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The Evaluation of Critical Materials for Five Advanced Design Photovoltaic Cells with an Assessment of Indium and Gallium

R.L. Watts, Project Manager

May 1980

Prepared for the Photovoltaic Program
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PRELIMINARY REPORT

THE EVALUATION OF CRITICAL MATERIALS FOR FIVE ADVANCED DESIGN PHOTOVOLTAIC CELLS WITH AN ASSESSMENT OF INDIUM AND GALLIUM

R. L. Watts
W. E. Gurwell[a]
W. M. Jamieson[a]
L. W. Long
W. T. Pawlewicz
S. A. Smith[a]
R. R. Teeter[a]

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Pacific Northwest Laboratory
Richland, Washington 99352

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SUMMARY

This section summarizes the results of the screening of the baseline and sensitivity case photovoltaic (PV) cells and the detailed analysis of indium and gallium availability.

AMORPHOUS SILICON SOLAR CELLS can be produced in large quantities without encountering serious constraints from materials supplies if plans for producing the needed materials such as silane are carried through before large-scale production is started. However, indium used as a conductive window layer may have to be eliminated, due to the large quantity used.

Indium may be used if ways are found to recycle the indium presently lost (≈60%) in the deposition process during cell manufacture and/or if low cost supplies of indium can be increased. There is large uncertainty concerning the ultimate capacity for indium production which can only be resolved by an extensive program of sampling and accurate assaying of zinc and other primary ores and process streams for indium content. This PV cell could use indium if the indium is recycled and the layer thickness reduced. However, establishing confidence in a strong PV market for indium is necessary before a large commitment can be made to use it at this level in PV cell manufacturing.

Silane raises questions since its use in PV would equal all other uses. Current and ongoing work should reduce the costs of silane (7¢/watt) and it should be available and affordable through good materials supply planning and management. Plans for producing amorphous silicon solar cells should not be considered complete unless they show firm plans for producing the silane or have firm supply contracts at affordable prices.

POLYCRYSTALLINE SILICON SOLAR CELLS can be produced with no serious material supply problems if good material planning is used. Trichlorosilane production capacity of the required purity would have to be increased about 21% per year (in 1991). Production plans for polycrystalline silicon solar cells should include firm plans for the production of the trichlorosilane or firm contracts for its purchase. Substituting silane would require a program to develop a lower cost production process. Thus, silane should be produced at the cell manufacturing sile or firm contracts should be in place to assure its availability in suitable quantity and quality at an affordable price. (At present prices it costs about 25¢/watt.)

CADMIUM SULFIDE/COPPER SULFIDE solar cells can be implemented on a large scale if the amount of gold used is drastically reduced and if the costs of high purity cadmium sulfide can be reduced.

In the sensitivity case suggested by the Solar Energy Research Institute, the thickness of the gold layer was reduced to .05 microns (from 5 microns) and brought gold usage down to a tolerable level (assuming that ways are found to recycle all gold lost in processing). Under these conditions the cost would only be 0.6¢/watt. If ways cannot be found to recycle the gold, it must be eliminated from the design.

PV grade cadmium sulfide presently costs 8.3¢/watt for a 25 micron layer. Success of this cell design depends on reducing this cost. This seems to be likely since bulk cadmium only costs 1.5¢/watt.

Plans for producing the cadmium sulfide/copper sulfide cell in large quantities should not be considered unless the consumption of gold and the cost of cadmium sulfide (PV grade) can be reduced.

The POLYCRYSTALLING GALLIUM ARSENIDE MIS cell base case is not practical for large-scale deployment without design and production process changes and careful materials supply management, due to the excessive use of gallium, germanium, and their compounds.

Design changes were studied in the sensitivity cases as suggested by the Solar Energy Research Institute. The layer thicknesses were reduced as follows: the active layer (GaAs) from 5 microns to 2 microns, the epitaxy substrate (Ge) from 5 microns to 1 micron.

The production process changes needed are those which will reduce the process losses of (or economically recycle) the gallium and germanium compounds and the materials from which they are made.

Even under these ideal circumstances, bulk supplies of gallium and germanium needed will be very large compared to non-PV uses. PV gallium requirements would still be 10 times greater than all other gallium uses in the world for a 25 GW on-line by the year 2000 deployment scenario. The sources of byproduct gallium could support the required gallium production if long-term contracts or other means were supplied to reduce the risk suppliers perceive in a single large market.

The most ideal case studied would still require 326 MT of germanium in 2000 compared to 127 MT in 2000 for all other uses. Present information is inadequate to predict whether this production level could be reached at an affordable price from byproduct streams.

The production of germanium and gallium from coal fly ash was investigated in this project with less than optimistic conclusions.

We recommend that germanium be eliminated from this cell or that work be initiated to accurately evaluate the germanium content of ores and process streams and subsequently to assess the significance of this increased information. A very large sampling program is needed (not just a literature review) to reduce this uncertainty level to allow a confident plan to use germanium in these quantities.

The high purity compounds of these materials are used in such large quantities that plans to produce these cells should not be considered complete unless they include the plans for producing or obtaining germane or trimethyl gallium.

Arsenic would be available as a bulk material, but arsine, in high purity form, is not presently available in a suitable quantity. Plans to produce it or firm contracts for its supply must be part of any complete production plan for polycrystalline gallium arsenide MIS cell production.

The ADVANCED CONCENTRATOR PV cell design will encounter serious delays in large-scale implementation if the materials are procured from the open market.

Such delays can be prevented by planning ahead (6-8 years) for adequate production capacity for:

- Gallium and its compounds, trimethyl gallium and gallium arsenide
- Trimethyl indium

Since gallium usage will be about equal to all non-PV uses, long-term contracts or some other means of reducing investment risk to bulk gallium producers will be required if an orderly market is to be preserved.

Indium use in this cell is only about 3% of the expected market for indium. Bulk indium should be available in these quantities in the open market.

Adequate supplies of the compounds of gallium and indium used in producing this cell, trimethyl gallium and trimethyl indium, can be assured by including their production facilities in the plans for manufacturing advanced concentrators. Similarly, gallium arsenide ingots and wafers need long-term planning to control costs and assure availability for these advanced concentrator cells.

These same conclusions apply for the range of cell designs considered practical, using 200 micron to 500 micron wafers of gallium arsenide.

INDIUM AND GALLIUM AVAILABILITY

Both indium and gallium are byproducts of the production of other materials. PV uses of these materials as projected in this study will require substantial increases in production of these materials. Economic domestic sources will not supply the needed increases in material supply for either material.

Domestic sources for indium appear limited to about 7 metric tons per year (from domestic zinc ores). Domestic capacity to refine indium is reported to be about 18 MT/year and apparently includes capacity to produce from foreign ores and/or concentrates. World production is about 40 MT/year and industry officials estimate that that could be about doubled. This would require most of the indium to be processed from world zinc production assuming an indium content of 45 ppm and a recovery factor of 40%.

The assumption that ores contain 45 ppm of indium would imply that much of the world's zinc comes from regions of tectonic activity (see the discussion of indium in Chapter 4.0).

If zinc production reaches projected levels (an 80% increase over 1976 data), the same assumptions just made would allow the production of about 150 MT/year. But almost all of it will come from ore produced outside the U.S. If world needs for indium reach the forecast level of about 100 MT/year, then 50 MT/year could conceiveably be left over for PV uses. The assumptions above are, however, not backed up by good data anywhere.

A major sampling and assaying program should be carried out before firm plans could be made to use that much indium in PV products.

Gallium will not be available at current prices from domestic sources to implement a substantial PV plan. In fact, domestic supplies are likely to supply no more than about half of U.S. needs for gallium (without PV). This includes consideration of obtaining gallium from bauxite processing, zinc production, phosphate production or coal fly ash processing. Gallium from coal fly ash processing will likely cost much more than foreign sources of gallium from bauxite processing.

Gallium can become available at reasonable prices from foreign bauxite production in adequate quantities to allow for a substantial PV industry. If all of the world's bauxite estimated to be processed in the year 2000 and contained 40 ppm gallium and recoveries were held at a little better than 40%, the world could supply about 5000 MT/year. This is 100 times the projected usage of gallium (not including PV requirements).

Bauxite will be processed in a number of countries, and the production of gallium is not likely to become subject to cartel action unless the limit of 5000 MT/year use level is approached.

Many of the uses for gallium and indium are rather inelastic in their demand for the short term. Relying on open market purchases for photovoltaic for quantities greater than 10% of the total production of indium and gallium without PV is likely to cause abrupt increases in price for these materials. Industry executives were blunt in their statement that they wouldn't increase capacity rapidly for a single technology such as photovoltaics.

Both of these metals have experienced several "marvelous new market opportunities" which have been drastically curtailed in spite of success of the product. This has occurred because the technology progressed by reducing its expensive "minor metal" content. Industry executives point out that byproduct revenue is about 1% of total revenue in the case of indium from zinc and about 5% in the case of gallium from processing bauxite into alumina. Long-term contracts between gallium and indium suppliers and PV manufacturers spread the risk of capital investment in gallium and indium production. These contracts may also reduce the prices of gallium and indium by reducing transaction costs.

A number of years will be required to increase capacity for indium and/or gallium. One industry executive said bluntly that he wouldn't change his flowsheet in an existing plant to get more of the byproduct. If increased byproduct capacity were to be limited to inclusion in new primary product facilities, then the time period for more capacity would be very long. Executives estimated that the capacity could be increased in 3 years. Presumably, one would have to add the time to get plants or plant modifications designed and approved by various agencies or boards of directors. This should be regarded as a conservative estimate since it is taking longer and longer to get these kinds of changes accomplished.

Summarizing, added materials capacity for a new industry like PV should be planned ahead 6-10 years if the usage is to be a substantial portion of the market in order to prevent supply constraints for photovoltaics.

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FIGURES

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1.0 INTRODUCTION

The objective of this study is to identify potential material supply constraints due to the large-scale deployment of five advanced photovoltaic (PV) cell designs, and to suggest strategies to reduce the impacts of these production capacity limitations and potential future material shortages. Some PV technologies supported by the Advanced Materials/Cell Research activity of the Solar Energy Research Institute (SERI) use materials which are potentially in short supply or are high in cost. These technologies may never achieve large-scale commercialization unless new, higher capacity sources of these critical materials are developed or their cost of production is reduced. In the past such situations have been encountered and new sources and production processes have been developed through deliberate, planned programs for managing the supply problem.

Material supply shortages occur either because: (1) the production capacity cannot cope with a sudden increase in demand for the material, or (2) the known sources for the supply are inadequate. The former problem can be averted if it is recognized early enough. Large capacity increases for many materials can require 10-20 years to achieve. Hence, early identification of potential shortages is required for timely planning and development of increased production. A radical example of sharply increased production capacity is the aluminum industry during World War II. The second kind of problem has also been successfully dealt with in the past. An instance is the nuclear industry, where many new sources of uranium were discovered as a result of deliberate programs to find and develop new resources. The mining and materials processing industries have an excellent record of successfully meeting new challenges to sharply increase supplies of unusual materials. Again, careful assessment of all potential supply sources is a necessary predecessor to the larger task of exploration and development of such sources. Besides adequate supplies, PV cell researchers need to know whether the materials are or will be affordable. The price of increased supplies for some photovoltaic materials may limit the ultimate size of a potential market application.

Materials availability studies are thus a necessary complement to the Advanced Materials/Cell Research activity. A unique tool is available for systematically reviewing PV technologies and the material supply chain to see if potential supply constraints may exist. This tool, the Critical Materials Assessment Program (CMAP), screens the designs and their supply chains and identifies potential shortages which might preclude large-scale use of the technologies. Then a review of the critical materials identified in the computer screening takes place, and options for coping with or mitigating the supply problems are presented.

This report presents the results of the screening of the five following advanced PV cell designs:

- polycrystalline silicon
- amorphous silicon
- cadmium sulfide/copper sulfide frontwall
- polycrystalline gallium arsenide MIS
- advanced concentrator-500X

Each of these five cells is screened individually assuming that they first come online in 1991, and that 25 GWe of peak capacity is online by the year 2000. (These individual cases are referred to as the "baseline cases" in this report.) A second computer screening assumes that each cell first comes online in 1991 and that each cell has 5 GWe of peak capacity by the year 2000, so that the total online capacity for the five cells is 25 GWe. (This case is referred to as the "mixed scenario".)

Based on a review of the preliminary baseline screening results, suggestions were made for varying such parameters as the layer thickness, cell production processes, etc. The resulting PV cell characterizations were then screened again by the CMAP computer code. (These cases are referred to as the "sensitivity cases".)

Earlier DOE sponsored work on the assessment of critical materials in PV cells conclusively identified indium and gallium as warranting further investigation as to their availability. Therefore, this report includes a discussion of the future availability of gallium and indium.

The work on this project is being performed for the Solar Energy Research Institute at the Pacific Northwest Laboratory (PNL) operated for the Department of Energy by Battelle Memorial Institute and at Battelle Columbus Laboratory.

2.0 METHODOLOGY AND DEPLOYMENT SCENARIOS USED IN THIS PV MATERIALS ASSESSMENT

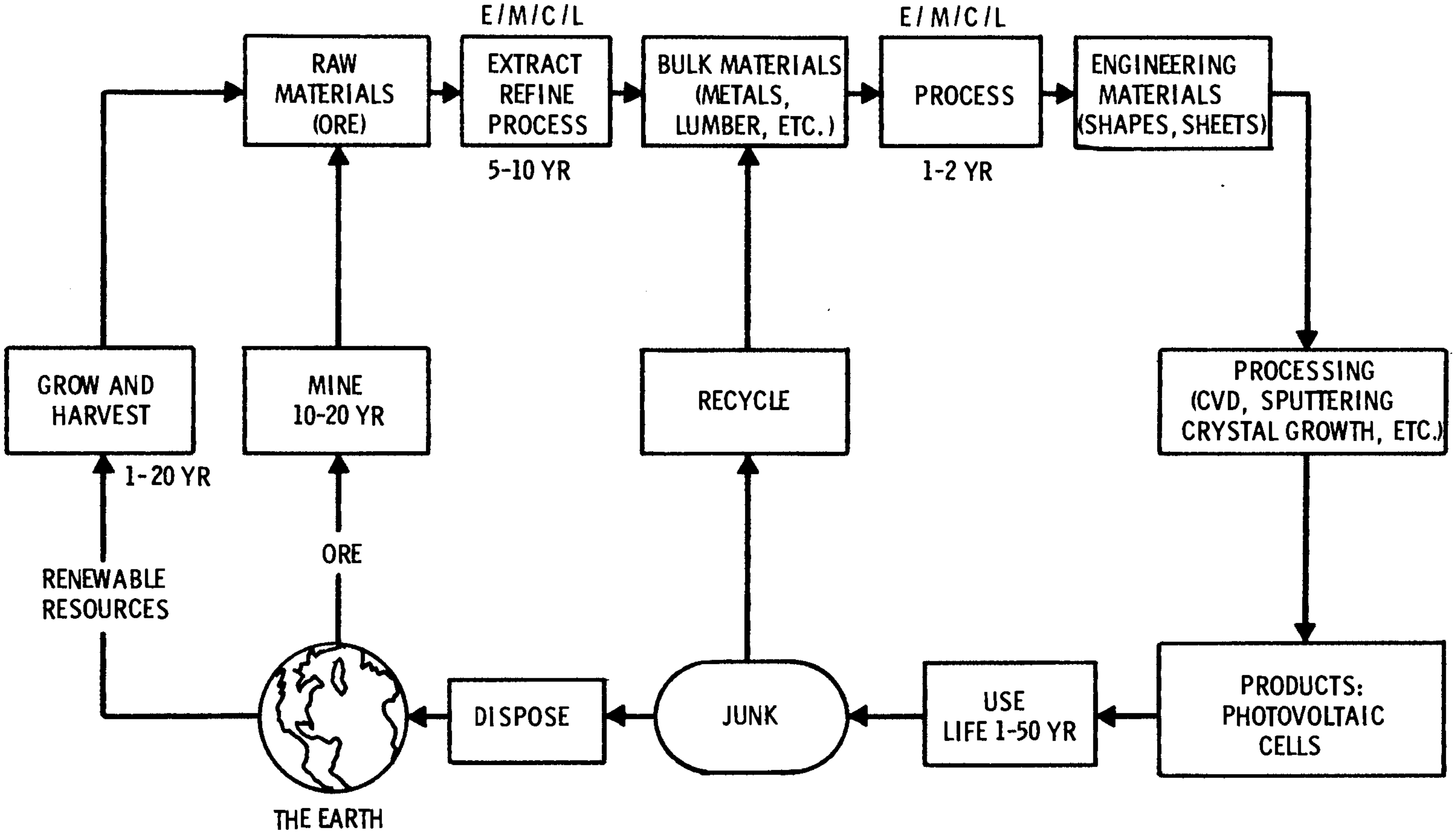
Modern industrial society rests on the continuation of adequate supplies of goods and services which require the operation of a massive industrial complex supported by a continuous supply of ores and renewable resources from the earth (see Figure 1). This supply chain is a complex one involving thousands of factories and mines. The key question addressed in this methodology is whether a given new PV technology will be supported in the future by an adequate industrial supply chain at an affordable price. The emphasis for this report is: "Will adequate supplies of quality PV materials be available and affordable?"

The answer to this question requires a different approach from the type usually taken in resource or strategic materials studies. Typically, the emphasis is on the supply situation for only raw materials. In this study the attitude is taken that supply constraints could arise anyplace in the material stream. Another key concept in the study is that we are less concerned about materials (the scarcity of gold, for instance) in general than whether or not it will be possible to obtain and afford the gold to build the needed photovoltaic cells, assuming a given production process.

In order to approach these problems it is necessary to characterize: (1) the final product desired, (2) the production process used to produce the product, (3) the materials processing stream, and (4) the available renewable and non-renewable resources (see Figure 2). The product and its production are unique to a specific product assessment. The materials processing streams and the characterization of the materials sources have many common elements with the data used to assess other designs and even technologies. Thus, the specific cell material needs are analyzed (starting with the cell itself) and the material streams are tracked back to raw materials, as is illustrated in Figure 2. During the tracking process the needs of PV are compared to normal industry capacity to see if production pinch points are likely and whether the materials are likely to be affordable for the desired cell production.

In order to make this comparison with normal industry capacity it is necessary to also know the desired rate and timing of installations of the new technology. There are practical limitations to the amount of change a given industry can accommodate without a disruption of the normal market. The prevention of such disruptions is precisely the end objective of this analysis. Mitigating strategies can be developed to minimize the impact of potential constraints on availability and prices.

THE MATERIALS CYCLE



TIME TO INCREASE CAPACITY

E/M/L/C - ENERGY, MATERIAL, LABOR, CAPITAL INPUTS

FIGURE 1. The Materials Cycle

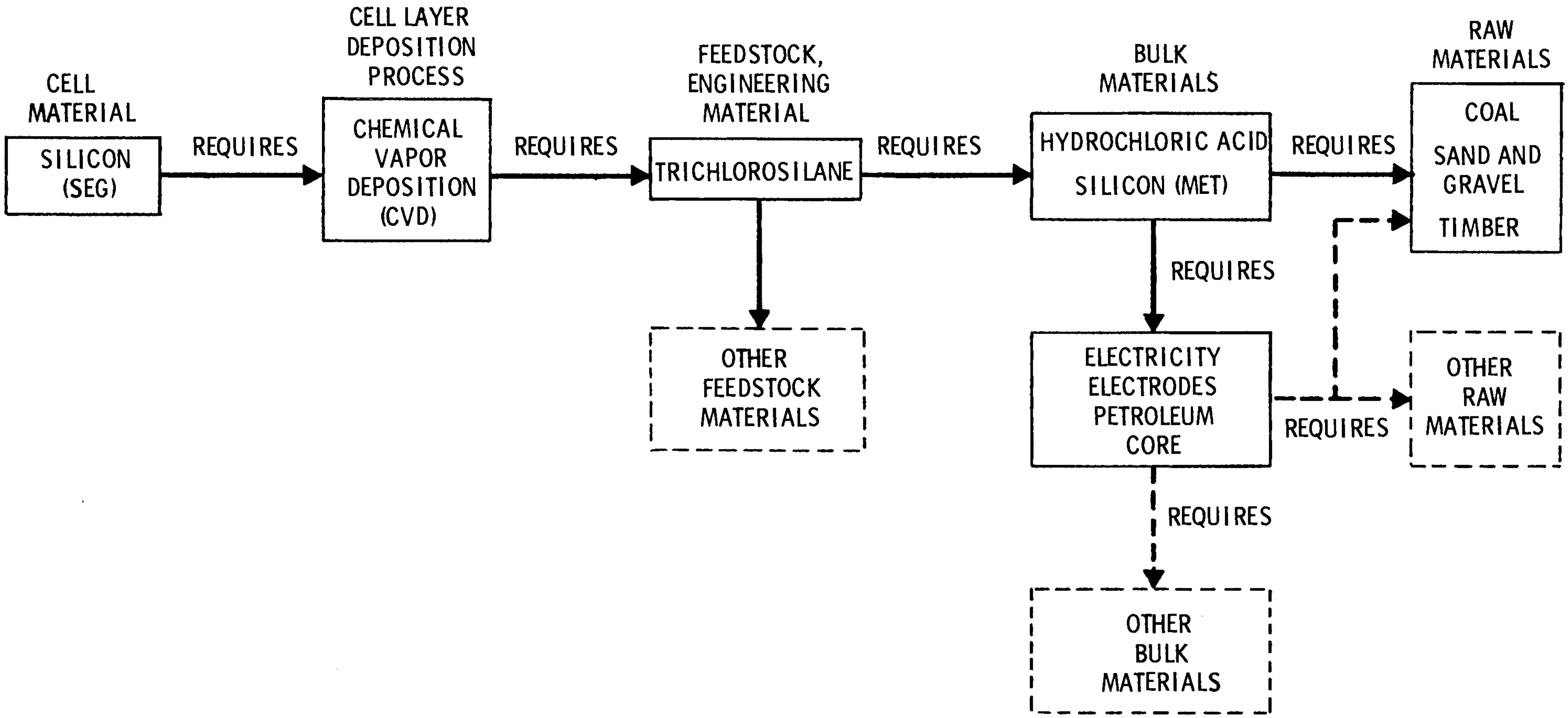


FIGURE 2. Typical Conversion Chain or Matrix

Tracking the material stream from the desired end product back through industrial and material production processes to identify potential constraints is not a rigorous, definitive process because of the dynamic nature of industrial processes and because there are many alternative pathways through the intermeshing material streams. In practice, it is usually satisfactory to identify the constraints in well known material flows.

One would normally think of tracking materials from the mine to final use. The opposite procedure is used in this materials assessment. Figure 2 illustrates this process. The cell materials, one of which can be silicon, must be deposited on previous layers of the cell. The process illustrates chemical vapor deposition (CVD) using a feedstock (or engineering material), in this case, trichlorosilane.

The CVD process, of course, requires other feedstocks to make a complete cell but these are omitted for clarity in Figure 2. The production of trichlorosilane requires "bulk materials" (hydrochloric acid and metallurgical grade silicon) for its manufacture but these, in turn, require both raw materials and yet other bulk materials in their manufacture. The "bulk materials", electrodes, electricity, and coke require yet other bulk materials and raw materials for their manufacture ad infinitum. Fortunately, this process can be truncated after a reasonable number of iterations without significant error for our purposes.

Tracking of material streams can introduce a great deal of arithmetic into the assessment process and leads to the need for mechanizing the tracking process. This has been done in a computer program: Critical Materials Assessment Program (CMAP).

The following sections of this chapter describe the material assessment process in greater detail and show how it is used to identify potential material problems. The sections contain:

- The detailed procedure used in making a materials assessment
- A discussion of the part CMAP plays in the materials assessment
- A description of the CMAP screening results
- A discussion of the descriptions used in CMAP to discriminate potential supply and price problems including typical threshold values for these descriptions
- A discussion of the effects of technology deployment rates on the materials supply streams
- A discussion of the methods used to evaluate the potential problems identified by CMAP

THE DETAILED MATERIAL ASSESSMENT PROCEDURE

When the simplified example (Figure 2) is expanded to an overall materials assessment of an entire technology, the problem becomes much more complex, involving large numbers of materials and production processes. The analysis required can best be described as consisting of the following nine basic steps (refer also to Figure 3):

Step 1. Identify Materials Requirements

The final construction materials (such as brass, concrete, composites, and trichlorosilane) for a technology under study are identified, preferably at the component or subsystem level. This results in a listing of the quantities of all materials required for the construction and installation of one system "unit" (such as one polycrystalline silicon cell) producing a specified amount of energy.

Step 2. Identify Process of Producing Cells

The process of producing the cell will have characteristic or typical material use efficiencies and these will affect the amount of feedstock materials required in producing cells for a given energy production.

Step 3. Specify Deployment Scenario

The scenario for a technology describes the annual and cumulative production of units over a specified period of time. (Production and deployment of units are assumed equivalent.)

Step 4. Compute Annual Materials Requirements

The annual materials requirements are calculated by multiplying the units per year by the quantities of each final material in one unit.

Step 5. Analyze Material Production Processes

Each final construction material is produced from bulk and secondary bulk materials (such as copper, cement, graphite, fiber, or sulfuric acid) and raw materials (such as sand and gravel, ore, or timber). Quantities of all such materials are calculated by year.

Step 6. Characterize the Materials Industry

For all materials, a data base is developed. It includes such factors as availability, source, production capacity, expected growth in demand, and prices on a domestic and worldwide basis for each material.

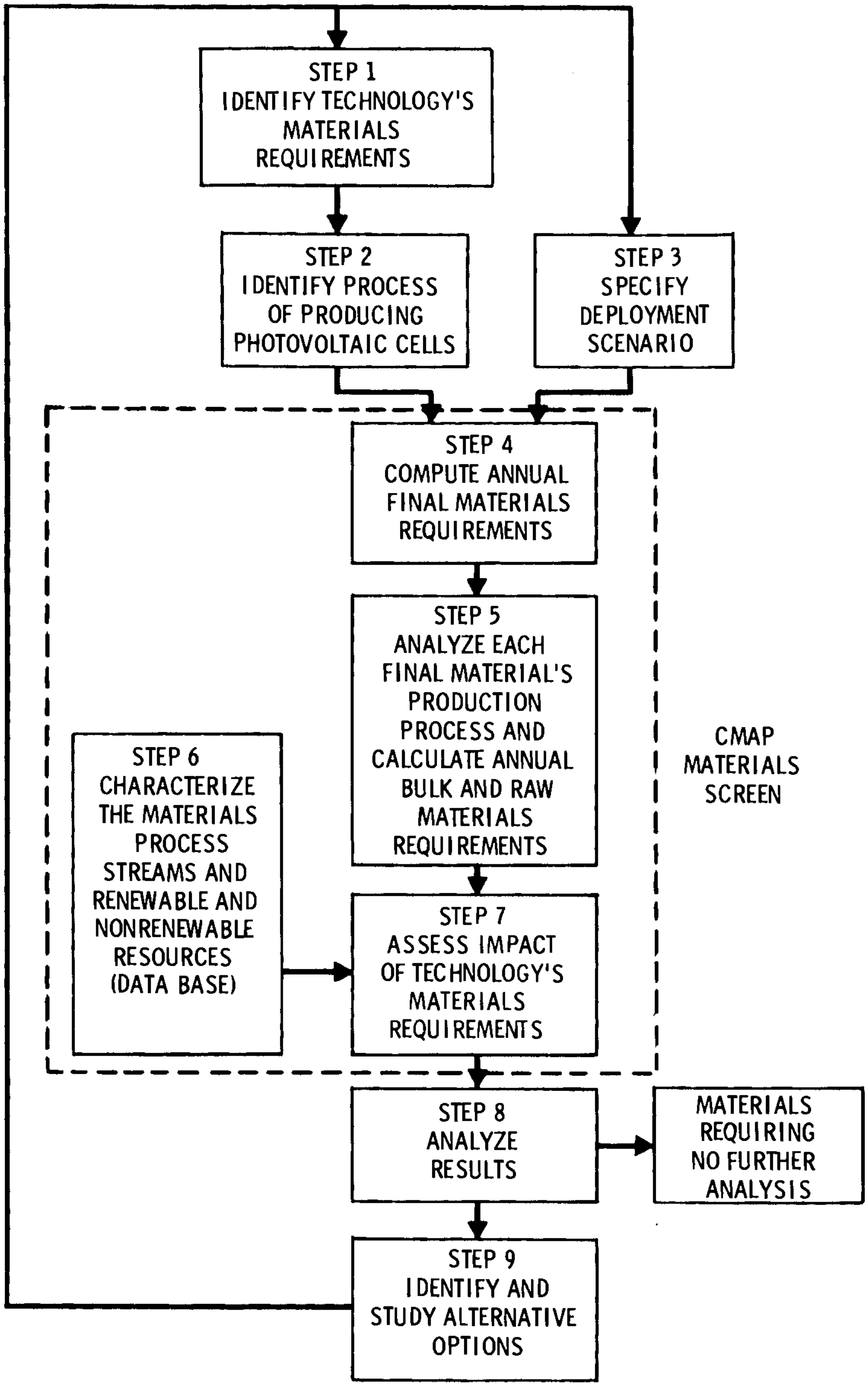


FIGURE 3. Overview of the Methodology

Step 7. Assess the Technology's Impact

The technology's annual demand for each material (as determined in Steps 1-4) is compared to pertinent information in the data base for that material. This reveals the impacts of the system, expressed in such terms as percentage of total production required, percentage of resources consumed, or dependency on imports.

Step 8. Analyze the Results

The significance of each impact identified in Step 6 is assessed by comparison to a predetermined threshold value. Some impacts will be of no concern; others will require further study.

Step 9. Study Alternative Options or Mitigating Strategies

For those materials involving significant uncertainties, or potential constraints, alternative options are identified and studied. One option is materials substitutions. If this is considered, Steps 1 through 7 are repeated to evaluate the effect of the substitution. Other options open to managers and planners for reducing uncertainties include redesigning a component, subsystem, or an entire system; undertaking R&D aimed at alleviating an uncertainty; exploring for new resources; or developing incentives for expanding manufacturing capacity.

CMAP'S ROLE IN MATERIALS ASSESSMENT

The computer algorithm, Critical Materials Assessment Program (CMAP), was specifically developed to aid in the overall materials assessment process by mechanizing Steps 4 through 7, as shown in Figure 3 and discussed in the previous section.

Thus, the analysis program is known as the Critical Materials Assessment Program (CMAP) and its functions are those enclosed by the dashed line in Figure 3. CMAP can accumulate all requirements for a given material regardless of the ultimate usage of that material in a system. It can give the bulk and raw constituents of a material; calculate the impacts of a system's materials requirements relative to worldwide availability, source, demand, etc.; screen out materials that are of no concern; and identify those that are of concern. It uses threshold values of pertinent ratios to make this discrimination.

These values are discussed in a subsequent section about the descriptions used to indicate potential problems.

The CMAP data base currently contains about 2000 data entries (covering hundreds of materials) developed from over a hundred information sources (see Appendix A). The sources include many government publications, technical handbooks, special reports, technical papers, trade association and technical association data, journal articles and the like. Where no secondary source data are available, information has been obtained directly from producers. All data entries are referenced for further examination when necessary.

In short, the methodology contains a data base on most of the materials information planners and designers of systems will need, and the means for rapidly compiling the information toward the desired result. Information on materials which is not already contained in the data base is easily added as additional studies are carried out for which they are required. This information then becomes part of the data base and is available to subsequent users.

CMAP does not do a materials assessment. What it does is to carry out a screening for potential problem areas using stored data and threshold values for the criteria. The screening results from the computer (see the following section) are printed out for analysis by knowledgeable individuals who analyze and interpret the results.

One of the reasons this is so important is that the key descriptions used in the screening process do not have convenient, universal levels at which they become important. An example follows.

One of the descriptions (or parameters) of interest for bulk material screening in CMAP is the production growth rate required to meet the demand of PV cells and all other industries (retrievable from the materials data base). The threshold value for this parameter is currently set at 10% per year. Thus, if the required growth rate exceeds 10% a flag is set on the printout signifying that a potential production capacity problem exists. If the material in question has a relatively small production base (e.g., hydrogen sulfide, 99.999%), then a 10% growth rate might not be difficult to achieve. However, if the material in question already has a large production base (e.g., aluminum) then a 10% growth rate would represent an enormous requirement for additional capital, labor, facilities, etc., and a definite problem exists.

Thus, in reality, an accurate "threshold value" for a given parameter might be different for each material considered. Any attempt to incorporate this reality into

CMAP would make the automated screening intractable and defeat its entire purpose. Therefore, a single threshold value is postulated for each parameter -- a value, based on Battelle's experience, that is representative and generally conservative for the majority of materials. These threshold values are not intended to be absolute measures of material criticality, but merely indicators that can speed and simplify the analysis of results. The responsibility for accurately interpreting those results properly remains the task of the experienced analyst.

THE CMAP SCREENING PROCESS

CMAP performs three principal functions: (1) calculation of total materials requirements; (2) determination (for each material) of a set of parameters that characterize the materials' demand impact; and (3) comparison of the parameter values so determined with certain "threshold" values for those parameters, which, when exceeded, triggers "flags" on the output printout that call attention to the potential problem.

Figure 4 depicts CMAP program operation. To facilitate and increase the flexibility of analyses, CMAP has been made interactive. This means that input data can be changed while cases are being examined. Thus, the top blocks of user-supplied impact can be changed to analyze desired case variations (e.g., different deployment scenarios) and/or to iterate based on results. The bottom left blocks contain the baseline system design characterization (material requirements) and the materials data base are entered by card deck. These data cannot be changed interactively, but can be updated periodically as needed.

Calculation of materials requirements begins with a technology materials list. Total amounts of the materials on that list required to support a specified deployment scenario are calculated (based on the number of units required). Then, using information stored in the materials data base, production processes required to produce those materials are analyzed to determine secondary bulk material and raw material requirements.

Once total materials demand has been established, attention turns to the material parameters and threshold values on which the screening is based. Since the parameters of interest and threshold values differ somewhat for bulk and raw materials, the screening of these two types of materials is done separately (separate printouts are produced), and the screening threshold values are, of course, discussed separately in the following section.

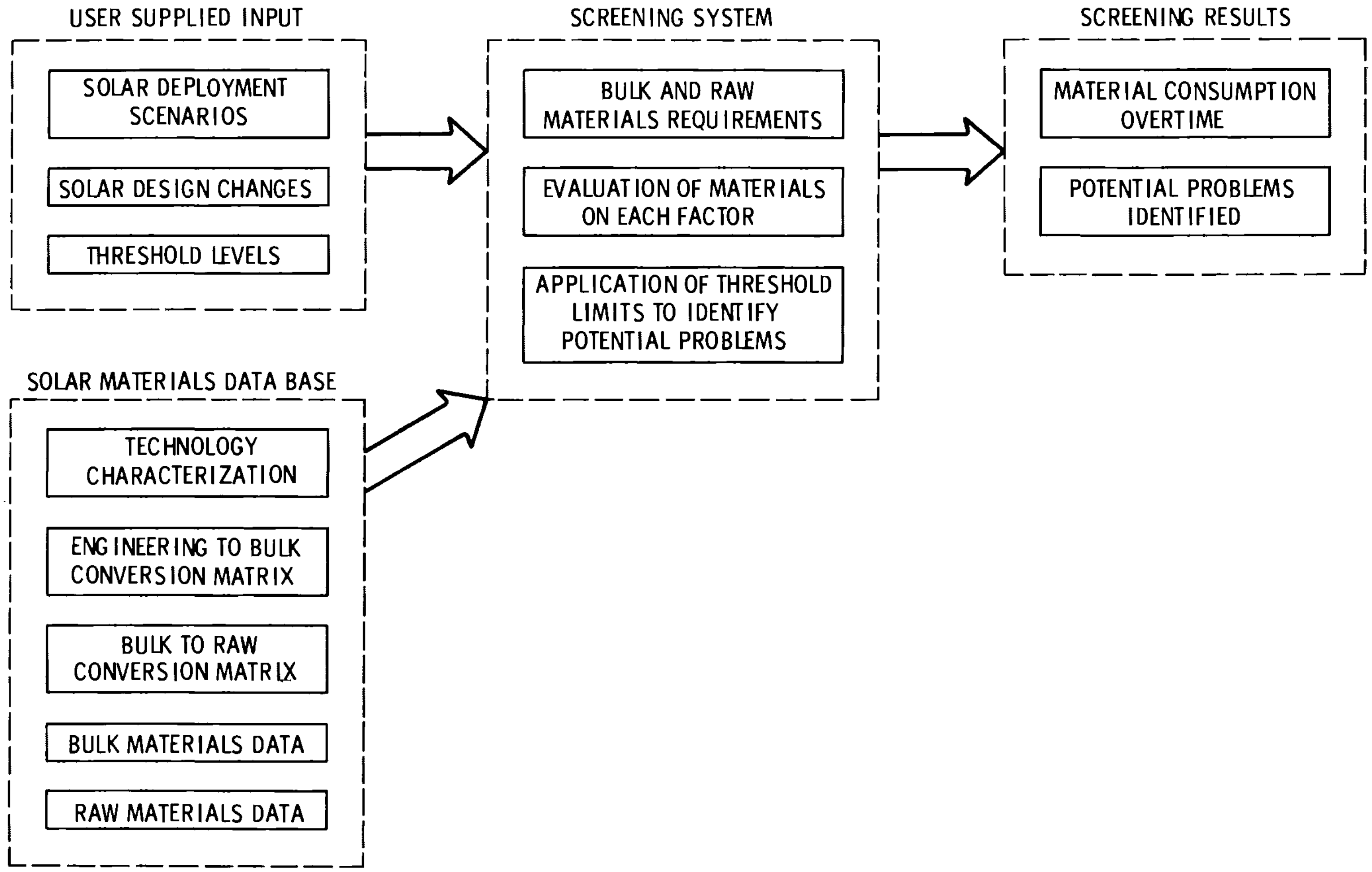


FIGURE 4. Screening System

THE CMAP SCREENING DESCRIPTIONS AND THRESHOLD VALUES

Bulk Materials Screening Parameters and Thresholds

The parameters of interest for bulk materials are listed below. These parameters are determined for each material required.

- Percent of the material which is produced as a byproduct of another material production process
- Maximum production growth rate required to meet solar and nonsolar material needs (This occurs between 1990 and 1991 for our deployment scenario.)
- Maximum percent demand of solar as a portion of total world demand
- Current percent of the world production attributable to a single foreign source
- Current material purchase cost contribution to solar power installed, \$/kW
- Current net percent of U.S. material consumption that is imported (from all foreign sources).

In the following paragraphs these parameters are discussed, the rationale for assessing criticality is developed, and currently used threshold values are identified.

Percent Supplied as Byproduct

The threshold value is set here at 50 percent. The frequent implication that byproduct dependence is constraining is often misleading. Materials sometimes considered today as byproducts may be viewed at other times as coproducts or even primary products depending upon supply/demand and market/price conditions. Hence, the term "byproduct material" should not necessarily be viewed as a "low-cost" or an "undesirable" material production consequence of a process stream. The economics of many extractive and manufacturing processes are highly dependent upon byproduct/coproduct recovery. That economic dependence or leverage frequently becomes important in assessing criticality of the material. However, where economic dependence is not present, only strong demand and attractive market prices will bring forth the capital investment required to recover the amounts of the byproduct material needed.

Growing demand for the primary product is of basic importance to sustaining given levels of byproduct production. If the technology requirements for the byproduct material are small, or if the market is "glutted", even declining primary material production levels can maintain adequate byproduct supplies.

World Production Growth Rate

The threshold value here is 10 percent. Many small volume or new materials can readily maintain a 10 percent annual rate of growth. However, large volume, capital-intensive commodities would have great difficulty in sustaining such a growth rate.

Maximum Percent Technology Demand, One Year World

This threshold is set at 10 percent. This figure represents the technology's market impact on material consumption at its potentially highest demand level relative to demand for that material for other uses. At high percentage of demand levels, the technology demand can be a market driver, perhaps bringing about higher prices or even a cartel. This criterion may also be viewed as a trigger for close examination of opportunity costs -- that is, the technology's potential for adverse impact on other segments of the economy demanding the same material.

Percent From One Nation, Non-U.S.

This threshold level is set at 35 percent. It represents a measure of supply domination in world markets by any one non-U.S. nation. If the technology material demand is also a significant proportion of total demand, then potential for supply disruption or the development of a cartel is present. The nature of the material demand, as well as the dominant nation identified, then becomes a part of the criticality judgment. This criterion usually assumes more importance in assessing raw materials, since bulk material production among industrial nations tends to disperse over time.

Present Costs in $/kW

This threshold is set at $50.00 per kW of constructed capacity. This value is calculated as MT required/kW cells x $ per MT. Values for material in excess of the $50.00 threshold deserve close examination. It should be emphasized that these figures represent present bulk material cost -- not the cost of the fabrication processes. The fabrication cost of cells can very substantially exceed the materials cost per se. Stated costs also are representative of the prevailing art for producing the materials -- often in low volumes in the case of new materials. For many newer materials, those production costs can be expected to be lowered over time.

Total cost of the cells attributable to these materials becomes sensitive to changes in price or required volume of the materials in question. Materials price forecasts, fabrication cost determinations, design review and possible materials substitutions might be considered.

Net Percent Imported

The threshold value is set at 50 percent and is based on current levels of net U.S. imports. If the maximum volume of material required by the technology is very small compared to total U.S. demand in the same time frame, there is probably little cause for concern regardless of the U.S. import level. For many materials -- particularly raw materials -- for which the U.S. is dependent on imports, that dependency is likely to grow in future years. This is a matter of general economic concern and not necessarily related to any specific technology under consideration. In other words, we would be concerned only if the technology and its deployment scenario might substantially exacerbate an already recognized U.S. import dependency for certain materials.

Raw Materials Screening Parameters and Thresholds

With respect to the screening of raw materials, levels of current reserves and resources estimates are introduced as screening parameters, in addition to those identified in the bulk material discussion. In general, where the U.S. is reserve/resource deficient, it is also import dependent. The focus of concern in these cases is levels of world reserves and resources and whether the system construction would substantially contribute to world resource deficiency or to substantially greater U.S. import dependency. The complete list of raw material screening parameters is given below.

- Average world production growth rate (per year) required to meet solar and all other projected demands
- Maximum percent demand (in any given year) of solar as a portion of total world demand
- Percent of U.S. reserves consumed by photovoltaics and all other projected demand
- Percent of U.S. resources consumed by photovoltaics and all other projected demand
- Percent of world reserves consumed by photovoltaics and all other projected demand
- Percent of world resources consumed by photovoltaics and all other projected demand
- Current percent of the world production attributable to a single foreign source
- Current material purchase cost contribution to photovoltaic power installed, $/kW
- Current net percent of U.S. material consumption that is imported (from all foreign sources).

The previous discussions of parameters under "Bulk Materials Screening" adequately describe those parameters which are common to both bulk and raw materials. Therefore, most of those discussions will not be repeated here. However, "World

Production Growth Rate", and "Percent From One Nation, Non-U.S.", where the raw material threshold value is different is discussed. The two parameters that change and the new parameters, U.S. and world reserve and resources, are discussed below.

World Production Growth Rate

The threshold value here is 7 percent rather than the 10 percent value used for bulk materials. Extractive operations usually require longer lead times and ary very capital-intensive. Sustained annual growth rates of 5 percent are not too unusual, but 7 percent could be.

Percent From One Nation, Non-U.S.

The threshold value here is 60 percent rather than the 35 percent value used for bulk materials. Developed resources tend to be more concentrated in specific locations than bulk material production facilities. However, the opportunity to exploit undeveloped resources in alternative locations generally exists. Consequently, the higher threshold value is used.

U.S. Reserves and Resources Consumed and World Reserves and Resources Consumed

The threshold values used are 400 percent, 300 percent, 300 percent, and 200 percent, respectively. For the 10-year time span considered, those threshold values are quite conservative. One could argue for many materials that they might even comfortably be doubled. In analyzing U.S. reserves and resources, sensitivity to doubling those values would be minimal, since we are usually either highly foreign source dependent or hardly at all.

Screening Process

CMAP screening consists of comparison of screening parameter values for each material with the parameter threshold values. CMAP asks whether or not the threshold value has been exceeded, and, if it has, sets a flag on the printout identifying the potential problem. The required logic is illustrated in Figure 5 for bulk and raw materials.

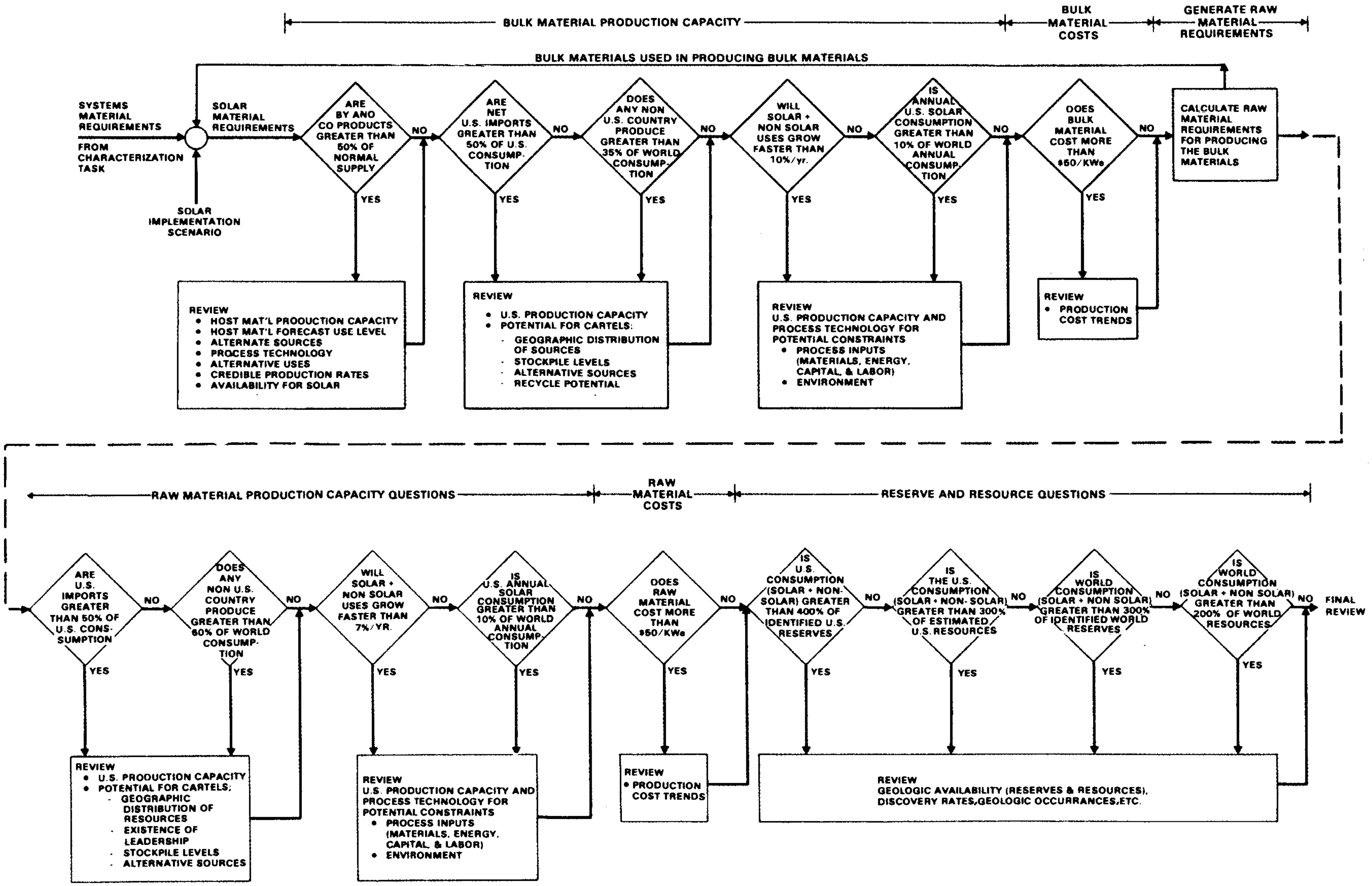


FIGURE 5. Assessment of Potential Bulk and Raw Materials Problems

THE IMPORTANCE OF THE DEPLOYMENT RATE OF A NEW TECHNOLOGY

New technologies bring changes to the materials supply industry. It is one of the important roles of CMAP to focus attention on potential material supply stresses caused by a planned rate of deployment for a new technology. New technologies tend to start out slowly because of initial conservatism of customers and of the supply chain. This conservatism tends to protect the materials industry from rapid, large-scale changes in demand for key materials.

Geopolitics and national needs may, however, produce stronger forces tending toward more rapid shifts in demand and these changes may produce severe dislocations in the materials supply industry. These more rapid changes can be accommodated more easily if problems are recognized ahead of time and dealt with by longer term strategies.

The photovoltaic program is a program capable of developing some of these material stress points because of two factors: (1) geopolitics is causing petroleum supplies to become expensive and undependable, and (2) very rapid progress is occurring in the development of higher efficiency, lower cost devices.

The Domestic Policy Review (DPR) of Solar Energy (1) gives one assessment of how fast this might occur. The DPR provides information on the amount of fuel displaced by various solar technologies now and in the year 2000. For photovoltaics the estimates for 2000 are:

	Base Case	Maximum Practical	Technical Limit
Quads displaced in the year 2000	.1	1.0	2.5
kWh generated at 1,000 Btu/kWh	10^{10}	10^{11}	2.5×10^{11}
Power, peak generating capacity on line in 2000, assuming 20% being the ratio of output power to peak operating capacity	5.7 GW	57 GW	142 GW

This particular study assumes that considerable capacity of silicon cells is online by the year 2000 and that 25 GW is supplied by advanced cell designs. It is also assumed that the advanced photovoltaic cells do not come online before 1990. This assumption places some interesting constraints on the manner by which 25 GW of advanced cells are placed online.

Two types of stress can be placed on the materials supply industry; one is, of course, the rate at which facilities for processing have to be expanded; the second type is encountered for materials which are byproducts of other industries where there is a practical limit to the quantity of byproduct material which can be produced. Both types of constraints are encountered in this study and are presented in Figure 6. The bottom curve illustrates the projected values of material usage without the new deployment of the PV cells. The dotted line just above this curve represents a 10% increase in capacity for the industry. The highest dotted line represents the limit placed on the byproduct because of its dependency on the production of primary material. The curves a, b, and c beginning at 1990, represent different usage levels of the byproduct in various designs and total usage (including both PV and non-PV uses).

Curve "a" exceeds the 110% production curve but its shape is such that it does not exceed 10% increase in any one year so that it does not create the rate of increased stress that would be encountered if curve "b" were followed. This curve exceeds the 10% criteria in the first year. Curve "b" represents a case where ultimate capacity could be handled but where special strategies may be required to assure quality and delivery at an affordable price.

Curve "c", on the other hand, represents a situation which calls for the development of new sources of material in addition to special strategies to assure quality, delivery and price.

Scenario #1

Production scenarios can be varied to help one or the other, but not likely both, of these constraints. The minimum stress on ultimate capacity results from the assumption that all PV cell manufacturing plants are (for our example) online in 1990 and produce 2.5 MW for 10 years (see Figure 7). This approach, however, maximizes the rate stress because it places an instantaneous demand on the materials market to support the 2.5 MW production facility. This scenario would be highly unlikely because it takes skilled engineers and contractors to build material production and cell production plants. It would be outrageously expensive to create and then almost immediately fold up a plant construction and process equipment manufacturing industry.

Scenario #2

A more realistic approach is to assume that capacity to fabricate cells is added linearly each year starting January 1, 1990 and assuming that plant construction continues to January 1, 2000. The online capacity to produce cells is thus assumed to

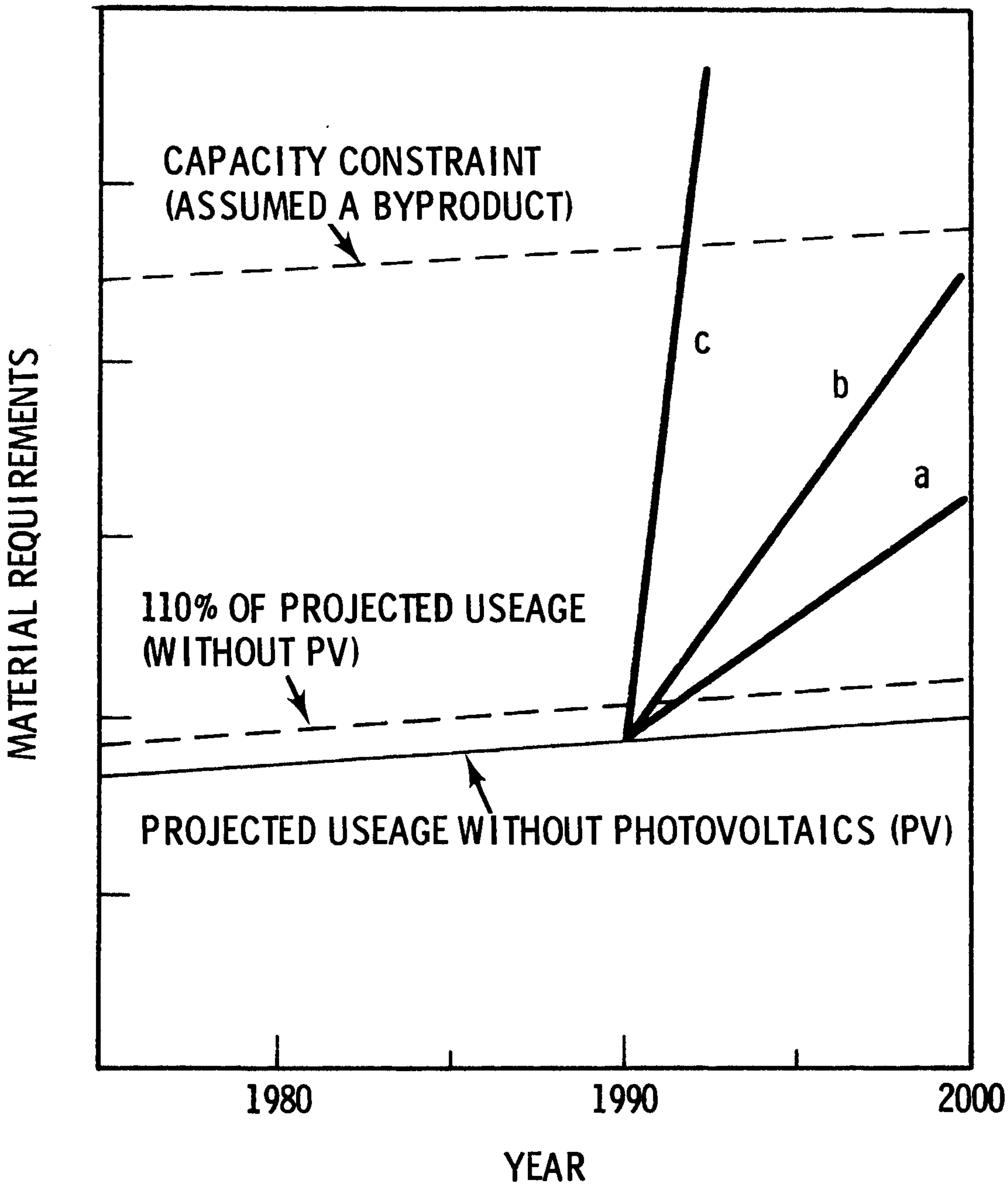


FIGURE 6. Projected Usage Levels of A Hypothetical Material With and Without Photovoltaic Usage Showing Rate and Capacity Constraints

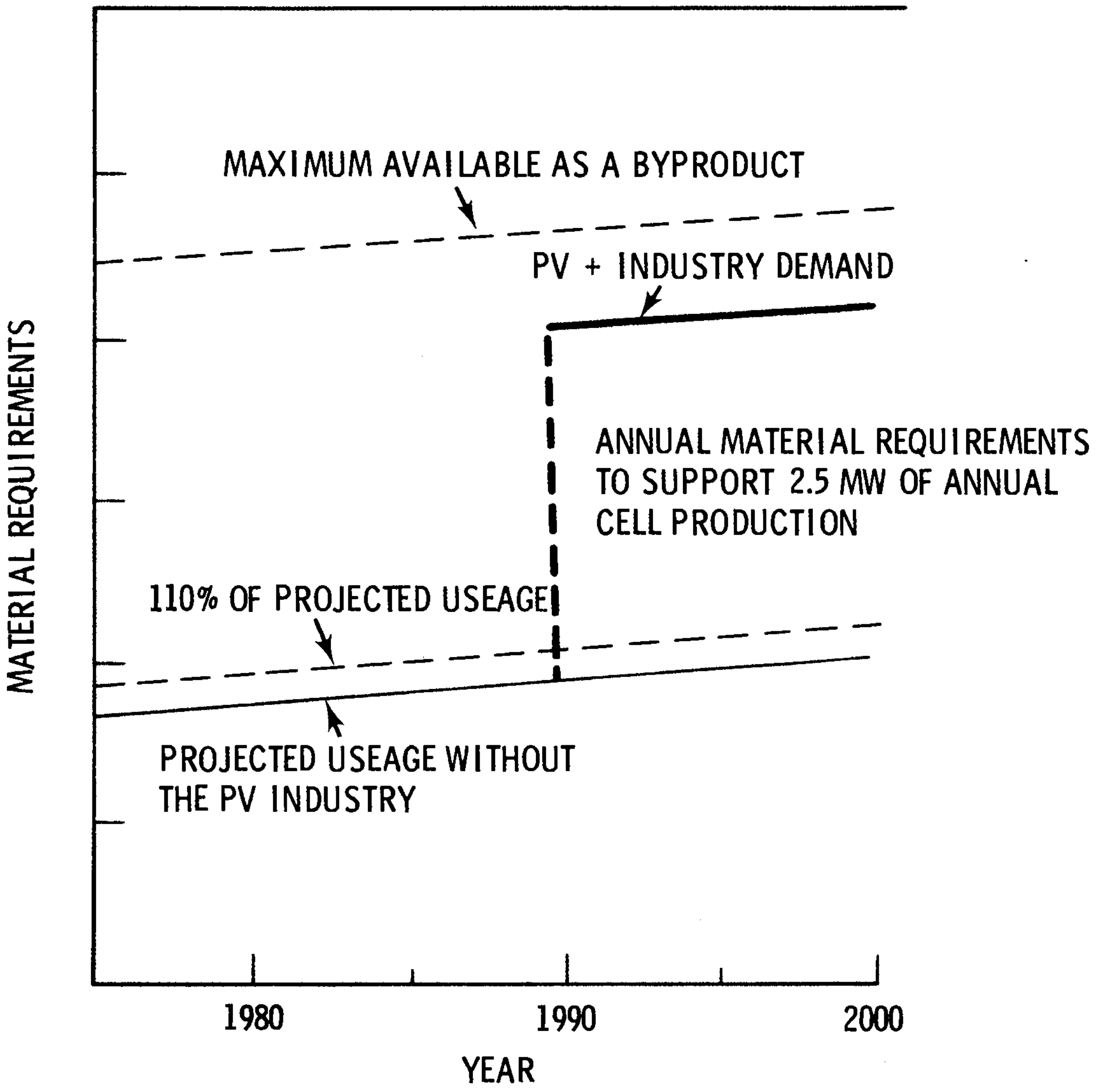


FIGURE 7. Material Requirements for 2.5 MW of Annual Cell Production

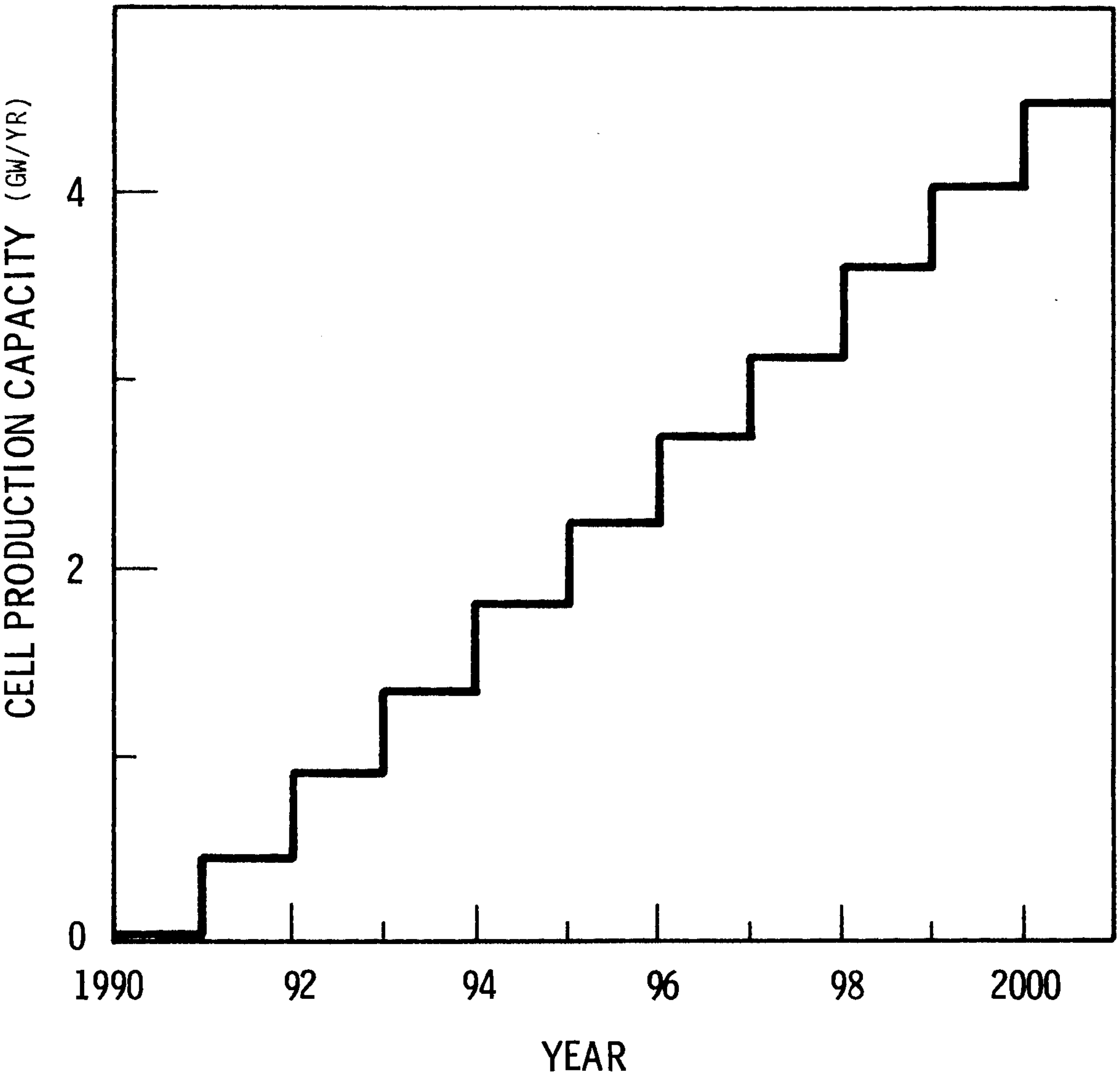


FIGURE 8. Cell Production Capacity

be as shown in Figure 8 . The area under this curve can be assumed to be the cumulative online cell capacity (assuming no failures) and for this study has been adjusted to equal 25 GW by the end of the year 2000. This means that 4.545 GW of cell fabrication will take place in the year 2000. This is shown in Table 1 for convenience.

TABLE 1 . Cell Production Capacity and Cumulative Production for 1990-2000 in GW

Year	Cell Production Capacity Added/Yr.	Cells Produced/Yr.	Cells Producing Electricity, Total
1990	0.4545	0	0
1991	0.4545	0.4545	0.4545
1992	0.4545	0.9091	1.3636
1993	0.4545	1.3636	2.7272
1994	0.4545	1.8182	4.5454
1995	0.4545	2.2727	6.8181
1996	0.4545	2.7273	9.5454
1997	0.4545	3.1818	12.7272
1998	0.4545	3.6364	16.3636
1999	0.4545	4.0909	20.4545
2000	0.4545	4.5455	25.0000

This set of assumed production values places 18.18% of the total 10 year production online in the year 2000. This is, of course, the largest material requirement for any year. The cases analyzed in this study all use this distribution of values.

Scenario #3

From the viewpoint of building plants, one could consider an alternative case, where each year the ability to build cell production plants is linearly increased. This is a way of reducing the pressure on process equipment manufacturers who would otherwise have to come to full production the first year for the previous example. This latter assumption also reduces the pressure on the materials supply industries in early years but increases it in the later years of the period being studied (see Figure 9). This scenario was rejected because of the severe pressure placed on the materials industry in the later years.

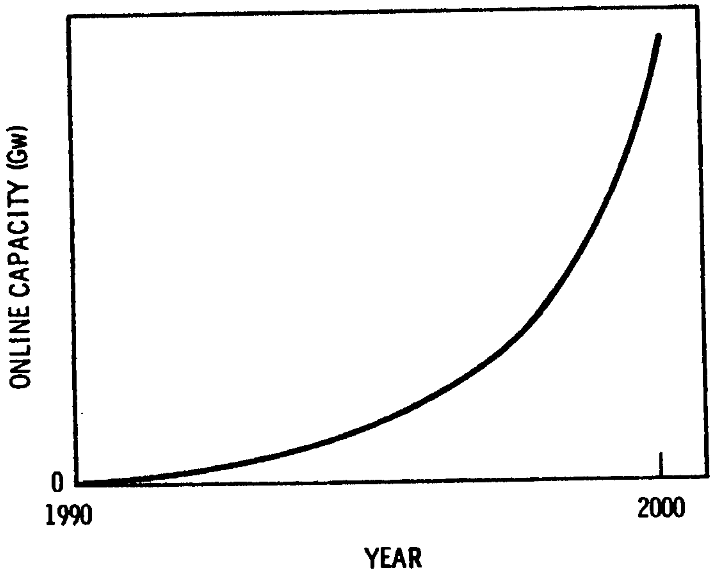


FIGURE 9. Online Capacity

This results in a maximum of about 27% of all PV cells being built in the last year. For this particular scenario (25 GW on line in 2000) this amounts to 6.75 GW going on line in the last year.

The following table compares the consequences of the three deployment pathways described above.

TABLE 2 . Consequences of Alternative Deployment Scenarios

Deployment Path	Maximum Cell Production GW/Yr	% of 25 GW in Maximum Year
Constant Cell Production	2.5	10%
Constant Cell Capacity Addition (Used in This Study)	4.54	18%
Constant Additional Construction Capability to Increase Production	6.75	27%

The next step in identifying potential material supply constraints is to analyze the computer screening results and to classify the materials. This procedure is discussed in the following section.

PROCEDURE FOR CLASSIFYING CELL MATERIALS

After the CMAP (computer program) has screened the photovoltaic cells it prints out the results in a form convenient for review. The manual review of screening results consider all materials which exceed any threshold even though many will not present any serious problems for the implementation of PV based on the desired deployment scenario.

This manual review process emphasizes the various data items concurrently to determine whether the material is economically important to the PV cell production or whether the PV level of usage is likely to be high enough to produce stresses in the material market. Based on this manual review of the CMAP results, materials are classified as "A", "B" or "C" materials.

An "A" material is a material that requires further investigation (beyond the computer analysis) to determine availability and/or cost constraints. Flags raised by the computer under the headings of "Max. % System 1 Year World" and "Present Cost in $/kW" usually indicate a problem worthy of future review.

A "B" material usually exceeds at least one threshold level, but is used in small quantities or at low costs. These materials should be reassessed in the future since some could become problems due to design changes, etc.

A "C" material does not exceed any of the threshold levels and is not now expected to present future materials constraints.

REFERENCES

1. "Domestic Policy Review of Solar Energy". U.S. Department of Energy, TID-28835, Washington, D.C., 1978.

3.0 CELL DESCRIPTIONS AND SCREENING RESULTS

The following five advanced photovoltaic cell designs were screened for critical materials using the CMAP computer code:

- Polycrystalline Silicon
- Amorphous Silicon
- Cadmium Sulfide/Copper Sulfide Frontwall
- Polycrystalline Gallium Arsenide MIS
- Advanced Concentrator

A brief description of the five baseline cells[a] is presented in this chapter, along with the changes made for the sensitivity analysis.

Also, the results of the CMAP computer screening are evaluated, concentrating on the "A" and "B" materials. The "A" materials are evaluated to determine whether or not the future availability of these materials at a reasonable price will be a problem. Mitigating strategies are suggested to help alleviate "A" material availability and cost problems.

The "B" materials are reviewed to determine if any should be reclassified to "A" material status to ensure availability. Specific mitigating strategies are not recommended for "B" materials since they are not expected to pose serious availability problems to photovoltaics. However, all "B" materials should be reassessed in the future in case their status changes. (Complete CMAP screening results are contained in Appendix B.)

The quantity of material in a cell layer required to generate 1 GW_p under AM1 insolation (1 kW/m^2 = 1 GW/km^2) was calculated using the layer thickness, material density and the cell efficiency. Adjustments were made for concentration factor and area coverage. (Grid contacts were assumed to cover 10% of the cell area.) In the discussion of each cell a figure is included which describes the baseline cell. The "most likely" layer thicknesses shown were picked in the Summer of 1979 by knowledgeable specialists in a working session at SERI.

The tabular data below the cell illustration figure gives the materials con-

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[a] Baseline cell characterizations were developed with the assistance of the SERI Photovoltaic Program Office.

tained in each layer in metric tons per GW_p. The corresponding amount of chemical feedstock required to deposit the layer of material can be calculated by dividing the quantity of material in the layer by the process efficiency and the chemical ratio. Chemical ratios are defined and listed in Table 3. Process efficiencies assumed for the baseline cases are given in Table 4 . In this program, the feedstock quantities are computer calculated as part of the computerized screening process.

TABLE 3. Chemical Conversion Ratios

Feedstock		Chemical Ratio*	Material Deposited	
Trichlorosilane	- $SiHCl_3$	.207	Si	- Silicon
Phosphine	- PH_3	.911	P	- Phosphorous
Diborane	- B_2H_6	.781	B	- Boron
Silane	- SiH_4	.874	Si	- Silicon
Cuprous Chloride	- Cu_2Cl_2	.804	Cu_2S	- Cuprous Sulfide
Zinc Borofluoride	- $Zn(BF_4)_2$	.274	Zn	- Zinc
Trimethyl Gallium	- $Ga(CH_3)_3$	.607	Ga	- Gallium
Trimethyl Indium	- $In(CH_3)_3$	.718	In	- Indium
Trimethyl Aluminum	- $Al(CH_3)_3$	.374	Al	- Aluminum
Arsine	- AsH_3	.961	As	- Arsenic
Germane	- GeH_4	.947	Ge	- Germanium
Hydrogen Sulfide	- H_2S	.941	S	- Sulphur
Tantalum	- Ta	1.22	Ta_2O_5	- Tantalum Pentoxide
Titanium	- Ti	1.67	TiO_2	- Titanium Dioxide

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*Chemical Ratio = MT of material deposited per MT of feedstock at 100% process efficiency.

TABLE 4 . Process Efficiencies Assumed for Baseline Cases

Process	Assumed Efficiency*
Chemical Spraying	20%
Chemical Vapor Deposition (CVD)	35%
Cuprous Ion Hot Dipping	10%
Electroless Plating	90%
Electroplating	80%
Energy Beam Deposition	45%
Evaporation	35%
Glow Discharge Decomposition	10%
Liquid Phase Epitaxy (LPE)	95%
Metal Organic Chemical Vapor Deposition (MO-CVD)	30%
Molecular Beam Epitaxy (MBE)	55%
Solder Dipping	90%
Sputtering	40%

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*Process efficiency = amount deposited/amount contained in the feedstock (precursor).

Where masks are used in vapor depositing grid contacts, the efficiency is reduced by a factor of 10, i.e., 10% cell area coverage, no recovery from mask.

A cell packing factor of 0.8 is assumed and included in the above figures.

POLYCRYSTALLINE SILICON SOLAR CELLS

Cell Description

A homojunction (p-n) cell was chosen for the baseline case which illustrates the material requirements of polycrystalline silicon solar cells. A cell conversion efficiency of 10% was assumed. Probable commercial layer thicknesses, based on state-of-the-art polycrystalline silicon cells, are shown in Figure 10. Probable commercial processes, and feedstocks used to fabricate the layers, are also shown in Figure 10. Cell characteristics were developed with the assistance of the SERI Photovoltaic Program Office.

This baseline cell has a graphite support substrate underneath a 500 micron thick wafer of polycrystalline, metallurgical grade silicon. The active layer (25 microns) and p-n junction layer (0.3 microns) are deposited epitaxially by CVD from trichlorosilane. The p and n dopants are deposited by CVD using diborane and phosphine, respectively. The top grid consists of 0.03 microns of evaporated nickel and 5 microns of 60-40 solder. An antireflective coating of tantalum pentoxide is evaporated on.

A variation of the baseline case (i.e., sensitivity case) was also screened to determine the impact of substituting silane, SiH_4, for trichlorosilane, $SiHCl_3$.

Screening Results

The computerized screening results for the baseline cell are given in Tables 5 and 6 for the bulk and raw materials, respectively. Similar results for the sensitivity case are given in Appendix B. The tables list all materials required to support the production of polycrystalline silicon solar cells. Screening criteria were discussed in Section II of this report, entitled "Methodology and Deployment Scenarios". All the materials which exceeded one or more of the threshold values of the criteria will be mentioned.

Review of the CMAP of the baseline and sensitivity polycrystalline silicon cell identified the following "A" materials:

Baseline	Sensitivity
Trichlorosilane	Silane

and the following "B" materials:

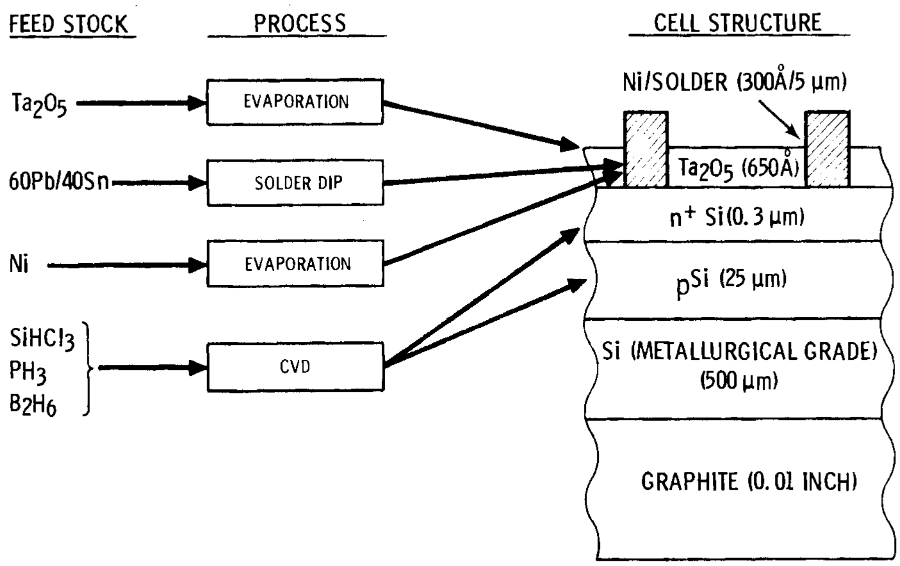

FIGURE10. Polycrystalline Silicon Homojunction (P-N) Solar Cell

Layer Function	Process & Feedstock To Material in Layer	Chem. Ratio	Process Effic.	Mat'l. in Layer MT/GWp
ACTIVE LAYER	CVD TRICHLOROSILANE TO-SI	0.21	0.35	583.0
P-DOPANT	CVD DIBORANE TO B	0.78	0.35	4.53-05
EPITAXY SUBSTRATE	SILICON-MET GRADE	1.	1.	1.17+04
P-N JUNCTION LAYER	CVD TRICHLOROSILANE TO SI	0.21	0.35	6.99
N-DOPANT	CVD PHOSPHINE TO P	0.91	0.35	1.55-02
AR COATING	EVAPORATED TANTALUM PENTOXIDE	1.0	0.35	5.34
GRID CONTACT	EVAPORATED NICKEL	1.0	.035	0.267
	SOLDER DIP 60-40 SOLDER	1.0	.90	42.1
SUPPORT SUBSTRATE	GRAPHITE,MFGD.	1.0	0.8	5.74+03

TABLE 5 .

BULK MATERIAL REQUIREMENTS FOR
POLYCRYST. SILICON-HOMOJUNCTION (P-N) SOLAR CELL
BASELINE CASE

SOLAR SCENARIO:
INTRODUCTION YEAR- 1991
CUMULATIVE CAPACITY 2000- 25. GW

FACTORS	BULK MATERIAL USAGE MT.	PERCENT SUPPLY AS BY-PROD	PRODTN GROWTH RATE 1990	MAX % SYSTEM 1 YEAR WORLD	% FROM ONE NATION NON-US	PRESENT COSTS IN $/KW	NET % IMPORT
THRESHOLD LEVELS--		50.	10.%	10.	35.	50.	50.
ALUMINUM (a)	0.	0.	7.	0.	13.	0.	9.
ALUMINUM FLUORIDE	0.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
AMMONIA	0.	0.	3.	0.	5.	0.	1.
BORAX	0.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
BORON TRIFLUORIDE ETHERAT	0.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
CALCIUM	0.	0.	5.	0.	20.	0.	0.
CARBON DIOXIDE	0.	100.*	3.	0.	5.	0.	0.
CAUSTIC SODA	0.	0.	3.	0.	5.	0.	1.
CHLORINE	18.	0.	3.	0.	5.	0.	1.
COAL, BITUMINOUS	0.	0.	2.	0.	20.	0.	10.
COKE	363.	0.	3.	0.	10.	0.	1.
CRYOLITE	0.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
DIBORANE	0.	0.	5.	0.	5.	0.	0.
DIETHYL ETHER	0.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
ELECTRICITY (KWH)	8659.E+6	0.	7.	0.	0.	10.	0.
ELECTRODES	92340.	0.	4.	1.	10.	6.	1.
FERROMANGANESE	0.	0.	3.	0.	22.	0.	98.*
FERROSILICON	1.	0.	3.	0.	10.	0.	35.
FERROUS SCRAP, PURCHASED	6.	0.	3.	0.	10.	0.	0.
FLUORSPAR	0.	0.	5.	0.	19.	0.	79.*
GRAPHITE, MFGD.	179375.	0.	4.	1.	10.	62.*	1.
HYDROCHLORIC ACID	963249.	92.*	4.	1.	5.	8.	2.
HYDROFLUORIC ACID	0.	0.	3.	0.	15.	0.	0.
LEAD	433.	13.	5.	0.	12.	0.	15.
LIME	63.	0.	3.	0.	20.	0.	2.
LIQUID FUELS	142.	0.	3.	0.	18.	0.	39.
MAGNESIUM	1.	1.	6.	0.	27.	0.	0.
METHANOL	0.	0.	5.	0.	10.	0.	0.
METHYL BORATE	0.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
NICKEL	191.	7.	3.	0.	33.	0.	70.*
ORTHO-PHOSPHOROUS ACID	12.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
OXYGEN, GASEOUS	725.	0.	4.	0.	21.	0.	0.
OXYGEN, LIQUID	2.	0.	4.	0.	21.	0.	0.
PETROLEUM COKE	505697.	100.*	3.	0.	15.	2.	0.
PHOSPHINE 99.999%	1.	0.	21.*	0.	10.	0.	0.
PHOSPHOROUS	5.	0.	6.	0.	22.	0.	0.
PHOSPHOROUS TRICHLORIDE	20.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
PITCH-IN-TAR	92808.	0.	3.	1.	5.	0.	5.
SILICON (MET)	505217.	0.	3.	2.	12.	22.	11.
SODIUM BOROHYDRIDE	0.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
SODIUM CARBONATE	10.	0.	0.	0.	10.	0.	0.
SODIUM HYDRIDE	0.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
STEAM	397.	1.	3.	0.	10.	0.	0.
STEEL & IRON	25.	1.	3.	0.	16.	0.	7.
SULFUR	154192.	31.	3.	0.	14.	0.	0.
SULFURIC ACID	457543.	20.	3.	0.	14.	1.	0.
TANTALUM PENTOXIDE	381.	100.*	9.	27.*	10.	5.	0.
TIN	737.	1.	3.	0.	28.	0.	85.*
TRICHLOROSILANE	200677.	0.	21.*	28.*	10.	16.	0.
(MISC. BULK MATERIALS)	157.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?

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a. The -99 represent process intermediates for which there is no data in the data base.

TABLE 6 .

