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ENERGY SYSTEMS STUDIES PROGRAM

**REFERENCE MATERIAL SYSTEMS:
A SOURCEBOOK FOR MATERIAL ASSESSMENT**

N. BHAGAT, Editor

MASTER

December 1976

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December 1976

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FOREWORD

This set of reference information on renewable resources and certain selected nonrenewables has been assembled for the assessment of material technologies, i.e., identification of significant new R&D opportunities in the materials field, and for the analysis of renewable materials as substitutes for energy intensive nonrenewables.

In creating this assessment tool, it became abundantly clear along the way that while strong specialization exists in forest sciences and wood products on the one hand, and agricultural sciences on the other, a broader systems perspective of the renewable resources is lacking. Correspondingly, integrated statistical information on resources, material flows, and utilization including associated energy, cost and environmental aspects, is not readily available in the case of renewables. The situation is somewhat better, but still not satisfactory in the case of nonrenewables. In view of this consideration and somewhat stringent time and resource constraints, some glaring gaps in the information could not be avoided and one purpose of this report has been to identify such gaps. The most significant need is for improved information on the installation and maintenance of materials in their end use. This information is needed for the analysis of substitution and conservation options. This report should, therefore, be considered only a first approximation to what should ultimately be desirable in this sort of work. It is hoped that the experience gained in employing this tool will be used to develop this instrument further as a consistent framework for materials policy analysis.

Most of the information on renewable materials was obtained in consultation with the members of the Committee on Renewable Resources for Industrial Materials (CORRIM) which was set up under the auspices of the National Academy of Sciences to examine the role of renewable resources in meeting the nation's future needs for materials. Information on nonrenewables was based on various published reports and existing compilation of original data. Our specific debts to such sources are clear throughout the report.

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Abstract

This report presents a reference set of data related to material systems and a framework for carrying out the material technologies assessment.

While the bulk of renewables have been considered in this report, the nonrenewable materials dealt with here include structural materials only, such as steel, aluminum, cement and concrete, and bricks. The complete data set is supposed to include material flows, energy requirements, capital and labor inputs, and environmental effects for each process that a resource must go through to become a useful material for an end use. Although effort has been made to obtain as much information as possible, considerable gaps in data, apparent throughout this report, could not be avoided.

A new material technology can be evaluated by substituting that technology for appropriate elements of the reference materials system and calculating the net change in material resource, energy, capital and labor requirements, and environmental impacts. This combination of information thus serves as a means of evaluating the potential benefits to be gained by research in various material technologies.

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I. INTRODUCTION AND SUMMARY

Background

A comprehensive systems approach to materials policy and analysis, the Reference Materials System (RMS), has been used in this report to assemble information on renewable resources and certain selected nonrenewables. The RMS methodology was initially developed at Brookhaven National Laboratory in connection with research underway at this institution, supported by the U.S. Energy Research and Development Administration (ERDA), for the assessment of the materials for the energy system. This methodology is similar to that used by Brookhaven in support of energy planning and analysis for ERDA. The background of application of RMS methodology for the assessment of the material technologies considered in this report is as follows.

At the request of the Science and Technology Office of the National Science Foundation, a study was carried out, under the auspices of the National Academy of Sciences, on the role of renewable resources in meeting the nation's future needs for materials. The intent was to identify the most promising areas for substituting nonrenewables by renewables, which in turn will highlight the R&D programs needed to overcome the barriers to production and use of renewable resources. In other words, the objective was to make an assessment of new renewable material technologies so that the nation's renewable resources could be put to a greater use in meeting future needs for materials.

The concern of this study was with the long-term effects of the material system on the environment, on human welfare, and on the nation's natural resources. Thus, resource and environmental considerations, as well as internal costs, provide the basic criteria in evaluating new material technologies. All aspects of the material system were open for consideration, from growing and harvesting of resources through conversion technologies to the various means of using the materials.

One of the drawbacks of dealing with the renewable resources lies in the nearly complete absence of coherent statistical information on resources and technologies--those presently in use and others with potential for future applications. In view of this, a task force called Committee on Renewable Resources for Industrial Materials (CORRIM) was formed and was divided into several panels to evaluate particular technical areas in connection with renewable resources. Coordination and interaction between panels was accomplished

through a systems panel. The final overall assessment was made by the executive committee, which was responsible for drawing conclusions from the study and for developing recommendations.

The major technological areas considered in relation to renewable resources by various panels were

- Materials for structural purposes
- Materials for fibers
- Extractive materials
- Lignocellulosic materials
- Materials for source of energy
- Productivity (resource base) for materials

The first task before CORRIM, in order to make the required materials assessment, was to assemble coherent and integrated information on resources and technologies. In doing so, it was important that the various panels operated within the same framework. They had to use a common set of assumptions regarding the future of the materials system and the characteristics of the existing technologies. They also had to address the same basic questions, insofar as applicable, and use common economic ground rules. Apart from being just a data base format, the materials systems framework also had to be used for the purpose of technology assessment, i.e., the identification of significant new R&D opportunities in the renewable materials field. In this context again, it had to be made sure that the assessments done by various panels were consistent so as to facilitate intercomparison of the benefits that would accrue from the R&D under consideration. The above requirements along with the diversity and complexity of the materials system, placed a premium on integration and simplification as the two features of the materials framework. In view of these considerations, RMS was adopted by CORRIM as the data base format and material assessment tool at an early stage of its study.

RMS Methodology

The RMS facilitates the integration of diverse information on the technical, economic, and environmental aspects of the materials system in a consistent manner. It also provides a technique for the rapid assessment of a materials substitution strategy or a new technology.

The concept of an RMS is straightforward. It is a description of the major components of the material system, specifying the processes ranging from extraction of resources through their refinement, transportation,

fabrication, and installation at the point of end use. The scope of the RMS is outlined in Figure 1. At the left hand side is a listing of resources corresponding to the materials to be considered, while the products and end uses are listed on the right hand side. The series of "activities", e.g., growing, harvesting, transportation, and fabrication, that a typical resource must go through to become a useful material for an end use are listed at the top of the figure. A completed RMS is a network representation of the flow of materials from the resource side through all the "activities" to the end uses. A path from a specific resource to a specific end use is called a trajectory. Each activity in the trajectory represents a technical process or production step that is characterized both by a flow element and by several data elements (e.g., land use, energy requirements, fertilizer and chemicals, labor, and cost).

To use the RMS in evaluating the impact of a new technology, the characteristics of the technology must first be defined in terms of resource consumption, environmental effects, energy consumption, and economics. Taking into consideration its rate of implementation, the new technology can then be inserted into the RMS to produce a Perturbed Material System (PMS). The impact of the new technology may then be evaluated by comparing the resource consumption, cost, environmental effects, etc. for the PMS with those of the RMS.

Summary

A complete RMS based on panel inputs, developed for the historical year 1972, is shown in Figure 2. The purpose of this representation is to provide an overview of the system and illustrate the interfacing between the panels' work. As an example, productivity and structural panels show logging and mill residue respectively, as outflows, while these residues are shown as inflows in the fiber trajectory. Similarly, dissolving pulp and spent liquor produced in the pulping process in the fiber trajectory are shown as inputs to lignocellulosic and extractive trajectories, respectively. This system serves to match such intertrajectory flows and thus acts as a guide to how the various trajectories, described in detail in section IV, fit together. In addition, a highly aggregated view of the Materials System is shown in Figure 2A, which displays material flows in aggregate form, as they existed in 1972. Energy requirements corresponding to these material flows, at the same level of detail, are presented in Figure 2B. These requirements may be converted to

unit requirements on the basis of either a pound of material throughput for an activity or some unit of the final material product delivered to an end use.

In section II, economic guidelines useful for compiling information on future RMS's are described. Section III deals with productivity information that cuts across the work of all other panels. Major sectors of the renewable material system and substitutable nonrenewables have been presented in RMS format under separate chapter headings in Section IV. RMS trajectories corresponding to these sectors are shown in figures at the end of the text. Arrangement of these figures is described at the beginning of section IV. Substitution (nonrenewables by renewables) analyses have been included wherever possible, and the deficiency of the system's data is also discussed in this section.

II. ECONOMIC GUIDELINES AND ASSUMPTIONS

This section outlines the economic projection guidelines developed for use by the panels. These projections provided a guide for estimating renewable resource usage in the years 1985 and 2000 under three sets of assumptions:

- a. A base case representing lowest use of renewable versus non-renewable resources under the assumption of "business-as-usual"
- b. A medium perturbation case representing increased potential for substituting renewable for nonrenewable resources
- c. A high perturbation case representing the greatest foreseeable potential for substitution.

Basic population-economic projections are presented below, followed by relative price assumptions to be used for each of the three cases.

