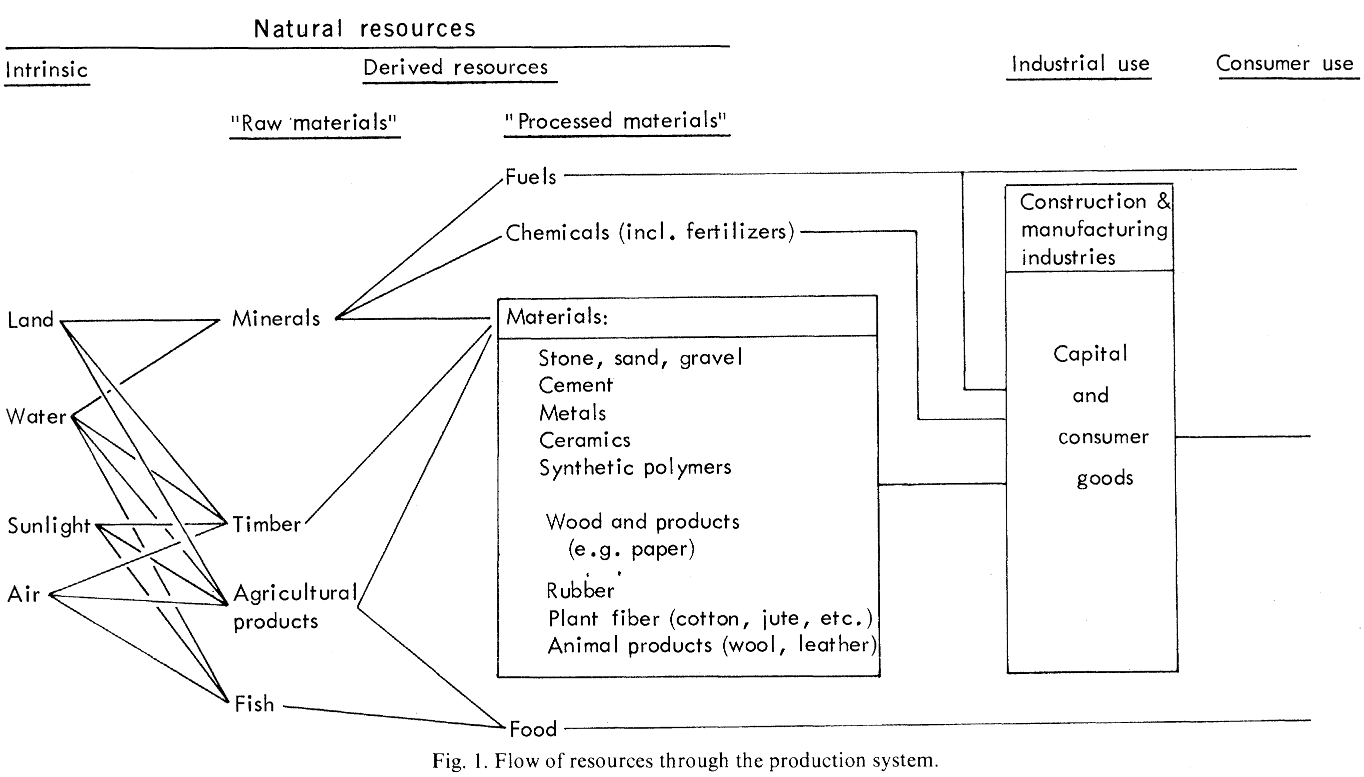

Fig. 1. Flow of resources through the production system.

more competitively than possible alternative materials. Some of these changes may be stimulated by the wood industry itself, as, for example, has been the case for chip board as a cheaper building material, but most are likely to arise elsewhere.