RAW MATERIAL REQUIREMENTS FOR:
POLYCRYST. SILICON-HOMOJUNCTION (P-N) SOLAR CELL
BASELINE CASE

SOLAR SCENARIO:
INTRODUCTION YEAR- 1991
CUMULATIVE CAPACITY 2000- 25. GW

FACTORS	RAW MATERIAL USAGE (1000MT)	%PRD GROW RATE FROM 1990	MAX% SYST ONE YEAR WRLD	%US RESERV CONSUM BY 2000	%US RESOUR CONSUM BY 2000	%FRM ONE NAT NON-US	%WORLD RESERV CONSUM BY 2000	%WORLD RESOUR CONSUM BY 2000	PRSNT COSTS IN $/KW	NET% IMPT
THRESHOLD LEVELS--		7.	10.	400.	300.	60.	300.	200.	50.	50.
BAUXITE	0.	5.	0.	2691.*	364.*	31.	15.	10.	0.	91.*
COAL, BITUMINOUS	8704.	2.	0.	5.	1.	7.	9.	1.	5.	0.
FLUORSPAR ORE	0.	5.	0.	1004.*	168.	19.	255.	140.	0.	79.*
IRON ORE	0.	5.	0.	29.	5.	27.	16.	5.	0.	29.
LEAD ORE	9.	3.	0.	95.	23.	12.	95.	39.	0.	15.
LIMESTONE	0.	3.	0.	0.	0.	20.	0.	0.	0.	2.
MANGANESE ORE	0.	3.	0.	100.	8.	22.	15.	8.	0.	98.*
NATURAL GAS	128.	5.	0.	258.	60.	23.	97.	10.	0.	5.
NICKEL ORE	19.	2.	0.	3533.*	9.	33.	48.	20.	0.	70.*
PETROLEUM	26145.	2.	0.	565.*	185.	18.	104.	34.	76.*	39.
PHOSPHATE ROCK	0.	6.	0.	30.	17.	14.	21.	7.	0.	0.
SALT	506.	6.	0.	0.	0.	18.	0.	0.	1.	7.
SAND & GRAVEL	1850.	4.	0.	0.	0.	6.	0.	0.	0.	0.
SILICA PEBBLE	0.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
SULFUR ORE	154.	3.	0.	189.	61.	14.	109.	34.	0.	0.
TANTALUM ORE	4.	10.*	0.	100.	1866.*	39.	59.	13.	0.	96.*
TIMBER, LUMBER	518.	1.	0.	0.	0.	12.	0.	0.	3.	18.
TIN ORE	74.	2.	0.	3491.*	705.*	28.	67.	18.	1.	85.*
WATER, FRESH	0.	2.	0.	0.	0.	5.	0.	0.	0.	0.
WATER, SEAWATER	1.	0.	0.	0.	0.	0.	0.	0.	0.	0.

Baseline

- Carbon Dioxide
- Ferromanganese
- Fluorspar
- Hydrochloric Acid
- Nickel
- Petroleum Coke
- Phosphine
- Tantalum Pentoxide
- Graphite-Substrate
- Tin
- Bauxite
- Fluorspar Ore
- Manganese Ore
- Nickel Ore
- Petroleum-Byproduct
- Tantalum Ore
- Tin Ore

Sensitivity

- Carbon Dioxide
- Ferromanganese
- Fluorspar
- Graphite-Substrate
- Hydrochloric Acid
- Lithium
- Nickel
- Petroleum Coke
- Phosphine
- Tantalum Pentoxide
- Tin
- Bauxite
- Fluorspar Ore
- Lithium Ore
- Manganese Ore
- Nickel Ore
- Petroleum-Byproduct
- Tantalum Ore
- Tin Ore

"A" MATERIALS DISCUSSION

The deployment of 25 GWe of polycrystalline silicon solar cells by the year 2000 could have a significant impact upon trichlorosilane supplies. In the year 2000, about 28% of the world supply of trichlorosilane would be used in polycrystalline silicon cell production. This would require a maximum growth rate of 21% per year. Short-term supply disruptions could result if photovoltaic requirements are not planned for. The principal problem is availability. The cost of trichlorosilane, 1.6¢/watt, is not excessive. Trichlorosilane is produced as a primary product, not as a byproduct, and imports are not a critical factor.

Trichlorosilane is produced by reacting copper catalyzed metallurgical grade silicon with anhydrous hydrogen chloride. Hence, there are no problems with basic materials supplies.

Trichlorosilane is a volatile liquid with a boiling point of about 32°C. It is flammable, but probably not highly toxic.

Trichlorosilane is the precursor for the manufacture of polycrystalline silicon as well as an important chemical precursor for silicones. In 1979, the U.S. probably consumed about 9100 metric tons for the manufacture of polycrystalline silicon. Captive consumption for making silicones is unpublished. A current spot price for trichlorosilane is about $2.00 per kg and contract prices are about $1.75 per kg.

The major U.S. manufacturers are Dow Corning, Union Carbide and Texas Instruments. Dow Corning production is largely consumed captively for manufacture of silicones and polycrystalline silicon. Texas Instruments production is also primarily for captive consumption. Reportedly, Union Carbide is the only domestic merchant supplier. European suppliers to the U.S. market include Wacker Chemical and Dynamit Nobel.

Expansion of trichlorosilane production capacity does not face the same magnitude of technological threat that the production of silane does. Hence, we would expect current manufacturers willing to expand production to accommodate the market.

It would seem to be prudent to involve trichlorosilane producers and plan for an orderly growth in trichlorosilane use in photovoltaic cells. Placing long-term supply contracts could assure adequate supplies for PV cells. The quantity of trichlorosilane required for PV cells is large enough that dedicated, onsite production may be economically feasible. If so, such an arrangement could assure availability, control quality, and allow the optimization of purity and cost.

In the sensitivity case, <u>silane</u> (SiH_4) was substituted for trichlorosilane ($SiHCl_3$) (feedstock for deposition of the active polycrystalline silicon layer). The material supply problem is worse for silane than for trichlorosilane. Polycrystalline cells would require 81% of the world production of silane in the year 2000. A maximum growth rate of 233% per year would be needed to reach this production. Finally, at present prices the silane would cost 25¢/watt.

Silane is a highly toxic, pyrophoric gas. It carries a DOT label and classification as "flammable gas".

Domestic production of silane in 1979 was probably in the range of 25 to 30 MT. The U.S. is a net exporter of silane.

By far the dominant use for silane is in the production of integrated circuits by the semi-conductor industry. A realistic 1979 price for silane in metric ton quantities is in the range of $130.00 to $140.00 per kg.

Major producers of silane include:

- Liquid Carbonic
- Union Carbide
- Air Products
- Matheson Gas
- Airco

Current producers contacted would not reveal their process route to silane. For the data base Battelle surmises that the process involves the electrolytic reaction of silicon tetrachloride or trichlorosilane with lithium hydride. There would appear to be no basic materials problems.

According to one major supplier, current production could be easily doubled or tripled within 12 to 18 months. It is very probable, however, that current manufacturers might be very reluctant to significantly expand silane production based on current technology. DOE's Low-Cost Solar Array program, managed by the Jet Propulsion Laboratory, shows strong indications of the feasibility of a new technology route to polycrystalline silicon production at costs of less than $12 per kg (Union Carbide Process)(1,2). The silane produced as an intermediate product in this process is easily retrievable from the buffer storage, although the purity of the silane is uncertain. This would imply feasible silane production cost much lower than the current price of $130/kg for silane. Current suppliers may want to wait until this new low cost process is available before increasing silane production capacity. Hence, any sizeable increase in silane consumption in the short run could present capacity problems.

The potential impact of polycrystalline silicon cells on the silane market is illustrated in Figure 11. Clearly, the silane market would be dominated by PV cell requirements. Planned increases in silane production capacity will have to be made to ensure availability of silane.

Figure 12 shows the impact of silane price and deposition efficiency on the silane cost for the 25 micron thick active polycrystalline silicon layer. At the current price of $130/kg (in metric ton quantities), silane is prohibitively expensive, greater than 8¢/watt at 100% deposition efficiency. With silane priced at $12/kg, silane cost is below 5¢/watt for deposition efficiencies greater than 16%.

From the supply viewpoint silane is a poor substitute for trichlorosilane in polycrystalline silicon cell production. The availability of trichlorosilane is better and the cost of trichlorosilane is lower at all deposition efficiencies. (For example, at 35% deposition efficiency silane costs 2.3¢/watt (at $12/kg) and trichlorosilane costs 1.6¢/watt.

If silane should become the technically desirable feedstock (compared to trichlorosilane), the following mitigating strategies might be desirable:

- Further promote the development of new, low cost production processes such as the Union Carbide process.
- Work closely with silane producers to coordinate silane production with PV cell needs, entering into long-term supply contracts with silane producers.

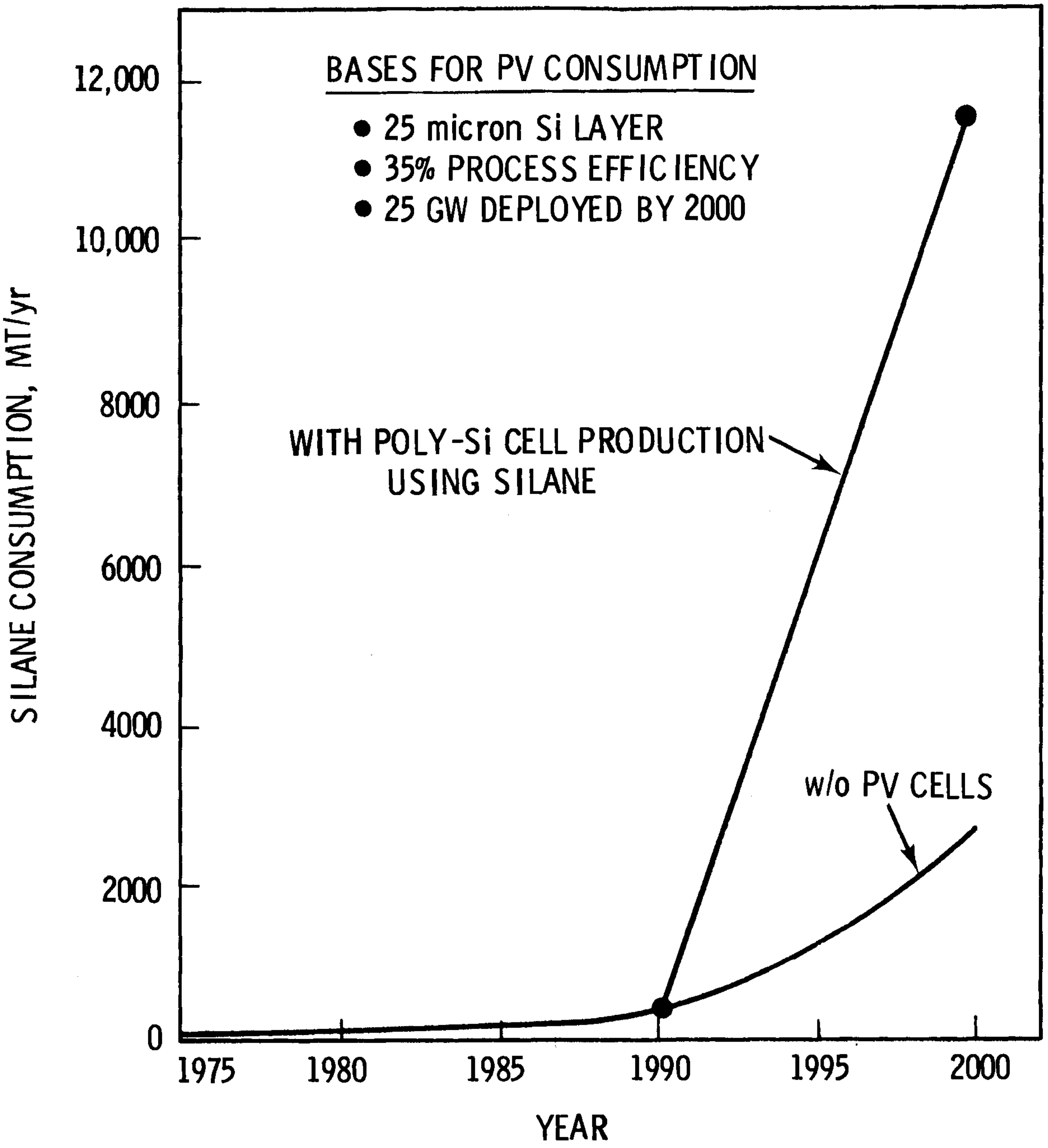

FIGURE 11. Projected Market for Silane With and Without its Use in Production Polycrystalline Silicon PV Cells

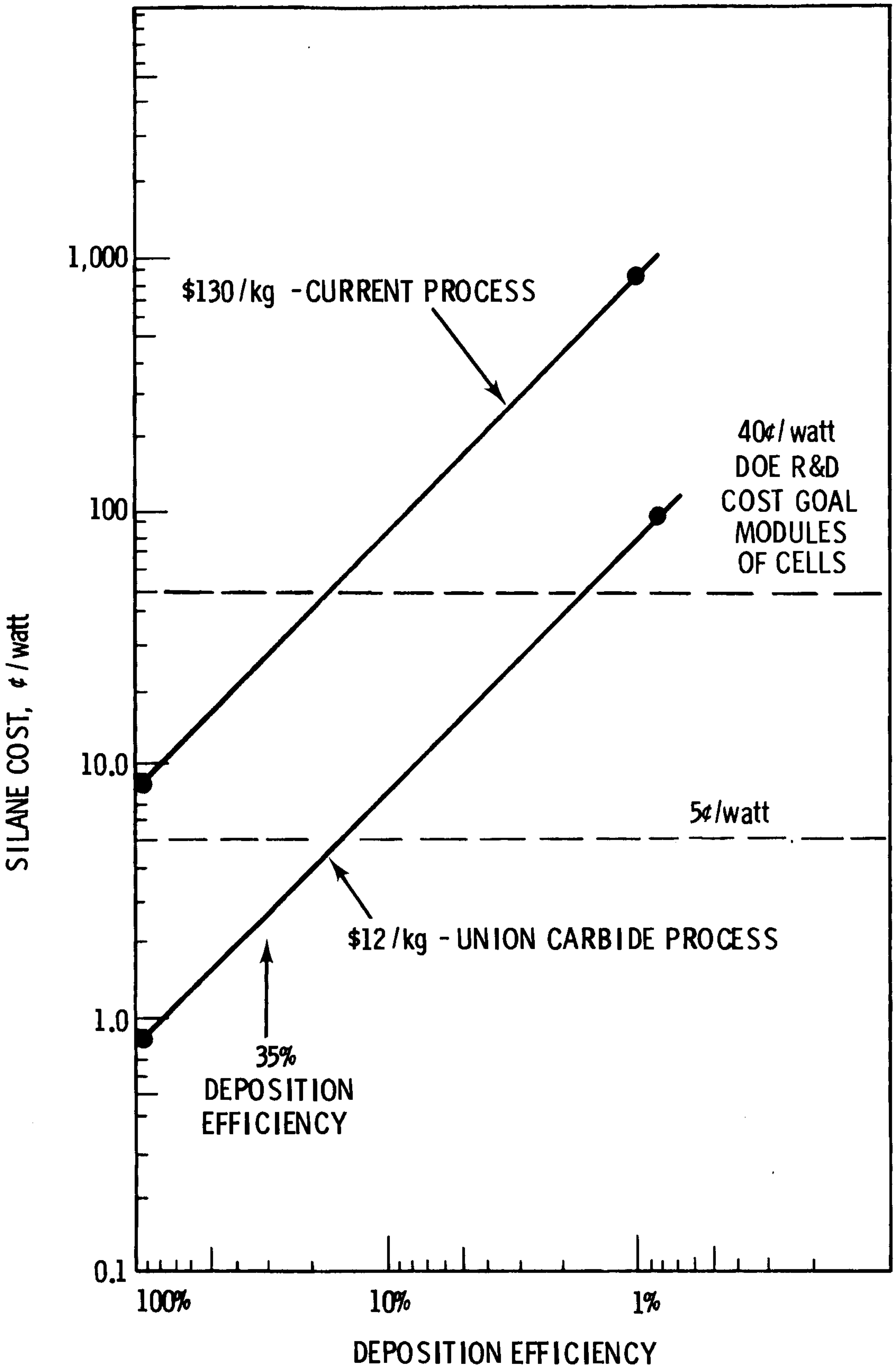

FIGURE 12. Silane Cost for 25 Microns of Polycrystalline Silicon vs. Deposition Efficiency and Silane Price

if necessary.

- Consider an onsite, dedicated silane production facility in order to ensure supply and to reduce transportation hazards.

"B" MATERIAL DISCUSSION

The following "B" materials were reviewed and found to not constrain the deployment of polycrystalline silicon solar cells. Generally, they are used in relatively small amounts and their cost to solar is low. Therefore, only severe supply disruptions, if they were to occur in the future, would significantly impact polycrystalline silicon solar cells. Supplies are adequate and stable. No supply disruptions are foreseen. These "B" materials should be subjected to periodic review.

Graphite-substrate is a "B" material representing a cost of 6.2¢/watt in the polycrystalline silicon cell. This represents a significant fraction of the DOE cost goals of 15 to 40¢/watt. The quantity of graphite used by PV cells alone is insignificant. Therefore, graphite availability is not a problem. The 6.2¢/watt is based upon an expected cost of $\$5/m^2$ for graphite substrates being developed at Poco Graphite for polycrystalline silicon cells. The cost is independent of thickness. The cost should ideally be less than $\$5/m^2$. However, the cost of graphite substrates is uncertain at this time and can only be confirmed after substrates are put into production. This important cost factor should be reassessed at a later date.

Carbon dioxide, hydrochloric acid, and petroleum coke are all produced as byproducts, and thus their supply is dependent upon the production of other materials. For this reason they are classified as "B" materials.

Ferromanganese, fluorspar, nickel, tin, tantalum ore and manganese ore are classified as "B" materials because they are 70 to 98% imported. (Also, tantalum is produced as a byproduct.)

Phosphine production will have to grow 21% per year, with or without solar requirements. However, since phosphine production is small (est. at 2.5 MT in 1976), such a high growth rate should be achieved. Phosphine is a "B" material.

Bauxite, fluorspar ore, nickel ore, and tin ore are "B" materials because they are largely imported and U.S. reserves and resources are small.

Petroleum byproduct appears here only because of its use in the production of petroleum coke for graphite substrate manufacture. The 7.6¢/watt cost of the petroleum is the value of the petroleum used in producing byproduct coke. Since coke is only a small part of the products obtained from the petroleum, only a small part of the 7.6¢/watt cost is attached to the coke as shown by the cost of petroleum coke to polycrystalline silicon cells, 0.2¢/W (see Table 5). U.S. reserves of petroleum are small, but world petroleum supplies and the increased use of coke from coal should assure an adequate supply of coke at a reasonable cost for solar cell substrates.

Polycrystalline silicon solar cells will use 27% of the world's supply of tantalum pentoxide. This will require only 2% of the world's tantalum production. Because the tantalum pentoxide cost is only 0.5¢ per watt and other antireflective coating materials are available (SiO, TiO_2, and MgF_2), the availability of tantalum pentoxide is not expected to be a problem.

Only two additional "B" materials appear in the sensitivity case in which silane is substituted for trichlorosilane. Polycrystalline silicon cells will consume about 27 to 29% of the yearly world supply of lithium and lithium ore in the year 2000 if silane were used as a feedstock. Also, these two materials would cost 7 and 5¢/watt, respectively. These materials are in the production chain for lithium hydride which is used to produce silane from trichlorosilane or silicon tetrachloride. However, lithium chloride is a product of both of these reactions, and lithium chloride is the feed material in lithium metal production. The quantities of lithium chloride involved would make recycling economic. With recycling, net usage of lithium and lithium ore would be negligible. Also, a new, low cost commercial process for making silane is being developed by Union Carbide under contract with the Jet Propulsion Laboratory(1,2). This process uses a special catalyst to convert trichlorosilane to silane without the use of lithium hydride.

AMORPHOUS SILICON SOLAR CELLS

Cell Description

The p-i-n cell on Indium Tin Oxide (ITO) coated glass was chosen for the baseline cell. A 0.058 micron thick ITO conducting window layer is sputtered onto a glass substrate, 0.125 inch thick. Next, a 0.012 micron thick diffusion layer of platinum and silica is sputtered on. The 1 micron thick active layer is formed by glow discharge decomposition of high purity silane. The p and n dopants are deposited from diborane and phosphine, respectively. The grid contact containing 5 microns of aluminum over 0.05 microns of titanium is formed by evaporation. This cell

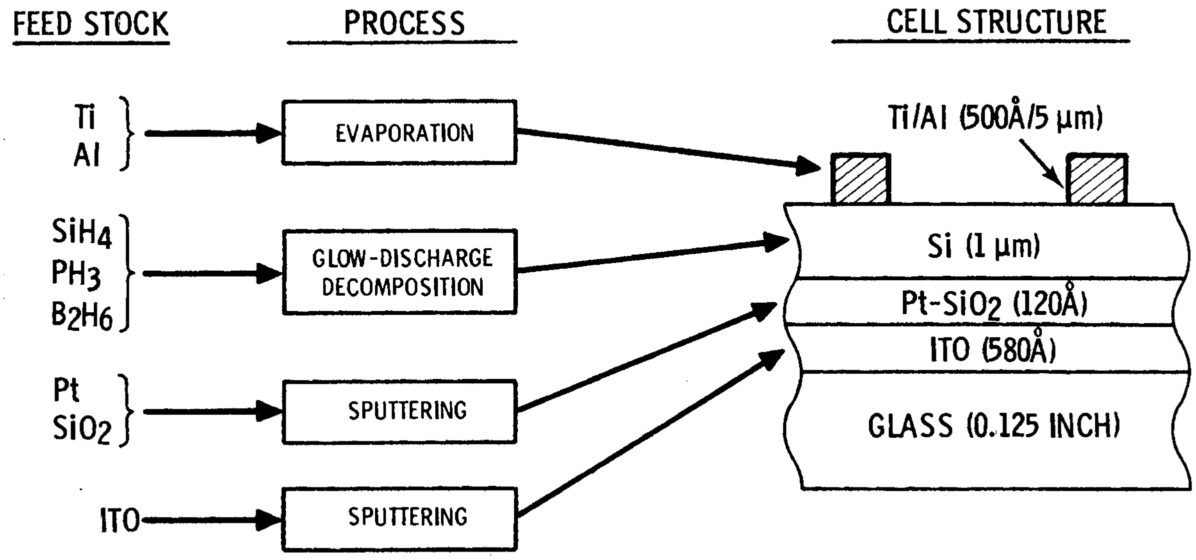

FIGURE 13. Amorphous Silicon P-I-N Solar Cell

Layer Function	Process & Feedstock To Material in Layer	Chem. Ratio	Pro-cess Effic.	Mat'l. in Layer MT/GWp
ACTIVE LAYER	GLOW DISCHARGE DECOMP. SILANE TO SI	0.87	0.10	46.6
N-DOPANT	GLO DISCH DECOMP PHOSPHINE TO P	0.91	0.10	2.59-03
P-DOPANT	GLO DISCH DECOMP DIBORANE TO B	0.78	0.10	9.05-04
GRID CONTACT	EVAPORATED			
	TITANIUM	1.0	.035	0.451
	ALUMINUM	1.0	.035	27.0
WINDOW LAYER	SPUTTERED INDIUM/TIN OXIDE	1.0	0.40	8.32
DIFFUSION BARRIER-	SPUTTERED PT/S102			
	PLATINUM	1.0	0.40	0.515
	SILICON DIOXIDE	1.0	0.40	1.09
SUPPORT SUBSTRATE				
	GLASS,SODA LIME	1.0	0.8	1.46+05

structure, the processes, and the feedstocks are illustrated and quantified in Figure 13. The material requirements are based on an assumed cell efficiency of 5%.

No variations in the baseline case were computer screened for critical materials. However, the impact of the price of the feedstock silane on the cost of the amorphous silicon active layer was examined.

Screening Results

The computerized screening results are given in Tables 7 and 8 for the bulk and raw materials, respectively. The tables list all materials required to support the production of polycrystalline silicon solar cells. Screening criteria were discussed in Section II of this report, entitled "Methodology and Deployment Scenarios". All the materials which exceed one or more of the threshold values of the criteria will be mentioned. Review of the CMAP screening of the baseline amorphous silicon cell identified the following "A" materials:

Baseline

Indium
Indium Tin Oxide
Silane

and the following "B" materials:

Baseline

Argon
Carbon Dioxide
Ferromanganese
Fluorspar
Soda Lime Glass
Helium
Hydrochloric Acid
Lithium
Petroleum Coke
Phosphine
Platinum
Tin
Titanium
Bauxite
Fluorspar Ore
Lithium Ore
Manganese Ore
Petroleum
Rutile (Conc.)
Tin Ore
Zinc Byproduct

TABLE 7 .

BULK MATERIAL REQUIREMENTS FOR AMORPHOUS SILICON, P-I-N, SOLAR CELL BASELINE CASE

SOLAR SCENARIO:
INTRODUCTION YEAR- 1991
CUMULATIVE CAPACITY 2000- 25. GW

FACTORS	BULK MATERIAL USAGE MT.	PERCENT SUPPLY AS BY-PROD	PRODTN GROWTH RATE 1990	MAX % SYSTEM 1 YEAR WORLD	% FROM ONE NATION NON-US	PRESENT COSTS IN $/KW	NET % IMPORT
THRESHOLD LEVELS--		50.	10.%	10.	35.	50.	50.
ALUMINUM	19398.	0.	7.	0.	13.	1.	9.
ALUMINUM FLUORIDE	388.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
AMMONIA	1966.	0.	3.	0.	5.	0.	1.
ARGON	9.	100.*	4.	0.	25.	0.	0.
BORAX	9.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
BORON TRIFLUORIDE ETHERAT	3.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
CARBON DIOXIDE	3.	100.*	3.	0.	5.	0.	0.
CAUSTIC SODA	2910.	0.	3.	0.	5.	0.	1.
CHLORINE	380.	0.	3.	0.	5.	0.	1.
COAL, BITUMINOUS	502.	0.	2.	0.	20.	0.	10.
COKE	60955.	0.	3.	0.	10.	0.	1.
CRYOLITE	679.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
DIBORANE	0.	0.	5.	0.	5.	0.	0.
DIETHYL ETHER	1.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
ELECTRICITY (KWH)	3213.E+6	0.	7.	0.	0.	4.	0.
ELECTRODES	3026.	0.	3.	0.	10.	0.	1.
FERROMANGANESE	44.	0.	3.	0.	22.	0.	98.*
FERROSILICON	913.	0.	3.	0.	10.	0.	35.
FERROUS SCRAP, PURCHASED	1468.	0.	3.	0.	10.	0.	0.
FLUORSPAR	89.	0.	5.	0.	19.	0.	79.*
GLASS, SODA LIME	4562500.	0.	2.	1.	5.	62.*	1.
HELIUM	1.	100.*	3.	0.	5.	0.	0.
HYDROCHLORIC ACID	87376.	92.*	3.	0.	5.	1.	2.
HYDROFLUORIC ACID	1.	0.	3.	0.	15.	0.	0.
HYDROGEN	2106.	40.	6.	0.	10.	0.	0.
INDIUM	416.	100.*	14.*	42.*	20.	6.	24.
INDIUM-TIN OXIDE	520.	0.	50.*	80.*	10.	7.	0.
LIME	2159.	0.	3.	0.	20.	0.	2.
LIQUID FUELS	211208.	0.	3.	0.	18.	1.	39.
LITHIUM	14907.	4.	7.	9.	2.	19.	0.
LITHIUM HYDRIDE	16203.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
MAGNESIUM	100.	1.	6.	0.	27.	0.	0.
METHANOL	8.	0.	5.	0.	10.	0.	0.
METHYL BORATE	2.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
NITRIC ACID	734.	0.	3.	0.	32.	0.	1.
ORTHO-PHOSPHOROUS ACID	7.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
OXYGEN, GASEOUS	283.	0.	4.	0.	21.	0.	0.
OXYGEN, LIQUID	283.	0.	4.	0.	21.	0.	0.
PETROLEUM COKE	20018.	100.*	3.	0.	15.	0.	0.
PHOSPHINE 99.999%	1.	0.	21.*	0.	10.	0.	0.
PHOSPHOROUS	3.	0.	6.	0.	22.	0.	0.
PHOSPHOROUS TRICHLORIDE	12.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
PITCH-IN-TAR	7339.	0.	3.	0.	5.	0.	5.
PLATINUM	32.	100.*	3.	3.	47.*	14.	90.*
SILANE	13391.	0.	79.*	54.*	10.	70.*	0.
SILICON DIOXIDE, 99.99%	68.	0.	3.	0.	10.	0.	0.
SILICON TETRACHLORIDE	97083.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
SILICON (MET)	16504.	0.	3.	0.	12.	1.	11.
SODIUM BOROHYDRIDE	1.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
SODIUM CARBONATE	593199.	0.	0.	1.	10.	2.	0.
SODIUM HYDRIDE	2.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
STEAM	668178.	1.	3.	0.	10.	0.	0.
STEEL & IRON	3980.	1.	3.	0.	16.	0.	7.
SULFUR	19695.	31.	3.	0.	14.	0.	0.
SULFURIC ACID	58443.	20.	3.	0.	14.	0.	0.
TIN	22.	1.	3.	0.	28.	0.	85.*
TITANIUM	322.	0.	6.	0.	39.*	0.	8.
(MISC. BULK MATERIALS)	84581.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?

TABLE 8 .

RAW MATERIAL REQUIREMENTS FOR:
AMORPHOUS SILICON, P-I-N, SOLAR CELL
BASELINE CASE

SOLAR SCENARIO:
INTRODUCTION YEAR- 1991
CUMULATIVE CAPACITY 2000- 25. GW

FACTORS	RAW MATERIAL USAGE (1000MT)	%PRD GROW RATE FROM 1990	MAX% SYST ONE YEAR WRLD	%US RESERV CONSUM BY 2000	%US RESOUR CONSUM BY 2000	%FRM ONE NAT NON-US	%WORLD RESERV CONSUM BY 2000	%WORLD RESOUR CONSUM BY 2000	PRSNT COSTS IN $/KW	NET% IMPT
THRESHOLD LEVELS--		7.	10.	400.	300.	60.	300.	200.	50.	50.
BAUXITE	91.	5.	0.	2691.*	364.*	31.	15.	10.	0.	91.*
COAL, BITUMINOUS	2409.	2.	0.	5.	1.	7.	9.	1.	1.	0.
FELDSPAR	421.	5.	1.	5.	0.	8.	12.	0.	0.	0.
FLUORSPAR ORE	0.	5.	0.	1004.*	168.	19.	255.	140.	0.	79.*
IRON ORE	6.	5.	0.	29.	5.	27.	16.	5.	0.	29.
LIMESTONE	3328.	3.	0.	0.	0.	20.	0.	0.	4.	2.
LITHIUM ORE	2370.	9.*	10.*	47.	21.	24.	51.	18.	14.	0.
MANGANESE ORE	0.	3.	0.	100.	8.	22.	15.	8.	0.	98.*
NATURAL GAS	804.	5.	0.	258.	60.	23.	97.	10.	3.	5.
PETROLEUM	1258.	2.	0.	565.*	185.	18.	104.	34.	4.	39.
PHOSPHATE ROCK	0.	6.	0.	30.	17.	14.	21.	7.	0.	0.
QUARTZ	0.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
RUTILE (CONC.)	1.	5.	0.	165.	54.	98.*	11.	9.	0.	98.*
SALT	980.	6.	0.	0.	0.	18.	0.	0.	1.	7.
SAND & GRAVEL	3031.	4.	0.	0.	0.	6.	0.	0.	0.	0.
SILICA PEBBLE	1.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
SODA ASH (NAT.)	396.	5.	1.	1.	0.	2.	1.	0.	1.	0.
SULFUR ORE	20.	3.	0.	189.	61.	14.	109.	34.	0.	0.
TIMBER, LUMBER	17.	1.	0.	0.	0.	12.	0.	0.	0.	18.
TIN ORE	2.	2.	0.	3489.*	705.*	28.	67.	18.	0.	85.*
WATER, FRESH	0.	2.	0.	0.	0.	5.	0.	0.	0.	0.
WATER, SEAWATER	72.	0.	0.	0.	0.	0.	0.	0.	0.	0.
ZINC BYPROD.	1664.	3.	0.	166.	100.	20.	125.	81.	0.	59.*

"A" MATERIAL DISCUSSIONS

Deployment of 25 GWe of amorphous silicon solar cells would require 54% of the world silane (SiH_4) production in the year 2000 as well as a maximum production growth rate of 79% per year. At present prices the silane cost is 7¢/watt, a significant fraction of the DOE cell cost goals of 15 to 40¢/watt. The same silane supply problems occur in amorphous silicon cells as in polycrystalline cells except they are not as severe because amorphous silicon cells require less silane. (Based on 1 micron thick - 10% process efficiency for a-Si. For poly-Si, 25 micron thick 35% process efficiency.)

Silane is a highly toxic, pyrophoric gas. It carries a DOT label and classification as "flammable gas".

Domestic production of silane in 1979 was probably in the range of 25 to 30 MT. The U.S. is a net exporter of silane.

By far the dominant use for silane is in the production of integrated circuits by the semi-conductor industry. A realistic 1979 price for silane in metric ton quantities is in the range of $130.00 to $140.00 per kg.

Major producers of silane include:

- Liquid Carbonic
- Union Carbide
- Air Products
- Matheson Gas
- Airco

Current producers contacted would not reveal their process route to silane. Battelle surmises that the process involves the electrolytic reaction of silicon tetrachloride or trichlorosilane with lithium hydride. There would appear to be no basic materials problems.

According to one major supplier, current production could be easily doubled or tripled within 12 to 18 months. It is very probable, however, that current manufacturers might be very reluctant to significantly expand silane production based on current technology. DOE's Low-Cost Solar Array program, managed by the Jet Propulsion Laboratory, shows strong indications of the feasibility of a new technology route to polycrystalline silicon production at costs of less than $12/kg (Union Carbide process)(1,2). The silane produced as an intermediate product in this process is easily retrievable from the buffer storage, although the purity of the silane is uncertain. This would imply feasible silane production costs much lower than the current price of \$130/kg for silane. Suppliers may want to wait until this new low cost process is available before increasing silane production capacity. Hence, any sizeable increase in silane consumption in the short run could present capacity problems.

Silane is marketed in several grades. Epitaxial, semiconductor, and electronic are all equivalent terminology for the grade currently used in photovoltaic cell research. To date a special solar photovoltaic grade has not been established. Chemically pure grade is roughly the same cost as electronic grade. Charge coupling devices grade costs approximately 2 to 3 times the above grades.

Since a mature market has not developed for these grades of silane, it was difficult to get prices for large quantity purchases.

Silane requirements are expected to double the projected silane consumption (without PV cells) in the year 2000, as shown in Figure 14. Clearly, advanced planning will be necessary to ensure adequate silane supply.

The silane cost of 7¢/watt is based on a silane price of \$130/kg and 10% deposition efficiency. As shown in Figure 15, the cost drops below 5¢/watt for deposition efficiencies greater than 15%, even at \$130/kg. However, deposition efficiencies below 10% may be the production norm. In that case, lower cost silane production processes such as the Union Carbide(1,2) process may be necessary. Deposition efficiencies down to 1.5% appear to be economically reasonable at the \$12/kg silane price.

Planning ahead to obtain silane supply for amorphous silicon cell production should include the following:

- Further promote the development of new, low cost production processes such as the Union Carbide process.
- Increase the efficiency of the a-Si deposition process.
- Consider long-term contracts with the silane producers.
- Consider an onsite, dedicated silane production plant in order to ensure supply and to reduce transportation hazards.

Any increase in cell efficiency above the 5% assumed here would ease silane supply problems. Of course, there is a large reduction in total array costs for every percent increase in cell efficiency.

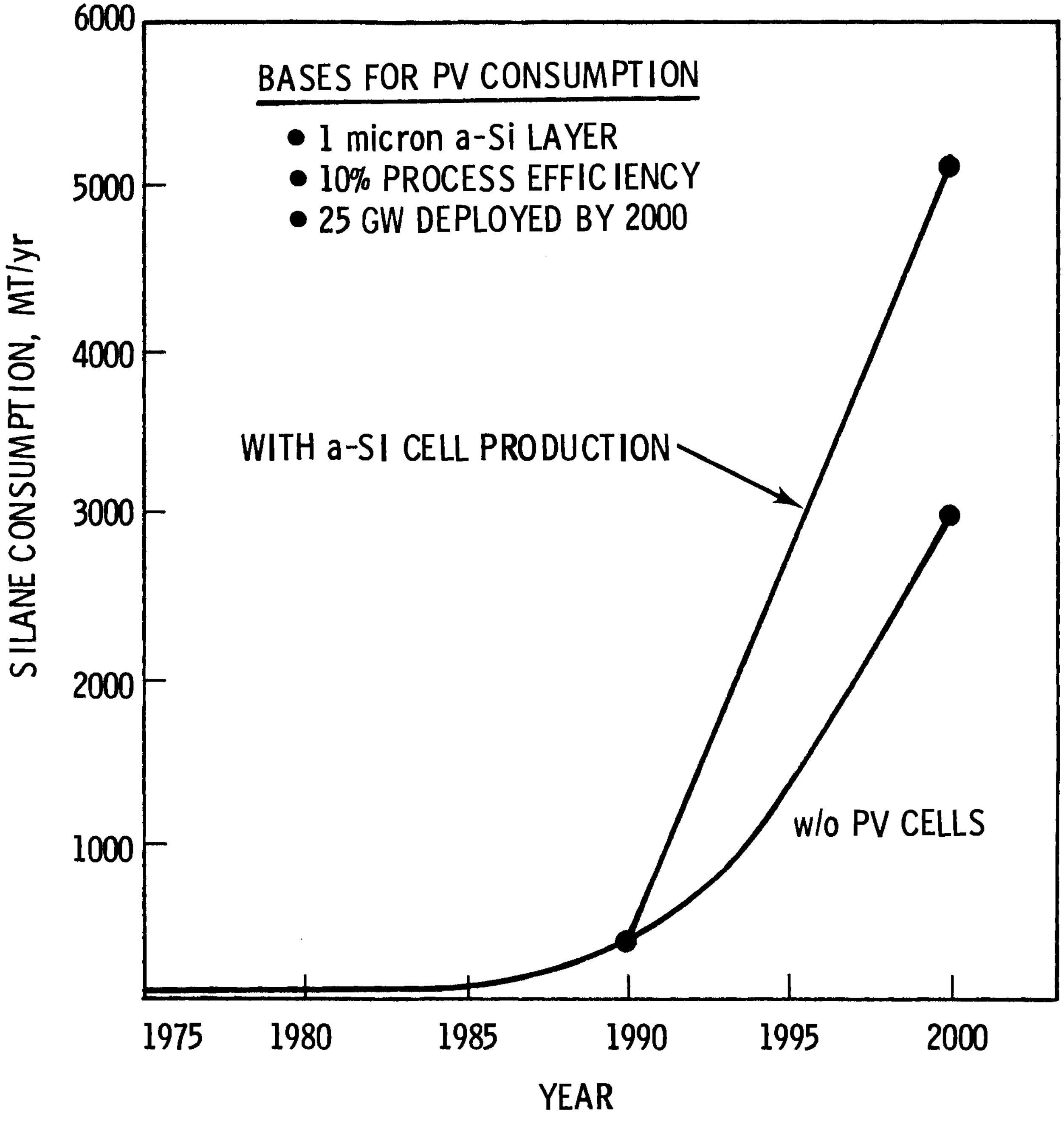

FIGURE 14. Projected Market for Silane With and Without Amorphous Silicon PV Cell Production

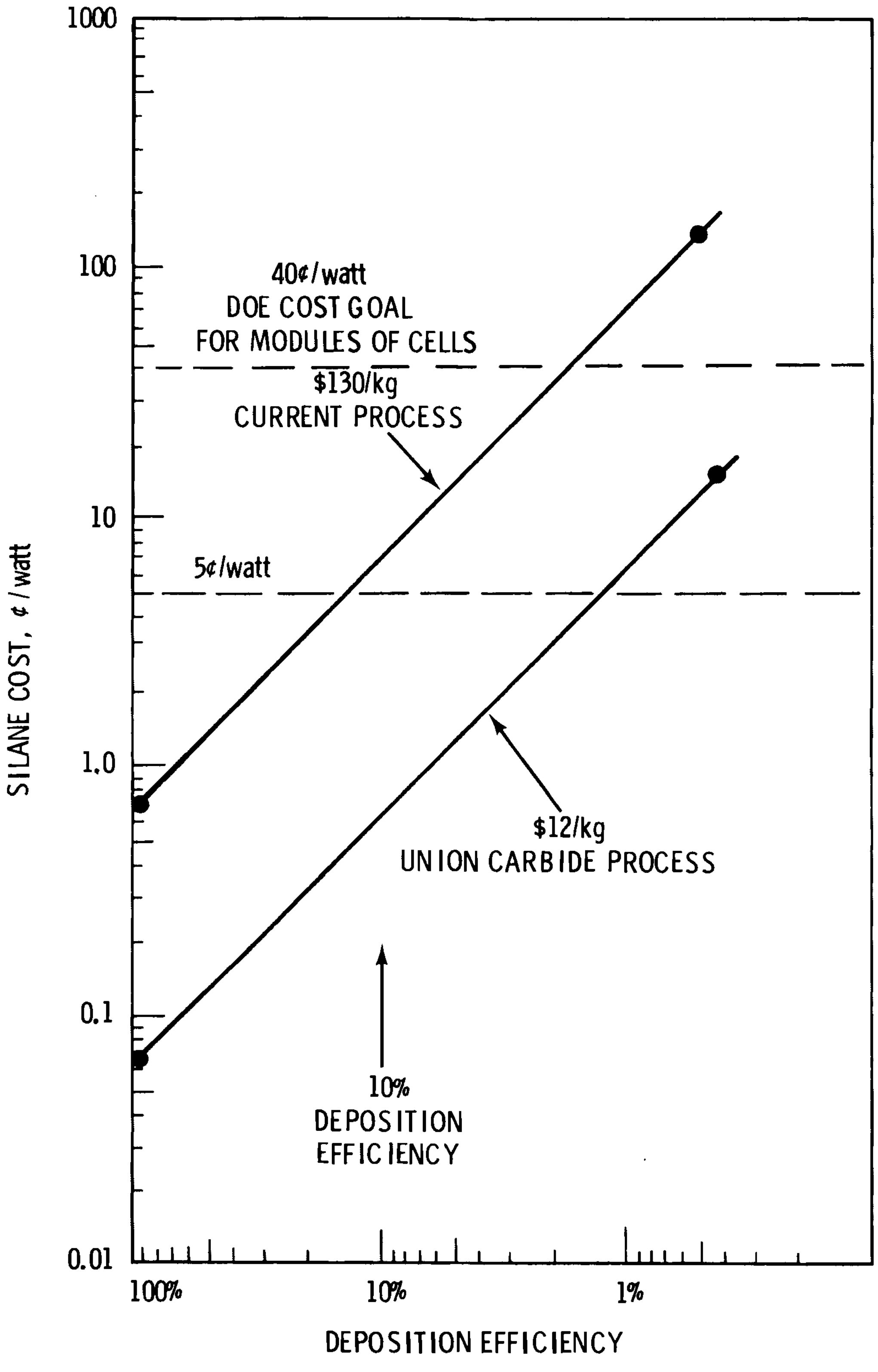

FIGURE 15. Silane Cost vs. Deposition Efficiency and Silane Price (Based on Depositing a 1 Micron Thick Amorphous Silicon Layer)

All of the indium requirements for amorphous silicon (a-Si) cells is converted to indium oxide (In_2O_3) and mixed with a small amount of tin oxide (Sn_2O_3) in making the feedstock, indium tin oxide, ITO ($In_{1.9}Sn_{0.1}O_3$). The ITO cell layers are fabricated by sputtering, evaporation, or chemical spraying.

The problem here is availability, not cost. The ITO and In costs are only 0.7 and 0.6¢/watt, respectively, based on a price of $10/troy oz for indium, which is a high for the last 30 years. (From 1947 to 1973 the price was nearly constant at $2.50/troy oz, in current dollars.) The indium price would have to increase to $90/troy oz before indium cost would reach 5¢/watt.

Indium Oxide (and indium tin oxide) is currently produced in small quantities, essentially on demand. It is probably not imported. Indium oxide is made by the thermal decomposition of indium nitrate which can be obtained by dissolving indium metal in nitric acid. This is a relatively well developed, simple flowsheet which means that increasing indium oxide production would not be difficult. Indium tin oxide requirements for a-Si cells are projected to expand to about 95 MT per year by the year 2000. If sufficient indium is available, sufficient supplies of indium oxide could be made available through cooperative planning between indium suppliers and the PV cell manufacturers. It may be necessary to enter into long-term supply agreements. Of course, no amount of planning for ITO production would compensate for a lack of indium. The availability of indium is the principal question here.

Deployment of 25 GW of a-Si cells by the year 2000 will require a maximum indium demand growth of 14% per year. About 42% of the world demand (or 76 MT) of indium in the year 2000 would be used in a-Si cells, as illustrated in Figure 16. A cumulative total of 416 MT of indium would be required for a-Si cells. Current U.S. indium production from U.S. ores is less than 3 MT per year.

A general discussion of indium supply problems is the subject of a following chapter of this report. The remainder of this discussion will be devoted to summarizing indium supply problems relative to a-Si cell requirements.

Indium is about as abundant as silver in the earth's crust. It is a byproduct of zinc refining, therefore the amount available depends upon zinc production. There are no deposits with sufficient concentration to process for indium alone. During zinc refining indium becomes concentrated in residues from retorts, and zinc anode slimes from which the indium is economically recoverable. Approximately 90 percent of the indium could be recovered from indium-rich residues; however, the overall recovery from zinc ores is 40 percent. Just how much of the available residues are being processed for indium recovery is unknown.

Three companies produce indium domestically. They are The Indium Corporation of America, its partner, New Jersey Alloy, and American Smelting and Refining Company. Canada is the main source of indium imports. Cominco, Ltd. is the only Canadian producer. A small percentage of foreign zinc plants produce indium. Production levels and stocks are largely unknown (company confidential).

The U.S. Bureau of Mines estimated 1973 world production at 54 MT, and refinery capacity at 128 MT. As was shown in Figure 16, world indium consumption, with a-Si cells, is projected to be 179 MT in the year 2000 (76 MT for a-Si cells). Whether or not that indium production level is attained depends upon the indium content of zinc ores being processed that year. Domestic production in the year 2000 is estimated at 7 MT based on projected zinc capacity, current indium recovery processes, and estimated indium concentrations. This would indicate that the majority of U.S. indium will come from imports and stockpiles of metal and concentrates.

The indium content of zinc ores is highly variable. Most ores are not assayed for indium. Hence, the knowledge of world reserves and resources is poor. In the U.S. there is a shift towards zinc ores having lower indium contents. Estimates of U.S. indium reserves range from 300 to 1800 metric tons with additional resources of 300 to 5400 metric tons. Deployment of 25 GW of a-Si cells will require 416 MT of indium.

The U.S. Bureau of Mines estimated (in 1975) that world reserves of indium were 1500 MT with almost 1900 MT of additional resources.

It is clear that world indium supplies may not be sufficient for the projected a-Si solar cell requirements. From the material supply viewpoint, the use of indium tin oxide should be reduced or eliminated. The ITO layer might be thinned from 580 Å to 50 Å(3). Or alternate substrate combinations could be substituted for ITO coated glass. Possible alternates are stainless steel or molybdenum, or glass or kapton metallized with molybdenum, chrome, or tungsten. Total ITO use could be reduced by increasing the a-Si solar cell efficiency above 5% or by increasing the efficiency of the ITO layer deposition process above 40%. Perhaps the 60% wasted ITO could be recycled, thus cutting the net indium use in half or less. At $10 per troy oz of indium recycling of ITO plated out on masks, chamber walls, and cold traps

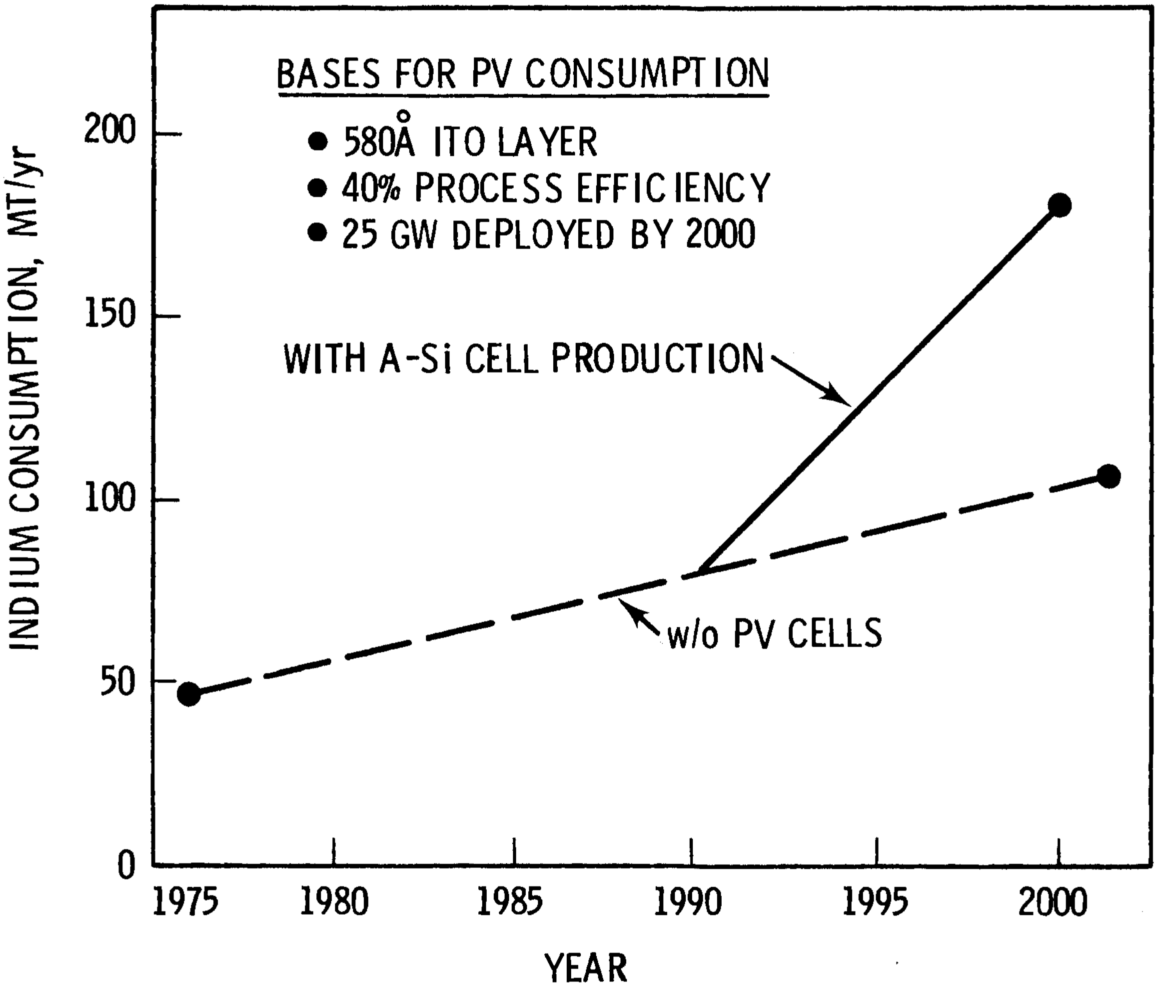

FIGURE 16. Projected Market for Indium With and Without Amorphous Silicon PV Cell Production

could be economically attractive.

If it is found that the use of ITO cannot be reduced significantly, or eliminated, the indium supply situation might be improved by several actions. Indium suppliers and PV cell fabricators should plan 5 to 10 years in advance for PV cell requirements. Stockpiling of indium would be wise. Long-term supply contracts would encourage indium producers to enlarge capacity and seek additional sources. Some work should be done to improve the efficiency of indium recovery from zinc processing by upgrading present processes or developing new processes. Finally, more knowledge of U.S. and world indium reserves and resources is needed. Efforts should be made to obtain indium assay data for all zinc ores and concentrates. Exploration for additional resources should also be done.

"B" MATERIAL DISCUSSION

The following "B" materials were reviewed and found to not constrain the deployment of amorphous silicon solar cells. Generally, they are used in relatively small amounts and their cost to solar is low. Therefore, only severe supply disruptions, if they were to occur in the future, would significantly impact amorphous silicon solar cells. Supplies are adequate and stable. No supply disruptions are foreseen. These "B" materials should be subjected to periodic review.

Argon, carbon dioxide, helium, hydrochloric acid, and petroleum coke are all byproducts and thus their production is dependent upon production of other materials. For this reason they are classified as "B" materials.

Tables 7 and 8 indicate that a-Si cells will consume about 10% of the yearly world supply of lithium and lithium ore in the year 2000. This is based upon the use of lithium hydride (made from lithium) to produce silane from trichlorosilane or silicon tetrachloride. However, lithium chloride is a product of both of these reactions, and lithium chloride is the feed material in lithium metal production. The quantities of lithium chloride involved would make recycling economic. With recycling, net usage of lithium and lithium ore would be negligible. Also, a new commercial process for making silane is being developed by Union Carbide under contract with the Jet Propulsion Laboratory. This process uses a special catalyst to convert trichlorosilane to silane without the use of lithium hydride. Classify lithium and lithium ore as "B" materials.

Ferromanganese, fluorspar, tin, manganese ore, rutile and zinc-byproduct are classified as "B" materials because they are 60 to 98% imported. (Zinc-byproduct refers to the zinc ore that must be processed to obtain the amount of byproduct indium required for amorphous silicon cells.)

Titanium is classified as a "B" material because 39% of the world's supply is produced by a single foreign nation, the U.S.S.R.

Platinum is a "B" material because it is both a byproduct and 100% imported.

Domestic reserves of bauxite, fluorspar ore, petroleum, and tin ore are small and most of their supplies are currently imported. They are "B" materials.

Phosphine production is expected to grow 21% per year, with or without solar requirements. However, since phosphine production is small (est. at 2.5 MT in 1976), such a high growth rate should be achieved. Phosphine is a "B" material.

Soda lime glass, 0.125 inch thick, is the substrate for this cell and costs 6.2¢/watt ($62/kW). It is classified as a "B" material. The 6.2¢ is a significant part of the 15-40¢ per watt goal for cell costs. As shown by the screening data in Table 7, there is no problem with availability, only cost. The glass industry is mature and stable. Since solar cell requirements are so small, there is ample capacity to supply solar cell substrates, and there will be a negligible impact on the glass industry from solar cells. It is reasonable to expect that some price reductions may be possible through the long-term contracts between the glass producers and solar cell manufacturers. Possibly, a dedicated glass plant would be cost-effective. Glass cost could be lowered by reducing the thickness from 0.125 inch, which is entirely dependent upon the design of the supports for the solar cell array. Lastly, the glass cost is based upon a cell efficiency of 5%. A 1 or 2% efficiency gain would sharply reduce glass substrate costs, as well as reducing array support costs. In summary, the cost of glass substrates is high and might be reduced by one or more of the avenues discussed above. Otherwise, alternative materials such as stainless steel, molybdenum, and kapton (all at 0.005 inch thickness) are reasonable substitutes offering possibilities for cost reduction.

CADMIUM SULFIDE/COPPER SULFIDE SOLAR CELLS

In the baseline cell structure and fabrication process details of Figure 17, the frontwall cell is used. This cell consists of 25 microns of evaporated cadmium sulfide on a zinc electroplated (1 micron thick) copper foil (25 microns thick). A copper sulfide layer is formed by dipping the cadmium sulfide in a hot solution of cuprous chloride. The grid contact is 5 microns of evaporated gold. The AR film is silicon monoxide, .08 micron thick. A cell conversion efficiency of 10% is assumed.

The sensitivity analysis investigated the impact of reducing the thickness of the cadmium sulfide layer from 25 to 10 microns, and substituting the 5 micron gold grid contact with 5 microns of copper over 0.05 microns of gold.

Screening Results

Analysis of the CMAP screening for the baseline and sensitivity cadmium sulfide/copper sulfide cell identified the following "A" materials:

Baseline	Sensitivity
Cadmium Sulfide	(None)
Gold	
Gold Ore	

and, the following "B" materials:

Baseline

Cadmium
Chlorine
Ferromanganese
Fluorspar
Hydrochloric Acid
Lime
Liquid Fuels
Petroleum Coke
Silicon (SEG)
Silicon Monoxide
Steel and Iron
Zinc
Zinc Fluoroborate
Bauxite
Chromite
Coal
Fluorspar Ore
Limestone
Manganese Ore
Petroleum
Zinc Byproducts
Zinc Ore

Sensitivity

Cadmium
Cadmium Sulfide
Ferromanganese
Fluorspar
Hydrochloric Acid
Petroleum Coke
Silicon (SEG)
Silicon Monoxide
Steel and Iron
Zinc
Zinc Fluoroborate
Gold
Bauxite
Chromite
Fluorspar Ore
Gold Ore
Manganese Ore
Petroleum
Zinc Byproducts
Zinc Ore

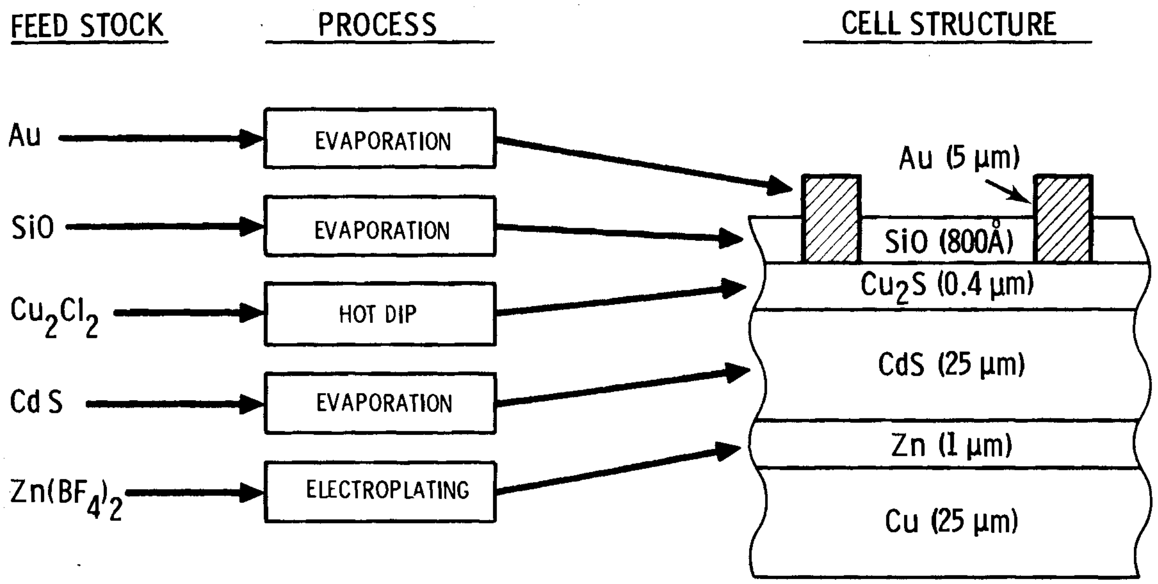

FIGURE 17 Cadmium Sulfide/Copper Sulfide Frontwall Solar Cell

	Layer Function	Process & Precurser To Material in Layer	Chem. Ratio	Process Effic.	Mat'l. in Layer MT/GWp
12.0	ENERGY COLLECTOR				
	12.03 ABSORBER- CAD	SULFIDE/CU SULFIDE CELL			
	ACTIVE LAYER	EVAPORATED CADMIUM SULFIDE	1.0	0.35	1.21+03
	ACTIVE LAYER	HOT DIPPED CUPROUS CHLORIDE TO CUPROUS SULFIDE	0.80	0.1	22.4
	BACK CONTACT	ELECTROPLATED ZINC FLUOROBORATE TO ZINC	0.27	0.8	71.4
	SUBSTRATE	COPPER	1.0	0.8	2.23+03
	GRID CONTACT	EVAPORATED GOLD	1.0	0.035	96.5
	AR COATING	EVAPORATED SILICON MONOXIDE	1.0	0.35	1.71

"A" MATERIAL DISCUSSIONS

For 25 GW_p of baseline case cells, 86,429 MT of cadmium sulfide would be required (Tables 7 and 8). In the year 2000 the cadmium sulfide requirements for solar cells would be 65% of the world production. However, the availability of cadmium should not be a constraining factor in the production of solar cells. World production, projected to the year 2000 by the Bureau of Mines, is greater than projected world consumption. Of this world consumption of cadmium, the requirements for solar cell production can be accommodated.

Proven world cadmium reserves in 1976 were reported to be almost 700,000 metric tons. When this figure is combined with potentially economic cadmium ores, the total resources jump to 18.125 million metric tons. By the year 2000 total nonsolar consumption has been forecast to be 37,000 metric tons and only about 13,000 metric tons would be utilized in the PV sector in that year.

In addition to sufficient future supplies of cadmium, there is minimal risk of this supply being disrupted by cartels. The U.S. controls 30% of all world proven reserves, while another 30% are distributed among major industrial noncommunist countries. Further, the U.S. General Services Administration stockpiles cadmium.

Therefore, cadmium should not be viewed as a constraint in the development and production of cadmium-based solar cells.

The domestic price history of cadmium is presented in Figure 18 (in constant 1972 dollars). This price is determined by six producers and fluctuates widely. The price of cadmium is expected to rise slightly.

The literature encountered did not clearly indicate the correlation between performance level versus purity level or that all species were equally harmful. Cadmium sulfide of the required purity for photovoltaic use is produced in smaller quantities than needed for 25 GWe on line by the year 2000. Since the material is required in large quantities, it is recommended that onsite production of the purified product be considered for photovoltaic plants. Further, it is recommended that work be done on producing cadmium sulfide at different purity levels (naturally resulting from the production steps) and on resulting cell performance to obtain an optimum purity level for the best overall value in the completed cell. It seems likely also that some methods will produce different impurity species which may be more or less deleterious.

Thus summarizing, it is recommended that the planning of production of cadmium sulfide/copper sulfide cells include the consideration of the production of the pure cadmium sulfide at the photovoltaic site to:

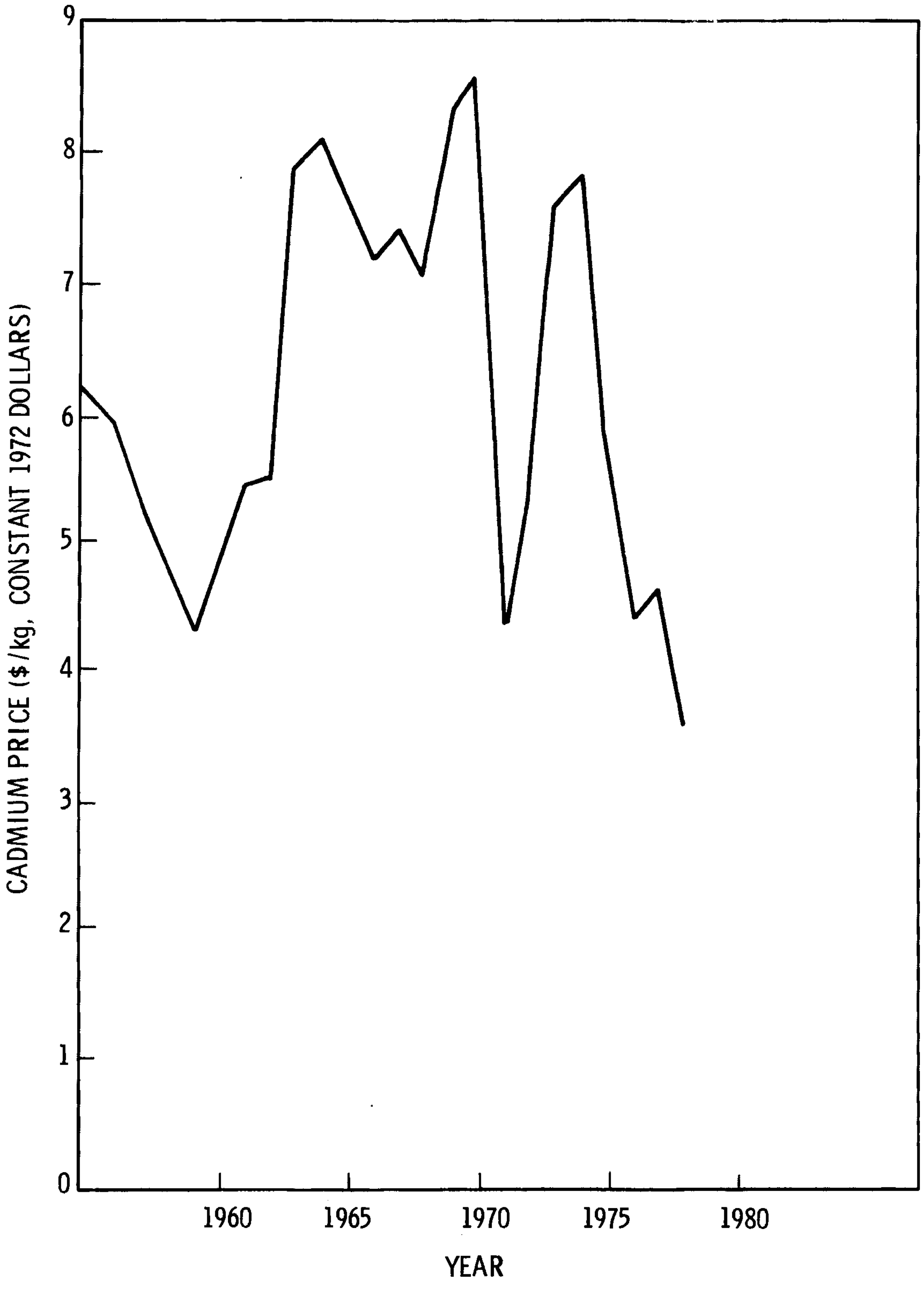

FIGURE 18 . Price History of Cadmium

- Control the purity at the optimum level;
- Reduce the 8¢/watt cost; and
- Maintain uniform quality of cell production.

Another mitigating strategy, as demonstrated in the sensitivity analysis, is to reduce the thickness of the cadmium sulfide layer. Reducing the layer thickness from 25 microns to 10 microns reduces the cadmium sulfide costs from 8¢/watt to about 3¢/watt. The cadmium itself costs only about 0.6¢/watt, so it may still pay to work on reducing the cost of the cadmium sulfide compound. (Figure 19)

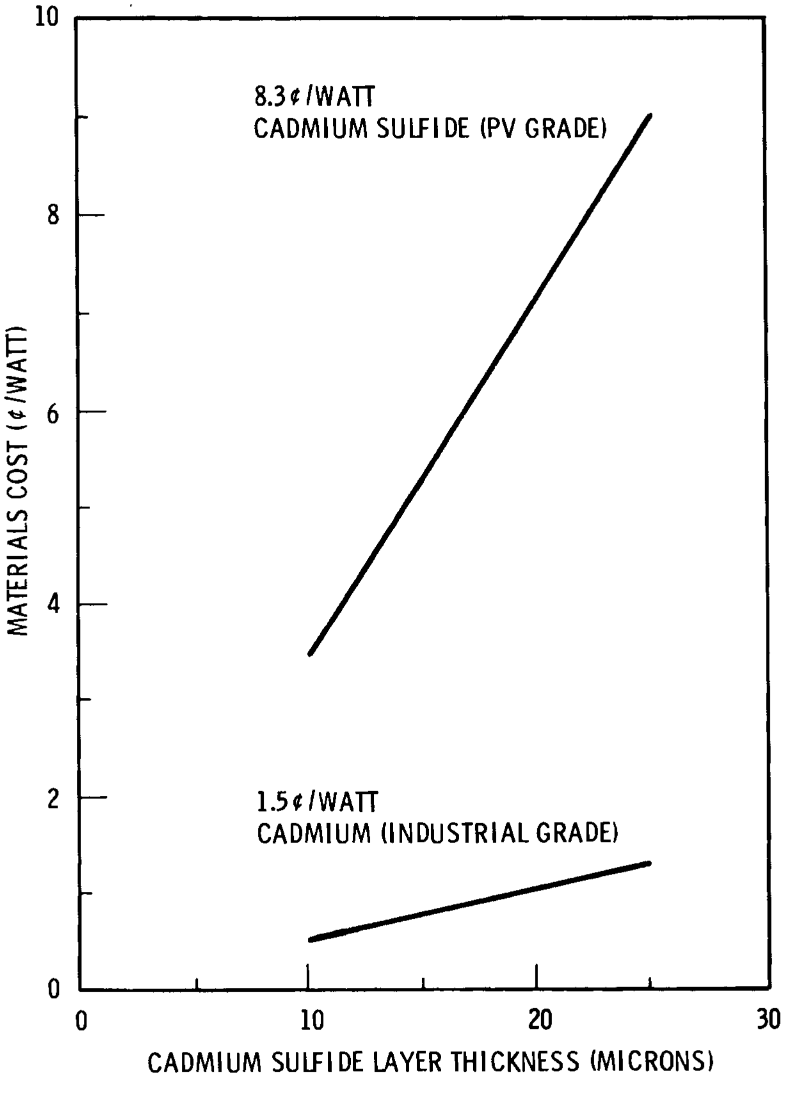

FIGURE 19 Materials Cost Versus Cadmium Sulfide Layer Thickness

Gold as used in the baseline case cells (68,929 MT for 25 GW_p) is obviously not practical, triggering the following threshold levels:

- Production growth rate, 79%
- Maximum percent of world production, 86%
- Percent from non-U.S. nations, 58%
- Present cost, \$17,728/kW (1773¢/watt)
- Net percent imported, 76%

The price used in screening gold as a bulk material was \$200/troy oz. Since then the price of gold has gone above \$600/troy oz. It is unlikely that its price will fall below \$200/troy oz (see Figure 20).

During the 1934-68 time period, the price of gold was held constant at \$35/troy oz. Domestic gold producers found it difficult to cover their costs of production, thus leaving the industry. With the uncertainty surrounding the strength of the U.S. dollar, investors have been exchanging their monies for gold, bidding-up its price. This explosion in the price of gold may entice producers to reopen mines and/or explore for new sources of gold that would help depress its price. It does seem likely that the price will stabilize above \$200/troy oz, making it difficult to meet the PV program cost goal.

Several intermediate bulk materials used primarily in the production of gold triggered the "present cost in \$/kW" threshold level: chlorine (\$83/kW), electricity (\$314/kW), lime (\$50/kW), liquid fuels (\$250/kW), and iron and steel (\$50/kW)(a). These materials costs set a high cost floor on the gold.

The apparent mitigating strategy already postulated by researchers working in this area is to reduce the quantity of gold in the cell. The sensitivity case assumes success in this attempt (assuming that the grid contact is 5 microns of copper over 0.05 microns of evaporated gold). The sensitivity case also assumes 100% recycle of gold deposited on screening masks, etc., in the evaporation chamber. The influence of thickness and deposition efficiency on the cost of gold in grid contacts is shown in Figure 21.

These changes to the cell characterization reduce the amount of gold consumed. Gold cost would be reduced to 0.6¢/watt; therefore, it no longer would be considered an "A" material. Gold would not be classified as an "A" material even if its price rose to \$1,000/troy oz. As shown in Figure 21, at \$1,000/troy oz, 0.05 microns of

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a. See Appendix A for specific material requirements (MT/MT) for producing gold.

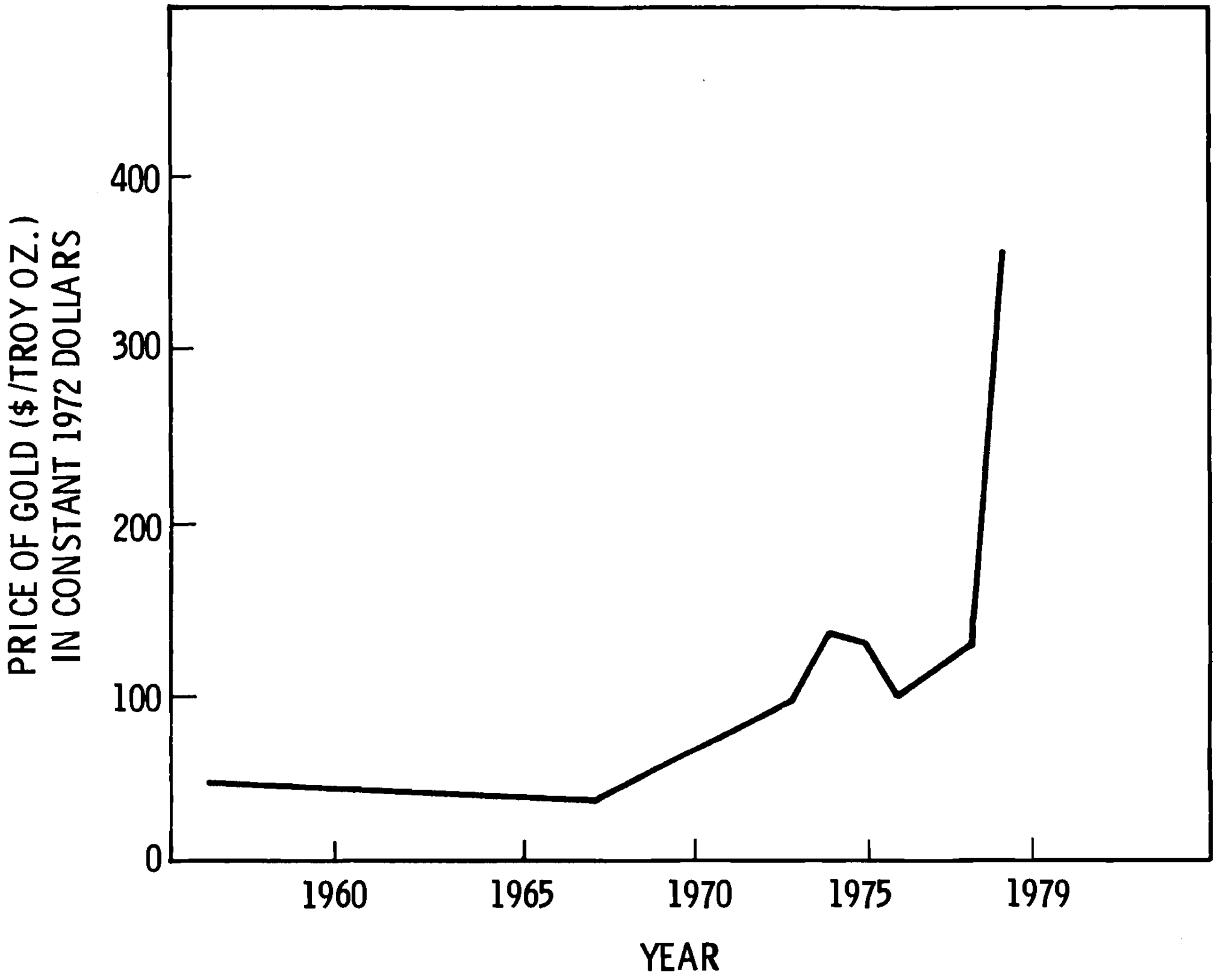

FIGURE 20 . Price History of Gold

gold costs 2.5¢/watt, assuming no gold wastage. Under these conditions the gold thickness could be doubled to 0.1 micron before reaching the screening threshold of 5¢/watt. The gold costs in Figure 21 do not include the cost of recycle, which is assumed to be negligible. At 0.1 micron thickness and full recycle, gold grid contacts would require 9.2 MT of gold, or about 0.5% of the projected gold consumption, in the year 2000, a tolerable level.

It is clear that gold grid contacts will have to be kept as thin as possible, about 0.1 micron maximum, and that all of the gold deposited on masks and deposition chambers will have to be recycled. If gold is to remain a component of grid contacts, the processes for recycling this wasted gold needs to be developed. It is recommended that the feasibility of recycling gold should be determined at an early date.

The only "A" raw material identified in the baseline screening of the cadmium sulfide/copper sulfide cell was gold ore at $5,098/kW. Reducing the amount of gold in the grid contact (i.e., sensitivity case), caused gold ore to be reclassified as a "B" material.

SELECTED "B" MATERIAL DISCUSSIONS

The "B" materials previously listed were reviewed and are not expected to present severe supply constraints for the cadmium sulfide/copper sulfide cell. It is recommended that all "B" materials be reassessed periodically.

The following provides the rationale used in stating that these materials should not present severe availability problems for photovoltaics.

Silicon monoxide (11% production growth rate and 36% world production) and semiconductor grade silicon (20% production growth rate) were identified as "B" materials, but both are used in small quantities in solar cells and their costs are well below the threshold level. Since current production of these materials is small, 20% production growth is relatively easy.

Zinc fluoroborate is used for electroplating the zinc onto a copper substrate, and would require a 26-54% production growth rate and would consume 99% of the world production in one year. Currently, this material is being produced in very small quantities. Other nonsolar uses have diminished over time. We suggest that either the feasibility of reducing the amount of zinc fluoroborate be investigated or a dedicated production facility be constructed near the generating facility to ensure

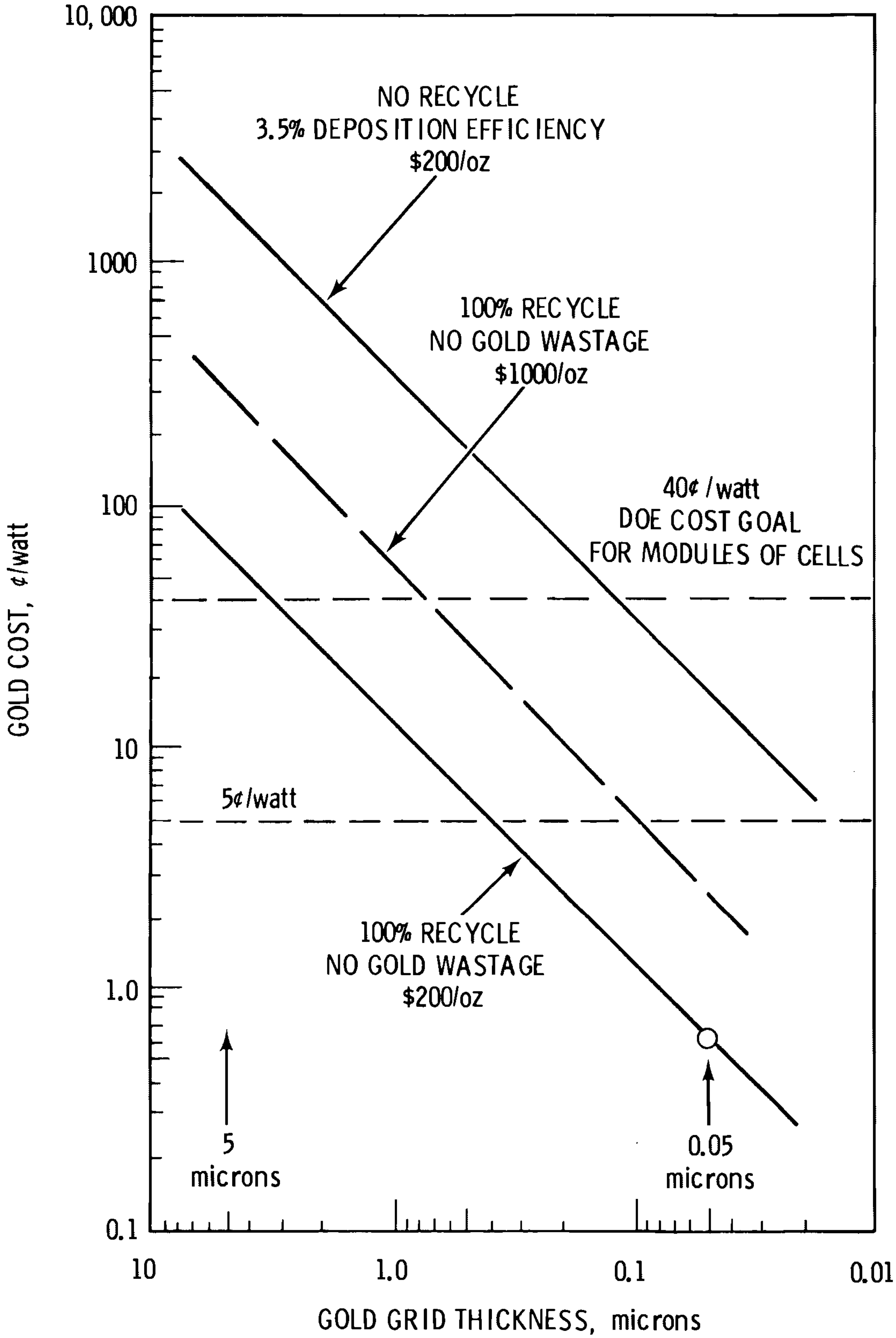

FIGURE 21. Gold Costs for Grid Contacts vs. Gold Thickness and Gold Price

TABLE 9 .