Population-Economic Projections

Basic assumptions for the year 2000 scenarios are as follows:

Population of 264 million

Modest prosperity

High environmental concern

Increasing competition for land

This population projection is consistent with the 1972 OBER's Projection,⁽¹⁾ Series E. Estimates of population, households, and per capita income to the year 2000 are presented in Table II-1. These estimates were used for material flow projections for all three cases.

TABLE II-1
POPULATION-ECONOMIC PROJECTIONS

Year	Population ⁽¹⁾ (millions)	Number of Households ⁽²⁾ (millions)	Per capita income ⁽¹⁾ (1972 dollars)
1970	204	63	3599
1972	209	65	3843
1980	224	77	5700
1985	235	84	6500
1990	246	90	7400
2000	264	100	9800

Institutional Framework

The major feature of this assumption is that the nation will retain a private market economy through the year 2000, i.e., the renewable resource sectors will be constituted primarily of private business and private consumption.

Relative Price Projections

Three sets of future price relationships are presented below for the three cases analyzed. Relative prices are an unknown parameter with regard to the future, and this uncertainty is handled by making the best possible estimate of the range over which relative prices may change. The worst relative price projection for renewable versus nonrenewable resources is then assumed for the base case, and the best relative price advantage is assumed for the high case. Relative prices half-way between these assumptions are used for the medium case.

Under all these price scenarios it is assumed that, by and large, there will be ample supply of renewable and nonrenewable materials at the prices projected.

1. Oil prices:

- Base case - ca. 1972 (pre-cartel).
- Medium case - 1975 oil prices.
- High case - higher than 1975 oil prices;
much higher than 1975 oil prices.

2. Prices of structural nonrenewable resources (iron, aluminum, non-metallic materials) vs. structural renewable resources (lumber, plywood, board products):

- Base case - constant relative prices, $NRR/RR^* = 1.0$
- Medium case - $NRR/RR = 1.2$.
- High case - $NRR/RR = 1.4$.

Demand elasticities (long-run) for lumber, plywood, and board products are shown in Table 11-2. Taken from The Outlook for Timber in the U.S.⁽³⁾ (p. 150), change in demand resulting from a sustained annual 1% decrease in relative prices of renewables is shown (corresponding to an ~30% decrease

* NRR = prices of nonrenewable resources; RR = prices of corresponding renewable resources.

in relative prices by 2000 or halfway between the medium and high case assumptions). An approximation to the medium and high cases for structural materials can thus be made by taking two-thirds of the increase in demand shown in the table for the medium case and four-thirds of the increase shown for the high case.

TABLE 11-2
Increase in Demand (%)

No. of years after relative price decrease	Lumber, Plywood	Board products
1	0.1	0.05
5	0.3	0.1
10	0.5	0.2
15 (extrapolated)	0.8	0.3
30 (extrapolated)	1.5	0.5

3. Prices of nonrenewable construction materials (aluminum, steel, cement, glass, etc.) vs. renewable construction materials (wood):

- Base case - Constant relative prices through year 2000.
- Medium case - $NRR/RR = 1.4$.
- High case - $NRR/RR = 1.8$.

The demand elasticities used for structural resources can also be used here in projecting 1985 and 2000 material flows for the medium and high cases.

4. Prices of nonrenewable fiber materials vs. renewable wood fiber materials:

- Base case - Constant relative prices.
- Medium case - $NRR/RR = 1.3$.
- High case - $NRR/RR = 1.6$.

Long-run demand elasticities for paper and paperboard products are shown in Table 11-3. Taken again from The Outlook for Timber in the U.S. ⁽³⁾ (p. 150), the figures show change in demand resulting from a sustained annual 1% decrease in relative prices for renewable materials (corresponding to an ~ 30% decrease in relative price by 2000). These values are used directly for medium case projections and are doubled for high case projections.

TABLE 11-3

No. of years after relative price decrease	Increase in demand for Paper and Paperboard Products (%)
1	0.05
5	0.1
10	0.2
15 (extrapolated)	0.3
30 (extrapolated)	0.5

III. PRODUCTIVITY

The productivity of natural ecosystems represents a wealth of resources, with forests the major contributors to the renewable resource material flows.* Forest products ultimately supplied include lumber, veneer, plywood, paper products, and chemicals. The Department of Commerce (1974) expects that, this year, lumber production will exceed 37×10^9 board feet valued at $\$8.8 \times 10^9$, plywood production will be 18.1×10^9 square feet with a value of $\$1.85 \times 10^9$, and paper production will be 69.8×10^6 tons (650 lb/capita) with a value of $\$16.4 \times 10^9$.

The United States consists of about 2.2 billion acres. Of these ≈ 753 million acres are forest, with ≈ 500 million acres of commercial timberland. This acreage can be divided into four major timber regions: Northern, Southern, Rocky Mountain, and Pacific Coast.

TABLE III-1
Commercial Timberland Acreage, Softwood Volume, Hardwood
Volume, and the Ratio of Softwood to Hardwood Volume

Region	Softwood		Hardwood	Softwood/ hardwood
	Acres $\times 10^6$	volume $\times 10^9$ cf.	volume $\times 10^9$ cf.	
Northern	175.5	40	119	0.34
Southern	190.6	80	82	0.98
Rocky Mountain	61.1	88	5	17.6
Pacific	67.2	225	15	15.0

Each of these forest regions has different species compositions and volumes of timber. Table III-1 summarizes acreage, softwood volume, and the ratio of softwood to hardwood for each of the four regions.

* In the RMS for renewables, forests are the primary resource base considered. Early in the study it was estimated that about 85% of the renewable materials would come from forest resources, 10% from cotton production, and 5% from other renewables.

Within each region there are four categories of commercial timberland: national forests, other public forests, industrial forests, and miscellaneous private forests. The national forests are administered by the U.S. Forest Service, while the other public forests are administered by local, state, and other federal agencies. Industrial forests are owned by corporations, while the miscellaneous private forests, often called the third forest, as opposed to industrial and public forest lands, consist of forested tracts owned by individuals. Table III-2 summarizes the acreage by forest and region.

TABLE III-2
Millions of Acres in Each Class of Forest in Each Region

Region	National forest	Other public forest	Industrial forest	Miscellaneous private forest	Total
Northern	10.4	21.1	17.8	126.2	175.5
Southern	10.7	6.4	35.9	137.6	190.6
Rocky Mountain	39.5	7.1	2.3	12.2	61.1
Pacific	30.7	8.9	12.4	15.2	67.2
Total	91.3	43.5	68.4	291.2	494.4

Although it is only after several years of growth that trees are harvested, it is important to know the annual rate of production of merchantable growth. Table III-3 summarizes the total volume of merchantable growth produced annually in each forest region in each class of forest. The annual rate of growth is the upper limit to the rate of removal of the forest resource. Indeed, sustained long-term harvest may be well below the annual growth rate.

TABLE III-3
Millions of Cubic Feet of Potentially Merchantable Timber Produced
Annually in Each Forest Region and Class

Region	National forest	Other Public forest	Industrial forest	Miscellaneous private forest	Total
Northern	410	703	712	3,686	5,511
Southern	594	299	1,931	5,846	8,670
Rocky Mountain	892	168	--	320	1,380
Pacific	843	552	814	889	3,098
Total	2,739	1,722	3,457	10,741	18,659

Of the 18.7×10^9 cubic feet of merchantable timber produced in all forest classes during 1970, $\sim 14 \times 10^9$ cubic feet were removed. Removals supplied five major demands: pulpwood, veneer logs, saw logs, miscellaneous industrial roundwood, and fuel wood. Table III-4 summarizes the volume of removals from each forest class for each of the five demands.

It is extremely difficult to obtain information regarding production costs for commercial timberlands. This is partially due to regional differences in forest productivity, differences in management activities for the four classes of forests, and in large part the unwillingness of forest products corporations to share information concerning the costs for labor, materials, fuels, fertilizer, etc. per unit of production. It is even more difficult to measure the tangible effects upon future forest productivity of present research programs (e.g., fertilization studies, genetic improvement programs, etc.). However, using the annual timber production in 1970 of 18.7 billion cubic feet, forest management costs per cubic foot of production can be estimated from information contained in The Outlook for Timber in the United States.⁽³⁾

Table III-5 summarizes estimates of forest management costs.