The above examination of use intensity for wood over a period of time supports the necessity for caution in extrapolating materials use intensities to forecast future consumption of specific materials. The forecasts for world consumption of major engineering and energy materials to the year 2000 prepared in 1972 for the U.S. National Commission on Materials Policy (*4*) are particularly open to question in this sense. The most detailed analyses concerning intensity of use draw on time series and cross-sectional information from different economies for examining relations among materials consumption, population, and GNP at different stages of economic development, and are coupled to micro- and macro-economic models for forecasting. Simpler variants of this approach applied to copper (*5, 6*), aluminum (*4*), and lead (*5*) indicate that, for aluminum and lead, the use intensity reaches saturation with increase in GNP per capita. However, for copper, there is disagreement as to whether saturation or a maximum occurs. The much more extensive analyses for steel (*7*), using a variety of modeling approaches, make it clear that, although the rate of growth of GNP is a key explanatory variable for steel consumption, several factors preclude accurate forecasting.

Thus, countries at the same stage of industrial development may have very different patterns of steel consumption, depending for example, on the presence or absence of a large steel user, such as shipbuilding. In addition, for the most advanced stages of development (in terms of GNP per capita), data are available only for the U.S. economy, and their utility is marred by disagreement among the models as to whether steel intensity is falling or constant at these higher levels of GNP. Likewise, the steel intensity behavior for Japan appears atypical. At present, it is apparent that theoretical understanding of the factors determining materials use intensities, even for relatively advanced countries, is at a very early stage of development.

Nonetheless, there are significant general indications of saturation in materials use levels as a function of disposable income. Likewise, evidence points to the importance of the technological character of the structure of a given economy in determining that level. The opportunities for a better grasp of the implications of further world economic growth for materials demand and the likely impacts that are offered by further improvements in this type of analysis are apparent. Of particular significance is the fact that, for the currently developing countries, the sequence of changes accompanying economic growth will not necessarily be the same as hitherto since the technologies used in their industries and infrastructures will have some opportunities to "leap frog" to the most modern forms. This is likely to occur even taking into account that appropriate technologies for many developing countries must be labor intensive if they are to contribute most effectively to raising economic well-being. The integration of use intensity analysis with the type of demand-sector approach used earlier by Landsberg *et al.* (*8*) to examine likely resource requirements for the United States appears to be a potentially promising combination for examining requirements for the world.

The second and third aspects of change—the economic and political—are so interwoven that they are most usefully considered together. The significant developments here relate to the growth, in the period following World War II, of pressures in both developing countries and the industrialized nations for greater economic autonomy in the face of the realities of increasing economic interdependence. The effectiveness of the action of the Organization of Petroleum Exporting Countries (OPEC) in October 1973 in exercising control, for both economic and political purposes, of the supply and price of oil as a central element of the world economy marked a specific point of change in the relations between advanced and developing nations. The basis for that change and its consequences for the future are clearly