BULK MATERIAL REQUIREMENTS FOR
CADMIUM SULFIDE/CU SULFIDE FRONTWALL SOLAR CELL
BASELINE CASE

SOLAR SCENARIO:
INTRODUCTION YEAR- 1991
CUMULATIVE CAPACITY 2000- 25. GW

FACTORS	BULK MATERIAL USAGE MT.	PERCENT SUPPLY AS BY-PROD	PRODTN GROWTH RATE 1990	MAX % SYSTEM 1 YEAR WORLD	% FROM ONE NATION NON-US	PRESENT COSTS IN $/KW	NET % IMPORT
THRESHOLD LEVELS--		50.	10.%	10.	35.	50.	50.
ALUMINUM	3820.	0.	7.	0.	13.	0.	9.
ALUMINUM FLUORIDE	76.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
AMMONIA	104.	0.	3.	0.	5.	0.	1.
BORAX	6611.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
CADMIUM	69143.	100.*	8.	25.*	17.	15.	64.*
CADMIUM SULFIDE	86429.	0.	32.*	65.*	10.	83.*	0.
CAUSTIC SODA	4929.	0.	3.	0.	5.	0.	1.
CHLORINE	13926091.	0.	4.	2.	5.	83.*	1.
COAL, BITUMINOUS	2101.	0.	2.	0.	20.	0.	10.
COKE	1484744.	0.	3.	0.	10.	5.	1.
COPPER	74237.	1.	6.	0.	13.	5.	12.
CRYOLITE	134.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
CUPROUS CHLORIDE	7000.	0.	4.	7.	20.	1.	20.
ELECTRICITY (KWH)	261.E+9	0.	7.	0.	0.	314.*	0.
ELECTRODES	10815.	0.	3.	0.	10.	1.	1.
FERROMANGANESE	42020.	0.	3.	0.	22.	1.	98.*
FERROSILICON	3820.	0.	3.	0.	10.	0.	35.
FERROUS SCRAP, PURCHASED	929021.	0.	3.	0.	10.	3.	0.
FLUORSPAR	39209.	0.	5.	0.	19.	0.	79.*
GOLD	68929.	47.	79.*	86.*	58.*	17728.*	76.*
HYDROCHLORIC ACID	688.	92.*	3.	0.	5.	0.	2.
HYDROFLUORIC ACID	5537.	0.	3.	0.	15.	0.	0.
HYDROGEN	8.	40.	6.	0.	10.	0.	0.
LIME	36398448.	0.	3.	3.	20.	50.*	2.
LIQUID FUELS	50848298.	0.	3.	0.	18.	250.*	39.
OXYGEN, GASEOUS	271219.	0.	4.	0.	21.	0.	0.
OXYGEN, LIQUID	271219.	0.	4.	0.	21.	0.	0.
PETROLEUM COKE	18035.	100.*	3.	0.	15.	0.	0.
PITCH-IN-TAR	6580.	0.	3.	0.	5.	0.	5.
SILICON MONOXIDE	122.	0.	11.*	36.*	20.	1.	30.
SILICON (MET)	175.	0.	3.	0.	12.	0.	11.
SILICON (SEG)	39.	0.	20.*	0.	10.	0.	0.
SODIUM CARBONATE	41546.	0.	0.	0.	10.	0.	0.
SODIUM DICHROMATE	1037.	0.	3.	0.	5.	0.	1.
STEAM	166.E+6	1.	3.	1.	10.	28.	0.
STEEL & IRON	3819987.	1.	3.	0.	16.	50.*	7.
SULFUR	464316.	31.	3.	0.	14.	1.	0.
SULFURIC ACID	1318804.	20.	3.	0.	14.	3.	0.
ZINC	831054.	25.	3.	1.	20.	25.	59.*
ZINC FLUOROBORATE	8264.	0.	2654.*	99.*	25.	1.	0.
(MISC. BULK MATERIALS)	14504392.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?

TABLE 10 .

RAW MATERIAL REQUIREMENTS FOR:
CADMIUM SULFIDE/CU SULFIDE FRONTWALL SOLAR CELL
BASELINE CASE

SOLAR SCENARIO:
INTRODUCTION YEAR- 1991
CUMULATIVE CAPACITY 2000- 25. GW

FACTORS	RAW MATERIAL USAGE (1000MT)	%PRD GROW RATE FROM 1990	MAX% SYST ONE YEAR WRLD	%US RESERV CONSUM BY 2000	%US RESOUR CONSUM BY 2000	%FRM ONE NAT NON-US	%WORLD RESERV CONSUM BY 2000	%WORLD RESOUR CONSUM BY 2000	PRSNT COSTS IN $/KW	NET% IMPT
THRESHOLD LEVELS--		7.	10.	400.	300.	60.	300.	200.	50.	50.
BAUXITE	18.	5.	0.	2691.*	364.*	31.	15.	10.	0.	91.*
CHROMITE	2.	3.	0.	100.	620.*	28.	117.	2.	0.	89.*
COAL, BITUMINOUS	126095.	2.	0.	6.	1.	7.	9.	1.	78.*	0.
COPPER ORE	10606.	4.	0.	73.	17.	13.	67.	16.	1.	12.
FLUORSPAR ORE	119.	5.	0.	1005.*	169.	19.	255.	140.	0.	79.*
GOLD ORE	8015014.	84.*	87.*	2191.*	1171.*	58.	277.	177.	5098.*	76.*
IRON ORE	6188.	5.	0.	29.	5.	27.	16.	5.	0.	29.
LIMESTONE	105506.	3.	3.	0.	0.	20.	0.	0.	133.*	2.
MANGANESE ORE	92.	3.	0.	100.	8.	22.	15.	8.	0.	98.*
NATURAL GAS	3318.	5.	0.	258.	60.	23.	97.	10.	12.	5.
PETROLEUM	54679.	2.	0.	566.*	185.	18.	104.	34.	160.*	39.
QUARTZ	0.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
SALT	25558.	6.	1.	0.	0.	18.	0.	0.	31.	7.
SAND & GRAVEL	1.	4.	0.	0.	0.	6.	0.	0.	0.	0.
SILICA PEBBLE	4.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
SODA ASH (NAT.)	2226.	5.	3.	1.	0.	2.	1.	0.	5.	0.
SULFUR ORE	464.	3.	0.	189.	61.	14.	109.	34.	1.	0.
TIMBER, LUMBER	0.	1.	0.	0.	0.	12.	0.	0.	0.	18.
ZINC BYPROD.	55314.	3.	4.	176.	106.	20.	126.	82.	0.	59.*
ZINC ORE	18449.	3.	1.	169.	102.	20.	125.	81.	9.	59.*

quality control and availability.

Hydrochloric acid is classified as a "B" material since it is largely produced as a byproduct (92%). Since the chlorination of hydrocarbons is expected to remain a fairly stable source in the future, hydrochloric acid should not present severe supply constraints for the Cd Su/Cu Sn cell.

Similar reasoning is used in assuming that petroleum coke (100% byproduct) will be available in the future.

The U.S. is a net importer of fluorspar (79%), but it is expected that it should be available for photovoltaics.

Bituminous coal and limestone and petroleum are "B" materials because of their high costs ($78, $133 and $160/kW, respectively). All three are used in the production of gold and are reduced or eliminated from the "B" materials list in the sensitivity analysis.

Bauxite, chromite, fluorspar ore, and zinc are all imported to the U.S., but should be available for use in the cadmium sulfide/copper sulfide cell.

POLYCRYSTALLINE GALLIUM ARSENIDE SOLAR CELLS

Cell Description

The MIS cell described in Figure 22 was chosen as the baseline polycrystalline GaAs solar cell. A 10% conversion efficiency was assumed. Cell fabrication begins with evaporation of 1 micron of tin (back contact) onto a stainless steel substrate, 0.005 inch thick. Next, 5 microns of germanium are CVD deposited. The Ge layer is subsequently annealed and, in large grain size form, epitaxially promotes grain growth in the following GaAs layers. The doped contact layer (2 microns thick) and the active layer (5 microns thick) are produced by MO-CVD of Ga As from trimethyl gallium and arsine. The n-dopant is sulfur. A negligible amount of p-dopant, zinc, is deposited from trimethyl zinc by MO-CVD. A semi-transparent layer of silver, 0.005 microns thick, is evaporated onto a native oxide tunnel (I) layer. The grid contact is 5 microns of evaporated copper*. The AR coating is assumed to be 0.06 microns of antimony oxide.

There are many possible interesting variations of this cell, including the following:

- Reduce active layer, GaAs, thickness from 5 to 2 microns.
- Change process for the GaAs layers from MO-CVD to CVD using the halide/hydride process.
- Reduce Ge epitaxy substrate thickness from 5 to 1 micron.
- Change back contact from tin to molybdenum.
- Varying CVD and MO-CVD process efficiencies from 20-100%.

Screening Results

Review of the CMAP screening of the baseline and sensitivity polycrystalline gallium arsenide solar cells identified the following "A" materials:

Baseline

Arsine
Gallium
Germane
Germanium
Trimethyl Gallium

---

*Technically tin should be used as the grid contact instead of copper. However, since such a small quantity of tin would be required there would be no impact on the matetials's availability.

Sensitivity Case 1: Active Layer 5 Microns, CVD

Arsenic
Arsine
Gallium
Germane
Germanium

Sensitivity Case 2: Active Layer 2 Microns, MO-CVD

Arsine
Gallium
Germane
Germanium
Trimethyl Gallium

Sensitivity Case 3: Active Layer 2 Microns, CVD

Arsine
Gallium
Germane
Germanium

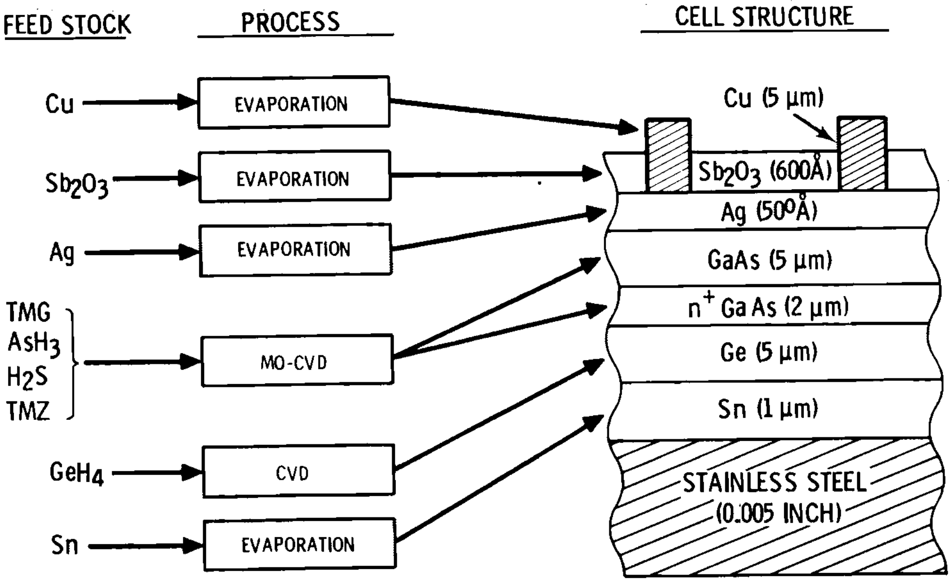

FIGURE 22 Polycrystalline Gallium Arsenide MIS Solar Cell

Layer Function	Process & Feedstock To Material in Layer	Chem. Ratio	Process Effic.	Mat'l. in Layer MT/GWp
ACTIVE LAYER	MO-CVD OF GAAS			
	TRIMETHYL GALLIUM TO GA	0.61	0.30	128.0
	ARSINE TO AS	0.96	0.30	138.0
DOPED CONTACT LAYER	MO-CVD OF GAAS			
	TRIMETHYL GALLIUM TO GA	0.61	0.30	51.0
	ARSINE TO AS	0.96	0.30	55.2
N-DOPANT	MO-CVD OF S			
	HYDROGEN SULFIDE TO S	0.94	0.30	1.07-02
M OF MIS	EVAPORATED			
	SILVER	1.0	0.35	0.525
GRID CONTACT	EVAPORATED			
	COPPER	1.0	0.035	44.7
AR COATING	EVAPORATED			
	ANTIMONY TRIOXIDE	1.0	0.35	3.11
EPITAXY SUBSTRATE	CVD			
	GERMANE TO GE	0.95	0.35	267.0
BACK CONTACT	EVAPORATED			
	TIN	1.0	0.35	57.5
SUPPORT SUBSTRATE				
	STAINLESS STEEL	1.0	0.8	9.99+03

and, the following "B" materials:

Baseline

Antimony
Arsenic
Arsenic Trioxide
Carbon Dioxide
Chromium
Ferromanganese
Fluorspar
Hydrochloric Acid
Hydrogen Sulfide
Nickel
Petroleum Coke
Silver
Tin
Antimony Ore
Bauxite
Bauxite Byproduct
Fluorspar Ore
Manganese Ore
Nickel Ore
Petroleum
Silver Ore
Tin Ore
Zinc Byproduct
Zinc Ore

Sensitivity 1: Active Layer 5 Microns, CVD

Antimony
Arsenic Trioxide
Carbon Dioxide
Chromium
Ferromanganese
Fluorspar
Hydrochloric Acid
Hydrogen Sulfide
Nickel
Petroleum Coke
Silver
Zinc
Antimony Ore
Bauxite
Bauxite Byproduct
Fluorspar Ore
Manganese Ore
Nickel Ore
Petroleum
Silver Ore
Zinc Ore
Zinc Byproduct

Sensitivity 2: Active Layer 2 Microns, MO-CVD

Antimony
Arsenic
Arsenic Trioxide
Carbon Dioxide
Chromium
Ferromanganese
Fluorspar
Hydrochloric Acid
Hydrogen Sulfide
Nickel
Petroleum Coke
Silver
Tin
Zinc
Antimony Ore
Bauxite
Bauxite Byproduct
Fluorspar Ore
Manganese Ore
Nickel Ore
Petroleum
Silver Ore
Tin Ore
Zinc Ore
Zinc Byproduct

Sensitivity 3: Active Layer 2 Microns, CVD

Antimony
Arsenic
Arsenic Trioxide
Carbon Dioxide
Chromium
Ferromanganese
Fluorspar
Hydrochloric Acid
Hydrogen Sulfide
Nickel
Petroleum Coke
Silver
Zinc
Antimony Ore
Bauxite
Bauxite Byproduct
Fluorspar Ore
Manganese Ore
Nickel Ore
Petroleum
Silver Ore
Zinc Ore
Zinc Byproduct

"A" MATERIAL DISCUSSIONS

Arsenic and arsenic compounds are important in this photovoltaic cell. At 10¢/watt, arsine is important to photovoltaics. Photovoltaics would require 93% of the market in the year 2000 and production capacity would have to grow 700% between 1990 and 1991. This raises the immediate concern that arsine simply will not be reliably available in the market. It should definitely be classified as an "A" material. We recommend that arsine production and purification processing be considered as an integral part of the production facilities for this type of cell. The use of arsine in the sensitivity case (#3) is reduced to about 5¢/watt but still requires 86% world production; so our recommended strategy remains to consider manufacturing the arsine in dedicated facilities at the photovoltaic manufacturing site to:

- Control the costs
- Arrive at the optimum purity
- Control quality
- Avoid problems of shipment and/or storage of potentially unstable compounds.

Gallium and gallium-containing materials such as gallium trichloride and trimethyl gallium are "A" materials since the costs of bulk gallium represents 81¢/watt and the purified process intermediate, trimethyl gallium, would cost much more (at present prices, $7.83/watt). This is displayed on Figure 23 where the maximum amount of gallium required in one year (MT/yr) is shown along with the material cost for the base case and sensitivity cases exploring the effects on material usage.

The usage, and consequently the costs, of the gallium are reduced -- the usage of 2,617 MT/yr and the cost of bulk gallium to 46¢/watt. The TMG at present prices is $4.46/watt.

Another approach being researched is CVD using $GaCl_3$, formed by passing HCl over elemental gallium. This gives comparable results in reducing bulk gallium to the previous sensitivity case using MO-CVD to deposit a 2 micron active layer even though it uses a 5 micron active layer. This results in 2,324 MT/yr maximum usage and in costs of 41¢/watt. Reducing the thickness of this CVD active layer to 2 microns reduces the requirements to 1,327 MT/year maximum with a resulting cost for gallium of 23¢/watt. In the CVD process described in this study it is assumed that the process is 35% efficient. If a means can be found to recycle the 65% now lost up the ventilator stacks, etc., these latter figures could be reduced to 465 MT/yr and a cost of 8.2¢/watt. This latter hypothetical example assumes reducing the active layer of the CVD cell to 2 microns and that perfect recycle of <u>all</u> gallium is achieved.

The cost of the bulk gallium is still above the threshold screening level of 5¢/watt. The annual requirements are also above the quantity threshold of about 5 MT/year based on 10% of the year 2000 gallium consumption without PV. This threshold is not displayed on Figure 23 because it is much less than the left hand margin value (10 MT/year) on the scale chosen.

Cost considerations become even more critical when future supply-demand relationships for gallium are projected. Gallium requirements to produce 25 GWe by the year 2000 are shown in Figure 24 for the base case and two of the three sensitivity scenarios. A measure of potential gallium supply can be obtained by referring to Figure 43 in Chapter 4.

Comparing the two graphs shows the base case would require 95% of all gallium that could be recovered from world alumina production in the year 2000. Producers have expressed serious concern about the risk of installing new capacity for gallium. They cite recent experiences with the LED market where technology changes drastically curtailed the market. Clearly, these gallium requirements could not be met with spot market purchases; therefore, some long-term mitigating strategy is needed.

Any mitigating action must reduce the amount of gallium used in the cell, reduce the cost of producing gallium, and/or increase quantities of gallium available. We recommend the following actions:

- Insure long-term supply by reducing risk to producers through long-term contracts
- Lower unit costs through economies-of-scale
- Lower unit costs through research on extraction efficiencies
- Consider a stockpile program
- Research methods to reduce gallium in cells

Risks faced by gallium producers are discussed in Chapter 4. Mitigating action to ensure long-term supply would have to shift some of this risk burden from gallium producers. Long-term contracts to purchase gallium would reduce this risk of income variability and create an incentive to enter the market or expand existing capacity.

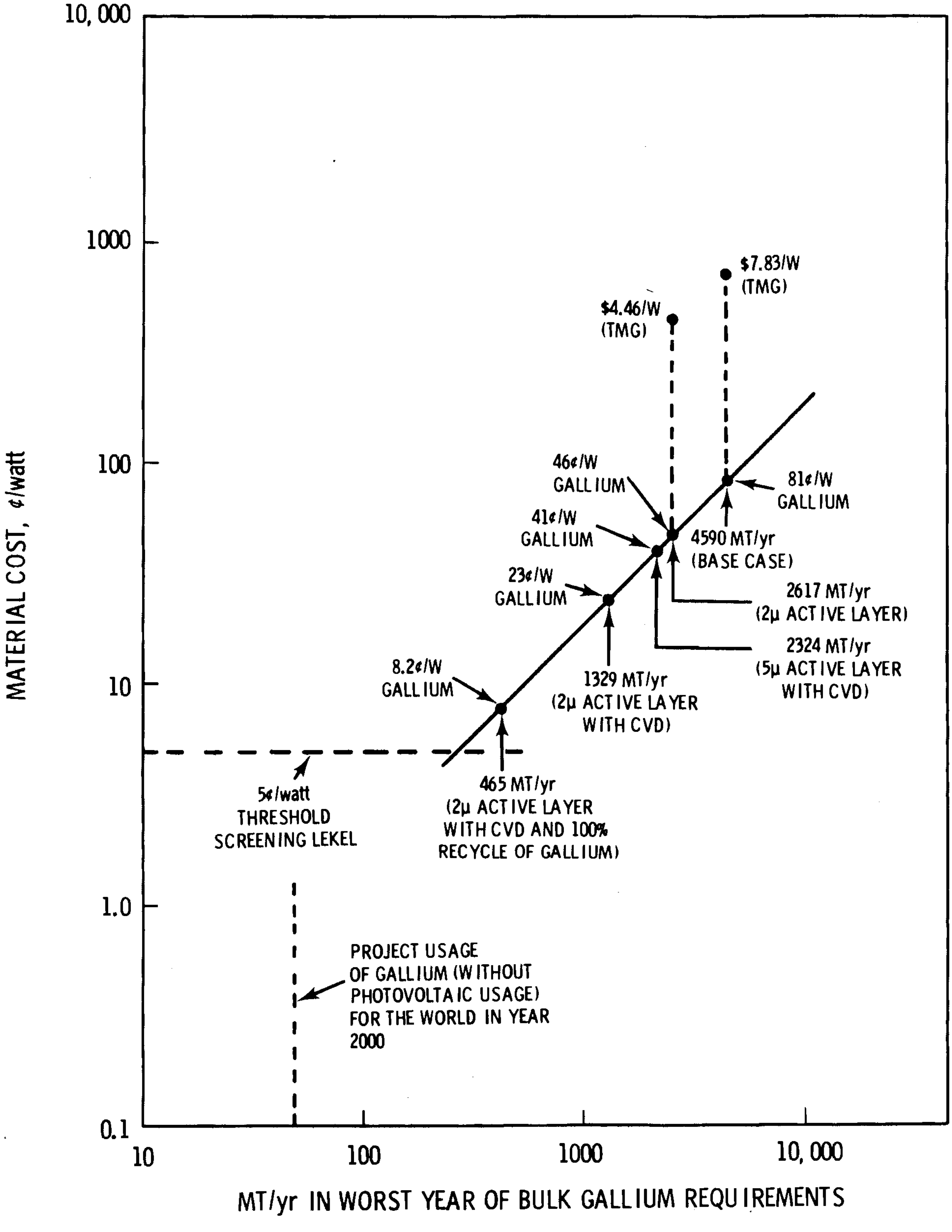

FIGURE 23. MT/YR of Gallium (Used for 25 GW Online by 2000 for Polycrystalline GaAs MIS PV Cell Production

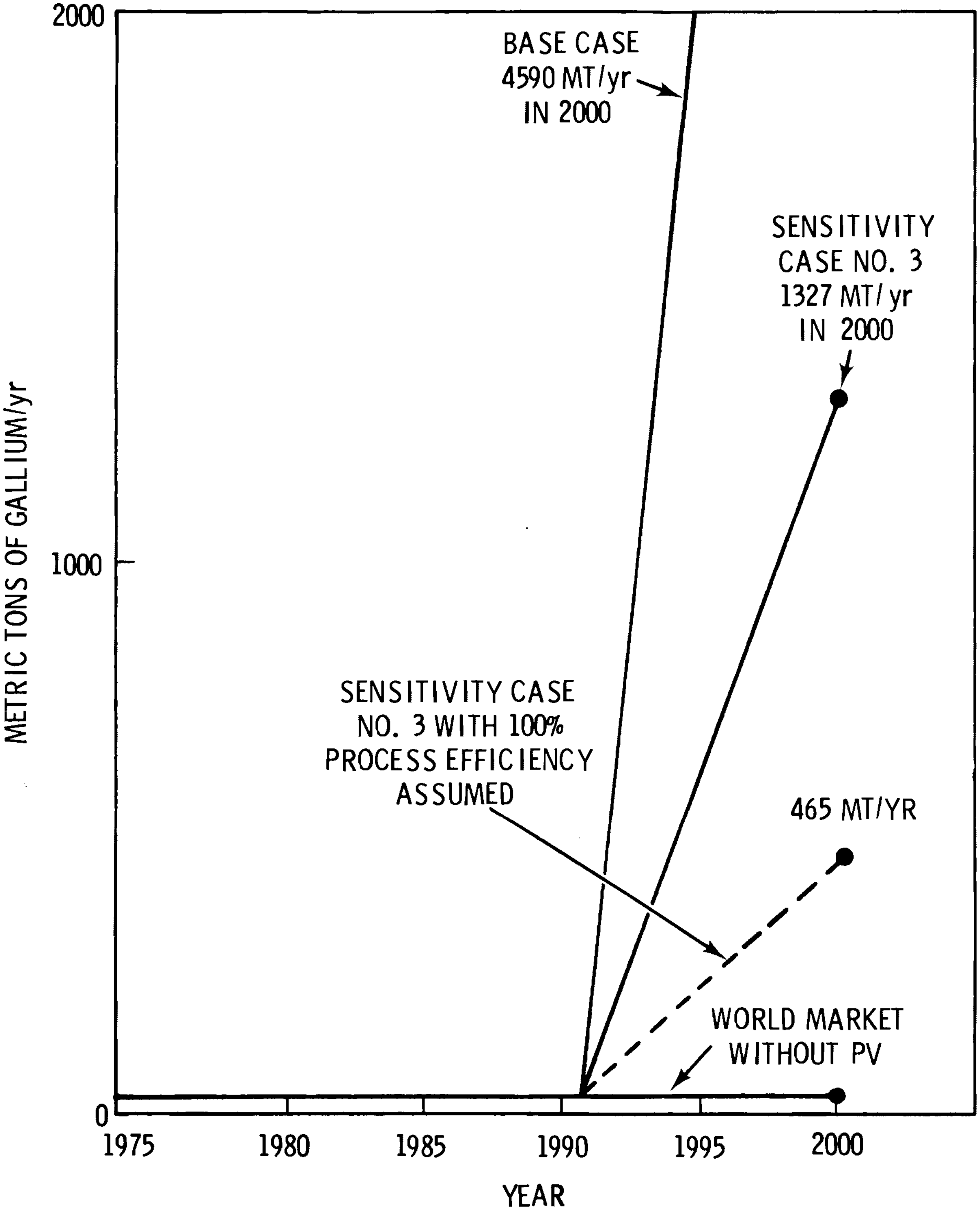

FIGURE 24. Projected Market for Gallium With and Without Polycrystalline GaAs MIS Cell Production (To Produce 25 GW Online by 2000)

Large, long-term contracts could serve to lower gallium costs. Specifically, these contracts would give alumina producers an incentive to install high volume recovery equipment and reduce unit costs through economies-of-scale. In addition, long-term contracts would be an incentive to increase recovery efficiencies through research and thus lower unit costs as well as increasing gallium availability.

We recommend funding a research program to investigate gallium recovery efficiencies to supplement industry funded programs.

Another strategy to be considered to help ensure future gallium availability and market stability is that of purchase and stockpile. Gallium could be purchased on world markets during development years when requirements are less. In later years when gallium requirements are heavy, stockpiles could act as a market buffer.

The final mitigating strategy we recommend is that of ongoing research to reduce the amount of gallium used. This research could parallel gallium extraction research.

One major concern is that gallium production in large quantities will likely be overseas. The gallium is recovered during the processing of bauxite into alumina (increasingly being done outside the U.S.).

Gallium trichloride is a process intermediate in the process for producing trimethyl gallium. Therefore, it will not be discussed separately but will be adequately considered by discussing trimethyl gallium.

Trimethyl gallium (TMG) would be nearly 100% used by the photovoltaic industry. The present price of $7.82/watt would undoubtedly be reduced in large-scale production (due to economies-of-scale). The suggested mitigating strategy is to design TMG production facilities as an integral part of the production plant for the polycrystalline gallium arsenide MIS photovoltaic cells in order to:

- Control purity
- Assure supply
- Control price

High purity trimethyl gallium is presently made in such small quantities that its large-scale production costs cannot be reasonably estimated from published data.

GERMANIUM AND ITS COMPOUNDS, GERMANE AND GERMANIUM TETRACHLORIDE

In the base case cell the germanium costs 32¢/watt and the germane produced from the germanium costs about 56¢/watt in high production. Photovoltaic cells would be using virtually all of the world's germanium production at 4,651 MT/year. In the sensitivity case (#1) this is reduced to 932 MT/year and 6.5¢/watt and germane to about 11¢/watt.

If the germanium losses in the cell can be fully reclaimed and recycled, then a hypothetical case could be imagined where the germanium is further reduced from 932 MT/year to about 326 MT/year and the cost to 2-1/4¢/watt and germane to about 5-1/4¢/watt (all shown on Figure 25).

Clearly, there is room for concern about future availability of germanium for this design of PV cell and we do regard it as an "A" material. World reserves are listed as 1,800 MT in Mineral Commodities Summaries, 1979 by Bu Mines. The clear implication is that higher prices would occur if germanium were to be needed in larger quantities (Figure 26). The relationship of projected usage for PV compared to other uses is shown in Figure 27.

Inadequate information is known about germanium availability in specific zinc ore bodies to allow a meaningful estimate of future potential increases in germanium production. Our recommended strategy for dealing with this material for the MIS cells remains:

- Try to eliminate the material from the cell
- Initiate further work to identify germanium availability (to increase confidence in its ultimate availability)
- Develop methods to recycle germanium during cell manufacture
- Expect to develop sources for the needed material well in advance (several years ahead of large-scale deployment of the technology)
- Plan to produce germane on the PV production site to assure quality, delivery and price
- Expect to pay very high prices for inadequate supplies of germanium if spot market purchases are relied upon for commercial supplies of germanium to produce substantial deployment of polycrystalline gallium arsenide MIS cells

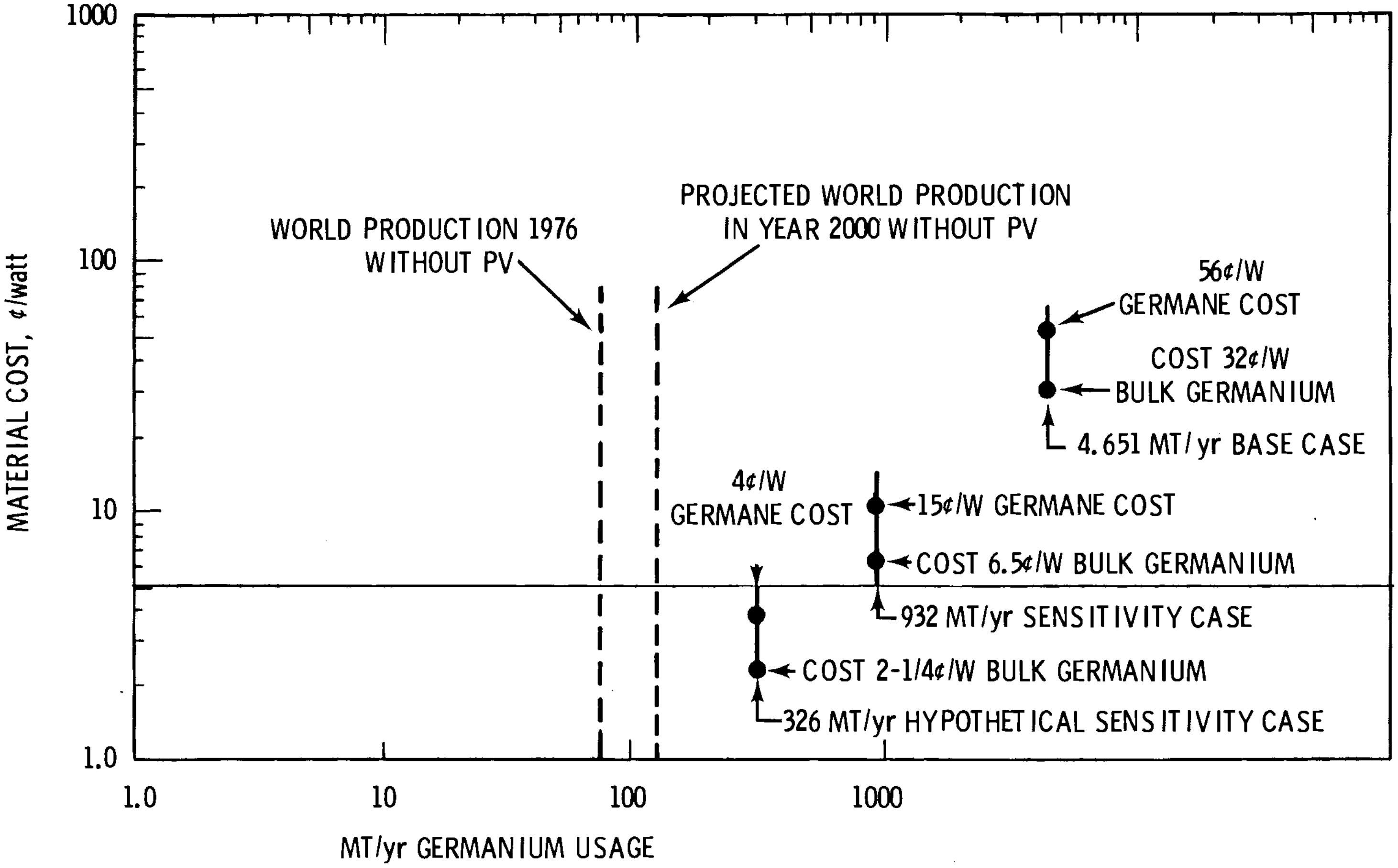

FIGURE 25. Projected Usage of Germanium (and Costs at Present Prices) for Polycrystalline Gallium Arsenide MIS PV Cells at 25 GW by Year 2000

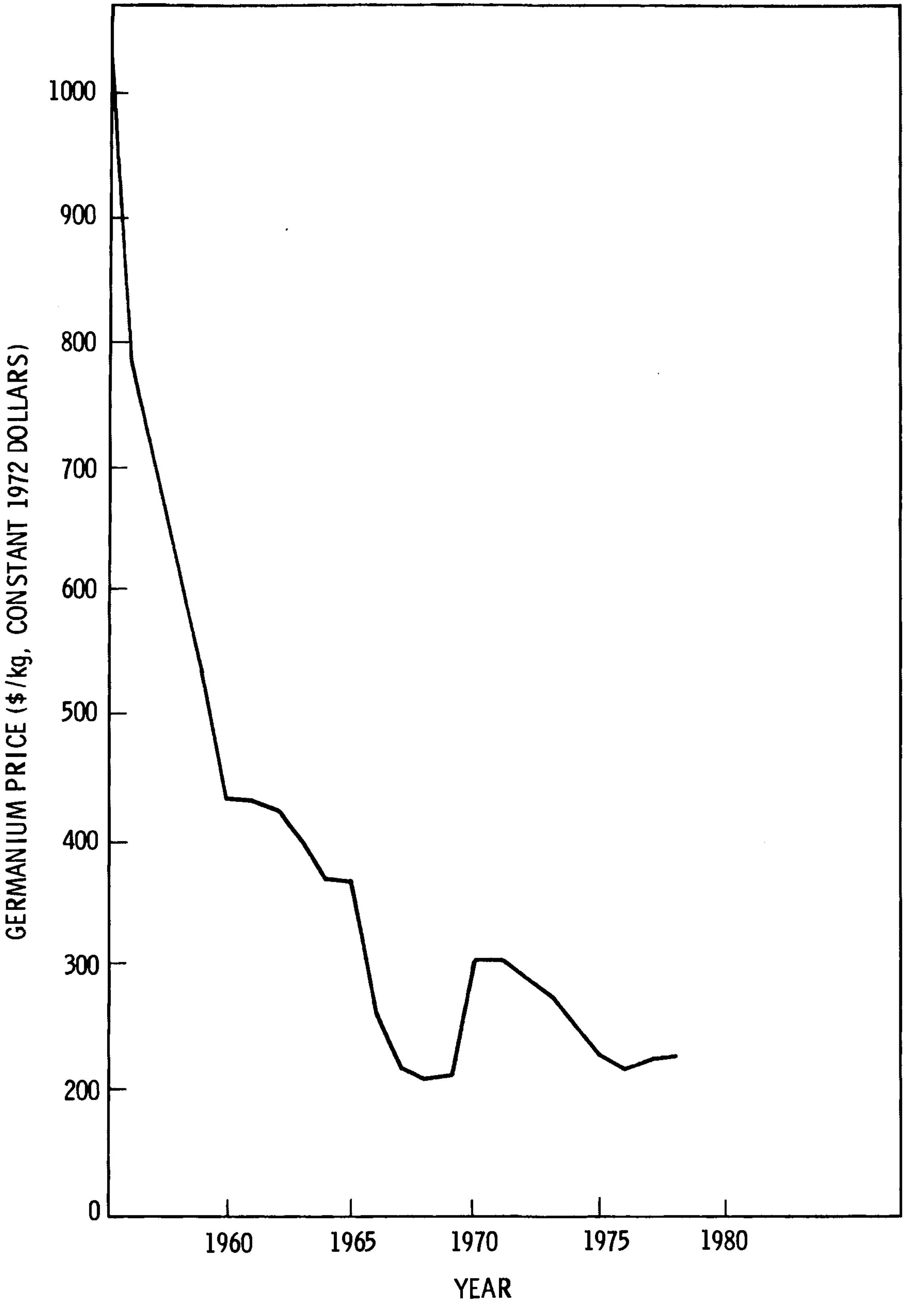

FIGURE 26 . Price History of Germanium

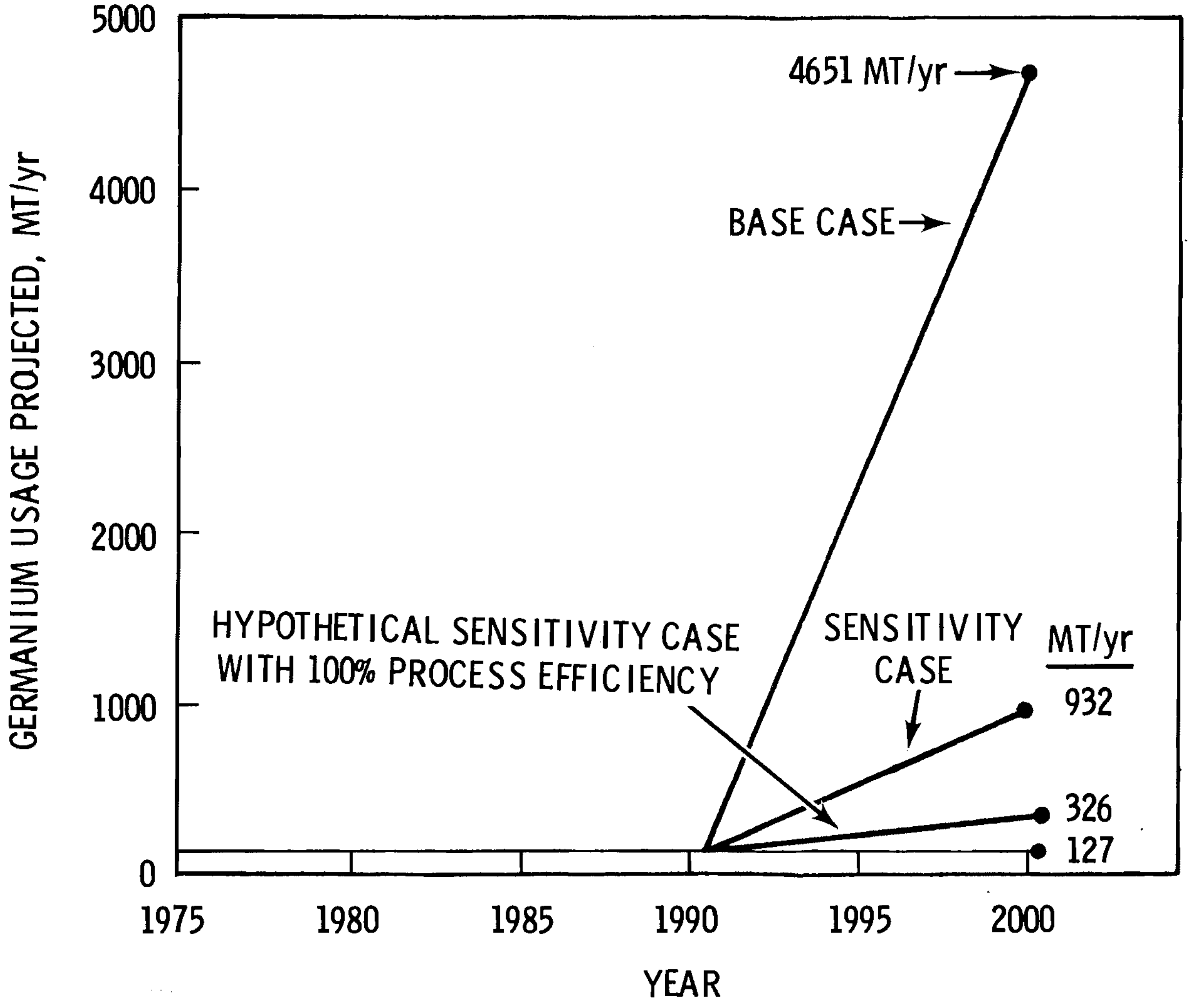

FIGURE 27. Germanium Usage Projections for PV and Other End Uses

"B" MATERIAL DISCUSSIONS

The baseline case bulk and raw material screening results are shown in Tables 11 and 12.

Antimony is 80% derived as a byproduct of silver/lead ores and 54% of domestic consumption is imported. The amount needed in photovoltaic cells would be less than 1% of the market and the cost of the antimony would be less than .1¢/watt of photovoltaic cell. We class it as a "B" material; in other words, as a material which should be reassessed in the future but does not appear likely to be a problem.

Carbon dioxide is used in large quantities but is readily available in any quantity needed. The low cost in the cell (0.3¢/watt) and the low percentage of the market clearly indicates a "B" material.

Chromium, used in producing 304 stainless steel (an engineering material), represents 2¢/watt at current prices and since it is 89% imported, it could present problems. Further review indicates that the chromium (in chromite concentrates) sells for about $500/MT compared to the purified metallic chromium at $6,590/MT. Less than 1% of the market would be required for photovoltaics. Thus, we stick to a "B" classification although the costs of winning chromium from the concentrate could go up due to the energy content of the process and the continuing trends in energy costs.

Ferromanganese and fluorspar are 98% and 79%, respectively, imported but are less than 0.1¢/watt in PV and the amount required is less than 1% of the market. They are both "B" materials.

Hydrochloric acid is 92% derived as a byproduct of producing other materials. There is, however, no probable serious concern for the production of this cell since quantities needed for PV are inexpensive and small compared to normal production. It is a "B" material.

Hydrogen sulfide 99.999% represents no material supply problems excepting that the purity requirements are higher than normal. It is regarded as a "B" material.

Molybdenum. In the sensitivity study the back contact was changed from tin to molybdenum. The impact on the costs of the cell would be negligible. (The tin and the molybdenum both cost about 0.3¢/watt.) The PV usage of the molybdenum is less than 1% of world usage. Molybdenum would be a "C" material since it would ex-

TABLE 11 .

BULK MATERIAL REQUIREMENTS FOR
POLYCRYSTALLINE GALLIUM ARSENIDE MIS SOLAR CELL
BASELINE CASE

SOLAR SCENARIO:
INTRODUCTION YEAR- 1991
CUMULATIVE CAPACITY 2000- . 25. GW

FACTORS	BULK MATERIAL USAGE MT.	PERCENT SUPPLY AS BY-PROD	PRODTN GROWTH RATE 1990	MAX % SYSTEM 1 YEAR WORLD	% FROM ONE NATION NON-US	PRESENT COSTS IN $/KW	NET % IMPORT
THRESHOLD LEVELS--		50.	10.%	10.	35.	50.	50.
ALUMINUM	73573.	0.	7.	0.	13.	3.	9.
ALUMINUM FLUORIDE	1471.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
AMMONIA	605.	0.	3.	0.	5.	0.	1.
ANTIMONY	187.	80.*	5.	0.	22.	0.	54.*
ANTIMONY TRIOXIDE	222.	0.	2.	0.	13.	0.	48.
ARSENIC	18227.	100.*	4.	6.	23.	73.*	39.
ARSENIC TRIOXIDE	25517.	100.*	4.	5.	23.	0.	39.
ARSINE, 99.999%	16771.	0.	688.*	93.*	10.	96.*	0.
BORAX	570989.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
CARBON DIOXIDE	6341709.	100.*	4.	7.	5.	12.	0.
CAUSTIC SODA	242854.	0.	3.	0.	5.	1.	1.
CHLORINE	105334.	0.	3.	0.	5.	1.	1.
CHROMIUM	84291.	0.	3.	0.	28.	22.	89.*
COAL, BITUMINOUS	117.	0.	2.	0.	20.	0.	10.
COKE	88410.	0.	3.	0.	10.	0.	1.
COPPER	31929.	1.	6.	0.	13.	2.	12.
CRYOLITE	2575.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
DIMETHYL ALUM. CHLORIDE	122268.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
ELECTRICITY (KWH)	11807.E+6	0.	7.	0.	0.	14.	0.
ELECTRODES	22855.	0.	3.	0.	10.	2.	1.
FERROMANGANESE	2337.	0.	3.	0.	22.	0.	98.*
FERROSILICON	212.	0.	3.	0.	10.	0.	35.
FERROUS SCRAP, PURCHASED	51659.	0.	3.	0.	10.	0.	0.
FLUORSPAR	1708.	0.	5.	0.	19.	0.	79.*
GALLIUM	25265.	100.*	1505.*	99.*	40.*	808.*	55.*
GALLIUM TRICHLORIDE	60156.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
GERMANE, 99.9%	20075.	0.	406482.*	100.*	5.	562.*	0.
GERMANIUM	25584.	100.*	447.*	97.*	29.	323.*	16.
GERMANIUM TETRACHLORIDE	71066.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
HYDROCHLORIC ACID	841676.	92.*	4.	1.	5.	7.	2.
HYDROGEN	2226.	40.	6.	0.	10.	0.	0.
HYDROGEN SULFIDE, 99.999%	1.	0.	1201.*	97.*	10.	0.	0.
LIME	29374.	0.	3.	0.	20.	0.	2.
LIQUID FUELS	28916.	0.	3.	0.	18.	0.	39.
METHANOL	575656.	0.	5.	1.	10.	3.	0.
METHYL BORATE	155583.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
METHYL CHLORIDE	204187.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
NICKEL	31219.	7.	3.	0.	33.	6.	70.*
NITRIC ACID	2021.	0.	3.	0.	32.	0.	1.
OXYGEN, GASEOUS	133401.	0.	4.	0.	21.	0.	0.
OXYGEN, LIQUID	15082.	0.	4.	0.	21.	0.	0.
PETROLEUM COKE	65558.	100.*	3.	0.	15.	0.	0.
PITCH-IN-TAR	33501.	0.	3.	0.	5.	0.	5.
SILVER	38.	70.*	4.	0.	14.	0.	50.*
SODIUM	30322.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
SODIUM BOROHYDRIDE	50188.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
SODIUM CARBONATE	7473.	0.	0.	0.	10.	0.	0.
SODIUM CYANIDE	15.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
SODIUM HYDRIDE	140526.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
STEAM	4814715.	1.	3.	0.	10.	1.	0.
STEEL & IRON	212414.	1.	3.	0.	16.	3.	7.
SULFUR	255064.	31.	3.	0.	14.	1.	0.
SULFURIC ACID	756861.	20.	3.	0.	14.	2.	0.
TIN	4107.	1.	3.	0.	28.	3.	85.*
TRIMETHYL AL., COMM.	48907.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
TRIMETHYL GA., 99.9995%	24454.	0.	247570.*	100.*	5.	7825.*	0.
ZINC	24034.	25.	2.	0.	20.	1.	59.*
ZINC ARSENIDE	41424.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
(MISC. BULK MATERIALS)	32782.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?

TABLE 12.

RAW MATERIAL REQUIREMENTS FOR:
POLYCRYSTALLINE GALLIUM ARSENIDE MIS SOLAR CELL
BASELINE CASE

SOLAR SCENARIO:
INTRODUCTION YEAR- 1991
CUMULATIVE CAPACITY 2000- 25. GW

FACTORS	RAW MATERIAL USAGE (1000MT)	%PRD GROW RATE FROM 1990	MAX% SYST ONE YEAR WRLD	%US RESERV CONSUM BY 2000	%US RESOUR CONSUM BY 2000	%FRM ONE NAT NON-US	%WORLD RESERV CONSUM BY 2000	%WORLD RESOUR CONSUM BY 2000	PRSNT COSTS IN $/KW	NET% IMPT
THRESHOLD LEVELS--		7.	10.	400.	300.	60.	300.	200.	50.	50.
ANTIMONY ORE	20.	3.	0.	887.*	822.*	22.	56.	47.	0.	54.*
BAUXITE	346.	5.	0.	2691.*	364.*	31.	15.	10.	0.	91.*
BAUXITE, BY PROD	1263270.	20.*	46.*	5802.*	785.*	31.	20.	13.	0.	91.*
COAL, BITUMINOUS	6899.	2.	0.	5.	1.	7.	9.	1.	4.	0.
COPPER BYPROD.	59.	4.	0.	73.	17.	13.	67.	16.	0.	12.
COPPER ORE	4561.	4.	0.	73.	17.	13.	67.	16.	0.	12.
FLUORSPAR ORE	5.	5.	0.	1004.*	168.	19.	255.	140.	0.	79.*
IRON ORE	344.	5.	0.	29.	5.	27.	16.	5.	0.	29.
LIMESTONE	129.	3.	0.	0.	0.	20.	0.	0.	0.	2.
MANGANESE ORE	5.	3.	0.	100.	8.	22.	15.	8.	0.	98.*
NATURAL GAS	735.	5.	0.	258.	60.	23.	97.	10.	3.	5.
NICKEL ORE	3122.	3.	0.	3550.*	9.	33.	48.	20.	2.	70.*
PETROLEUM	3420.	2.	0.	565.*	185.	18.	104.	34.	10.	39.
PROPANE	43.	2.	0.	221.	22.	23.	78.	8.	0.	5.
SALT	1011.	6.	0.	0.	0.	18.	0.	0.	1.	7.
SAND & GRAVEL	323.	4.	0.	0.	0.	6.	0.	0.	0.	0.
SILICA PEBBLE	0.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
SILVER ORE	54.	4.	0.	277.	73.	14.	208.	56.	0.	50.*
SULFUR ORE	255.	3.	0.	189.	61.	14.	109.	34.	0.	0.
TIN ORE	411.	2.	0.	3499.*	707.*	28.	67.	18.	7.	85.*
WATER, FRESH	72.	2.	0.	0.	0.	5.	0.	0.	0.	0.
ZINC BYPROD.#3	2558382.	30.*	67.*	636.*	382.*	20.	205.	133.	0.	59.*
ZINC ORE	534.	3.	0.	166.	100.	20.	125.	81.	0.	59.*

ceed no threshold criteria. It is included in this discussion only because it is specifically changed in the sensitivity analysis.

Nickel is mostly imported, but is regarded as a "B" material for this cell because not much is used and PV needs represent a small part of the nickel market.

Petroleum coke is a 100% byproduct but is needed for this cell in inconsequential quantities and PV use will be an inconsequential part of the market, so we rate it a "B" material.

Silver is 70% byproduct of mining other minerals such as lead and zinc, etc., and is 50% imported. But we rate it a "B" material in this PV cell because less than 0.1¢/watt are required and less than 1% of the silver market is involved.

Tin and zinc are 85% and 59% imported, respectively, but their use in the cell is less than 1% of the market and the cost in the cell only about 0.3¢/watt or less so we class them as "B" materials.

A fairly large number of raw materials are classified as "B" materials but the cell production uses insignificant quantities of the world supplies and the usage does not represent a significant cost in producing the cells. There are, however, two raw materials which are at a significant level and they are bauxite (because of the production of gallium) and zinc, byproduct #3 (because of the production of germanium). Both of these materials were discussed previously and the implication for both of these materials is that conventional sources would be strained. At 46% of world supply the world use of bauxite would be virtually all required to produce the gallium needed. The percent of material required for the PV systems compared to world needs is calculated in CMAP by dividing PV needs by the sum of PV needs plus non-PV world needs. In this way when the CMAP printout for a byproduct reads 50% required, it actually means that the PV requirements are as large as the non-PV requirements. Thus, when more than 50% of a "byproduct" is called for, the supply is actually exceeded because theeconomics of these byproducts are such that bauxite (or zinc) would not be processed for the byproducts alone. This printout merely confirms that gallium and germanium are "A" materials and mitigating strategies are required as previously discussed. These two materials are less serious concerns in the sensitivity cases due to the reduction in demand for both gallium and germanium.

ADVANCED CONCENTRATOR SOLAR CELLS

Cell Description

Figure 23 illustrates the structure, materials, and processes for a generalized advanced concentrator. A cell conversion efficiency of 30% and sunlight concentration of 500 times are assumed.

The generalized advanced concentrator cell characterized here consists of a 250 μm thick wafer of GaAs onto which is first deposited 15 μm of lattice matching layers, a 4 μm thick p-n junction and a 1 μm thick tunnel junction. These first layers, totaling 20 μm of material, are assumed to have a composition equivalent to $Ga_{0.75}In_{0.25}As$. Although this composition is not likely to be the exact one used, it does allow explicit accounting for the use of Ga, In, and As in these layers of the stacked cells. The top p-n junction next deposited is assumed to be 4 μm of $Ga_{0.8}Al_{0.2}As$. $Ga_{0.1}Al_{0.9}As$, 0.3 μm thick, is selected for the window layer. Grid contacts are (80% Au-20% Zn)/Ag in a thickness of (0.05 μm)/10 μm. (The large thickness selected here is necessary for conducting the high currents generated by the concentrator cell.) Finally, a broad-band AR coating is assumed fabricable from 3 or more layers of Ta_2O_5 and SiO_2 with thicknesses on the order of quarter-wavelength at 600 nm. The GaAs substrate thickness probably could vary from 200 to 500 microns. The effect of changing the thickness from 250 microns to 500 microns is investigated in a sensitivity case.

Screening Results

Review of the CMAP screening of the baseline and sensitivity advanced concentrator cell identified the following "A" materials:

Baseline and Sensitivity

Gallium Arsenide (Ingots and Wafers)

Gallium

Trimethyl Indium

Trimethyl Gallium

and the following "B" materials:

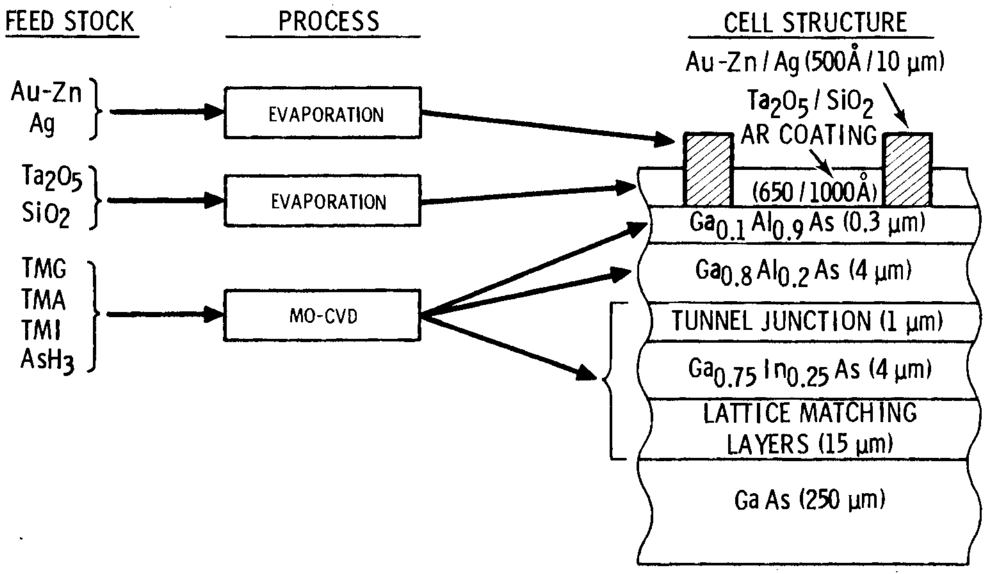

FIGURE 28. Advanced Concentrator Solar Cell 500X

Layer Function	Process & Feedstock To Material in Layer	Chem. Ratio	Process Effic.	Mat'l. in Layer MT/GWp
SUBSTRATE	SINGLE CRYSTAL GALLIUM ARSENIDE	1.0	1.0	8.86
LATTICE MATCHING LAYERS, BOTTOM & TUNNEL JUNCTIONS	MO-CVD OF GA0.75IN0.25AS			
	TRIMETHYL GALLIUM TO GA	0.61	0.3	0.242
	TRIMETHYL INDIUM TO IN	0.72	0.3	0.133
	ARSINE TO AS	0.96	0.3	0.346
TOP JUNCTION	MO-CVD OF GA0.8AL0.2AS			
	TRIMETHYL GALLIUM TO GA	0.61	0.3	5.48-02
	TRIMETHYL ALUMIN. TO AL	0.37	0.3	5.30-03
	ARSINE TO AS	0.96	0.3	7.36-02
WINDOW LAYER	MO-CVD OF GA0.1AL0.9AS			
	TRIMETHYL GALLIUM TO GA	0.61	0.3	5.20-04
	TRIMETHYL ALUMIN. TO AL	0.37	0.3	1.81-03
	ARSINE TO AS	0.96	0.3	5.59-03
GRID CONTACTS	EVAP. OF (.8AU-.2ZN)/AG			
	GOLD	1.0	.035	5.15-04
	ZINC	1.0	.035	4.76-05
	SILVER	1.0	.035	7.00-02
AR COATINGS	EVAPORATION			
	TANTALUM TO TA2O5	1.22	0.40	3.55-03
	SILICON TO SIO2	1.0	0.40	1.51-03

Baseline

Arsenic
Arsenic Trioxide
Arsine
Carbon Dioxide
Ferromanganese
Fluorspar
Hydrochloric Acid
Hydrogen Sulfide
Indium
Petroleum Coke
Tantalum
Trimethyl Aluminum
Bauxite
Bauxite Byproducts
Fluorspar Ore
Gold Ore
Manganese Ore
Petroleum
Silver Ore
Tantalum Ore
Zinc Byproduct
Zinc Ore

Sensitivity

Arsine
Arsenic
Arsenic Trioxide
Carbon Dioxide
Ferromanganese
Fluorspar
Hydrochloric Acid
Indium
Petroleum Coke
Tantalum
Trimethyl Aluminum
Zinc
Gold
Bauxite
Bauxite Byproduct
Fluorspar Ore
Gold Ore
Manganese Ore
Petroleum
Silver Ore
Tantalum Ore
Zinc Byproduct
Zinc Ore

"A" MATERIAL DISCUSSIONS

Gallium and gallium arsenide (ingots and wafers) for the advanced concentrator appear to present materials availability problems as shown on Figure 29 in which both the sensitivity case and the base case are shown.

The material gallium and its use in PV single crystal wafers of GaAs is important in terms of potential cost since PV will likely be the dominant user of gallium so it is likely to set the tone for the market. Relying on spot purchases of gallium for placing 25 GWe online (of advanced concentrator PV cells) will clearly be disrupting to the gallium market where as much as 70% of the market would be required with production growth rates of up to 40% per year for gallium. An orderly market with this level of spot purchases is unlikely. This is illustrated in Figure 30. where it is inferentially apparent that long-term supply contracts will be required to have the gallium available. This level of gallium production (about 4.5 GWe in largest year) would be achieveable since the world annual maximum capability is estimated at about 5,000 MT/yr. (See separate section on gallium and the discussion of polycrystalline GaAs MIS cells which use much more gallium than the advanced concentrator.)

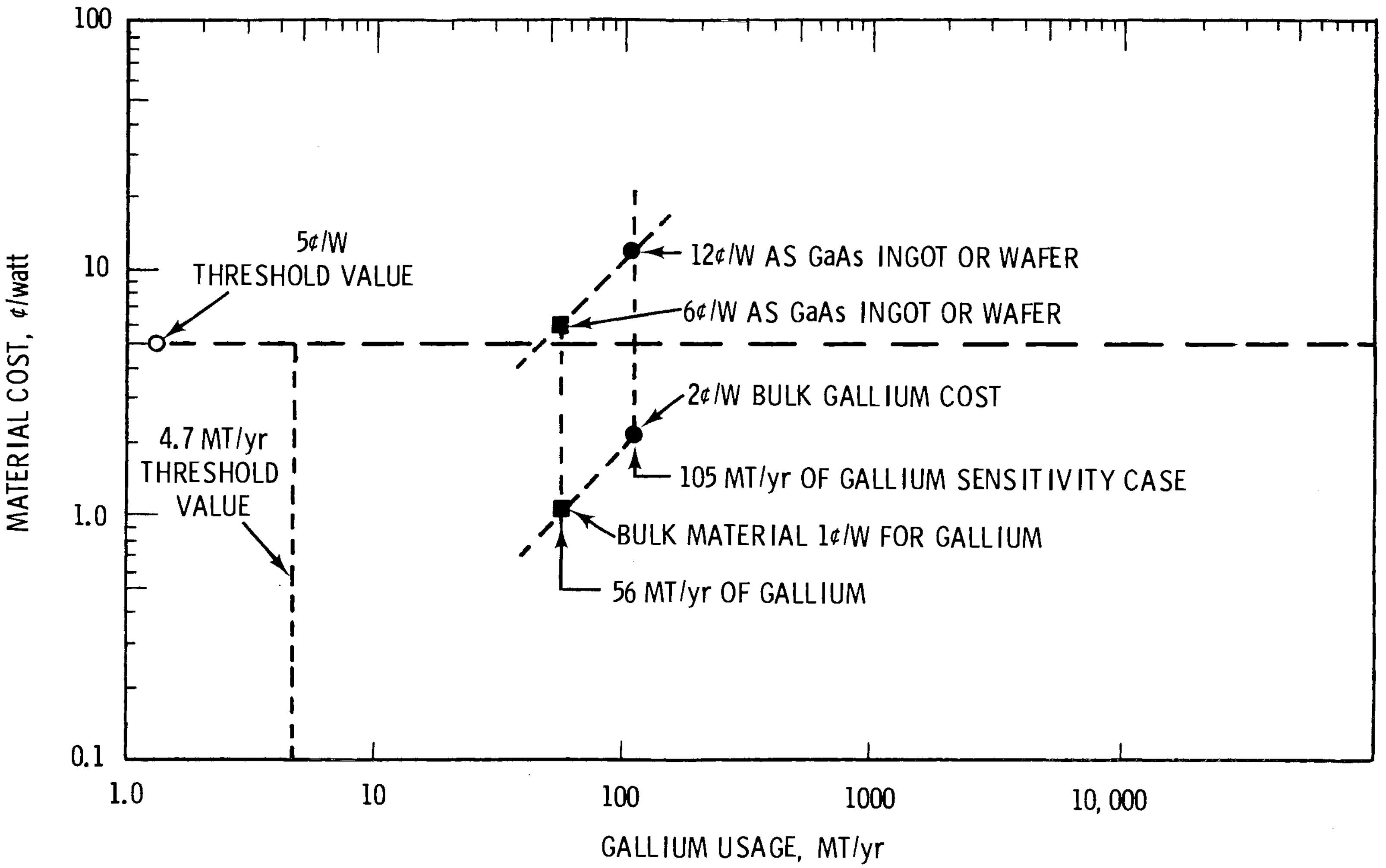

FIGURE 29. Gallium Cost and Usage

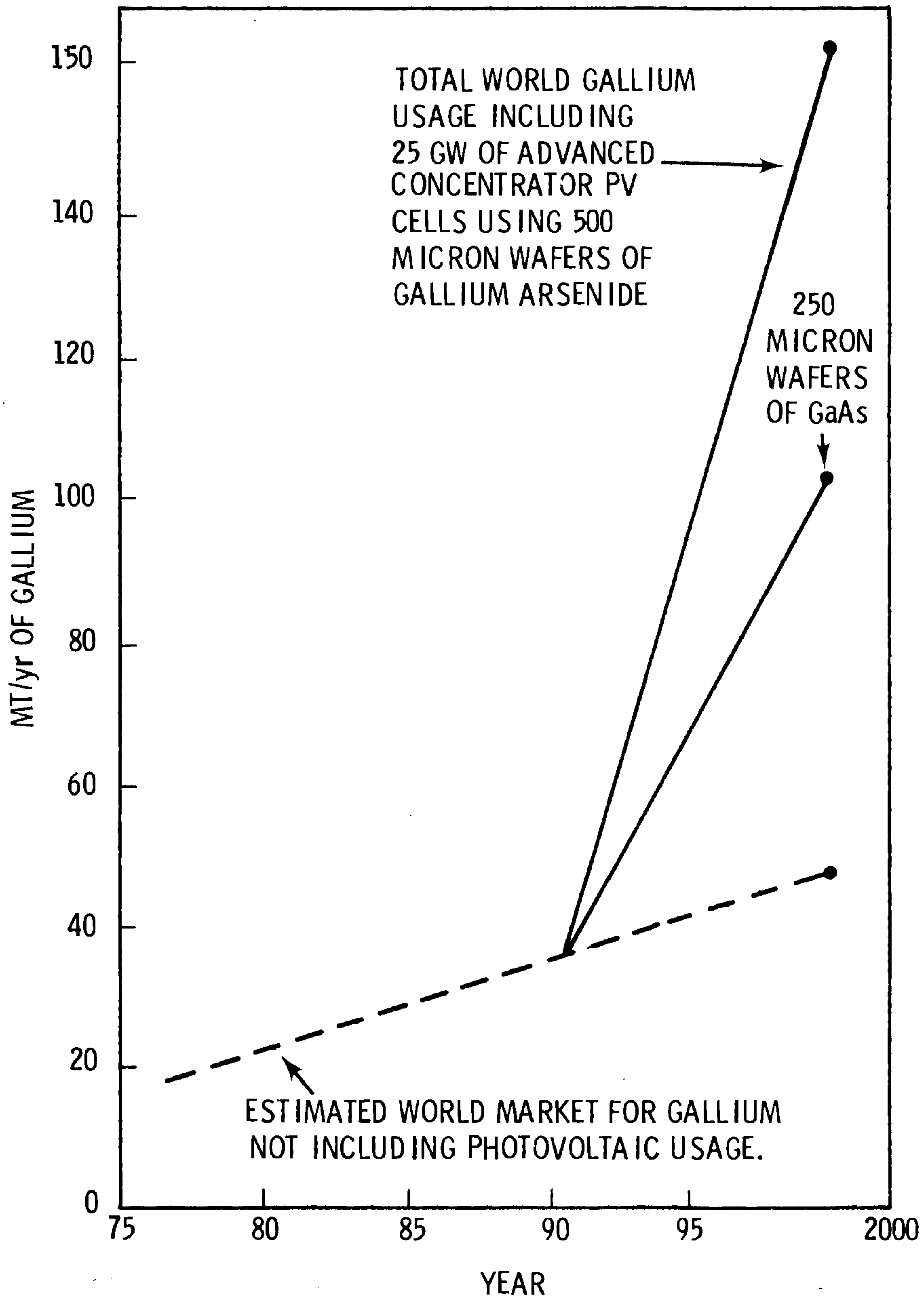

FIGURE 30. Gallium Usage Projections With and Without Advanced Concentrator PV Cell Production

Gallium arsenide and ingots and wafers are presently made in limited quantities (about 11 and 5 MT/yr, respectively). These quantities would have to be increased dramatically to satisfy the needs of the PV industry for the projected 25 GW of advanced concentrators to be online by the year 2000. The industry could probably absorb this kind of growth -- providing some means is supplied to reduce the risk to the suppliers caused by the need to grow at rates up to nearly 70% annually for a single technology market comprising 3/4 of the total market. Our recommendation here is:

- Support research early to reduce cost from the present 6 to 12¢/watt and improve material recycle efficiency for producing the fragile wafers and reduce capital investment in facilities for ingot production -- similar to work presently being done by JPL and others for silicon PV cells.
- Plan to subsidize early production capacity in some way to reduce risk to early suppliers.

Trimethyl gallium 99.9995%, at 1.3¢/watt, requires 96% of world production in the year 2000 and requires a 41% production growth rate between 1990 and 1991. It's an "A" material that should be investigated to see if it should be made on the PV cell production site to: (1) control quality, (2) control cost, and (3) assure availability, simplify storage and transport problems. It is discussed previously in the polycrystalline GaAs MIS cell screening results. Such a program should ensure adequate capacity.

There are no raw material shortages foreseen for producing the advanced concentrator cells.

Trimethyl indium 99.998%, at 2.2¢/watt, does not exceed the cost threshold, but it clearly raises questions of potential availability because of PV requiring 95% of world production in the year 2000 and it has a production growth rate of 318% between 1990 and 1991.

Trimethyl indium is presently made from trimethyl aluminum and indium chloride in small quantities (5 kg/yr), probably in glassware. The process is described as difficult. The material is available from Texas Alkyds, a division of Stauffer Chemical, and from Ventron. The mitigating strategy we recommend is to fund additional study of manufacturing, transporting and storing the material.

It may be wise to consider making it onsite since its manufacture should be quite straightforward (according to a paper by J. J. Eisch$^{(4)}$.

It seems quite plausible that triethylindium and trimethylgallium could both be made by Eisch's procedure to some advantage over the procedure described in Inorganic Synthesis for trimethylgallium.

If it is not made onsite there will likely have to be some means of compensating a supplier for the risks of installing production facilities for a single technology use. One means of compensating is charging higher prices. Locating production onsite, of course, makes it easier to control: (1) quality, (2) availability, and (3) cost, and it simplifies storage and handling.

"B" MATERIAL DISCUSSIONS

Arsenic, arsenic trioxide and arsine. Although arsenic and arsenic trioxide are 100% byproducts, their use in the cells is inexpensive and the PV use is inconsequential in the market. So there is not likely to be any problems obtaining the needed supplies of these materials (Tables 13 and 14).

Arsine, on the other hand, does present one problem as it is not presently available in the needed quantities so that a 23% growth would be required in one year. This could likely be accommodated, however, since the industry will be small. We leave arsine as a "B" material with the recommendation that quality, price and delivery may be optimized by having onsite facilities for its generation at the PV cell manufacturing facility.

Carbon dioxide and petroleum coke raise a question because of their byproduct nature (100%) and there is no reason to be concerned about their availability. They are "B" materials.

Ferromanganese, fluorspar, gold, silver, tantalum and zinc are all imported heavily but are used in small quantities in this cell and the PV use consists of only a small part of the market so that they are all "B" materials.

Trimethyl aluminum 99.9999% is classified as a "B" material because its use in the cell is inexpensive and its total use per year is about 0.4 MT/yr. Its use is hardly above the laboratory use level at this quantity so that its 11% growth rate is easily accommodated and the 23% of world use is not of any concern in this instance.

TABLE 13 .

BULK MATERIAL REQUIREMENTS FOR
ADVANCED CONCENTRATOR SOLAR CELL-500X
BASELINE CASE

SOLAR SCENARIO:
INTRODUCTION YEAR- 1991
CUMULATIVE CAPACITY 2000- 25. GW

FACTORS	BULK MATERIAL USAGE MT.	PERCENT SUPPLY AS BY-PROD	PRODTN GROWTH RATE 1990	MAX % SYSTEM 1 YEAR WORLD	% FROM ONE NATION NON-US	PRESENT COSTS IN $/KW	NET % IMPORT
THRESHOLD LEVELS—		50.	10.%	10.	35.	50.	50.
ALUMINUM	145.	0.	7.	0.	13.	0.	9.
ALUMINUM FLUORIDE	3.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
AMMONIA	19.	0.	3.	0.	5.	0.	1.
ARSENIC	324.	100.*	3.	0.	23.	1.	39.
ARSENIC TRIOXIDE	453.	100.*	3.	0.	23.	0.	39.
ARSINE, 99.999%	37.	0.	23.*	3.	10.	0.	0.
CARBON DIOXIDE	74865.	100.*	3.	0.	5.	0.	0.
CAUSTIC SODA	2833.	0.	3.	0.	5.	0.	1.
CHLORINE	155.	0.	3.	0.	5.	0.	1.
COAL, BITUMINOUS	0.	0.	2.	0.	20.	0.	10.
COKE	66.	0.	3.	0.	10.	0.	1.
CRYOLITE	5.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
DIMETHYL ALUM. CHLORIDE	233.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
ELECTRICITY (KWH)	166.E+6	0.	7.	0.	0.	0.	0.
ELECTRODES	0.	0.	3.	0.	10.	0.	1.
FERROMANGANESE	1.	0.	3.	0.	22.	0.	98.*
FERROSILICON	0.	0.	3.	0.	10.	0.	35.
FERROUS SCRAP, PURCHASED	24.	0.	3.	0.	10.	0.	0.
FLUORSPAR	1.	0.	5.	0.	19.	0.	79.*
GALLIUM	309.	100.*	23.*	54.*	40.*	10.	55.*
GALLIUM ARSENIDE (INGOT)	492.	0.	38.*	61.*	10.	59.*	0.
GALLIUM ARSENIDE (WAFER)	222.	0.	38.*	61.*	10.	62.*	0.
GALLIUM TRICHLORIDE	100.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
GOLD	0.	47.	2.	0.	58.*	0.	76.*
HYDROCHLORIC ACID	31.	92.*	3.	0.	5.	0.	2.
INDIUM	18.	100.*	4.	3.	20.	0.	24.
INDIUM TRICHLORIDE	32.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
LIME	755.	0.	3.	0.	20.	0.	2.
LIQUID FUELS	730.	0.	3.	0.	18.	0.	39.
METHYL CHLORIDE	389.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
NITRIC ACID	25.	0.	3.	0.	32.	0.	1.
OXYGEN, GASEOUS	8.	0.	4.	0.	21.	0.	0.
OXYGEN, LIQUID	8.	0.	4.	0.	21.	0.	0.
PETROLEUM COKE	62.	100.*	3.	0.	15.	0.	0.
PITCH-IN-TAR	43.	0.	3.	0.	5.	0.	5.
SILICON DIOXIDE, 99.99%	0.	0.	3.	0.	10.	0.	0.
SILVER	50.	70.*	4.	0.	14.	0.	50.*
SODIUM	58.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
SODIUM CARBONATE	278.	0.	0.	0.	10.	0.	0.
SODIUM CYANIDE	20.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
STEAM	31996.	1.	3.	0.	10.	0.	0.
STEEL & IRON	99.	1.	3.	0.	16.	0.	7.
SULFUR	338.	31.	3.	0.	14.	0.	0.
SULFURIC ACID	1002.	20.	3.	0.	14.	0.	0.
TANTALUM PENTOXIDE	0.	100.*	4.	0.	10.	0.	0.
TRIMETHYL AL., COMM.	93.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
TRIMETHYL AL., 99.9999%	2.	0.	11.*	23.*	5.	0.	0.
TRIMETHYL GA., 99.9995%	41.	0.	417.*	96.*	5.	13.	0.
TRIMETHYL INDIUM, 99.998%	15.	0.	318.*	95.*	5.	22.	0.
ZINC	68.	25.	2.	0.	20.	0.	59.*
ZINC ARSENIDE	91.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
(MISC. BULK MATERIALS)	204.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?

TABLE 14 .

RAW MATERIAL REQUIREMENTS FOR:
ADVANCED CONCENTRATOR SOLAR CELL-500X
BASELINE CASE

SOLAR SCENARIO:
INTRODUCTION YEAR- 1991
CUMULATIVE CAPACITY 2000- 25. GW

FACTORS	RAW MATERIAL USAGE (1000MT)	%PRD GROW RATE FROM 1990	MAX% SYST ONE YEAR WRLD	%US RESERV CONSUM BY 2000	%US RESOUR CONSUM BY 2000	%FRM ONE NAT NON-US	%WORLD RESERV CONSUM BY 2000	%WORLD RESOUR CONSUM BY 2000	PRSNT COSTS IN $/KW	NET% IMPT
THRESHOLD LEVELS--		7.	10.	400.	300.	60.	300.	200.	50.	50.
BAUXITE	1.	5.	0.	2691.*	364.*	31.	15.	10.	0.	91.*
BAUXITE, BY PROD	15449.	6.	1.	2729.*	369.*	31.	15.	10.	0.	91.*
COAL, BITUMINOUS	69.	2.	0.	5.	1.	7.	9.	1.	0.	0.
COPPER BYPROD.	1.	4.	0.	73.	17.	13.	67.	16.	0.	12.
FLUORSPAR ORE	0.	5.	0.	1004.*	168.	19.	255.	140.	0.	79.*
GOLD ORE	43.	2.	0.	187.	100.	58.	94.	60.	0.	76.*
IRON ORE	0.	5.	0.	29.	5.	27.	16.	5.	0.	29.
LIMESTONE	3.	3.	0.	0.	0.	20.	0.	0.	0.	2.
MANGANESE ORE	0.	3.	0.	100.	8.	22.	15.	8.	0.	98.*
NATURAL GAS	1.	5.	0.	258.	60.	23.	97.	10.	0.	5.
PETROLEUM	4.	2.	0.	565.*	185.	18.	104.	34.	0.	39.
QUARTZ	0.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
SALT	5.	6.	0.	0.	0.	18.	0.	0.	0.	7.
SILICA PEBBLE	0.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
SILVER ORE	71.	4.	0.	277.	73.	14.	208.	56.	0.	50.*
SODA ASH (NAT.)	0.	5.	0.	1.	0.	2.	1.	0.	0.	0.
SULFUR ORE	0.	3.	0.	189.	61.	14.	109.	34.	0.	0.
TANTALUM ORE	0.	10.*	0.	100.	1865.*	39.	59.	13.	0.	96.*
ZINC BYPROD.	70.	3.	0.	166.	100.	20.	125.	81.	0.	59.*
ZINC ORE	2.	3.	0.	166.	100.	20.	125.	81.	0.	59.*

The Potential Material Constraints for Five Cells Analyzed Together

There are interesting effects resulting from 25 GW of PV online by the year 2000 made up of a variety of cells. In this study the 25 GW is composed of 5 GW each of the five baseline cells being studied in this report. As we would expect, the pressure on specific materials markets would be significantly reduced as can be seen in the results (Tables 15 and 16) discussed below.

It could be argued that the market would more likely be made up using several cell designs rather than a single one since they will not be strictly identical in performance characteristics, etc. Spectral response characteristics of cells are different, application needs will vary, and solar insolation characteristics are site-specific. These are some of the factors arguing for plurality of approach. In any case, it was decided to balance off the analysis of cells individually with an analysis of five cells together making up 25 GW.

CMAP was designed with this problem in mind and it can accumulate the materials requirements from several PV cells; screen this accumulation using the stored data just as if it were analyzing an individual cell. One difficulty encountered with this process is that the \$/kW computed is an average over all of the cells (25 GW each of 5 cells in this case). Normally the \$/kW would be interpreted as a measure of the importance of the material in a specific cell. In the summary analysis, that is not what is being given. Rather, it is a measure of an "average importance". Fortunately, the importance to the single cell can be obtained by referring to the base cases for the individual cells (the \$/kW is independent of the amount of GW installed).

TABLE 15 .

BULK MATERIAL SUMMARY REPORT

THIS REPORT IS A SUMMARY OF THESE 5 DESIGNS:
SILCNHOMOJ BASELINE TOTAL=5. GW
FRONTWALL BASELINE TOTAL=5. GW
AMORPHOPIN BASELINE TOTAL=5. GW
PCRYSTGAAS BASELINE TOTAL=5. GW
ADVCON500X BASELINE TOTAL=5. GW

FACTORS	BULK MATERIAL USAGE MT.	PERCENT SUPPLY AS BY-PROD	PRODTN GROWTH RATE 1990	MAX % SYSTEM 1 YEAR WORLD	% FROM ONE NATION NON-US	PRESENT COSTS IN $/KW	NET % IMPORT
THRESHOLD LEVELS--		50.	10.%	10.	35.	50.	50.
ANTIMONY	37.	80.*	5.	0.	22.	0.	54.*
ARGON	2.	100.*	4.	0.	25.	0.	0.
ARSENIC	3710.	100.*	3.	1.	23.	15.	39.
ARSENIC TRIOXIDE	5194.	100.*	3.	1.	23.	0.	39.
ARSINE, 99.999%	3362.	0.	155.*	72.*	10.	19.	0.
CADMIUM	13829.	100.*	4.	6.	17.	3.	64.*
CADMIUN SULFIDE	17286.	0.	9.	27.*	10.	17.	0.
CARBON DIOXIDE	1283342.	100.*	4.	2.	5.	2.	0.
CHROMIUM	16858.	0.	3.	0.	28.	4.	89.*
ELECTRICITY (KWH)	57067.E+6	0.	7.	0.	0.	68.*	0.
FERROMANGANESE	8880.	0.	3.	0.	22.	0.	98.*
FLUORSPAR	8545.	0.	5.	0.	19.	0.	79.*
GALLIUM	5115.	100.*	308.*	95.*	40.*	164.*	55.*
GALLIUM ARSENIDE (INGOT)	98.	0.	13.*	24.*	10.	12.	0.
GALLIUM ARSENIDE (WAFER)	44.	0.	13.*	24.*	10.	12.	0.
GERMANE, 99.9%	4015.	0.	81301.*	100.*	5.	56.*	0.
GERMANIUM	5117.	100.*	91.*	88.*	29.	63.*	16.
GOLD	13786.	47.	18.*	55.*	58.*	3546.*	76.*
HELIUM	0.	100.*	3.	0.	5.	0.	0.
HYDROCHLORIC ACID	378706.	92.*	3.	0.	5.	3.	2.
HYDROGEN SULFIDE, 99.999%	0.	0.	252.*	86.*	10.	0.	0.
INDIUM	87.	100.*	6.	13.*	20.	1.	24.
INDIUM-TIN OXIDE	104.	0.	12.*	44.*	10.	1.	0.
LIQUID FUELS	10217860.	0.	3.	0.	18.	50.*	39.
NICKEL	6282.	7.	3.	0.	33.	1.	70.*
PETROLEUM COKE	121874.	100.*	3.	0.	15.	0.	0.
PHOSPHINE 99.999%	0.	0.	21.*	0.	10.	0.	0.
PLATINUM	6.	100.*	3.	1.	47.*	3.	90.*
SILANE	2678.	0.	32.*	19.*	10.	14.	0.
SILICON MONOXIDE	24.	0.	5.	10.*	20.	0.	30.
SILICON (SEG)	8.	0.	20.*	0.	10.	0.	0.
SILVER	18.	70.*	4.	0.	14.	0.	50.*
TANTALUM	76.	100.*	5.	0.	24.	0.	96.*
TIN	973.	1.	3.	0.	28.	1.	85.*
TITANIUM	64.	0.	6.	0.	39.*	0.	8.
TRICHLOROSILANE	40135.	0.	13.*	7.	10.	3.	0.
TRIMETHYL GA., 99.9995%	4899.	0.	49601.*	100.*	5.	1568.*	0.
TRIMETHYL INDIUM, 99.998%	3.	0.	68.*	78.*	5.	4.	0.
ZINC	171031.	25.	2.	0.	20.	5.	59.*
ZINC FLUOROBORATE	1653.	0.	534.*	97.*	25.	0.	0.