TABLE III-4

Millions of Cubic Feet of Timber Harvested From Each Forest
Class to Supply Specified Demands

Demand	National forest	Other public forest	Industrial forest	Miscellaneous private forest	Other sources	Total
Pulpwood	233	169	901	2,431	441	4,175
Veneer logs	253	95	359	374	94	1,175
Saw logs	1,360	503	1,859	2,656	289	6,667
Miscellaneous						
Industrial						
Roundwood	43	26	100	258	54	481
Fuel Wood	13	15	87	270	281	666
Residue	283	139	424	409	---	1,255
Other removals	59	117	498	63	---	737
Total removal	2,244	1,064	4,228	6,461	---	13,997
Total production	2,739	1,722	3,457	10,741	---	18,659
Production less removals	495	658	-771	4,280	---	4,662

TABLE III-5
Cost of Forest Management Practices in 1971 (1972 Dollars)

Practice	Total cost (millions of dollars)	Acreage (millions of acres)	Cost per acre of resource (dollars)	Cost per thousand cubic feet of production (dollars)
Fire control	266	500	0.53	14.22
Pest control	13	500	0.03	0.70
Reforestation	106	500	0.21	5.67
Fertilization	---	0.15	---	---
Research	213	500	0.43	11.39
Total	598		1.20	31.98

Five major activities are associated with the removal of forest production: harvest planning and layout, road construction and maintenance, stump to mill handling, equipment maintenance, and supervision. The structural materials panel has made estimates of the man-hours, energy inputs, and capital costs per unit of removal in the Pacific and Southern forest regions. Table III-6 summarizes labor, fuel, and capital inputs per cubic foot of timber removed in the Pacific and Southern regions. A mean value for each input is also given. Table III-7 applies the mean values to the 14 billion cubic feet of timber harvested in 1970. Table III-8 converts the labor and fuel inputs to dollars. An average hourly wage of \$4.05 and a fuel cost of \$0.30/gal are assumed. The hourly wage is based on information in the 1972 Census of Manufacturers for logging camps and logging contractors. The average cost per cubic foot of timber removed is \$0.19. Combining the per cubic foot production cost (Table III-5) with the removal cost (Table III-8), the total cost for producing and removing one cubic foot of timber is estimated to be \$0.22.

TABLE III-6
Forest Harvest Labor, Fuel, and Capital Inputs for 1972

Region	Man-hours per cubic foot	Gal. fuel per cubic foot	Capital, dollars per cubic foot
Pacific	0.025	0.0548	0.0213
Southern	0.046	0.0605	0.0341
Mean	0.0355	0.05765	0.02635

TABLE III-7
Estimated Inputs of Labor, Fuel, and Capital for National Annual
Timber Harvest of 14.0×10^9 Cubic Feet

Timber harvest, 10^9 cubic feet	Labor, 10^6 man-hours	Fuel, 10^6 gallons	Capital, 10^6 dollars
14	497	807	369

TABLE III-8
Estimated Cost of Forest Harvest Labor, Fuel, and Capital Inputs
for National Annual Timber Harvest of 14.0×10^9 cubic feet

Timber harvest, 10^9 cubic feet	Wages, 10^6 dollars	Fuel costs, 10^6 dollars	Capital, 10^6 dollars	Total 10^6 dollars
14	2,012	242	369	2,623

Energy required for the production and removal of a cubic foot of timber can also be estimated. Assuming the energy required to produce a cubic foot of timber is one-tenth the energy expended to remove a cubic foot of timber, the total fuel input is ≈ 8000 Btu per cubic foot. Therefore, producing and removing 14 billion cubic feet of timber annually would require about 112×10^{12} Btu.

Major policy issues influencing forest productivity include maintenance of intensive forest management, thinning, tree improvements, fertilization and site class improvement, and withdrawal of forest acreage.

The following excerpts from the report of the productivity panel are germane to the above issues.

Any effort to estimate the total productivity of the U.S. forests must be highly tentative and based upon assumptions that greatly simplify the actual situation. However, it can be said that forest management over the past 20 years has been steadily growing more intensive, and we find that the United States, with an annual harvest of 14.0 billion cubic feet of wood in 1970, could produce 17.5 billion cubic feet in 1985 and 20.3 billion cubic feet in 2000.

Using the following assumptions, and rounding off each category to the nearest million acres, the acreage of softwoods would be increased from 242 million to 261 million acres despite the overall loss of 20 million acres of commercial forest land, and most of this increase would be on the better sites.

Assumptions:

1. The acreage of commercial land is expected to decline from 495 million to 475 million acres, the level predicted in the Outlook Study for the year 2020.
2. All Site* I, II, and III nonstocked lands, 3 million acres of Site IV lands, and 1 million of Site V would be reforested with softwoods.
3. 4.9 million acres of Douglas-fir types would be raised one site class through nitrogen fertilization, and 5.8 million acres of southern pine types would also be raised one site class through drainage and phosphate fertilization.

* I through V are the site quality ratings based on yields (c.f./acre/yr).

These yields are: I and II ~ 160 ; III ~ 110 ; IV ≈ 70 ; V ~ 40 .

4. 15 million acres of pine and hardwood, and 5 million acres of upland hardwood in the South would be converted through clearcutting and planting to southern pines, with an average increase in site quality of one class due to the faster growth rate of pines on these sites.
5. Commercial forest lands would be kept well stocked with desirable species by planting and weeding as needed to produce 90% of yield table growth on Sites I and II, 80% on Site III, 70% on Site IV, and 60% on Site V.

The potential productivity of softwoods is >17 billion cubic feet per year, and that of hardwoods is >11 billion, for a total of 28 billion cubic feet. This estimated productive potential is twice the 1970 consumption of 14 billion cubic feet. Anticipated production is 67 cubic feet per acre for softwoods and 56 cubic feet per acre for hardwoods. For all species, it is 62 cubic feet per acre, compared with the present actual rate of 30 cubic feet per acre per year.

In general, normal yield table values can be increased by 25% by regular thinnings on areas clearcut and planted with softwoods, and growth would be increased by ~ 1% per year if tree improvement programs were vigorously applied.

Applying the potential gain in growth from thinning and genetic improvement, an increase in the productive potential of 760 million cubic feet annually in the Douglas-fir region and 1119 million from southern pine is predicted. Adding these two gains to the intensive management estimate, a total biological productive potential of 19 billion cubic feet for all softwoods and >30 billion cubic feet for all species is predicted.

It seems that it is entirely feasible to double the production of wood from the forests of the United States through the application of present technology while continuing to manage our forests on a sustained yield basis.

IV MAJOR SECTORS OF THE MATERIALS SYSTEM

Seven major sectors are considered here under separate headings: (a) Productivity, (b) Structural Materials, (c) Fibers, (d) Extractives, (e) Lignocellulosic Materials, (f) Fuels, and (g) Nonrenewables. The figures showing the RMS trajectories and subtrajectories corresponding to these sectors have been put together at the end of this report. In order to display as many data elements as available, the RMS trajectories of renewable resources used as structural materials, fibers, extractives and lignocellulosic materials were broken down into eleven subtrajectories and are shown in figures 3 through 13. The matching of these subtrajectories is facilitated by identifying these on the master RMS and by indicating for each subtrajectory, inputs from the preceding and outputs to the succeeding subtrajectories.

Four copies of each of these figures, designated A through D, are used to display material flow, energy, labor and capital costs, respectively. The figures are arranged in serial order so that all four copies, i.e., A, B, C, and D of a figure appear before the next figure number appears. If no information on a particular data type is available for any subtrajectory, it is excluded and, therefore, the numbers do not always run consecutively. Complete trajectories and the corresponding data for other sectors, i.e., fuels, nonrenewables, and containers and packaging are confined to one figure each.

The list denoting the major sectors that the figures represent and the type of information they contain is included at the beginning of this report.

IV (a) PRODUCTIVITY

The RMS for productivity is divided into two parts, one for forest productivity (Figures 3 and 4) and the other for agricultural, marine, and other resources (Figure 5).

Forest Resources Productivity

Source: The information in Figures 3A and 4A came from The Outlook for Timber in the United States, 1970.⁽³⁾ Projections for 1980 were used to interpolate 1972 estimates from the 1970 data. Acreages were taken from 1970 data. In order to display the timber inventory and growth data in a more meaningful way, many of the data from the Timber Outlook were recalculated.

For example, the Timber Outlook does not include a breakdown of growth by class of ownership and geographical area. This was calculated with use of ratios developed from information presented in other forms.

Data Mismatches and Discrepancies: Since the 1972 growth and harvest data are interpolated by using projections made for 1980, they are unlikely to accurately reflect the actual 1972 figures. The Census of Manufactures provides data on wood consumed in the manufacture of various wood products, and this information can be used in place of the estimated data on timber removals from the Timber Outlook, if greater accuracy is desired.

Agricultural and Other Productivity

Source: The trajectories and mass flows in Figure 5A were provided by panels on fibers and extractives. In the case of agricultural and animal products, these trajectories were modified to fit the requirements of the RMS in consultation with members of the fibers panel.

Data Mismatches and Discrepancies: The mass flows of wool, provided by the USDA Economic Research Service, ⁽⁴⁾ and of cotton, provided by the National Cotton Council, ⁽⁵⁾ do not account for all of the wool and cotton used in 1972 as indicated by the 1972 Census of Manufactures ⁽⁶⁾ for the textile industry. Acreages of available crop and range land and the amount planted in various crops could not be obtained.