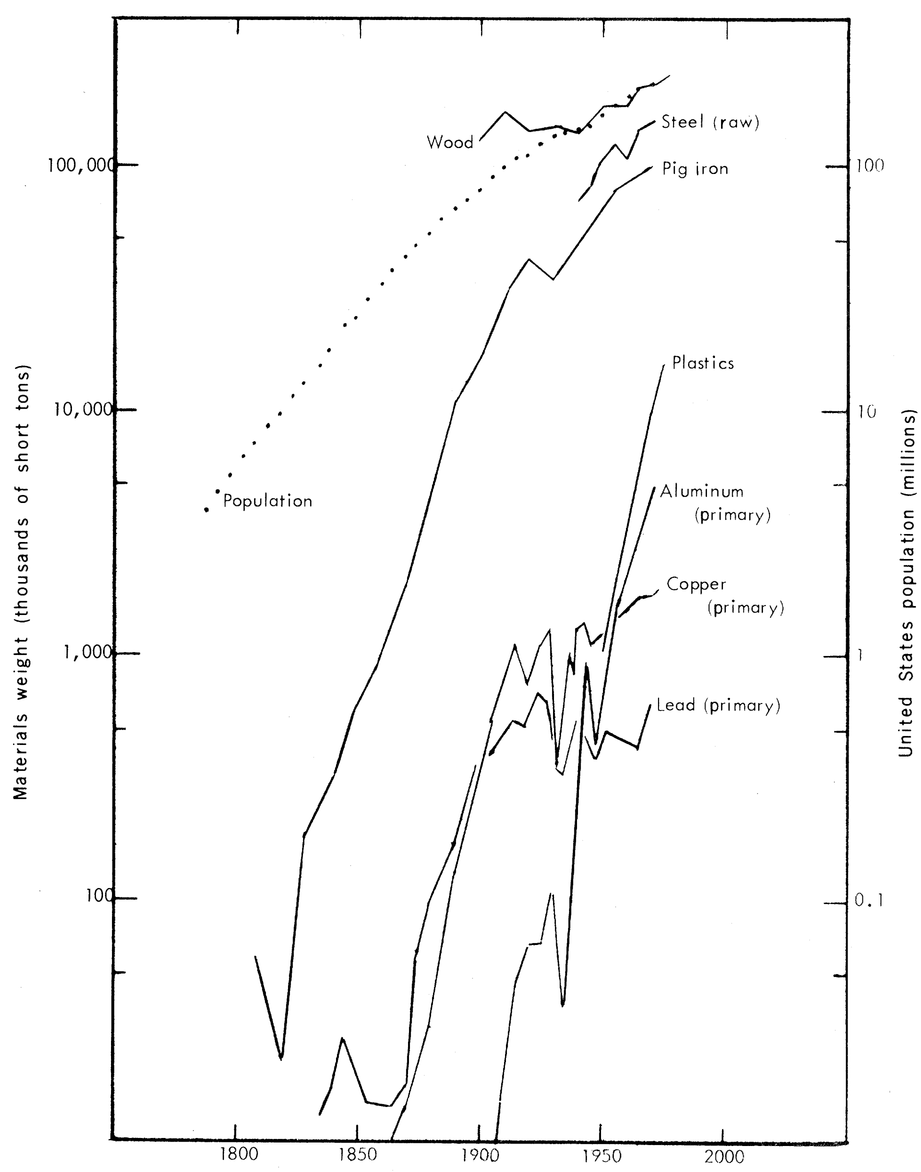

Fig. 2. Growth in the production of selected materials in the United States economy compared with the population growth since the early 19th century (*35, 36*).

much broader than the conditions under which oil (and other fuel minerals), food, and materials—the primary commodities—participate in world trade (*9, 10*). Nevertheless, the proven world interdependence of the producing and consuming countries for such commodities points to opportunities as well as problems. The potential mutual benefits to resolution of the so-called North-South confrontations on materials issues over the past two years (*11*) are a practical case in point, in addition to the currently more pressing and important one of oil.

The main changes demanding the attention of materials producers and consumers alike are (i) the increasing dependence of many countries on imports of materials, (ii) the greater uncertainty of their prices, (iii) the rising interest of producer countries (whether developing or advanced) in domestic ownership and management, and in shifting toward exporting locally processed materials rather than raw materials; and (iv) the tendency on the part of some developing country producers and producer associations to try to use control of materials access and price as an instrument of advantage in international business and political negotiations (*12*). Examination of the makeup of world trade in materials and recent trends suggests some areas of leverage and mutual advantage.

The composition of world export trade (Table 2) for 1971 (the period just prior to the boom in commodity prices during the worldwide period of rapid economic expansion of 1972 and 1973) indicates that primary materials constitute about one-third of total world exports; the inclusion of processed metals in that category would not change the proportion dramatically. Except for fuels, exports from the advanced countries have the largest share for each commodity class; that is, some industrialized countries are major producers and exporters of materials and food, as well as being major consumers (Table 2). Correspondingly, the degree of dependence on developing countries for supplies varies widely. In the case of materials, the United States, for example, imported only 5 percent of its materials requirements in 1973 from developing countries, although some of those imports are considered relatively critical for reasons of security or economic health. The European countries and Japan are much more dependent on imported materials generally (for more than three-fourths of their consumption as compared with about 15 percent for the United States) and on developing country sources particularly.