TABLE 16 .

```
                         RAW MATERIAL SUMMARY REPORT

THIS REPORT IS A SUMMARY OF THESE    5 DESIGNS:
SILCNHOMOJ BASELINE TOTAL=5. GW
FRONTWALL  BASELINE TOTAL=5. GW
AMORPHOPIN BASELINE TOTAL=5. GW
PCRYSTGAAS BASELINE TOTAL=5. GW
ADVCON500X BASELINE TOTAL=5. GW


                                       %PRD MAX%  %US    %US   %FRM %WORLD %WORLD
                                  RAW  GROW SYST RESERV RESOUR ONE  RESERV RESOUR PRSNT
   FACTORS                   MATERIAL  RATE ONE  CONSUM CONSUM NAT  CONSUM CONSUM COSTS
                                USAGE  FROM YEAR   BY     BY   NON-   BY     BY    IN   NET%
                             (1000MT)  1990 WRLD  2000   2000   US   2000   2000  $/KW  IMPT
                            --------- ---- ---- ------ ------ ---- ------ ---------- ----
THRESHOLD LEVELS--                      7.  10.   400.   300.  60.   300.   200.   50.  50.
                            --------- ---- ---- ------ ------ ---- ------ ---------- ----
ANTIMONY ORE                       4.  3.    0.   887.*  822.* 22.    56.    47.    0.  54.*
BAUXITE                           91.  5.    0.  2691.*  364.* 31.    15.    10.    0.  91.*
BAUXITE, BY PROD             255744.  8.* 15.*  3320.*  449.* 31.    16.    10.    0.  91.*
CHROMITE                           0.  3.    0.   100.   620.* 28.   117.     2.    0.  89.*
FLUORSPAR ORE                     26.  5.    0.  1004.*  168.  19.   255.   140.    0.  79.*
GOLD ORE                     1603011. 18.* 58.*  588.*  314.* 58.   131.    84. 1020.* 76.*
LITHIUM ORE                      474.  7.*   2.    43.    19.  24.    49.    17.    3.   0.
MANGANESE ORE                     20.  3.    0.   100.     8.  22.    15.     8.    0.  98.*
NICKEL ORE                       628.  2.    0.  3536.     9.  33.    48.    20.    0.  70.*
PETROLEUM                      17101.  2.    0.   565.*  185.  18.   104.    34.   50.* 39.
RUTILE (CONC.)                     0.  5.    0.   165.    54.  98.*   11.     9.    0.  98.*
SILVER ORE                        25.  4.    0.   277.    73.  14.   208.    56.    0.  50.*
TANTALUM ORE                      61. 10.*   0.   100.  1870.* 39.    59.    13.    0.  96.*
TIN ORE                           97.  2.    0.  3491.*  705.* 28.    67.    18.    2.  85.*
ZINC BYPROD.                   11410.  3.    1.   168.   101.  20.   125.    81.    0.  59.*
ZINC BYPROD.#3                511676.  8.* 29.*   260.   156.  20.   141.    91.    0.  59.*
ZINC ORE                        3797.  3.    0.   167.   100.  20.   125.    81.    2.  59.*
```

Discussion of Screening Results of Mixed Scenario

Antimony is 80% a byproduct and 54% imported, but is not important to the PV cells and PV usage would be inconsequential to the antimony market. It is a "B" material.

Argon, arsenic, arsenic trioxide, cadmium, carbon dioxide, and chromium are all "B" materials following similar logic.

Arsine, on the other hand, is still an "A" material because its usage requires 72% of the world supply and the cost is \$96/kW, i.e., 9.6¢/watt. (The cost is from the base case.) The multiple cell scenario has not ameliorated this problem and we recommend that the material be produced onsite as required to: (1) control cost, (2) maintain needed purity, (3) guarantee availability, and (4) reduce storage and shipping problems. (The same recommendation is given for the base case which used arsine which was the polycrystalline gallium arsenide MIS cell.)

Cadmium sulfide has a requirement for 27% of the market and has 8¢/watt costs. Therefore, it is an "A" material. The mitigating strategy is recommended in the discussion of the cadmium sulfide/copper sulfide base case screening results.

Electricity. The excessive use of electricity was traced to the amount of gold used in the cadmium sulfide cell base case. Gold is simply too expensive to use in those quantities. The problem disappears with the reduction of gold usage as is done in the sensivitity case.

Ferromanganese and fluorspar are "B" materials because they are mostly important but used in very small quantities in this scenario.

Gallium, gallium arsenide (ingots and wafers), and trimethyl gallium. These are "A" materials because their usage in the cell is large (8¢/watt for bulk gallium from the base case polycrystalline GaAs MIS cell) and the pressures on the material supply are still considerable for the mixed scenario case. The discussion of these materials and the mitigating strategies under screening results for the polycrystalline gallium arsenide MIS and the advanced concentrator are valid, although the quantities of each cell have been reduced to 5 GW online. The reduction in quantity of cells has not mitigated the problems.

Germane and germanium are still "A" materials and the previous discussion for these materials under the polycrystalline gallium arsenide MIS cell screening results still apply at 5 GW of cells online.

Gold is still an "A" material and the discussions of gold in the cadmium sulfide/copper sulfide PV cell screening results is still applicable.

Helium and hydrochloric acid are byproducts. They are "B" materials because of insignificant cost impact on the PV cells and the PV usage is a negligible part of the market.

Hydrogen sulfide is made in large quantities, but in five nines purity its use is small and is classified as a "B" material. Manufacture onsite should be considered to control cost and purity and ensure availability with a minimum of storage and transportation problems.

Indium, indium tin oxide and trimethyl indium are "A" materials because their supply capacity will still be receiving considerable pressure. The previous discussion of the amorphous silicon cell screening results with its recommended mitigating strategies still applies.

Liquid fuels are a problem only because of the excessive use of gold. They are not a problem if the gold is reduced as in the sensitivity analysis case of the cadmium sulfide/copper sulfide PV cell. It is a "B" material.

Nickel, petroleum coke, platinum, silver, tantalum, tin, titanium and zinc are all "B" materials, although they exceed one or more threshold levels for a byproduct or import level because they are economically not important to the PV cell and their use is in the PV cell is modest compared to the market.

Silane, silicon monoxide, silicon (SEG), trichlorosilane, and zinc fluoroborate are all "B" materials in this usage level. However, most of these materials should still be considered for local manufacture where they are to be used to:

- Control quality
- Control cost
- Assume Availability
- Reduce storage and transport costs

Summarizing, then, the "A" materials for the mixed scenario are as shown in Table 17.

SUMMARY

Thus, the mixed scenario at 5 GWe each has almost all the problem materials that would be involved with larger quantities of each cell (at 25 GW online). 25 GW of the mixed scenario has 13 problem materials -- more than 25 GW of any single cell.

TABLE 17. Mixed Scenario "A" Bulk Materials

Factors	Bulk[(a)] Material Usage MT	Percent Supply as By-Products	Production Growth Rate 1990	Maximum % System 1 Year World	% From One Nation Non-US	Present Costs in $/kW	Net $ Import
Threshold Levels		50.	10.%	10.	10.	50.	50.
Arsine	3,362	0	155*	72*	10	19	0
Cadmium Sulfide	17,286	0	9	27*	10	17	0
Gallium	5,115	100*	308*	95*	40*	164*	55*
Gallium Arsenide (Ingot)	98	0	13*	24*	0	12	0
Gallium Arsenide (Wafer)	44	0	13*	24*	10	12	0
Trimethyl Gallium	4,899	0	49,601*	100*	5	1,568*	0
Germane	4,015	0	81,301*	100*	5	56*	0
Germanium	5,117	100*	91*	88*	29	65*	16
Gold	13,786	47	18*	55*	58*	3,546*	76*
Indium	87	100*	6	13*	20	1	24
Indium Tin Oxide	104	0	12*	44*	10	1	0
Trimethyl Indium	3	0	68*	78*	5	4	0

SUMMARY OF THE SCREENING RESULTS

The screening of the five baseline photovoltaic cells identified 16 "A" materials and 1 "A" raw material (Tables 18 and 19). The polycrystalline GaAs and advanced concentrator cells had the greatest number of "A" materials with five, and the polycrystalline silicon had the least with only one. However, the most serious constraint was gold as used in the cadmium sulfide/copper sulfide cell (5 microns), at $17/watt. Gold was eliminated from the "A" materials list in the sensitivity case when its thickness was reduced to .05 microns. (Tables 20 and 21 list the "B" materials for baseline screening.)

Gallium and gallium-containing materials present both cost and availability constraints in the polycrystalline GaAs MIS and advanced concentrator cells. It is strongly recommended that research be directed towards the technical feasibility of reducing the thickness of these layers and recycling the gallium lost in production of these cells. Also, the possibility of establishing long-term contracts with gallium manufacturers should be investigated to help reduce and control materials costs and to ensure availability.

The screening of the four sensitivity cell characterizations identified several "A" bulk materials, but no "A" raw materials (Tables 22 and 23). The advanced concentrator and polycrystalline gallium arsenide had the greatest number of "A" bulk materials with five. Gallium and gallium-containing materials continued to be identified as the critical materials in the large-scale deployment of this cell. (Tables 24 and 25 list the "B" materials for the sensitivity screening.)

The screening of the mixed scenario identified 12 "A" bulk materials and 1 "A" raw material (Tables 26 and 27) with gallium and gallium-containing materials being of primary concern. (Tables 28 and 29 list the "B" materials for the mixed scenarios.)

TABLE 18. "A" Materials (Baseline Cases)

Factors	Bulk(a) Material Usage MT	Percent Supply as By-Products	Production Growth Rate 1990	Maximum % System 1 Year World	% From One Nation Non-US	Present Costs in $/kW	Net % Import
Threshold Levels		50.	10.%	10.	35.	50.	50.
Polycrystalline Silicon							
Trichlorosilane	200,677	0	21.*	28.*	10.	16.	0
Cadmium Sulfide/Copper Sulfide							
Cadmium Sulfide	86,429	0	32.*	65.*	10.	83.*	0
Gold	68,929	47.	79.*	86.*	58.*	17728.*	76.*
Polycrystalline GaAs MIS							
Arsine	16,771	0	688.*	93.*	10.	96.*	0
Gallium	25,265	100.*	1505.*	99.*	40.*	808.*	55.*
Germane	20,075	0	406482.*	100.*	5.	281.*	0
Germanium	25,584	100.*	477.*	97.*	29.	323.*	16.
Trimethyl Gallium	24,454	0	247570.*	100.*	5.	7825.*	0
Amorphous Silicon							
Indium Tin Oxide	520	0	50.*	80.*	10.	7.	0
Silane	13,391	0	79.*	54.*	10.	70.*	0
Indium	416	100.*	14.*	42.*	20.	6.	24.
Advanced Concentrator							
Gallium Arsenide (Ingots)	492	0	38.*	61.*	10.	59.*	0
Gallium Arsenide (Wafers)	222	0	38.*	61.*	10.	62.*	0
Gallium	309	100.*	23.*	54.*	40.*	10.	55.*
Trimethyl Indium	15	0	318.*	95.*	5.	22.	0
Trimethyl Gallium	41	0	417.*	96.*	5.	13.	0

---

a. Material to produce 25 GWe peak capacity

TABLE 19. "A" Raw Materials (Baseline Cases)

Factors	Raw Material Usage (1000 MT)	% Production Growth Rate From 1990	Maximum % System One Year World	% U.S. Reserves Consumed by 2000	% U.S. Resources Consumed by 2000	% From One Nation Non-US	serves Consumed by 2000	% World Resources Consumed by 2000	Present Costs in $/Kw	Net % Import
Threshold Levels		7.	10.	400.	300.	60.	300.	200.	50.	50.
Cadmium Sulfide/ Copper Sulfide										
Gold Ore	8,015,014	84.*	87.*	2191.*	1171.*	58.	277.	177.	5098.*	76.*

TABLE 20. "B" Bulk Materials (Baseline Cases)

Material	Polycrystalline Silicon	Cadmium Sulfide/ Copper Sulfide	Polycrystalline GaAs MIS	Amorphous Silicon	Advanced Concentrator
Antimony			B		B
Argon				B	
Arsenic			B		B
Arsenic Trioxide			B		B
Arsine					B
Cadmium		B			
Carbon Dioxide	B			B	
Chlorine		B			
Chromium			B		
Ferromanganese	B	B	B	B	B
Fluorspar	B	B	B	B	B
Glass, Soda Lime				B	
Graphite MFG	B				
Helium				B	
Hydrochloric Acid	B	B	B	B	B
Hydrogen Sulfide			B		B
Indium					B
Lime		B			
Liquid Fuels		B			
Nickel	B		B		
Petroleum Coke	B	B	B	B	B
Phosphine				B	
Platinum				B	
Silicon (SEG)		B			
Silicon Monoxide		B			
Silver			B		
Steel and Iron		B			
Tantalum	B				B
Tin	B		B	B	
Titanium				B	
Trimethyl Aluminum					B
Zinc		B			
Zinc Fluoroborate		B			

TABLE 21. "B" Raw Materials (Baseline Cases)

Material	Polycrystalline Silicon	Cadmium Sulfide/ Copper Sulfide	Polycrystalline GaAs MIS	Amorphous Silicon	Advanced Concentrator
Antimony Ore			B		
Bauxite	B	B	B	B	B
Bauxite Byproducts			B		B
Chromite		B			
Coal, Bituminous		B			
Fluorspar Ore	B	B	B	B	B
Gold Ore					B
Limestone		B			
Lithium Ore				B	
Manganese Ore	B	B	B	B	B
Nickel Ore	B		B		
Petroleum	B	B	B	B	B
Rutile (Conc.)				B	
Silver Ore			B		B
Tantalum Ore	B				B
Tin Ore	B		B	B	
Zinc Byproducts		B		B	B
Zinc Byproducts #3			B		
Zinc Ore		B	B		B

TABLE 22. "A" Bulk Materials (Sensitivity Cases)

Factors	Bulk Material Usage MT	Percent Supply as By-Prod	Production Growth Rate Rate 1990	Max % System 1 Year World	% From One Nation Non-US	Present Costs in $/Kw	Net % Import
Threshold Levels		50.	10.%	10.	35.	50.	50.
Polycrystalline Silicon							
Silane	48439	0	233.*	81.*	10.	252.*	0
Cadmium Sulfide/Copper Sulfide							
None							
Polycrystalline GaAs MIS							
Case 1: 5 Microns, CVD							
Arsenic	15623	100.*	4.	5.*	23.	62.*	39.
Arsine	14375	0.	593.*	92.*	10.	82.*	0.
Gallium	12786	100.*	764.*	98.*	40.*	409.*	55.*
Germane	4023	0.	81,453.*	100.*	5.	113.*	0.
Germanium	5126	100.*	91.*	88.*	29.	65.*	16.
Case 2: 2 Microns, MO-CVD							
Arsine	9583	0.	403.*	88.*	10.	55.*	0.
Gallium	14,397.	100.*	859.*	98.*	40.*	461.*	55.*
Germane	20,075.	0.	406,482.*	100.*	5.	562.*	0.
Germanium	25,584.	100.*	447.*	97.*	29.	323.*	16.
Trimethyl Gallium	13,934	0.	141,076.*	100.*	5.	4459.*	0.
Case 3: 2 Microns, CVD							
Arsine	8,214	0.	348.*	86.*	10.	47.	0.
Gallium	7,280	100.*	437.*	97.*	40.*	233.*	55.*
Germane	4,023	0.	81,453.*	100.*	5.	56.*	0.
Germanium	5,126	100.*	91.*	88.*	29.	65.*	16.

TABLE 22. "A" Bulk Materials (Sensitivity Cases)
(Continued)

Factors	Bulk Material Usage MT	Percent Supply as By-Prod	Production Growth Rate Rate 1990	Max % System 1 Year World	% From One Nation Non-US	Present Costs in $/Kw	Net % Import
Threshold Levels		50.	10.%	10.	35.	50.	50.
Advanced Concentrator							
Gallium Arsenide (Ingot)	985	0.	69.*	76.*	10.	118.*	0
Gallium Arsenide (Wafer)	444	0.	69.*	76.*	10.	124.*	0
Gallium	577	100.*	39.*	69.*	40.*	18.	55.*
Trimethyl Gallium	41	0	417.*	96.*	5.	13.	0
Trimethyl Indium	15	0	318.*	95.*	5.	22.	0

TABLE 23. "A" Raw Materials (Sensitivity Cases)

Factors	Raw Material Usage (1000 MT)	% Production Growth Rate from 1990	Maximum System % One Year World	% U.S. Reserves Consumed by 2000	% U.S. Resources Consumed by 2000	% World Reserves Consumed by 2000	% World Resources Consumed by 2000	Present Costs in $/Kw	Net % Import
Threshold Levels		7.	10.	400.	300.	60.	200.	50.	50.
Polycrystalline Silicon									
None									
Cadmium Sulfide/Copper Sulfide									
None									
Polycrystalline GaAs MIS									
None									
Advanced Concentrator									
None									

TABLE 24. "B" Bulk Materials (Sensitivity Cases)

Materials	Polycrystalline Silicon	Cadmium Sulfide/ Copper Sulfide	Polycrystalline GaAs MIS	Advanced Concentrator
Antimony			B	
Arsine			B	B
Arsenic			B	B
Arsenic Trioxide			B	B
Cadmium		B		
Cadmium Sulfide		B		
Carbon Dioxide	B		B	B
Chromium			B	
Ferromanganese	B	B	B	B
Fluorspar	B	B	B	B
Graphite (MFG)	B			
Hydrochloric Acid	B	B	B	B
Hydrogen Sulfide			B	
Indium				B
Nickel	B		B	
Petroleum Coke	B	B	B	B
Phosphate	B			
Silicon (SEG)		B		
Silicon Monoxide		B		
Silver			B	
Tantalum	B			B
Tin	B			
Trichlorosilane	B			
Trimethyl Aluminum				B
Zinc		B	B	B
Zinc Fluoroborate		B		
Gold		B		B

TABLE 25. "B" Raw Materials (Sensitivity Cases)

Materials	Polycrystalline Silicon	Cadmium Sulfide/ Copper Sulfide	Polycrystalline GaAs MIS	Advanced Concentrator
Antimony Ore			B	
Bauxite	B	B	B	B
Bauxite Byproducts			B	B
Chromite		B		
Fluorspar Ore	B	B	B	B
Gold Ore		B		B
Manganese Ore	B	B	B	B
Molybdenum Ore			B	
Nickel Ore	B		B	
Petroleum	B	B	B	B
Silver Ore			B	B
Tantalum Ore	B			B
Tin Ore	B			
Zinc Byproducts		B	B	B
Zinc Ore		B	B	B

TABLE 26. Mixed Scenario "A" Bulk Materials

Factors	Bulk(a) Material Usage MT	Percent Supply as By-Products	Production Growth Rate 1990	Maximum % System 1 Year World	% From One Nation Non-US	Present(1) Costs in $/kW	Net % Import
Threshold Levels		50.	10.%	10.	35.	50.	50.
Arsine	3,362	0	155.*	72.*	10.	19.	0
Cadmium Sulfide	17,286	0	9.	27.*	10.	17.	0
Gallium	5,115	100.*	308.*	95.*	40.*	164.*	55.*
Gallium Arsenide (Ingot)	98	0	13.*	24.*	0	12.	0
Gallium Arsenide (Wafer)	44	0	13.*	24.*	10.	12.	0
Trimethyl Gallium	4,899	0	49,601.*	100.*	5.	1,568.*	0
Germane	4,015	0	81,301.*	100.*	5.	56.*	0
Germanium	5.117	100.*	91.*	88.*	29.	65.*	16.
Gold	13,786	47.	18.*	55.*	58.	3,546.*	76.*
Indium	87	100.*	6.*	13.*	20.	1.	24.
Indium Tin Oxide	104	0	12.*	44.*	10.	1.	0
Trimethyl Indium	3	0	68.*	78.*	5.	4.	0

---

(1) This cadmium is an average of all the cells considered and must therefore be interpreted with care. For instance, if only 20% of the cells use a given material, then the $/kW would actually be 5 times as high for those cells (i.e., the 20%).

TABLE 27. Mixed Scenario "A" Raw Materials

Factors	Raw Material Usage (1000 MT)	% Production Growth Rate From 1990	Maximum Percent System One Year World	% U.S. Reserves Consumed by 2000	% U.S. Resources Consumed by 2000	% From One Nation Non-US	% World Reserves sumed by 2000	% World Resources Consumed by 2000	Present Costs in $/Kw	Net % Import
Threshold Levels		7.	10.	400.	300.	60.	300.	200.	50.	50.
Gold Ore	1603011.	18.*	58.*	588.*	314.*	58.	131.	84.	1020.*	76.*

TABLE 28. Mixed Scenario "B" Bulk Materials

Factors	Bulk Material Usage MT	Percent Supply as By-Products	Production Growth Rate 1990	Maximum % System 1 Year World	% From One Nation Non-US	Present Costs in $/kW	Net % Import
Threshold Levels		50.	10.%	10.	35.	50.	50.
Antimony		80.					54.*
Argon		100.*					
Arsenic		100.*					
Cadmium		100.*					64.*
Carbon Dioxide		100.*					
Chromium							89.*
Electricity						68.*	
Ferromanganese							98.*
Fluorspar							79.*
Helium		100.*					
Hydrochloric Acid		92.*					
Hydrogen Sulfide			252.*				
Liquid Fuels						50.*	
Nickel							70.*
Petroleum Coke							
Phosphine		100.*	21.*				
Platinum		100.*			47.*		90.*
Silane			32.*	19.*			
Silicon Monoxide				10.*			
Silicon (SEG)			20.*				
Silver		70.*					50.*
Tantalum		100.*					96.*
Tin							85.*
Titanium				39.*			
Zinc							
Zinc Fluoroborate			534.*	97.*			59.*

TABLE 29. Mixed Scenario "B" Raw Materials

Factors	Raw Material Usage (1000 MT)	% Production Growth Rate From 1990	Maximum Percent System 1 Year World	% U.S. Reserves Consumed by 2000	Percent U.S. Resources Consumed by 2000	% From One Nation Non-US	% World Reserves Consumed by 2000	% World Resources Consumed by 2000	Present Costs in $/Kw	Net % Import
Threshold Levels		7.	10.	400.	300.	60.	300.	200.	50.	50.
Antimony Ore				887.*	822.*					54.*
Bauxite				2691.*	364.*					91.*
Bauxite Byproducts		8.*	15.*	3320.*	449.*					91.*
Chromite				620.*						89.*
Fluorspar Ore				1004.*						79.*
Lithium Ore		7.*								
Manganese Ore										98.*
Nickel Ore				3536.*						70.*
Petroleum				565.*					50.*	
Rutile (Conc.)						98.*				98.*
Silver Ore										50.*
Tantalum Ore		10.*			1870.*					96.*
Tin Ore				3491.*	705.*					85.*
Zinc Byproducts										59.*
Zinc Byproducts #3		8.*	29.*							59.*
Zinc Ore										59.*

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4.0 INDIUM AND GALLIUM AVAILABILITY

Development of large-scale photovoltaic cell systems are being considered as a means to help alleviate the growing domestic energy problem. Photovoltaic systems capable of producing 50 GWe of power by the year 2000 would significantly increase the demand for several rare metals now in limited production. Earlier work on this problem has resulted in the development of the Critical Materials Assessment Program (CMAP) to identify these potential supply constraints(1). Through the use of CMAP, potential shortages of indium and gallium have been identified as adversely influencing the orderly and timely construction of photovoltaic systems. As a follow-up to that work, this study will evaluate the future availability of the two metals in more depth. Specific constraining factors will be identified and mitigating action recommended.

In an attempt to systematically evaluate indium and gallium, the following areas of interest have been investigated:

- Geologic occurrence and distribution;
- Evaluation of known and potential resources;
- Assessment of processing efficiencies;
- Evaluation of industry structure and production capability;
- Assessment of current markets and market conditions; and
- Identification of domestic production constraints.

Because indium and gallium do not occur in primary minerals to any great significance, it is necessary to study the more common ore minerals in which they occur as trace elements. To better assess availability, known resources of indium and gallium were outlined. Generally this was an evaluation of zinc and aluminum ores. In addition, potential new sources of the two metals are investigated.

TECHNICAL APPROACH

A systematic evaluation of any metal resource should begin by analyzing the following:

- Geologic occurrence and ore forming processes.
- Identification of exploration methods by which to expand the resource base.

As a base upon which to predicate this investigation, the geochemical properties of indium and gallium have been reviewed. Characteristics of the metals that can be used in future exploration programs are taken from this geochemical data.

One of the major problems often encountered in the evaluation of any rare element is a paucity of data in the literature. Indium and gallium are no exception. A general lack of economic interest in the past has resulted in little practical research having been done on specific geologic concentrating processes. Russian literature is most fruitful in this area. However, Russian research on rare metals tends to be highly theoretical with little practical application. In an effort to bridge this gap, domestic and Canadian base metal producers were contacted. Because indium and gallium are known to occur with more common base metals, the producers of these metals were able to provide practical information on current and potential availability of the less common byproducts. Also, U.S. Geologic Survey and Bureau of Mines geologists and commodity specialists were interviewed to obtain information on modes of occurrence as well as known and potential resource areas of indium and gallium.

Another area of interest in the evaluation is that of recovery efficiency. To the extent that the two metals are byproducts of more common base metals, this involves an evaluation of the base metal industry. Currently, indium and gallium are recovered from zinc and aluminum processes, respectively. Current extractive processes of indium and gallium are well documented in numerous accounts in the literature and have been referenced. Because we were informed by industry officials that no technology changes have been implemented in the recent past, detailed descriptions of these processes are not included herein.

Current and near-term economics of indium and gallium dictate that these metals will remain byproduct in nature. Thus, our concern is with recovery efficiencies from given base metal processes. In addition to efficiency of attempted recovery, the overall efficiency of material balance from mine to waste dump is of concern and will be addressed.

Nonconventional sources of indium and gallium and their recovery technologies are also relevant to the study. Unfortunately, little research has been done in this area. What data is available has been synthesized with information from industry contacts in an effort to address the problem.

Evaluation of future availability of critical materials should also consider the following market factors:

- Current production and potential production capacity;
- Current markets and market conditions; and
- Future expectations of industry officials.

Comparing current levels of market production with historical productions and demand can offer insight into the current state of the industry. In addition, evaluating potential production capacities is a major thrust of the study. Unfortunately, the production figures of both indium and gallium are not made public. However, reasonable estimates can be made considering import quantities and apparent domestic demand. Information on production potentials were outlined mainly from interviews with industry officials. In addition, conceptual models were used in estimating future supply.

Obtaining information on the current demand for indium and gallium as well as current and historical market conditions will also facilitate the study. Other uses of indium and gallium will directly compete with photovoltaic uses. This assessment of nonsolar uses will be valuable to decision making. Moreover, historical market conditions will give an indication of how markets respond to external stimuli.

Another aspect of the market place, all important to future supplies of indium and gallium, is expectations of the producers. Assessment of these expectations can be used to determine what incentives will be needed to meet photovoltaic demands. Transaction costs into and out of rare metal production are quite high. Further, producers recognize it as a volatile, risky industry. Thus, if expectations are low, laissez-faire market conditions may not provide a great enough incentive to increase production. For the most part, a feeling for industry expectations was obtained through written correspondence and telephone conversations as well as personal interviews with industry officials.

INDIUM

BACKGROUND

Because of its highly dispersed occurrence in low concentrations as well as a lack of known practical uses, indium remained a novelty for nearly 70 years after it was discovered in 1863 by spectrographic analysis. Several alloy and plating applications had been developed in the 1930's and put to widespread use during the second world war. Since that time developing technologies have expanded the use of indium into solid state electronics.

Geochemical properties of indium are such that it tends to occur in nature with base metals of Groups IIA and IIIB of the periodic table. Historically, indium has almost exclusively been recovered as a byproduct of zinc refining from sphalerite ores. However, indium is also known to occur in a variety of other base metal ores: specifically, lead, tin, and copper. Most domestic production of indium has been from high temperature western sulfide deposits. However, zinc mining has taken a recent trend away from these mines to lower temperature strataband deposits of the Mississippi Valley type. A result has been ores barren of indium. This trend, however, has been offset somewhat by increased domestic smelting of indium-rich South American concentrates and the overall production of indium has remained steady.

While indium is known to occur in other base metal ores, demand has not warranted any effort to recover the metal. In fact, most base metal producers admit that once the initial development work has been done on a deposit, ore concentrates are not assayed for indium at all.

As a result, published data on indium resources are rough approximations at best. U.S. Bureau of Mines commodity specialists report domestic indium reserves from sphalerite to be at 310 metric tons. However, using concentrations reported by the U.S.G.S., indium reserves may be as high as 800 metric tons and total domestic resources around 1,300 metric tons of indium. Indium from base metal ores other than zinc have not been considered in any of the estimates.

Economics of indium are such that it has been completely byproduct in nature. That is, all historical demand for the metal has been more than satisfied through byproduct recovery of base metal smelting. Further, because of low-grade natural occurrence and high costs of primary recovery, indium will undoubtedly retain this byproduct status.

Indium can become concentrated at different stages in the zinc smelting process, depending on which method is being used. Generally the indium will concentrate in flue dross and smelter slags. Also, indium is concentrated and recovered through the process of removing other impurities such as cadmium or iron. It is interesting that currently base metal producers at no time ever intentionally make an effort to concentrate indium in smelter residues. It is a naturally occurring phenomenon of the smelting process.

A lack of firm demand in the recent past has resulted in an indifference toward byproduct indium by zinc smelters. During years of high demand in the 1940's and '50's, as many as 10 firms were producing indium domestically in addition to several large foreign producers. Currently only three U.S. firms are producing the metal. Furthermore, one of these is producing on an intermittent basis. While new applications of the metal have resulted in a steady increase in price in the past few years, zinc residues have adequately met the demand. Nonzinc ores as a source of indium have not yet been considered.

Data on indium production is sketchy. Production peaked during World War II at around 3 short tons. After a decline in the late 1940's, production peaked again in the middle '50's to nearly 10 short tons. This was followed by a ten year period with an annual production average of approximately 8 tons of metal. Current domestic indium production is estimated to be between 10 to 15 short tons of contained metal.

Indium price underwent a significant decrease during the early 1940's as production rose. After the war, prices stabilized and displayed little change until the 1970's. Increasing demand for indium has resulted in substantial price increases since 1973, changing from $1.77 per troy ounce to $13.50 per troy ounce in June of 1979.

Industry officials predict both production and price will continue to rise in the foreseeable future. Moreover, they feel the current domestic industry structure could at least double indium production from conventional zinc sources by the year 2000. Any additional demands on the market would have to be satisfied by increased zinc production or from nonzinc sources.

GEOCHEMISTRY

Geochemically indium is very similar to several other S-P metals(1,2,3,4). Indium has natural valence states of +1 and +3 and can readily proxy for zinc in four-fold coordination with sulfur. Tin and copper positions are also replaced by indium in sulfide minerals but to a lesser degree than zinc. Indium does not readily camouflage for iron in sulfide minerals because of iron's six-fold coordination with sulfur. However, the regional mobility of indium is influenced by iron and thus the presence of iron can be used as an exploration tool.

A brief description of indium's geochemical properties are discussed below.

Atomic Characteristics

Indium occurs in the periodic table in Group IIIB of the S-P metals having two valence electrons in the S orbital and one in the P orbital. Included in that group and related geochemically is aluminum, gallium, and thallium. In addition, indium is among a group of metals that contain 18 electrons in the last complete energy shell. Electron configuration is significant in that it determines characteristics of occurrence. Atomic structure of indium and some related metals are given in Table 30.

TABLE 30. Electronic Configuration of Indium and Some Related Elements (Electrons in Each Shell)

Shell	In	Ga	TL	Cu	Zn	Cd	Sn	Pb	Fe
K	2	2	2	2	2	2	2	2	2
L	8	8	8	8	8	8	8	8	8
M	18	18	18	18	18	18	18	18	16
N	18	3	32	1	2	2	18	32	2
O	3		18				4	18	
P			3					4	

Examining ionization potentials of valence electrons will help predict the most probable natural occurring valence state. Ionization potentials for indium's outer three electrons are given in Table 31.

TABLE 31. Ionization Potentials for Indium's Outer 3 Electrons (Electron Volts)

Element	I1	I2	I3
Indium	5.76	18.76	27.85

It can be seen that I2-I1 is greater than I3-I2. Thus, once the second electron is removed the third will also be detached. This would indicate indium's two natural valence states are +1 and +3.

Also useful as a basis on which to predict crustal occurrence are atomic and ionic size and electronegativity as well as ionic potential (charge/radius). Further, the difference between atomic and ionic size times the ionization potential (K = (ra-ri)I1) can be used to predict behavior. These values for indium and some related metals are given in Table 32.

TABLE 32. Geochemical Data for Some Related Metals

	In^{+3}	Zn^{+2}	Fe^{+2}	Sn^{+4}	Pb^{+4}	Cd^{+2}	Ga^{+3}	Cu^{+2}	Fe^{+3}
Electronegativity	1.60	1.50	1.70	1.65	1.60	1.50	1.60	1.90	1.80
K = (ra-ri)I1	4.00	4.80	3.20	5.10	5.10	3.90	3.70	3.30	4.00
Atomic Radii	1.50	1.25	1.16	1.41	1.54	1.41	1.24	1.17	1.16
Ionic Radii	0.81	0.74	0.76	0.71	0.84	0.97	0.62	0.74	0.65
Ionic Potential	3.70	2.70	2.60	5.63	4.76	2.06	4.84	2.70	4.62

These geochemical data will be useful later in the discussion on geologic occurrence.

Complexing Characteristics

A characteristic of indium that has significance in controlling its occurrence is a strong tendency to form a face centered cube in four-fold coordination with sulfur. Zinc also complexes in four-fold coordination with sulfur, the most notable mineral being sphalerite. Because of this, indium has a relatively strong affinity for zinc and often occurs in solid solution with zinc in the sphalerite lattice. While iron substitutes for zinc in sphalerite, its natural tendency to coordinate with sulfur is six-fold rather than four-fold. Thus, indium is less likely to occur in iron sulfide minerals. Copper also displays four-fold coordination with sulfur; likewise, indium tends to occupy atomic positions in copper sulfide minerals. In fact, it has been shown that indium will replace iron in chalcopyrite to form $CuInFeS_2$(4,5).

Indium will also coordinate with oxygen to form In_2O_3. However, a more common form is the hydroxide $In(OH)_3$. Generally, indium occurs in six-fold coordination in oxycomplexes, resulting in a tendency to replace tin and iron in oxide mineralization.

Other factors that influence the behavior of indium are its measure of electronegativity and ionic potential. Electronegativity is a measure of an element's tendency to form covalent bonds and has an important influence on the extent to which it will proxy for another element of similar size. Given two ions of similar size, there is a greater tendency for substitution between those that have the least difference in electronegativity. In addition, if diadochy is possible between two elements having appreciably different electronegativities, the ion with the lower electronegativity will be preferentially incorporated into the lattice because it forms a stronger, more ionic bond. From the data presented in Table 3 we can see that on the basis of electronegativity alone, indium should readily substitute for Fe^{+2}, Sn^{+2}, Pb^{+2} and Ga^{+3}. However, considering ionic sizes, Pb^{+2}, Fe^{+2} and Zn^{+2} would more readily allow substitution.

Ionic size and charge are also useful measures of pH and solubility of depositional environments. Ionic charge divided by ionic size reduces to a factor known as ionic potential (not to be confused with ionization potential) and, in effect, is a measure of electronegativity. A small cation with relatively high charge, in an aqueous solution, will tend to form bonds with oxygen that are stronger than the oxygen-hydrogen bond. This results in the detaching of H^+ ions and the precipitation of oxides and hydroxides under acidic conditions. The reverse is also true -- the larger the size and smaller the charge, the more alkaline the oxide. Metal cations from Table 3 are rank ordered by increasing ionic potential (thus increasing acidity) in Table 33.

TABLE 33. Ionic Potential of Indium and Related Elements

Element	Cd^{+2}	Fe^{+2}	Zn^{+2}	Cu^{+2}	In^{+3}	Fe^{+3}	Pb^{+4}	Ga^{+3}	Sn^{+4}
Ionic Potential	2.06	2.62	2.70	2.70	3.70	4.62	4.76	4.84	5.63

Increasing Acidity ——>

From the above data it can be seen that the optimum pH for mineralizing solutions concentrating indium would occur when Fe^{+2} compounds are precipitated in the presence of Cu^{+2} and Fe^{+3}. This relationship does occur in nature as evidenced in the pyrrhotite-sphalerite-chalcopyrite mineral assembleages associated with cassiterite-silicate-sulfide deposits described by Ivanov(5).

In aqueous solutions indium reacts with alkali metals to form complexes of the type $Me(In(OH)_6)$ where Me is an alkali metal. It is noteworthy that these complexes are very similar to those formed by tin under the same conditions. However, this might be expected in view of the fact that indium, like tin, tends to form six-fold coordination in oxycompounds.

Isomorphism

The most common occurrences of indium is isomorphic solid solution with more common base metal ores. Of principal interest is the substitution of indium into zinc sulfides. Indium can also reach significant concentrations in sulfide and oxide ores of tin, iron, copper and lead. In addition, the metal can be incorporated into the lattice of ferromagnesium silicates. In this occurrence, however, concentrations approach the Clarke value and rarely have any economic significance.

Sulfide minerals that are most notable as indium concentrators are given in Table 34.

TABLE 34. Indium Concentrating Sulfide Minerals

Mineral	Composition	Structure	Symmetry	Bond Type
Sphalerite	ZnS	Cubic	Tetrahedral	Mostly Covalent
Chalcopyrite	$CuFeS_2$	Tetragonal	Scalenohedral	Mostly Covalent
Stannite	Cu_2FeSnS_4	Tetragonal	Scalenohedral	Mostly Covalent

One characteristic common to all three minerals is the fact that the metal cation enters the lattice in four-fold tehedral coordination with sulfur. Also, there is a strong tendency for covalent bonding.

In sphalerite it is believed indium enters the mineral in the form In_2S_3. Also, sphalerite can contain up to 20% iron in structural sites analogous to those occupied by zinc. There is no evidence to suggest indium makes preferential substitution with respect to zinc or iron. However, it is significant that in terms of regional mineralization, indium is usually associated with the presence of iron.

Because the lattice constants of $CuInS_2$ are close to those of $CuFeS_2$, it is believed indium-bearing chalcopyrite contains solid solutions of $CuFeS_2$ and $CuInS_2$. In effect, indium is substituting into a lattice position normally occupied by an iron ion.

Stannite also has lattice constants similar to those of $CuInS_2$ and $CuFeS_2$, as well as four-fold coordination with sulfur, and under certain depositional conditions can be a concentrator of indium.

Indium is also known to occur in iron-bearing sulfides such as pyrrhotite (Fel-xS), pyrite (FeS_2), and arsenopyrite (FeAsS). However, in these minerals the cation is in six-fold coordination with sulfur. Because indium tends to be unstable in this structure, it only occurs in very minor traces. Substitution of indium for lead is also possible due to similarities between the covalent ionic radii of Pb^{+2} and In^{+3}. Lead sulfide minerals, however, are not significant concentrators of indium because of other geochemical dissimilarities between the two metals such as ionic potential.

Oxide compounds can also contain indium. Most notable is iron-rich cassiterite. Electrochemical calculations indicate In_2O_3 is unstable and should not occur under the conditions in which most cassiterite is formed. Solubility studies, however, indicate indium may occur in cassiterite in the form of soluble hydroxide compounds.

Concentrations of indium higher than the crustal average (about 0.1 ppm) also occur in a number of ferromagnesium silicate minerals. A concentrating factor common to all is the presence of iron. While these minerals generally are of no economic significance as a source of indium, they emphasize the indium-iron association. This may prove to be an important exploration tool when looking for economic sources of indium.

Factors that tend to increase indium substitution into the lattice of more common minerals are given below:

- Presence of iron (primary and substituted)
- High degree of covalent bonding
- Low coordination number of replaced cation
- Defect structure (free sulfur position)

GEOLOGIC OCCURRENCE OF INDIUM

Indium occurs in minor amounts and is widely distributed in the earth's crust. On a crustal average composed of equal parts felsic and mafic rocks, indium concentrations are very similar to that of silver, or about 0.1 ppm(6).

Because of low crustal abundance, primary indium minerals are rare and have little economic significance. Only at the Tsumeb deposits, in South West Africa, have the mineralizing solutions contained high enough concentrations of indium to form primary minerals. More often indium tends to proxy for cations having similar geochemical characteristics in the lattice of common rock forming minerals. Average indium occurrence by generic rock type is given in Figure 1. From the curve it can be seen that on a crustal average, indium tends to favor higher temperature environments. Also, in igneous rocks, abundance tends to increase with decreasing content of mafic minerals. Other generalizations can also be made. Average concentrations of indium are highest in rocks that have feldspars with low calcium end members.

More important observations may also be made from the data in Figure 31. Nowhere does the average indium concentration reach what can be considered an economic level

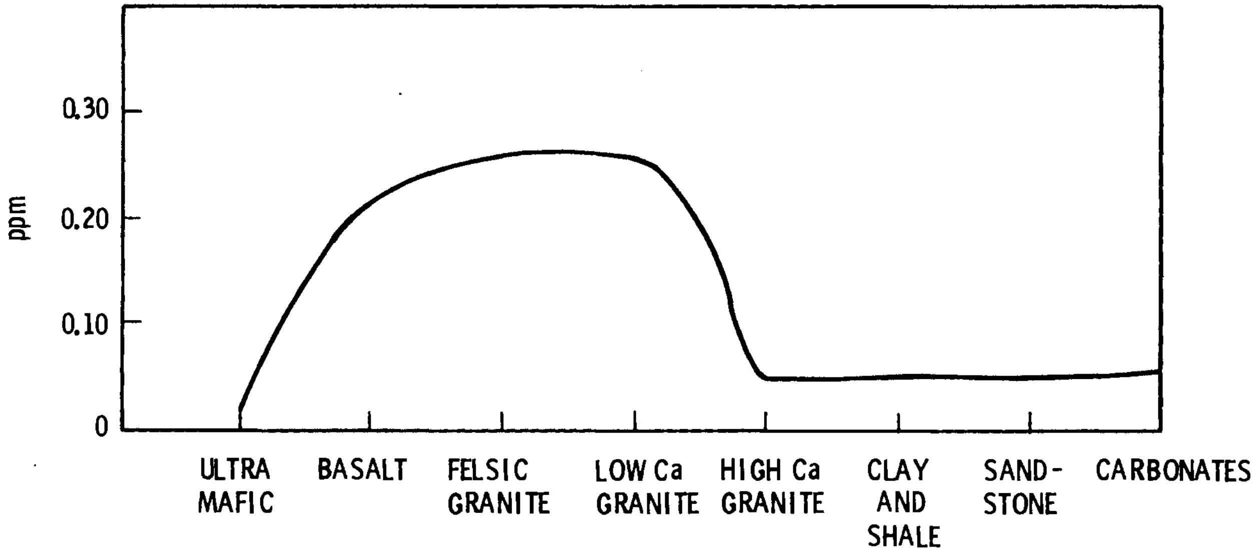

FIGURE 31. Average Indium Abundance by Rock Type

in any of the rock types. What is more, concentrations are so low remobilization by surface processes are not likely to produce economic deposits. Thus, exploration should focus on secondary mineralization processes that have primary sources of indium such as deep rooted hydrothermal solutions.

Most notable concentrations of indium are known to occur in polymetallic sulfide mineral regimes. Highest concentrations are in sphalerite, particularly marmatitic sphalerite, and chalcopyrite. Also, indium can proxy for tin and become concentrated in tin oxides. Appendix C contains a list of minerals known to contain indium.

Because these mineral suites are generally products of hydrothermal alteration, that mineralization process should be of special concern when exploring for indium. Specifically, the cassiterite-sulfide-silicate mineral facies is formed under conditions favorable to indium concentration.

Primary Differentiation

Understanding geochemical properties that control crustal mobility of indium are important in predicting geologic environments of occurrence. Elemental affinity for distinct chemical phases in the earth can provide a basis for this understanding.

A complete description of phase chemistry is beyond the scope of this discussion. Suffice it to say that before primary differentiation of the earth, a system of Fe-Mg-Si-O-S existed in which oxygen greatly exceeded sulfur and the sum of the two was insufficient to completely combine with the electropositive elements. Because iron had the greatest affinity for sulfur, was most easily reduced to metal, and was more abundant than magnesium and silica combined, three immiscible phases developed.

Metals more active than iron would react with silica leaving the remaining silica to react with iron. Those metals less active than iron would be displaced by iron from the silicate phase and remain as free metals soluable in the free iron phase. Remaining metals and metalloids that tend to form covalent homopolar bonds with sulfur were concentrated in the iron-sulfide phase. Thus, depending upon their electrochemical properties, minor elements would be expected to occur in one of the three phases: covalent iron sulfide phase (chalcophile), ionic iron-magnesium silicate phase (lithophile), or metallic free iron phase (siderophile).

Classic work by Goldschmidt(7) identified characteristics of elements in an attempt to classify them by phase of occurrence. Significant characteristics are summarized in Table 35.

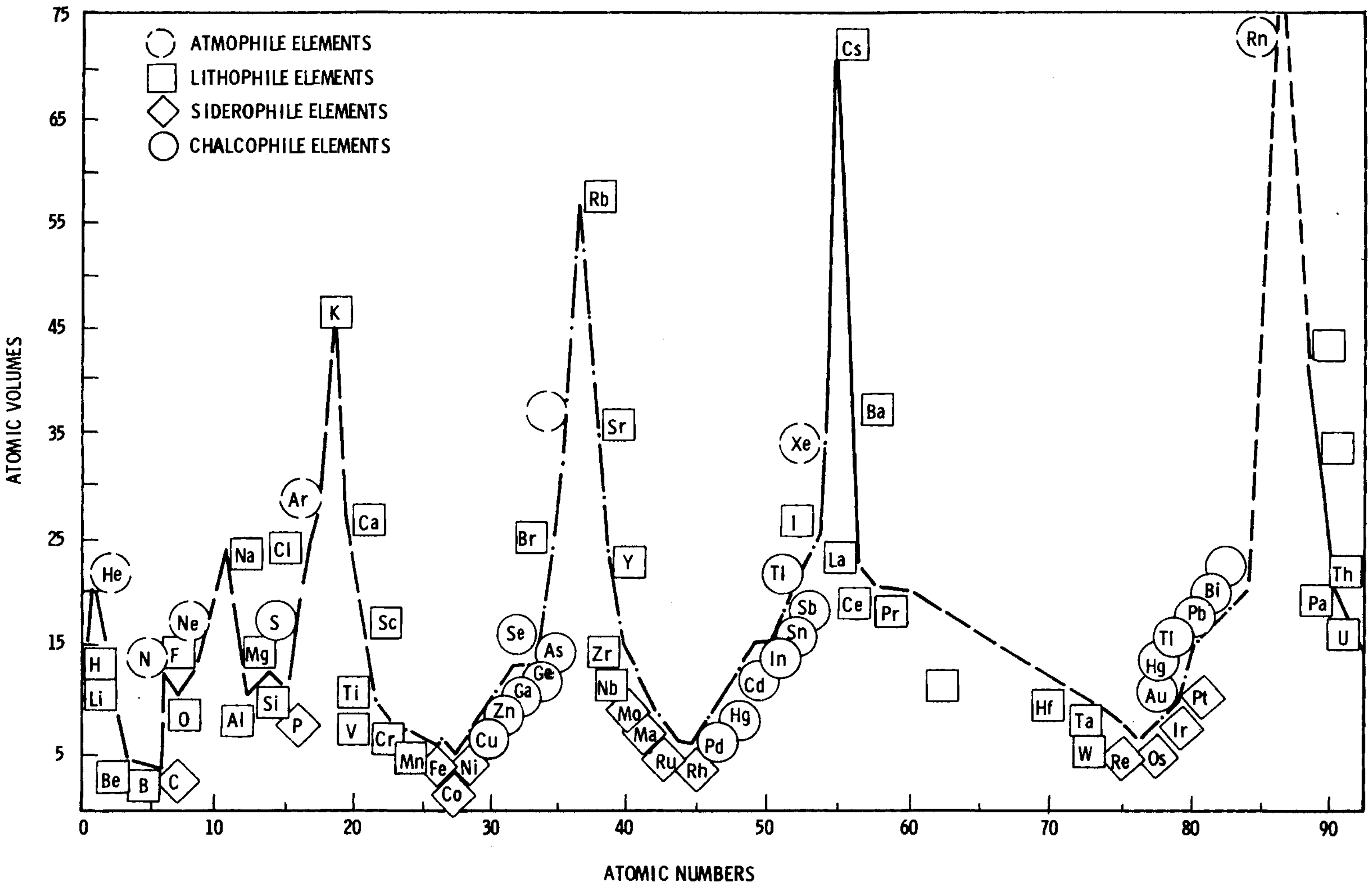

FIGURE 32. Atomic Volume Curve

TABLE 35. Elemental Characteristics by Chemical Phase

Chemical Phase	Electrons in Last Complete Shell	Bonding Tendency
Lithophile	8	Ionic
Siderophile	Partial Filling	Metallic
Chalcophile	18	Covalent

As might be expected, chemical phase characteristics of an element are related to periodic law. When atomic volume is plotted against atomic number, elements that occur in the same phase occupy similar positions on the minima and maxima curves. These relationships are shown in Figure 32. It can be seen that siderophile elements occupy positions on the curve that descend toward minima while chalcophile elements occupy ascending sections.

Indium occupies a small plateau on the curve similar to tin and germanium, both of which have siderophile tendencies(7). In fact, indium displays both chalcophile and siderophile phase characteristics(2).

Dual phase characteristics are based on empirical evidence and can be explained as a crustal phenomenon. Specifically, classical phase characteristics are highly theoretical and only hold in a liquid-liquid equilibria between melts. Moreover, once chemical differentiation was complete, gravitational differentiation commenced resulting in the concentration of siderophile elements at the earth's core. Crustal material was then formed from a blend of primarily lithophile elements with smaller amounts of the siderophile and chalcophile phase.

Under crustal conditions the geologic occurrence of an element is greatly influenced by temperature and pressure as well as the chemical environment of deposition. In addition, ion exchange between solid phases is common. Because of this, phase characteristics lose some of their impact as exploration tools when dealing with elements such as indium. More important is the characterization of secondary mineralizing environments.

Behavior During Geologic Processes

Data from Figure 31 would indicate igneous and sedimentary rock forming environments in general are poor concentrators of indium. Highest values observed are less than 0.3 ppm from fractional crystallization and much lower for sedimentary processes. Clearly, economic quantities of indium result from secondary mineralization.

All indications are that hydrothermal alteration is the principal concentrating mechanism(2,4,5,8,9). Indium most commonly occurs with zinc in intermediate temperature sphalerite vein deposits. This type of mineral regime has accounted for virtually all domestic indium production, past and present.

Depositional processes that concentrate indium in sphalerite ores also enrich other associated base metal sulfides. Chalcopyrite and galena (PbS), associated with indium-rich zinc ores, virtually always contain some indium. In fact, some domestic indium is currently being produced on a small scale from lead smelter baghouse dust.

Because of a drouth of analytical work on the subject, little is known about factors that control indium during the hydrothermal depositional process. Empirical evidence, however, can be useful in characterizing these controls. Historically, indium has been produced from iron-rich marmititic sphalerite occurring in lode vein deposits. In addition, the temperature of the mineralizing solutions was intermediate to high, typically above 200°C.

Also, there is evidence that indium can be locally influenced by minor elements closely related to it by periodic law. As an example, if cadmium is present it will characteristically occur with indium. Currently, the American Smelting and Refining Company (ASARCO) has a process whereby they recover indium from lead smelter baghouse dust as a byproduct of cadmium production. In addition, U.S.G.S. zinc specialists confirm the association between indium and cadmium in their field studies. Further, officials of Cominco, Ltd. of Canada, indicate there is a relationship between the occurrence of tin and indium in their zinc ore feeds. That is, the sphalerites that contain tin are almost always the indium-rich ores.

Associations of indium with other minor elements cannot, however, be considered to have any significant value in characterizing occurrence. Crustal concentrations of trace metals are too low to exert any regional influence. Thus, the presence of trace elements would be a local phenomenon and be of little use as a regional exploration tool.

More important in the regional control of indium mineralization is the presence of iron. Based on physical evidence, this relationship cannot be overlooked. Deposit descriptions in the literature show distinct associations of iron and indium, particularly in cassiterite-silicate-sulfide ores(2,4,5,10,11,12). Officials from Cominco, Ltd. indicate the source of their indium is virtually always from iron-rich marmititic sphalerite. Other evidence is present in base metal deposits being developed in Wisconsin and New Mexico by Exxon. Massive sulfide deposits in Wisconsin yielded zinc concentrates of 37 ppm indium and 2000 ppm cadmium with a iron/indium ratio of over 2000. Copper concentrates from the same deposit had 51 ppm indium with an iron ratio of nearly 6000. Zinc concentrates from New Mexico had about 90 ppm indium with a Fe/In ratio around 1200. Copper concentrates from that mine had 53 ppm indium with an iron ratio over 5000.

Little analytical work has been done to characterize this association between indium and iron. Because iron is common in the earth's crust and often becomes remobilized on a regional basis, it would be reasonable to assume that indium's siderophile tendencies account for its regional control by iron.

Ivanov(5) notes significant decreases in indium content between four-fold coordinated sulfides (sphalerite, stannite, chalcopyrite) and six-fold coordinated sulfides (pyrite, pyrrhotite). One explanation is that in low coordinations the effective radii of the elements decrease, allowing In^{+3} to more readily substitute into a position occupied by a Fe^{+2}.

Indium's affinity for a low coordination number would also help explain its presence in hydrothermal fluids. Iron-rich common rock forming minerals have octahedral and higher coordinations and would not accommodate indium into the lattice. As a result, the indium ions become concentrated in post magmatic mineralizing solutions.

Another geologic factor that exerts regional control over the occurrence of indium is that of orogenic activity. Typically indium-rich deposits are associated with mountain roots and tectonic belts. Virtually all domestic indium has historically been produced from western deposits in the Cascade and Rocky Mountains as well as from deposits in the Appalachian chain. Mid-continent ores of the stratabound Mississippi Valley type have been notably barren. In addition, foreign indium in the free world has been produced from mountain belts in Canada and the Andes of Western South America.

This tectonic control of indium occurrence can be illustrated graphically when indium concentrations of ore samples are plotted by geographic area. During the 1950's the Department of the Interior conducted an exploration study on domestic sources of minor elements(12). Over a thousand samples were taken across the country from mill and smelter products as well as from ore concentrates and rocks. A majority of the samples were "grab samples" and cannot be considered statistically

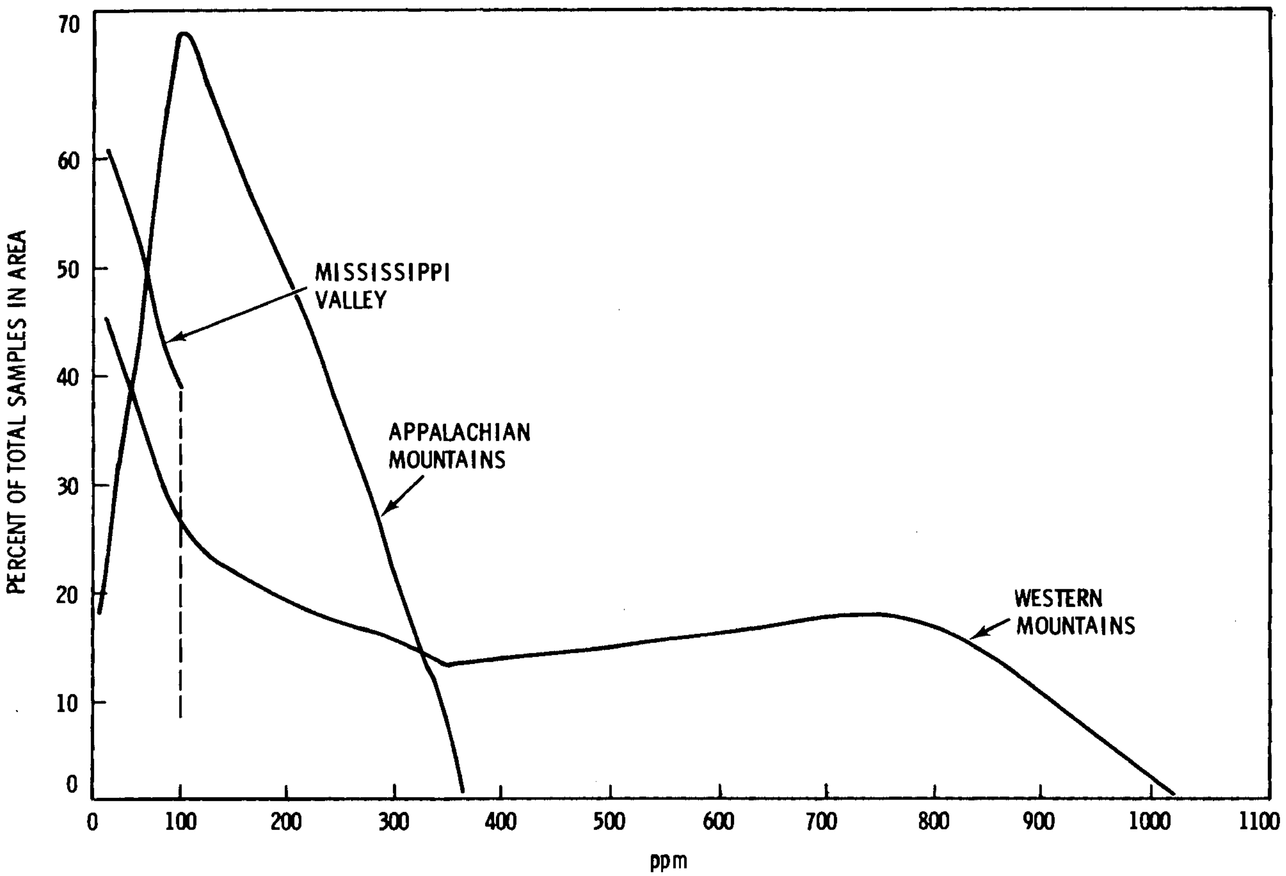

FIGURE 33. Indium Occurrence Trends by Geographic Region

representative of a large volume of material. Moreover, the accuracy of the early analytical methods have subsequently been questioned. Nevertheless, the study is unique as a country wide assessment of minor elements and has some value in predicting geographic trends of occurrence.

For the purposes of this study, samples were segregated that contained indium and that could be considered to be from ore sources. Generally these were from zinc concentrates and amounted to 76 sample points from western mountain regions, 11 samples from the Appalachian Mountains, and 31 samples from Mississippi Valley deposits. Curves were fitted through histograms of indium concentration versus percent of total samples in each of the three areas. Results are given in Figure 33. It is obvious from the sample points given that indium has the highest concentrations in orogenic belts. Thus, exploration efforts should be focused on sulfide deposits in these regions.

Exploration Techniques

Indium does not occur in significant quantities in nature to warrant mining as a primary product. Rather, recovery is a byproduct of base metal sulfides. Because of this, exploration techniques should focus on new discoveries of these ores, particularly sphalerite. Prospecting techniques for zinc as well as tin and copper ores have been outlined in U.S.G.S. professional paper 820(8) and will not be repeated here. However, factors that may indicate the presence of indium in these base metal ores are relevant.

Work on specific occurrences of indium is incomplete. Moreover, much of the work that has been done appears in dated Russian literature and there is some doubt about the accuracy of indium analysis at the low concentrations they were working with.

In the formulation of tools to characterize indium occurrence we must then rely on empirical evidence as observed in nature. Using this approach it is important to keep in mind that conditions of deposition are site-specific and observed deposits should only be used as guidelines to predict other occurrences. Also, it should be emphasized that geologic and geochemical environments favorable to the formation of indium minerals are of no consequence unless a primary source of indium is present. Thus, predicting this primary source is an important first step.

A majority of indium has been produced from areas associated with regional tectonic activity. From this we can assume indium-rich mineralizing fluids originate in the roots of mountains through anatextic melting or from emplacement of magmatic masses. Several deposit types are typical of these regions and should be considered a criteria when exploring for potential indium sources:

- Contact metamorphic deposits
- Replacement and fissure filling ores
- Lode veins
- Stratabound deposits in metamorphic rocks

As a rule, favorable deposits are associated with hydrothermal fluids of at least 200°C. Also, physical control of the ore would be related to structural features produced by the tectonism. Deposits that have proved to be indium-poor are pods of massive sulfides formed at low temperatures, usually in a carobonate host in stable continental areas.

Exploration for indium should not be confined to zinc ores just because that has been a dominant source in the past. Copper and tin sulfide ores from South America are also known to contain significant amounts of indium(8).

Another possible indicator of indium in base metal ores is the presence of impurities. Historically indium has been produced from iron-rich marmititic zinc ores. Also, base metal producers indicate tin and cadmium are often associated with indium-bearing ores. Indium assays could begin with ores known to contain these impurities.

In summary, some useful exploration tools for indium could include base metal deposits associated with the following:

- Mountain roots and regional tectonic activity;
- Hydrothermal and pneumatolitic mineralizing activity above 200°C;
- Lode vein, fracture filling or contact metamorphic base metal deposits; and
- Presence of iron, cadmium and tin in zinc and copper sulfides.

Geographic Occurrence of Domestic Indium

Indium occurs as a trace element in base metal sulfides and most typically in zinc ores associated with tectonic regions. Although no concerted effort has been made by industry to assay ores of indium, some data is available. Naturally occurring concentrations of indium in smelter residues give some indication of occurrence provided mill feeds have not been mixed. Also, geographic occurrence of indium can be predicted based on geologic environments favorable to indium concentration.

From characterizations of indium occurrence presented in earlier sections, some definitive statements can be made about geographic occurrence and concentrations in zinc ore. First, all evidence tends to indicate the low temperature stratabound sulfide deposits of the Mississippi Valley type do not contain significant amounts of indium relative to lode veins and massive deposits of tectonic regions. Thus, they should not be included as indium deposits.

Secondly, because indium tends to follow iron during deposition, emphasis should be focused on marmititic zinc ores. While specific assay information is not available, depositional environments can be used as a criteria to identify those deposits that may contain the highest amounts of indium. Deposits listed in Table 36 contain iron-rich sphalerite and occur near areas of past tectonic activity.

TABLE 36. Zinc Deposits with Favorable Indium Depositional Environments

District	State	Owner
Ward	Nevada	Gulf Minerals
Pioche	Nevada	Bunker Hill
Coeur 'd Alene	Idaho	Bunker Hill
Los Pintos	New Mexico	Exxon
Park City	Utah	-
Bingham	Utah	Kennecott
Leadville	Colorado	ASARCO
Gilman	Colorado	N. J. Zinc
Hannover	New Mexico	N. J. Zinc
Sterline	New Jersey	N. J. Zinc
Bald Mountain	Maine	Superior Oil
Balmat	New York	St. Joe
Crandon	Wisconsin	Exxon

Indium has also been reported to occur in numerous locations in Alaska. Bureau of Mines officials from the Juneau office have compiled a list of nearly 70 deposits in Alaska that are known to contain indium. Much of the detection work was done by qualitative spectroscopic examination and lack the quantitative precision needed to evaluate resources. Nevertheless, these deposits have some value in characterizing the geologic and geographic occurrence of indium for future exploration programs. A selected list of the deposits is given in Appendix D.

Evaluating indium occurrences in lead deposits is even more difficult than zinc deposits. Because this has been a very minor source of indium in the past, virtually no field data exists on the indium/lead association.

Currently, ASARCO recovers indium from lead smelter bag house dust as a byproduct of another byproduct, cadmium. Company officials indicate the bag house dust comes from lead smelters in Montana and Texas. However, this is not necessarily an indication of where the indium originated. Mill feed at the two smelters comes from a number of different locations and is not assayed for indium. In addition, foreign concentrates are often mixed in the feed. Therefore, there is little on which to base the geographic occurrence of indium in lead ores.

Indium is also known to occur in other domestic base metal ores such as porphyry copper or tin deposits. Both the Kennecott Company and Anaconda have reported finding minor traces of indium in their porphyry copper ores, but considered the amounts too insignificant to warrant further investigation. While most data supplied by the two companies is qualitative, Kennecott reported ore deposits in Utah that had an indium concentration of 10 ppm. Because indium is not naturally concentrated during any step of the copper refining process, producers have shown little interest in characterizing its occurrence in disseminated copper deposits.

Although tin ores are known to be concentrators of indium, no significant domestic tin deposits are currently being exploited. The Lost River area on the Seward Peninsula, Alaska was the only U.S. tin deposit to be developed and it closed down after World War II.

Traces of indium have been reported in those ores by the Bureau of Mines. Although analytical methods were spectroscopic and qualitative in nature, the Bureau of mines did report that all indium concentrations at Lost River were less than 1000 ppm.

RESERVES AND RESOURCES

Reserves and additional resources of indium are contained in ores of other base metals, most notably zinc ores. Based on available analytical data, as well as modes of indium occurrence, we estimate there may be around 800 metric tons of domestic indium reserves with about 1300 metric tons in total resources. In addition, world indium reserves are estimated to be 1,600 metric tons.

Resource estimates of indium cited in past literature have not been consistent. From analytical data available to the U.S.G.S., indium concentrations in selected sphalerite ores were determined to range from 0.5 to 10,000 with a median of 40. Using the assumption that all zinc resources are contained in sphalerite having an indium concentration of 40 ppm, the U.S.G.S. estimated indium reserves to be 1,800 metric tons with additional resources about three times that amount(8).

In contrast, the U.S. Bureau of Mines estimates indium reserves to be about 310 metric tons with about that same amount in additional resources(14,15).

In an effort to resolve these discrepancies, our estimates are based on modes of occurrence described in earlier sections. Specifically, depositional environments that tend to concentrate indium should be weighted more heavily than those that are typically indium-barren. Thus, low temperature zinc ores of the Mississippi Valley should have less of an impact on resource estimates than higher temperature mineral regimes associated with tectonic regions.

U.S.G.S. zinc specialists report recent estimates of domestic zinc resources are approximately 30 million metric tons of proved reserves with an additional 20 million metric tons of paramarginal resources. Of this amount, about 45 percent are contained in Mississippi Valley deposits with the remainder in western mountain belts and the eastern Appalachain region(16).

When estimating indium content in the zinc ores, it can be assumed the highest concentration occurs within the higher temperature tectonic regions. A conservative yet realistic estimate would be the median value from the U.S.G.S. concentration ranges, i.e., 40 ppm. Because lower temperature mid-continent zinc deposits are less favorable to indium concentration, an overall average of 10 ppm will be assumed for these regions.

Using these assumptions and the above data on zinc resources, an estimate of indium resources was calculated and presented in Table 37.

TABLE 37. Estimates of Domestic Indium in Zinc Deposits (Metric Tons)

	Zinc	Indium Concentration	Indium
Reserves			
Mid-Continent	13.5×10^6	10 ppm	135
Mountain Regions	16.5×10^6	40 ppm	660
Total Reserves			795
Resources			
Mid-Continent	9×10^6	10 ppm	90
Mountain Regions	11×10^6	40 ppm	440
Total Additional Resources			530
Total Resources			1,325

In addition to domestic indium resources, the U.S. Bureau of Mines estimates world reserves of indium at 1,600 metric tons. The Bureau of Mines also estimates at least 1,800 metric tons of additional indium are contained in marginal deposits of the world(15). World indium resources are summarized in Table 38.

TABLE 38. Estimates of World Indium in Zinc Deposits
(Metric Tons)

Reserves	
U.S.	795
Rest of World	1,280
	2,075
Resources	
U.S.	530
Rest of World	1,345
	1,875
Total World Indium	4,000[1/]

---

1. Estimate rounded

INDIUM PROCESS TECHNOLOGIES

There are at least six different processes by which indium has been recovered on a commercial basis. Although exact processes are considered to be company confidential, general descriptions are available in the literature(17).

While the methods all differ, a somewhat similar flow is common to most indium recovery circuits. Specifically, indium becomes concentrated, along with other impurities, such as iron, cadmium and tin, when zinc concentrates are calcined. These indium-rich residues can also come from lead blast furnace slag, lead smelter baghouse dust as well as zinc anode slime.

In each refining process the indium residues undergo a series of dissolution and precipitation to leach out impurities and precipitate richer and richer compounds of indium. Finally, the indium is purified either by direct electrolysis or by sponging with zinc and electrolyzing. A conceptual schematic of this general flow is given in Figure 34.

Under current technology, overall recovery efficiency of indium from zinc ore is quite low. It is important to remember that at no point in the zinc processing flow is there ever any effort made to concentrate indium. Isolating and purifying zinc is the primary concern; that indium happens to become slightly concentrated at a couple of points in the process flow is an added benefit. However, because there has been no engineering design to recover indium, much of it is lost.

Because indium and zinc have similar physical properties, virtually all indium contained in ores follows zinc through the milling process and into zinc concentrates. Major losses of indium occur in refining when zinc concentrates are volatized in the pyrometallurgical process or leached in the electrolytic process.

While about 90 percent of the indium can be recovered from indium-rich process residues, industry officials report that only about 40 percent can be recovered from zinc concentrates under current extraction techniques.

INDIUM SUPPLY CONSIDERATIONS

Because of its byproduct nature, indium supply becomes a function of zinc supply. Using indium concentrations outlined earlier, about 7 metric tons of indium per year could be extracted from projected domestic zinc production to the year 2000. In addition, if imported indium-rich residues can be obtained, the domestic indium industry could currently produce around 18 metric tons of indium per year. World

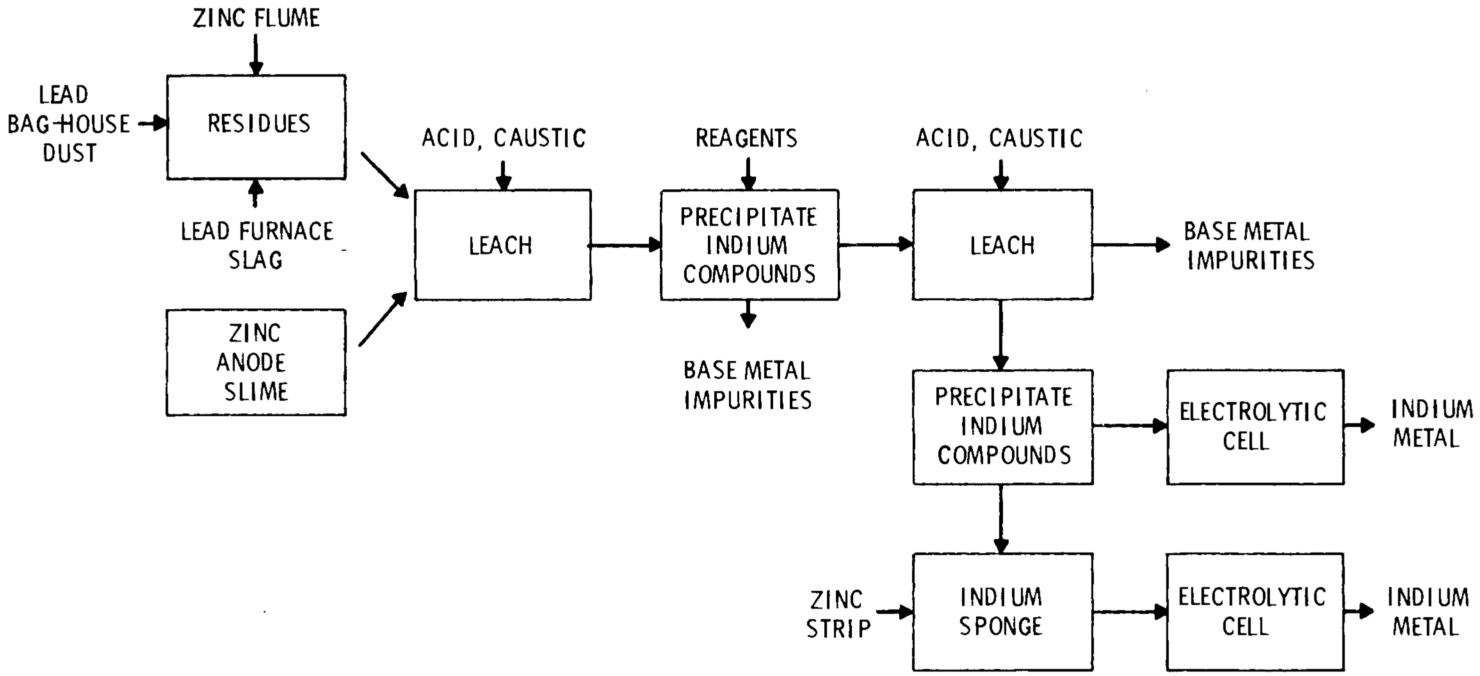

FIGURE 34. Indium Recovery from Base Metal Processing

indium production capacity has been estimated by the Bureau of Mines to be between 125 to 165 metric tons per year(14). World production of indium in 1977 was estimated to be 40 metric tons. Of that amount the U.S. produced approximately 9 tons(21).

Supply is defined as the quantity that would be made available at some given price. Because indium production is completely dependent upon the amount of zinc produced, the quantity of indium available is a function of the price of zinc.

Clearly, if indium-bearing residues are being dumped, an increase in indium price would lead to an increase in indium production. However, if the demand for indium is increased by photovoltaic technology, and all possible indium is extracted from zinc production, then zinc price is the constraining factor.

Zinc production from domestic mines was about 3.1×10^5 metric tons in 1978(18). About half this amount came from the mid-continent with the other half being mined in Appalachia and the western mountain regions. Based on concentrations and recoveries presented earlier, approximately 3 metric tons of indium were recoverable from 1978 U.S. zinc production.

It is not known how much indium was actually produced from these ores, but it is assumed a large share of domestic production is from imported zinc concentrates as well as from imported and stockpiled indium-bearing smelter residues. In this situation there is excess capacity in the domestic indium industry and the quantity produced can be influenced by indium price. When the price of zinc is held constant, an increase in the price of indium will cause an increase in the quantity of indium supplied. However, when the maximum amount of indium is recovered from zinc, indium becomes infinitely price inelastic. No change in indium price will increase the quantity supplied. At this point the price of zinc controls the quantity of indium supplied. Thus, it becomes clear that estimating indium supply involves predicting future zinc production levels.

Future levels of zinc production are dependent upon an interaction of factors such as demand, cost, environmental constraints as well as government policy, and are beyond the scope of this discussion. However, some estimates can be made based on current capacity. With the completion of a new electrolytic plant in Tennessee in May of 1979, domestic zinc capacity now stands at 717,000 metric tons of metal per year(18). In addition, some industry experts feel there are good reasons to believe no new domestic zinc refining capacity will be constructed in the foreseeable future(19).

If long-term indium supply is defined as being produced under existing technology within the next twenty years, it would be realistic to assume all indium would come from existing zinc capacity.

Moreover, if it is assumed mills run at full capacity and that ores come from geographic areas in the same ratios as they currently are, the maximum amount of indium available from domestic zinc production to the year 2000 can be estimated. This long-term indium availability is summarized in Table 39.

TABLE 39. Domestic Indium Availability Per Year to the Year 2000
(717,000 M.T./yr. Zn Capacity)
(Data in Metric Tons)

Ore Region	Zinc1/ Production	Indium Concentration	Recovery Ratio	Recovered Indium
Mid-Continent	3.59×10^5	.00001 ppm	.4	1.43
Mountain Belts	3.59×10^5	.00004 ppm	.4	5.74
Total				7.17

Current production is roughly equal between mountain belts and mid-continent regions(20). Estimating current annual indium supply is difficult because it requires knowledge of existing indium production capacity that is not public information. In their bicentennial issue of Minerals Facts and Problems, the U.S. Bureau of Mines estimated 1974 domestic indium capacity to be approximately 18 metric tons(14). For lack of additional data, it is assumed this is the maximum amount that could be supplied in any given year, provided raw materials were made available.

One final indium supply consideration that should be addressed is the discrepancy between domestic zinc ore production and estimated indium production. Bureau of Mines data indicates 1977 indium demand was around 18.5 metric tons while imports of metal were 8.9 metric tons(21). From this it can be assumed 1977 domestic production of indium was at least 9 metric tons. On the other hand, 1977 domestic zinc production was only 408,000 metric tons(18). Using the indium concentration and recovery assumptions presented earlier, only about 4 metric tons of indium could have been made available from domestic zinc ores in 1977. This would indicate a majority of U.S. indium is coming from foreign concentrates or stockpiled mill residues.

INDUSTRY AND MARKET FACTORS

Currently, 3 U.S. firms have capacity to produce indium. Two of these firms operate under a joint agreement and produce and market the majority of all domestic indium. The third company recovers indium on a campaign basis as a byproduct of a byproduct and has little impact on the indium market.

Constant dollar prices of indium generally declined for 3 decades after World War II. New uses of indium has resulted in a steady price increase from 1975 to the present. In addition, this price increase is expected to continue with new technological developments.

Indium Industry Structure

Domestic indium was first produced on a small scale for experimental purposes during the 1930's when The Indium Corporation of America was established. Production did not reach significant levels until the early 1940's with an increasing demand for war materials. Since that time as many as 10 firms have produced indium in the U.S. Currently, only 3 domestic companies have online capacity to produce indium.

Of the three current producers, The Indium Corporation of America is the biggest producer. Headquartered in Utica, New York, with a foreign affiliate in Marselle, France, the firm recovers indium from slags and other residues purchased from base metal refineries. High purity metal is produced in a variety of sizes and shapes. In addition, the company develops and markets a wide range of indium products.

Interviews with The Indium Corporation of America's officials reveal the firm's strategic profile is to continue to expand indium production capacity. Plans call for obtaining raw materials through contracts or joint ventures with base metal producers or possible backward vertical integration into base metal mining. In addition, product lines and markets would be developed in an orderly fashion. Although the company welcomes an increase in indium demand from photovoltaics, they view this as being somewhat more risky than current markets.

Another domestic indium producer closely linked to The Indium Corporation of America is New Jersey Alloy. Developed through a joint effort between New Jersey Zinc Corporation and The Indium Corporation of America, New Jersey Alloy is located in Palmerton, Pennsylvania. Smelter residues from New Jersey Zinc refineries are processed to extract indium that is used exclusively by The Indium Corporation of America.

While exact information is not available, production estimates would indicate much of the indium comes from foreign concentrates.

American Smelting and Refining's (ASARCO) Globe plant in Denver, Colorado is the third domestic producer of indium. At this facility indium is recovered from lead smelter baghouse dust that is processed to recover another byproduct, cadmium.

Currently, the baghouse dust comes from ASARCO smelters in Montana and Texas. Due to high start-up costs, indium-rich filter cake from the cadmium process is accumulated until the process can run for at least 3 months on a campaign basis. Indium is refined to five nines purity and sold on the open market.

Company officials indicate the Globe plant has a maximum capacity of about 15 metric tons of indium per year if operated continuously at full capacity. However, at current cadmium production levels, ASARCO accumulates less than 1.5 metric tons of indium per year. In addition, the Globe plant manager reports decreasing concentrations of indium in their baghouse dust.

Because the facility needs at least 1.5 metric tons of indium on hand to run a batch process, no indium was produced by ASARCO over the past year. Furthermore, K. D. Loughridge, senior vice-president of smelting and refining, reports ASARCO's indium production in the next few years will be minimal and not subject to increase with demand.

Historical Market Conditions

Indium is primarily produced as a byproduct of zinc ore processing. Currently, there are only three domestic producers of indium: The Indium Corporation of America, New Jersey Alloy, and ASARCO.

Indium price information over time is presented in Table 40 in current and constant 1972 dollars. From this table and Figures 35 and 36, it is apparent that the price of indium failed to keep pace with the increase in the general price level between 1947 and the early 1970's. This price-versus-time relationship could indicate either: (1) a reduction in the unit costs of production (i.e., economies of scale) due to a steadily increasing market for indium, or (2) a steadily decreasing market for indium and low profitability. Unfortunately, limited information is published on domestic indium consumption or production (in order to avoid disclosing company confidential data). However, industry sources indicate that the indium industry suffered from low profitability during this period and several firms left the industry. The remaining indium producers did not invest in new indium processing equipment or update old machinery.

During the 1970's there has been an increase in demand for indium due to its use in silver-indium-cadmium control rods for nuclear reactors. Most of this increase in demand has been met by stocks of indium accumulated during the 1964-1970 period.