IV (b) STRUCTURAL MATERIALS

The RMS for this sector is broken down into two sequential parts, shown in Figures 6 and 7 respectively.

Source: Most of the information on material flows, energy, man-hours, and capital costs displayed in the structural sector trajectories was provided by the structural materials panel. The Timber Outlook ⁽³⁾ was used as the data source for materials inputs from the productivity sector to the structural sector in the year 1972. The mass flows for end uses were extracted from the 1972 Census of Manufactures. ⁽⁶⁾ All data on energy, capital costs and man-hours, supplied by the structural panel, were converted to a "per pound" basis for consistency and displayed as such on the trajectories.

Data Deficiencies: Data in the "Additional Fabrication" (or Erection) column were not available at the level of detail desired so aggregation had to be done in this part of the trajectory. Although materials flow data for 1972 is nearly complete, several other data gaps could not be avoided.

IV (c) FIBERS

The RMS for fibers is divided into two parts, one for pulp and paper (Figures 8 and 9), and the other for textiles (Figure 10 and 11).

Pulp and Paper

Source: The wood fibers inputs in Figure 8A are from The Outlook for Timber in the United States.⁽³⁾ Cubic feet volume was converted to oven-dry (OD) pounds using average weighted densities⁽⁷⁾ for roundwood pulpwood of 29.5 OD lbs/ft³ and for mill residue chips of 28.1 OD lbs/ft³. Import and export figures came from the 1972 FAO Yearbook of Forest Products⁽⁸⁾ data converted to oven-dry pounds. The remaining mass flows in Figures 8A and 9A were taken from the RMS prepared by the fibers panel. This data was in air-dry tons and was converted using factors of 1800 OD lbs/air-dry ton for pulp, and 1900 OD lbs/air-dry ton for paper.⁽⁷⁾ The fibers panel had obtained most of the data from the American Paper Institute,⁽⁹⁾ and some from the 1972 Census of Manufactures.⁽⁶⁾ Energy and man-hours data (Figures 8B and C) were taken from the 1972 Census of Manufactures⁽⁶⁾ and divided by the respective mass flows.

Data Mismatches and Deficiencies: The pulpwood inputs were projected from 1970 data as noted in the discussion on productivity. The Census of Manufactures⁽⁶⁾ gives pulpwood consumption figures by mill type for 1972 and this data should provide a better match with the remaining pulp and paper flows. The detailed breakdown of converting operations and end use categories was not used in preparing this RMS because of unavailability of disaggregated data.

Textiles and Apparel

Source: The inputs in Figure 10A comprise of fiber materials from productivity (Figure 5A) and lignocellulosic (Figure 13A) sectors. The remaining flows were calculated from the 1972 Census of Manufactures.⁽⁶⁾ Up to the fabrication step, all flows could be kept in pounds; however, data on products such as carpets are available in traditional units of square yards, and no satisfactory conversion factor was available. Therefore, the traditional units are used in Figure 11A. Energy and man-hour data (Figures 10B and 10C, 11B and 11C) were extracted from the Census of Manufactures.⁽⁶⁾

Data Mismatches and Deficiencies: The mass flow inputs in Figure 10A do not match those in the transportation column, which were taken from the "materials consumed" tables in the Census of Manufactures.⁽⁶⁾ No satisfactory explanation was found for the inconsistency in the two sets of data, and therefore this mismatch remained unresolved. Some of the links do not have mass flows in the "additional fabrication" and "end use" columns of the trajectory because several diverse products combine along such links.

IV (d) EXTRACTIVES

Source: Most of the quantities on mass flow, energy, man-hours and capital cost displayed in the trajectories on extractives were provided by the extractives panel. The RMS for this sector is shown in Figure 12.

Data Deficiencies: Several mass flow data are missing and the information on energy, labor, and capital requirements is extremely sparse. In addition, projections for the years 1985 and 2000 are not available.

IV (e) LIGNOCELLULOSIC MATERIALS

The RMS for lignocellulosic materials sector is shown in Figure 13. The major material inputs to this trajectory are dissolving pulp and pulping co-products and by-products from the fibers' sector (Figure 8). Agricultural residues (oat hulls and corncobs) from the productivity sector (Figure 5) constitute other input materials. The outputs of this sector are chemicals, and fibers that are used as inputs to weaving mills for production of fabrics (Figure 10 and 11).

Source: The trajectory and the data in Figure 13 were developed in conjunction with the lignocellulosic panel.

Data Mismatches and Deficiencies: Several contradictions were noted with respect to the total amount of dissolving pulp and chemical cellulose produced in 1972, as reported by the 1972 Census of Manufactures,⁽⁶⁾ the Daily News Record of June 16, 1975, the Stanford Research Institute's Chemical Economics Handbook,⁽¹⁰⁾ and the American Paper Institute.⁽⁹⁾ In this report, the Daily News Record data were used at the suggestion of the lignocellulosic panel. Data on energy consumption and man-hours are available on an aggregate basis in the 1972 Census of Manufactures,⁽⁶⁾ but transformation to conform to the activities' classification shown on the RMS trajectory was not possible.

IV (f) FUELS (11-16)

Biomass is a renewable resource that has significant potential as a source of energy. Several potential sources of biomass are available. Formal plantation entailing the cultivation of selected, high-yield plant species, e.g., red alder, for the sole purpose of biomass production constitutes one source. Reported growth for red alder stands in the Pacific Coast area ranges from 4 to 33 tons/acre-year. Marine plantations are another source of biomass that require further exploration. Other biomass sources include natural land vegetation produced under natural conditions and agricultural/forest wastes and residues. Environmental implications of harvesting wild vegetation warrant close inspection of exploitation of this resource. Agricultural/forest wastes and residues constitute an impressive tonnage of biomass when viewed on the national scale. According to a Bureau of Mines ⁽¹³⁾ study, 650 million dry tons of such residues are generated in the United States each year. Still another source of biomass is provided by municipal waste. One estimate ⁽¹⁴⁾ of collected or collectible municipal waste biomass in the U.S. is 170 million tons/year.

The following conversion schemes provide the most feasible alternatives to obtaining fuels from biomass:

- . Electric power generation by direct combustion or low Btu gas/combined cycle
- . Production of methanol
- . Production of substitute natural gas (SNG)

In Figure 14 the RMS trajectory incorporating the above conversion technologies is shown. For the purpose of comparison, the trajectory for coal conversion to the same end-use fuel forms is included. Numbers in parentheses below the activity links are the process efficiencies, and those just above the product names are their heating values. No mass flows are shown, since commercial biomass-to-energy conversion did not exist in 1972. Table IV-1 includes various conversion costs (capital plus O&M) in aggregated form.

Assuming the price of coal to be \$10/ton or 50¢/10⁶ Btu, the cost of electricity by direct combustion of coal is \$3.49/10⁶ Btu, obtained by summing the conversion and fuel cost. For biomass to be competitive with coal for power generation, its price should be no more than 57¢/10⁶ Btu which is the difference between coal-to-electric total cost and biomass-to-electric conversion cost (from Table IV-1). This is equivalent to \$9.12 per ton of agricultural/forest waste assuming biomass to have an average heating value

Table IV-1

Energy from Biomass Conversion--Costs and Efficiencies

Energy Resource	Heating Value Btu/lb	Energy Products					
		Power (by direct Combustion)		Methanol		Synthetic natural gas	
		Efficiency of conversion	Cost (a) (Capital + O & M), \$/10 ⁶ Btu	Efficiency of conversion	Cost (a) (Capital + O & M), \$/10 ⁶ Btu	Efficiency of conversion	Cost (a) (Capital + O & M), \$/10 ⁶ Btu
1. Coal	~ 10,000	0.36 ^(b)	(1.81 + 0.294) ^(b) = 2.104	0.50 ^(c)	(0.64 + 0.53) ^(c) = 1.17	0.62 ^(c)	(0.66 + 0.26) ^(c) = 0.92
2. Energy plantation or agricultural/forestry waste & residues	~ 8,000	0.34 ^(b)	(1.53 + 0.294) ^(b) = 1.824	0.40 ^(b)	(0.912 + 0.86) ^(c,d) = 1.772	0.60 ^(b)	(0.594 + 0.26) ^(b,c) = 0.854
3. Municipal waste	~ 4,500			0.40 ^(b)	(1.27 + 1.44) ^(c,d) = 2.71		

(a) Costs are based on an approximate plant size of 250x10⁹ Btu/day.

(b) From Ref. 15

(c) From Ref. 16

(d) From Ref. 14

Notes: 1. Total collected or collectible municipal waste is 170x10⁶ dry tons annually.

2. Logging and mill residues amount to 23.9 & 24.3 million tons, respectively, per year.

3. Total agricultural/forestry wastes and residues equal 650 million dry tons each year.

of 8000 Btu/lb. Similarly, maximum competitive prices of biomass can be computed for other conversions, as tabulated below.