However, while the share of developing countries in primary commodity trade is not dominant, except for oil and some critical metals, such trade *is* dominant in their sources of export earnings, even after discounting oil. Thus, there is a convergence of the interests of such exporting producer countries with those of importing consumer countries in that both groups stand to gain by expansion of materials production and export by the producers, the one expanding its industrial base and the other gaining a supply of materials needed for its existing industry. Despite this fact, the trends over the past two decades have been toward only a modest expansion of such exports from developing countries in terms of current dollar values and a decline relative to food and fuel exports (Table 3). Furthermore, the data show the relative decline of nonfood agricultural materials (or natural polymers) from being twice the export value of minerals and metals in 1955 to being close to the same value in 1972.

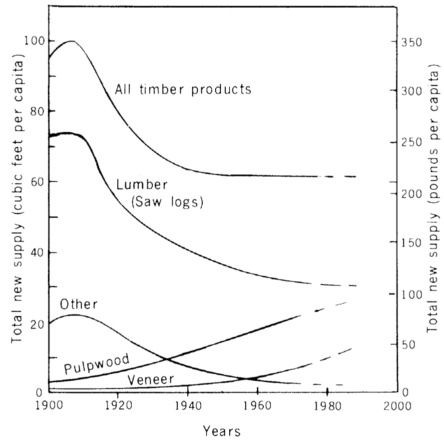

Fig. 3. Changes in the use intensities of wood and its principal functional applications in the United States economy since 1900 (*35, 37*).

For metals and minerals exports, which increased in absolute value almost three times over the period, the detailed statistics from which the data in this table were calculated show that the nonferrous group approached 60 percent of the export earnings from that sector, with copper minerals close to 60 percent of that amount. The aluminum mineral group increased in value fourfold over the period and shows a significant shift toward local processing. Thus, aluminum metal exports were 19 percent of the group value in 1972, up from essentially zero in 1955. Likewise, alumina (as opposed to bauxite) was up to 48 percent of the group value in 1972, compared with 18 percent in 1955.

The natural polymer sector, which includes the natural fibers, rubber, and wood, showed an increase of one-third in export value overall, but with absolute declines in jute, hard fibers, wood pulp, and rubber. The only strong increase was in wood, which increased by a factor of 3. (Correction of these various figures for inflation over the period would reduce the gains and increase the declines.) Over the past two decades, all these natural polymers have consistently lost markets to the synthetic polymers, which are derived largely from oil and natural gas and are manufactured almost entirely in the industrialized countries. With the exception of rubber and to some extent cotton, the intensity of research to improve the production, functional performance, and market competitiveness of the natural polymers has been minimal compared with the analogous efforts on the synthetics. Yet these nonfood agricultural products are strong elements of export earnings for a wide range of developing countries and are critical for some of the poorest. A good example of the latter is Bangladesh, which has derived as much as 85 percent of export earnings from a single natural product, jute. Thus, the further decline of the natural polymers in the export "basket" of the Third World countries could have significant effects on their rate of development over the next several decades, especially for those that lack or have been unable to develop mineral resources.

The preceding discussion points to the fact that, in practice, the major materials issues of the near- and medium-term future are concerned less with the "running out" of materials physically than with questions of their price and accessibility, and of shifts in the location of the materials industry (*13*). Thus, for 5 and 35 years into the future (that is, 1980 and 2010), the issues focus on continuity of economic activity and development in the industrialized countries, and stimulation of industrialization and economic growth in developing countries. While for many nations, the important issue of an adequate supply of strategic materials critical for military defense equipment must be addressed also, the character of contemporary defense strategies has, in principle, simplified resolution of that issue by use of stockpiles.