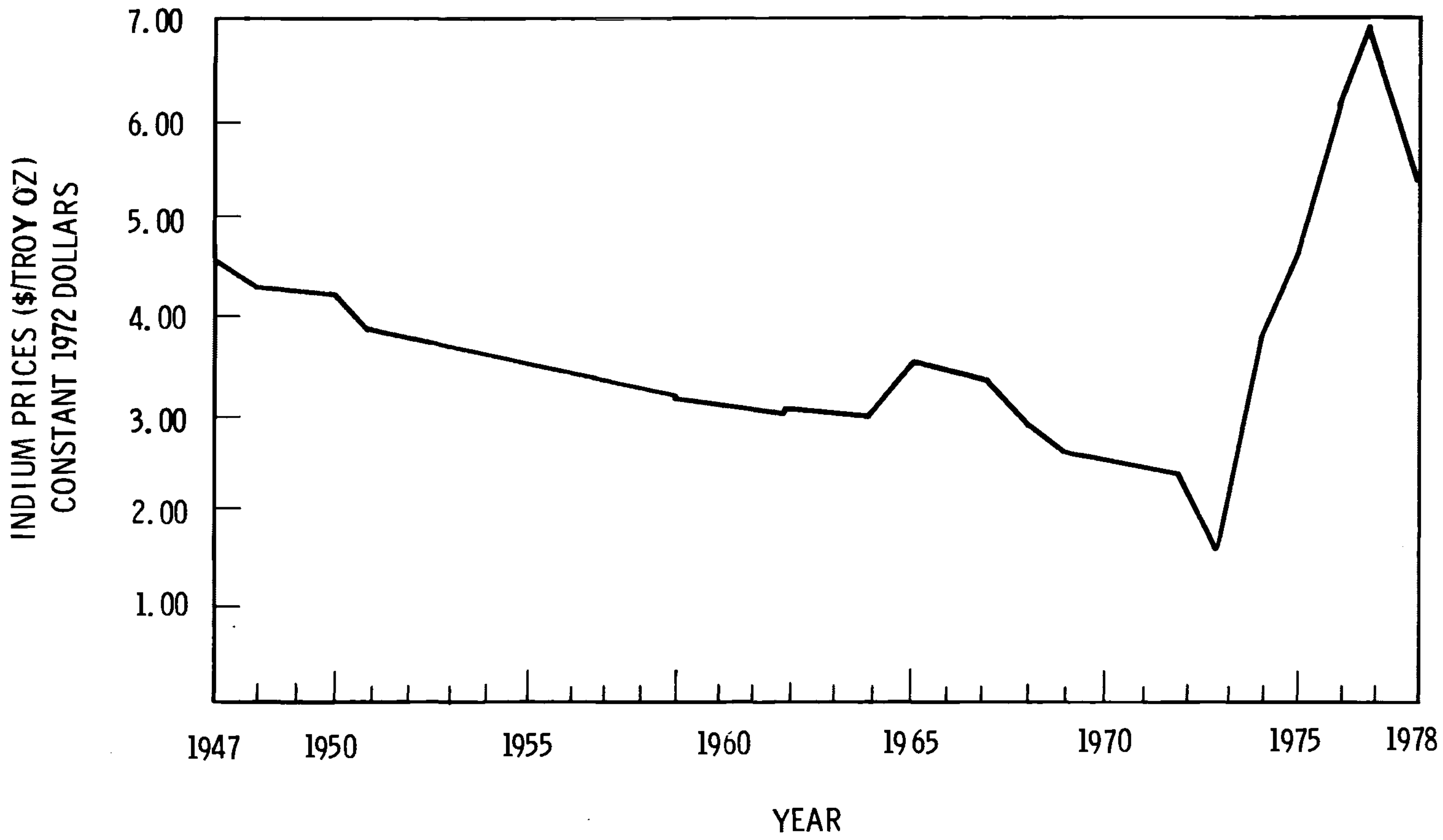

FIGURE 35. Historical Indium Prices

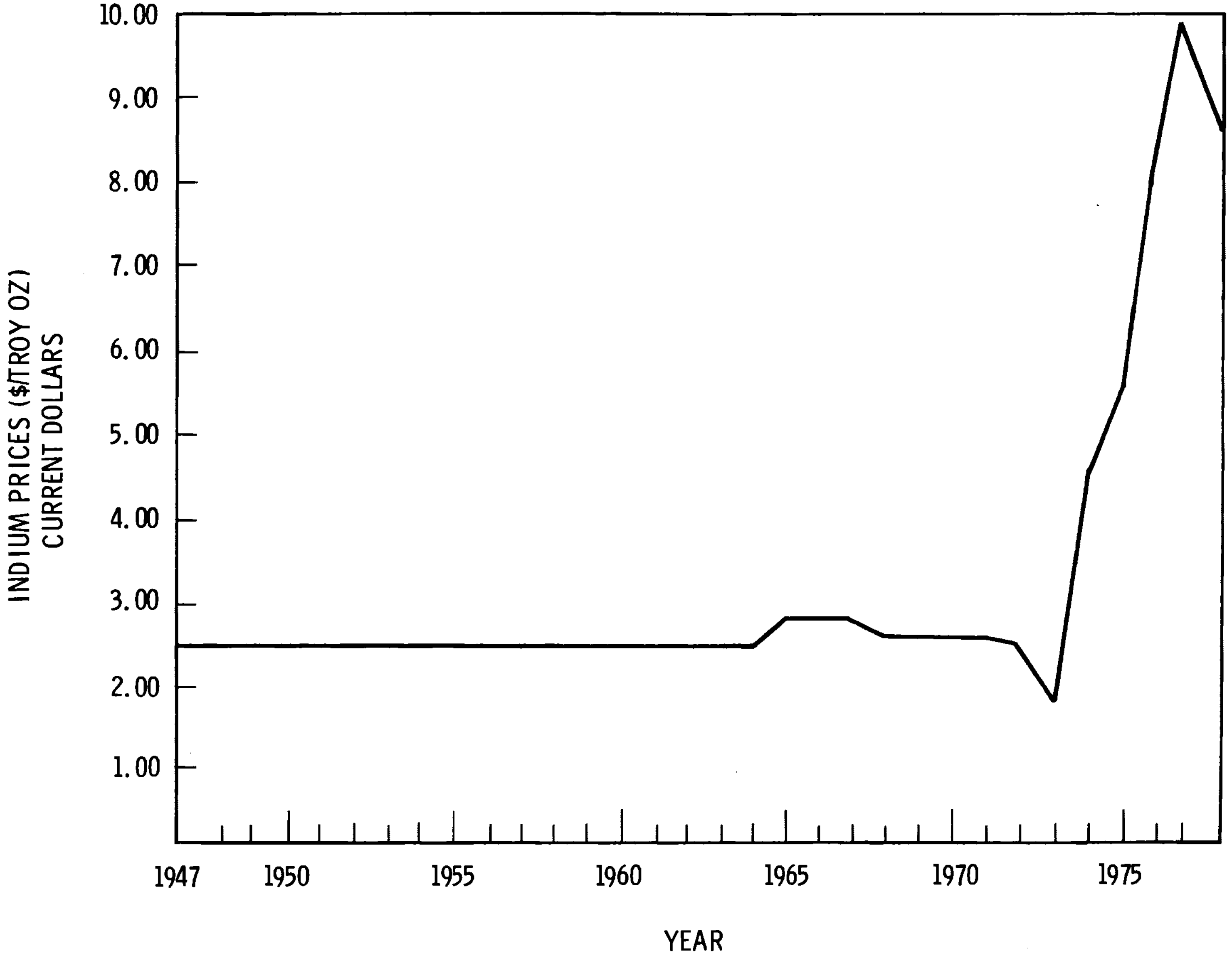

FIGURE 36. Historical Indium Prices

TABLE 40. Indium Prices ($/Troy Oz.)

Year	Current Dollars	Constant[(a)] Dollars
1947	2.24	4.51
1948	2.24	4.22
1949	2.24	4.26
1950	2.24	4.18
1951	2.24	3.91
1952	2.24	3.86
1953	2.24	3.80
1954	2.24	3.75
1955	2.24	3.67
1956	2.24	3.56
1957	2.24	3.45
1958	2.24	3.39
1959	2.24	3.32
1960	2.24	3.26
1961	2.24	3.23
1962	2.24	3.18
1963	2.24	3.13
1964	2.24	3.08
1965	2.74	3.69
1966	2.74	3.57
1967	2.74	3.47
1968	2.50	3.03
1969	2.50	2.88
1970	2.50	2.74
1971	2.50	2.60
1972	2.42	2.42
1973(b)	1.77	1.67
1974	4.42	3.80
1975	5.67	4.48
1976	8.03	6.00
1977	9.77	6.89
1978	8.45	5.53

TABLE 40. (Continued)

Source: "Mineral Facts and Problems", Bureau of Mines, Bulletin 667, Washington, D.C., 1976, p. 510.

a. With 1972 as the base year. Deflated using the Implicit GNP Price Deflator "Business Statistics", U.S. Department of Commerce, Washington D.C., 1975.

b. 1947-1972 indium prices for lots less than 100 troy oz., 1973-1978 indium prices for lots greater than 10,000 troy oz.

POTENTIAL INDIUM PRODUCTION CONSTRAINTS

From the data presented in earlier sections, several factors have been identified that may constrain future indium availability. Factors seen as having the most significant impact on future indium availability are the following:

- Lack of assay data with which to identify indium occurrence.
- Industry officials discount future indium opportunities.
- Trend in zinc mining to indium-poor ores.

Each of these possible production constraints will be discussed in more detail to better understand the problems.

Lack of Assay Data on Indium Occurrence

Although several attempts have been made to estimate domestic indium reserves and resources, large discrepancies exist between the estimates. At least two factors contribute to this lack of reliable resource data.

First is the fact that indium is completely byproduct in nature. Although some depositional environments may be more favorable than others for concentrating indium, there are no indium minerals that make its physical presence obvious. Therefore, each and every base metal deposit must be routinely assayed to obtain a valid measure of reserves. That this assay work is not being done is the second factor that contributes to the low degree of certainty in indium resource estimates.

During the summer of 1979 an industry survey of domestic base metal producers was conducted to obtain information on the degree to which domestic ores are being tested for indium. Respondents to the survey are presented in Exhibit 1.

EXHIBIT 1. Respondents to Indium Information Survey

Respondent	Company	Address
R. N. Gilges	Bunker Hill	P. O. Box 29 Kellogg, Idaho 83837
T. P. McNulty	Anaconda	P. O. Box 27007 Tucson, Arizona 85726
K. J. Richards	Kennecott	P. O. Box 11295 Salt Lake City, Utah 84147
R. T. Moolick	Phelps Dodge	300 Park Avenue New York, New York 10022
W. L. Cameron	Pacific Tin	280 Park Avenue New York, New York 10017
T. C. Osborne	ASARCO	120 Broadway New York, New York 10005
A. Reef	AMAX	AMAX Center Greenwich, Connecticut 06830
J. E. Thompson	Newmont	300 Park Avenue New York, New York 10022
R. L. Bullock	Exxon Minerals	P. O. Box 2100 Houston, Texas 77001

Data collected from the survey was consistent among a majority of the respondents. Generally, the base metal producers assay for a variety of rare elements during initial development work to insure against missing some anomalous concentration that may be economic. However, this is not always the case. For example, AMAX reports their ores in the Missouri lead-zinc district have never been assayed for indium. More significant is the fact that routine ongoing assays for indium in ores or mill concentrates are virtually never done.

In addition, the base metal producers report that foreign ores and concentrates are not assayed for indium before being mixed with domestic mill feed. The result is that when indium is present in smelter residues there is no way of telling where it came from. Developing a reliable data base on indium would be useful in predicting future availability of the metal. Collecting this data would greatly reduce the risk of decision making based on indium resource estimates.

Industry Perception of Future Opportunities

Another potential constraint to the future availability of indium is the low expectations producers have for opportunities within the industry. Perceived risk in rare metals markets contributes greatly to this discounting of future opportunities. Another contributing factor is the relative economics between byproduct indium and the primary metal, zinc.

Many base metal producers are reluctant to install expensive equipment to recover rare metals because the markets have been so volatile. In a world of rapidly changing technology, markets can dissipate as quickly as they precipitate.

This general feeling of risk is also expressed by J. E. Thompson, president of Newmont Mining Corporation. He reports that Newmont produced metallic germanium for a while, but discontinued the operation because markets were so volatile and substitutes so easily available. In addition, Mr. Thompson states Newmont would only consider recovering indium if a short payout could be projected.

The general opinion conveyed by Indium Corporation of America is that large quantities of indium could be supplied if market incentives were strong enough. However, strong market incentives such as a very high price could exclude indium as a photovoltaic material if solar power is to be competitive. Thus, officials at the Indium Corporation feel there is risk involved in large capital expansion to meet a single industry such as photovoltaics.

Relative economics between indium and zinc may also be a significant deterrent to future supplies of indium. Although data on profitability is not available, some insight can be gleaned from revenue alone.

Estimates of revenue ratios can be made by assuming zinc contains 40 ppm indium and that recovery efficiencies for zinc concentrates are 80% for zinc and 40% for indium. For each metric ton of contained zinc, about 1,750 pounds of zinc and 0.5 troy ounces of indium could be recovered. Using 1979 commodity prices of approximately $0.40/lb for zinc and $14/troy ounce for indium, revenues would be about $700 and $7.00, respectively. Investing large amounts of capital to generate one percent of total revenue may not be justified.

If the producer is to assume all the risk, a high profitability would be required on indium-generated revenues to decrease the capital recovery period and thus decrease the risk of future uncertainty. However, this high profitability may price indium out of the photovoltaic market, a fear expressed by officials of The Indium Corporation of America. As an alternative, if risks could be shared equally between producers and buyers through long-term contracts, profitability would not need to be so high and indium may remain competitive as a photovoltaic material.

Changing Geographical Trend in Zinc Mining

A changing geographical trend in zinc mining has had an impact on indium availability and may continue to do so in the future. Specifically, this trend in zinc mining is moving away from lode vein deposits in western mountainous regions and into the lower grade, more disseminated deposits of the mid-continent. This is significant because mid-continent deposits typically contain lower concentrations of indium.

Western zinc mines have been closing down for a number of reasons. First, these are some of the oldest mines in the country and ores are simply being depleted, or are becoming too deep to be economical. In addition, most western deposits are lode veins and are too narrow to be mined with high volume equipment. A result is that vein deposits cannot remain competitive with high volume disseminated deposits of the mid-continent.

Although many geologists feel tectonic belts hold good potential for finding new base metal deposits, the trend away from mining in these regions may continue. Because mountainous regions have high aesthetic value, environmental roadblocks to mine development are formidable. Also, much of this area may be placed off-limits to mineral exploration by public land withdrawal bills now being debated before Congress.

In any event, a continued trend away from higher temperature zinc sulfide deposits will undoubtedly mean smaller quantities of indium being concentrated in process residues.

Indium Supply vs. Photovoltaic Demand

Photovoltaic development scenarios and cell screening results defining indium demandhave been addressed in Chapters 2.0 and 3.0. In this investigation it was determined significant amounts of indium would be required in the amorphous silicon cell.

Indium in the form of indium oxide and indium tin oxide is utilized in the amorphous silicon cell. Development of 25 GW of a-Si cells would require 76 metric tons of indium per year by the year 2000. Cumulative demand by the year 2000 would be 416 metric tons of indium.

Earlier in this chapter we saw that current world production of indium is about 40 metric tons with about 9 metric tons being produced in the U.S. Also, world indium production capacity was estimated to be between 125 and 165 metric tons per year with about 18 metric tons of that capacity being in the U.S. In addition, indium supply from domestic raw materials was estimated to be 7 metric tons per year to the year 2000.

To satisfy indium demand for the amorphous silicon cell, world production would have to increase at 14% per year starting in 1990. Using this scenario, indium demand from the a-Si cell alone would be about 42% of the world total in the year 2000, as illustrated in Figure 16.

Indium is also used as thimethyl indium in the advanced concentrator cell. However, a cumulative total of only 15 metric tons would be required to produce 25 GW peak capacity by the year 2000.

CONCLUSIONS AND RECOMMENDATIONS

Given the indium requirements of the a-Si cell, it is clear world supplies of indium may not be sufficient to meet solar demand. Certainly, the domestic indium industry could not satisfy solar demand withoug large-scale expansion of capacity and substantial imports of raw materials. In addition, production growth rates, the percent of supply as a byproduct and percent of world demand required are all above threshold levels defined in the CMAP. These problems and action recommended to mitigate supply constraints have been addressed in "A" materials discussions in Chapter 3.0.

To summarize, the following actions have been recommended to decrease indium supply constraints in a-Si cells:

- Reduce or eliminate the amount of indium tin oxide used;
- Recycle wasted indium tin oxide;
- Formulate long-range plans between suppliers and cell fabricators to insure future supplies of indium;

- Initiate a stockpile program in early years when indium demand is the lowest;
- Establish long-term contracts with suppliers to reduce the risk of expanding capacity;
- Research improved indium recovery from zinc processing; and
- Expand data base on indium occurrence and distribution.

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GALLIUM

BACKGROUND

Nearly a decade before its discovery in 1875, periodic law predicted the occurrence of gallium in Group IIIB of the S-P metals along with aluminum, indium, and thallium. Because no primary gallium minerals could be identified, initial indications were that gallium was a very rare element.

As detection methods became more sophisticated, it was apparent that gallium is rather common, having approximately the same crustal abundance as lead (15 ppm) and being much more abundant than metals such as molybdenum or tin (1.5-2.0 ppm) that form large deposits of primary minerals. It is now known that gallium's close geochemical similarity to aluminum allows it to effectively camouflage for that element in the common rock forming minerals. As a result, gallium is uniformly dispersed in low concentrations in most crustal rocks.

Several geologic processes result in secondary mobilization and enrichment of gallium. Specifically, gallium can reach typical concentrations of 50 ppm in bauxite ores and low temperature zinc sulfide minerals. In addition, gallium becomes concentrated in fly ash when coal is burned and also in phosphate flue dust during the burning of phosphate material to produce elemental phosphorous.

Domestic reserves of gallium are estimated to be two thousand metric tons of metal from bauxite sources and about 6 thousand metric tons of metal contained in Western U.S. phosphate rock. Total U.S. resources of gallium have been estimated to be 15 million metric tons in bauxite material, one million tons in zinc ores and over one million metric tons of gallium in Western phosphate deposits. In addition, an estimated 1.5 million metric tons of gallium are contained in total producable bituminous and sub-bituminous domestic coals.

Currently, the largest domestic source of gallium is precipitate from aluminum industry Bayer liquors. Gallium has also been recovered from base metal residues as well as phosphate flue dust and coal fly ash.

When all recovery factors are considered, total domestic gallium supply is calculated to be approximately 600 MT from bauxite, 210 MT from zinc ores and 1,584 MT from western phosphate material as well as 750,000 MT from producable coal. In addition, short-term domestic supply is estimated to be 10 to 12 MT annually from bauxite and zinc combined with an additional 5 MT from phosphate flue dust and 1,200 MT from coal fly ash. World supply from bauxite processing could reach 5,000 MT/year by the year 2000.

Because of unique physical characteristics, gallium has valuable applications within industry. Gallium's low melting point (29.8°C) and high boiling point (2000°C) make it useful in high temperature thermometry and fusible cut out devices. Also, gallium has desirable alloy characteristics. Small amounts of gallium exert a considerable influence on melting point, electrical resistivity, strength and malleability as well as corrosion resistance of other metals. Further, electronic technology is expanding the use of gallium into such things as digital displays, semiconductors and photovoltaic cells.

Gallium markets have been volatile in the past decade and have resulted in current domestic capacity greatly exceeding demand. With the exit of Canyonlands 21st Century Corporation, The Alcoa Company and Eagle-Picher Industries are the only remaining domestic producers of primary gallium. However, Canyonlands still recovers secondary gallium and anticipates renewed primary recovery if markets improve.

Possible constraints to gallium availability include industry's perception of future market conditions and a lack of long-term incentives that would warrant retrofitting primary alumina loops in the aluminum industry.

If gallium production is to meet future projected photovoltaic demand, action will have to be taken to help mitigate these constraints.

GEOCHEMISTRY

Because of gallium's close geochemical association with aluminum, it can and does proxy for aluminum in virtually all the alumino-silicate rock forming minerals. Gallium also has an affinity for sulfur and commonly occupies zinc cation positions in zinc sulfide ore.

Chemistry and geochemistry of gallium received much attention from Russian scientists in the early and middle part of the 20th century(1,2,3). Although much of this work is dated, valuable contributions were made to the basic understanding of gallium and its behavior in the earth's crust. In addition, more recent research on the chemical behavior of gallium has helped alleviate shortcomings in earlier works(4).

In an attempt to characterize the occurrence and distribution of gallium, data has been abstracted from this literature. Because much of the geochemical data presented in the indium section applies to gallium, that information will not be repeated here.

Atomic Characteristics

Gallium occurs in the periodic table in Group IIIB of the S-P metals, along with aluminum, indium and thallium. All four metals of the group are characterized by having 2 valence electrons in the S level and one in the P level. Aluminum differs from the other three metals in the group by having 8 electrons in the last complete shell rather than 18. Some physical characteristics of the group are listed in Table 41.

TABLE 41. Physical Data of the Group IIIB Metals

	Al^{+3}	Ga^{+3}	In^{+3}	Tl^{+3}
Ionic Radii	0.51	0.62	0.81	0.96
Ionic Potential	5.88	4.84	3.70	3.13

Gallium's relatively small ionic size and high ionic potential allow it to be accommodated into common rock forming minerals with aluminum. As a result, gallium is highly dispersed in the crust and rarely forms ore minerals. Although gallium can proxy for other S-P metals, this close association with aluminum has the most significant impact on gallium's crustal occurrence.

Complexing Characteristics and Isomorphism

Gallium has the ability to form both covalent or ionic bonds. Because of this, the metal will complex with oxygen as well as sulfur. In addition, because gallium can act both as an acid and a base, it will complex as a cation as well as an anion(3).

Typically, when gallium complexes with oxygen it will act as a cation and form an ionic bond in eight-fold coordination. In contrast, the anion gallium complex is predominantly covalent and displays four-fold coordination in a crystal lattice. The anion complex itself may be an oxide or hydroxide as well as a chloride, fluoride or ferrocyanide(1). As a rule, gallium can substitute into any position occupied by aluminum in the common rock forming minerals.

When complexing with sulfur, gallium also acts as a cation. Gallium enters the sulfide lattice in much the same way as indium. Common occurrences are isomorphic solid solutions between gallium and zinc or iron in sphalerite. Bonds are more covalent than ionic and the gallium cation is in four-fold coordination with sulfur. Further, rather than replacing a zinc or iron ion, gallium will often occupy a defect structure in the lattice.

GEOLOGIC OCCURRENCE OF GALLIUM

Gallium occurs in about the same crustal abundance as lead and is approximately 5 times as abundant as tin in the earth's crust. Because gallium can proxy for aluminum in all the common aluminum silicate minerals, it is rather evenly dispersed in low concentrations throughout crustal rocks. Nowhere have geochemical conditions been such that significant quantities of primary gallium minerals were formed. Rather, secondary geologic processes are the principal concentrators of gallium.

Lateritic weathering and leaching of alumino-silicate minerals produces the greatest amounts of gallium-rich deposits. Specifically, weathering causes aluminum silicate minerals to alter to a number of aluminum hydroxide minerals such as diaspore ($AlO(OH)$) or gibbsite ($Al(OH)_3$). These minerals along with silica, silt, clay and iron hydroxides form a material known as bauxite, the primary ore of aluminum. Gallium concentrations in bauxites range from 40 to 70 ppm. Domestic bauxites typically contain 50 ppm gallium.

Secondary concentrations of gallium also occur in base metal sulfide deposits. In particular, sulfide environments produced by low temperature hydrothermal alteration in non-silicious host rocks are known to contain gallium concentrations greater than 50 ppm(3,5). Stratabound zinc deposits in carbonate rocks of the Mississippi Valley are the most notable domestic occurrences of this type.

Two additional sources of gallium are coal and phosphate rock. However, natural geologic processes do not tend to concentrate gallium in these two materials. In fact, in the natural state, gallium concentrations rarely exceed the crustal average of 15 ppm in coal or phosphate material.

Economic concentrations of gallium are produced when coal and phosphate are burned. Specifically, coal burning produces fly ash that can contain from 20 to 100 ppm gallium. Also, burning of phosphate rock to produce elemental phosphorous yields flue dust that ranges from 230 to 600 ppm gallium.

Crustal Mobility of Gallium

There is strong geologic evidence that gallium has multiple phase characteristics. Gallium's ability to proxy for aluminum and enter the silicate lattice of common rock forming minerals gives it strong lithophile phase characteristics. However, gallium can also undergo considerable volume contraction and form covalent bonds with sulfur, making it chalcophile in nature. In addition to phase characteristics, it is also important to identify secondary processes that tend to remobilize and concentrate gallium.

Lateritic weathering in wet climates is the most significant concentrator of gallium. This concentration results from solubility differences between silica and oxides of aluminum and gallium under different pH conditions. In Figure 37 the solubility of silica increases with pH while gallium and aluminum oxide are practically insoluble through a pH of 4 to 9. Because normal depositional environments rarely have extremely high or low pH, silica tends to leach out of alumina-silicate rocks leaving hydroxides of aluminum and gallium behind to form bauxite.

Another geologic process that tends to concentrate gallium is hydrothermal alteration and deposition. In high temperature fluids associated with magma emplacement, gallium will tend to be incorporated into silicate minerals along with aluminum. However, if gallium-rich fluids drop in temperature and percolate through non-silicious host rocks such as limestone, the gallium will enter into the sulfide phase and enrich minerals such as sphalerite.

Empirical evidence of these processes can be seen in many domestic base metal deposits. Dr. James Stephens of the Kennecott Research Center reports gallium is present in Utah porphyry copper ore, but is associated with the higher temperature silicate phase rather than with sulfide minerals. Furthermore, Dr. Stephens indicates Kennecott's lower temperature zinc deposits from the Big Cottonwood Mining District, Utah, contains more than 700 ppm gallium. Gallium-rich zinc deposits in carbonate rocks of the mid-continent are further examples of low temperature sulfide enrichment.

Exploration Techniques

Because gallium is byproduct in nature, exploration techniques amount to exploring for such things as bauxite and zinc ores.

Exploration techniques to locate additional bauxite deposits have been outlined by the U.S.G.S. in professional paper 820 and will not be repeated here. That document also outlines a number of alternate sources of aluminum. Because gallium is associated with aluminum, these may also prove to be potential sources of gallium.

Methods used to explore for zinc deposits have also been addressed in U.S.G.S. professional paper 820. However, no special consideration has been given to those specific zinc deposits that tend to concentrate gallium.

From the information presented above, the following factors should be considered when exploring for gallium-rich zinc ores:

- Low temperature or telethermal environments of sulfide deposition
- Non-silicate host rocks

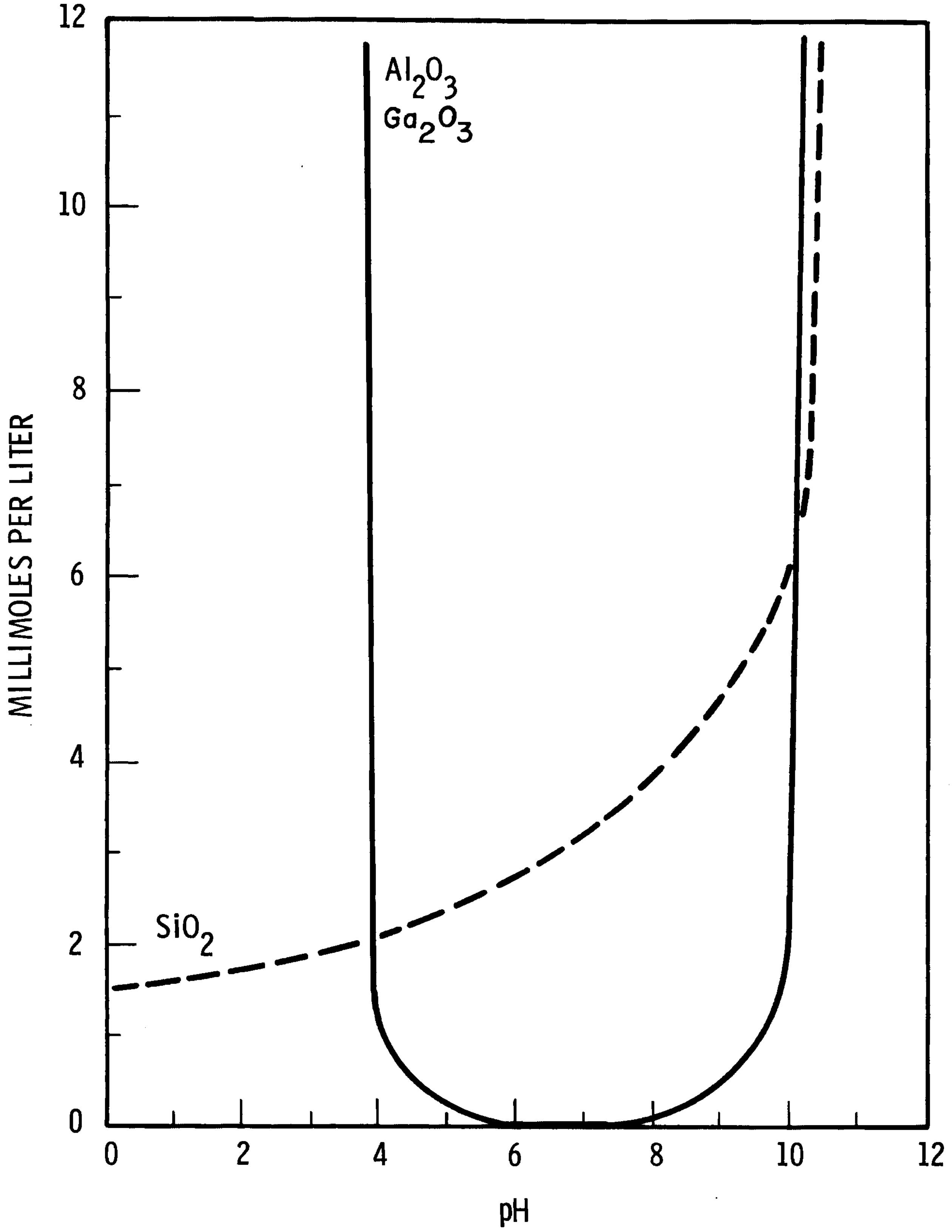


FIGURE 37. Solubilities of Aluminum, Gallium and Silica

- Absence of gallium dispersion in gangue material
- Hydrothermal transportation of base metal cations in soluble complexes

In addition to the above factors, sulfide mineral regimes that have been deposited under extremely high or low pH conditions may also tend to be enriched in gallium.

GEOGRAPHIC OCCURRENCE OF GALLIUM

Evaluating geographic occurrence of gallium involves identifying deposits of bauxite and zinc sulfide ores.

Currently, only about 10 percent of U.S. alumina production comes from domestic bauxite. Of that 10 percent, virtually all was produced from deposits in Bauxite, Arkansas. Although approximately 10 percent of domestic bauxite is produced in Alabama and Georgia, this material is used for abrasives and refractories rather than alumina(6).

In addition to bauxite reserves in Arkansas, resources also occur in weathered sections of the Columbia River Basalts in Washington and Oregon. Also, bauxite resources occur in lateritic soils of Hawaii(5).

Although little effort has been made to characterize the geographic occurrence of gallium in domestic base metal sulfide deposits, typically these are restricted to lead-zinc districts of the mid-continent. Specifically, stratabound deposits of the Mississippi Valley contain the most notable amounts of gallium.

GALLIUM RESERVES AND RESOURCES

Because gallium is closely associated with aluminum in nature, bauxite ore has been the primary host of gallium reserves. Proved reserves of bauxite within the U.S. have been well defined and documented(6,7). In addition, it can be assumed with a reasonable degree of certainty that the gallium concentration in this bauxite will be between 40 to 50 ppm. Using this concentration, arriving at gallium reserve estimates from bauxite sources is straightforward. Gallium estimates from bauxite resources are derived in a similar fashion. The only difference is a higher degree of uncertainty that is inherited from the bauxite resource estimates.

Low temperature base metal sulfide ores of the Tri-State and upper Mississippi Valley districts are also known to contain gallium. Concentrations are reported to range from 1 to 10,000 ppm gallium with a median around 45 ppm(5). However, estimating gallium resources from base metal sulfide ores is more difficult than making estimates from bauxite sources. Because gallium has a lower affinity for zinc, lead, and copper than aluminum, concentrations are highly dependent upon specific depositional environments and thus much less uniform than in bauxites. In addition, historical demand for gallium has been too low to stimulate interest within the base metal industry. As a result, base metal concentrates are seldom assayed for gallium. Thus, much less information is available on gallium occurrence in sulfide ores.

Another potential source of gallium is from furnace fly ash created by burning phosphate rock to produce elemental phosphorous. While the process is not widely known, it has progressed past the conceptual stages and was implemented on a small scale commercial basis during the early 1970's. Domestic phosphate reserves and resources are vast. However, data on gallium concentrations are lacking on all resources but the western phosphoria formation. Using this formation alone, conservative estimates of gallium from phosphate material are large.

Gallium is also contained in coal deposits. Although primary gallium concentrations in coal are low (about 7 ppm), concentrations in coal fly ash average 50 ppm, thus making coal a viable source of gallium.

From the information available, domestic gallium reserves and resources have been estimated and summarized in Table 42. More specific descriptions of the estimating assumptions are detailed in following sections.

TABLE 42. Domestic Gallium Reserve and Resource Estimates (Rounded Metric Tons of Metal)

Source	Reserves	Resources
Bauxite	2,000	15,000
Zinc Ore (Mississippi Valley)	--	1,000
Phosphate Rock (Western)	6,000	1,012,000
Coal	1,640,000	--
Total	1,648,000	1,028,000

Gallium From Bauxite

All domestic proved reserves of gallium are contained in bauxite deposits. Further, the majorityof these reserves are in Arkansas. However, small amounts occur in bauxite deposits in Alabama and Georgia.

Reserve estimates are based on the U.S.G.S. and U.S. Bureau of Mines assumption that all bauxite deposits contain 50 ppm gallium(5,7). Because domestic bauxite reserves are estimated to be 40 x 10^6 metric tons, gallium reserves from that material are estimated at 2,000 metric tons.

Total bauxite resources in the U.S. are estimated to be 300 x 10^6 metric tons. Using the above assumption that .005 percent gallium is present, total domestic gallium from bauxite is estimated to be 15,000 metric tons of contained metal.

When world bauxite reserves and resources are considered, estimates of contained gallium are very large. Total world bauxite reserves are estimated to be 27 x 10^9 metric tons while total resources are estimated at 45 x 10^9 metric tons(6). Using the above assumption that average concentration is 50 ppm, world gallium reserves and resources from bauxite are 1.35 x 10^6 and 2.25 x 10^6, respectively.

Resource estimates of gallium from bauxite are summarized in Table 43.

TABLE 43. Gallium Contained in Bauxite
(Metric Tons)

Area	Reserves	Resources
U.S.	2,000	15,000
World	1.35 x 10^6	2.25 x 10^6

Domestic Gallium Resources Contained in Phosphates

Potential resources of gallium have been identified from several sources other than bauxite rock. One significant resource is gallium byproduct recovery from flue dust produced by thermal smelting of elemental phosphorous. During this process, electrostatic precipitators recover furnace dust containing concentrations of gallium ranging from 250 to 600 ppm. That this source can be commercially feasible was demonstrated by Canyonlands 21st Century Corporation, a specialties metal firm in Utah, which actually produced gallium from phosphate residues during the mid-1970's.

Depositional environments of phosphate deposits do not tend to concentrate gallium. Of 600 samples analyzed from the phosphoria formation in the Western U.S., none contained gallium concentrations as high as the earth's crustal average (15 to 20 ppm) and the majority failed to exceed 10 ppm gallium(8). However, officials of the Stauffer Chemical Company and The FMC Corporation report their processes of burning phosphate rock to produce elemental phosphorous yields furnace dust with gallium concentrations that range from 230 to 600 ppm. Because of this secondary concentration, phosphate residues become a viable source of gallium.

Domestic deposits of phosphate material are vast. The U.S. Bureau of Mines estimates proved reserves of marketable phosphate rock to be 2.2 x 10^9 metric tons(9). In addition, a recent comprehensive study commissioned by the Department of Energy to evaluate phosphate as a source of uranium estimates total domestic recoverable phosphate resources to be 222.214 x 10^9(10) metric tons.

Because data on gallium concentrations have only been collected on the Western U.S. phosphoria formation, only that deposit will be considered in estimating gallium resources. It should be remembered that a majority of domestic phosphate material has been deposited in a marine environment similar to the western phosphoria formation. If all deposits contain similar concentrations of gallium, the following estimates will be ultra conservative.

Based on U.S.G.S. estimates, approximately 1.2 x 10^9 metric tons of phosphate rock reserves occur in the Western U.S. deposits(11). In addition, the DOE study estimates 202.3 x 10^9 metric tons of phosphate resources are potentially recoverable from this western phosphate field. Assuming the deposit has a uniform gallium concentration of 5 ppm, resource estimates of gallium have been summarized in Table 44.

TABLE 44. Estimated Gallium Contained in the Phosphoria Formation
(Assumes 5 ppm Gallium Concentration)
(Metric Tons)

	Reserves		Resources	
Area	Phosphate Rock	Gallium	Phosphate Rock	Gallium
Idaho, Utah Montana, Wyoming	1.2 x 10^9	6,000	202.3 x 10^0	1,012,000

Domestic Gallium Resources Contained in Zinc Ores

Base metal sulfides can also be a source of gallium. Low temperature stratabound deposits of the Mississippi Valley type are known to contain unusually high concentrations of gallium relative to higher temperature vein type sulfide deposits in western mountain regions(5). In fact, gallium is currently being recovered from this source by the Eagle-Picher Company in Oklahoma.

Recent quotes by U.S.G.S. zinc specialists estimate economic and paramarginal zinc resources in the Mississippi Valley and Tri-State district to be approximately 23.4 x 10^6 metric tons of contained metal. Median gallium concentrations in these zinc deposits have been reported to be about 45 ppm(5). Using this concentration, gallium resources from zinc ores are summarized in Table 45.

TABLE 45. Gallium Contained in Economic and Paramarginal Zinc Ores of the Mid-Continent (Metric Tons)

Area	Zinc	Ga Concentration	Gallium
Tri-State District Mississippi Valley	23.4×10^6	45 ppm	1,053

Domestic Gallium Resources Contained in Coal

Gallium is one of the many trace elements that occur rather consistently in domestic coal deposits. Although primary concentrations are low, gallium becomes enriched in fly ash when coal is burned, thus making coal-fired plants a potential source of the metal.

Domestic coal deposits are large; producable bituminous and sub-bituminous reserves alone are estimated to be 2.34×10^{11} metric tons(15). Assuming an average concentration of 7 ppm gallium from data presented in Chapter 5.0, it is estimated 1,640,000 metric tons of gallium is contained in these U.S. coal reserves.

GALLIUM PROCESS TECHNOLOGIES

A number of processes have been demonstrated to be viable in the commercial production of gallium. Of these processes, the extraction from aluminum industry Bayer liquors has the most significance in worldwide gallium production. What is more, the process is relatively simple and inexpensive when compared to extracting gallium from other sources. However, because gallium markets have been volatile and the amount of gallium recovered is small compared to aluminum recovered, producers are reluctant to retrofit Bayer process loops. Currently, Alcoa is the only domestic aluminum company with inplace gallium capacity.

Some domestic gallium is also produced from impurity residues isolated during zinc refining. Recovering gallium from this source is typically more complicated and labor-intensive than the Bayer process. Also, methods to recover gallium from zinc ores have not been widely used. Therefore, descriptions in the literature are very general in nature. At present Eagle-Picher Industries, Inc. is the only U.S. firm with capacity to recover gallium from base metal sulfide ores.

Phosphate flue dust has also been processed on a commercial scale for the recovery of gallium. However, when the gallium market took a down turn in the middle 1970's, this operation was closed down. The actual recovery process is considered proprietary and not available in the public domain.

Gallium From Bauxite

As a primary step in the production of aluminum, bauxite ore is digested with NaOH in a method known as the Bayer Process. After clarification and removal of insoluble red mud, the liquor is cooled and seeded with $Al_2O_3 \cdot 3H_2O$ which causes the sodium aluminate to hydrolyze to caustic and precipitate alumina trihydrate. Spent liquor is recirculated while the $Al_2O_3 \cdot 3H_2O$ is washed, calcined and electrolytically reduced to aluminum.

Mother and recycle liquors produced in the Bayer Process loop serve as feed stock in gallium production. If gallium is not removed from the Bayer liquor it will build up to a saturation equilibrium point at which time additional gallium entering the system will be lost to red mud or alumina. When gallium is removed from the liquor, the gallium equilibrium concentration will drop accordingly.

Liquor carefully treated with CO_2 will preferentially precipitate alumina (Al_2O_3) and thus enrich the solution in gallium. This gallium-rich solution is then treated electrolytically to produce metallic gallium. A simplified flowsheet of the process is given in Figure 38.

When evaluating gallium extraction efficiency, the liquor equilibrium concentration must be considered. Specifically, gallium will concentrate in the solution until an equilibrium is reached, at which time the remaining gallium will leave the system in red mud or alumina. If gallium is recovered from the liquor, this equilibrium concentration will drop accordingly. Likewise, there is an optimal operating concentration past which further gallium recovery will yield a diminishing return. Because gallium concentration is a function of the amount of mother liquor treated, it is possible to determine an optimal operating volume as a percent of the total liquor.

In a study done by Alcoa Company, this relationship has been illustrated rather well(12). A gallium material balance equation was written as follows:

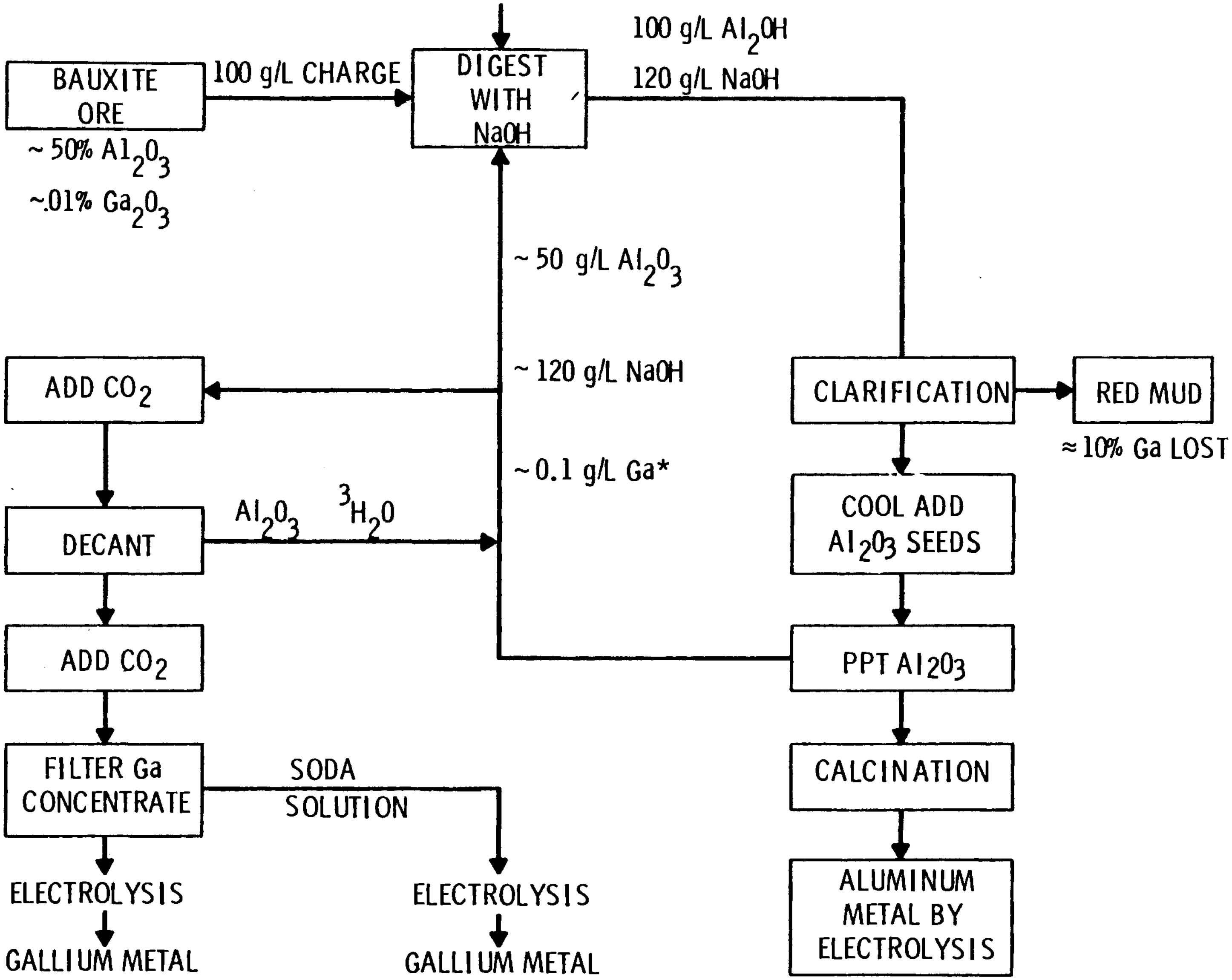


FIGURE 38. Gallium Recovery from Bayer Liquors

*When equilibrium is reached ≈0.1 g/l Ga is present throughout the loop in the form of sodium gallate ($NaGaO_2$)

$$\text{Ga in Bauxite} = \underset{\text{red mud}}{\text{Ga in}} + \underset{\text{alumina}}{\text{Ga in}} + \underset{\text{production}}{\text{Ga}}$$

$$Gb = (M)(Gm) + (K)(C)(E) + \frac{(P)(E)}{A}$$

WHERE:

Gm = % gallium in red mud

Gb = % gallium in bauxite

M = units of red mud to units of bauxite

K = constant, relating Ga in Al_2O_3 to Ga in liquor

C = gallium concentration in liquor

E = % Al_2O_3, extracted from bauxite

P = production of gallium (grams per liter of flow)

A = Al_2O_3 yield

Assuming the gallium concentration of treated liquor falls to 0.003 g/l and that 75% of the gallium entering the system can be recovered, values were calculated for a typical processing plant using Arkansas bauxite with an annual throughput of 1.97 x 10^6 metric tons. In addition, the Arkansas bauxite was reported to have the following characteristics:

M = .57

E = 48.5%

Gb = .0067%

Gm = .0007%

Calculated results of gallium recovered as a function of percent mother liquor processed are given in Table 46.

TABLE 46. Gallium Recovery From Arkansas Bauxite

Percent Mother Liquor Processed	Ga Concentration M Liquor (gram liter)	Recovered Ga per Units Bauxite (x 10^{-6})	Possible Annual Ga Production (Metric Tons)
0	.119	-	-
1	.106	7.18	14.1
2	.095	12.87	25.3
5	.073	24.44	48.0
10	.053	34.88	68.6

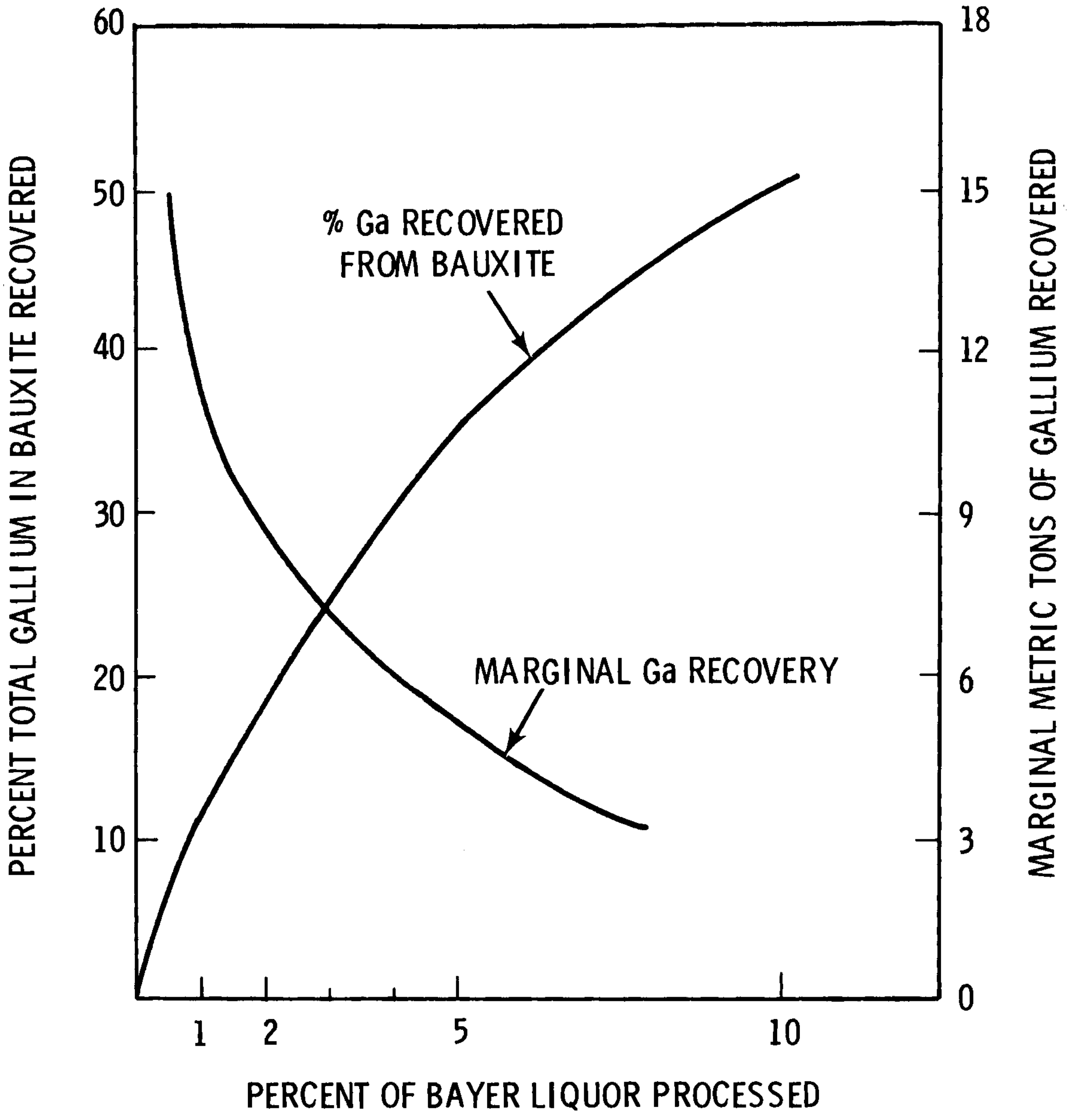


FIGURE 39. Gallium Recovery Efficiency from Bayer Liquors

Marginal recovery can be plotted by normalizing the change in gallium production as a percentage of the change in liquor processed. These values have been displayed graphically in Figure 39.

Considering the gallium that is lost to red mud, nearly all recoverable gallium is extracted after a relatively small percentage of total liquor has been processed. In addition, marginal returns decrease rapidly as an increasing percent of the mother liquor is processed. This data will be useful when considering supply in a later section.

Gallium From Zinc Ores

Residues from domestic zinc refining are a commercial source of gallium. Currently, the Eagle-Picher Company is recovering gallium as a byproduct of zinc processing at their plant in Quapaw, Oklahoma.

Of the methods used to recover zinc, the pyrometallurgical process is the only one that naturally concentrates gallium in recoverable quantities. A general schematic of this materials flow is given in Figure 40.

Zinc ore is first crushed and concentrated by flotation before being roasted to volatize sulfur and produce zinc oxide. In the pyrometallurgical process this treated concentrate is then sent to be smelted.

Because of gallium oxide's low vapor tension and high boiling point, the gallium becomes concentrated in smelter slag along with lead and iron. When these residues are leached with sulfuric acid, the gallium and iron are dissolved leaving the lead in residue. Zinc oxide is then added to precipitate hydroxides of gallium and iron. Following this, gallium is leached with hydrochloric acid and transferred to an ether phase by the addition of ether. Distillation then produces a gallium-rich residue. Finally sodium hydroxide is used to dissolve the gallium so it can be electrolyzed to a pure metal.

Because the exact process is considered confidential, detailed material balances are not available. Thus, it is difficult to quantify gallium recovery efficiency. However, officials of the Eagle-Picher Company have supplied estimates of recovery from a typical ore averaging 4% zinc. These estimates are given below in Table 46.

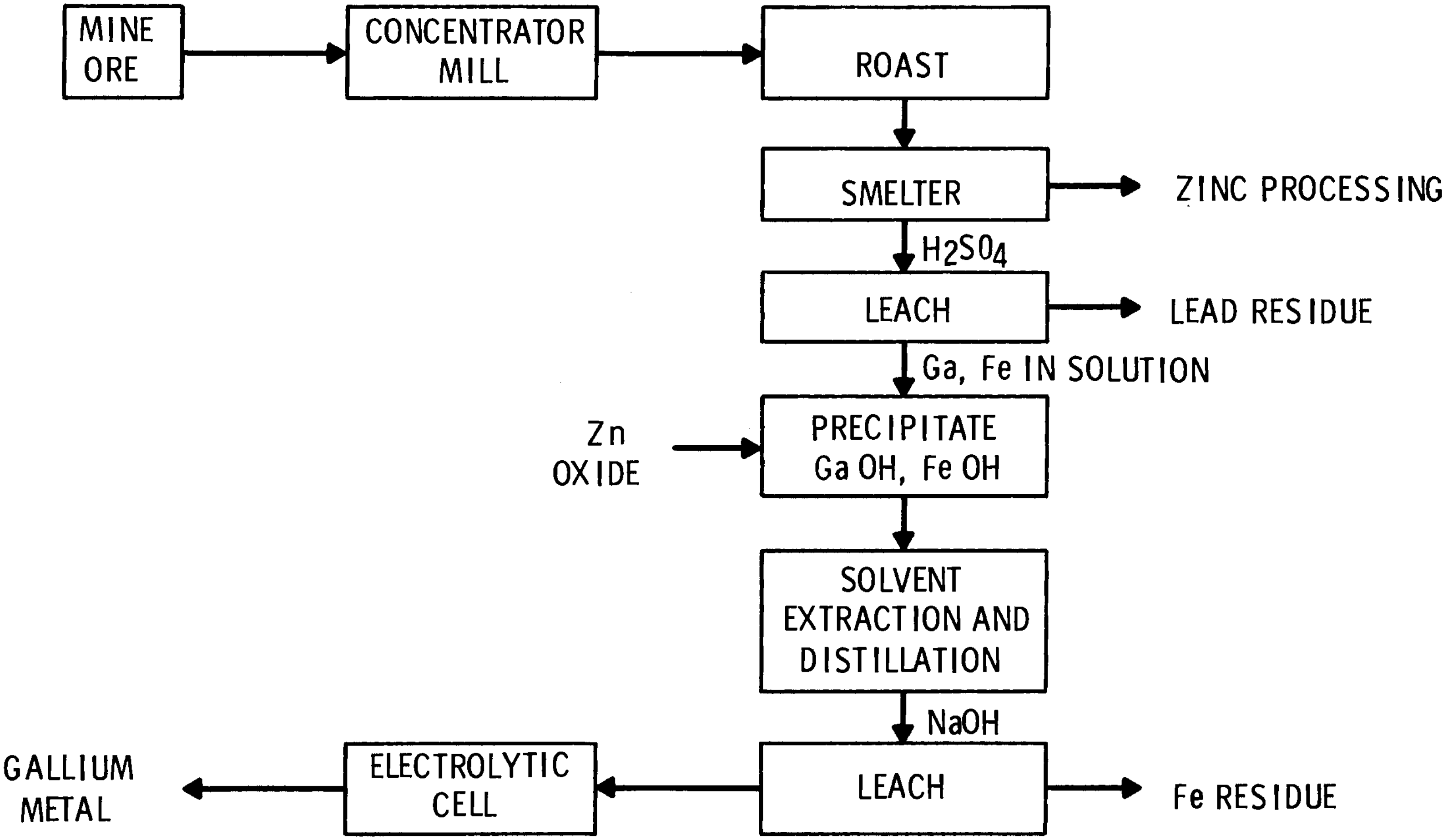


FIGURE 40. Gallium Recovery from Zinc Processing

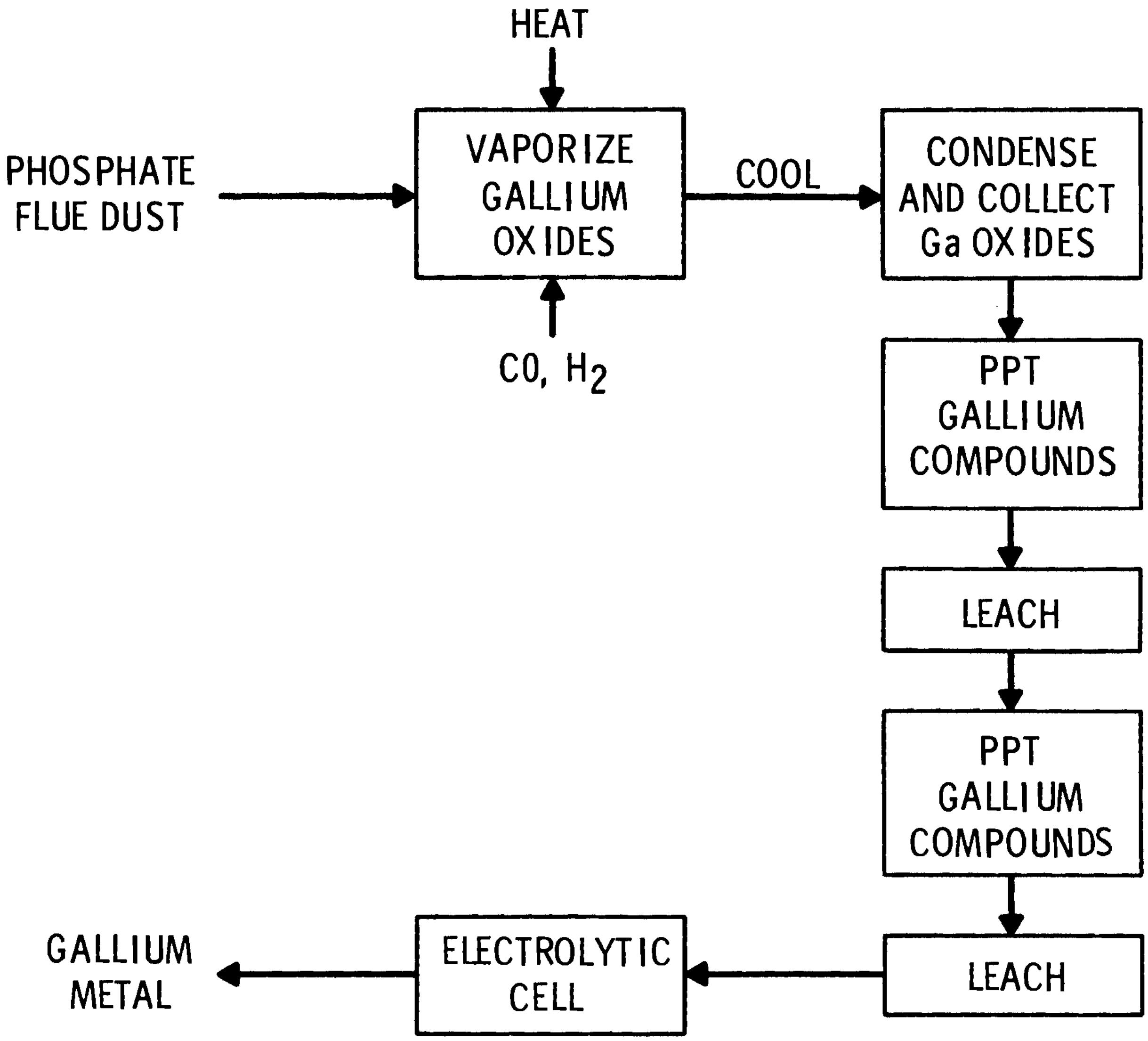


FIGURE 41. Gallium Recovery from Phosphate Flue

TABLE 46. Estimated Recovery Efficiency of Gallium From Zinc Ore

Process Step	Approximate Percent Gallium Lost
Mining	15
Concentrating Mill	20
Smelter	40
Metal Refining	5
Overall Losses	80

Gallium From Phosphate Flue Dust

Phosphate material contains gallium in concentrations at or below the established Clarke value. However, when this material is burned to produce elemental phosphorous, the plant flue dust can contain concentrations up to 600 ppm gallium. Research on methods to recover this gallium has been conducted by the U.S. Bureau of Mines, Eagle-Picher Industries, Inc., and the Monsanto Corporation(13). During the early 1970's a recovery process was commercialized by the Canyonlands 21st Century Corporation of Blanding, Utah.

Descriptions of the commercial process to recover gallium from phosphate are considered proprietary and have not been placed in the public domain. However, early work by the Bureau of Mines developed many of the concepts that are believed to be used in the process. In general, the flue dust is heated in a reducing environment to volatize the gallium and produce a vapor rich in lower oxides of gallium.

Depending on the source material, phosphate flue dust will often contain enough unburned carbonaceous material to create a reducing environment. If reductants are absent in the primary material, volatilization of lower oxides can be enhanced by introducing reagent gases such as Co and H_2. Once the gallium compounds have been vaporized, they are collected by impinging the gas upon some cooled absorbing solution. After being concentrated in solution, the gallium is further concentrated by a series of leaching and reprecipitation. It is assumed the final production of gallium metal would be from an electrolytic cell as in the Bayer and zinc ore processes. A generalized conceptualization of the process is shown in Figure 41.

Because the exact process is not known, evaluating gallium recovery efficiency is difficult. During the laboratory scale volatilization research conducted by the Bureau of Mines, it was demonstrated between 75 to 97 percent of the gallium was recovered from phosphate flue dust as lower oxide or trichloride.

Officials of the Canyonlands 21st Century Corporation indicate the efficiency of their process was as high as 98%. However, they are currently working on a new recovery process that is less costly but also less efficient. Their feeling is that if gallium is recovered from phosphate flue dust in the future this new process will be used and will have an efficiency of about 66%.

Gallium From Coal

Domestic coals have an average gallium concentration of about 7 ppm. However, when coal is burned, gallium concentrations in the fly ash can range from 20 to 100 ppm.

Gallium has been recovered from coal fly ash in the past and the process considered to be viable. Given the vast domestic coal resources, fly ash may be an alternative to foreign bauxite as a source of gallium. Because of this, fly ash has been investigated in greater depth than the other, more conventional, sources of domestic gallium. Specifically, coal fly ash supply and recovery points were identified and evaluated and process costs developed. In addition, economic factors and institutional constraints were reviewed. Finally conclusions are drawn and recommendations are offered.

This complete investigation is presented in a later chapter. However, salient data will be abstracted and included in the following sections.

GALLIUM SUPPLY CONSIDERATIONS

When recovery factors are applied to raw material reserve data, long-term gallium supply can be estimated. Specifically, 800 metric tons of gallium are available from U.S. bauxite reserves, 210 metric tons from mid-continent zinc reserves and 1584 metric tons from western phosphate reserves. In addition, 820,000 metric tons of gallium could be supplied from producable U.S. bituminous and sub-bituminous coal reserves. On an annual basis, about 12 metric tons of gallium could be supplied from domestic zinc and bauxite sources combined with an additional 5 tons coming from phosphate flue dust and 1200 tons from coal fly ash. An estimated 1500 metric tons of gallium per year could currently be supplied from world bauxite and alumina production. By the year 2000 it is estimated 5000 metric tons of gallium per year could be supplied from world bauxite sources.

Both long and short-term domestic gallium supply is summarized in Figure 42. More specific descriptions of the estimating procedures and assumptions made are outlined in following sections.

Gallium Supply From Bauxite

Under existing technology, it is estimated 600 metric tons of gallium could be recovered from U.S. bauxite reserves. Although the gallium contained in domestic bauxite reserves is much larger than 600 metric tons, technological and economic factors reduce the amount that can be considered supply.

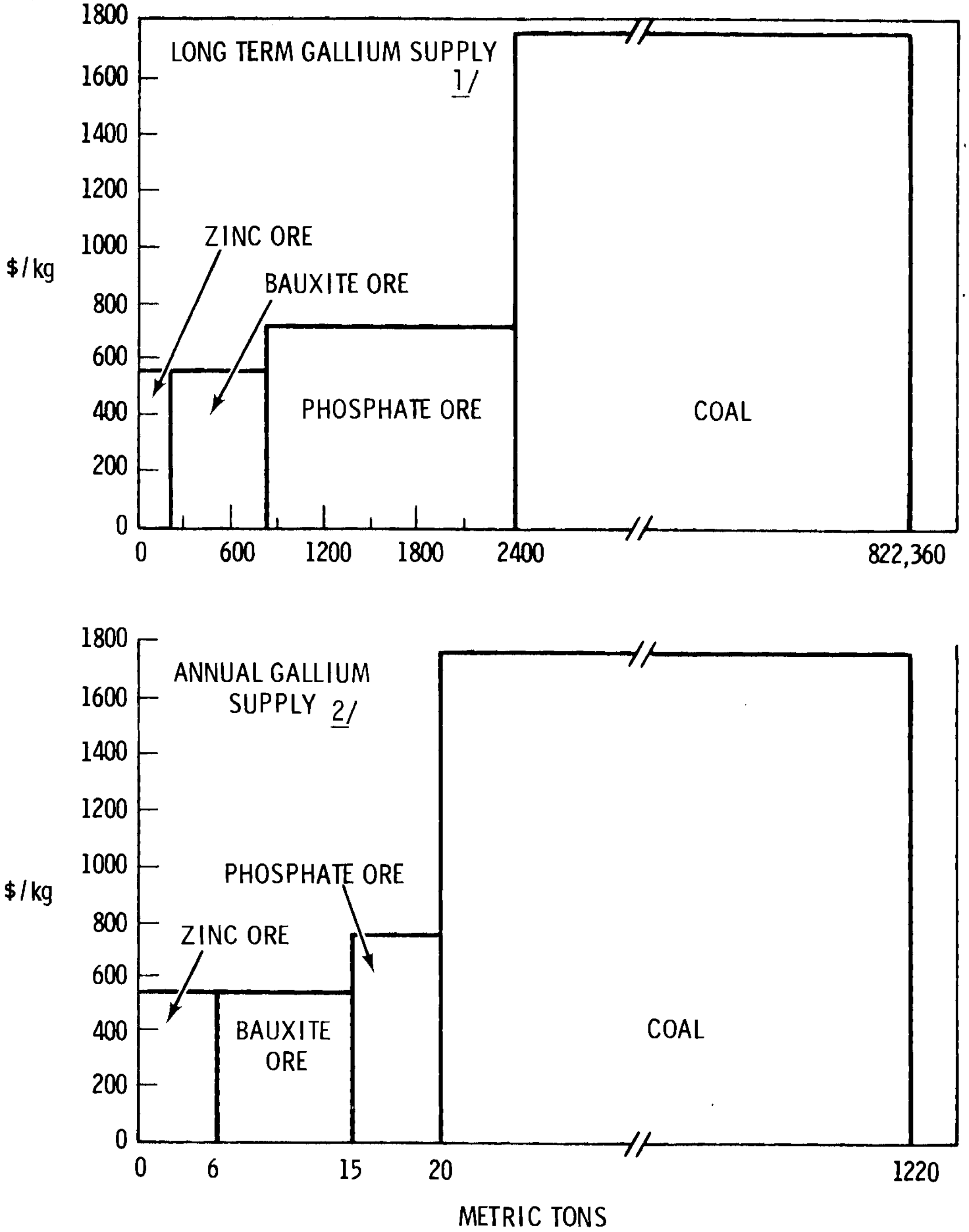
A substantial amount of gallium is lost to red mud residues. In Arkansas bauxites, this loss is approximately 10% but can go as high as 50% in some foreign ores.

Further, the diminishing marginal product curve shown in Figure 39 indicates gallium equilibrium concentration drops dramatically when a relatively small percentage of mother liquor is processed. Because a firm will produce at a point where the value of the last unit produced equals the additional cost of that unit, estimating production levels requires knowledge of market demand and marginal revenue. Scenarios developed in Chapter 3.0 estimate cumulative totals for gallium demand needed to produce 25 GW of peak photovoltaic capacity in the year 2000 will be 309 and 25,265 metric tons for the advanced concentrator and polycrystalline cells, respectively. Because this increased demand will undoubtedly disrupt current markets, estimating price and therefore marginal revenue, is extremely difficult. However, production levels of gallium can be estimated by other means.

As the mother liquor gallium concentration drops below 0.05 grams/liter, recovery decreases rapidly and unit production costs increase as larger volumes are processed to extract smaller amounts of gallium. Thus, it is unlikely a producer would operate below that concentration. From Table 46 the optimal operating range is between 5 to 10% of the mother liquor. This operating range would limit recovery to about 40% of the total gallium in bauxite.

If a 10% mining loss is assumed, then no more than 30% of proved domestic gallium reserves in bauxite will ever become supply under existing technology.

Because supply is defined as a quantity at some specific cost, the cost of producing gallium must also be determined.



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1. Total amount recoverable from proved reserves
2. Amount that could be produced with existing online capacity and recoverable gallium from online powerplant fly ash

FIGURE 42. Domestic Gallium Supply

Currently only two domestic sources are producing gallium and all cost data is considered company confidential. However, recent trends in the marketplace may be an indication of production costs. Between 1975 and 1976 the price of gallium underwent a rapid decline from $800 per kilogram to $550 per kilogram and has been oscillating around that lower price for the past four years. Given that there is excess gallium on the market, this price of $550/kg can be taken to reflect a minimum acceptable price or, in effect, the cost of production.

Using the above assumptions that 30% of the gallium can be recovered from domestic bauxite reserves at $550/kg in 1979 dollars, the long-term supply from that source is 600 metric tons.

Estimating gallium supply in the short term requires knowledge of existing production capacity. In a study on gallium done by the Alcoa Company, an estimate of total U.S. gallium capacity was given as 10 to 12 metric tons per year(12). It was also estimated that 95% of world gallium comes from bauxite sources with the remainder from zinc systems. However, there is no evidence to suggest what this relationship holds for domestic capacity. Officials of the Eagle-Picher Company report their current gallium production is about 3 metric tons per year and they estimate Alcoa's online capacity may be three times that amount. If Alcoa would produce at total capacity, the domestic annual gallium supply from bauxite is estimated to be 9 metric tons at $550/kg.

Gallium supplied from world bauxite production to the year 2000 can also be estimated. Total world bauxite processed in 1978 is estimated to be 84 million metric tons(6). If we assume an industry growth rate of 6 percent per year, a gallium content of 40 ppm and a gallium recovery of 40 percent, about 5000 metric tons of gallium per year could be supplied by the year 2000. The estimated gallium supply from world bauxite is presented in Figure 43.

Gallium Supply From Zinc Ore

Long-term gallium supply from domestic zinc ores under existing technology is estimated to be 210 metric tons of contained metal. In addition, it is estimated that 6 tons of gallium could be produced annually as a byproduct of zinc.

From the information on gallium occurrence presented earlier, it will be assumed that zinc ores from the Mississippi Valley and Tri-State District contain the highest and most consistent concentrations of gallium. Thus, only these ore deposits will be included when estimating gallium supply from base metal sulfide sources.

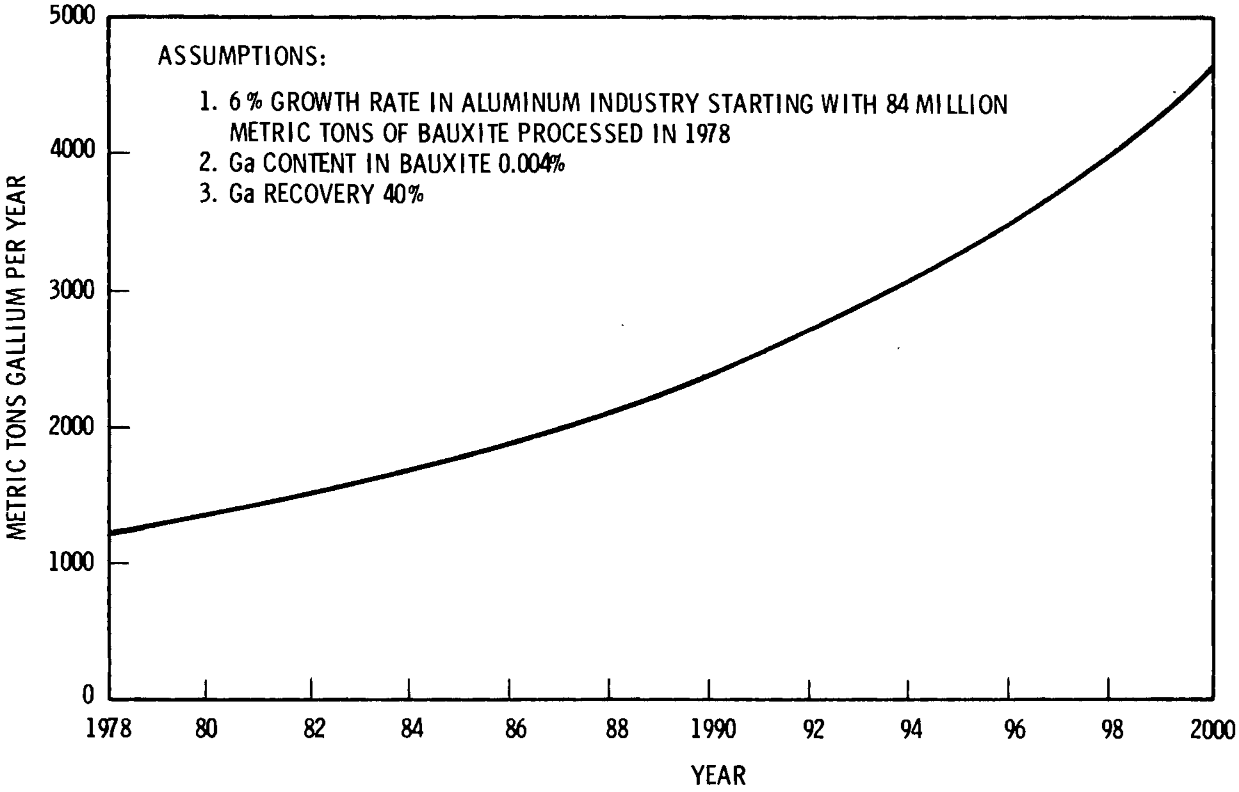

FIGURE 43. Annual Gallium Supply from World Bauxite

An assumption must also be made that the majority of zinc is contained in sphalerite mineralization and that the gallium-to-zinc concentration ratio in this sphalerite averages between .0045 and .005 percent.

Supply estimates should also consider recovery efficiency of existing technology. Alluding to efficiency data presented in an earlier section, it was seen that current operations producing gallium from sphalerite are only about 20% efficient.

Obtaining cost information on producing gallium from zinc can be difficult. Currently, the Eagle-Picher Company is the only domestic producer recovering gallium from sulfide ores and they consider their cost information to be confidential. However, officials of the Eagle-Picher Company indicate that at the present price of \$550/kg, revenues will just cover variable costs of production with a small margin for capital recovery. Thus, it can be assumed that current market price is not substantially different from the total cost of production.

Current U.S.G.S. estimates of economic and paramarginal zinc ores in the Tri-State and Mississippi Valley District are quoted by zinc specialists as being 23.4×10^6 metric tons of contained zinc. Assuming a gallium-to-zinc ratio of .0045 percent as well as an overall recovery efficiency of 20 percent, the long-term gallium supply from zinc ore under existing technology is estimated to be 210 metric tons of contained metal at a 1979 cost of \$550/kg.

Because the Eagle-Picher Company is the only domestic producer of gallium from zinc, annual supply from that source is a function of their online capacity. Eagle-Picher officials indicate they are currently producing about 3 metric tons of gallium per year from zinc residues. However, they also report their maximum production from existing capacity is around 500 kg/month or double current production. Thus, it is estimated the annual domestic gallium supply from zinc is 6 metric tons at a price of \$550/kg.

Gallium Supply From Phosphate Material

Gallium supply potentially available from phosphate material contained in the western phosphoria formation is estimated to be 1580 metric tons. Furthermore, an estimated 5 tons of gallium could be produced annually from this source with existing online capacity.

Although phosphate rock only contains around 5 ppm gallium, when the material is burned to produce elemental phosphorous, concentrations in the flue dust can be as high as 600 ppm gallium. Thus, phosphate rock is a potential source of gallium supply.

Domestic reserves of phosphate material are mainly contained in the phosphoria formation of Idaho, Montana and Utah as well as in formations along the Mid and Southern Atlantic Seaboard. Unfortunately, data on gallium content has only been systematically collected from deposits within the phosphoria formation. Therefore, only these phosphate reserves will be used to estimate domestic gallium supply from phosphates.

From phosphate reserves outlined in earlier sections, it was seen that 1.2×10^9 metric tons of phosphate rock reserves are contained in the western phosphoria formation. Assuming a constant gallium concentration of 5 ppm, approximately 6000 metric tons of gallium are contained in the rock.

Estimating potentially available gallium supply from phosphate must consider mining and milling losses. In a comprehensive study on phosphate reosurces recently done for the Department of Energy, combined mining and milling losses averaged about 60 percent. Using data presented in the phosphate resource section, recovery efficiency for extracting gallium from phosphate flue dust will be taken as 66 percent. Based on these assumptions, the long-term supply of gallium from western phosphate material can be estimated by the following computation:

$$\text{Long-Term Supply from Phosphate} = (1.2 \times 10^9)(5 \times 10^{-6})(.66)(.40) = 1584 \text{ metric tons}$$

Associating a cost with this gallium is difficult considering the recovery technology is not public information. However, an interview with one of the founders of Canyonlands 21st Century Corporation disclosed that an average 1973 cost to produce gallium from phosphate flue dust was around $0.45 per gram. When this price is escalated to current dollars using an inflation rate of 8%, the 1979 cost to supply gallium from phosphate residue would be around $715/kg.

Short-term supply of gallium from phosphate can also be estimated. Data on phosphate flue dust currently being produced has been obtained from chemical firms operating in the western states and summarized in Table 47.

TABLE 47. Annual Production of Western Phosphate Flue Dust

	Chemical Firm (Tons in Metric)	
	FMC	Stauffer
Plant Capacity (tons ph/year)	145,000	37,000
Dust Production (tons/year)	13,000	5,000
Gallium Concentration in Dust (ppm)	230 to 480	300 to 600
Stockpiles of Dust (tons)	--	200,000

In addition, the Monsanto Corporation in Soda Springs, Idaho burns phosphate rock and collects flue dust. While they did not release specific information, it is known their plant capacity is approximately 110,000 tons per year(14). Based on data from the other two producers, it is estimated Monsanto's plant could produce approximately 11,000 tons of gallium-rich dust per year.

If the dust output from all three plants is combined and assumed to have an average gallium concentration of 360 ppm, over 10 metric tons of recoverable gallium are being concentrated annually from western phosphate material. However, capacity does not currently exist to recover all of this gallium.

Given availability of these raw materials, Canyonlands 21st Century Corporation estimates it could bring their recovery process back online and in less than a year's time produce at near capacity of around 5 tons of gallium annually.

Gallium Supply From Coal

The potential long-term supply of gallium in domestic coal is estimated to be 820,000 metric tons. In addition, if gallium is recovered from fly ash currently produced by large domestic utilities, annual gallium supply could be increased by 1200 metric tons.

Reserves of producable bituminous and sub-bituminous coal in the U.S. are estimated to be 2.34 x 10^{11} metric tons(15).

Data presented in Chapter 5.0 estimates domestic coal averages 7 ppm gallium. Also, gallium losses are stated to be 30 percent in coking and 20 percent in the gallium recovery process. Using this information, it is estimated 820,000 metric tons of gallium could be supplied from domestic producable bituminous and sub-bituminous coals alone.

Several scenarios are used in Chapter 5 to estimate annual gallium supply from domestic coal. Using only those domestic utilities that consume at least 465,000 metric tons of coal per year and assuming the fly ash produced contains 50 ppm gallium, as much as 1200 metric tons of gallium per year could be supplied from coal.

Again, abstracting data from Chapter 5.0, it is estimated this gallium from coal fly ash could be produced for about $1.78 per gram.

INDUSTRY AND MARKET FACTORS

Currently there are two domestic producers of primary gallium. A third firm has online capacity to produce primary gallium but is currently only recovering recycle scrap. In constant dollars gallium prices have undergone a steady decline over the past 25 years. At present the industry is operating far below capacity.

Current and historical market conditions are useful in characterizing the general nature of the gallium industry. Specific information on these market factors are presented below.

Gallium Industry Structure

Domestic gallium production is limited to the Alcoa Company of America, Eagle-Picher Industries, Inc., and Canyonlands 21st Century Corporation. Alcoa and Eagle-Picher produce primary gallium while Canyonlands recovers gallium from new scrap and gallium-bearing electronic components.

The Eagle-Picher Company reports its current production of gallium is about 3 metric tons per year and they estimate Alcoa is producing between 5 and 6 tons per year. It is not known how much gallium scrap Canyonlands recycles per year. However, officials of that company report the domestic gallium scrap market is between 3 to 4 metric tons per year and they feel Canyonlands has the majority of the market.

Alcoa's gallium processing capacity is located in Bauxite, Arkansas and is a byproduct recovery of aluminum production. The raw material is primarily domestic bauxite from Arkansas; however, some mixing of foreign ores may occur. A gallium recovery loop was also installed at one of Alcoa's alumina plants in Mobile, Alabama. However, after completion in 1975, the gallium market took a down turn and that facility ceased operation. The state of readiness of the Mobile plant is not known.

Gallium is also recovered as a byproduct of base metal production by Eagle-Picher Industries, Inc. at their processing facility in Quapaw, Oklahoma. Although company officials report current production is only about 3 tons, they feel online capacity is double that amount. One source of gallium was lost when the Environmental Protection Agency recently closed down an Eagle-Picher mine in Kansas. However, company officials indicate they are optimistic about obtaining gallium-rich residues if the gallium market takes an upturn.

Canyonlands 21st Century Corporation is the third member of the domestic gallium industry. That company was founded in the early 1970's to recover rare metals from new scrap and recycled electronic components.

Subsequently, the firm developed a commercial process to extract gallium from phosphate flue dust. This process of primary gallium recovery was discontinued when the price dropped in the late 1970's. However, the capacity is intact and could be restarted in a relatively short time.

Currently, Canyonlands is only producing gallium from new scrap. The firm's primary sources of gallium are listed in Table 48.

TABLE 48. Sources of Recycle Scrap Gallium Processed by Canyonlands 21st Century Corporation

Source	Percent Gallium Present
Metal (up to 4 9's purity)	90 to 100
Chips and Wafers	45
Chip Cuttings	40
Epitaxial Conductors	35
Lapping Compounds	1 to 15

Company officials indicate recovery efficiencies for scrap are about 90% if the scrap contains over 20% gallium and about 60% if the scrap contains less than 20% gallium.

Interviews with one of the company founders indicates the firm would like to again become a primary producer of gallium from phosphate flue dust. Currently, they are working on an extraction process that is less efficient in gallium recovery, but significantly cheaper than the one previously used. Should this process prove commercially competitive, the gallium industry will have three primary producers.

Historical Market Conditions

The price of gallium dropped dramatically from \$93/troy oz in 1954-59 to \$22/troy oz in the early 1970's (Table 49). This drop in price is due to the continual increasing consumption of gallium (Table 50) which allowed domestic producers to add larger, more efficient processing equipment, reducing their unit costs of production. In the 1950's and '60's, gallium was used exclusively in the research and development of light-emitting diodes (LED's) used in calculators and digital watches. Domestic consumption was only 37 kgs in 1954, and rose to 1561 kgs in 1969. LED's became commercially available in the late 1960's and early '70's with domestic consumption of gallium rising to 8496 kg in 1973. By the mid-1970's, liquid quartz was substituted for LED's in calculators and digital watches, reducing the consumption of gallium. Since the domestic gallium producers expected the LED market to continue to grow, they overexpanded their production capacity in the 1960's, and stocks of gallium began to develop and gallium producers reacted by lowering the price of gallium.