<u>End-use fuel form</u>	<u>Assumed coal price (\$/ton)</u>	<u>Maximum Competitive Price</u>	
		<u>Agric./forest residue & waste (\$/ton)</u>	<u>Municipal waste (\$/ton)</u>
1. Electricity (by direct combustion)	10	9.12	---
2. Methanol	10	2.56	-1.94
3. SNG	10	8.41	---

From the above results it is clear that direct combustion of biomass for generation of power is the most attractive alternative for biomass to be used as a source of energy. Conversion to methanol turns out to be least attractive because of the high capital expenditures involved. The cost disadvantage for municipal waste is not surprising, given its low heating value. Municipal waste would not be attractive as a fuel unless new environmental regulations required much greater expenditures for its disposal than is now the case in incineration or in sanitary landfills.

For a biomass conversion scheme to be economically feasible, the "competitive price" of biomass given above would have to be as high as its prevailing market value, which, of course, depends on the other uses of biomass. Alternative uses of biomass are numerous -- crop residues are used for livestock feed, field mulch and improvement of soil tilth, and some forest residues are used for soil amendment and manufacture of wood products. With the continued depletion of fossil fuels, it seems likely that future energy prices will put biomass in a more favorable position as an energy feedstock. The present lack of commercial methods for removing sulfur from coal or sulfur oxide compounds from the combustion products makes the low sulfur content of biomass even more important. On the cost front, one of the most significant factors is transportation. This factor can lead to highly attractive localized situations for biomass conversion to energy when supply and demand centers are located in close proximity.

IV. (g) NONRENEWABLES

The RMS trajectories for aluminum, steel, and cement and concrete, shown in Figures 15, 16, & 17 respectively, display the mass flow and energy data. Capital and labor costs, available only on a more aggregate basis, have been tabulated along with the energy data in Table IV-2 through IV-5.

Source: Most of the energy data were obtained from the Conference Board's book, Energy Consumption in Manufacturing, ⁽¹⁷⁾ while the Census of Manufactures ⁽⁶⁾ was used for capital and labor costs for processing and manufacturing. Energy data associated with mining, refining, etc. was taken from Energy Expenditures Associated with the Production and Recycling of Metals. ⁽¹⁸⁾ Capital and labor data for mining and related activities were obtained from the 1972 Census of Minerals ⁽¹⁹⁾ and the Minerals Yearbook. ⁽²⁰⁾

Table IV - 2

RMS Data for Aluminum, 1972

Activity	Energy Input		Labor		Capital	
	Nonelectric	Electric	Scientific	Production	(\$/10 ³	(\$/10 ³
	(Btu/lb)	(Btu/lb)	(Man-hr/lb)	(man-hr/10 ³ lb)	lb/yr)	lb)
Production / growing (mining)	0	305	N.A.	0.294	11.3	1.7
Harvesting/ extraction (ore treat- ment)	7,643	1,843	N.A.			
Processing	606	67,059	N.A.	26.6	257.6	38.6
Transporta- tion (aggregate)	801	0	N.A.			
Fabrication	10,675	9,466	N.A.			
Additional fabrication			N.A.			
Total	19,725	82,673		26.9	268.9	40.3

Notes:

- Current stock (reserve): 4.2×10^{10} lb (metal content in high-grade ore)
- Usage/yr: 9.6×10^9 lb
- N.A. stands for "not available".
- Mass units in the above data elements refer to pounds of aluminum ingots.

Table IV - 3

RMS data for Steel, 1972

Activity	Energy Input		Labor		Capital	
	Nonelectric	Electric	Scientific	Production	(\$/10 ³	(\$/10 ³
	(Btu/lb)	(Btu/lb)	(Man-hr/lb)	(man-hr/10 ³ lb)	lb/yr)	lb)
Production/ growing (mining)	6.87	17.6	N.A.	0.267	14.3	2.14
Harvesting/ extraction (ore treat- ment)	431.2	277.0	N.A.			
Processing	6,572	1,231	N.A.	5.07	50.0	7.47
Transporta- tion (aggregate)	474	0				
Fabrication	491	1,291	N.A.			
Additional fabrication	2,000	2,232	N.A.			
Total	9,975	5,049		5.34	64.3	9.61

Notes:

- Current stock (reserve): 6.4×10^{13} lb (metal content of ore)
- Usage/yr: 1.75×10^{11} lb (metal content of ore)
- N.A. stands for "not available"
- Mass units in the above data elements refer to pounds of raw (ingot) steel.

Table IV- 4
RMS Data for Cement and Concrete, 1972

Activity	Energy Input		Labor		Capital	
	Nonelectric (Btu/lb)	Electric (Btu/lb)	Scientific (Man-hr/lb)	Production (man-hr/10 ³ lb)	(\$/10 ³ lb/yr)	(\$/10 ³ lb)
Production/ growing (mining)	9	20	N.A.	0.357	6.96	1.04
Harvesting/ extraction (ore treat- ment)	0	231	N.A.			
Processing	3,050	477	N.A.	4.25	29.9	4.49
Transporta- tion (aggregate)	275	0	N.A.			
Fabrication	264	107	N.A.			
Additional fabrication			N.A.			
Total	3,598	835		4.61	36.86	5.53

Notes:

- a. Current stock (reserve): Unknown. 15-20% of the surface of the U.S. is estimated to be underlaid with limestone.
- b. Usage/yr: 1.29×10^{11} lb limestone; 3.23×10^{10} lb clay.
- c. N.A. stands for "not available"
- d. Mass units in the above data elements refer to pounds of cement.

Table IV - 5

RMS Data for Building Brick, 1972

Activity	Energy Input		Labor		Capital	
	Nonelectric	Electric	Scientific	Production	(\$/10 ³	(\$/10 ³
	(Btu/lb)	(Btu/lb)	(Man-hr/lb)	(man-hr/10 ³ lb)	lb/yr)	lb)
Production/ growing (mining)	9	20	N.A.	N.A.	0.925	0.139
Harvesting/ extraction (ore treat- ment)	0	254	N.A.	N.A.		
Processing	3,580	0	N.A.	1.46	29.9	4.63
Transporta- tion (aggregate)	146		N.A.			
Fabrication	0	0	N.A.			
Additional fabrication	226	56.8	N.A.			
Total	3,961	331		1.46	30.83	4.63

Notes:

- Current stock (reserve): Clay is plentiful on a nationwide basis.
- Usage/yr: 3.31×10^{10} lb for 1967.
- N.A. stands for "not available"
- Mass units in the above data elements refer to pounds of brick produced.

V. MATERIALS SUBSTITUTION ANALYSIS

The Reference Materials System is used for the analysis of materials use and substitution by the technique of perturbation analysis. Depending on the details of the analysis to be performed, RMS may be used at the level of aggregation presented in a previous section or at the more detailed level. Regardless of the level of detail used in the analysis, however, the results may be presented for overview or policy purposes in RMS format used in the previous section of this report.

The technique of perturbation analysis involves the following basic steps:

1. Analysis of the specific end use involved in a use or substitution problem.
2. Definition of any new processes to be used in the affected trajectory from the resources to the specific end use (definition of losses; energy, labor, and capital requirements; and environmental effects).
3. Revision of flows through the affected trajectories in RMS to reflect the revised use or substitution of materials and/or new processes.
4. Accumulation and tabulation of resources, energy, labor, capital, and environmental consequences of the use or substitution.

In analyzing the specific nature of the substitution, it is necessary to address the specific application. The mass ratio of substitution (e.g., pounds of paper that would replace a pound of plastic) depends on the specific application and the nature of the material. One would thus have to focus, for example, on paper bags as a substitute for polyethylene bags. The determination of these substitution ratios must be done exogenously to RMS and the results reflected in the revised or perturbed RMS. In certain instances, material preferences and substitution may be constrained or influenced by such factors as esthetics and codes or standards. The parameters of the technical characteristics of new processes must also be estimated exogenously to RMS by people with a processing background. The intent of RMS format is to capture those characteristics of the technology that are important to materials policy. Such technical detail, or reality, is often overlooked in policy formulation because it is not available in a consistent and comprehensive format.

Following these steps, the perturbation of the appropriate trajectories and the accumulation of information on detailed consequences is straightforward using RMS. In the case of an analysis of the substitution of paper bags for polyethylene bags, for example, the flows through the wood to paper trajectory would increase by the appropriate amount, while the flow of crude oil and natural gas through the petrochemical trajectory would be decreased. The full materials system implications may then be traced all the way back to the forest and the source of the oil, imported or domestic. The results of the analysis may then be used as a basis of support or revision of the original use or substitution measure.

When used in this fashion, RMS can be a useful technique for the analysis of materials policy. It must be recognized that the technique focuses on the physical structure of the system and its requirements. Thus, although substitution analysis may be performed in a rather direct manner; in cases of more general policy analysis, the effects of a policy action on the supply or demand for materials used, and on the physical structure of the system, must be developed or estimated prior to use of RMS.