The issue of price involves both stability and level. Excessive price fluctuations make export earnings and the availability of foreign investment capital uncertain for developing countries, tend to add to inflation (since price reductions in primary goods are seldom reflected by proportionate reductions in the price of manufactured goods), and stimulate substitution by consuming industries. Price levels partly determine profitability and, correspondingly, the ability to attract investment for further resource development. The upward pressures on costs from accommodating increased energy prices (and pollution control costs in the industrialized producer countries), from higher costs of capital equipment due to inflation, and from increased economic rents sought developing countries, to the extent that they are passed on, both raise prices of manufactured goods and encourage materials conservation and substitution. There are indications that such pressures may be reversing the downward trend, apparent from the early 1900's, in the relative costs of materials in industrial production shown by Barnett and Morse (*14*). The second issue, materials accessibility, subsumes their physical availability and addresses both consumer access to supply and producer access to markets. It involves variations in supply due to production undercapacity, producer restrictions or embargoes, export controls, and commodity market instabilities. Likewise, access to consumer markets varies with import controls, duties, and trade barriers on processed materials. Finally, the third of these major issues, that of industry shift, relates to the interest of developing countries in using indigenous materials resources to accelerate economic development through "value-added" industries—that is, to export semifinished and finished materials rather than raw materials. Parallel to this interest is that of the world materials industries in locating production facilities so as to minimize overall costs of energy, pollution control, and transportation in the price of finished materials delivered to the major consumer markets.

Full recognition of the importance of these materials issues in international relations, and of the improbability of their resolution automatically by market operation or by such interventions as price indexing, has been relatively recent. Such recognition was included in the array of specific proposals for action put forward by the U.S. Secretary of State at the United Nations Seventh Special Session in October 1975. It is also emphasized by the inclusion of raw materials as one of four commissions (the others being energy, development, and finance) established at its initial working meeting in December 1975 by the Conference on International Economic Cooperation, as a forum for 27 nations representing the interests of industrial powers, oil-producing countries, and less fortunate developing countries.

The newness of such international activities emphasizes the present unreality of developing a world policy for materials; at best one can expect only guidelines and agreements on specific cases, especially in the face of the modest progress made up to now on the more pressing resource questions of food, energy, and environment. Nevertheless, there is much to be gained from efforts to develop a better framework for policy analysis relative to materials, rather than to continue to try to deal with specific questions in a compartmentalized manner. For minerals, both fuel and nonfuel, the concept of the "resource quadrilateral" frame of reference formalized by Connelly and Perlman (*15*) offers advantage in clarifying the different perceptions of the economic and political issues involving such energy and materials resources, together with the corresponding requirements from technology. The quadrilateral comprises four sets of countries grouped according to their relation to the major mineral resources—the "independent" exporters (Australia, Canada, U.S.S.R., and the People's Republic of China), the less-developed country exporters, the industrialized-country importers, and the poor countries that are deficient in mineral resources. The translation of this type of conceptual framework into one for renewable and nonrenewable materials resources merits attention as a context for the analysis of materials issues.

Even for individual nations, the formulation of materials policies that are both comprehensive and operational is lacking. In a few developing countries that are rich in one or two specific mineral resources, the simple operational mode of maximum mineral exploitation in a manner to enhance economic development coincides with materials policy in this sense. However, as an advanced country rich in both minerals and timber, Canada is more illustrative of the present stage of materials policy development. There, the most relevant policy analysis is an ongoing study of minerals policy (*16*) (defined as policy for nonfuel minerals as sources of metals, nonmetallic materials, and chemicals) undertaken cooperatively by federal and provincial governments. It is oriented primarily to resource supply, in that it examines how best to use a particular class of raw material. As such, it can represent only a component of a materials policy for Canada. Nevertheless, the approach is innovative and of broad implication conceptually. The analysis identifies some 13 mineral policy objectives in the context of the three broader national goals of economic growth and development, sovereignty and unity, and quality of life. It suggests four options as the major policy directions possible for Canada:

1) Continue, as in the past, to encourage maximum mineral production.

2) Encourage economic diversification and growth through increased mineral processing and mineral-based manufacturing in Canada.

3) Obtain the highest possible net financial return to Canadians from minerals.

Table 2. Origin and composition of world exports, 1971 (*33*).