Recently, gallium has continued being used in the research and development of new products. Some of these include: infrared laser diodes for telephone transmission, magnetic bubble memories for information storage and manipulation, high-field superconducting magnets for fusion and magnetohydrodynamic power systems, and photovoltaic solar cells.

POTENTIAL GALLIUM PRODUCTION CONSTRAINTS

Background data on gallium recovery technology and market factors provide some insight into potential production constraints. When this data is combined with information obtained through interviews with industry officials, several problem areas can be identified as having a negative impact on the future availability of domestic gallium production. Factors seen as having the most significant effect on future gallium availability are as follows:

- Industry officials perceive future volatility and risk.
- Gallium economics relative to aluminum economics do not justify retrofitting primary alumina loops.
- Lack of long-term incentives in gallium market.
- Phosphate production changing from thermal to wet process.

Clearly, there is some interrelationship between these potential production constraints. However, in an effort to better understand some of the problems, each will be discussed individually.

TABLE 49. Gallium Price
($ per Troy oz)

Year	Current Dollars	1972 Constant Dollars
1954	93.31	156.32
1955	93.31	153.02
1956	93.31	148.35
1957	93.31	143.51
1958	93.31	141.25
1959	13.31	138.20
1960	80.87	117.77
1961	69.98	101.01
1962	54.43	77.15
1963	37.32	52.13
1964	37.32	51.33
1965	37.32	50.22
1966	37.32	48.62
1967	37.32	47.23
1968	37.32	45.20
1969	21.77	25.10
1970	21.77	23.83
1971	21.77	22.67
1972	21.77	21.77
1973	21.77	20.55
1974	21.77	18.73
1975	24.88	19.65
1976	17.11	12.79
1977	17.11	12.07
1978	17.11	11.19

TABLE 50. Domestic Gallium Consumption

Year	Domestic Consumption[a] (kg)
1954	37
1955	32
1956	39
1957	30
1958	76
1959	118
1960	172
1961	180
1962	140
1963	185
1964	305
1965	373
1966	313
1967	764
1968	1217
1969	1561
1970	1297
1971	2289
1972	5076
1973	8496
1974	6941
1975	7493
1976	8880
1977	8789
1978	8500

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a. 1954-1974 data from Mineral Facts and Problems, Bureau of Mines #667, Washington, D.C., 1975, p. 406.

1975-1978 data from Mineral Commodity Summaries 1979, Bureau of Mines, Washington, D.C. 1979, p. 54.

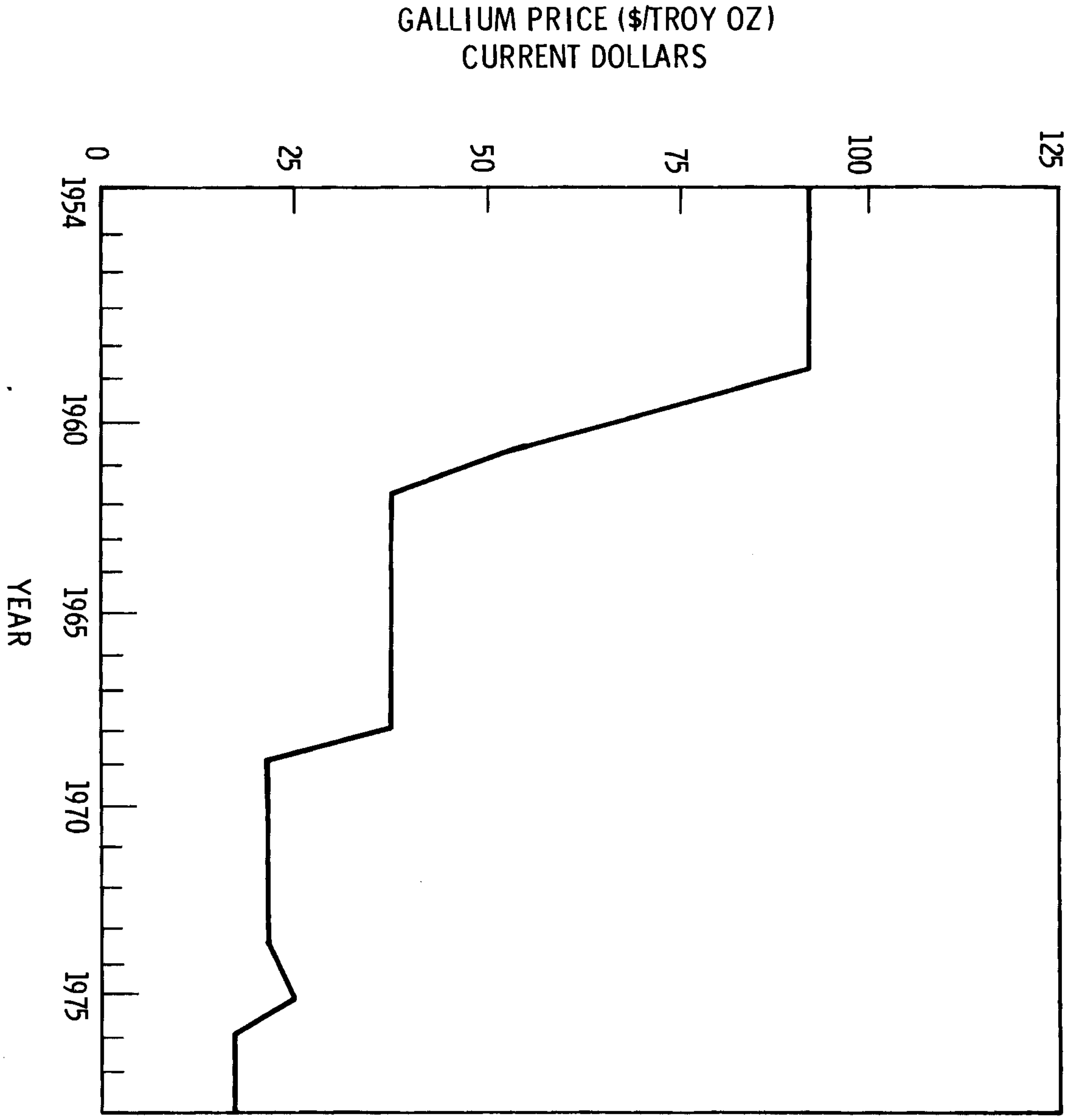

FIGURE 44. Historical Gallium Price

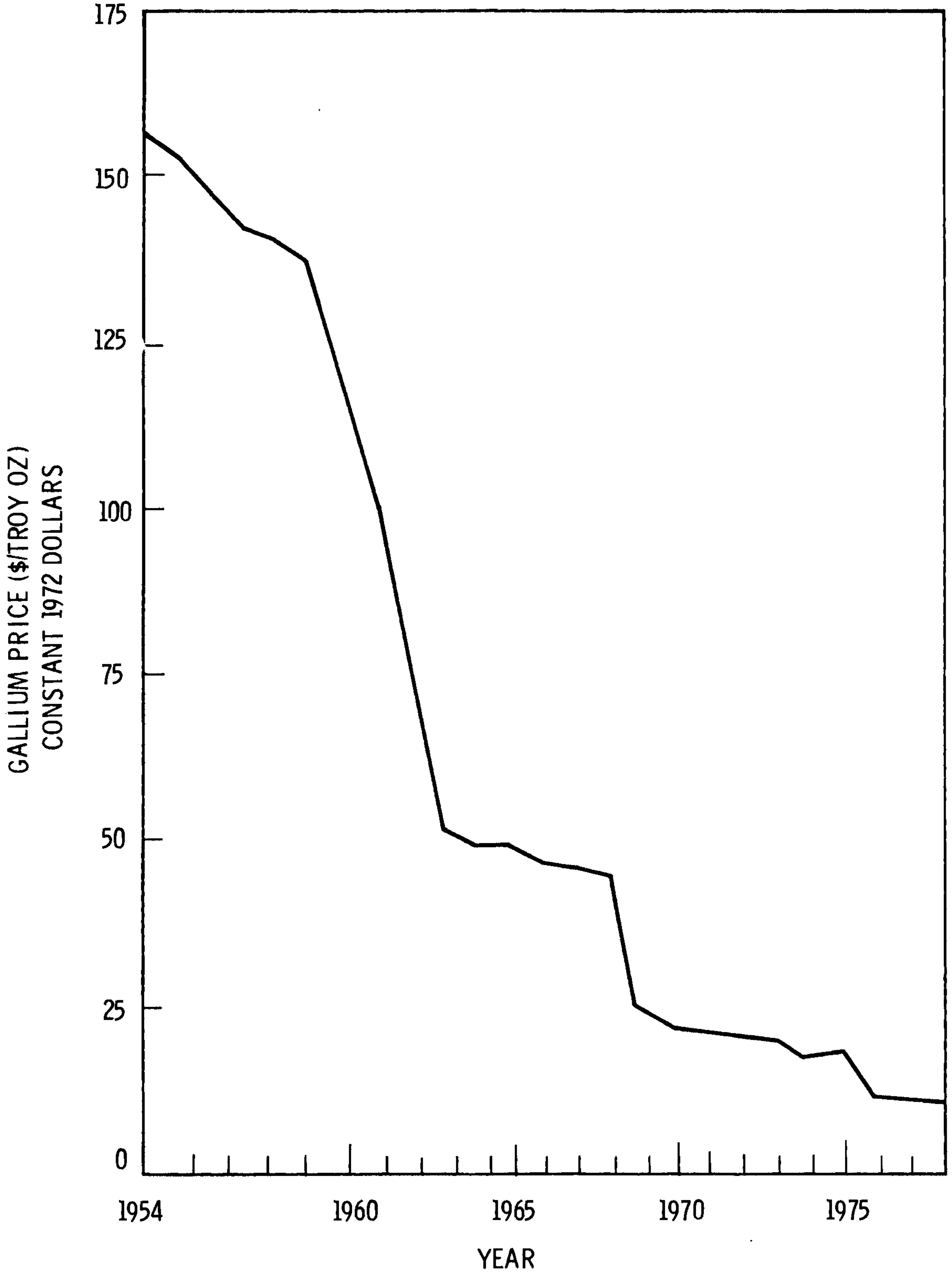

FIGURE 45. Historical Gallium Price

Industry Perception of Market Risk

A significant factor that would tend to constrain gallium producers is their perception of volatility, and therefore risk, in future markets.

There was a great deal of anticipation among potential gallium producers during the late 1960's over the prospect of profitable markets in the electronics industry. These markets did materialize and demand was high during the early 1970's. However, the phenomenon was short-lived. When liquid crystals replaced LED's in watch and calculator displays, a large percentage of the gallium markets disappeared interrupting anticipated cash flow. Producers that had financed capital expansion with debt had to meet fixed charges with funds from operations other than gallium. In addition to creating a weaker balance sheet, there is greater variability in cash flows and, thus, greater risk to the firm.

Industry officials that were interviewed conveyed a feeling of caution with regard to future gallium production. Officials of Eagle-Picher Industries feel any large increase in gallium demand from photovoltaics would only last until the next generation of technology evolved and serve to create short-lived, chaotic markets similar to the LED boom. What is more, they feel an expansion of gallium capacity by alumina producers would be especially detrimental to producers of gallium from base metal ores. Specifically, alumina producers have a greater degree of protection in times of overcapacity because extracting gallium from Bayer liquor is less complicated and less labor-intensive than the base metal gallium recovery process. Thus, the first marginal producers to drop out would be base metal producers of gallium.

There is a general feeling among potential gallium producers that the industry is characterized by large variability in future cash flows and thus high risk. Incentives to make large capital commitments to gallium production would have to be either a high profitability offsetting the risk of income variability or long-term contracts lowering the risk of income variability.

Economics of Primary Aluminum vs. Byproduct Gallium

When the economics of aluminum are compared to its byproduct gallium, insight can be gained as to why aluminum producers are reluctant to disrupt Bayer loops for gallium recovery.

In the aluminum industry, plant capacity is measured in digester units, where one digester unit can process 1.5 million pounds of Al_2O_3 per day. Typically, an aluminum plant will range from 2 to 4 digester units.

Gallium efficiency calculations presented in the gallium supply section were based on throughput of the Alcoa Arkansas plant which has a 4-digester capacity of about 990,000 metric tons of Al_2O_3 per year. Assuming an approximate aluminum-to-alumina ratio of .52, about 515,000 tons of aluminum can be recovered each year from the Arkansas plant.

By comparison, if a gallium recovery process operated in the optimal recovery range by treating between 5 to 10 percent of the mother liquor, only about 50 MT of gallium could be recovered annually.

At 1978 prices, this annual production would represent about 620 million dollars in revenues from aluminum and about 28 million dollars in gallium revenues. Although data on profitability are not available, insight can be gained by looking at historical market conditions of aluminum and gallium.

The aluminum industry has had strong markets and generally increasing prices since the 1950's. Because of these conditions, we can assume aluminum producers are recovering capital investments and making normal economic profits.

In contrast, the gallium industry has had a history of declining market conditions. Rapid changes in technology has caused declining demand and the gallium industry has been left with overcapacity. As a result, gallium prices have been falling in both real and nominal terms since the middle 1950's. Considering these declining market conditions, it can be assumed medium to long-term profitability in the gallium industry has been marginal.

In an aluminum plant with a capacity of 4 digesters, gallium sales would represent only 4 percent of total revenue under current conditions. Considering the risk associated with the gallium market, there is no incentive for aluminum producers to retrofit Bayer loops with gallium recovery capacity.

Lack of Long-Term Incentives in Gallium Market

Weak markets created by changing technology and overcapacity, as well as perceived future economic risk, combine to form the greatest constraint on the gallium industry. Specifically, there are no long-term incentives for gallium producers to enter the market or expand existing facilities.

Investment decisions are based on inferences made about future market conditions. In turn, these inferences are typically based on historic conditions as well as predictions about factors that affect the market, such as changes in technology.

After the sharp market decline when liquid crystals replaced LED's, gallium producers admit they are a bit more cautious about high technology gallium markets.

Photovoltaic energy systems would require quantities of gallium that are orders of magnitude greater than current world production. However, producers feel greatly expanding capacity to meet such a demand may be somewhat self-defeating. A strong demand for gallium would mean higher prices and may result in photovoltaic energy not being competitive with other sources of energy. Action taken to mitigate the situation would have to be either lowering the price of gallium or decreasing the amount of gallium used. Because of this uncertainty, gallium producers lack incentives to expand capacity.

Changing Methods of Phosphate Production

Another factor that may limit future domestic gallium production is the changing trend in phosphate processing. Specifically, the burning of phosphate rock is being replaced by digesting the rock with acid in what is known as the "wet process". Gallium-rich flue dust is not produced during the wet process. In addition, no research has been done to determine if gallium can be concentrated and extracted during this wet processing of phosphate material.

During the early 1970's only about one-fourth of all domestic phosphate material was processed with acid(16). Currently, about 88 percent of all domestic phosphate rock mined is consumed by the wet process with only 12 percent being smelted in furnaces(14,17). Furthermore, if energy costs continue to increase, even more of U.S. phosphate rock may be refined by the cheaper acid process.

This trend in phosphate production may have an impact of future gallium supply. Estimates of gallium supply from phosphate rock presented in Section 4.7.3 assumed all the western phosphate material would be burned. If this phosphate rock is processed with acid and no technology has been developed to recover gallium, the supply estimates would be reduced substantially.

If the photovoltaic industry is to rely on phosphate deposits as a source of gallium, there is clearly a need for research on extracting gallium from the wet process.

Gallium Supply vs. Photovoltaic Demand

Scenarios estimating photovoltaic and nonphotovoltaic gallium demand were developed in earlier chapters. Specifically, it was determined gallium bulk material requirements may prove to be constraining in the polycrystalline GaAs and advanced concentrator cells.

In the polycrystalline GaAs base case, gallium demand from world markets would increase significantly after 1990 and reach an annual requirement of approximately 4600 metric tons per year in the year 2000. Cumulative gallium demand under this scenario is estimated to be 25,000 metric tons to produce 25 GW peak capacity in the year 2000. Gallium requirements in the Advanced Concentrator solar cells is estimated to be 150 metric tons per year in the year 2000. Cumulative gallium demand to produce 25 GW of peak capacity in the year 2000 has been estimated to be 309 metric tons.

Referring to supply estimates presented earlier in this chapter, it can be seen that domestic sources of gallium may not be sufficient to meet photovoltaic demand. Further, the development of nonconventional sources of gallium may make photo cells too expensive to compete with other forms of energy.

Current domestic gallium capacity is less than 20 metric tons per year. This annual domestic supply could be increased to over 1200 metric tons if gallium were recovered from fly ash produced in existing coal fired power plants. However, gallium from fly ash would be approximately three times as expensive as gallium from bauxite or zinc ores.

In addition, there is some doubt as to how much domestic gallium capacity could be increased from zinc and phosphate ores. The supply estimates in Figure 42 indicate zinc ores will not have a significant impact on gallium availability in the future. Phosphate ores could potentially supply large amounts of gallium provided the material is refined by the burning process. However, increasing energy costs may result in more phosphate being reduced by the wet process. Currently, no technology has been developed to extract gallium from phosphoric acid.

Future supply projections indicate photovoltaic gallium demand would have to be met from bauxite sources. Gallium supply from world bauxite production to the year 2000 has been estimated and presented in Figure 43. Given the assumptions of a 6% growth rate and 40% recovery, as much as 5000 metric tons of gallium per year could be recovered from world bauxite production by the turn of the century. Gallium from world bauxite would be more than sufficient to meet demand from the Advanced Concentrator cell. The polycrystalline GaAs cell would require a majority of gallium that could be produced from world bauxite in the year 2000. Depending on nonphotovoltaic gallium demands, the polycrystalline cell may require gallium from more expensive nonbauxite sources.

CONCLUSIONS AND RECOMMENDATIONS

From a materials supply standpoint, it is clear that domestic sources of gallium are not adequate to meet 25 GW of photovoltaic peak capacity by the year 2000 using the polycrystalline GaAs cell. Domestic sources of gallium may meet photovoltaic requirements for the Advanced Concentrator cell to the year 2000, but more expensive nonbauxite gallium would be required. In addition, during the screening process gallium requirements in both cells exceeded many of the threshold levels.

Those problems and actions recommended to mitigate the problems have been addressed in Chapter 3.0 under the heading, "A" Materials Discussions. To summarize, the following actions have been recommended to reduce the amount of gallium used in the cell, reduce the cost of producing gallium, and/or increase the quantity of gallium available:

- Insure long-term supply by reducing risk to producers through long-term contracts
- Lower unit costs through economies of scale
- Lower unit costs through research on extraction efficiencies
- Consider a stockpile program
- Research methods to eliminate or reduce gallium in cells

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5.0 GALLIUM FROM COAL

REPORT ABSTRACT

The following summarizes the study of the feasibility of gallium recovery from coal. Gallium origins and concentrations in U.S. coals are reviewed. Six potential recovery points were selected and investigated in the coal processing cycle, and the most feasible was selected. Process costs are developed. Economic factors and institutional constraints are reviewed. Finally, conclusions are drawn and recommendations are offered.

ORIGINS, CONCENTRATIONS AND ANALYSIS OF GALLIUM IN COAL

Coal is a carbonaceous, nonhomogeneous, highly fossilized material formed from decayed plant residues. Gallium is found in small concentrations in living plants(1,2) which suggests that the gallium in coal comes from plant material. It is generally assumed that the gallium in coal is part of the organic complex resulting from the release of the gallium by plant decay during coal formation and subsequent reaction with complex humic acid hydroxyl groups. In some respects this is analogous to the organic complexes found in crude oil that contains nickel and vanadium. Gallium appears to be concentrated in the upper and lower parts of coal seams, probably because of the greater volume of water passing through or adjacent to these parts of the coal beds during their formation because of the low permeability of the enclosing clay strata.

Gallium is also found in the inorganic fraction of coal. This is not surprising because of the similarity of gallium to aluminum which is part of the inorganic fraction of coal. No conclusive evidence was found in the literature regarding the split of gallium between the inorganic and organic fractions of raw coal during this program. The results of discussions with investigators studying trace elements in coal fractions were also inconclusive. Gallium is not of particular interest because it is considered non-toxic and the principal work done on trace elements in coal is related to those considered to be hazardous or at least potentially hazardous.

Analyses of Gallium in Coal

Literally thousands of analyses of gallium content in coals have been made. A part of this work was done shortly after World War II in the early 1950's. Most investigators feel that this work is suspect because analytical procedures were not as reliable as present methods. During the past 15 years or so, considerably more work has been done and vast improvements in analytical procedures have been made.

Table 51 shows typical analytical values for gallium in whole coal samples(3). The results indicate that Eastern coals contain the highest level of gallium, the Illinois Basin coals somewhat less, and Western coals least. Table 52 presents average gallium values in different coals by rank(3). It is felt that these figures are representative and that an average or normal gallium content in coals is in the range of 7 ppm, recognizing that even coals from the same seam may vary in gallium content.

TABLE 51. Mean Analytical Values for Whole Coal Samples, Gallium, ppm

	Illinois Basin Coals 114 Samples	Eastern Coals 23 Samples	Western Coals 28 Samples
Arithmatic Means	3.2	5.7	2.5
Geometric Mean	3.0	5.2	2.1
Minimum	0.8	2.9	0.80
Maximum	10	11	6.5

TABLE 52. Average Amounts of Gallium in All Coal Samples and in Different Ranks of Coal, Presented on a Whole-Coal Basis. For Comparison Average Amounts in Shale are Listed (Turekian and Wedepohl, 1961) in ppm

All Coal (799 samples)	Anthracite (53 samples)	Bituminous (509 samples)	Subbituminous (183 samples)	Lignite (54 samples)	Average Shale
7	7	7	3	7	19

For contrast, Table 53 shows gallium content for British and West German coals(2).

TABLE 53. Minor Elements in British and German Coals and Ashes, Gallium

	In Ash (ppm)	In Coal (ppm)
Barnsley, Vitrain	80-300	--
Great Britain		
Germany	>3000	30-100
Ruhr, German	1000	20

Many investigators have analyzed coal ashes to determine their gallium content. Several examples of results are shown in Tables 54, 55, and 56. In this work, the coals were ashed under controlled conditions in the laboratory prior to analyses. The conclusion reached from these studies is that gallium content is higher in ashes than in the original coals.

TABLE 54. Average Trace Element Content in Ash of Coals from Various States, Gallium, Percent of Ash

	Province	Interior Province		Western States	
Alabama	0.0055	Arkansas	0.0025	Arizona	0.0050
Eastern Kentucky	0.0099	Illinois	0.0035	Colorado	0.0032
Maryland	0.0020	Indiana	0.0035	Montana	0.0039
Ohio	0.0050	Iowa	0.0070	New Mexico	0.0034
Pennsylvania	0.0071	Kansas	0.0020	North Dakota	0.0020
Tennessee	0.0057	Missouri	0.0065	Utah	0.0030
Virginia	0.0085	West Kentucky	0.0040	Washington	0.0059
West Virginia	0.0077			Wyoming	0.0017

TABLE 55. Range in Amount of Trace Elements Present in Coal Ashes, Gallium, ppm

Anthracites			Lignites and Subbituminous		
Max	Min	Avg	Max	Min	Avg
71	30	42	30	10	23

TABLE 56. Range in Amount of Trace Elements Present in Coal Ashes, Gallium, ppm

	Max.	Min	Average
Anthracites	71	30	42
High Volatile Bituminous	98	17	40
Low Volatile Bituminous	135	10	41
Medium Volatile Bituminous	52	10	*
Lignities and Subbituminous	30	10	23

Analytical Procedures

Trace elements in coal and coal ashes may be identified and quantified by a variety of methods. Each appears to have some limitations and the choice of method is usually made on the basis of one or more factors. The major factors considered are cost and time required for analysis, availability of equipment, sensitivity needed, concentration of the particular elements being sought, and interference from other elements. The techniques often used are(2):

- Atomic absorption spectrometry - AAS
- Spark - source mass spectrometry - SSMS
- Microwave plasma emission - MPES
- X-ray fluoresence - XRF
- Neutron activation analysis - NAA
- Optical emission spectrometry

Generally it appears that NAA is preferred if available.

U.S. COAL MINING AND CONSUMPTION AND POTENTIAL POINTS FOR GALLIUM RECOVERY

Table 57 presents data on coal consumption for the five-year period 1974-1978. The major consuming sector, power production, will continue to dominate coal consumption. Under an optimistic assumption, synthetic fuels from coal could begin to consume significant tonnages of coal in 1985. Table 58 presents one forecast of coal consumption after 1985.

TABLE 57. Consumption by Sector Bituminous Coal and Lignite
(Million Tons)

	1974	1975	1976	1977	1978
Electric Utility	392	406	448	477	480
Domestic Coking	90	83	84	77	71
Industrial and Retail	73	70	68	67	67

Source: Minerals Year Book 1976, Table 10, page 365.
EIA Annual Report to Congress, 1978

TABLE 58. Projected Coal Consumption by Sector
(Million Tons)

	1985	1990	1995
Electric Utility	733	1066	1377
Industrial and Retail	128	200	307
Domestic Coking	86	91	96
Synthetics	13	28	131

Source: Minerals Year Book 1976, Table 10, page 365.
EIA Annual Report to Congress, 1978

As can be noted, electric utilities are projected to be the very dominant consumer of coal.

Figure 46 presents Battelle's estimate of the materials flow within the coal producing and coal consuming sectors of the economy. The tonnage numbers (or lack of) appearing in Figure 46 need qualification. First, there are no published data on whole coal (raw-coal) mined. There are no published data on the split between whole coal going directly to steam generation and the amount that goes to coal cleaning plants. There are no published data on the amount of coal cleaning plant waste generated. Finally, there are no published data on the amount of cleaned coal going to steam generating units. Hence, it is not possible to balance those flows in the figure. The data on coal consumption are reliable, as well as the data on utility ash streams.

The numbers in parentheses (1 through 6) represent the potential gallium recovery points that Battelle selected for further investigation. Since gallium concentration in coal is very low, averaging perhaps 5 to 7 parts per million (ppm), it is obvious that large volumes of coal or coal byproducts must be handled in concentrated geographic locations if economic recovery of gallium is to be accomplished. The recovery points selected best meet those conditions. A discussion of each follows:

1. Selective Mining. The range of gallium occurrence in various U.S. coal seams is 0 to 61 ppm. It might be possible to selectively mine for gallium-rich coals and ship the higher gallium content coals to the designated utilities, coking plants or coal conversion plants equipped to recover gallium.
2. Coal Preparation (Washing). Run-of-the-mine coal may contain as much as 50 percent extraneous inorganic materials. Consequently, about 40-45 percent of U.S. coals are washed to remove a large part of these materials. On the average, about 20 percent of the whole coal volume (run-of-the-mine) ends up washing plant waste. Data are sparse, but one estimate indicated as much as 100 million metric tons(7) of such wastes are produced per year*and some 3 billion tons already have accumulated at some 3000-5000 disposal sites in the U.S. If gallium is found to be more highly concentrated in coal refuse rather than clean coal, then the refuse from coal washing operations might offer points of recovery.

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*Not all that waste is represented by coal washing refuse per se. A very large portion is separated mechanically before washing, e.g., slate, etc.

3. Coking. When coal is coked for metallurgical uses (primarily iron and steel), an average of some 17,500 tons of byproduct coal tar is produced per coking plant per year. About 60 byproduct coke-oven plants exist in the U.S. If gallium is found to concentrate in the coal tar, it might be recovered in subsequent coal tar refining operations.

4. Combustion. There seems to be ample evidence that upon combustion of coal, gallium concentrates in the coal ash. Further, gallium seems to be more highly concentrated in the fly ash as opposed to the bottom ash. In all but the lignites, the gallium concentration ratio of coal feed to ash is about 1:10 or better. It may run considerably higher than that in the fly ash fraction of the ash. Hence, very large coal burning plants (electric utilities) offer potential points of recovery.

5. Coal Conversion. There is future potential for building a number of very large coal conversion plants in the U.S. (e.g., coal to gas, coal to methanol, and coal to petroleum-like liquid fuels). If gallium is found to concentrate in any of the byproduct or waste-product streams, these plants may offer potential recovery points.

6. Pozzolan Cement Manufacture. About 2.3 million tons of fly ash per year are used in the production of Pozzolan cements. If Pozzolan cement manufacture and processing is sufficiently concentrated and is compatible with gallium recovery, potential economic recovery sources may exist.

As a result of the above postulations, Battelle's literature survey and contacts with outside information sources concentrated on gallium origin and occurrence in various U.S. coals, and the fate of gallium as a coal proceeds through various process/utilization channels. The potential volumes of contained gallium available at various recovery points (individually and collectively) were also subject to investigation and analysis.

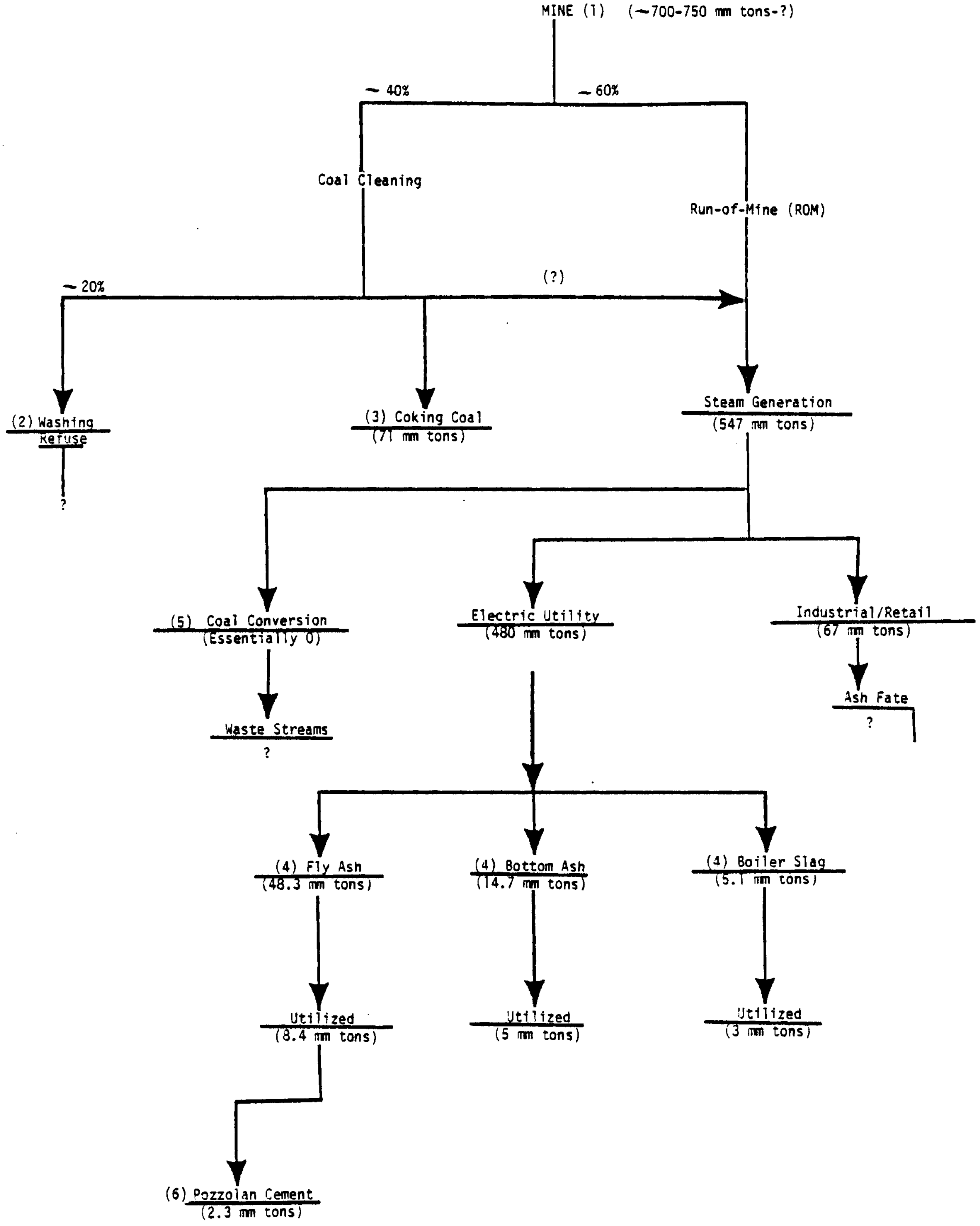

FIGURE 46. Coal and Ash Flows, 1978 (Short Tons)

Source: Coal Data: Minerals Year Book 1976, Table 10, p. 365. EIA Annual Report to Congress, 1978, Table 132, Coal Week, October 1, 1979. Ash Data: National Ash Association *Ash At Work* Vol XI, No. 2, 1979

INVESTIGATION OF SIX RECOVERY POINTS

Very few investigators in recent years have been interested in determining the fate of gallium when coal is subjected to various processes. Therefore, only meager data and information were found in the literature or obtained from scientists working with different processes. There is reasonable justification for this lack of interest because: (1) gallium content is very low, (2) it is considered non-hazardous, (3) apparently it causes no problems in processing, and (4) there has been little interest in recovering gallium for marketing.

Selective Mining

Even within a given coal seam, gallium occurrence is not uniform. Higher concentrations may often be observed at the top and bottom of the seam as well as in different coal formations within the seam. Analytic determination of gallium content in whole coal is not an easy nor fast procedure. Hence, the logistics of carefully pre-selecting gallium-rich seams and layers to be mined and keeping that coal separate from all other coals becomes a very formidable task. If practical at all, feasibility would probably be relegated to small surface mines of over 100,000 tons per year where operations could be carefully controlled. Even if selective mining of coals with an average of 200 ppm gallium (very high) were to be accomplished, perhaps 10 to 50 small surface mines would be required to produce 20 tons of potentially recoverable gallium contained in 1,000,000 tons of coal burned at one or more combustion sites. Further, gallium content would then become another economic determinant of the coal's value and the problems of sampling and even of possibly segregating each mine's output at a large coal consuming site appear intractable.

Coal Preparation (Washing)

Gallium and aluminum have many similar chemical properties and often gallium can be substituted for aluminum in various compounds. On this basis, it is logical to expect that gallium will be found along with aluminum in the refuse from coal cleaning. There is no agreement on this point. One investigator stated that more than 50 percent of the gallium content in coal will be found in the 20 percent of refuse resulting from coal cleaning(8), while other investigators feel this will not occur(9).

Table 59 presents the results of work done on coal cleaning and identification of minor elements(10).

TABLE 59. Distribution of Elements in Float Sink Separation of Illinois Coals at Varying Specific Gravity to Achieve 75 Percent Weight Recovery, Gallium(7)

Concentration, ppm			Concentration Factor	
Raw Coal	Clean Coal	Refuse	Clean Coal	Refuse
3.0	2.7	4.1	0.90	1.37

In the case of certain Illinois coals at least, it appears that the refuse was enriched in gallium content while the coal was depleted to some extent.

Based on admittedly meager evidence, it was concluded that coal refuse did not appear promising as a gallium recovery point. Even if all the gallium in whole coal were to end up with the waste residue, the gallium concentration would not exceed 25 to 35 ppm. (This assumes a 5 to 7 ppm "average" of gallium in whole coal, and the waste residue representing 20 percent of the whole coal.)

Coking

Coke is produced by the destructive distillation of coal in oven coke plants at 1650-2000°F in a reducing atmosphere. The coke, including the ash, remains in the oven while crude tar, crude light oil, ammonia, and gases are emitted and collected. The crude tar is further refined to recover valuable chemicals and part of the remaining pitch is sold to graphite product manufacturers who use it as a binder. The rest of the pitch is burned for its fuel value. There are some 60 byproduct coke oven plants in the U.S. They produce an average of 17,500 tons of byproduct coal tar per year per plant.

Because of the reducing atmosphere and high temperature in a coke oven, it is reasonable to assume that gallium in the coal will volatilize as it does in coal combustion. Review of the literature revealed no information on the fate of gallium in coal coking. Discussions were held with coke oven operators, processors of the crude tar from coke ovens, and users of the remaining pitch. The net result was that gallium is not of interest to these companies and that no attempts to determing gallium in the various products have been made. The consensus is that gallium probably will volatilize and be carried out of the off stream with the crude tar. The fate of gallium in crude tar processing is unknown but the opinion is that it will probably end up in the pitch.

One large user of coal tar pitch regularly analyzes pitch for 17 metals, not including gallium. The metals of interest are those that are deleterious to their products or are hazardous in nature.

Coking was therefore eliminated as a recovery point based on a complete lack of any analytical evidence of gallium concentration in coal tar or pitch. Even if gallium were to be found in very high concentrations (300 ppm) in coal tar, the total potential for recovery would not exceed 315 tons of gallium per year.

Coal Conversion Processes

Coal can be gasified and upgraded to produce a useful gas, or methanol, or it can be liquefied to produce a fuel that can be used as a substitute for crude petroleum. There are a number of coal conversion processes under study at the present time because of the urgency to reduce our reliance on imported crude oil. There is future potential for building a number of very large conversion plants in the U.S.

Trace elements are of interest to the operators of these processes because of their potential effect on the system. Little information on the fate of gallium in coal conversion processes was found in the literature or by discussions with individuals involved in such processes. One company representative said that 85 metals have been analyzed for in the various streams in 2 different processes, but gallium was not included. This work has been mainly for identification of trace elements, especially those that might cause adverse conditions in the system or are hazardous. A program to obtain mass balances for trace elements is just getting underway.

Table 60 presents one set of data on coal conversion.

Limited data on the Synthoil process indicate coal-feed to waste-stream residue concentration ratios of perhaps up to 5, the greatest concentration appearing in centrifuge residues (coal feed 2.3 ppm, centrifuge residue 9.9 ppm Ga)(11).

Similar data on coal gasification waste streams from the Synthane process reported a highest concentration ratio for Ga of about 7 in the filter fines (coal feed 3 ppm, filter fines 21 ppm Ga)(12).

The limited data on coal conversion residues is not encouraging with respect to gallium concentration ratios. In addition, the sizes, timing, or preferred processes for coal conversion have not been determined as a matter of national policy. Therefore, pending considerably more research and policy making, coal conversion plants do not appear viable as gallium recovery points.

TABLE 60. Trace Element Results for the COED[(a)] Process, Gallium, ppm

Feed	1
Raw Oil	0.5
Filter Coke	2.0
Syncrude	0.2
2nd Stage Liquors	0.1
1st Stage Liquors	<0.1
Char	4
Fines, Oils	0.3
Fines Cyclone	<0.1
Filtrate	0.2

Source: Reference 1, Table 4.35

(a) COED = Char-Oil-Energy Development

Pozzolan Cement

Fly ash is utilized economically in the production of Pozzolan cements. In essence, fly ash is blended with cement to produce concretes with superior properties for selected uses. This occurs mostly at the concrete producing plant, but sometimes blending is done by the cement manufacturer and that produce is shipped directly to the construction site. Since the production of concrete is a very locally oriented industry, the concrete producing plants that do this are relatively small and widely scattered. Hence, the desired logistics of large and concentrated processing sites for gallium recovery does not appear attainable.

Coal Combustion

The fate of gallium during coal combustion is not entirely clear. Current thinking is that gallium will volatilize as the suboxide during combustion and be carried off in the gas stream where part of it, at least, condenses on the fly ash which is removed from the gas stream. It is known that some minor part of the gallium remains in the bottom ash, and that part of the gallium can be found in the flue gas beyond the particulate removal device. The theory is that the gallium condenses on the finer particulates of fly ash, some of which are not removed by the control device. Gallium has been identified in minor amounts in other waste streams such as scrubber water from coal-fired power plants.

Bolton, et al.(13), found gallium concentrations of 40 ppm in the slag tank, 100 ppm in the precipitator inlet and 100 ppm in the precipitator outlet. In another run 71 ppm were found in precipitator inlet stream, 93 ppm in the precipitator outlet, and 130 ppm in stack gas in one empirical run. Apparently, no attempt was made to obtain a mass balance.

Klein, et al.(14), analyzed coal, fly ash, slag and combustion gases from a large cyclone-fed power plant for a suite of elements. Mass balance calculations show that the sampling and analyses were generally adequate to describe the flows of these elements through the plant. The conclusion was that gallium was quite concentrated in fly ash as compared to the slag. Coal feed was 4.5 ppm Ga, slag was 5.0 ppm and fly ash precipitator inlet was 81 ppm. Precipitator outlet values were not determined for gallium.

Coles, et al.(15), reported on the concentrations of 42 minor and trace elements in four size fractions of stack fly ash from a large Western coal-fired power plant. Mass median diameters of the four size fractions were 2.4, 3.7, 6.0, and 18.5 μm. Based on the enrichments relative to coal as a function of fly ash particle size, the elements are grouped into three classes: Group I, elements that show little or no enrichment in the small particle fraction; Group II, elements whose enrichments increase with decreasing particle size; and Group III elements whose behavior is intermediate to that of elements in Group I and II. The elements in Groups I and II are described in terms of their lithophilic and chalophilic geochrmical behavior, respectively. Gallium falls in Group II. The enrichment factors for gallium in size-classified stack fly ash are presented in the following tabulation.

Element	Fraction 1	Fraction 2	Fraction 3	Fraction 4
Size	18.5μm	6.0μm	3.7μm	2.4μm
Gallium	1.2	3.0	3.6	4.7

KaaKinen(16) measured gallium content by x-ray fluorescence analysis for:

- Ashed coal
- Whole coal
- Bottom ash
- Mechanical collector hopper ash
- Electrostatic precipitator hopper ash
- Scrubber inlet fly ash
- Scrubber outlet thimble fly ash

- Electrostatic precipitator outlet fly ash
- Scrubber slurry solids
- Make-up water
- Ash pond overflow
- Slurry water

It appears that no mass balances were calculated. Rather, the work was aimed at obtaining information on where the individual elements would be found after coal combustion. The whole coal averaged about 2.5 ppm gallium. Small quantities of gallium were found in bottom ash (<5 ppm), mechanical collector hopper ash (about 10 ppm and in ESP hopper ash (about 30 ppm). The scrubber inlet fly ash contained about 35 ppm while the scrubber outlet thimble fly ash was higher with some samples showing 50 ppm of gallium. ESP outlet fly ash was also high, 45+ ppm. Scrubber slurry solids showed gallium in the range of 5 ppm, make-up water, ash pond overflow, and slurry water were all much lower.

These results offer credence to the theory that gallium tends to concentrate on the smaller particle size fly ash and that some of this ash is not removed from the gas stream by control devices.

KaaKinen, et al.(17), calculated mass balance for 11 elements as part of a study designed to study the character of trace element partitioning within a single pulverized coal-fired power plant. Unfortunately, gallium was not included in the major work. However, semi-quantitative data on 5 additional elements suggested enrichment patterns more consistent with Group B elements for gallium and tin, but no convincing enrichment of potassium, calcium, or manganese.

While the evidence is fragmentary and often incomplete (a shortage of mass balance studies), it seems logical to conclude that based on coal feed stocks containing 5 to 7 ppm Ga, fly ash could contain a minimum of 20 ppm Ga, and quite possibly as much as 100 ppm under favorable circumstances. Probably 50 ppm Ga is a reasonable conservative estimate for "average" fly ash from "average" coal feed stocks.

Since evidence further seems to indicate that Ga concentrations rise with decreasing fly ash particle size, the Ga concentration ratios in hopper ash may also be a function of precipitator efficiency in removal of small particle sizes. Efficient precipitators can remove 80-85 percent of particles in the .1 to 0.5 micron range. Filters of this efficiency were in place during the Klein study previously cited(14). Based, then, upon the available evidence concerning gallium concentration ratios in fly ash, together with knowledge of the volume and geographic concentration of potential fly ash feed stocks, recovery of gallium from fly ash waste streams from electric utility power plants is probably the most feasible of the recovery point options originally hypothesized.

Battelle therefore developed cost estimates for gallium recovery from fly ash based on concentrations of 20, 50 and 100 ppm Ga.

GALLIUM FROM FLY ASH -- COST ESTIMATES

This evaluation considers a process in which fly ash is processed only to recover gallium and one other coproduct (germanium). Alternative processes for the treatment of fly ash and the recovery of numerous products such as alumina (Al_2O_3), titania (TiO_2), iron values, and portland cement are being researched in the U.S. and one is claimed to be operating in eastern Europe.

Conditions of Process Evaluation

The data on gallium concentrations in fly ash are few in number and often are of low confidence level due to interference from other elements in most analytical procedures.

The data on gallium content of fly ash shows great variance. Unpublished data compiled or generated in a recent program at Oak Ridge National Laboratory established a range of gallium content in fly ash from 1.1 to 360 ppm(18). For the purpose of this study, gallium contents of from 20 to 100 ppm were used as a basis for comparison.

The single process which was evaluated was the subject of a generally descriptive paper and was actually operated on a pilot-plant basis in Great Britain circa 1950(19). Time and distance precluded the acquisition of any information not included in the published papers. Numerous parts of material-balance information, energy and reagent consumption, and other factors were necessarily based on estimates from first principles. The principal uncertainty was the energy consumption of a furnacing operation which, by virtue of relatively lower gallium content and relatively high current energy costs, is one of the major processing cost elements in the evaluation presented in the following paragraphs.

The other major overall consideration was the selection of projected plant sizes, which were assumed as 50 and/or 100 metric tons of gallium per year. These plant sizes were selected on the basis of potential scenarios for gallium consumptions which ranged from 50 to 2500 metric tons per year.

Process Description

The process found in the published literature is indicated in Figure 47 on the following page. This process was developed and piloted as a joint effort of General Electric, Ltd., and the Johnson-Matthey Chemical Company to exploit the relatively rich flue dusts available in England at the time and form a domestic supply of gallium and germanium for use in semiconductors(19). The key step in the process is the ash-smelting operation which serves to concentrate the gallium (and germanium, arsenic, etc.) in an iron-copper matte (metallic mixture). The need for this step is apparently related to the variable distribution of gallium in fly ash between condensed layers in some cases and in glassy oxides in other cases. In brief, the smelting operation contacts the melted ash (largely silica) with molten copper. The gallium dissolves or transfers preferentially into the molten copper from the fused ash; the copper acts as a selective solvent or getter. The balance or vastly major part of the fused ash is discarded as waste.

The relatively small quantity of iron-copper matte is then treated in a process comparable to wet-chemistry analytical procedures to separate and recover the gallium and germanium. The matte is dissolved in an aqueous solution of ferric chloride injected with gaseous chlorine. The resulting solution contains a mixture of chlorides of iron, copper, arsenic, gallium, and germanium. This mixture is boiled at an estimated 150°C and the vapors condensed separately from the feed to the boiler. The condensed vapor (overhead) contains a mixture of copper, germanium, and arsenic chlorides, hydrochloric acid, and water. The solution which remains in the boiler contains water, hydrochloric acid, and chlorides of gallium, iron, copper, some arsenic, and various other salts and impurities.

The solution from the bottom of the boiler contains the gallium, which is recovered by the following treatments of the solution:

- cooling and filtration to remove copper salts
- addition of aluminum to precipitate the remaining copper salts; filtration
- solvent extraction with isopropyl ether to produce a concentrated gallium chloride solution

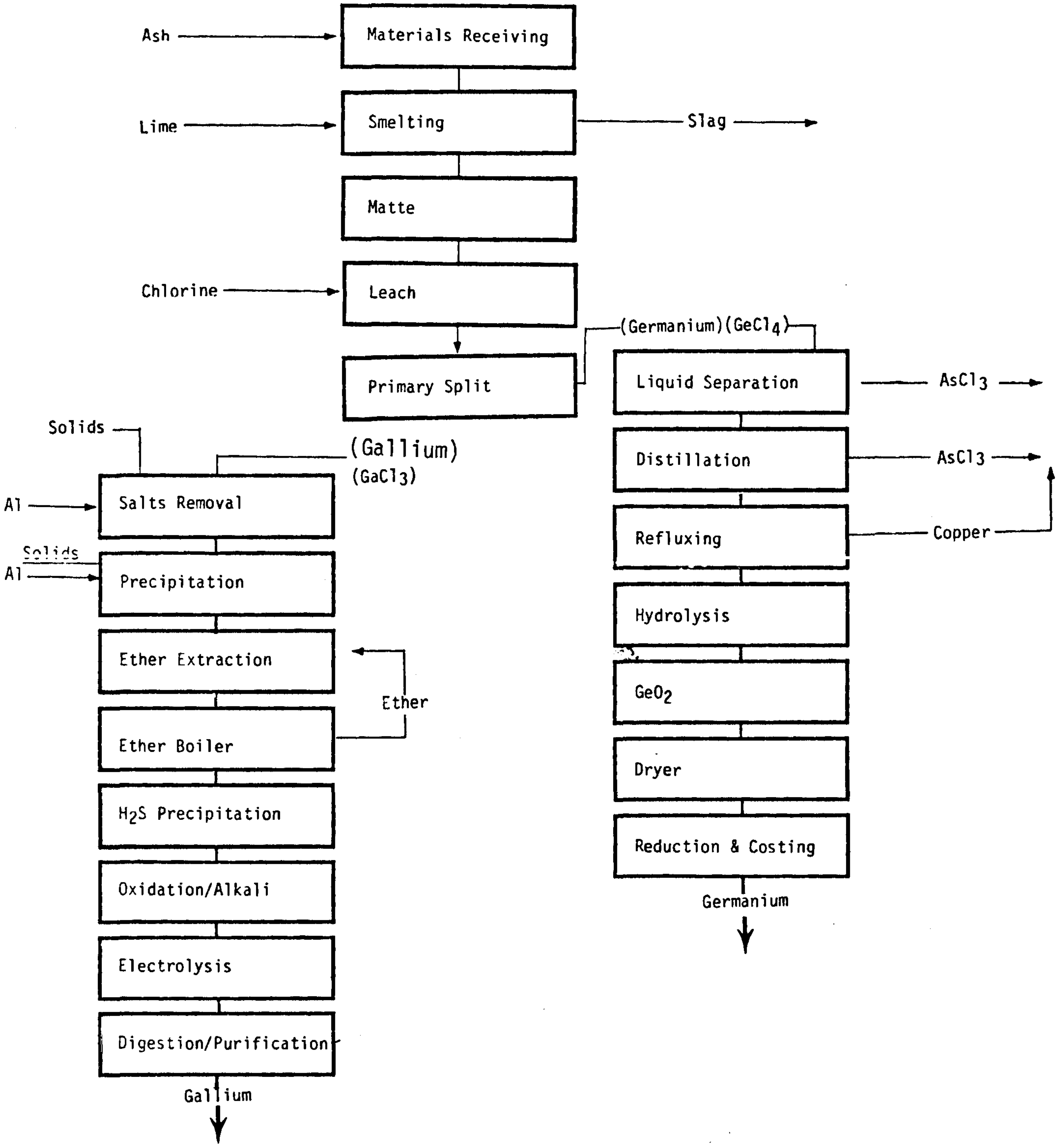

FIGURE 47. Diagram of Process for Recovery of Gallium from Fly Ash

- treatment with hydrogen sulfide to precipitate any trace impurities; filtration
- oxidation with nitric acid; conversion to alkaline sodium hydroxide; filtration
- electrolysis of the sodium gallate solution to produce gallium
- treatment in nitric acid and the hydrochloric acid to produce gallium metal.

The overhead from the boiler contains the germanium and the condensed solution is treated in the following manner:

- adjustment of pH to produce two immiscible liquid layers; the lower contains the germanium chloride and some arsenic chloride; the upper is discarded
- reflux distillation to separate the gallium chloride from the arsenic chloride
- reflux distillation of the germanium chloride over copper turnings to remove traces of arsenic
- hydrolysis of the germanium chloride to oxide; filtration and drying
- hydrogen-furnace reduction of the oxide to cast metal.

On the basis of the available description, supplemented with estimates, the above process was scaled and proportioned to the concept of using current utility fly ash as a feed material.

Quantities of Materials

From front end of the process (materials handling and smelting) is much larger than the latter steps (chemical processing). The capital cost ratio is probably more than 200:1. Some selected quantities involved are listed below as estimated for a 50 ton/year operation based on the published data and the conditions previously stated.

Assumptions:

Ash:	50 w/o SiO_2, 20 ppm Ga, 20 ppm Ge, 340 ppm As
Yields:	80 percent for Ga, 90 percent for Ge
Net Plant Production:	50 metric tons per year gallium; 56 metric tons per year germanium
Plant Operation:	350 days per year.

Charge to the Smelting Furnaces, metric tons per day:

Ash:	9,400
Lime:	4,700
Coal:	0.4

Products from Smelting Furnaces, metric tons per day:

Slag:	14,000
Matte:	4.3 (Iron, Copper, with 2.5 w/o gallium)

Leach Operation:

4,000 gallons per day dilute ferric chloride
9.3 metric tons per day chlorine

Gallium Process Line:

3,000 gallons per day of solution reduced after solvent extraction to 200 gallons per day for purification and electrolysis; net 0.14 metric tons per day gallium metal (50 MT/yr)

Germanium Process Line:

1,000 gallons per day reduced to 70 gallons per day in the first separation; net 0.16 metric tons per day germanium metal (56 MT/yr)

The quantities of ash and lime are directly related to the assumed gallium (and germanium) content of the ash and would, obviously, be smaller by a factor of 5 if the gallium content of the ash were taken to be 100 ppm. The quantities of matte and especially leach solution are less sensitive to variations in gallium content in the ash, due to wide ranges of solubility of gallium in the matte and chlorides in acid aqueous solution. There is considerable uncertainty with regard to the probable arsenic balance; arsenic is considered to partition to the smelting furnace flue dust (which is recirculated), the slag, and the matte.

As here hypothesized, the major process step is the smelting operation which, for the assumed 20 ppm gallium in ash, involves the smelting of a calculated 3.1 million metric tons of ash (plus 1.6 million metric tons of lime) per year to produce 50 metric tons per year of gallium and 56 metric tons of germanium per year. The smelting of this amount of charge is of the same order of magnitude as the entire present primary copper industry in the U.S.

No practical experience exists on the consumption of energy during the large scale melting or smelting of fly ash. Since there is no significant chemical reduction, i.e., all that is being done is liquid-liquid exchange, this reaction was estimated as being most similar to glass melting (e.g., when compared to sulfide smelting, or ferrosilicon production). The published values for energy consumption for glass melting are given as the range of 11.3 x 10^6 to 17.43 x 10^6 Btu's per metric ton of product(20). These are overall energy consumption figures for gas-fired reverberatory furnaces which are operating at efficiencies of 35 to 45 percent. Other technologies were considered, i.e., submerged-arc electric furnaces as used in steelmaking and ferroalloy production, or immersed-element electric-resistance heating as currently under development and scale-up in the glass industry. Submerged-arc heating approaches 100 percent heat efficiency, while the resistance heating reportedly approaches 85 percent efficiency. After a comparison of recent energy costs(21) it was concluded that submerged arc electric heating at 100 percent efficiency was very nearly the same cost as gas-fired reverberatory furnace heating at 25 percent efficiency. The gas-fired technology was assumed.*

Furnace size appears to be limited by technology, i.e., expansion during heat-up limits the roof span. The largest smelting-furnace size documented in the literature was rated at 815 tons per day of charge (essentially equal to smelted products)(22). Thus, at the projected scale of operation there is no economy of scale: the amount of ash or feed becomes some multiple of maximum furnace size.

The melting cost per ton of ash is likewise fixed by the cost of operation of the maximum furnace unit size.

Tables 61 and 62, listing elements of the estimated capital investment and operating and maintenance costs, are given on the following pages. Cost estimating data were taken from various sources; some of the source documents supplied costs on an installed basis (i.e., a sum including both equipment costs and installation labor); other costs were developed on a bare equipment basis(21,22,23,24,25,26).

The cost estimate provided here should be regarded as showing the order of magnitude of costs of the process considered. Preliminary cost estimates are usually low. The process evaluation merely shows that gallium content in fly ash determines the magnitude of the operation, and that energy consumption in the smelting step is the cost parameter of paramount significance.

Not listed as cost elements are the potential costs of:

- acquisition and transport of fly ash
- disposal of slag.

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*The present pragmatic aspects of possibly limited natural gas supply are noted but bypassed for the purposes of this estimate.

These elements of cost depend greatly on: location of the operation of unit operations relative to supplies of fly ash and the conditions of slag disposal, i.e., whether the slag was classed as a hazardous waste or, alternatively, whether it was considered an inert waste or was useful as fill, road ballast, etc. Transport and acquisition costs may be considered in terms of separate siting of furnacing unit operations, e.g., the furnacing units could be scattered about near power plants, and the relatively small quantity of matte transported to a central processing plant. Slag disposal could be the same as present ash disposal at the power plant.

Estimated Unit Processing Costs

Using the values of annual operating costs from the cost tables, unit costs of processing may be derived. The basis of the cost estimate was the processing of a total of 3.1 million metric tons of ash containing 20 ppm gallium and 20 ppm germanium, yielding 50 metric tons of gallium per year. Unit costs for the furnacing operation are the same for either a single furnace processing about 290,000 metric tons of charge per year (193,000 MT of fly ash) or for all the furnaces collectively, namely \$72 to \$88 per metric ton of ash charged; the chemical process line, treating the matte from the same quantity of ash (3.1×10^6 tons) has a cost of \$0.26 per metric ton of ash charged.

The contained values in a ton of ash may be restated as 20 ppm (20 grams per metric ton) of gallium of which 80 percent (16 grams per metric ton) are recovered, and 20 ppm of germanium (20 grams per metric ton) of which 90 percent (18 grams per metric ton) is assumed to be recovered. The price history of germanium has shown fairly consistent trends over the years and was \$348 per kilogram in December, 1978(27). The value for germanium which will be used consistently throughout the balance of this evaluation is \$350 per kilogram. The price of gallium has shown, in recent years, a decrease from \$800 per kilogram to a current price of \$550 per kilogram, which is currently judged to reflect actual production costs at the present scale of production: 15 metric tons per year. The value of gallium used here is \$550 per kilogram.

On the basis of the 20 ppm level considered, the value realized from a metric ton of ash consists of 16 grams of gallium and 18 grams of germanium, or \$15.10. This may be compared to the above estimated processing cost of \$72 to \$88 per metric ton of ash. If the value of germanium is considered fixed (\$350/kg) and the balance of process costs were assigned to gallium, the assigned cost of gallium would be \$4100-

$5100 per kilogram.

Other scenarios may be envisioned, based on other concentrations of metals in the ash. Concentration is the only important variable, in that the furnacing operation costs are limited by maximum furnace size and the chemical process operation is almost negligible in cost relative to the furnacing step. Economics of scale have less effect than the uncertainty present in the estimate.

The effect of varying concentrations of metal in the ash is twofold: less material is charged and more product is obtained. The assumption of a fixed value $350/ kg) for the coproduct germanium and the assignment of all other costs to gallium results in rapid variation of the cost of gallium with ash analysis.

If, for example, fly ash were assumed to contain 100 ppm gallium and 100 ppm germanium, the recoverable materials become 80 grams of gallium and 90 grams of germanium. The germanium value is $31.50, and the process costs assigned to gallium result in a unit cost of $510 to $710 per kilogram.

It may be of interest to note that the process evaluated here was operated in Britain using dusts containing on the order of 2,000 ppm or more of gallium. These dusts were flue dusts from selected producer-gas plants then operating in England; dusts were selected carefully and variation of dust composition was related to different types of coal.

The effect of variations in the concentration of gallium (and germanium) on estimated gallium costs and relationships for feed materials, number of furnaces required, and the associated utility capacity are shown in Table 63. The values displayed in Table 13 are based on the set of assumptions used for the previous process evaluation:

- a germanium content equal to the gallium content
- eighty percent recovery of gallium; 90 percent recovery of germanium
- a fixed value of $0.35 per gram for germanium, the balance of process costs assigned to gallium
- a process cost of $72 to $88 per ton of fly ash input, depending on energy consumption.

TABLE 61. Estimated Capital Investment Cost Elements (1979 Dollars)

(50 MT Gallium/Year)

Stage/Process/Equipment	
Materials Receiving and Smelting	Installed Costs
(Single Furnace Basis)	
Car Dumper	210,000
Storage Silos	390,000
Conveyors; hoppers; feeders	50,000
Furnace (815 tons/day)	5,800,000
Waste Heat Boiler	800,000
Stack	1,500,000
Slag Handling Tanks, Track, Locomotive, Cars	1,900,000
Subtotal	10,600,000
Piping, Concrete, Steel, Instruments Electrical	1,900,000
Engineering, Overhead, Fee, Contingency	2,300,000
Total (Single Furnace Basis)	14,800,000
Total (18 Furnaces)	266,000,000
Chemical Processing Section	Bare Equipment Costs
1. Leaching and Primary Separation (4000 gallons per day)	12,000
Leach tanks, pipes, pumps, materials handling	12,000
Boiler and condenser	137,000
Subtotal	149,000
2. Gallium Line (3000 gal/day)	
Cooler tanks, centrifuge, pumps	66,000
Copper precipitation--tanks, mixer, filter, pumps, pipe	38,000
Ether extraction-mixer-settler boiler, pump, pipe	14,000
Impurity Removal--tank, filter, pumps, pipe	5,200

TABLE 61. (Continued)

Stage/Process/Equipment	Bare Equipment Costs
Oxidation/alkali--tank, filters, pumps, pipe	5,200
Electrolysis--tank, rectifier, pumps, pipe	7,200
Subtotal	136,000
3. Germanium Line (1000 gal/day)	
Decant vessel, pumps, pipe	7,000
Fractionating Still	12,000
Refluxing Purification Still	12,000
Hydrolysis--tank, mixer filter, pumps, pipe	14,000
Drying (Oven)	3,000
Reduction and Casting Furance	12,000
Subtotal	60,000
Chemical Process Total Equipment	420,000
Chemical Process Installation (Labor, Engineering, Fees, etc.)	820,000
Chemical Process Total Installed	1,200,000

TABLE 62. Estimated Operating Cost Elements
(50 MT Gallium/yr) (1979 Dollars per year)

Stage/Process/Equipment	
Materials Handling and Smelting (Single Furnace Basis)	
Power: conveyors, misc.	80,000
Chemicals	
Lime 97,000 tons/yr at $34.38/ton	3,300,000
Coal 140 tons at $42/ton	6,000
Labor 84,000 man-hr/yr at $7/hr	590,000
Supervision and Overhead	650,000
Maintenance	
Refractories	500,000
Other Materials	210,000
Labor and Supervision	390,000
Taxes and Insurance	210,000
Total O & M Without Fuel Costs	5,900,000
Fuel Cost Ranges ($1.77/$10^6$ Btu's)	
Low Energy Consumption (11.2 x 10^6 Btu/ton)	5,700,000
High Energy Consumption (17.4 x 10^6 Btu/ton)	8,800,000
Total O & M (Single Furnace Basis)	
Low Energy Consumption	11,600,000
High Energy Consumption	14,700,000
Total O & M (16 furnaces assumed running)	
Low Energy Consumption	186,000,000
High Energy Consumption	235,000,000
Annualized Capital Costs (20 years at 13 percent)	
Single Furnace Basis	2,100,000
Eighteen Furnace Basis	37,800,000
Total Annual Cost (Annualized Capital plus O & M)	
Single Furnace Basis	
Low Energy Consumption	13,700,000
High Energy Consumption	16,800,000
Eighteen Furnace Basis (16 furnaces assumed running)	
Low Energy Consumption	224,000,000
High Energy Consumption	273,000,000

TABLE 62. (Continued)

Stage/Process/Equipment	
Chemical Processing Section	
Electrical Power-electrolysis, pumps, etc., 345,000 kwh/yr at 2.5¢ kwh	10,000
Steam-from waste heat boiler	
Chemicals	
Chlorine-3200 tons/yr at $135/ton	440,000
Aluminum-91 tons/yr at $0.20/pound	36,800
Ether-150 gal/yr at $0.90 gal	150
H_2S at $0.10/lb	Nom
Nitric Acid-29 tons/yr at $8.75/100 lbs	5,000
Sodium Hydroxide-29 tons/yr 76 percent at $350/ton	13,000
HCl-29 tons at $63/ton	2,000
Labor 4200 man-hrs per year at $7/hr	29,400
Supervision and overhead	32,300
Maintenance at 4 percent of investment	50,000
Taxes and Insurance at 2 percent of investment	25,000
Total Operating and Maintenance	643,000
Annualized Capital 20 years at 13 percent	180,000
Total Annual Costs	820,000

TABLE 63. Estimated Parameters Associated with Production of 50 Metric Tons per Year of Gallium

• Gallium and Germanium Content in Flyash, ppm	20	50	100
• Assigned Gallium Cost, $/gram	4.00-5.00	1.40-1.80	0.49-0.69
• Flyash Intake, millions of metric tons/year	3.1	1.25	0.63
• Associated Number of Ash Smelting Furnaces	16	7	4
• Associated Electric Utility Coal Consumption - Million MT/year	31	12.5	6.3

The values in Table 63 indicate that the concept of gallium recovery as discussed here becomes more feasible at the 100 ppm level of gallium in fly ash, i.e., unit cost, size of installation, and siting (i.e., proximity to power plant capacity) all approach the range of credibility.

Consideration of the projected relationships in Table 63 leads to a recommendation or the visualization of a "prospecting" campaign to identify gallium (and germanium) contents of fly ash to see if appreciable quantities or precipitator fractions of fly ash can be identified at the 50 to 100 (or greater) ppm level. A favorable scenario might be hypothesized on the basis of a 20 percent fraction of separated fly ash containing 100 ppm or more each of gallium and germanium.

Alternative Processes

During this evaluation, contacts and discussions proceeded with numerous interested groups including staff at Oak Ridge National Laboratory and Ames Laboratory. Both laboratories are currently working on research relating to characterization and utilization of fly ash. These studies emphasize the recovery of such values as alumina (Al_2O_3), titania (TiO_2), etc. At a minimum, the contacts made during this evaluation have alerted these research staffs to the potential needs for recovery of trace metals which are in short supply and/or will be in greater demand in the future. The large number of trace metals in fly ash makes it difficult to allocate emphasis of research. Hopefully, these research programs will proceed with increased awareness of potential future needs for gallium.

The research at Oak Ridge is centered on the Calsinter process, which involves the sintering of fly ash with lime, followed by sulfuric acid leaching of the sinter product(28,29). Gallium is solubilized in this process and appears in the sulphate leach liquor. The recovery of gallium from sulfate solution is not a current commercial process, and such chemistry would probably require research and development efforts.

The work at Ames has centered on recovery of values by processes involving acid leaching, but future work will emphasize work on chlorination processes(30,31).

Both the above research programs consider the recovery of a number of products from fly ash, and such corecovery operations are judged to be more promising sources of byproduct gallium than the process evaluated here. The economic evaluations of these processes which have been published indicate that their economic feasibility is marginal until further detailed evaluations are performed.

ECONOMIC/INSTITUTIONAL FACTORS FOR GALLIUM RECOVERY

As discussed earlier, for the foreseeable future fly ash generated in the electric utility sector seems the most feasible source material for gallium recovery from coal in major quantities.

A viable furnace size for the production of gallium from fly ash was estimated to require 193,000 metric tons of ash per year. Based on the generation of approximately 1 ton of fly ash from each 10 tons of coal consumed in the electric utility sector, a utility plant consuming approximately 1.9 million metric tons (2.1 million short tons) of coal would be a logical furnace location.

Table 64 tabulates plants that, in 1977, consumed at least 1.9 million metric tons of coal. There were 72 such locations and as is evident from Table 64, some of the locations could support more than one furnace. The table suggests those identified locations could supply fly ash for 96 furnaces.

The quantity and quality of the ash from generating plants is not uniform. However, based on the assumption that the listed plants would produce fly ash with only 20 ppm of gallium, it can be hypothesized that material availability for producing 50 metric tons of gallium per year is not a problem. If, indeed, the identified locations could supply 96 furnaces, approximately 298 metric tons of gallium capacity is indicated.

If the reasonably conservative base case assumption of a national average of 50 ppm of gallium in fly ash is correct, those locations could supply ash for production of approximately 745 metric tons of gallium per year.

TABLE 64. Generating Plants Grouped by Coal Consumption

Coal Consumption (Million Metric Tons/Yr)	1977 Number of Plants	Furnaces Sustainable (Full Size or Equivalent)
5.7 or more	4	12
3.8	16	32
1.9	52	52
Total Full Size Furnace Sites	72	96
		Equivalent Full Size Furnaces
.95 to 1.9 (1/2 size furnace sites)	74	37
.48 to .95 (1/4 size furnace sites)	90	22
Total Full Size or Full Size Equivalents:		155

It seems probable that the total quantity of fly ash currently and expected to be generated would be sufficient to supply a sizeable portion of projected gallium requirements. However, sufficient single supply fly ash source plants capable of supplying one or more furnaces with 193,000 metric tons of ash per year may not exist.

It is Battelle's opinion that transportation of ash any great distance would not be feasible. As an alternate to ash transportation smaller furnaces might prove to be a viable option. In 1977, 74 half size furnace sites and 90 quarter size sites existed. These sites represent the equivalent of an additional 59 full size plants. Although coal consumption is a function of utilization or plant capacity factor, it is reasonable to assume that all the sites tabulated would generate sufficient fly ash to produce over 1200 tons of gallium per year based on ash containing 50 ppm of gallium. Any additional tonnage would have to rely on transportation of fly ash to furnaces located at sites selected for their proximity to more than one small power plant.

Institutional Factors

Electric utilities are chartered to perform certain functions by a state public utility commission. Holding companies operating interstate are also subject to regulation by FERC and the Securities and Exchange Commission (SEC). Hence, if an electric utility wished to enter into production of gallium it would need approval by a state public utility commission, and if it were also part of a holding company and operating interstate, it would need approval by FERC and the SEC.

The capital and operating costs of such a production unit by a utility would almost surely not be allowed in their rate base. Therefore, such a utility venture would be viewed purely on its economic merits. Even with much additional reasearch, recovery of gallium from fly ash would likely be viewed as very risky. Public utilities, by their nature, are not motivated toward high risk ventures. It would seem very unlikely, therefore, that a public utility would enter into this area unless: (1) such operations had strong government sanction, (2) government capital would be available, and (3) problems of process waste were satisfactorily resolved.

The disposal of fly ash does represent an allowable operating cost to the utility. The average cost of fly ash disposal is about \$5.00 to \$10.00 per ton. The capital costs of disposal (e.g., conveyors, silos, disposal land) are allowed in capital base. However, fly ash disposal is an increasingly worrisome concern of the utility. _If_ the federal EPA should declare fly ash a hazardous material, disposal costs could increase by as much as a factor of 10.

A utility would probably be happy to dispose of its fly ash "across the fence", on very attractive terms, for someone else to recover the gallium. The utility would need assurance that its responsibility for the fly ash ends at the fence.

It should be noted that the recovery process postulated _increases_ the amount of waste to be disposed of by nearly 50 percent, because of the large volume of lime needed in the furnace charge.

Some observers also express concern that acid or base _leaching_ treatments of fly ash may _increase_ the potential hazard of fly ash. Fly ash particles are vitreous in nature, and the breaking down of that structure could release contaminant materials that are distinctly hazardous (e.g., cadmium).

The Johnson-Matthey process described in this report is a smelting treatment, and the waste residue would be a glassy slag. That slag should be probably no more hazardous than the original fly ash -- perhaps even less so. The volatiles from the process are unknown.

GALLIUM SUPPLY AND PRICE

Within the recognizable limits of cost and recovery estimating in a speculative area, Table 65 presents a composite picture of the supply and price for gallium from maximum economic size furnaces (815 MT/day of charge) as well as furnaces 1/2 and 1/4 that size. Gallium supply and the price is a function of gallium concentration in the fly ash as well as the number of, and size of furnaces employed.

The table is predicated on fly ash quantities available at _single_ coal burning electric generating locations. Rather than transporting fly ash to maximum size furnaces, the table introduces furnaces of 1/2 maximum economic size and 1/4 maximum size. The economic wisdom of this concept may be questionable, but the trade-off between fly ash transport costs versus smaller furnace sizes is very complex and becomes very "situation" specific. The analysis does indicate the relative scale of the cost penalty in utilizing fly ash at single generating sites that could only accommodate smaller than maximum economic size furnaces. The cost penalties for transporting fly ash in favorable situations (e.g., barge transport) could well be less than cost penalties incurred by reducing furnace sizes.

TABLE 65. Metric Tons of Gallium Potentially Recoverable from Fly Ash (1977) and Corresponding Estimated Prices

Number of Furnaces and Sizes	Metric Tons Available as a Function of Gallium Concentration in Fly Ash			Price of Gallium ($/qm) as a Function of Concentration and Furnace Size		
	20 ppm	50 ppm	100 ppm	20 ppm	50 ppm	100 ppm
72 Utility plant locations consuming over 1,900,000 metric tons of coal per year (96 furnaces @ 815 MT/day)	298	745	1490	$4.00-$5.00	$1.40-$1.80	$0.49-$0.69
74 Utility plant locations consuming at least 950,000 and less than 1,900,000 metric tons of coal per year (74 furnaces @ 408 MT/day)	115	288	575	$4.86-$5.92	$1.70-$2.13	$0.65-$0.87
90 Utility plant locations consuming at least 465,000 and less than 950,000 metric tons of coal per year (90 furnaces @ 204 MT/day)	69	173	345	$5.73-$7.04	$2.06-$2.58	$0.83-$1.09
TOTALS	482	1206	2410			
		* *				
Recoverable from All Utility Fly Ash (44,000,000 MT)	770	1925	3850	-	-	-

The 72 locations or 96 maximum size furnaces would utilize nearly 39% of the total of all 1977 utility production of fly ash of 44 million metric tons. Expressed another way, these locations could recover 39% of the recoverable gallium in <u>all</u> utility fly ash. Increasing the supply of gallium from fly ash beyond that scale could be achieved only by incurring increased costs either through use of smaller furnaces or transporting fly ash.

CONCLUSIONS

The concentration ratio of gallium in fly ash to whole coal appears to be on the order of 10:1 or better. This is substantially higher than <u>reported</u> gallium concentrations in any other coal processing streams. Therefore, recovery of gallium from combustion fly ash is probably the most feasible of the recovery points investigated.

The lone process, that has been practiced (on a developmental scale) for recovering gallium (and germanium) from fly ash is limited by a maximum furnace size of 815 MT/day of charge (2.3 ash, 1/3 lime). Hence, no economics of scale exist beyond that unit size.

The recovery process can be characterized as being very energy intensive and very capital intensive. The sheer volume of materials to be handled and the energy required to melt a vitreous like feed stock make it so.

Battelle's cost estimates indicate that "feasibility" is approached only if gallium concentration reaches 100 ppm or better in the fly ash. The energy and capital intensive nature of the process raises the question as to whether some separable fractions of precipitator fly ash might contain 100 ppm or more of gallium. Literature suggests that gallium concentration increases with smaller particle size. Conventionally, all fly ash from a bank of several precipitator units (in series) goes to one collection point. Precipitator units successively remove about 80 percent of fly ash in the combustion stream, removing the heavier particles first. Individual precipitator unit streams of fly ash <u>could</u> technically be separated. Any scheme that would significantly increase the concentration of gallium, and at the same time reduce the volume of ash to be processed, would have major influence on production costs and energy consumption.

Until such possibilities are researched further, it is not prudent to state that recovery of gallium from coal is <u>not</u> feasible.

RECOMMENDATIONS

Before concluding that recovery of gallium from coal is not feasible or is marginal, some "prospecting" activity should be undertaken.

- A program to analyze for gallium concentrations in fly ash from the successive stages of one or more efficient precipitator installations should be undertaken.
- A very modest program should seek analysis of gallium concentrations in coal tar and pitch. The total potential for gallium recovery might be much less than for fly ash, but recovery from coal tar or pitch *might* be less costly.
- Coal conversion processes should be monitored as they are developing, and contractors should be made aware of SERI/DOE's interest in possible trace element recovery from waste streams.
- Finally, close liaison should be maintained with the ongoing research programs at Oak Ridge and Ames that seek recovery routes for alumina, titania, iron values, etc., from fly ash. Further, SERI/DOE should seek to "publicize" their interest in expanded domestic sources of gallium and perhaps other trace elements (e.g., germanium and indium).

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APPENDIX A

CMAP DATA BASES

THE DATA BASES

This appendix presents the complete materials assessment data base as it was used for this study. Table A-1 contains the bulk materials screening data on materials availability, cost, consumption, and import dependency. Table A-2 is the raw materials screening data -- similar to that for bulk materials (Table 1), but also containing current estimates of U.S. and World reserves and resources. Table A-3 contains the engineering material to bulk material conversions, and Table A-4 summarizes bulk material production processes. Quantities shown in Table A-4 are those needed to produce one metric ton (MT) of the desired material.

This data base represents an updating and upgrading of that used in previous materials assessment studies (References 1-3). These changes include:

- Additions required for SPS and this photovoltaic study
    - engineering materials
    - bulk materials
    - raw materials
- Conversion of data base from gross imports to net imports
- Updating various data parameters to 1976 actual values as published by U.S. Bureau of Mines. (Previous data were 1976 estimates of consumption, reserves, imports, etc.)
- Bulk material prices were updated to January 1, 1979
- Incorporation of intermediate bulk materials into the bulk to raw conversion data
- A number of recalculations and corrections.