Case Study In Containers and Packaging Sector

The Reference Materials System provides a basis for analysis of the consequences of materials substitution. The RMS data on mass flow, energy, labor, and capital requirements allows these factors to be addressed in some detail. In order to demonstrate the application of RMS to materials substitution analysis, two illustrative case studies have been developed. These deal with the area of containers and packaging where paper products compete with plastics.

These case studies illustrate the use of RMS to analyze energy requirements of alternative materials used in the same end use. It should be remembered that, before economic analysis can be performed, similar RMS analyses should be performed on labor requirements, capital cost requirements, and other aspects important to the situation. These case studies are therefore illustrations of the use of RMS and insights gained, rather than a complete economic analysis among the alternatives presented.

Because numerous possibilities of material substitution exist in the field of containers and packaging, this particular area was chosen to be the subject of our case study. Packaging and containers are also important because they consume significantly larger amounts of energy than other consumer services such as transportation, storage and marketing, etc.

Packaging is used for three major classes of goods, durables, nondurables, and foodstuffs. The overwhelming fraction of durable goods are packaged in corrugated cardboard. Corrugated cardboard is also most commonly used as a packing material in case of durables. Nondurables consist of clothing, textiles, and chemicals and require a variety of packaging characteristics. Foodstuffs, the third major area for packaging, represent about 15% of the production activity of the U.S. economy and account for 60% of the total shipment value of the entire range of goods that are packaged. This sector involves the widest variety and largest amount of packaging materials, apart from corrugated cardboard (produced from renewable resources). In the following discussion, specific examples are given for which the technology for substitution already exists, i.e., packaging cases in which both non-renewables and renewables can be interchangeably used to meet certain packaging requirements. Such examples are:

- Sanitary food containers, used for milk, butter, margarine, frozen foods, ice cream, shortening, etc.

- Trays for packaging meats, eggs, and produce.

- Flexible containers, e.g., bags and sacks.

Although labor requirements and capital costs are also important considerations in the comparison of alternative materials, attention is focused exclusively on energy implications in this case study of materials for containers and packaging.

In connection with sanitary food containers, ⁽²¹⁾ two RMS trajectories are shown in Figure 18. These correspond to the special case of half-gallon containers made of plastic and of paper. Mass flows and energy values shown in the figure under each activity link refer to requirements for manufacture of one container of each type. Energy data ⁽²¹⁾ are in terms of the "gross"

value of energy requirement. Summing all the energy components along the two trajectories, one can see that a plastic bottle weighing 0.12 lb needs about 8495 Btu's, whereas an equivalent paper carton weighing 0.14 lb needs 6053 Btu's. Also, the plastic bottle requires 0.038 lb and 0.107 lb of natural gas and crude oil, respectively, as chemical feedstock, while an equivalent paper carton needs 0.28 lb of groundwood. Adding the energy content of raw materials, the total energy inputs to a plastic bottle and an equivalent paper carton work out to 11,310 and 7453 Btu's respectively. In Figure 19 two trajectories for the manufacture of size 6 meat trays from Styrofoam and from molded wood pulp are shown. The energy requirements in the two cases add up to about the same value, 875 Btu's each. Here again, taking into account that 0.0047 lb of natural gas and 0.013 lb of crude oil are needed as chemical feedstocks in the case of the polystyrene tray and 0.064 lb of groundwood is needed as raw material for one pulp tray, the total energy values increase to 1219 and 1195 Btu's respectively. In the case of flexible containers, polyethylene is used for plastic bags and Kraft paper for paper bags. The energy cost of Kraft paper ⁽²¹⁾ is $\approx 20,500$ Btu/lb, and that of polyethylene, ⁽²²⁾ $\approx 68,250$ Btu/lb., or 3.3 times as much. But, because medium-weight polyethylene bags weigh only half as much as an equivalent paper bag, the ratio of energy consumption of plastic and paper bags is $\approx 1.65:1$.

The above comparison is not entirely fair to plastics if there is the possibility of reusing the plastic containers. As an example, to make and fill a half-gallon plastic milk container a single time requires about 8500 Btu of energy. If it were reused, and the washing and filling costs remained the same with each use (≈ 3070 Btu), then the cost would drop to 5785 Btu with one reuse, to 4880 with two reuses, and to 4427 with three reuses. Similarly, although a single use of plastic bags requires more energy than paper bags, the two become comparable if more durable polyethylene bags are reused once. Despite significant energy savings as a result of reuse, it is not certain that the creation of commercial facilities to make such reuse possible is economical. These results are summarized in Table IV-6.

Table IV-6
Energy Requirement for Typical Containers and Packaging

Container/packag- ing (product) type	Unit weight (lb)	Raw material requirements Per unit product			Energy of manufacture		Energy con- tent of raw materials	Total Energy
		Natural gas (lb)	Crude oil (lb)	Wood (lb)	per unit product (Btu)	(Btu/lb of product)	per unit product (Btu)	per unit product (Btu)
1. <u>Half-gallon Milk Container</u>								
Polyethylene Plastic	0.12	0.038	0.107	-----	{ 8,495 5,445*	{ 70,790 45,370*	2,814	11,310
Paper	0.14	-----	-----	0.28	{ 6,053 2,840*	{ 43,230 20,280*	1,400	7,453
2. <u>Size 6 Meat Tray</u>								
Polystyrene plastic	0.0148	0.0047	0.013	-----	875	59,120	344	1,219
Wood pulp	0.045	-----	-----	0.064	875	19,440	320	1,195
3. <u>Flexible Container (bag or sack)</u>								
Polyethylene plastic	0.04	0.013	0.036	-----	2,730	68,250	951	3,681
Kraft paper	0.08	-----	-----	0.16	1,640	20,500	800	2,440

*These values exclude the energy required for filling the containers.

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<u>Resource base</u>	<u>Production (growing)</u>	<u>Harvesting or extraction</u>	<u>Processing</u>	<u>Transportation (aggregate)</u>	<u>Fabrication and recycling</u>	<u>Product Identification</u>	<u>Additional Fabrication (e.g., Erection) & Maintenance</u>	<u>End use and recycling</u>
<u>Renewables</u> Forest resources Grazing and rearing land resources -birds -cattle -sheep Crop land resources -cotton -cereal and sugar cane -others Other forest resources -coconuts -citrus peel -gum Marine resources including agricultural types -algae -menhaden etc. <u>Nonrenewables</u> Aluminum Iron and steel Cement and concrete Oil and gas Coal		Land use Energy Fertilizer and chemicals Labor Environmental -solid waste Capital Cost Operating Cost Institutional and organization problems	Data Elements to be identified for each resource/activity combination			Lumber Plywood Paper Particle board and fiberboard Chemicals Fibers and woven fabrics Nonwoven fabrics Elastomers Fuels Plastics Aluminum mill products Steel mill products Concrete		Commercial and industrial structures Housing Transportation Furniture and upholstery Energy -fuel -power Books and publications Producer goods Textiles -clothing -soft goods (footware) -packaging Communication Disposable products -packaging -other Recreation (competes for use of land)

Figure 1. Scope of reference material system and associated data elements.

NOTES :

- (1) IN THE OIL & GAS TRAJECTORY, THE NUMBERS IN THE PARENTHESES, SEPARATED BY SLASH, ARE MILLION BARRELS OF OIL & BILLION FEET³ OF GAS RESPECTIVELY.
- (2) THE PUMBERS WITH ASTERISKS, COEFFICENT ONLY TO OIL & GAS AND COAL TRAJECTORIES, INDICATE FLOW IN TERMS OF PRIMARY RESOURCES INSTEAD OF PRODUCTS.
- (3) "FRACTION FROM RECYCLE" REFERS TO THE MATERIAL OBTAINED FROM MANUFACTURING AND POST-USER WASTE. HOME SCRAP IS NOT INCLUDED.
- (4) MATERIAL FLOW INFORMATION IS GENERALLY SPARSE AT THE LEVEL OF CONSTRUCTION-TYPE. AS A RESULT, MANY ENTRIES IN THIS CATEGORY ARE EMPTY AT THIS TIME.

Figure 2A. Aggregate reference material system. Mass flow in million pounds (year 1972).

NOTE: NUMBERS IN PARENTHESES REFER TO FRACTION ELECTRICAL, AT A HEAT RATE OF 10,500 BTU PER KWH.

Figure 2B. Aggregate reference material system. Energy requirement in 10^{12} Btu (year 1972).

NOTES: (i) RMS INPUTS AND OUTPUTS IDENTIFY THE FIGURE NUMBERS ALONG WITH SECTORS IN PARENTHESES, FROM AND INTO WHICH THE MATERIAL FLOWS TAKE PLACE, RESPECTIVELY.