Commodity	Billions of U.S. dollars (f.o.b.)			
	Total world export	Advanced market economies	Centrally planned economies	Developing countries
Manufactured and processed products*	233.3	193.5	24.2	15.6
Primary commodities				
Food	50.4	30.8	4.7	14.9
Fuels	35.9	8.8	3.6	23.5
Materials	28.2	16.6	3.4	8.2
{Nonfood agricultural	18.4	11.2	2.2	5.0}
{Ores and minerals	9.8	5.4	1.2	3.2}
Totals	347.8	249.7	35.9	62.2

*Includes metals as distinct from ores.

Table 3. Developing country trade in primary commodities, 1955–1972: distribution of export shares between and within major classes (*34*).

Commodity	Relative dollar value (percent)				
	1955	1960	1965	1970	1972
Food	39.6	37.0	36.5	32.0	30.0
Fuels	27.3	30.8	35.3	39.8	46.9
Materials	33.1	32.2	28.2	28.2	23.1
{Nonfood agricultural	22.2	20.2	14.9	12.1	11.5}
{Minerals and metals	10.9	12.0	13.3	16.1	11.6}
Dollar value (current dollars in millions f.o.b.)					
	21,911	24,798	32,035	45,480	57,640

4) Conserve mineral resources for long-term domestic requirements.

The analysis defines as overriding concerns that minerals be managed to make best contribution to overall Canadian policies and priorities, and to ensure that Canadian mineral needs be met (either from foreign or domestic sources). It concludes that option 1 is no longer appropriate and ranks economic diversification as the highest priority objective, with increased financial returns from exports next. One immediate result of the analysis has been the enactment of federal legislation designed to achieve additional mineral processing in Canada.

While the Canadian study is intended to provide a basis for public discussion rather than a blueprint for action and is restricted to minerals, it exemplifies the type of larger public policy perspective desirable for the analysis of issues of national materials policy. Various recent studies have been directed toward examining country or regional policies for materials—as part of natural resources policy in Norway (*17*) and Sweden (*18*); as minerals policy in France (*19*); as raw materials policy (but specifically excluding food policy and energy policy) by the European Community (*20*); as part of commodity trade policy by the United Kingdom (*21*); and in the United States with respect to labor policy (*22*); to "materials" policy for minerals (including fuels) and renewable materials (*4*), and to critical imported raw materials (*23*). To varying degrees, all of these studies exhibit shortcomings in delineating clearly the overall policy issues for materials and the time scales over which these issues can be expected to be important. Correspondingly, they generally fail to offer priorities of objectives and actions, or a rationale for articulating a coherent policy for materials, as opposed to de facto existing policies or ad hoc developments that are common in all countries. Too frequently, such analyses give rise to questions as to whether the "problems" defined or the "solutions" offered are indeed the most appropriate on the basis of rigorous analysis of the context of the issues and the options available to respond to them.

Nonetheless, although the experiences of the past decade have shown how difficult it is to develop national policies for the other key resource areas of food, energy, and environmental quality, such policies are emerging to provide guidelines for both public and private sector activities in domestic and international affairs. A clearer understanding of the materials system in the sense in which we are now beginning to understand the other derived resource systems of energy and food, as well as their interrelations to one another and to the environment, is a prerequisite to a productive attack on addressing issues and options for materials policy.

Perspective for Materials Research

The above discussion has indicated a perspective for materials research that is new in emphasizing shifts in the priorities of government attention and public concern in some of the industrialized countries from the earlier role of science and technology in stimulating innovation through new and improved technologies and products. Materials research has been a key factor in that previous role, with innovative contributions in the form of materials having new or better properties to meet the stringent performance requirements of advanced technologies in the then high priority areas of defense, atomic energy, space exploration, and communications.

In the advanced market economies, the thrust of publicly supported activities in science and technology over the past several decades has been directed to areas predominantly the responsibility of governments, or to other areas where contributions to national prestige or to the economy appeared promising, but where the relevant private interests were unable or unwilling to provide support (*24*). Recently, the importance of continued economic development in the advanced countries has been contrasted with the ineffectiveness in some of these countries of much private and publicly supported research for sectors of industry that are large factors in the economy and in employment; the situations in the United Kingdom (*25*) and the United States (*26*), for example, have been compared with the experience of Japan through the 1960's. Likewise, in developing countries, where investment in research has been necessarily more modest, analogous criticism is being directed to what is now construed as a previous overemphasis on basic science compared with the technological needs of such countries. Thus, in both industrialized and developing countries, there is currently a strong effort to better relate research emphasis to its potential and actual contribution to economic strength and development under the likely world conditions of the next several decades.