BULK MATERIAL DATA SUMMARY

01/24/80

MATERIAL NAME	% SUPPLIED AS BY-PRODUCT	WORLD CONSUMPTION 1976 MT	WORLD CONSUMPTION 2000 MT	% FROM LARGEST NON US COUNTRY	PRICE $/MT	NET PERCENT IMPORTED	U.S. CONSUMPTION 1976 MT	U.S. CONSUMPTION 2000 MT
ABS RESINS	0	717.K	3.64M	19	1.25K	1.0	400.K	2.03M
ACETYLENE	0	815.K	1.82M	5.0	890.	0	222.K	495.K
ACRYLIC	0	829.K	4.2M	5.0	1.23K	1.0	226.K	1.15M
ALKYD RESIN	0	1.21M	6.13M	5.0	968.	1.0	330.K	1.67M
ALUMINUM	0	12.5M	60.2M	13	1.17K	9.0	4.64M	19.M
ALUMINUM OXIDE	0	25.M	120.M	13	220.	9.0	9.28M	38.M
AMMONIA	0	51.7M	115.M	5.0	132.	1.0	12.7M	26.3M
ANTIMONY	80	66.5K	232.K	22	2.72K	54	36.1K	81.6K
ANTIMONY TRIOXIDE	0	36.K	59.K	13	4.2K	48	9.8K	16.K
ARGON	100	439.K	1.21M	25	240.	0	239.K	599.K
ARSENIC	100	24.7K	50.7K	23	100.K	39	22.1K	23.8K
ARSENIC TRIOXIDE	100	39.6K	81.1K	23	255.	39	35.4K	38.1K
ARSINE, 99.999%	0	3.	320.	10	143.K	0	2.	160.
ASBESTOS	0	5.05M	9.56M	31	550.	85	658.K	1.01M
ASPHALT	0	109.M	204.M	5.0	14.3	0	24.9M	55.5M
BORON OXIDE	20	1.43M	3.01M	39	350.	0	327.K	994.K
BORON, 99.9995%	0	.	.13	0	50.M	0	.	.1
BROMINE	10	297.K	1.03M	9.0	550.	0	169.K	499.K
CADMIUM	100	17.1K	37.K	17	5.29K	64	5.38K	11.5K
CADMIUM SULFIDE	0	3.3K	8.4K	10	24.K	0	900.	2.3K
CALCIUM	0	67.9	219.	20	3.97K	0	18.5	59.7
CARBON BLACK	0	3.5M	5.M	12	440.	0	1.41M	2.02M
CARBON DIOXIDE	100	6.86M	15.3M	5.0	46.	0	1.87M	4.17M
CAUSTIC SODA	0	35.M	78.2M	5.0	154.	1.0	9.55M	21.3M
CEMENT	0	694.M	1.44G	18	44.	4.0	67.2M	200.M
CHLORINE	0	51.M	114.M	5.0	149.	1.0	13.9M	31.M
CHLOROFORM	0	488.K	1.1M	5.0	440.	1.0	133.K	300.K
CHROMIUM	0	2.58M	5.45M	28	6.59K	89	480.K	1.13M
COAL, BITUMINOUS	0	3.19G	4.86G	20	23.	10	541.M	1.41G
COBALT	100	26.K	65.K	42	44.1K	98	9.K	20.3K
COKE	0	200.M	448.M	10	90.	1.0	54.6M	122.M
COPPER	1.0	7.45M	27.2M	13	1.57K	12	2.03M	5.44M
COTTON FIBERS	0	3.M	5.85M	16	885.	1.0	1.4M	3.6M
CUPROUS CHLORIDE	0	7.3K	16.K	20	2.7K	20	2.K	4.4K
DIBORANE	0	16.1	52.1	5.0	1.9M	0	4.4	14.2
ELECTRICITY (KWH)	0	6.79T	31.8T	0	.03	0	1.85T	8.65T
ELECTRODES	0	771.K	1.72M	10	1.68K	1.0	210.K	468.K
EPOXY RESIN	0	419.K	2.12M	5.0	1.67K	1.0	114.K	578.K
ETHYLENE GLYCOL	0	5.25M	26.6M	5.0	539.	1.0	1.43M	7.25M
ETHYLENE PROPYLENE	0	190.K	963.K	13	1.1K	1.0	11.K	558.K

BULK MATERIAL DATA SUMMARY

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MATERIAL NAME	% SUPPLIED AS BY-PRODUCT	WORLD CONSUMPTION 1976 MT	WORLD CONSUMPTION 2000 MT	% FROM LARGEST NON US COUNTRY	PRICE $/MT	NET PERCENT IMPORTED	U.S. CONSUMPTION 1976 MT	U.S. CONSUMPTION 2000 MT
EVA	0	551.K	2.79M	5.0	484.	5.0	150.K	761.K
FELDSPAR	8.0	2.58M	7.26M	12	20.	0	666.K	1.81M
FERROCHROME	0	2.23M	4.53M	28	630.	50	378.K	768.K
FERROMANGANESE	0	14.2M	26.5M	22	420.	98	988.K	2.51M
FERROSILICON	0	2.58M	5.76M	10	400.	35	702.K	1.57M
FERROUS SCRAP, PURCHASED	0	138.M	307.M	10	85.	0	37.5M	83.6M
FLUORINE	8.0	2.03M	6.51M	19	1.3K	79	432.K	1.72M
FLUORSPAR	0	4.61M	14.8M	19	125.	79	982.K	3.91M
GALLIUM	100	16.8	47.	40	800.K	55	8.88	32.
GALLIUM ARSENIDE (DEP)	0	26.	84.3	10	700.K	0	14.	45.4
GALLIUM ARSENIDE (INGOT)	0	11.1	57.8	10	3.M	0	8.9	35.5
GALLIUM ARSENIDE (WAFER)	0	5.	26.	10	7.M	0	4.	16.
GERMANE, 99.9%	0	.04	.16	5.0	700.K	0	.03	.08
GERMANIUM	100	79.4	127.	29	316.K	16	21.3	36.7
GLASS, BOROSILIC	0	117.K	262.K	5.0	735.	1.0	32.K	71.4K
GLASS, FIBER	0	771.K	7.22M	5.0	1.35K	2.0	210.K	1.97M
GLASS, SODA LIME	0	68.3M	117.M	5.0	340.	1.0	18.6M	32.M
GOLD	47	1.2K	2.01K	58	6.43M	76	145.	528.
GRAPHITE FIBER, SYNTHETIC	0	215.	6.16K	35	57.2K	0	118.	3.38K
GRAPHITE, MFGD.	0	1.2M	2.67M	10	8.7K	1.0	326.K	727.K
GYPSUM, CALCINED	5.0	64.6M	113.M	10	28.	35	16.3M	31.6M
HELIUM	100	10.6K	23.7K	5.0	4.37K	0	2.9K	6.47K
HYDROCHLORIC ACID	92	8.33M	18.6M	5.0	200.	2.0	2.27M	5.06M
HYDROFLUORIC ACID	0	947.K	2.11M	15	981.	0	258.K	575.K
HYDROGEN	40	22.M	90.M	10	600.	0	7.9M	37.M
HYDROGEN SULFIDE, 99.999%	0	.	.01	10	195.K	0	.	.
INDIUM	100	46.5	103.	20	338.K	24	37.6	47.3
INDIUM-TIN OXIDE	0	15.	24.	10	320.K	0	9.	12.
KAPTON	0	1.K	5.06K	0	66.K	5.0	273.	1.38K
KRAFT FIBERS	0	60.M	120.M	10	425.	15	28.M	60.M
LEAD	13	3.35M	10.6M	12	838.	15	1.38M	2.2M
LIME	0	105.M	217.M	20	34.	2.0	18.6M	39.3M
LINSEED OIL	0	1.5M	2.M	5.0	1.03K	1.0	230.K	290.K
LIQUID FUELS	0	2.72G	5.4G	18	123.	39	631.M	1.47G
LITHIUM	4.0	7.5K	27.K	2.0	32.K	0	2.64K	13.1K
LUMBER,SOFTWOOD	0	300.M	780.M	20	188.	12	70.M	180.M
MAGNESIUM	1.0	229.K	889.K	27	2.23K	0	94.3K	358.K
MERCURY	2.0	8.4K	10.2K	18	4.5K	62	2.36K	2.K
METHANOL	0	6.M	19.4M	10	146.	0	2.71M	8.75M
MOLYBDENUM	42	86.8K	266.K	17	11.7K	0	27.1K	87.5K

BULK MATERIAL DATA SUMMARY

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MATERIAL NAME	% SUPPLIED AS BY-PRODUCT	WORLD CONSUMPTION 1976 MT	WORLD CONSUMPTION 2000 MT	% FROM LARGEST NON US COUNTRY	PRICE $/MT	NET PERCENT IMPORTED	U.S. CONSUMPTION 1976 MT	U.S. CONSUMPTION 2000 MT
NATURAL GAS REFINED	0	1.01G	3.04G	23	94.	5.0	406.M	551.M
NEOPRENE (POLYCHOROPRENE)	0	404.K	899.K	5.0	1.32K	6.0	110.K	245.K
NICKEL	7.0	804.K	1.81M	33	4.59K	70	198.K	499.K
NITRIC ACID	0	46.8M	104.M	32	116.	1.0	7.17M	16.M
NYLON RESINS	0	341.K	1.73M	20	2.55K	2.0	100.K	507.K
OXYGEN, GASEOUS	0	35.5M	93.8M	21	20.	0	10.1M	39.3M
OXYGEN, LIQUID	0	15.2M	40.2M	21	18.	0	4.32M	16.9M
PALLADIUM	100	76.6	188.	47	2.17M	90	27.3	49.2
PETROLEUM COKE	100	55.7M	110.M	15	84.	0	12.9M	30.M
PHENOLIC RESIN	0	2.18M	11.1M	13	1.03K	1.0	593.K	3.01M
PHOSPHATE ROCK	0	107.M	414.M	22	22.	0	31.1M	62.6M
PHOSPHINE 99.999%	0	2.5	240.	10	187.K	0	1.5	120.
PHOSPHOROUS	0	14.3M	55.4M	22	1.21K	0	4.17M	8.39M
PIG IRON	0	487.M	1.05G	22	210.	0	78.9M	148.M
PITCH-IN-TAR	0	757.K	1.45M	5.0	33.1	5.0	349.K	890.K
PLATINUM	100	87.8	180.	47	10.7M	90	31.3	44.8
POLYACRYLONITE FIBER	0	1.72M	3.84M	18	1.63K	3.0	285.K	636.K
POLYCARBONATE RESIN	0	100.K	507.K	10	2.49K	1.0	51.K	259.K
POLYESTER RESIN	0	1.6M	8.11M	5.0	792.	1.0	436.K	2.2M
POLYETHYLENE (LDPE+HDPE)	0	11.M	20.5M	14	693.	1.0	4.04M	20.5M
POLYPROPYLENE	0	2.81M	14.2M	18	726.	0	1.15M	5.83M
POLYSULFONE	0	18.4K	93.3K	5.0	4.4K	5.0	5.K	25.4K
POLYURETHANE RIGID FOAM	0	635.K	3.22M	5.0	3.85K	1.0	173.K	877.K
POLYVINYL FLUORIDE	0	10.5K	53.2K	5.0	19.8K	5.0	4.68K	23.7K
PORCELAIN	0	543.K	1.21M	5.0	2.2K	0	148.K	330.K
PROPYLENE GLYCOL	0	870.K	4.41M	5.0	561.	5.0	237.K	1.2M
PVC PLASTIC	0	8.36M	42.4M	19	594.	1.0	2.11M	10.7M
RUBBER, SBR	0	3.19M	16.2M	14	748.	4.0	1.23M	6.24M
SALT	0	166.M	686.M	18	49.	7.0	43.1M	124.M
SAND & GRAVEL	0	6.49G	15.7G	10	2.18	0	800.M	1.9G
SAPPHIRE	0	20.	1.6K	25	800.K	0	10.	800.
SELENIUM	100	1.26K	3.49K	37	39.7K	59	448.	1.41K
SILANE	0	30.	2.7K	10	130.K	0	17.	1.35K
SILICA FIBER	0	41.9	83.8	0	300.K	4.0	1.9	3.8
SILICON DIOXIDE, 99.99%	0	1.8K	4.K	10	106.K	0	500.	1.1K
SILICON MONOXIDE	0	18.	40.	20	120.K	30	5.	11.
SILICON (MET)	0	2.21M	4.72M	12	1.07K	11	548.K	1.09M
SILICON (SEG)	0	1.4K	111.K	10	60.K	0	700.	55.6K
SILICONES	0	266.K	591.K	5.0	6.27K	1.0	72.4K	161.K
SILVER	70	9.48K	26.1K	14	196.K	50	5.3K	9.64K

BULK MATERIAL DATA SUMMARY

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MATERIAL NAME	% SUPPLIED AS BY-PRODUCT	WORLD CONSUMPTION 1976 MT	WORLD CONSUMPTION 2000 MT	% FROM LARGEST NON US COUNTRY	PRICE $/MT	NET PERCENT IMPORTED	U.S. CONSUMPTION 1976 MT	U.S. CONSUMPTION 2000 MT
SODIUM CARBONATE	0	18.5M	11.5M	10	64.	0	1.57M	0.
SODIUM DICHROMATE	0	477.K	1.06M	5.0	815.	1.0	130.K	290.K
STAINLESS STEEL	0	6.45M	16.5M	30	1.37K	15	1.03M	2.09M
STEAM	1.0	2.57G	5.72G	10	4.25	0	700.M	1.56G
STEEL & IRON	1.0	773.M	1.75G	16	330.	7.0	131.M	246.M
STONE, CRUSHED & SIZED	0	7.G	13.4G	3.0	2.63	0	818.M	2.27G
SULFUR	31	52.2M	112.M	14	62.	0	10.9M	23.4M
SULFURIC ACID	20	144.M	308.M	14	55.	0	30.M	64.4M
TANTALUM	100	1.36K	4.17K	24	143.K	96	602.	2.4K
TANTALUM PENTOXIDE	100	73.	187.	10	330.K	0	20.	51.
TEFLON	0	11.8K	59.8K	10	6.82K	8.0	7.08K	35.9K
TELLURIUM	100	260.	349.	21	44.1K	53	173.	231.
TIN	1.0	226.K	410.K	28	16.4K	85	65.4K	81.3K
TITANIUM	0	57.1K	213.K	39	7.23K	8.0	21.1K	63.5K
TRICHLOROSILANE	0	8.45K	92.K	10	1.98K	0	4.65K	45.8K
TRIMETHYL AL., 99.9999%	0	.25	1.	5.0	5.M	0	.15	.5
TRIMETHYL GA., 99.9995%	0	.08	.32	5.0	8.M	0	.05	.16
TRIMETHYL INDIUM, 99.998%	0	.04	.16	5.0	35.M	0	.03	.08
TUNG OIL	0	45.K	45.1K	45	2.2K	70	15.K	15.1K
TUNGSTEN	10	40.7K	80.2K	7.0	32.4K	54	7.81K	23.5K
WATER, FRESH	0	1.6T	2.86T	5.0	4.25	0	437.G	778.G
ZINC	25	5.86M	10.5M	20	760.	59	1.03M	2.49M
ZINC FLUOROBORATE	0	3.5	8.	25	2.85K	0	1.	2.2
.BENZENE.	0	9.13M	29.4M	16	239.	1.0	4.9M	15.8M
.BUTADIENE.	40	3.32M	10.7M	14	451.	16	1.73M	5.59M
.ETHYLENE.	0	37.4M	12.1M	13	286.	0	10.2K	32.9M
.O-XYLENE.	0	2.37M	5.33M	12	248.	0	388.K	865.K
.PROPYLENE.	25	16.7M	53.9M	14	220.	0	4.55M	14.7M
/*NONAME*/	0	1.33M	6.74M	18	175.	1.0	362.K	1.84M

RAW MATERIAL DATA SUMMARY

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MATERIAL NAME	WORLD CONSUMP 1976 MT	WORLD CONSUMP 2000 MT	PRICE $/MT	RAW RESERVES WORLD MT	RAW RESOURCES WORLD MT	% LARGEST COUNTRY	% RESERVES TOP 3 COUNTRIES	NET PERCENT IMPORTED	U.S. CONSUMP 1976 MT	U.S. CONSUMP 2000 MT	RAW RESERVES U.S. MT	RAW RESOURCES U.S. MT
AIR	50.7M	134.M	20.	1.0E+20	1.0E+20	21	36	0	14.4M	56.2M	1.0E+20	1.0E+20
ANTIMONY ORE	7.28M	14.5M	11.7	453.M	533.M	22	60	54	3.8M	4.73M	11.5M	12.4M
ASBESTOS ORE	84.2M	159.M	5.46	1.45G	2.25G	31	81	85	11.M	16.8M	60.5M	106.M
BARITE	4.95M	10.3M	26.	181.M	1.81G	7.0	14	42	1.99M	2.44M	59.M	227.M
BAUXITE	77.6M	271.M	15.	24.9G	38.G	31	62	91	20.5M	85.5M	40.6M	300.M
BAUXITE, BY PROD	77.6M	271.M	0.	24.9G	38.G	31	62	91	20.5M	85.5M	40.6M	300.M
BORON OXIDE	1.43M	3.02M	130.	300.M	1.2G	39	62	0	327.K	995.K	63.M	250.M
BUTANE	135.M	227.M	35.	5.4G	54.G	23	78	5.0	36.7M	61.9M	520.M	5.2G
CHROMITE	8.61M	16.M	59.	245.M	16.3G	28	97	89	912.K	3.33M	0.	7.23M
CLAYS	563.M	962.M	22.	1.0E+20	1.0E+20	12	39	0	45.7M	164.M	1.0E+20	1.0E+20
COAL BYPROD.	3.19G	4.86G	0.	1.07T	11.5T	7.0	47	0	541.M	1.41G	397.G	3.6T
COAL BYPROD.#2	3.19G	4.86G	0.	1.07T	11.5T	7.0	47	0	541.M	1.41G	397.G	3.6T
COAL, BITUMINOUS	3.19G	4.86G	15.4	1.07T	11.5T	7.0	47	0	541.M	1.41G	397.G	3.6T
COPPER BYPROD.	1.06G	2.88G	0.	65.2G	267.G	13	32	12	235.M	544.M	12.1G	53.1G
COPPER BYPROD.#2	1.06G	2.88G	0.	65.2G	267.G	13	32	12	235.M	544.M	12.1G	53.1G
COPPER ORE	1.06G	2.88G	1.96	65.2G	267.G	13	32	12	235.M	544.M	12.1G	53.1G
COTTON	13.2M	19.1M	885.	1.0E+20	1.0E+20	16	35	1.0	1.6M	2.M	1.0E+20	1.0E+20
CU ANODE SLIMES	1.06G	2.88G	0.	65.2G	267.G	13	32	12	235.M	544.M	12.1G	53.1G
FELDSPAR	2.58M	7.26M	25.	907.M	1.0E+20	8.0	3.0	0	666.K	1.81M	544.M	1.0E+20
FLAX SEED	2.5M	3.3M	160.	1.0E+20	1.0E+20	25	35	20	350.K	380.K	1.0E+20	1.0E+20
FLUORSPAR ORE	14.M	45.M	0.	250.M	456.M	19	43	79	2.98M	11.9M	15.4M	91.8M
GOLD ORE	140.M	211.M	15.9	4.4G	6.87G	58	79	76	15.3M	55.3M	400.M	748.M
GYPSUM, CRUDE	64.6M	113.M	5.28	1.81G	1.0E+20	10	35	35	16.3M	31.6M	317.M	1.0E+20
IRON ORE	895.M	2.83G	2.	259.G	813.G	27	67	29	127.M	325.M	17.3G	110.G
LEAD ORE	63.1M	130.M	5.49	2.33G	5.65G	12	33	15	13.5M	26.2M	486.M	2.04G
LIMESTONE	302.M	625.M	31.6	1.0E+20	1.0E+20	20	40	2.0	53.6M	113.M	1.0E+20	1.0E+20
LITHIUM ORE	810.K	3.86M	143.	96.4M	273.M	24	78	0	377.K	1.87M	52.7M	120.M
MANGANESE ORE	24.8M	46.4M	126.	5.44G	10.8G	22	91	98	2.81M	4.39M	0.	1.03G
MERCURY ORE	290.K	320.K	33.8	6.19M	20.8M	18	63	62	81.3K	55.9K	484.K	1.07M
MILK BYPRODUCTS	100.M	200.M	220.	1.0E+20	1.0E+20	20	20	1.0	52.M	100.M	1.0E+20	1.0E+20
MOLYBDENUM ORE	28.9M	88.6M	12.	2.99G	10.4G	17	46	0	9.04M	29.2M	1.15G	5.31G
NATURAL GAS	1.01G	3.04G	94.	45.7G	457.G	23	50	5.0	406.M	551.M	4.41G	18.9G
NICKEL ORE	80.4M	144.M	15.8	5.44G	13.G	33	69	70	19.8M	34.9M	18.1M	7.G
PETROLEUM	2.88G	5.11G	73.	89.6G	272.G	18	45	39	667.M	1.55G	4.45G	13.6G
PETROLEUM BYPROD	2.88G	5.11G	73.	89.6G	272.G	18	45	39	667.M	1.55G	4.45G	13.6G
PHOSPHATE ROCK	101.M	414.M	22.	25.8G	76.1G	14	77	0	31.1M	62.6M	3.55G	6.35G
PROPANE	78.5M	132.M	35.	3.16G	31.6G	23	78	5.0	21.4M	36.1M	305.M	3.05G
RUTILE (CONC.)	399.K	1.15M	396.	160.M	200.M	98	91	98	256.K	521.K	5.44M	16.5M
SALT	166.M	686.M	30.	1.0E+20	1.0E+20	18	10	7.0	43.1M	124.M	1.0E+20	1.0E+20
SAND & GRAVEL	6.49G	15.7G	2.18	1.0E+20	1.0E+20	6.0	10	0	800.M	1.9G	1.0E+20	1.0E+20

RAW MATERIAL DATA SUMMARY

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MATERIAL NAME	WORLD CONSUMP 1976 MT	WORLD CONSUMP 2000 MT	PRICE $/MT	RAW RESERVES WORLD MT	RAW RESOURCES WORLD MT	% LARGEST COUNTRY	% RESERVES TOP 3 COUNTRIES	NET PERCENT IMPORTED	U.S. CONSUMP 1976 MT	U.S. CONSUMP 2000 MT	RAW RESERVES U.S. MT	RAW RESOURCES U.S. MT
SILVER ORE	13.6M	37.3M	4.85	271.M	1.01G	14	52	50	5.7M	10.2M	67.1M	253.M
SODA ASH (NAT.)	4.85M	14.M	60.	31.G	92.G	2.0	.40	0	4.7M	14.2M	30.G	46.G
SODIUM NITRATE	536.K	1.2M	110.	1.0E+20	1.0E+20	16	10	1.0	146.K	326.K	1.0E+20	1.0E+20
SOYBEAN	62.M	120.M	180.	1.0E+20	1.0E+20	12	25	0	31.M	80.M	1.0E+20	1.0E+20
STONE	7.G	13.4G	2.63	1.0E+20	1.0E+20	3.0	10	0	818.M	2.27G	1.0E+20	1.0E+20
SULFUR ORE	52.2M	112.M	45.8	1.73G	5.49G	14	33	0	10.9M	23.4M	208.M	640.M
TANTALUM ORE	310.K	2.9M	125.	47.2M	209.M	39	83	96	482.K	1.67M	0.	1.23M
TIMBER, LUMBER	1.4G	1.9G	140.	1.0E+20	1.0E+20	12	20	18	210.M	340.M	1.0E+20	1.0E+20
TIN ORE	22.6M	35.1M	421.	1.02G	3.76G	28	50	85	5.18M	6.5M	4.M	19.8M
TUNG NUTS	105.K	1.15G	880.	1.0E+20	1.0E+20	70	35	80	13.K	20.K	1.0E+20	1.0E+20
TUNGSTEN ORE	5.09M	9.89M	24.4	225.M	646.M	21	75	54	868.K	2.8M	15.6M	54.3M
WATER, FRESH	1.6T	2.86T	.16	1.0E+20	1.0E+20	5.0	20	0	437.G	778.G	1.0E+20	1.0E+20
WATER, SEAWATER	10.T	11.T	0.	1.0E+20	1.0E+20	0	0	0	10.T	11.T	1.0E+20	1.0E+20
WHEAT	340.M	710.M	130.	1.0E+20	1.0E+20	10	25	0	23.M	30.M	1.0E+20	1.0E+20
ZINC BYPROD.	117.M	224.M	0.	3.17G	4.9G	20	43	59	24.2M	55.3M	544.M	907.M
ZINC BYPROD.#2	117.M	224.M	0.	3.17G	4.9G	20	43	59	24.2M	55.3M	544.M	907.M
ZINC BYPROD.#3	117.M	224.M	0.	3.17G	4.9G	20	43	59	24.2M	55.3M	544.M	907.M
ZINC ORE	117.M	224.M	12.7	3.17G	4.9G	20	43	59	24.2M	55.3M	544.M	907.M

ENGINEERING MATERIAL : ALUMINUM BRONZE D

BULK MATERIALS

NAME	PERCENT
ALUMINUM	7.00
COPPER	91.00
STEEL & IRON	2.00

ENGINEERING MATERIAL : ALUMINUM, 6061

BULK MATERIALS

NAME	PERCENT
ALUMINUM	97.80
COPPER	.25
FERROCHROME	.35
MAGNESIUM	1.00
SILICON (MET)	.60

ENGINEERING MATERIAL : ALUMINUM, 6063

BULK MATERIALS

NAME	PERCENT
ALUMINUM	98.90
MAGNESIUM	7.00
SILICON (MET)	4.00

ENGINEERING MATERIAL : ANTIMONY LEAD, 5%

BULK MATERIALS

NAME	PERCENT
ANTIMONY	5.00
LEAD	95.00

ENGINEERING MATERIAL : ANTIMONY TIN SOLDER

BULK MATERIALS

NAME	PERCENT
ANTIMONY	5.00
TIN	95.00

ENGINEERING MATERIAL : ANTMONIAL LEAD

BULK MATERIALS

NAME	PERCENT
ANTIMONY	5.00
LEAD	95.00

ENGINEERING MATERIAL : BRASS

BULK MATERIALS

NAME	PERCENT
COPPER	70.00
ZINC	32.00

ENGINEERING MATERIAL : CALCIUM LEAD

BULK MATERIALS

NAME	PERCENT
LEAD	99.70
LIME	.30

ENGINEERING MATERIAL : CALCIUM LEAD, .3%

BULK MATERIALS	NAME	PERCENT
	CALCIUM	.30
	LEAD	97.00

ENGINEERING MATERIAL : CARBON STEEL

BULK MATERIALS	NAME	PERCENT
	FERROMANGANESE	.60
	STEEL & IRON	99.40

ENGINEERING MATERIAL : CARBON-CARBON

BULK MATERIALS	NAME	PERCENT
	GRAPHITE FIBER, SYNTHETIC	176.00

ENGINEERING MATERIAL : CAST IRON

BULK MATERIALS	NAME	PERCENT
	FERROMANGANESE	.80
	SILICON (MET)	2.50
	STEEL & IRON	96.70

ENGINEERING MATERIAL : CONCRETE

BULK MATERIALS	NAME	PERCENT
	CEMENT	14.00
	SAND & GRAVEL	29.00
	STONE, CRUSHED & SIZED	57.00

ENGINEERING MATERIAL : COPPER NICKEL 10 %

BULK MATERIALS	NAME	PERCENT
	COPPER	88.70
	NICKEL	10.00
	STEEL & IRON	1.30

ENGINEERING MATERIAL : EPOXY GLASS LAM

BULK MATERIALS	NAME	PERCENT
	EPOXY RESIN	35.00
	GLASS, FIBER	65.00

ENGINEERING MATERIAL : FLAT BLACK ALKYD PAINT

BULK MATERIALS	NAME	PERCENT
	ALKYD RESIN	13.00
	CARBON BLACK	62.00
	PAINT THINNER	25.00

ENGINEERING MATERIAL : FRP POLYESTER

BULK MATERIALS

NAME	PERCENT
GLASS, FIBER	30.00
POLYESTER RESIN	70.00

ENGINEERING MATERIAL : FRP POLYESTER

BULK MATERIALS

NAME	PERCENT
GLASS, FIBER	47.00
POLYESTER RESIN	53.00

ENGINEERING MATERIAL : GFRTP

BULK MATERIALS

NAME	PERCENT
GRAPHITE FIBER, SYNTHETIC	60.00
POLYSULFONE	40.00

ENGINEERING MATERIAL : LEADED RED BRASS

BULK MATERIALS

NAME	PERCENT
COPPER	85.00
LEAD	5.00
TIN	5.00
ZINC	5.00

ENGINEERING MATERIAL : LEADED TIN BRONZE

BULK MATERIALS

NAME	PERCENT
COPPER	88.00
LEAD	2.00
TIN	6.00
ZINC	5.00

ENGINEERING MATERIAL : MASONITE

BULK MATERIALS

NAME	PERCENT
COTTON FIBERS	35.00
KRAFT FIBERS	15.00
PHENOLIC RESIN	50.00

ENGINEERING MATERIAL : MICARTA

BULK MATERIALS

NAME	PERCENT
COTTON FIBERS	35.00
KRAFT FIBERS	15.00
PHENOLIC RESIN	50.00

ENGINEERING MATERIAL : NICHROME

BULK MATERIALS

NAME	PERCENT
CHROMIUM	20.00
NICKEL	78.00
SILICON (MET)	2.00

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ENGINEERING MATERIAL : PLYWOOD
          BULK MATERIALS                NAME                      PERCENT
                                  LUMBER,SOFTWOOD                   98.00


ENGINEERING MATERIAL : R-22
          BULK MATERIALS                NAME                      PERCENT
                                  TEFLON                           100.00


ENGINEERING MATERIAL : SILICA TILE
          BULK MATERIALS                NAME                      PERCENT
                                  SILICA FIBER                     900.00

ENGINEERING MATERIAL : SILICON STEEL
          BULK MATERIALS                NAME                      PERCENT
                                  SILICON (MET)                      3.00
                                  STEEL & IRON                      97.00


ENGINEERING MATERIAL : SOLDER, 50-50
          BULK MATERIALS                NAME                      PERCENT
                                  LEAD                              50.00
                                  TIN                               50.00


ENGINEERING MATERIAL : SOLDER, 60-40
          BULK MATERIALS                NAME                      PERCENT
                                  LEAD                              37.00
                                  TIN                               63.00


ENGINEERING MATERIAL : STAINLESS STEEL, 304
          BULK MATERIALS                NAME                      PERCENT
                                  CHROMIUM                          27.00
                                  NICKEL                            10.00
                                  STEEL & IRON                      63.00


ENGINEERING MATERIAL : STAINLESS STEEL, 316
          BULK MATERIALS                NAME                      PERCENT
                                  CHROMIUM                          24.00
                                  MOLYBDENUM                         3.00
                                  NICKEL                            12.00
                                  STEEL & IRON                      61.00


ENGINEERING MATERIAL : STAINLESS STEEL, 416
          BULK MATERIALS                NAME                      PERCENT
                                  CHROMIUM                          19.00
                                  STEEL & IRON                      81.00
                                  SULFUR                             2.00
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ENGINEERING MATERIAL : TIN BRONZE

BULK MATERIALS	NAME	PERCENT
	COPPER	89.00
	TIN	11.00

ENGINEERING MATERIAL : TRANSITE

BULK MATERIALS	NAME	PERCENT
	ASBESTOS	25.00
	CEMENT	75.00

ENGINEERING MATERIAL : VARNISH

BULK MATERIALS	NAME	PERCENT
	ALKYD RESIN	100.00
	LINSEED OIL	50.00
	TUNG OIL	150.00

BULK MATERIAL : ABS RESINS

RAW MATERIALS	NAME	AMOUNT(MT)
	COAL, BITUMINOUS	.0240
	NATURAL GAS	.0300

BULK MATERIALS	NAME	AMOUNT(MT)
	ALUMINUM CHLORIDE	.0050
	AMMONIA	.1460
	ELECTRICITY (KWH)	217.0000
	LIQUID FUELS	.0160
	.BENZENE.	.5220
	.BUTADIENE.	.1400
	.ETHYLENE.	.1940
	.PROPYLENE.	.3620

BULK MATERIAL : ACETYLENE

RAW MATERIALS	NAME	AMOUNT(MT)
	NATURAL GAS	6.8770

BULK MATERIALS	NAME	AMOUNT(MT)
	ELECTRICITY (KWH)	155.0000
	STEAM	29.0000

BULK MATERIAL : ACRYLIC

RAW MATERIALS	NAME	AMOUNT(MT)
	COAL, BITUMINOUS	1.3620
	NATURAL GAS	.1290

BULK MATERIALS	NAME	AMOUNT(MT)
	AMMONIA	.5000
	ELECTRICITY (KWH)	1188.0000
	LIQUID FUELS	1.4520
	.PROPYLENE.	1.2370

BULK MATERIAL : ALKYD RESIN

BULK MATERIALS	NAME	AMOUNT(MT)
	CAUSTIC SODA	.1940
	ELECTRICITY (KWH)	72.0000
	METHANOL	.2020
	OXYGEN, GASEOUS	.4140
	STEAM	.6150
	.ETHYLENE.	.0950
	.O-XYLENE.	.7600
	(MISC. BULK MATERIALS)	.2220

BULK MATERIAL : ALUMINUM

RAW MATERIALS	NAME	AMOUNT(MT)
	BAUXITE	4.7000
	COAL, BITUMINOUS	.0200
	NATURAL GAS	.2576

BULK MATERIALS	NAME	AMOUNT(MT)
	ALUMINUM FLUORIDE	.0200
	CAUSTIC SODA	.1500
	CRYOLITE	.0350
	ELECTRICITY (KWH)	17940.0000
	FLUORSPAR	.0030
	LIME	.1000
	PETROLEUM COKE	.4250
	PITCH-IN-TAR	.3000
	STEAM	9.8720
	(MISC. BULK MATERIALS)	.0050

BULK MATERIAL : ALUMINUM OXIDE

RAW MATERIALS	NAME	AMOUNT(MT)
	BAUXITE	2.2500

BULK MATERIALS	NAME	AMOUNT(MT)
	CAUSTIC SODA	.0880
	ELECTRICITY (KWH)	220.0000
	LIQUID FUELS	.1210
	STEAM	2.0000

BULK MATERIAL : AMMONIA

RAW MATERIALS	NAME	AMOUNT(MT)
	NATURAL GAS	.8531

BULK MATERIALS	NAME	AMOUNT(MT)
	ELECTRICITY (KWH)	15.0000
	(MISC. BULK MATERIALS)	.0044

BULK MATERIAL : ANTIMONY

RAW MATERIALS	NAME	AMOUNT(MT)
	ANTIMONY ORE	105.0000
	IRON ORE	.0800
	LIMESTONE	1.2300
	NATURAL GAS	.1522
	SAND & GRAVEL	.3200

BULK MATERIALS	NAME	AMOUNT(MT)
	CAUSTIC SODA	3.3400
	COKE	.5600
	ELECTRICITY (KWH)	170.0600
	ELECTRODES	.0020
	LIQUID FUELS	.0070
	SODIUM CARBONATE	.0260
	STEEL & IRON	.0070
	(MISC. BULK MATERIALS)	.0120

BULK MATERIAL : ANTIMONY TRIOXIDE

BULK MATERIALS	NAME	AMOUNT(MT)
	ANTIMONY	.8400

BULK MATERIAL : ARGON

BULK MATERIALS	NAME	AMOUNT(MT)
	ELECTRICITY (KWH)	428.0000
	HYDROGEN	.0015

BULK MATERIAL : ARSENIC

RAW MATERIALS	NAME	AMOUNT(MT)
	COAL, BITUMINOUS	.3400

BULK MATERIALS	NAME	AMOUNT(MT)
	ARSENIC TRIOXIDE	1.4000

BULK MATERIAL : ARSENIC TRIOXIDE

RAW MATERIALS	NAME	AMOUNT(MT)
	COPPER BYPROD.	2.3000
	NATURAL GAS	.1170

BULK MATERIALS	NAME	AMOUNT(MT)
	ELECTRICITY (KWH)	121.0000

BULK MATERIAL : ARSINE, 99.999%

BULK MATERIALS	NAME	AMOUNT(MT)
	SULFURIC ACID	2.1400
	ZINC ARSENIDE	2.4700

BULK MATERIAL : BORON OXIDE

RAW MATERIALS	NAME	AMOUNT(MT)
	BORON OXIDE	1.0000

BULK MATERIAL : BORON TRIFLUORIDE ETHERAT

BULK MATERIALS	NAME	AMOUNT(MT)
	BORAX	.6700
	DIETHYL ETHER	.5200
	HYDROFLUORIC ACID	.4300
	SULFURIC ACID	.3500

BULK MATERIAL : BORON, 99.9995%

BULK MATERIALS	NAME	AMOUNT(MT)
	BORON OXIDE	5.3500
	CHLORINE	14.7000
	ELECTRICITY (KWH)	1100000.0000
	ELECTRODES	4.2000
	HYDROGEN	.3730
	PETROLEUM COKE	3.2100

BULK MATERIAL : BROMINE

RAW MATERIALS	NAME	AMOUNT(MT)
	WATER, SEAWATER	1000.0000

BULK MATERIALS	NAME	AMOUNT(MT)
	CHLORINE	.5000
	ELECTRICITY (KWH)	153.0000
	STEAM	.5600

BULK MATERIAL : CADMIUM

RAW MATERIALS	NAME	AMOUNT(MT)
	NATURAL GAS	2.0370
	ZINC BYPROD.	400.0000

BULK MATERIALS	NAME	AMOUNT(MT)
	CAUSTIC SODA	.0630
	ELECTRICITY (KWH)	221.0000
	SODIUM DICHROMATE	.0150
	SULFURIC ACID	8.2000
	ZINC	1.0200

BULK MATERIAL : CADMIUM SULFIDE

BULK MATERIALS	NAME	AMOUNT(MT)
	CADMIUM	.8000
	SULFUR	.2300

BULK MATERIAL : CALCIUM

RAW MATERIALS	NAME	AMOUNT(MT)
	NATURAL GAS	1.9500
BULK MATERIALS	NAME	AMOUNT(MT)
	ELECTRICITY (KWH)	25.0000
	FERROSILICON	1.4000
	LIME	1.5600

BULK MATERIAL : CARBON BLACK

RAW MATERIALS	NAME	AMOUNT(MT)
	NATURAL GAS	5.1710

BULK MATERIAL : CAUSTIC SODA

RAW MATERIALS	NAME	AMOUNT(MT)
	SALT	1.5000
BULK MATERIALS	NAME	AMOUNT(MT)
	ELECTRICITY (KWH)	2750.0000
	SODIUM CARBONATE	.0250
	STEAM	10.0000
	SULFURIC ACID	.1000

BULK MATERIAL : CEMENT

RAW MATERIALS	NAME	AMOUNT(MT)
	CLAYS	.1440
	COAL, BITUMINOUS	.0908
	GYPSUM, CRUDE	.0480
	LIMESTONE	1.3700
	NATURAL GAS	.0700
	SAND & GRAVEL	.0570
BULK MATERIALS	NAME	AMOUNT(MT)
	ELECTRICITY (KWH)	131.0000
	LIQUID FUELS	.0240
	STEEL & IRON	.0010

BULK MATERIAL : CHLORINE

RAW MATERIALS	NAME	AMOUNT(MT)
	SALT	1.8300
BULK MATERIALS	NAME	AMOUNT(MT)
	ELECTRICITY (KWH)	3310.0000
	ELECTRODES	.0005
	SODIUM CARBONATE	.0029
	STEAM	11.4250
	SULFURIC ACID	.0010

BULK MATERIAL : CHLOROFORM

RAW MATERIALS	NAME	AMOUNT(MT)
	NATURAL GAS	.1750

BULK MATERIALS	NAME	AMOUNT(MT)
	CHLORINE	1.7800

BULK MATERIAL : COKE

RAW MATERIALS	NAME	AMOUNT(MT)
	COAL, BITUMINOUS	1.4500

BULK MATERIALS	NAME	AMOUNT(MT)
	ELECTRICITY (KWH)	36.4000
	STEAM	.5000
	(MISC. BULK MATERIALS)	.0010

BULK MATERIAL : COPPER

RAW MATERIALS	NAME	AMOUNT(MT)
	COAL, BITUMINOUS	.0033
	COPPER ORE	142.8600
	NATURAL GAS	.6670

BULK MATERIALS	NAME	AMOUNT(MT)
	ELECTRICITY (KWH)	5000.0000
	LIQUID FUELS	.4790
	STEAM	.1835
	STEEL & IRON	.3865
	SULFURIC ACID	.0165
	(MISC. BULK MATERIALS)	.3620

BULK MATERIAL : CUPROUS CHLORIDE

BULK MATERIALS	NAME	AMOUNT(MT)
	CHLORINE	.3600
	COPPER	.6500

BULK MATERIAL : DIBORANE

BULK MATERIALS	NAME	AMOUNT(MT)
	BORON TRIFLUORIDE ETHERAT	8.8000
	SODIUM BOROHYDRIDE	2.3000

BULK MATERIAL : DIMETHYL ALUM. CHLORIDE

BULK MATERIALS	NAME	AMOUNT(MT)
	ALUMINUM	.6000
	METHYL CHLORIDE	1.6700

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BULK MATERIAL : ELECTRICITY (KWH)
      RAW MATERIALS            NAME                      AMOUNT(MT)
                         COAL, BITUMINOUS                   .0004


BULK MATERIAL : ELECTRODES
      RAW MATERIALS            NAME                      AMOUNT(MT)
                         NATURAL GAS                        .6720

      BULK MATERIALS           NAME                      AMOUNT(MT)
                         ELECTRICITY (KWH)              7750.0000
                         PETROLEUM COKE                    1.5000
                         PITCH-IN-TAR                       .5000


BULK MATERIAL : EPOXY  RESIN
      RAW MATERIALS            NAME                      AMOUNT(MT)
                         COAL, BITUMINOUS                   .0330
                         NATURAL GAS                        .0410

      BULK MATERIALS           NAME                      AMOUNT(MT)
                         CAUSTIC SODA                       .6650
                         CHLORINE                          1.2390
                         ELECTRICITY (KWH)                300.0000
                         LIQUID FUELS                       .0220
                         .BENZENE.                          .7240
                         .PROPYLENE.                        .7880


BULK MATERIAL : ETHYLENE GLYCOL
      BULK MATERIALS           NAME                      AMOUNT(MT)
                         .ETHYLENE.                         .9000


BULK MATERIAL : ETHYLENE PROPYLENE
      RAW MATERIALS            NAME                      AMOUNT(MT)
                         NATURAL GAS                        .8140

      BULK MATERIALS           NAME                      AMOUNT(MT)
                         DUYCLOPINTADIENE                   .0530
                         ELECTRICITY (KWH)                653.0000
                         SULFURIC ACID                      .0370
                         .ETHYLENE.                         .6460
                         .PROPYLENE.                        .4550
                         (MISC. BULK MATERIALS)             .0870
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BULK MATERIAL : EVA

BULK MATERIALS	NAME	AMOUNT(MT)
	ELECTRICITY (KWH)	35.0000
	STEAM	.2640
	.ETHYLENE.	1.0270

BULK MATERIAL : FERROCHROME

RAW MATERIALS	NAME	AMOUNT(MT)
	CHROMITE	2.5000
	SILICA PEBBLE	.2130

BULK MATERIALS	NAME	AMOUNT(MT)
	COKE	.3750
	ELECTRODES	.0220
	(MISC. BULK MATERIALS)	.1210

BULK MATERIAL : FERROMANGANESE

RAW MATERIALS	NAME	AMOUNT(MT)
	LIMESTONE	.3000
	MANGANESE ORE	2.2000

BULK MATERIALS	NAME	AMOUNT(MT)
	COKE	.5000
	ELECTRICITY (KWH)	3064.0000
	FERROUS SCRAP, PURCHASED	.1500
	(MISC. BULK MATERIALS)	.2190

BULK MATERIAL : FERROSILICON

RAW MATERIALS	NAME	AMOUNT(MT)
	NATURAL GAS	.0640
	SILICA PEBBLE	1.1500

BULK MATERIALS	NAME	AMOUNT(MT)
	COAL, BITUMINOUS	.5500
	COKE	.0900
	ELECTRICITY (KWH)	5934.0000
	FERROUS SCRAP, PURCHASED	.5500
	PETROLEUM COKE	.0300
	PITCH-IN-TAR	.0070
	(MISC. BULK MATERIALS)	.1380

BULK MATERIAL : FLUORINE

RAW MATERIALS	NAME	AMOUNT(MT)
	NATURAL GAS	.2440

BULK MATERIALS	NAME	AMOUNT(MT)
	ELECTRICITY (KWH)	3738.0000
	FLUORSPAR	2.5000
	STEAM	1.9500
	SULFURIC ACID	3.1700

BULK MATERIAL : FLUORSPAR

RAW MATERIALS	NAME	AMOUNT(MT)
	FLUORSPAR ORE	3.0400
	NATURAL GAS	.0400

BULK MATERIALS	NAME	AMOUNT(MT)
	ELECTRICITY (KWH)	297.0000
	LIQUID FUELS	.0044
	STEEL & IRON	.0032
	(MISC. BULK MATERIALS)	.0300

BULK MATERIAL : GALLIUM

RAW MATERIALS	NAME	AMOUNT(MT)
	BAUXITE, BY PROD	50000.0000

BULK MATERIALS	NAME	AMOUNT(MT)
	CARBON DIOXIDE	242.3000
	CAUSTIC SODA	9.1000
	ELECTRICITY (KWH)	151170.0000
	HYDROCHLORIC ACID	.1000
	NITRIC ACID	.0800
	STEAM	.0820

BULK MATERIAL : GALLIUM ARSENIDE (DEP)

BULK MATERIALS	NAME	AMOUNT(MT)
	ARSENIC	.5770
	GALLIUM	.5430

BULK MATERIAL : GALLIUM ARSENIDE (INGOT)

BULK MATERIALS	NAME	AMOUNT(MT)
	ARSENIC	.5770
	ELECTRICITY (KWH)	200000.0000
	GALLIUM	.5430

BULK MATERIAL : GALLIUM ARSENIDE (WAFER)

BULK MATERIALS	NAME	AMOUNT(MT)
	GALLIUM ARSENIDE (INGOT)	2.2200

BULK MATERIAL : GALLIUM TRICHLORIDE

BULK MATERIALS	NAME	AMOUNT(MT)
	CHLORINE	.6400
	GALLIUM	.4200

BULK MATERIAL : GERMANE, 99.9%

RAW MATERIALS	NAME	AMOUNT(MT)
	WATER, FRESH	3.5700
BULK MATERIALS	NAME	AMOUNT(MT)
	GERMANIUM TETRACHLORIDE	3.5400
	SODIUM BOROHYDRIDE	2.5000

BULK MATERIAL : GERMANIUM

RAW MATERIALS	NAME	AMOUNT(MT)
	PROPANE	1.6700
	ZINC BYPROD.#3	100000.0000
BULK MATERIALS	NAME	AMOUNT(MT)
	CAUSTIC SODA	.0500
	CHLORINE	.6600
	ELECTRICITY (KWH)	185808.0000
	HYDROCHLORIC ACID	32.8000
	HYDROGEN	.0870

BULK MATERIAL : GERMANIUM TETRACHLORIDE

BULK MATERIALS	NAME	AMOUNT(MT)
	CHLORINE	.7000
	GERMANIUM	.3600

BULK MATERIAL : GLASS, BOROSILIC

RAW MATERIALS	NAME	AMOUNT(MT)
	NATURAL GAS	.1700
	SAND & GRAVEL	.8530
	SODA ASH (NAT.)	.0900
BULK MATERIALS	NAME	AMOUNT(MT)
	ALUMINUM OXIDE	.0210
	BORON OXIDE	.1270
	ELECTRICITY (KWH)	330.0000
	LIQUID FUELS	.0430
	(MISC. BULK MATERIALS)	.0152

BULK MATERIAL : GLASS, FIBER

	NAME	AMOUNT(MT)
RAW MATERIALS	BORON OXIDE	.1050
	NATURAL GAS	.7930
	SAND & GRAVEL	.5680
BULK MATERIALS	ALUMINUM OXIDE	.1470
	ELECTRICITY (KWH)	885.0000
	LIME	.1580
	LIQUID FUELS	.1360
	SODIUM CARBONATE	.0360
	(MISC. BULK MATERIALS)	.0530

BULK MATERIAL : GLASS, SODA LIME

	NAME	AMOUNT(MT)
RAW MATERIALS	FELDSPAR	.0922
	LIMESTONE	.1999
	NATURAL GAS	.1700
	SAND & GRAVEL	.6510
	SODA ASH (NAT.)	.0867
BULK MATERIALS	ELECTRICITY (KWH)	330.0000
	LIQUID FUELS	.0430
	SODIUM CARBONATE	.1300
	(MISC. BULK MATERIALS)	.0152

BULK MATERIAL : GOLD

	NAME	AMOUNT(MT)
RAW MATERIALS	GOLD ORE	116280.0000
	SODA ASH (NAT.)	32.3000
BULK MATERIALS	CHLORINE	202.0000
	ELECTRICITY (KWH)	3000000.0000
	LIME	525.0000
	LIQUID FUELS	727.0000
	STEAM	60.9000
	STEEL & IRON	54.7000
	SULFURIC ACID	9.4000
	ZINC	11.0000
	(MISC. BULK MATERIALS)	205.9000

BULK MATERIAL : GRAPHITE FIBER, SYNTHETIC

	NAME	AMOUNT(MT)
BULK MATERIALS	POLYACRYLONITE FIBER	2.2500

BULK MATERIAL : GRAPHITE, MFGD.

RAW MATERIALS	NAME	AMOUNT(MT)
	NATURAL GAS	.2400

BULK MATERIALS	NAME	AMOUNT(MT)
	ELECTRICITY (KWH)	7000.0000
	PETROLEUM COKE	.8500
	PITCH-IN-TAR	.2600

BULK MATERIAL : GYPSUM, CALCINED

RAW MATERIALS	NAME	AMOUNT(MT)
	COAL, BITUMINOUS	.0020
	GYPSUM, CRUDE	1.0620
	NATURAL GAS	.0229

BULK MATERIALS	NAME	AMOUNT(MT)
	ELECTRICITY (KWH)	34.3750
	LIQUID FUELS	.0035

BULK MATERIAL : HYDROCHLORIC ACID

RAW MATERIALS	NAME	AMOUNT(MT)
	SALT	.5250

BULK MATERIALS	NAME	AMOUNT(MT)
	SULFURIC ACID	.4750

BULK MATERIAL : HYDROFLUORIC ACID

RAW MATERIALS	NAME	AMOUNT(MT)
	NATURAL GAS	.2190

BULK MATERIALS	NAME	AMOUNT(MT)
	ELECTRICITY (KWH)	383.0000
	FLUORSPAR	2.2500
	STEAM	1.7500
	SULFURIC ACID	2.8500

BULK MATERIAL : HYDROGEN

RAW MATERIALS	NAME	AMOUNT(MT)
	NATURAL GAS	5.6250

BULK MATERIALS	NAME	AMOUNT(MT)
	ELECTRICITY (KWH)	354.4000
	STEAM	64.1800

BULK MATERIAL : HYDROGEN SULFIDE, 99.999%

BULK MATERIALS	NAME	AMOUNT(MT)
	STEEL & IRON	1.6400
	SULFUR	1.8800
	SULFURIC ACID	5.8000

BULK MATERIAL : INDIUM

RAW MATERIALS	NAME	AMOUNT(MT)
	NATURAL GAS	9.9500
	SALT	1.8400
	ZINC BYPROD.	4000.0000

BULK MATERIALS	NAME	AMOUNT(MT)
	ALUMINUM	.2600
	AMMONIA	.6500
	ELECTRICITY (KWH)	2087.0000
	SULFURIC ACID	21.2600

BULK MATERIAL : INDIUM TRICHLORIDE

BULK MATERIALS	NAME	AMOUNT(MT)
	CHLORINE	.5100
	INDIUM	.5500

BULK MATERIAL : INDIUM-TIN OXIDE

BULK MATERIALS	NAME	AMOUNT(MT)
	INDIUM	.8000
	NITRIC ACID	1.4000
	TIN	.0430

BULK MATERIAL : KAPTON

RAW MATERIALS	NAME	AMOUNT(MT)
	PETROLEUM	44.6250

BULK MATERIALS	NAME	AMOUNT(MT)
	CHLORINE	1.2290
	HYDROGEN	.0470
	NITRIC ACID	1.0630
	SULFURIC ACID	1.4460
	.BENZENE.	1.7110

BULK MATERIAL : LEAD

RAW MATERIALS	NAME	AMOUNT(MT)
	IRON ORE	.0700
	LEAD ORE	21.0000
	LIMESTONE	.1200
	NATURAL GAS	.1610
	SAND & GRAVEL	.0900
	SULFUR ORE	.0020

BULK MATERIALS	NAME	AMOUNT(MT)
	CALCIUM	.0010
	CAUSTIC SODA	.0010
	COKE	.2550
	ELECTRICITY (KWH)	1003.0000
	LIQUID FUELS	.0220
	MAGNESIUM	.0020
	SODIUM CARBONATE	.0100
	STEEL & IRON	.0190
	(MISC. BULK MATERIALS)	.0120

BULK MATERIAL : LIME

RAW MATERIALS	NAME	AMOUNT(MT)
	COAL, BITUMINOUS	.1557
	LIMESTONE	2.8800
	NATURAL GAS	.0790

BULK MATERIALS	NAME	AMOUNT(MT)
	ELECTRICITY (KWH)	63.2800
	LIQUID FUELS	.0160
	(MISC. BULK MATERIALS)	.0005

BULK MATERIAL : LIQUID FUELS

RAW MATERIALS	NAME	AMOUNT(MT)
	PETROLEUM	1.0570

BULK MATERIAL : LITHIUM

RAW MATERIALS	NAME	AMOUNT(MT)
	COAL, BITUMINOUS	24.0000
	LIMESTONE	113.0000
	LITHIUM ORE	159.0000

BULK MATERIALS	NAME	AMOUNT(MT)
	ELECTRICITY (KWH)	71042.0000
	FERROSILICON	.0610
	LIQUID FUELS	1.0000
	STEAM	18.5180
	STEEL & IRON	.2670
	SULFURIC ACID	.5230
	(MISC. BULK MATERIALS)	.9680

BULK MATERIAL : LITHIUM HYDRIDE

BULK MATERIALS	NAME	AMOUNT(MT)
	HYDROGEN	.1300
	LITHIUM	.9200

BULK MATERIAL : MAGNESIUM

RAW MATERIALS	NAME	AMOUNT(MT)
	LIMESTONE	7.6000
	NATURAL GAS	3.4240
	WATER, SEAWATER	721.0000

BULK MATERIALS	NAME	AMOUNT(MT)
	CHLORINE	.4900
	ELECTRICITY (KWH)	19076.0000
	ELECTRODES	.1000
	LIQUID FUELS	.0062
	(MISC. BULK MATERIALS)	.0022

BULK MATERIAL : MERCURY

RAW MATERIALS	NAME	AMOUNT(MT)
	MERCURY ORE	34.4800

BULK MATERIALS	NAME	AMOUNT(MT)
	ELECTRICITY (KWH)	18630.0000
	LIME	.0900
	LIQUID FUELS	4.9400
	(MISC. BULK MATERIALS)	.0750

BULK MATERIAL : METHANOL

RAW MATERIALS	NAME	AMOUNT(MT)
	NATURAL GAS	1.0120

BULK MATERIALS	NAME	AMOUNT(MT)
	CARBON DIOXIDE	.3820
	ELECTRICITY (KWH)	38.0500
	STEAM	.3120

BULK MATERIAL : METHYL BORATE

BULK MATERIALS	NAME	AMOUNT(MT)
	BORAX	3.6700
	METHANOL	3.7000
	SULFURIC ACID	1.8900

BULK MATERIAL : MOLYBDENUM

RAW MATERIALS	NAME	AMOUNT(MT)
	MOLYBDENUM ORE	333.0000
	NATURAL GAS	.6200

BULK MATERIALS	NAME	AMOUNT(MT)
	ELECTRICITY (KWH)	10500.0000
	HYDROGEN	.0700
	LIQUID FUELS	.1822
	STEEL & IRON	.1900
	(MISC. BULK MATERIALS)	.7405

BULK MATERIAL : NATURAL GAS REFINED

RAW MATERIALS	NAME	AMOUNT(MT)
	NATURAL GAS	1.0000

BULK MATERIAL : NEOPRENE (POLYCHOROPRENE)

BULK MATERIALS	NAME	AMOUNT(MT)
	HYDROCHLORIC ACID	.4570
	KAPTON	.6510

BULK MATERIAL : NICKEL

RAW MATERIALS	NAME	AMOUNT(MT)
	NATURAL GAS	1.1130
	NICKEL ORE	100.0000
	SAND & GRAVEL	10.3360

BULK MATERIALS	NAME	AMOUNT(MT)
	CHLORINE	.0065
	COKE	.1300
	ELECTRICITY (KWH)	7270.0000
	ELECTRODES	.7236
	LIME	.3180
	LIQUID FUELS	.2220
	OXYGEN, GASEOUS	3.7900
	SODIUM CARBONATE	.0300
	STEEL & IRON	.0874
	(MISC. BULK MATERIALS)	.2280

BULK MATERIAL : NITRIC ACID

BULK MATERIALS	NAME	AMOUNT(MT)
	AMMONIA	.2900
	ELECTRICITY (KWH)	385.0000

BULK MATERIAL : NYLON RESINS

RAW MATERIALS	NAME	AMOUNT(MT)
	COAL, BITUMINOUS	.0740
	NATURAL GAS	.0340

BULK MATERIALS	NAME	AMOUNT(MT)
	AMMONIA	.2070
	ELECTRICITY (KWH)	533.0000
	HYDROGEN	.1580
	LIQUID FUELS	.1070
	NITRIC ACID	1.4540
	.BENZENE.	1.0880
	(MISC. BULK MATERIALS)	.0011

BULK MATERIAL : ORTHO-PHOSPHOROUS ACID

RAW MATERIALS	NAME	AMOUNT(MT)
	WATER, FRESH	.6600

BULK MATERIALS	NAME	AMOUNT(MT)
	PHOSPHOROUS TRICHLORIDE	1.6800

BULK MATERIAL : OXYGEN, GASEOUS

BULK MATERIALS	NAME	AMOUNT(MT)
	ELECTRICITY (KWH)	244.0000

BULK MATERIAL : OXYGEN, LIQUID

BULK MATERIALS	NAME	AMOUNT(MT)
	ELECTRICITY (KWH)	937.0000
	OXYGEN, GASEOUS	1.0000

BULK MATERIAL : PALLADIUM

RAW MATERIALS	NAME	AMOUNT(MT)
	CU ANODE SLIMES	476190.0000

BULK MATERIALS	NAME	AMOUNT(MT)
	AMMONIA	.6400
	ELECTRICITY (KWH)	25.0000
	HYDROCHLORIC ACID	1.3740

BULK MATERIAL : PETROLEUM COKE

RAW MATERIALS	NAME	AMOUNT(MT)
	PETROLEUM	51.7000

BULK MATERIAL : PHENOLIC RESIN

RAW MATERIALS	NAME	AMOUNT(MT)
	COAL, BITUMINOUS	.1540
	NATURAL GAS	.0720

BULK MATERIALS	NAME	AMOUNT(MT)
	CARBON MONOXIDE	.6010
	ELECTRICITY (KWH)	798.0000
	HYDROGEN	.0860
	LIQUID FUELS	.0380
	STEAM	3.4500
	.BENZENE.	.8060
	.PROPYLENE.	.4330

BULK MATERIAL : PHOSPHINE 99.999%

BULK MATERIALS	NAME	AMOUNT(MT)
	ORTHO-PHOSPHOROUS ACID	10.0000

BULK MATERIAL : PHOSPHOROUS

RAW MATERIALS	NAME	AMOUNT(MT)
	NATURAL GAS	.0470
	PHOSPHATE ROCK	10.3000
	SAND & GRAVEL	1.3600

BULK MATERIALS	NAME	AMOUNT(MT)
	COKE	1.6000
	ELECTRICITY (KWH)	15216.0000
	ELECTRODES	.0200

BULK MATERIAL : PHOSPHOROUS TRICHLORIDE

BULK MATERIALS	NAME	AMOUNT(MT)
	CHLORINE	.7800
	PHOSPHOROUS	.2300

BULK MATERIAL : PITCH-IN-TAR

RAW MATERIALS	NAME	AMOUNT(MT)
	COAL, BITUMINOUS	51.6000

BULK MATERIAL : POLYACRYLONITE FIBER

RAW MATERIALS	NAME	AMOUNT(MT)
	COAL, BITUMINOUS	1.3620
	NATURAL GAS	.1290

BULK MATERIALS	NAME	AMOUNT(MT)
	AMMONIA	.5000
	ELECTRICITY (KWH)	1188.0000
	LIQUID FUELS	1.4520
	.PROPYLENE.	1.2370

BULK MATERIAL : POLYCARBONATE RESIN

RAW MATERIALS	NAME	AMOUNT(MT)
	COAL, BITUMINOUS	.0330
	NATURAL GAS	.0410

BULK MATERIALS	NAME	AMOUNT(MT)
	CARBON MONOXIDE	.2660
	CHLORINE	.6670
	ELECTRICITY (KWH)	300.0000
	LIQUID FUELS	.0220
	.BENZENE.	1.9590
	.PROPYLENE.	1.0520

BULK MATERIAL : POLYESTER RESIN

RAW MATERIALS	NAME	AMOUNT(MT)
	COAL, BITUMINOUS	.0400
	NATURAL GAS	.0490

BULK MATERIALS	NAME	AMOUNT(MT)
	ELECTRICITY (KWH)	280.0000
	LIQUID FUELS	.0260
	STEAM	.9000
	.BENZENE.	.5330
	.ETHYLENE.	.1420
	.O-XYLENE.	.2710
	.PROPYLENE.	.2030
	(MISC. BULK MATERIALS)	.0040

BULK MATERIAL : POLYETHYLENE (LDPE+HDPE)

RAW MATERIALS	NAME	AMOUNT(MT)
	COAL, BITUMINOUS	.0840
	NATURAL GAS	.1040

BULK MATERIALS	NAME	AMOUNT(MT)
	ELECTRICITY (KWH)	1145.0000
	LIQUID FUELS	.0540
	.ETHYLENE.	1.0940

BULK MATERIAL : POLYPROPYLENE

RAW MATERIALS	NAME	AMOUNT(MT)
	COAL, BITUMINOUS	.0340
	NATURAL GAS	.0420

BULK MATERIALS	NAME	AMOUNT(MT)
	ELECTRICITY (KWH)	662.0000
	LIQUID FUELS	.0220
	.PROPYLENE.	1.0530

BULK MATERIAL : POLYSULFONE

BULK MATERIALS	NAME	AMOUNT(MT)
	CHLORINE	1.0610
	SULFURIC ACID	.4910
	.BENZENE.	1.6360
	.PROPYLENE.	.2820

BULK MATERIAL : POLYURETHANE RIGID FOAM

RAW MATERIALS	NAME	AMOUNT(MT)
	COAL, BITUMINOUS	.0010
	NATURAL GAS	.0040

BULK MATERIALS	NAME	AMOUNT(MT)
	CHLORINE	.0460
	DUYCLOPINTADIENE	.2540
	ELECTRICITY (KWH)	75.3600
	FLUORSPAR	.0080
	HYDROGEN	.0300
	METHANOL	.3580
	NITRIC ACID	.3480
	OXYGEN, GASEOUS	1.0850
	STEAM	.0060
	SULFURIC ACID	.4830
	.PROPYLENE.	.3800
	.TOLUENE.	.2540
	(MISC. BULK MATERIALS)	.0170

BULK MATERIAL : POLYVINYL FLUORIDE

RAW MATERIALS	NAME	AMOUNT(MT)
	COAL, BITUMINOUS	.2130

BULK MATERIALS	NAME	AMOUNT(MT)
	ACETYLENE	.6040
	ELECTRICITY (KWH)	164.0000
	FLUORSPAR	1.0440
	STEAM	.8120
	SULFURIC ACID	1.3230

BULK MATERIAL : PORCELAIN

RAW MATERIALS	NAME	AMOUNT(MT)
	CLAYS	.6950
	FELDSPAR	.3580
	NATURAL GAS	1.0500

BULK MATERIALS	NAME	AMOUNT(MT)
	ELECTRICITY (KWH)	25.0000

BULK MATERIAL : PROPYLENE GLYCOL

BULK MATERIALS	NAME	AMOUNT(MT)
	CHLORINE	1.2130
	LIME	.8320
	.PROPYLENE.	.7170

BULK MATERIAL : PVC PLASTIC

RAW MATERIALS	NAME	AMOUNT(MT)
	COAL, BITUMINOUS	.0540
	NATURAL GAS	.0670

BULK MATERIALS	NAME	AMOUNT(MT)
	CHLORINE	1.3900
	ELECTRICITY (KWH)	1830.0000
	LIQUID FUELS	.0350
	.ETHYLENE.	.5470

BULK MATERIAL : RUBBER, SBR

RAW MATERIALS	NAME	AMOUNT(MT)
	COAL, BITUMINOUS	.0380
	NATURAL GAS	.1040

BULK MATERIALS	NAME	AMOUNT(MT)
	CARBON BLACK	.3400
	ELECTRICITY (KWH)	183.6000
	.BENZENE.	.1400
	.BUTADIENE.	.3780
	.ETHYLENE.	.0520
	(MISC. BULK MATERIALS)	.1370

BULK MATERIAL : SILANE

BULK MATERIALS	NAME	AMOUNT(MT)
	LITHIUM HYDRIDE	1.2100
	SILICON TETRACHLORIDE	7.2500

BULK MATERIAL : SILICA FIBER

BULK MATERIALS	NAME	AMOUNT(MT)
	SAND & GRAVEL	3.0000

BULK MATERIAL : SILICON DIOXIDE, 99.99%

RAW MATERIALS	NAME	AMOUNT(MT)
	QUARTZ	1.0000

BULK MATERIALS	NAME	AMOUNT(MT)
	HYDROCHLORIC ACID	.0100

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BULK MATERIAL : SILICON MONOXIDE
       RAW MATERIALS           NAME                       AMOUNT(MT)
                          QUARTZ                             .7000

       BULK MATERIALS          NAME                       AMOUNT(MT)
                          SILICON (SEG)                      .3200


BULK MATERIAL : SILICON TETRACHLORIDE
       BULK MATERIALS          NAME                       AMOUNT(MT)
                          HYDROCHLORIC ACID                  .9000
                          SILICON (MET)                      .1700


BULK MATERIAL : SILICON (MET)
       RAW MATERIALS           NAME                       AMOUNT(MT)
                          COAL, BITUMINOUS                  1.2350
                          SAND & GRAVEL                     3.6570
                          TIMBER, LUMBER                    1.0250

       BULK MATERIALS          NAME                       AMOUNT(MT)
                          ELECTRICITY (KWH)             13200.0000
                          ELECTRODES                         .1825
                          PETROLEUM COKE                     .4250


BULK MATERIAL : SILICON (SEG)
       BULK MATERIALS          NAME                       AMOUNT(MT)
                          ELECTRICITY (KWH)           2304000.0000
                          HYDROCHLORIC ACID                17.6000
                          HYDROGEN                           .1930
                          SILICON (MET)                     4.4900


BULK MATERIAL : SILICONES
       RAW MATERIALS           NAME                       AMOUNT(MT)
                          NATURAL GAS                        .6730

       BULK MATERIALS          NAME                       AMOUNT(MT)
                          CHLORINE                          2.9650
                          SILICON (MET)                      .5850
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BULK MATERIAL : SILVER

	NAME	AMOUNT(MT)
RAW MATERIALS	NATURAL GAS	8.2740
	SILVER ORE	1430.0000

	NAME	AMOUNT(MT)
BULK MATERIALS	ELECTRICITY (KWH)	164350.0000
	LIME	10.8300
	LIQUID FUELS	8.9000
	OXYGEN, LIQUID	.0140
	SODIUM CARBONATE	2.0700
	SODIUM CYANIDE	.4000
	STEAM	7.0200
	STEEL & IRON	1.5400
	SULFURIC ACID	4.8600
	ZINC	.2200
	(MISC. BULK MATERIALS)	2.3300

BULK MATERIAL : SODIUM BOROHYDRIDE

	NAME	AMOUNT(MT)
BULK MATERIALS	METHYL BORATE	3.1000
	SODIUM HYDRIDE	2.8000

BULK MATERIAL : SODIUM CARBONATE

	NAME	AMOUNT(MT)
RAW MATERIALS	COAL, BITUMINOUS	.4500
	LIMESTONE	1.2200
	SALT	1.5650

	NAME	AMOUNT(MT)
BULK MATERIALS	AMMONIA	.0025
	COKE	.1000
	ELECTRICITY (KWH)	47.0000
	(MISC. BULK MATERIALS)	.0005

BULK MATERIAL : SODIUM DICHROMATE

	NAME	AMOUNT(MT)
RAW MATERIALS	CHROMITE	1.4500
	NATURAL GAS	1.0500

	NAME	AMOUNT(MT)
BULK MATERIALS	ELECTRICITY (KWH)	551.0000
	LIME	.4500
	SODIUM CARBONATE	1.0000
	SULFURIC ACID	.5880

BULK MATERIAL : STAINLESS STEEL

RAW MATERIALS	NAME	AMOUNT(MT)
	CHROMITE	.7680
	LIMESTONE	.0100
	NATURAL GAS	.0030
	NICKEL ORE	8.4000

BULK MATERIALS	NAME	AMOUNT(MT)
	ALUMINUM	.0010
	ELECTRICITY (KWH)	606.0000
	ELECTRODES	.0060
	FERROMANGANESE	.0110
	FERROSILICON	.0010
	FERROUS SCRAP, PURCHASED	.6620
	FLUORSPAR	.0050
	LIME	.0300
	OXYGEN, GASEOUS	.0110
	(MISC. BULK MATERIALS)	.0130

BULK MATERIAL : STEAM

RAW MATERIALS	NAME	AMOUNT(MT)
	COAL, BITUMINOUS	.1120

BULK MATERIAL : STEEL & IRON

RAW MATERIALS	NAME	AMOUNT(MT)
	IRON ORE	1.6200
	LIMESTONE	.1610
	NATURAL GAS	.0150

BULK MATERIALS	NAME	AMOUNT(MT)
	ALUMINUM	.0010
	COKE	.3820
	ELECTRICITY (KWH)	159.0000
	ELECTRODES	.0010
	FERROMANGANESE	.0110
	FERROSILICON	.0010
	FERROUS SCRAP, PURCHASED	.2410
	FLUORSPAR	.0070
	LIME	.0550
	LIQUID FUELS	.0190
	OXYGEN, LIQUID	.0710
	STEAM	.3840
	(MISC. BULK MATERIALS)	.0490

BULK MATERIAL : STONE, CRUSHED & SIZED

RAW MATERIALS	NAME	AMOUNT(MT)
	STONE	1.0000

BULK MATERIALS	NAME	AMOUNT(MT)
	ELECTRICITY (KWH)	1.8535
	LIQUID FUELS	.0008
	(MISC. BULK MATERIALS)	.0002

BULK MATERIAL : SULFUR

RAW MATERIALS	NAME	AMOUNT(MT)
	NATURAL GAS	.1450
	SULFUR ORE	1.0000

BULK MATERIALS	NAME	AMOUNT(MT)
	ELECTRICITY (KWH)	3.3000

BULK MATERIAL : SULFURIC ACID

BULK MATERIALS	NAME	AMOUNT(MT)
	ELECTRICITY (KWH)	9.0000
	SULFUR	.3370

BULK MATERIAL : TANTALUM

RAW MATERIALS	NAME	AMOUNT(MT)
	NATURAL GAS	.1560
	TANTALUM ORE	800.0000

BULK MATERIALS	NAME	AMOUNT(MT)
	ELECTRICITY (KWH)	636.0000
	HYDROCHLORIC ACID	1.3400
	HYDROFLUORIC ACID	2.0000
	METHANOL	.9000
	STEAM	2.1600
	(MISC. BULK MATERIALS)	7.7360

BULK MATERIAL : TANTALUM PENTOXIDE

RAW MATERIALS	NAME	AMOUNT(MT)
	TANTALUM ORE	11.0000

BULK MATERIAL : TEFLON

RAW MATERIALS	NAME	AMOUNT(MT)
	NATURAL GAS	.6380

BULK MATERIALS	NAME	AMOUNT(MT)
	CHLORINE	4.2290
	HYDROFLUORIC ACID	.7960

BULK MATERIAL : TIN

RAW MATERIALS	NAME	AMOUNT(MT)
	LIMESTONE	.0470
	TIN ORE	100.0000

BULK MATERIALS	NAME	AMOUNT(MT)
	COKE	.2850
	ELECTRICITY (KWH)	16733.0000
	LIQUID FUELS	.1210
	(MISC. BULK MATERIALS)	.1440

BULK MATERIAL : TITANIUM

RAW MATERIALS	NAME	AMOUNT(MT)
	LIMESTONE	.0061
	NATURAL GAS	.3502
	RUTILE (CONC.)	2.1740

BULK MATERIALS	NAME	AMOUNT(MT)
	ARGON	.0271
	CHLORINE	1.0000
	ELECTRICITY (KWH)	25855.0000
	HELIUM	.0029
	MAGNESIUM	.3100
	NITRIC ACID	.0171
	PETROLEUM COKE	.6000

BULK MATERIAL : TRICHLOROSILANE

BULK MATERIALS	NAME	AMOUNT(MT)
	HYDROCHLORIC ACID	4.8000
	SILICON (MET)	1.0600

BULK MATERIAL : TRIMETHYL AL., COMM.

BULK MATERIALS	NAME	AMOUNT(MT)
	DIMETHYL ALUM. CHLORIDE	2.5000
	SODIUM	.6200

BULK MATERIAL : TRIMETHYL AL., 99.9999%

BULK MATERIALS	NAME	AMOUNT(MT)
	TRIMETHYL AL., COMM.	1.0800

BULK MATERIAL : TRIMETHYL GA., 99.9995%

BULK MATERIALS	NAME	AMOUNT(MT)
	GALLIUM TRICHLORIDE	2.4600
	TRIMETHYL AL., COMM.	2.0000

BULK MATERIAL : TRIMETHYL INDIUM, 99.998%

BULK MATERIALS	NAME	AMOUNT(MT)
	INDIUM TRICHLORIDE	2.0700
	TRIMETHYL AL., COMM.	.6700

BULK MATERIAL : TUNGSTEN

RAW MATERIALS	NAME	AMOUNT(MT)
	NATURAL GAS	1.4760
	SODA ASH (NAT.)	.2415
	TUNGSTEN ORE	167.0000

BULK MATERIALS	NAME	AMOUNT(MT)
	AMMONIA	.4400
	CAUSTIC SODA	1.2350
	ELECTRICITY (KWH)	4102.0000
	HYDROCHLORIC ACID	5.0400
	HYDROGEN	.0904
	LIME	.1095
	LIQUID FUELS	4.6080
	SODIUM CYANIDE	.0550
	STEEL & IRON	.3065
	(MISC. BULK MATERIALS)	.1870

BULK MATERIAL : ZINC

RAW MATERIALS	NAME	AMOUNT(MT)
	NATURAL GAS	.1350
	ZINC ORE	22.2000

BULK MATERIALS	NAME	AMOUNT(MT)
	ELECTRICITY (KWH)	5413.0000
	LIQUID FUELS	.0560
	STEEL & IRON	.0250
	SULFURIC ACID	.0840
	(MISC. BULK MATERIALS)	.0810

BULK MATERIAL : ZINC ARSENIDE

BULK MATERIALS	NAME	AMOUNT(MT)
	ARSENIC	.4400
	ZINC	.5800

BULK MATERIAL : ZINC FLUOROBORATE

BULK MATERIALS	NAME	AMOUNT(MT)
	BORAX	.8000
	HYDROFLUORIC ACID	.6700
	SULFURIC ACID	.2100
	ZINC	.2800

```
BULK MATERIAL : .BENZENE.
       RAW MATERIALS           NAME                          AMOUNT(MT)
                          NATURAL GAS                           .0350
                          PETROLEUM                          174.2200

       BULK MATERIALS          NAME                          AMOUNT(MT)
                          ELECTRICITY (KWH)                   15.6790


BULK MATERIAL : .BUTADIENE.
       RAW MATERIALS           NAME                          AMOUNT(MT)
                          NATURAL GAS                           .2950
                          PETROLEUM                           73.7460

       BULK MATERIALS          NAME                          AMOUNT(MT)
                          ELECTRICITY (KWH)                   15.4870


BULK MATERIAL : .ETHYLENE.
       RAW MATERIALS           NAME                          AMOUNT(MT)
                          NATURAL GAS                           .3100
                          PETROLEUM                           10.0120

       BULK MATERIALS          NAME                          AMOUNT(MT)
                          ELECTRICITY (KWH)                   15.4190


BULK MATERIAL : .O-XYLENE.
       RAW MATERIALS           NAME                          AMOUNT(MT)
                          NATURAL GAS                           .5850
                          PETROLEUM                          146.3300

       BULK MATERIALS          NAME                          AMOUNT(MT)
                          ELECTRICITY (KWH)                   30.7300


BULK MATERIAL : .PROPYLENE.
       RAW MATERIALS           NAME                          AMOUNT(MT)
                          NATURAL GAS                           .3030
                          PETROLEUM                           20.2100

       BULK MATERIALS          NAME                          AMOUNT(MT)
                          ELECTRICITY (KWH)                   15.3600
```

APPENDIX B

CMAP SCREENING RESULTS

The following Appendix contains the screening results of the baseline, sensitivity and mixed scenario cases.

POLYCRYSTALLINE SILICON
HOMOJUNCTION (P-N)
SOLAR CELL

BASELINE CASE

THIS CELL HAS A GRAPHITE SUPPORT SUBSTRATE AND A 500 MICRON THICK POLYCRYSTALLINE SILICON WAFER OF METALLURGICAL GRADE PURITY. THE ACTIVE LAYERS ARE DEPOSITED EPITAXIALLY BY CVD (25 MICRONS) FROM TRICHLOROSILANE. P AND N DOPANTS ARE DEPOSITED BY CVD USING DIBORANE AND PHOSPHINE RESPECTIVELY. THE TOP GRID CONSISTS OF .03 MICRONS OF EVAPORATED NICKEL AND 5 MICRONS OF 60-40 SOLDER. AN AR COATING OF TANTALUM OXIDE IS EVAPORATED ON.

TECHNOLOGY	PHOTOVOLTAICS
CAPACITY	1 GW
APPLICATION	ELECTRIC POWER GENERATION
LOCATION	
INSOLATION	1 KW/M*M
SOLAR CONTRIBUTION	APPROX. 1500 GW-HR/YR
SUPPLEMENT	
SOLAR EFFICIENCY	10%
COLLECTOR AREA	10 KM*KM
OPERATING TEMPERATURE	
ENERGY TRANSPORT MEDIUM	ELECTRICAL
STORAGE TYPE	
STORAGE CAPACITY	

MATERIAL REQUIREMENTS
BY
FUNCTIONAL COMPONENTS

12.0 ENERGY COLLECTOR

12.03 ABSORBER- POLY-SI (P-N) CELL

ACTIVE LAYER	CVD	TRICHLOROSILANE TO-SI	0.21	0.35	583.0
P-DOPANT	CVD	DIBORANE TO B	0.78	0.35	4.53-05
EPITAXY SUBSTRATE		SILICON-MET GRADE	1.	1.	1.17+04
P-N JUNCTION LAYER	CVD	TRICHLOROSILANE TO SI	0.21	0.35	6.99
N-DOPANT	CVD	PHOSPHINE TO P	0.91	0.35	1.55-02
AR COATING	EVAPORATED	TANTALUM PENTOXIDE	1.0	0.35	5.34
GRID CONTACT	EVAPORATED	NICKEL	1.0	.035	0.267
	SOLDER DIP	60-40 SOLDER	1.0	.90	42.1
SUPPORT SUBSTRATE		GRAPHITE,MFGD.	1.0	0.8	5.74+03

BULK MATERIAL REQUIREMENTS FOR
POLYCRYST. SILICON-HOMOJUNCTION (P-N) SOLAR CELL
BASELINE CASE

SOLAR SCENARIO:
INTRODUCTION YEAR- 1991
CUMULATIVE CAPACITY 2000- 25. GW

FACTORS	BULK MATERIAL USAGE MT.	PERCENT SUPPLY AS BY-PROD	PRODTN GROWTH RATE 1990	MAX % SYSTEM 1 YEAR WORLD	% FROM ONE NATION NON-US	PRESENT COSTS IN $/KW	NET % IMPORT
THRESHOLD LEVELS--		50.	10.%	10.	35.	50.	50.
ALUMINUM	0.	0.	7.	0.	13.	0.	9.
ALUMINUM FLUORIDE	0.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
AMMONIA	0.	0.	3.	0.	5.	0.	1.
BORAX	0.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
BORON TRIFLUORIDE ETHERAT	0.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
CALCIUM	0.	0.	5.	0.	20.	0.	0.
CARBON DIOXIDE	0.	100.*	3.	0.	5.	0.	0.
CAUSTIC SODA	0.	0.	3.	0.	5.	0.	1.
CHLORINE	18.	0.	3.	0.	5.	0.	1.
COAL, BITUMINOUS	0.	0.	2.	0.	20.	0.	10.
COKE	363.	0.	3.	0.	10.	0.	1.
CRYOLITE	0.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
DIBORANE	0.	0.	5.	0.	5.	0.	0.
DIETHYL ETHER	0.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
ELECTRICITY (KWH)	8659.E+6	0.	7.	0.	0.	10.	0.
ELECTRODES	92340.	0.	4.	1.	10.	6.	1.
FERROMANGANESE	0.	0.	3.	0.	22.	0.	98.*
FERROSILICON	1.	0.	3.	0.	10.	0.	35.
FERROUS SCRAP, PURCHASED	6.	0.	3.	0.	10.	0.	0.
FLUORSPAR	0.	0.	5.	0.	19.	0.	79.*
GRAPHITE, MFGD.	179375.	0.	4.	1.	10.	62.*	1.
HYDROCHLORIC ACID	963249.	92.*	4.	1.	5.	8.	2.
HYDROFLUORIC ACID	0.	0.	3.	0.	15.	0.	0.
LEAD	433.	13.	5.	0.	12.	0.	15.
LIME	63.	0.	3.	0.	20.	0.	2.
LIQUID FUELS	142.	0.	3.	0.	18.	0.	39.
MAGNESIUM	1.	1.	6.	0.	27.	0.	0.
METHANOL	0.	0.	5.	0.	10.	0.	0.
METHYL BORATE	0.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?

BULK MATERIAL REQUIREMENTS FOR
POLYCRYST. SILICON-HOMOJUNCTION (P-N) SOLAR CELL
BASELINE CASE

SOLAR SCENARIO:
INTRODUCTION YEAR- 1991
CUMULATIVE CAPACITY 2000- 25. GW

FACTORS	BULK MATERIAL USAGE MT.	PERCENT SUPPLY AS BY-PROD	PRODTN GROWTH RATE 1990	MAX % SYSTEM 1 YEAR WORLD	% FROM ONE NATION NON-US	PRESENT COSTS IN $/KW	NET % IMPORT
THRESHOLD LEVELS--		50.	10.%	10.	35.	50.	50.
NICKEL	191.	7.	3.	0.	33.	0.	70.*
ORTHO-PHOSPHOROUS ACID	12.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
OXYGEN, GASEOUS	725.	0.	4.	0.	21.	0.	0.
OXYGEN, LIQUID	2.	0.	4.	0.	21.	0.	0.
PETROLEUM COKE	505697.	100.*	3.	0.	15.	2.	0.
PHOSPHINE 99.999%	1.	0.	21.*	0.	10.	0.	0.
PHOSPHOROUS	5.	0.	6.	0.	22.	0.	0.
PHOSPHOROUS TRICHLORIDE	20.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
PITCH-IN-TAR	92808.	0.	3.	1.	5.	0.	5.
SILICON (MET)	505217.	0.	3.	2.	12.	22.	11.
SODIUM BOROHYDRIDE	0.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
SODIUM CARBONATE	10.	0.	0.	0.	10.	0.	0.
SODIUM HYDRIDE	0.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
STEAM	397.	1.	3.	0.	10.	0.	0.
STEEL & IRON	25.	1.	3.	0.	16.	0.	7.
SULFUR	154192.	31.	3.	0.	14.	0.	0.
SULFURIC ACID	457543.	20.	3.	0.	14.	1.	0.
TANTALUM PENTOXIDE	381.	100.*	9.	27.*	10.	5.	0.
TIN	737.	1.	3.	0.	28.	0.	85.*
TRICHLOROSILANE	200677.	0.	21.*	28.*	10.	16.	0.
(MISC. BULK MATERIALS)	157.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?