(ii) TWO NUMBERS IN PARENTHESES BELOW THE ACTIVITY LINKS REFER TO MATERIAL FLOW IN MILLION CUBIC FEET AND ACREAGE IN MILLION ACRES, RESPECTIVELY. IN CASE OF EXCEPTIONS, UNITS ARE STATED IN THE HEADINGS. THIS DATA CORRESPONDS TO THE YEAR 1972

Figure 3A. Reference material system. Productivity sector I.

NOTES: (I) RMS INPUTS AND OUTPUTS IDENTIFY THE FIGURE NUMBERS ALONG WITH SECTORS IN PARENTHESES, FROM AND INTO WHICH THE MATERIAL FLOWS TAKE PLACE, RESPECTIVELY.

(II) THE NUMBERS BELOW THE LINKS REFER TO MATERIAL FLOWS IN MILLION CUBIC FEET, FOR THE YEAR 1972

Figure 4A. Reference material system. Productivity sector II.

NOTES: (i) RMS INPUTS AND OUTPUTS IDENTIFY THE FIGURE NUMBERS ALONG WITH SECTORS IN PARENTHESES, FROM AND INTO WHICH THE MATERIAL FLOWS TAKE PLACE, RESPECTIVELY.

(ii) THE NUMBERS BELOW ACTIVITY LINKS REFER TO MATERIAL FLOWS IN MILLION POUNDS, OR AS INDICATED, FOR THE YEAR 1972

Figure 5A. Reference material system. Productivity sector III.

NOTES: (i) RMS INPUTS AND OUTPUTS IDENTIFY THE FIGURE NUMBERS ALONG WITH SECTORS IN PARENTHESES, FROM AND INTO WHICH THE MATERIAL FLOWS TAKE PLACE, RESPECTIVELY.

(ii) NUMBERS BELOW THE ACTIVITY LINKS REFER TO LABOR REQUIREMENT IN MAN-HOURS PER POUND OF MATERIAL OUTPUT OR AS INDICATED. THE DATA CORRESPONDS TO THE YEAR 1972.

Figure 5C. Reference material system. Productivity sector III.

NOTES: (i) RMS INPUTS AND OUTPUTS IDENTIFY THE FIGURE NUMBERS ALONG WITH SECTORS IN PARENTHESES, FROM AND INTO WHICH THE MATERIAL FLOWS TAKE PLACE, RESPECTIVELY.

(ii) THE NUMBERS BELOW ACTIVITY LINKS REFER TO MATERIAL FLOWS IN MILLION POUNDS, FOR THE YEAR 1972

Figure 6A. Reference material system. Structural sector 1.

NOTES: (i) RMS INPUTS AND OUTPUTS IDENTIFY THE FIGURE NUMBERS ALONG WITH SECTORS IN PARENTHESES, FROM AND INTO WHICH THE MATERIAL FLOWS TAKE PLACE, RESPECTIVELY.

(ii) NUMBERS BELOW THE ACTIVITY LINKS REFER TO ENERGY REQUIREMENT IN THOUSAND BTU THERMAL PER POUND OF MATERIAL OUTPUT OR AS INDICATED. THE DATA CORRESPONDS TO THE YEAR 1972

* THESE VALUES DENOTE LOGGING ENERGY

Figure 6B. Reference material system. Structural sector I.

NOTES: (i) RMS INPUTS AND OUTPUTS IDENTIFY THE FIGURE NUMBERS ALONG WITH SECTORS IN PARENTHESES, FROM AND INTO WHICH THE MATERIAL FLOWS TAKE PLACE, RESPECTIVELY.

(ii) NUMBERS BELOW THE ACTIVITY LINKS REFER TO LABOR REQUIREMENT IN MAN-HOURS PER POUND OF MATERIAL OUTPUT OR AS INDICATED. THE DATA CORRESPONDS TO THE YEAR 1972.

* THESE VALUES DENOTE LABOR REQUIREMENT FOR LOGGING.

Figure 6C. Reference material system. Structural sector I.

NOTES: (i) RMS INPUTS AND OUTPUTS IDENTIFY THE FIGURE NUMBERS ALONG WITH SECTORS IN PARENTHESES, FROM AND INTO WHICH THE MATERIAL FLOWS TAKE PLACE, RESPECTIVELY.

(ii) NUMBERS BELOW THE ACTIVITY LINKS REFER TO CAPITAL REQUIREMENT IN 10^3 DOLLARS PER POUND OF MATERIAL OUTPUT OR AS INDICATED. THE DATA CORRESPONDS TO THE YEAR 1972.

* THESE VALUES DENOTE CAPITAL REQUIREMENT FOR LOGGING.

Figure 6D. Reference material system. Structural sector I.

NOTES: (i) RMS INPUTS AND OUTPUTS IDENTIFY THE FIGURE NUMBERS ALONG WITH SECTORS IN PARENTHESES, FROM AND INTO WHICH THE MATERIAL FLOWS TAKE PLACE, RESPECTIVELY.

(ii) THE NUMBERS BELOW ACTIVITY LINKS REFER TO MATERIAL FLOWS IN MILLION POUNDS, FOR THE YEAR 1972

Figure 7A. Reference material system. Structural sector II.

NOTES: (i) RMS INPUTS AND OUTPUTS IDENTIFY THE FIGURE NUMBERS ALONG WITH SECTORS IN PARENTHESES, FROM AND INTO WHICH THE MATERIAL FLOWS TAKE PLACE, RESPECTIVELY.

(ii) NUMBERS BELOW THE ACTIVITY LINKS REFER TO ENERGY REQUIREMENT IN THOUSAND BTU THERMAL PER POUND OF MATERIAL OUTPUT OR AS INDICATED. THE DATA CORRESPONDS TO THE YEAR 1972

Figure 7B. Reference material system. Structural sector II.

RMS INPUT	ADDITIONAL FABRICATION	END USE
FACE VENEER 6C (STRUCTURAL)	0.0040	(HOUSING CONSTRUCTION)
HARDBOARD PLYWOOD 6C (STRUCTURAL)	0.0040	ROOFING 0.0264
COMMERCIAL VENEER 6C (STRUCTURAL)	0.0040	FLOORING 0.0445
LAMINATED LUMBER 6C (STRUCTURAL)	0.0023	EXTERIOR WALLS 0.0369
		INTERIOR WALLS 0.0067
		CONCRETE FORMS
		MOBILE HOMES
		PREFABRICATED WOOD BLDGS.
PARTICLEBOARD 6C (STRUCTURAL)	0.0013	
INTERIOR SOFTWOOD PLYES 6C (STRUCTURAL)	0.0023	FURNITURE
INTERIOR & EXTERIOR STRUCTURAL PLYWOOD 6C (STRUCTURAL)	0.0023	MILLWORK
		MATCHES, TOOTHPICKS, PENCILS
HARDWOOD LUMBER 6C (STRUCTURAL)	0.0040	WOODEN CONTAINERS & CRATES
FLAKEBOARD 6C (STRUCTURAL)	0.002	STRUCTURAL WOOD MEMBERS
FIBERBOARD (MEDIUM DENSITY) 6C (STRUCTURAL)	0.0014	
INSULATION BOARD 6C (STRUCTURAL)	0.0033	
HARDBOARD 6C (STRUCTURAL)	0.0074	MISCELLANEOUS INDUSTRIAL USE
SOFTWOOD LUMBER 6C (STRUCTURAL)	0.0015	
YARD SOFTWOOD LUMBER 6C (STRUCTURAL)	0.0015	
FACTORY & SHOP SOFTWOOD LUMBER 6C (STRUCTURAL)	0.0015	
POLES, PILINGS, POSTS, ETC. 6C (STRUCTURAL)	0.0015	

NOTES: (i) RMS INPUTS AND OUTPUTS IDENTIFY THE FIGURE NUMBERS ALONG WITH SECTORS IN PARENTHESES, FROM AND INTO WHICH THE MATERIAL FLOWS TAKE PLACE, RESPECTIVELY.
(ii) NUMBERS BELOW THE ACTIVITY LINKS REFER TO LABOR REQUIREMENT IN MAN-HOURS PER POUND OF MATERIAL OUTPUT OR AS INDICATED. THE DATA CORRESPONDS TO THE YEAR 1972.

Figure 7C. Reference material system. Structural sector II.

NOTES: (i) RMS INPUTS AND OUTPUTS IDENTIFY THE FIGURE NUMBERS ALONG WITH SECTORS IN PARENTHESES, FROM AND INTO WHICH THE MATERIAL FLOWS TAKE PLACE, RESPECTIVELY.

(ii) NUMBERS BELOW THE ACTIVITY LINKS REFER TO CAPITAL REQUIREMENT IN 10^3 DOLLARS PER POUND OF MATERIAL OUTPUT OR AS INDICATED. THE DATA CORRESPONDS TO THE YEAR 1972.

Figure 7D. Reference material system. Structural sector II.