While the specific emphasis that is appropriate in materials research will vary in different countries, there are eight key categories through which science and technology can address issues of materials supply and demand (*27*). Increases in supply can be developed through: (i) advances in the understanding of mineral formation and the techniques for exploration, and of plant biochemistry; (ii) the creation of new materials or processes that open up new resources (for example, synthetic polymers, new mining techniques for minerals on land and in the oceans); (iii) improving the physical efficiency of the extraction of resources (for example, increased energy efficiency in processes for aluminum and steelmaking, or wood products); and (iv) developing lower cost alternatives for existing materials (that is, substitution of materials or systems to provide the same performance or function), including the possibilities for greater use of the more abundant materials, such as magnesium and silicon, or of renewable materials, including current organic wastes such as lignin. Likewise, opportunities for reducing demand for new supply lie in: (i) better integration of materials selection with component design to develop manufacturing processes that reduce materials loss during manufacturing; (ii) new or improved materials to permit engineering designs that reduce the amounts of material required to perform a given function (for example, miniaturization, as in solid-state devices, or improved reliability); (iii) conservation in use through improved materials performance that provides increased service life (for example, reduction in rates of deterioration by corrosion and wear); and (iv) improved recovery or direct reuse of materials during processing, manufacturing, and after completion of the useful life of capital or consumer goods.

Before these types of contributions can be effectively translated into specific research programs, a framework is needed in order to assess priorities of contributions and research. The study of materials science and engineering referred to earlier (*2*) identified for the first time the character of the total materials system in the larger economy as the basic reference frame against which to judge needs for materials research. At the same time, it clarified the complementary roles of materials research directed toward specific national goals or economic sectors—as for energy, health, or materials production—and of basic research that may have implications for several such sectors. Developments since then have been directed to improving quantitative understanding of the materials system, of its relation to broader domestic and international issues, and of the pattern of current emphasis in materials research in the advanced countries.

With respect to the latter, an initial analysis (*28*) of U.S. government-supported research and development defined the relative intensity of such effort across the materials system in terms of materials supply, utilization, and recovery; materials structure, properties, and performance; and materials-associated R & D on energy use in the materials system and with environmental effects resulting from its operations. More quantitative studies (*29, 30*) have confirmed the strong differences in effort among these areas and questioned the adequacy of relevant policies as guides for materials research (*29*). Such questioning reflects the fact that the current overall program, in contrast with that for federal energy research, is simply the sum of efforts of different government agencies directed to different national concerns.

Whether the present spectrum is indeed the most appropriate one can be judged only against an analytical overview of national needs concerning materials, together with an evaluation of the significance and cost of research contributions compared with other ways of meeting those needs. Such questions of the points of maximum leverage for research within the materials system in relation to specific national objectives—for example, to minimize import requirements or energy costs—are being explored in a study involving economic and physical modeling through the Organisation for Economic Co-operation and Development (OECD).

In conclusion, it is suggested that there are three approaches by which materials research might address, for both industrialized and developing countries, the needs of the transition period and the future that lies beyond it. The first is in further examining the present system of materials extraction through recovery to improve its quantitative analysis and understanding as a basis for decisions on materials research in relation to given national or international concerns. The second is in assessing materials needs of the future with respect to the major technological and economic changes that appear most likely in the world economy (*31*). The corresponding constraints and opportunities, including questions as to the sociological factors determining materials consumption, have implications for the strategies for current research. Finally, there is the question of evaluating the effort necessary in basic research to assure provision of science-driven opportunities for future technological change. For all three of these approaches, the new perspective argued here for materials research relates them to the changing character of the interplay between government and industrial support for science and technology and the needs of economic and social development.

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