NOTES: (i) RMS INPUTS AND OUTPUTS IDENTIFY THE FIGURE NUMBERS ALONG WITH SECTORS IN PARENTHESES, FROM AND INTO WHICH THE MATERIAL FLOWS TAKE PLACE, RESPECTIVELY.

(ii) THE NUMBERS BELOW ACTIVITY LINKS REFER TO MATERIAL FLOWS IN MILLION POUNDS, FOR THE YEAR 1972

Figure 9A. Reference material system. Fibers (pulp & paper) sector I.

- NOTES: (i) RMS INPUTS AND OUTPUTS IDENTIFY THE FIGURE NUMBERS ALONG WITH SECTORS IN PARENTHESES, FROM AND INTO WHICH THE MATERIAL FLOWS TAKE PLACE, RESPECTIVELY.
- (ii) TWO NUMBERS IN PARENTHESES BELOW THE ACTIVITY LINKS REFER TO ELECTRICAL & TOTAL ENERGY REQUIREMENT RESPECTIVELY, IN THOUSAND Btu THERMAL PER POUND OF MATERIAL OUTPUT OR AS INDICATED. THE DATA CORRESPONDS TO THE YEAR 1972
- (iii) ENERGY CONSUMED IN PAPER AND BOARD MANUFACTURE INCLUDES PULPING ON SITE

Figure 8B. Reference material system. Fibers (pulp & paper) sector I.

NOTES: (i) RMS INPUTS AND OUTPUTS IDENTIFY THE FIGURE NUMBERS ALONG WITH SECTORS IN PARENTHESES, FROM AND INTO WHICH THE MATERIAL FLOWS TAKE PLACE, RESPECTIVELY.

(ii) NUMBERS BELOW THE ACTIVITY LINKS REFER TO LABOR REQUIREMENT IN MAN-HOURS PER POUND OF MATERIAL OUTPUT OR AS INDICATED. THE DATA CORRESPONDS TO THE YEAR 1972.

* MANHOURS PER POUND OF PAPER & BOARD INCLUDES PULPING ON SITE. ADDITIONAL TOTAL MANHOURS USED IN PULPMILLS EQUAL 17.6×10^6

Figure 8C. Reference material system. Fibers (pulp & paper) sector I.

NOTES: (i) RMS INPUTS AND OUTPUTS IDENTIFY THE FIGURE NUMBERS ALONG WITH SECTORS IN PARENTHESES, FROM AND INTO WHICH THE MATERIAL FLOWS TAKE PLACE, RESPECTIVELY.

(ii) THE NUMBERS BELOW ACTIVITY LINKS REFER TO MATERIAL FLOWS IN MILLION POUNDS, FOR THE YEAR 1972

Figure 9A. Reference material system. Fibers (pulp & paper) sector II.

NOTES: (i) RMS INPUTS AND OUTPUTS IDENTIFY THE FIGURE NUMBERS ALONG WITH SECTORS IN PARENTHESES, FROM AND INTO WHICH THE MATERIAL FLOWS TAKE PLACE, RESPECTIVELY.

(ii) THE NUMBERS BELOW ACTIVITY LINKS REFER TO MATERIAL FLOWS IN MILLION POUNDS, FOR THE YEAR 1972

Figure 10A. Reference material system. Fibers (textiles & apparel) sector III.

NOTES: (i) RMS INPUTS AND OUTPUTS IDENTIFY THE FIGURE NUMBERS ALONG WITH SECTORS IN PARENTHESES, FROM AND INTO WHICH THE MATERIAL FLOWS TAKE PLACE, RESPECTIVELY.

(ii) TWO NUMBERS IN PARENTHESES BELOW THE ACTIVITY LINKS REFER TO ELECTRICAL & TOTAL ENERGY REQUIREMENT RESPECTIVELY, IN THOUSAND Btu THERMAL PER POUND OF MATERIAL OUTPUT OR AS INDICATED. THE DATA CORRESPONDS TO THE YEAR 1972

(iii) ENERGY CONSUMED IN MILLING INCLUDES YARN MANUFACTURE ON SITE

Figure 10B. Reference material system. Fibers (textiles & apparel) sector III.

NOTES: (i) RMS INPUTS AND OUTPUTS IDENTIFY THE FIGURE NUMBERS ALONG WITH SECTORS IN PARENTHESES, FROM AND INTO WHICH THE MATERIAL FLOWS TAKE PLACE, RESPECTIVELY.

(ii) NUMBERS BELOW THE ACTIVITY LINKS REFER TO LABOR REQUIREMENT IN MAN-HOURS PER POUND OF MATERIAL OUTPUT OR AS INDICATED. THE DATA CORRESPONDS TO THE YEAR 1972.

* MAN-HOURS FOR MILLING INCLUDE YARN SPINNING ON SITE. ADDITIONAL TOTAL MANHOURS FOR YARN MILLS EQUAL 193×10^6

Figure 10C. Reference material system. Fibers (textiles & apparel) sector III.

NOTES: (i) RMS INPUTS AND OUTPUTS IDENTIFY THE FIGURE NUMBERS ALONG WITH SECTORS IN PARENTHESES, FROM AND INTO WHICH THE MATERIAL FLOWS TAKE PLACE, RESPECTIVELY.

(ii) THE NUMBERS BELOW ACTIVITY LINKS REFER TO MATERIAL FLOWS IN MILLION POUNDS, OR AS INDICATED, FOR THE YEAR 1972

Figure 11A. Reference material system. Fibers (textiles & apparel) sector IV.

Figure 11C. Reference material system. Fibers (textiles & apparel) sector IV.

NOTES: (1) RMS INPUTS AND OUTPUTS IDENTIFY THE FIGURE NUMBERS ALONG WITH SECTORS IN PARENTHESES, FROM AND INTO WHICH THE MATERIAL FLOWS TAKE PLACE, RESPECTIVELY.

(2) THE NUMBERS BELOW ACTIVITY LINKS REFER TO MATERIAL FLOWS IN MILLION POUNDS, FOR THE YEAR 1972

Figure 12A. Reference material system. Extractives.

NOTES: (i) RMS INPUTS AND OUTPUTS IDENTIFY THE FIGURE NUMBERS ALONG WITH SECTORS IN PARENTHESES, FROM AND INTO WHICH THE MATERIAL FLOWS TAKE PLACE, RESPECTIVELY.

(ii) THE NUMBERS BELOW ACTIVITY LINKS REFER TO MATERIAL FLOWS IN MILLION POUNDS, FOR THE YEAR 1972

Figure 13A. Reference material system. Fibers V & Ligno cellulosic sector.

Note: Numbers below resource or product names refer to the corresponding heating values, and the ones below activity links are the efficiencies of the corresponding processes.

Figure 14. Reference material system. Energy from biomass conversion.

RESOURCE	PRODUCTION OR GROWING	HARVESTING OR EXTRACTION	PROCESSING	TRANSPORT.	INTERMED. PRODUCT IDENT.	FABRICATION	PRODUCT IDENT.	ADDITIONAL FABRICATION	END USE
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TOTAL ENERGY CONSUMPTION /lb. OF
ALUMINUM INGOTS & MILL
PRODUCTS = 102,341 BTU

NOTES

1. TWO VALUES IN PARENTHESIS BELOW AN ACTIVITY LINK REFER TO ELECTRIC & TOTAL ENERGY REQUIREMENT RESPECTIVELY IN Btu/lb OF ALUMINUM INGOTS & MILL PRODUCTS.
2. VALUE IN PARENTHESIS ABOVE AN ACTIVITY LINK REFERS TO MASS FLOW IN 10⁶ lb OF ALUMINUM METAL CONTENT.

Figure 15. Reference material system. Aluminum (year 1972).

Figure 16. Reference material system. Iron & steel (year 1972).

NOTES

1. TWO VALUES IN PARENTHESIS BELOW AN ACTIVITY LINK REFER TO ELECTRIC & TOTAL ENERGY REQUIREMENT RESPECTIVELY IN Btu/lb OF CEMENT

2. VALUE IN PARENTHESIS ABOVE AN ACTIVITY LINK REFERS TO MASS FLOW IN 10⁹ lb OF CEMENT

TOTAL ENERGY CONSUMPTION/lb. OF CEMENT = 4,158 Btu

Figure 17. Reference material system. Cement & concrete (year 1972).

NOTE: Numbers in the parentheses below the activity links refer to mass flow in lb and energy requirement in Btu respectively for the corresponding steps in the manufacture of one half gallon milk containers.

Figure 18. Reference material system. Half gallon milk container (plastic bottle vs. paper carton).

NOTE: Numbers in the parentheses below the activity links refer to mass flow in lb. and energy requirement in Btu respectively for the corresponding steps in the manufacture of one Size 6 meat tray.

Figure 19. Reference material system. Size 6 meat tray (polystyrene vs. molded pulp).