RAW MATERIAL REQUIREMENTS FOR:
POLYCRYST. SILICON-HOMOJUNCTION (P-N) SOLAR CELL
BASELINE CASE

SOLAR SCENARIO:
INTRODUCTION YEAR- 1991
CUMULATIVE CAPACITY 2000- 25. GW

FACTORS	RAW MATERIAL USAGE (1000MT)	%PRD GROW RATE FROM 1990	MAX% SYST ONE YEAR WRLD	%US RESERV CONSUM BY 2000	%US RESOUR CONSUM BY 2000	%FRM ONE NAT NON-US	%WORLD RESERV CONSUM BY 2000	%WORLD RESOUR CONSUM BY 2000	PRSNT COSTS IN $/KW	NET% IMPT
THRESHOLD LEVELS--		7.	10.	400.	300.	60.	300.	200.	50.	50.
BAUXITE	0.	5.	0.	2691.*	364.*	31.	15.	10.	0.	91.*
COAL, BITUMINOUS	8704.	2.	0.	5.	1.	7.	9.	1.	5.	0.
FLUORSPAR ORE	0.	5.	0.	1004.*	168.	19.	255.	140.	0.	79.*
IRON ORE	0.	5.	0.	29.	5.	27.	16.	5.	0.	29.
LEAD ORE	9.	3.	0.	95.	23.	12.	95.	39.	0.	15.
LIMESTONE	0.	3.	0.	0.	0.	20.	0.	0.	0.	2.
MANGANESE ORE	0.	3.	0.	100.	8.	22.	15.	8.	0.	98.*
NATURAL GAS	128.	5.	0.	258.	60.	23.	97.	10.	0.	5.
NICKEL ORE	19.	2.	0.	3533.*	9.	33.	48.	20.	0.	70.*
PETROLEUM	26145.	2.	0.	565.*	185.	18.	104.	34.	76.*	39.
PHOSPHATE ROCK	0.	6.	0.	30.	17.	14.	21.	7.	0.	0.
SALT	506.	6.	0.	0.	0.	18.	0.	0.	1.	7.
SAND & GRAVEL	1850.	4.	0.	0.	0.	6.	0.	0.	0.	0.
SILICA PEBBLE	0.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
SULFUR ORE	154.	3.	0.	189.	61.	14.	109.	34.	0.	0.
TANTALUM ORE	4.	10.*	0.	100.	1866.*	39.	59.	13.	0.	96.*
TIMBER, LUMBER	518.	1.	0.	0.	0.	12.	0.	0.	3.	18.
TIN ORE	74.	2.	0.	3491.*	705.*	28.	67.	18.	1.	85.*
WATER, FRESH	0.	2.	0.	0.	0.	5.	0.	0.	0.	0.
WATER, SEAWATER	1.	0.	0.	0.	0.	0.	0.	0.	0.	0.

AMORPHOUS SILICON
P-I-N
SOLAR CELL

BASELINE CASE

THIS CELL HAS A 1 MICRON THICK ACTIVE LAYER FORMED BY GLOW DISCHARGE DECOMPOSITION OF HIGH PURITY SILANE. P AND N DOPANTS ARE DEPOSITED FROM DIBORANE AND PHOSPHINE RESPECTIVELY. SPUTTERING IS USED TO DEPOSIT A 0.012 MICRON THICK PT-SIO2 DIFFUSION BARRIER OVER A 0.058 MICRON THICK INDIUM-TIN OXIDE (ITO) WINDOW LAYER ON A GLASS SUPPORT SUBSTRATE. THE GRID CONTACT CONTAINING 5 MICRONS ALUMINUM OVER 0.05 MICRONS TITANIUM IS FORMED BY EVAPORATION.

TECHNOLOGY	PHOTOVOLTAICS
CAPACITY	1 GW
APPLICATION	ELECTRIC POWER GENERATION
LOCATION	
INSOLATION	1 KW/M*M
SOLAR CONTRIBUTION	APPROX. 1500 GW-HR/YR
SUPPLEMENT	
SOLAR EFFICIENCY	5%
COLLECTOR AREA	20 KM*KM
OPERATING TEMPERATURE	
ENERGY TRANSPORT MEDIUM	ELECTRICAL
STORAGE TYPE	
STORAGE CAPACITY	

MATERIAL REQUIREMENTS
BY
FUNCTIONAL COMPONENTS

12.0	ENERGY COLLECTOR				
12.03	ABSORBER- A-SILICON, P-I-N, CELL				
	ACTIVE LAYER	GLOW DISCHARGE DECOMP.			
		SILANE TO SI	0.87	0.10	46.6
	N-DOPANT	GLO DISCH DECOMP			
		PHOSPHINE TO P	0.91	0.10	2.59-03
	P-DOPANT	GLO DISCH DECOMP			
		DIBORANE TO B	0.78	0.10	9.05-04
	GRID CONTACT	EVAPORATED			
		TITANIUM	1.0	.035	0.451
		ALUMINUM	1.0	.035	27.0
	WINDOW LAYER	SPUTTERED			
		INDIUM/TIN OXIDE (ITO)			
		IND,SN/1.9,.103	1.0	0.40	8.32
	DIFFUSION BARRIER-	SPUTTERED PT/S102			
		PLATINUM	1.0	0.40	0.515
		SILICON DIOXIDE	1.0	0.40	1.09
	SUPPORT SUBSTRATE				
		GLASS,SODA LIME	1.0	0.8	1.46+05

BULK MATERIAL REQUIREMENTS FOR
AMORPHOUS SILICON, P-I-N, SOLAR CELL
BASELINE CASE

SOLAR SCENARIO:
INTRODUCTION YEAR- 1991
CUMULATIVE CAPACITY 2000- 25. GW

FACTORS	BULK MATERIAL USAGE MT.	PERCENT SUPPLY AS BY-PROD	PRODTN GROWTH RATE 1990	MAX % SYSTEM 1 YEAR WORLD	% FROM ONE NATION NON-US	PRESENT COSTS IN $/KW	NET % IMPORT
THRESHOLD LEVELS--		50.	10.%	10.	35.	50.	50.
ALUMINUM	19398.	0.	7.	0.	13.	1.	9.
ALUMINUM FLUORIDE	388.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
AMMONIA	1966.	0.	3.	0.	5.	0.	1.
ARGON	9.	100.*	4.	0.	25.	0.	0.
BORAX	9.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
BORON TRIFLUORIDE ETHERAT	3.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
CARBON DIOXIDE	3.	100.*	3.	0.	5.	0.	0.
CAUSTIC SODA	2910.	0.	3.	0.	5.	0.	1.
CHLORINE	380.	0.	3.	0.	5.	0.	1.
COAL, BITUMINOUS	502.	0.	2.	0.	20.	0.	10.
COKE	60955.	0.	3.	0.	10.	0.	1.
CRYOLITE	679.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
DIBORANE	0.	0.	5.	0.	5.	0.	0.
DIETHYL ETHER	1.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
ELECTRICITY (KWH)	3213.E+6	0.	7.	0.	0.	4.	0.
ELECTRODES	3026.	0.	3.	0.	10.	0.	1.
FERROMANGANESE	44.	0.	3.	0.	22.	0.	98.*
FERROSILICON	913.	0.	3.	0.	10.	0.	35.
FERROUS SCRAP, PURCHASED	1468.	0.	3.	0.	10.	0.	0.
FLUORSPAR	89.	0.	5.	0.	19.	0.	79.*
GLASS, SODA LIME	4562500.	0.	2.	1.	5.	62.*	1.
HELIUM	1.	100.*	3.	0.	5.	0.	0.
HYDROCHLORIC ACID	87376.	92.*	3.	0.	5.	1.	2.
HYDROFLUORIC ACID	1.	0.	3.	0.	15.	0.	0.
HYDROGEN	2106.	40.	6.	0.	10.	0.	0.
INDIUM	416.	100.*	14.*	42.*	20.	6.	24.
INDIUM-TIN OXIDE	520.	0.	50.*	80.*	10.	7.	0.
LIME	2159.	0.	3.	0.	20.	0.	2.
LIQUID FUELS	211208.	0.	3.	0.	18.	1.	39.

BULK MATERIAL REQUIREMENTS FOR AMORPHOUS SILICON, P-I-N, SOLAR CELL BASELINE CASE

SOLAR SCENARIO:
INTRODUCTION YEAR- 1991
CUMULATIVE CAPACITY 2000- 25. GW

FACTORS	BULK MATERIAL USAGE MT.	PERCENT SUPPLY AS BY-PROD	PRODTN GROWTH RATE 1990	MAX % SYSTEM 1 YEAR WORLD	% FROM ONE NATION NON-US	PRESENT COSTS IN $/KW	NET % IMPORT
THRESHOLD LEVELS--		50.	10.%	10.	35.	50.	50.
LITHIUM	14907.	4.	7.	9.	2.	19.	0.
LITHIUM HYDRIDE	16203.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
MAGNESIUM	100.	1.	6.	0.	27.	0.	0.
METHANOL	8.	0.	5.	0.	10.	0.	0.
METHYL BORATE	2.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
NITRIC ACID	734.	0.	3.	0.	32.	0.	1.
ORTHO-PHOSPHOROUS ACID	7.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
OXYGEN, GASEOUS	283.	0.	4.	0.	21.	0.	0.
OXYGEN, LIQUID	283.	0.	4.	0.	21.	0.	0.
PETROLEUM COKE	20018.	100.*	3.	0.	15.	0.	0.
PHOSPHINE 99.999%	1.	0.	21.*	0.	10.	0.	0.
PHOSPHOROUS	3.	0.	6.	0.	22.	0.	0.
PHOSPHOROUS TRICHLORIDE	12.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
PITCH-IN-TAR	7339.	0.	3.	0.	5.	0.	5.
PLATINUM	32.	100.*	3.	3.	47.*	14.	90.*
SILANE	13391.	0.	79.*	54.*	10.	70.*	0.
SILICON DIOXIDE, 99.99%	68.	0.	3.	0.	10.	0.	0.
SILICON TETRACHLORIDE	97083.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
SILICON (MET)	16504.	0.	3.	0.	12.	1.	11.
SODIUM BOROHYDRIDE	1.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
SODIUM CARBONATE	593199.	0.	0.	1.	10.	2.	0.
SODIUM HYDRIDE	2.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
STEAM	668178.	1.	3.	0.	10.	0.	0.
STEEL & IRON	3980.	1.	3.	0.	16.	0.	7.
SULFUR	19695.	31.	3.	0.	14.	0.	0.
SULFURIC ACID	58443.	20.	3.	0.	14.	0.	0.
TIN	22.	1.	3.	0.	28.	0.	85.*
TITANIUM	322.	0.	6.	0.	39.*	0.	8.
(MISC. BULK MATERIALS)	84581.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?

RAW MATERIAL REQUIREMENTS FOR:
AMORPHOUS SILICON, P-I-N, SOLAR CELL
BASELINE CASE

SOLAR SCENARIO:
INTRODUCTION YEAR- 1991
CUMULATIVE CAPACITY 2000- 25. GW

FACTORS	RAW MATERIAL USAGE (1000MT)	%PRD GROW RATE FROM 1990	MAX% SYST ONE YEAR WRLD	%US RESERV CONSUM BY 2000	%US RESOUR CONSUM BY 2000	%FRM ONE NAT NON-US	%WORLD RESERV CONSUM BY 2000	%WORLD RESOUR CONSUM BY 2000	PRSNT COSTS IN $/KW	NET% IMPT
THRESHOLD LEVELS--		7.	10.	400.	300.	60.	300.	200.	50.	50.
BAUXITE	91.	5.	0.	2691.*	364.*	31.	15.	10.	0.	91.*
COAL, BITUMINOUS	2409.	2.	0.	5.	1.	7.	9.	1.	1.	0.
FELDSPAR	421.	5.	1.	5.	0.	8.	12.	0.	0.	0.
FLUORSPAR ORE	0.	5.	0.	1004.*	168.	19.	255.	140.	0.	79.*
IRON ORE	6.	5.	0.	29.	5.	27.	16.	5.	0.	29.
LIMESTONE	3328.	3.	0.	0.	0.	20.	0.	0.	4.	2.
LITHIUM ORE	2370.	9.*	10.*	47.	21.	24.	51.	18.	14.	0.
MANGANESE ORE	0.	3.	0.	100.	8.	22.	15.	8.	0.	98.*
NATURAL GAS	804.	5.	0.	258.	60.	23.	97.	10.	3.	5.
PETROLEUM	1258.	2.	0.	565.*	185.	18.	104.	34.	4.	39.
PHOSPHATE ROCK	0.	6.	0.	30.	17.	14.	21.	7.	0.	0.
QUARTZ	0.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
RUTILE (CONC.)	1.	5.	0.	165.	54.	98.*	11.	9.	0.	98.*
SALT	980.	6.	0.	0.	0.	18.	0.	0.	1.	7.
SAND & GRAVEL	3031.	4.	0.	0.	0.	6.	0.	0.	0.	0.
SILICA PEBBLE	1.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
SODA ASH (NAT.)	396.	5.	1.	1.	0.	2.	1.	0.	1.	0.
SULFUR ORE	20.	3.	0.	189.	61.	14.	109.	34.	0.	0.
TIMBER, LUMBER	17.	1.	0.	0.	0.	12.	0.	0.	0.	18.
TIN ORE	2.	2.	0.	3489.*	705.*	28.	67.	18.	0.	85.*
WATER, FRESH	0.	2.	0.	0.	0.	5.	0.	0.	0.	0.
WATER, SEAWATER	72.	0.	0.	0.	0.	0.	0.	0.	0.	0.
ZINC BYPROD.	1664.	3.	0.	166.	100.	20.	125.	81.	0.	59.*

CADMIUM SULFIDE/COPPER SULFIDE FRONTWALL SOLAR CELL

BASELINE CASE

THIS CELL CONSISTS OF 25 MICRONS OF EVAPORATED CADMIUM SULFIDE ON A ZINC ELECTROPLATED (1 MICRON THICK) COPPER FOIL (25 MICRONS THICK) A COPPER SULFIDE LAYER IS FORMED BY DIPPING THE CADMIUM SULFIDE IN A HOT SOLUTION OF CUPROUS CHLORIDE. THE GRID CONTACT IS 5 MICRONS OF EVAPORATED GOLD. THE AR FILM IS SILICON MONOXIDE, .08 MICRON THICK.

TECHNOLOGY	PHOTOVOLTAICS
CAPACITY	1 GW
APPLICATION	ELECTRIC POWER GENERATION
LOCATION	
INSOLATION	1 KW/M*M
SOLAR CONTRIBUTION	APPROX. 1500 GW-HR/YR
SUPPLEMENT	
SOLAR EFFICIENCY	10%
COLLECTOR AREA	10 KM*KM
OPERATING TEMPERATURE	
ENERGY TRANSPORT MEDIUM	ELECTRICAL
STORAGE TYPE	
STORAGE CAPACITY	

MATERIAL REQUIREMENTS
BY
FUNCTIONAL COMPONENTS

12.0 ENERGY COLLECTOR

12.03 ABSORBER- CAD SULFIDE/CU SULFIDE CELL

ACTIVE LAYER	EVAPORATED	CADMIUM SULFIDE	1.0	0.35	1.21+03
ACTIVE LAYER	HOT DIPPED	CUPROUS CHLORIDE TO CUPROUS SULFIDE	0.80	0.1	22.4
BACK CONTACT	ELECTROPLATED	ZINC FLUOROBORATE TO ZINC	0.27	0.8	71.4
SUBSTRATE		COPPER	1.0	0.8	2.23+03
GRID CONTACT	EVAPORATED	GOLD	1.0	0.035	96.5
AR COATING	EVAPORATED	SILICON MONOXIDE	1.0	0.35	1.71

BULK MATERIAL REQUIREMENTS FOR CADMIUM SULFIDE/CU SULFIDE FRONTWALL SOLAR CELL BASELINE CASE

SOLAR SCENARIO:
INTRODUCTION YEAR- 1991
CUMULATIVE CAPACITY 2000- 25. GW

FACTORS	BULK MATERIAL USAGE MT.	PERCENT SUPPLY AS BY-PROD	PRODTN GROWTH RATE 1990	MAX % SYSTEM 1 YEAR WORLD	% FROM ONE NATION NON-US	PRESENT COSTS IN $/KW	NET % IMPORT
THRESHOLD LEVELS--		50.	10.%	10.	35.	50.	50.
ALUMINUM	3820.	0.	7.	0.	13.	0.	9.
ALUMINUM FLUORIDE	76.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
AMMONIA	104.	0.	3.	0.	5.	0.	1.
BORAX	6611.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
CADMIUM	69143.	100.*	8.	25.*	17.	15.	64.*
CADMIUM SULFIDE	86429.	0.	32.*	65.*	10.	83.*	0.
CAUSTIC SODA	4929.	0.	3.	0.	5.	0.	1.
CHLORINE	13926091.	0.	4.	2.	5.	83.*	1.
COAL, BITUMINOUS	2101.	0.	2.	0.	20.	0.	10.
COKE	1484744.	0.	3.	0.	10.	5.	1.
COPPER	74237.	1.	6.	0.	13.	5.	12.
CRYOLITE	134.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
CUPROUS CHLORIDE	7000.	0.	4.	7.	20.	1.	20.
ELECTRICITY (KWH)	261.E+9	0.	7.	0.	0.	314.*	0.
ELECTRODES	10815.	0.	3.	0.	10.	1.	1.
FERROMANGANESE	42020.	0.	3.	0.	22.	1.	98.*
FERROSILICON	3820.	0.	3.	0.	10.	0.	35.
FERROUS SCRAP, PURCHASED	929021.	0.	3.	0.	10.	3.	0.
FLUORSPAR	39209.	0.	5.	0.	19.	0.	79.*
GOLD	68929.	47.	79.*	86.*	58.*	17728.*	76.*
HYDROCHLORIC ACID	688.	92.*	3.	0.	5.	0.	2.
HYDROFLUORIC ACID	5537.	0.	3.	0.	15.	0.	0.
HYDROGEN	8.	40.	6.	0.	10.	0.	0.
LIME	36398448.	0.	3.	3.	20.	50.*	2.
LIQUID FUELS	50848298.	0.	3.	0.	18.	250.*	39.
OXYGEN, GASEOUS	271219.	0.	4.	0.	21.	0.	0.
OXYGEN, LIQUID	271219.	0.	4.	0.	21.	0.	0.
PETROLEUM COKE	18035.	100.*	3.	0.	15.	0.	0.
PITCH-IN-TAR	6580.	0.	3.	0.	5.	0.	5.

BULK MATERIAL REQUIREMENTS FOR CADMIUM SULFIDE/CU SULFIDE FRONTWALL SOLAR CELL
BASELINE CASE

SOLAR SCENARIO:
INTRODUCTION YEAR- 1991
CUMULATIVE CAPACITY 2000- 25. GW

FACTORS	BULK MATERIAL USAGE MT.	PERCENT SUPPLY AS BY-PROD	PRODTN GROWTH RATE 1990	MAX % SYSTEM 1 YEAR WORLD	% FROM ONE NATION NON-US	PRESENT COSTS IN $/KW	NET % IMPORT
THRESHOLD LEVELS--		50.	10.%	10.	35.	50.	50.
SILICON MONOXIDE	122.	0.	11.*	36.*	20.	1.	30.
SILICON (MET)	175.	0.	3.	0.	12.	0.	11.
SILICON (SEG)	39.	0.	20.*	0.	10.	0.	0.
SODIUM CARBONATE	41546.	0.	0.	0.	10.	0.	0.
SODIUM DICHROMATE	1037.	0.	3.	0.	5.	0.	1.
STEAM	166.E+6	1.	3.	1.	10.	28.	0.
STEEL & IRON	3819987.	1.	3.	0.	16.	50.*	7.
SULFUR	464316.	31.	3.	0.	14.	1.	0.
SULFURIC ACID	1318804.	20.	3.	0.	14.	3.	0.
ZINC	831054.	25.	3.	1.	20.	25.	59.*
ZINC FLUOROBORATE	8264.	0.	2654.*	99.*	25.	1.	0.
(MISC. BULK MATERIALS)	14504392.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?

RAW MATERIAL REQUIREMENTS FOR:
CADMIUM SULFIDE/CU SULFIDE FRONTWALL SOLAR CELL
BASELINE CASE

SOLAR SCENARIO:
INTRODUCTION YEAR- 1991
CUMULATIVE CAPACITY 2000- 25. GW

FACTORS	RAW MATERIAL USAGE (1000MT)	%PRD GROW RATE FROM 1990	MAX% SYST ONE YEAR WRLD	%US RESERV CONSUM BY 2000	%US RESOUR CONSUM BY 2000	%FRM ONE NAT NON-US	%WORLD RESERV CONSUM BY 2000	%WORLD RESOUR CONSUM BY 2000	PRSNT COSTS IN $/KW	NET% IMPT
THRESHOLD LEVELS--		7.	10.	400.	300.	60.	300.	200.	50.	50.
BAUXITE	18.	5.	0.	2691.*	364.*	31.	15.	10.	0.	91.*
CHROMITE	2.	3.	0.	100.	620.*	28.	117.	2.	0.	89.*
COAL, BITUMINOUS	126095.	2.	0.	6.	1.	7.	9.	1.	78.*	0.
COPPER ORE	10606.	4.	0.	73.	17.	13.	67.	16.	1.	12.
FLUORSPAR ORE	119.	5.	0.	1005.*	169.	19.	255.	140.	0.	79.*
GOLD ORE	8015014.	84.*	87.*	2191.*	1171.*	58.	277.	177.	5098.*	76.*
IRON ORE	6188.	5.	0.	29.	5.	27.	16.	5.	0.	29.
LIMESTONE	105506.	3.	3.	0.	0.	20.	0.	0.	133.*	2.
MANGANESE ORE	92.	3.	0.	100.	8.	22.	15.	8.	0.	98.*
NATURAL GAS	3318.	5.	0.	258.	60.	23.	97.	10.	12.	5.
PETROLEUM	54679.	2.	0.	566.*	185.	18.	104.	34.	160.*	39.
QUARTZ	0.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
SALT	25558.	6.	1.	0.	0.	18.	0.	0.	31.	7.
SAND & GRAVEL	1.	4.	0.	0.	0.	6.	0.	0.	0.	0.
SILICA PEBBLE	4.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
SODA ASH (NAT.)	2226.	5.	3.	1.	0.	2.	1.	0.	5.	0.
SULFUR ORE	464.	3.	0.	189.	61.	14.	109.	34.	1.	0.
TIMBER, LUMBER	0.	1.	0.	0.	0.	12.	0.	0.	0.	18.
ZINC BYPROD.	55314.	3.	4.	176.	106.	20.	126.	82.	0.	59.*
ZINC ORE	18449.	3.	1.	169.	102.	20.	125.	81.	9.	59.*

POLYCRYSTALLINE GALLIUM ARSENIDE
MIS
SOLAR CELL

BASELINE CASE

THE ACTIVE LAYER (5 MICRONS THICK) AND THE DOPED CONTACT LAYER (2 MICRONS) ARE PRODUCED BY CVD OF GAAS. THE N-DOPANT IS SULFUR. THESE TWO LAYERS ARE DEPOSITED ON A GERMANIUM EPITAXY SUBSTRATE (5 MICRONS) WHICH IS SUPPORTED BY A TIN COATED (1 MICRON) STAINLESS STEEL SUPPORT SUBSTRATE (.005 INCH). A SEMI-TRANSPARENT LAYER OF SILVER .005 MICRONS THICK IS EVAPORATED ONTO THE ACTIVE LAYER. THE GRID CONTACT IS 5 MICRONS OF COPPER. THE AR COATING IS ASSUMED TO BE 0.06 MICRONS OF ANTIMONY OXIDE.

TECHNOLOGY	PHOTOVOLTAICS
CAPACITY	1 GW
APPLICATION	ELECTRIC POWER GENERATION
LOCATION	
INSOLATION	1 KW/M*M
SOLAR CONTRIBUTION	APPROX. 1500 GW-HR/YR
SUPPLEMENT	
SOLAR EFFICIENCY	10%
COLLECTOR AREA	10 KM*KM
OPERATING TEMPERATURE	
ENERGY TRANSPORT MEDIUM	ELECTRICAL
STORAGE TYPE	
STORAGE CAPACITY	

MATERIAL REQUIREMENTS
BY
FUNCTIONAL COMPONENTS

```
12.0   ENERGY COLLECTOR
       12.03  ABSORBER- POLYCRYST. GAAS MIS CELL
              ACTIVE LAYER   MO-CVD OF GAAS
                                TRIMETHYL GALLIUM TO GA 0.61  0.30   128.0
                                ARSINE TO AS            0.96  0.30   138.0
              DOPED CONTACT LAYER   MO-CVD OF GAAS
                                TRIMETHYL GALLIUM TO GA 0.61  0.30    51.0
                                ARSINE TO AS            0.96  0.30    55.2
              N-DOPANT       MO-CVD OF S
                                HYDROGEN SULFIDE TO S   0.94  0.30   1.07-02
              M OF MIS       EVAPORATED
                                SILVER                  1.0   0.35    0.525
              GRID CONTACT   EVAPORATED
                                COPPER                  1.0   0.035    44.7
              AR COATING     EVAPORATED
                                ANTIMONY TRIOXIDE       1.0   0.35     3.11
              EPITAXY SUBSTRATE   CVD
                                GERMANE TO GE           0.95  0.35    267.0
              BACK CONTACT    EVAPORATED
                                TIN                     1.0   0.35     57.5
              SUPPORT SUBSTRATE
                                STAINLESS STEEL         1.0   0.8    9.99+03
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BULK MATERIAL REQUIREMENTS FOR POLYCRYSTALLINE GALLIUM ARSENIDE MIS SOLAR CELL BASELINE CASE

SOLAR SCENARIO:
INTRODUCTION YEAR- 1991
CUMULATIVE CAPACITY 2000- 25. GW

FACTORS	BULK MATERIAL USAGE MT.	PERCENT SUPPLY AS BY-PROD	PRODTN GROWTH RATE 1990	MAX % SYSTEM 1 YEAR WORLD	% FROM ONE NATION NON-US	PRESENT COSTS IN $/KW	NET % IMPORT
THRESHOLD LEVELS--		50.	10.%	10.	35.	50.	50.
ALUMINUM	73573.	0.	7.	0.	13.	3.	9.
ALUMINUM FLUORIDE	1471.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
AMMONIA	605.	0.	3.	0.	5.	0.	1.
ANTIMONY	187.	80.*	5.	0.	22.	0.	54.*
ANTIMONY TRIOXIDE	222.	0.	2.	0.	13.	0.	48.
ARSENIC	18227.	100.*	4.	6.	23.	73.*	39.
ARSENIC TRIOXIDE	25517.	100.*	4.	5.	23.	0.	39.
ARSINE, 99.999%	16771.	0.	688.*	93.*	10.	96.*	0.
BORAX	570989.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
CARBON DIOXIDE	6341709.	100.*	4.	7.	5.	12.	0.
CAUSTIC SODA	242854.	0.	3.	0.	5.	1.	1.
CHLORINE	105334.	0.	3.	0.	5.	1.	1.
CHROMIUM	84291.	0.	3.	0.	28.	22.	89.*
COAL, BITUMINOUS	117.	0.	2.	0.	20.	0.	10.
COKE	88410.	0.	3.	0.	10.	0.	1.
COPPER	31929.	1.	6.	0.	13.	2.	12.
CRYOLITE	2575.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
DIMETHYL ALUM. CHLORIDE	122268.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
ELECTRICITY (KWH)	11807.E+6	0.	7.	0.	0.	14.	0.
ELECTRODES	22855.	0.	3.	0.	10.	2.	1.
FERROMANGANESE	2337.	0.	3.	0.	22.	0.	98.*
FERROSILICON	212.	0.	3.	0.	10.	0.	35.
FERROUS SCRAP, PURCHASED	51659.	0.	3.	0.	10.	0.	0.
FLUORSPAR	1708.	0.	5.	0.	19.	0.	79.*
GALLIUM	25265.	100.*	1505.*	99.*	40.*	808.*	55.*
GALLIUM TRICHLORIDE	60156.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
GERMANE, 99.9%	20075.	0.	406482.*	100.*	5.	562.*	0.
GERMANIUM	25584.	100.*	447.*	97.*	29.	323.*	16.
GERMANIUM TETRACHLORIDE	71066.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?

BULK MATERIAL REQUIREMENTS FOR POLYCRYSTALLINE GALLIUM ARSENIDE MIS SOLAR CELL BASELINE CASE

SOLAR SCENARIO:
INTRODUCTION YEAR- 1991
CUMULATIVE CAPACITY 2000- 25. GW

FACTORS	BULK MATERIAL USAGE MT.	PERCENT SUPPLY AS BY-PROD	PRODTN GROWTH RATE 1990	MAX % SYSTEM 1 YEAR WORLD	% FROM ONE NATION NON-US	PRESENT COSTS IN $/KW	NET % IMPORT
THRESHOLD LEVELS--		50.	10.%	10.	35.	50.	50.
HYDROCHLORIC ACID	841676.	92.*	4.	1.	5.	7.	2.
HYDROGEN	2226.	40.	6.	0.	10.	0.	0.
HYDROGEN SULFIDE, 99.999%	1.	0.	1201.*	97.*	10.	0.	0.
LIME	29374.	0.	3.	0.	20.	0.	2.
LIQUID FUELS	28916.	0.	3.	0.	18.	0.	39.
METHANOL	575656.	0.	5.	1.	10.	3.	0.
METHYL BORATE	155583.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
METHYL CHLORIDE	204187.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
NICKEL	31219.	7.	3.	0.	33.	6.	70.*
NITRIC ACID	2021.	0.	3.	0.	32.	0.	1.
OXYGEN, GASEOUS	133401.	0.	4.	0.	21.	0.	0.
OXYGEN, LIQUID	15082.	0.	4.	0.	21.	0.	0.
PETROLEUM COKE	65558.	100.*	3.	0.	15.	0.	0.
PITCH-IN-TAR	33501.	0.	3.	0.	5.	0.	5.
SILVER	38.	70.*	4.	0.	14.	0.	50.*
SODIUM	30322.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
SODIUM BOROHYDRIDE	50188.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
SODIUM CARBONATE	7473.	0.	0.	0.	10.	0.	0.
SODIUM CYANIDE	15.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
SODIUM HYDRIDE	140526.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
STEAM	4814715.	1.	3.	0.	10.	1.	0.
STEEL & IRON	212414.	1.	3.	0.	16.	3.	7.
SULFUR	255064.	31.	3.	0.	14.	1.	0.
SULFURIC ACID	756861.	20.	3.	0.	14.	2.	0.
TIN	4107.	1.	3.	0.	28.	3.	85.*
TRIMETHYL AL., COMM.	48907.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
TRIMETHYL GA., 99.9995%	24454.	0.	247570.*	100.*	5.	7825.*	0.
ZINC	24034.	25.	2.	0.	20.	1.	59.*
ZINC ARSENIDE	41424.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
(MISC. BULK MATERIALS)	32782.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?

RAW MATERIAL REQUIREMENTS FOR:
POLYCRYSTALLINE GALLIUM ARSENIDE MIS SOLAR CELL
BASELINE CASE

SOLAR SCENARIO:
INTRODUCTION YEAR- 1991
CUMULATIVE CAPACITY 2000- 25. GW

FACTORS	RAW MATERIAL USAGE (1000MT)	%PRD GROW RATE FROM 1990	MAX% SYST ONE YEAR WRLD	%US RESERV CONSUM BY 2000	%US RESOUR CONSUM BY 2000	%FRM ONE NAT NON-US	%WORLD RESERV CONSUM BY 2000	%WORLD RESOUR CONSUM BY 2000	PRSNT COSTS IN $/KW	NET% IMPT
THRESHOLD LEVELS--		7.	10.	400.	300.	60.	300.	200.	50.	50.
ANTIMONY ORE	20.	3.	0.	887.*	822.*	22.	56.	47.	0.	54.*
BAUXITE	346.	5.	0.	2691.*	364.*	31.	15.	10.	0.	91.*
BAUXITE, BY PROD	1263270.	20.*	46.*	5802.*	785.*	31.	20.	13.	0.	91.*
COAL, BITUMINOUS	6899.	2.	0.	5.	1.	7.	9.	1.	4.	0.
COPPER BYPROD.	59.	4.	0.	73.	17.	13.	67.	16.	0.	12.
COPPER ORE	4561.	4.	0.	73.	17.	13.	67.	16.	0.	12.
FLUORSPAR ORE	5.	5.	0.	1004.*	168.	19.	255.	140.	0.	79.*
IRON ORE	344.	5.	0.	29.	5.	27.	16.	5.	0.	29.
LIMESTONE	129.	3.	0.	0.	0.	20.	0.	0.	0.	2.
MANGANESE ORE	5.	3.	0.	100.	8.	22.	15.	8.	0.	98.*
NATURAL GAS	735.	5.	0.	258.	60.	23.	97.	10.	3.	5.
NICKEL ORE	3122.	3.	0.	3550.*	9.	33.	48.	20.	2.	70.*
PETROLEUM	3420.	2.	0.	565.*	185.	18.	104.	34.	10.	39.
PROPANE	43.	2.	0.	221.	22.	23.	78.	8.	0.	5.
SALT	1011.	6.	0.	0.	0.	18.	0.	0.	1.	7.
SAND & GRAVEL	323.	4.	0.	0.	0.	6.	0.	0.	0.	0.
SILICA PEBBLE	0.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
SILVER ORE	54.	4.	0.	277.	73.	14.	208.	56.	0.	50.*
SULFUR ORE	255.	3.	0.	189.	61.	14.	109.	34.	0.	0.
TIN ORE	411.	2.	0.	3499.*	707.*	28.	67.	18.	7.	85.*
WATER, FRESH	72.	2.	0.	0.	0.	5.	0.	0.	0.	0.
ZINC BYPROD.#3	2558382.	30.*	67.*	636.*	382.*	20.	205.	133.	0.	59.*
ZINC ORE	534.	3.	0.	166.	100.	20.	125.	81.	0.	59.*

ADVANCED CONCENTRATOR
SOLAR CELL
500X

BASELINE CASE
THE GENERALIZED ADVANCED CONCENTRATOR CHARACTERIZED HERE HAS
SUBSTRATE-250 MICRONS OF SINGLE CRYSTAL GAAS.
LATTICE MATCHING LAYERS, BOTTOM AND TUNNEL JUNCTIONS-20 MICRONS OF
GA0.5IN0.5AS DEPOSITED BY MO-CVD.
TOP JUNCTION-4 MICRONS OF GA0.7AL0.3AS BY MO-CVD.
WINDOW LAYER-0.3 MICRONS OF GAP BY MO-CVD.
GRID CONTACTS-.05 MICRONS GOLD-ZINC AND 10 MICRONS SILVER-EVAPORATED
AR COATINGS-.065 MICRONS TA2O5 AND .1 MICRONS SIO2 BY EVAPORATION.

TECHNOLOGY	PHOTOVOLTAICS
CAPACITY	1 GW
APPLICATION	ELECTRIC POWER GENERATION
LOCATION	
INSOLATION	1 KW/M*M
SOLAR CONTRIBUTION	APPROX. 1500 GW-HR/YR
CONCENTRATION FACTOR	500X
SOLAR EFFICIENCY	30%
APERATURE AREA	3.33 KM*KM
ACTIVE CELL AREA	0.00667 KM*KM (6667 M*M)
ENERGY TRANSPORT MEDIUM	ELECTRICAL
STORAGE TYPE	
STORAGE CAPACITY	

MATERIAL REQUIREMENTS
BY
FUNCTIONAL COMPONENTS

12.0 ENERGY COLLECTOR

12.03 ABSORBER-ADVANCED CONCENTRATOR CELL-500X

SUBSTRATE	SINGLE CRYSTAL				
		GALLIUM ARSENIDE	1.0	1.0	8.86
LATTICE MATCHING LAYERS, BOTTOM & TUNNEL JUNCTIONS	MO-CVD OF GA0.75IN0.25AS				
		TRIMETHYL GALLIUM TO GA	0.61	0.3	0.242
		TRIMETHYL INDIUM TO IN	0.72	0.3	0.133
		ARSINE TO AS	0.96	0.3	0.346
TOP JUNCTION	MO-CVD OF GA0.8AL0.2AS				
		TRIMETHYL GALLIUM TO GA	0.61	0.3	5.48-02
		TRIMETHYL ALUMIN. TO AL	0.37	0.3	5.30-03
		ARSINE TO AS	0.96	0.3	7.36-02
WINDOW LAYER	MO-CVD OF GA0.1AL0.9AS				
		TRIMETHYL GALLIUM TO GA	0.61	0.3	5.20-04
		TRIMETHYL ALUMIN. TO AL	0.37	0.3	1.81-03
		ARSINE TO AS	0.96	0.3	5.59-03
GRID CONTACTS	EVAP. OF (.8AU-.2ZN)/AG				
		GOLD	1.0	.035	5.15-04
		ZINC	1.0	.035	4.76-05
		SILVER	1.0	.035	7.00-02
AR COATINGS	EVAPORATION				
		TANTALUM PENTOXIDE	1.00	0.35	3.55-03
		SILICON DIOXIDE	1.00	0.35	1.51-03

BULK MATERIAL REQUIREMENTS FOR
ADVANCED CONCENTRATOR SOLAR CELL-500X
BASELINE CASE

SOLAR SCENARIO:
INTRODUCTION YEAR- 1991
CUMULATIVE CAPACITY 2000- 25. GW

FACTORS	BULK MATERIAL USAGE MT.	PERCENT SUPPLY AS BY-PROD	PRODTN GROWTH RATE 1990	MAX % SYSTEM 1 YEAR WORLD	% FROM ONE NATION NON-US	PRESENT COSTS IN $/KW	NET % IMPORT
THRESHOLD LEVELS--		50.	10.%	10.	35.	50.	50.
ALUMINUM	145.	0.	7.	0.	13.	0.	9.
ALUMINUM FLUORIDE	3.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
AMMONIA	19.	0.	3.	0.	5.	0.	1.
ARSENIC	324.	100.*	3.	0.	23.	1.	39.
ARSENIC TRIOXIDE	453.	100.*	3.	0.	23.	0.	39.
ARSINE, 99.999%	37.	0.	23.*	3.	10.	0.	0.
CARBON DIOXIDE	74865.	100.*	3.	0.	5.	0.	0.
CAUSTIC SODA	2833.	0.	3.	0.	5.	0.	1.
CHLORINE	155.	0.	3.	0.	5.	0.	1.
COAL, BITUMINOUS	0.	0.	2.	0.	20.	0.	10.
COKE	66.	0.	3.	0.	10.	0.	1.
CRYOLITE	5.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
DIMETHYL ALUM. CHLORIDE	233.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
ELECTRICITY (KWH)	166.E+6	0.	7.	0.	0.	0.	0.
ELECTRODES	0.	0.	3.	0.	10.	0.	1.
FERROMANGANESE	1.	0.	3.	0.	22.	0.	98.*
FERROSILICON	0.	0.	3.	0.	10.	0.	35.
FERROUS SCRAP, PURCHASED	24.	0.	3.	0.	10.	0.	0.
FLUORSPAR	1.	0.	5.	0.	19.	0.	79.*
GALLIUM	309.	100.*	23.*	54.*	40.*	10.	55.*
GALLIUM ARSENIDE (INGOT)	492.	0.	38.*	61.*	10.	59.*	0.
GALLIUM ARSENIDE (WAFER)	222.	0.	38.*	61.*	10.	62.*	0.
GALLIUM TRICHLORIDE	100.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
GOLD	0.	47.	2.	0.	58.*	0.	76.*
HYDROCHLORIC ACID	31.	92.*	3.	0.	5.	0.	2.
INDIUM	18.	100.*	4.	3.	20.	0.	24.
INDIUM TRICHLORIDE	32.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
LIME	755.	0.	3.	0.	20.	0.	2.
LIQUID FUELS	730.	0.	3.	0.	18.	0.	39.

BULK MATERIAL REQUIREMENTS FOR ADVANCED CONCENTRATOR SOLAR CELL-500X BASELINE CASE

SOLAR SCENARIO:
INTRODUCTION YEAR- 1991
CUMULATIVE CAPACITY 2000- 25. GW

FACTORS	BULK MATERIAL USAGE MT.	PERCENT SUPPLY AS BY-PROD	PRODTN GROWTH RATE 1990	MAX % SYSTEM 1 YEAR WORLD	% FROM ONE NATION NON-US	PRESENT COSTS IN $/KW	NET % IMPORT
THRESHOLD LEVELS--		50.	10.%	10.	35.	50.	50.
METHYL CHLORIDE	389.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
NITRIC ACID	25.	0.	3.	0.	32.	0.	1.
OXYGEN, GASEOUS	8.	0.	4.	0.	21.	0.	0.
OXYGEN, LIQUID	8.	0.	4.	0.	21.	0.	0.
PETROLEUM COKE	62.	100.*	3.	0.	15.	0.	0.
PITCH-IN-TAR	43.	0.	3.	0.	5.	0.	5.
SILICON DIOXIDE, 99.99%	0.	0.	3.	0.	10.	0.	0.
SILVER	50.	70.*	4.	0.	14.	0.	50.*
SODIUM	58.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
SODIUM CARBONATE	278.	0.	0.	0.	10.	0.	0.
SODIUM CYANIDE	20.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
STEAM	31996.	1.	3.	0.	10.	0.	0.
STEEL & IRON	99.	1.	3.	0.	16.	0.	7.
SULFUR	338.	31.	3.	0.	14.	0.	0.
SULFURIC ACID	1002.	20.	3.	0.	14.	0.	0.
TANTALUM PENTOXIDE	0.	100.*	4.	0.	10.	0.	0.
TRIMETHYL AL., COMM.	93.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
TRIMETHYL AL., 99.9999%	2.	0.	11.*	23.*	5.	0.	0.
TRIMETHYL GA., 99.9995%	41.	0.	417.*	96.*	5.	13.	0.
TRIMETHYL INDIUM, 99.998%	15.	0.	318.*	95.*	5.	22.	0.
ZINC	68.	25.	2.	0.	20.	0.	59.*
ZINC ARSENIDE	91.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
(MISC. BULK MATERIALS)	204.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?

RAW MATERIAL REQUIREMENTS FOR:
ADVANCED CONCENTRATOR SOLAR CELL-500X
BASELINE CASE

SOLAR SCENARIO:
INTRODUCTION YEAR- 1991
CUMULATIVE CAPACITY 2000- 25. GW

FACTORS	RAW MATERIAL USAGE (1000MT)	%PRD GROW RATE FROM 1990	MAX% SYST ONE YEAR WRLD	%US RESERV CONSUM BY 2000	%US RESOUR CONSUM BY 2000	%FRM ONE NAT NON-US	%WORLD RESERV CONSUM BY 2000	%WORLD RESOUR CONSUM BY 2000	PRSNT COSTS IN $/KW	NET% IMPT
THRESHOLD LEVELS--		7.	10.	400.	300.	60.	300.	200.	50.	50.
BAUXITE	1.	5.	0.	2691.*	364.*	31.	15.	10.	0.	91.*
BAUXITE, BY PROD	15449.	6.	1.	2729.*	369.*	31.	15.	10.	0.	91.*
COAL, BITUMINOUS	69.	2.	0.	5.	1.	7.	9.	1.	0.	0.
COPPER BYPROD.	1.	4.	0.	73.	17.	13.	67.	16.	0.	12.
FLUORSPAR ORE	0.	5.	0.	1004.*	168.	19.	255.	140.	0.	79.*
GOLD ORE	43.	2.	0.	187.	100.	58.	94.	60.	0.	76.*
IRON ORE	0.	5.	0.	29.	5.	27.	16.	5.	0.	29.
LIMESTONE	3.	3.	0.	0.	0.	20.	0.	0.	0.	2.
MANGANESE ORE	0.	3.	0.	100.	8.	22.	15.	8.	0.	98.*
NATURAL GAS	1.	5.	0.	258.	60.	23.	97.	10.	0.	5.
PETROLEUM	4.	2.	0.	565.*	185.	18.	104.	34.	0.	39.
QUARTZ	0.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
SALT	5.	6.	0.	0.	0.	18.	0.	0.	0.	7.
SILICA PEBBLE	0.	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?	-99.?
SILVER ORE	71.	4.	0.	277.	73.	14.	208.	56.	0.	50.*
SODA ASH (NAT.)	0.	5.	0.	1.	0.	2.	1.	0.	0.	0.
SULFUR ORE	0.	3.	0.	189.	61.	14.	109.	34.	0.	0.
TANTALUM ORE	0.	10.*	0.	100.	1865.*	39.	59.	13.	0.	96.*
ZINC BYPROD.	70.	3.	0.	166.	100.	20.	125.	81.	0.	59.*
ZINC ORE	2.	3.	0.	166.	100.	20.	125.	81.	0.	59.*

POLYCRYSTALLINE SILICON
HOMOJUNCTION (P-N)
SOLAR CELL

BASELINE CASE ALTERED: SIH4 SUBSTITUTED FOR SIHCL3.

THIS CELL HAS A GRAPHITE SUPPORT SUBSTRATE AND A 500 MICRON THICK POLYCRYSTALLINE SILICON WAFER OF METALLURGICAL GRADE PURITY. THE ACTIVE LAYERS ARE DEPOSITED EPITAXIALLY BY CVD (25 MICRONS) FROM SILANE. P AND N DOPANTS ARE DEPOSITED BY CVD USING DIBORANE AND PHOSPHINE RESPECTIVELY. THE TOP GRID CONSISTS OF .03 MICRONS OF EVAPORATED NICKEL AND 5 MICRONS OF 60-40 SOLDER. AN AR COATING OF TANTALUM OXIDE IS EVAPORATED ON.

TECHNOLOGY	PHOTOVOLTAICS
CAPACITY	1 GW
APPLICATION	ELECTRIC POWER GENERATION
LOCATION	
INSOLATION	1 KW/M*M
SOLAR CONTRIBUTION	APPROX. 1500 GW-HR/YR
SUPPLEMENT	
SOLAR EFFICIENCY	10%
COLLECTOR AREA	10 KM*KM
OPERATING TEMPERATURE	
ENERGY TRANSPORT MEDIUM	ELECTRICAL
STORAGE TYPE	
STORAGE CAPACITY	

MATERIAL REQUIREMENTS
BY
FUNCTIONAL COMPONENTS

12.0	ENERGY COLLECTOR					
12.03	ABSORBER- POLY-SI (P-N) CELL					
	ACTIVE LAYER	CVD				
			SILANE TO SI	0.87	0.35	583.0
	P-DOPANT	CVD				
			DIBORANE TO B	0.78	0.35	4.53-05
	EPITAXY SUBSTRATE					
			SILICON-MET GRADE	1.	1.	1.17+04
	P-N JUNCTION LAYER	CVD				
			SILANE TO SI	0.87	0.35	6.99
	N-DOPANT	CVD				
			PHOSPHINE TO P	0.91	0.35	1.55-02
	AR COATING	EVAPORATED				
			TANTALUM PENTOXIDE	1.0	0.35	5.34
	GRID CONTACT	EVAPORATED				
			NICKEL	1.0	.035	0.267
		SOLDER DIP				
			60-40 SOLDER	1.0	.90	42.1
	SUPPORT SUBSTRATE					
			GRAPHITE,MFGD.	1.0	0.8	5.74+03

BULK MATERIAL REQUIREMENTS FOR
PCRYST. SILICON-HOMOJ. (P-N) SENSITIVITY CASE
SENSITIVITY CASE

SOLAR SCENARIO:
INTRODUCTION YEAR- 1991
CUMULATIVE CAPACITY 2000- 25. GW

FACTORS	BULK MATERIAL USAGE MT.	PERCENT SUPPLY AS BY-PROD	PRODTN GROWTH RATE 1990	MAX % SYSTEM 1 YEAR WORLD	% FROM ONE NATION NON-US	PRESENT COSTS IN $/KW	NET % IMPORT
THRESHOLD LEVELS--		50.	10.%	10.	35.	50.	50.
CARBON DIOXIDE	0.	100.*	3.	0.	5.	0.	0.
FERROMANGANESE	159.	0.	3.	0.	22.	0.	98.*
FLUORSPAR	101.	0.	5.	0.	19.	0.	79.*
GRAPHITE, MFGD.	179375.	0.	4.	1.	10.	62.*	1.
HYDROCHLORIC ACID	316066.	92.*	3.	0.	5.	3.	2.
LITHIUM	53923.	4.	12.*	27.*	2.	69.*	0.
NICKEL	191.	7.	3.	0.	33.	0.	70.*
PETROLEUM COKE	398904.	100.*	3.	0.	15.	1.	0.
PHOSPHINE 99.999%	1.	0.	21.*	0.	10.	0.	0.
SILANE	48439.	0.	233.*	81.*	10.	252.*	0.
TANTALUM PENTOXIDE	381.	100.*	9.	27.*	10.	5.	0.
TIN	737.	1.	3.	0.	28.	0.	85.*

RAW MATERIAL REQUIREMENTS FOR:
PCRYST. SILICON-HOMOJ. (P-N) SENSITIVITY CASE
SENSITIVITY CASE

SOLAR SCENARIO:
INTRODUCTION YEAR- 1991
CUMULATIVE CAPACITY 2000- 25. GW

FACTORS	RAW MATERIAL USAGE (1000MT)	%PRD GROW RATE FROM 1990	MAX% SYST ONE YEAR WRLD	%US RESERV CONSUM BY 2000	%US RESOUR CONSUM BY 2000	%FRM ONE NAT NON-US	%WORLD RESERV CONSUM BY 2000	%WORLD RESOUR CONSUM BY 2000	PRSNT COSTS IN $/KW	NET% IMPT
THRESHOLD LEVELS--		7.	10.	400.	300.	60.	300.	200.	50.	50.
BAUXITE	0.	5.	0.	2691.*	364.*	31.	15.	10.	0.	91.*
FLUORSPAR ORE	0.	5.	0.	1004.*	168.	19.	255.	140.	0.	79.*
LITHIUM ORE	8574.	14.*	29.*	59.	26.	24.	58.	20.	49.	0.
MANGANESE ORE	0.	3.	0.	100.	8.	22.	15.	8.	0.	98.*
NICKEL ORE	19.	2.	0.	3533.*	9.	33.	48.	20.	0.	70.*
PETROLEUM	20681.	2.	0.	565.*	185.	18.	104.	34.	60.*	39.
TANTALUM ORE	4.	10.*	0.	100.	1866.*	39.	59.	13.	0.	96.*
TIN ORE	74.	2.	0.	3491.*	705.*	28.	67.	18.	1.	85.*

CADMIUM SULFIDE/COPPER SULFIDE
FRONTWALL
SOLAR CELL

BASELINE CASE ALTERED: CADMIUM SULFIDE LAYER TO 10 MICRONS.
GRID CONTACT TO CU/AU.

THIS CELL CONSISTS OF 10 MICRONS OF EVAPORATED CADMIUM SULFIDE ON A ZINC ELECTROPLATED (1 MICRON THICK) COPPER FOIL (25 MICRONS THICK) A COPPER SULFIDE LAYER IS FORMED BY DIPPING THE CADMIUM SULFIDE IN A HOT SOLUTION OF CUPROUS CHLORIDE. THE GRID CONTACT IS 5 MICRONS OF COPPER OVER 0.05 MICRONS OF GOLD BY EVAPORATION. THE AR FILM IS SILICON MONOXIDE, 0.08 MICRON THICK.

TECHNOLOGY	PHOTOVOLTAICS
CAPACITY	1 GW
APPLICATION	ELECTRIC POWER GENERATION
LOCATION	
INSOLATION	1 KW/M*M
SOLAR CONTRIBUTION	APPROX. 1500 GW-HR/YR
SUPPLEMENT	
SOLAR EFFICIENCY	10%
COLLECTOR AREA	10 KM*KM
OPERATING TEMPERATURE	
ENERGY TRANSPORT MEDIUM	ELECTRICAL
STORAGE TYPE	
STORAGE CAPACITY	

MATERIAL REQUIREMENTS
BY
FUNCTIONAL COMPONENTS

12.0 ENERGY COLLECTOR

12.03 ABSORBER- CAD SULFIDE/CU SULFIDE CELL

ACTIVE LAYER	EVAPORATED				
		CADMIUM SULFIDE	1.0	0.35	482.0
ACTIVE LAYER	HOT DIPPED				
		CUPROUS CHLORIDE TO CUPROUS SULFIDE	0.80	0.1	22.4
BACK CONTACT	ELECTROPLATED				
		ZINC FLUOROBORATE TO ZINC	0.27	0.8	71.4
SUBSTRATE					
		COPPER	1.0	0.8	2.23+03
GRID CONTACT	EVAPORATED				
		GOLD	1.0	0.035	0.965
		COPPER	1.0	0.035	44.7
AR COATING	EVAPORATED				
		SILICON MONOXIDE	1.0	0.35	1.71

BULK MATERIAL REQUIREMENTS FOR
CAD. SULFIDE/CU. SULFIDE FRONTWALL SENSITIVITY CAS
SENSITIVITY CASE

SOLAR SCENARIO:
INTRODUCTION YEAR- 1991
CUMULATIVE CAPACITY 2000- 25. GW

FACTORS	BULK MATERIAL USAGE MT.	PERCENT SUPPLY AS BY-PROD	PRODTN GROWTH RATE 1990	MAX % SYSTEM 1 YEAR WORLD	% FROM ONE NATION NON-US	PRESENT COSTS IN $/KW	NET % IMPORT
THRESHOLD LEVELS--		50.	10.%	10.	35.	50.	50.
CADMIUM	27543.	100.*	5.	12.*	17.	6.	64.*
CADMIUM SULFIDE	34429.	0.	15.*	43.*	10.	33.	0.
FERROMANGANESE	877.	0.	3.	0.	22.	0.	98.*
FLUORSPAR	13016.	0.	5.	0.	19.	0.	79.*
GOLD	689.	47.	3.	6.	58.*	177.*	76.*
HYDROCHLORIC ACID	688.	92.*	3.	0.	5.	0.	2.
PETROLEUM COKE	385.	100.*	3.	0.	15.	0.	0.
SILICON MONOXIDE	122.	0.	11.*	36.*	20.	1.	30.
SILICON (SEG)	39.	0.	20.*	0.	10.	0.	0.
ZINC	37990.	25.	2.	0.	20.	1.	59.*
ZINC FLUOROBORATE	8264.	0.	2654.*	99.*	25.	1.	0.

RAW MATERIAL REQUIREMENTS FOR:
CAD. SULFIDE/CU. SULFIDE FRONTWALL SENSITIVITY CAS
SENSITIVITY CASE

SOLAR SCENARIO:
INTRODUCTION YEAR- 1991
CUMULATIVE CAPACITY 2000- 25. GW

FACTORS	RAW MATERIAL USAGE (1000MT)	%PRD GROW RATE FROM 1990	MAX% SYST ONE YEAR WRLD	%US RESERV CONSUM BY 2000	%US RESOUR CONSUM BY 2000	%FRM ONE NAT NON-US	%WORLD RESERV CONSUM BY 2000	%WORLD RESOUR CONSUM BY 2000	PRSNT COSTS IN $/KW	NET% IMPT
THRESHOLD LEVELS--		7.	10.	400.	300.	60.	300.	200.	50.	50.
BAUXITE	0.	5.	0.	2691.*	364.*	31.	15.	10.	0.	91.*
CHROMITE	1.	3.	0.	100.	620.*	28.	117.	2.	0.	89.*
FLUORSPAR ORE	40.	5.	0.	1004.*	168.	19.	255.	140.	0.	79.*
GOLD ORE	80150.	3.	6.	207.	111.	58.	96.	62.	51.*	76.*
MANGANESE ORE	2.	3.	0.	100.	8.	22.	15.	8.	0.	98.*
PETROLEUM	613.	2.	0.	565.*	185.	18.	104.	34.	2.	39.
ZINC BYPROD.	22034.	3.	2.	170.	102.	20.	125.	81.	0.	59.*
ZINC ORE	843.	3.	0.	166.	100.	20.	125.	81.	0.	59.*

POLYCRYSTALLINE GALLIUM ARSENIDE
MIS
SOLAR CELL

BASELINE CASE ALTERED: ACTIVE LAYER, 5 MICRONS, BY CVD FROM
GA,HCL AND ASH3, ETC.

THE ACTIVE LAYER (5 MICRONS THICK) AND THE DOPED CONTACT LAYER (2 MICRONS) ARE PRODUCED BY CVD OF GAAS. THE N-DOPANT IS SULFUR. THESE TWO LAYERS ARE DEPOSITED ON A GERMANIUM EPITAXY SUBSTRATE (1 MICRON) WHICH IS SUPPORTED BY A MOLYBD. (1 MICRON) STAINLESS STEEL SUPPORT SUBSTRATE (.005 INCH). A SEMI-TRANSPARENT LAYER OF SILVER .005 MICRONS THICK IS EVAPORATED ONTO THE ACTIVE LAYER. THE GRID CONTACT IS 5 MICRONS OF COPPER. THE AR COATING IS ASSUMED TO BE 0.06 MICRONS OF ANTIMONY OXIDE.

TECHNOLOGY	PHOTOVOLTAICS
CAPACITY	1 GW
APPLICATION	ELECTRIC POWER GENERATION
LOCATION	
INSOLATION	1 KW/M*M
SOLAR CONTRIBUTION	APPROX. 1500 GW-HR/YR
SUPPLEMENT	
SOLAR EFFICIENCY	10%
COLLECTOR AREA	10 KM*KM
OPERATING TEMPERATURE	
ENERGY TRANSPORT MEDIUM	ELECTRICAL
STORAGE TYPE	
STORAGE CAPACITY	

MATERIAL REQUIREMENTS
BY
FUNCTIONAL COMPONENTS

12.0 ENERGY COLLECTOR

12.03 ABSORBER- POLYCRYST. GAAS MIS CELL

ACTIVE LAYER	CVD OF GAAS				
		GALLIUM TO GA	1.0	0.35	128.
		ARSINE TO AS	0.96	0.35	138.
DOPED CONTACT LAYER	CVD OF GAAS				
		GALLIUM TO GA	1.0	0.35	51.0
		ARSINE TO AS	0.96	0.35	55.2
N-DOPANT	CVD OF S				
		HYDROGEN SULFIDE TO S	0.94	0.35	1.07-02
M OF MIS	EVAPORATED				
		SILVER	1.0	0.35	0.525
GRID CONTACT	EVAPORATED				
		COPPER	1.0	0.035	44.7
AR COATING	EVAPORATED				
		ANTIMONY TRIOXIDE	1.0	0.35	3.11
EPITAXY SUBSTRATE	CVD				
		GERMANE TO GE	0.95	0.35	53.5
BACK CONTACT	SPUTTERED				
		MOLYBDENUM	1.0	0.40	102.0
SUPPORT SUBSTRATE					
		STAINLESS STEEL	1.0	0.8	9.99+03

BULK MATERIAL REQUIREMENTS FOR
POLYCRYST. GAAS MIS. SENSITIVITY, 5 MICRONS CVD
SENSITIVITY CASE

SOLAR SCENARIO:
INTRODUCTION YEAR- 1991
CUMULATIVE CAPACITY 2000- 25. GW

FACTORS	BULK MATERIAL USAGE MT.	PERCENT SUPPLY AS BY-PROD	PRODTN GROWTH RATE 1990	MAX % SYSTEM 1 YEAR WORLD	% FROM ONE NATION NON-US	PRESENT COSTS IN $/KW	NET % IMPORT
THRESHOLD LEVELS--		50.	10.%	10.	35.	50.	50.
ANTIMONY	187.	80.*	5.	0.	22.	0.	54.*
ARSENIC	15623.	100.*	4.	5.	23.	62.*	39.
ARSENIC TRIOXIDE	21872.	100.*	4.	5.	23.	0.	39.
ARSINE, 99.999%	14375.	0.	593.*	92.*	10.	82.*	0.
CARBON DIOXIDE	3142041.	100.*	4.	4.	5.	6.	0.
CHROMIUM	84291.	0.	3.	0.	28.	22.	89.*
FERROMANGANESE	2349.	0.	3.	0.	22.	0.	98.*
FLUORSPAR	1495.	0.	5.	0.	19.	0.	79.*
GALLIUM	12786.	100.*	764.*	98.*	40.*	409.*	55.*
GERMANE, 99.9%	4023.	0.	81453.*	100.*	5.	113.*	0.
GERMANIUM	5126.	100.*	91.*	88.*	29.	65.*	16.
HYDROCHLORIC ACID	169423.	92.*	3.	0.	5.	1.	2.
HYDROGEN SULFIDE, 99.999%	1.	0.	1032.*	96.*	10.	0.	0.
NICKEL	31219.	7.	3.	0.	33.	6.	70.*
PETROLEUM COKE	34313.	100.*	3.	0.	15.	0.	0.
SILVER	38.	70.*	4.	0.	14.	0.	50.*
ZINC	20602.	25.	2.	0.	20.	1.	59.*

RAW MATERIAL REQUIREMENTS FOR:
POLYCRYST. GAAS MIS. SENSITIVITY, 5 MICRONS CVD
SENSITIVITY CASE

SOLAR SCENARIO:
INTRODUCTION YEAR- 1991
CUMULATIVE CAPACITY 2000- 25. GW

FACTORS	RAW MATERIAL USAGE (1000MT)	%PRD GROW RATE FROM 1990	MAX% SYST ONE YEAR WRLD	%US RESERV CONSUM BY 2000	%US RESOUR CONSUM BY 2000	%FRM ONE NAT NON-US	%WORLD RESERV CONSUM BY 2000	%WORLD RESOUR CONSUM BY 2000	PRSNT COSTS IN $/KW	NET% IMPT
THRESHOLD LEVELS--		7.	10.	400.	300.	60.	300.	200.	50.	50.
ANTIMONY ORE	20.	3.	0.	887.*	822.*	22.	56.	47.	0.	54.*
BAUXITE	1.	5.	0.	2691.*	364.*	31.	15.	10.	0.	91.*
BAUXITE, BY PROD	639286.	13.*	30.*	4265.*	577.*	31.	17.	11.	0.	91.*
FLUORSPAR ORE	5.	5.	0.	1004.*	168.	19.	255.	140.	0.	79.*
MANGANESE ORE	5.	3.	0.	100.	8.	22.	15.	8.	0.	98.*
NICKEL ORE	3122.	3.	0.	3550.*	9.	33.	48.	20.	2.	70.*
PETROLEUM	1805.	2.	0.	565.*	185.	18.	104.	34.	5.	39.
SILVER ORE	54.	4.	0.	277.	73.	14.	208.	56.	0.	50.*
ZINC BYPROD.#3	512635.	8.*	29.*	260.	156.	20.	141.	91.	0.	59.*
ZINC ORE	457.	3.	0.	166.	100.	20.	125.	81.	0.	59.*

POLYCRYSTALLINE GALLIUM ARSENIDE
MIS
SOLAR CELL

BASELINE CASE ALTERED:

THE ACTIVE LAYER (2 MICRONS THICK) AND THE DOPED CONTACT LAYER (2 MICRONS) ARE PRODUCED BY CVD OF GAAS. THE N-DOPANT IS SULFUR. THESE TWO LAYERS ARE DEPOSITED ON A GERMANIUM EPITAXY SUBSTRATE (5 MICRONS) WHICH IS SUPPORTED BY A TIN COATED (1 MICRON) STAINLESS STEEL SUPPORT SUBSTRATE (.005 INCH). A SEMI-TRANSPARENT LAYER OF SILVER .005 MICRONS THICK IS EVAPORATED ONTO THE ACTIVE LAYER. THE GRID CONTACT IS 5 MICRONS OF COPPER. THE AR COATING IS ASSUMED TO BE 0.06 MICRONS OF ANTIMONY OXIDE.

TECHNOLOGY	PHOTOVOLTAICS
CAPACITY	1 GW
APPLICATION	ELECTRIC POWER GENERATION
LOCATION	
INSOLATION	1 KW/M*M
SOLAR CONTRIBUTION	APPROX. 1500 GW-HR/YR
SUPPLEMENT	
SOLAR EFFICIENCY	10%
COLLECTOR AREA	10 KM*KM
OPERATING TEMPERATURE	
ENERGY TRANSPORT MEDIUM	ELECTRICAL
STORAGE TYPE	
STORAGE CAPACITY	

BULK MATERIAL REQUIREMENTS FOR POLYCRYST. GAAS MIS. SENSITIVITY, 2 MICRONS MO-CVD SENSITIVITY CASE

SOLAR SCENARIO:
INTRODUCTION YEAR- 1991
CUMULATIVE CAPACITY 2000- 25. GW

FACTORS	BULK MATERIAL USAGE MT.	PERCENT SUPPLY AS BY-PROD	PRODTN GROWTH RATE 1990	MAX % SYSTEM 1 YEAR WORLD	% FROM ONE NATION NON-US	PRESENT COSTS IN $/KW	NET % IMPORT
THRESHOLD LEVELS--		50.	10.%	10.	35.	50.	50.
ANTIMONY	187.	80.*	5.	0.	22.	0.	54.*
ARSENIC	10415.	100.*	4.	4.	23.	42.	39.
ARSENIC TRIOXIDE	14581.	100.*	3.	3.	23.	0.	39.
ARSINE, 99.999%	9583.	0.	403.*	88.*	10.	55.*	0.
CARBON DIOXIDE	3708306.	100.*	4.	4.	5.	7.	0.
CHROMIUM	84291.	0.	3.	0.	28.	22.	89.*
FERROMANGANESE	2334.	0.	3.	0.	22.	0.	98.*
FLUORSPAR	1611.	0.	5.	0.	19.	0.	79.*
GALLIUM	14397.	100.*	859.*	98.*	40.*	461.*	55.*
GERMANE, 99.9%	20075.	0.	406482.*	100.*	5.	562.*	0.
GERMANIUM	25584.	100.*	447.*	97.*	29.	323.*	16.
HYDROCHLORIC ACID	840589.	92.*	4.	1.	5.	7.	2.
HYDROGEN SULFIDE, 99.999%	1.	0.	1201.*	97.*	10.	0.	0.
NICKEL	31219.	7.	3.	0.	33.	6.	70.*
PETROLEUM COKE	52133.	100.*	3.	0.	15.	0.	0.
SILVER	38.	70.*	4.	0.	14.	0.	50.*
TIN	4107.	1.	3.	0.	28.	3.	85.*
TRIMETHYL GA., 99.9995%	13934.	0.	141076.*	100.*	5.	4459.*	0.
ZINC	13737.	25.	2.	0.	20.	0.	59.*

MATERIAL REQUIREMENTS
BY
FUNCTIONAL COMPONENTS

12.0 ENERGY COLLECTOR

12.03 ABSORBER- POLYCRYST. GAAS MIS CELL

ACTIVE LAYER	MO-CVD OF GAAS				
		TRIMETHYL GALLIUM TO GA	0.61	0.30	51.0
		ARSINE TO AS	0.96	0.30	55.2
DOPED CONTACT LAYER	MO-CVD OF GAAS				
		TRIMETHYL GALLIUM TO GA	0.61	0.30	51.0
		ARSINE TO AS	0.96	0.30	55.2
N-DOPANT	MO-CVD OF S				
		HYDROGEN SULFIDE TO S	0.94	0.30	1.07-02
M OF MIS	EVAPORATED				
		SILVER	1.0	0.35	0.525
GRID CONTACT	EVAPORATED				
		COPPER	1.0	0.035	44.7
AR COATING	EVAPORATED				
		ANTIMONY TRIOXIDE	1.0	0.35	3.11
EPITAXY SUBSTRATE	CVD				
		GERMANE TO GE	0.95	0.35	267.0
BACK CONTACT	EVAPORATED				
		TIN	1.0	0.35	57.5
SUPPORT SUBSTRATE					
		STAINLESS STEEL	1.0	0.8	9.99+03

RAW MATERIAL REQUIREMENTS FOR:
POLYCRYST. GAAS MIS. SENSITIVITY, 2 MICRONS MO-CVD
SENSITIVITY CASE

SOLAR SCENARIO:
INTRODUCTION YEAR- 1991
CUMULATIVE CAPACITY 2000- 25. GW

FACTORS	RAW MATERIAL USAGE (1000MT)	%PRD GROW RATE FROM 1990	MAX% SYST ONE YEAR WRLD	%US RESERV CONSUM BY 2000	%US RESOUR CONSUM BY 2000	%FRM ONE NAT NON-US	%WORLD RESERV CONSUM BY 2000	%WORLD RESOUR CONSUM BY 2000	PRSNT COSTS IN $/KW	NET% IMPT
THRESHOLD LEVELS--		7.	10.	400.	300.	60.	300.	200.	50.	50.
ANTIMONY ORE	20.	3.	0.	887.*	822.*	22.	56.	47.	0.	54.*
BAUXITE	197.	5.	0.	2691.*	364.*	31.	15.	10.	0.	91.*
BAUXITE, BY PROD	719852.	13.*	33.*	4464.*	604.*	31.	18.	12.	0.	91.*
FLUORSPAR ORE	5.	5.	0.	1004.*	168.	19.	255.	140.	0.	79.*
MANGANESE ORE	5.	3.	0.	100.	8.	22.	15.	8.	0.	98.*
NICKEL ORE	3122.	3.	0.	3550.*	9.	33.	48.	20.	2.	70.*
PETROLEUM	2725.	2.	0.	565.*	185.	18.	104.	34.	8.	39.
SILVER ORE	54.	4.	0.	277.	73.	14.	208.	56.	0.	50.*
TIN ORE	411.	2.	0.	3499.*	707.*	28.	67.	18.	7.	85.*
ZINC BYPROD.#3	2558382.	30.*	67.*	636.*	382.*	20.	205.	133.	0.	59.*
ZINC ORE	305.	3.	0.	166.	100.	20.	125.	81.	0.	59.*

POLYCRYSTALLINE GALLIUM ARSENIDE
MIS
SOLAR CELL

BASELINE CASE ALTERED: ACTIVE LAYER, 2 MICRONS, BY CVD FROM GA,HCL AND ASH3, ETC.

THE ACTIVE LAYER (2 MICRONS THICK) AND THE DOPED CONTACT LAYER (2 MICRONS) ARE PRODUCED BY CVD OF GAAS. THE N-DOPANT IS SULFUR. THESE TWO LAYERS ARE DEPOSITED ON A GERMANIUM EPITAXY SUBSTRATE (1 MICRON) WHICH IS SUPPORTED BY A MOLYBD. (1 MICRON) STAINLESS STEEL SUPPORT SUBSTRATE (.005 INCH). A SEMI-TRANSPARENT LAYER OF SILVER .005 MICRONS THICK IS EVAPORATED ONTO THE ACTIVE LAYER. THE GRID CONTACT IS 5 MICRONS OF COPPER. THE AR COATING IS ASSUMED TO BE 0.06 MICRONS OF ANTIMONY OXIDE.

TECHNOLOGY	PHOTOVOLTAICS
CAPACITY	1 GW
APPLICATION	ELECTRIC POWER GENERATION
LOCATION	
INSOLATION	1 KW/M*M
SOLAR CONTRIBUTION	APPROX. 1500 GW-HR/YR
SUPPLEMENT	
SOLAR EFFICIENCY	10%
COLLECTOR AREA	10 KM*KM
OPERATING TEMPERATURE	
ENERGY TRANSPORT MEDIUM	ELECTRICAL
STORAGE TYPE	
STORAGE CAPACITY	

MATERIAL REQUIREMENTS
BY
FUNCTIONAL COMPONENTS

PAGE 1

12.0 ENERGY COLLECTOR

12.03 ABSORBER- POLYCRYST. GAAS MIS CELL

ACTIVE LAYER	CVD OF GAAS				
		GALLIUM TO GA	1.0	0.35	51.0
		ARSINE TO AS	0.96	0.35	55.2
DOPED CONTACT LAYER	CVD OF GAAS				
		GALLIUM TO GA	1.0	0.35	51.0
		ARSINE TO AS	0.96	0.35	55.2
N-DOPANT	CVD OF S				
		HYDROGEN SULFIDE TO S	0.94	0.35	1.07-02
M OF MIS	EVAPORATED				
		SILVER	1.0	0.35	0.525
GRID CONTACT	EVAPORATED				
		COPPER	1.0	0.035	44.7
AR COATING	EVAPORATED				
		ANTIMONY TRIOXIDE	1.0	0.35	3.11
EPITAXY SUBSTRATE	CVD				
		GERMANE TO GE	0.95	0.35	53.5
BACK CONTACT	SPUTTERED				
		MOLYBDENUM	1.0	0.40	102.0
SUPPORT SUBSTRATE					
		STAINLESS STEEL	1.0	0.8	9.99+03

BULK MATERIAL REQUIREMENTS FOR
POLYCRYST. GA/AS MIS. SENSITIVITY CASE
SENSITIVITY CASE

PAGE 1
12/04/79

SOLAR SCENARIO:
INTRODUCTION YEAR- 1991
CUMULATIVE CAPACITY 2000- 25. GW

FACTORS	BULK MATERIAL USAGE MT.	PERCENT SUPPLY AS BY-PROD	PRODTN GROWTH RATE 1990	MAX % SYSTEM 1 YEAR WORLD	% FROM ONE NATION NON-US	PRESENT COSTS IN $/KW	NET % IMPORT
THRESHOLD LEVELS--		50.	10.%	10.	35.	50.	50.
ANTIMONY	187.	80.*	5.	0.	22.	0.	54.*
ARSENIC	8927.	100.*	3.	3.	23.	36.	39.
ARSENIC TRIOXIDE	12498.	100.*	3.	3.	23.	0.	39.
ARSINE, 99.999%	8214.	0.	348.*	86.*	10.	47.	0.
CARBON DIOXIDE	1809391.	100.*	4.	2.	5.	3.	0.
CHROMIUM	84291.	0.	3.	0.	28.	22.	89.*
FERROMANGANESE	2346.	0.	3.	0.	22.	0.	98.*
FLUORSPAR	1494.	0.	5.	0.	19.	0.	79.*
GALLIUM	7286.	100.*	437.*	97.*	40.*	233.*	55.*
GERMANE, 99.9%	4023.	0.	81453.*	100.*	5.	56.*	0.
GERMANIUM	5126.	100.*	91.*	88.*	29.	65.*	16.
HYDROCHLORIC ACID	168873.	92.*	3.	0.	5.	1.	2.
HYDROGEN SULFIDE, 99.999%	1.	0.	1032.*	96.*	10.	0.	0.
NICKEL	31219.	7.	3.	0.	33.	6.	70.*
PETROLEUM COKE	34313.	100.*	3.	0.	15.	0.	0.
SILVER	38.	70.*	4.	0.	14.	0.	50.*
ZINC	11776.	25.	2.	0.	20.	0.	59.*

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          RAW MATERIAL REQUIREMENTS FOR:
          POLYCRYST. GA/AS MIS. SENSITIVITY CASE                        PAGE  1
          SENSITIVITY CASE                                            12/04/79

 SOLAR SCENARIO:
   INTRODUCTION YEAR- 1991
   CUMULATIVE CAPACITY 2000-   25. GW

                                    %PRD MAX%  %US    %US    %FRM %WORLD %WORLD
                              RAW   GROW SYST RESERV RESOUR ONE  RESERV RESOUR PRSNT
   FACTORS                MATERIAL  RATE ONE  CONSUM CONSUM NAT  CONSUM CONSUM COSTS
                            USAGE   FROM YEAR   BY     BY   NON-   BY     BY    IN   NET%
                          (1000MT)  1990 WRLD  2000   2000   US   2000   2000  $/KW  IMPT
                          --------- ---- ---- ------ ------ ---- ------ ----------- ----
THRESHOLD LEVELS--                   7.  10.   400.   300.  60.   300.   200.   50.  50.
                          --------- ---- ---- ------ ------ ---- ------ ----------- ----
ANTIMONY ORE                    20. 3.   0.    887.*  822.* 22.    56.    47.    0.  54.*
BAUXITE                          1. 5.   0.   2691.*  364.* 31.    15.    10.    0.  91.*
BAUXITE, BY PROD           364286. 9.* 20.* 3588.*  486.* 31.    16.    11.    0.  91.*
FLUORSPAR ORE                    5. 5.   0.   1004.*  168.  19.   255.   140.    0.  79.*
MANGANESE ORE                    5. 3.   0.    100.     8.  22.    15.     8.    0.  98.*
NICKEL ORE                    3122. 3.   0.   3550.*    9.  33.    48.    20.    2.  70.*
PETROLEUM                     1804. 2.   0.    565.*  185.  18.   104.    34.    5.  39.
SILVER ORE                      54. 4.   0.    277.    73.  14.   208.    56.    0.  50.*
ZINC BYPROD.#3             512635. 8.* 29.*  260.   156.  20.   141.    91.    0.  59.*
ZINC ORE                       261. 3.   0.    166.   100.  20.   125.    81.    0.  59.*
```

ADVANCED CONCENTRATOR
SOLAR CELL
500X

BASELINE CASE ALTERED: GAAS SUBSTRATE TO 500 MICRONS.

THE GENERALIZED ADVANCED CONCENTRATOR CHARACTERIZED HERE HAS
SUBSTRATE-500 MICRONS OF SINGLE CRYSTAL GAAS.
LATTICE MATCHING LAYERS, BOTTOM AND TUNNEL JUNCTIONS-20 MICRONS OF
GA0.5IN0.5AS DEPOSITED BY MO-CVD.
TOP JUNCTION-4 MICRONS OF GA0.7AL0.3AS BY MO-CVD.
WINDOW LAYER-0.3 MICRONS OF GAP BY MO-CVD.
GRID CONTACTS-.05 MICRONS GOLD-ZINC AND 10 MICRONS SILVER-EVAPORATED
AR COATINGS-.065 MICRONS TA205 AND .1 MICRONS SIO2 BY EVAPORATION.

TECHNOLOGY	PHOTOVOLTAICS
CAPACITY	1 GW
APPLICATION	ELECTRIC POWER GENERATION
LOCATION	
INSOLATION	1 KW/M*M
SOLAR CONTRIBUTION	APPROX. 1500 GW-HR/YR
CONCENTRATION FACTOR	500X
SOLAR EFFICIENCY	30%
APERATURE AREA	3.33 KM*KM
ACTIVE CELL AREA	0.00667 KM*KM (6667 M*M)
ENERGY TRANSPORT MEDIUM	ELECTRICAL
STORAGE TYPE	
STORAGE CAPACITY	

MATERIAL REQUIREMENTS
BY
FUNCTIONAL COMPONENTS

12.0	ENERGY COLLECTOR				
12.03	ABSORBER-ADVANCED CONCENTRATOR CELL-500X				
	SUBSTRATE	SINGLE CRYSTAL			
		GALLIUM ARSENIDE	1.0	1.0	17.74
	LATTICE MATCHING LAYERS, BOTTOM & TUNNEL JUNCTIONS	MO-CVD OF GA0.75IN0.25AS			
		TRIMETHYL GALLIUM TO GA	0.61	0.3	0.242
		TRIMETHYL INDIUM TO IN	0.72	0.3	0.133
		ARSINE TO AS	0.96	0.3	0.346
	TOP JUNCTION	MO-CVD OF GA0.8AL0.2AS			
		TRIMETHYL GALLIUM TO GA	0.61	0.3	5.48-02
		TRIMETHYL ALUMIN. TO AL	0.37	0.3	5.30-03
		ARSINE TO AS	0.96	0.3	7.36-02
	WINDOW LAYER	MO-CVD OF GA0.1AL0.9AS			
		TRIMETHYL GALLIUM TO GA	0.61	0.3	5.20-04
		TRIMETHYL ALUMIN. TO AL	0.37	0.3	1.81-03
		ARSINE TO AS	0.96	0.3	5.59-03
	GRID CONTACTS	EVAP. OF (.8AU-.2ZN)/AG			
		GOLD	1.0	.035	5.15-04
		ZINC	1.0	.035	4.76-05
		SILVER	1.0	.035	7.00-02
	AR COATINGS	EVAPORATION			
		TANTALUM PENTOXIDE	1.00	0.35	3.55-03
		SILICON DIOXIDE	1.00	0.35	1.51-03

BULK MATERIAL REQUIREMENTS FOR
ADVANCED CONCENTRATOR-500X, SENSITIVITY CASE
SENSITIVITY CASE

SOLAR SCENARIO:
INTRODUCTION YEAR- 1991
CUMULATIVE CAPACITY 2000- 25. GW

FACTORS	BULK MATERIAL USAGE MT.	PERCENT SUPPLY AS BY-PROD	PRODTN GROWTH RATE 1990	MAX % SYSTEM 1 YEAR WORLD	% FROM ONE NATION NON-US	PRESENT COSTS IN $/KW	NET % IMPORT
THRESHOLD LEVELS--		50.	10.%	10.	35.	50.	50.
ARSENIC	608.	100.*	3.	0.	23.	2.	39.
ARSENIC TRIOXIDE	851.	100.*	3.	0.	23.	0.	39.
ARSINE, 99.999%	37.	0.	23.*	3.	10.	0.	0.
CARBON DIOXIDE	139707.	100.*	3.	0.	5.	0.	0.
FERROMANGANESE	1.	0.	3.	0.	22.	0.	98.*
FLUORSPAR	1.	0.	5.	0.	19.	0.	79.*
GALLIUM	577.	100.*	39.*	69.*	40.*	18.	55.*
GALLIUM ARSENIDE (INGOT)	985.	0.	69.*	76.*	10.	118.*	0.
GALLIUM ARSENIDE (WAFER)	444.	0.	69.*	76.*	10.	124.*	0.
GOLD	0.	47.	2.	0.	58.*	0.	76.*
HYDROCHLORIC ACID	58.	92.*	3.	0.	5.	0.	2.
INDIUM	18.	100.*	4.	3.	20.	0.	24.
PETROLEUM COKE	62.	100.*	3.	0.	15.	0.	0.
SILVER	50.	70.*	4.	0.	14.	0.	50.*
TANTALUM PENTOXIDE	0.	100.*	4.	0.	10.	0.	0.
TRIMETHYL AL., 99.9999%	2.	0.	11.*	23.*	5.	0.	0.
TRIMETHYL GA., 99.9995%	41.	0.	417.*	96.*	5.	13.	0.
TRIMETHYL INDIUM, 99.998%	15.	0.	318.*	95.*	5.	22.	0.
ZINC	68.	25.	2.	0.	20.	0.	59.*

RAW MATERIAL REQUIREMENTS FOR:
ADVANCED CONCENTRATOR-500X, SENSITIVITY CASE
SENSITIVITY CASE

SOLAR SCENARIO:
INTRODUCTION YEAR- 1991
CUMULATIVE CAPACITY 2000- 25. GW

FACTORS	RAW MATERIAL USAGE (1000MT)	%PRD GROW RATE FROM 1990	MAX% SYST ONE YEAR WRLD	%US RESERV CONSUM BY 2000	%US RESOUR CONSUM BY 2000	%FRM ONE NAT NON-US	%WORLD RESERV CONSUM BY 2000	%WORLD RESOUR CONSUM BY 2000	PRSNT COSTS IN $/KW	NET% IMPT
THRESHOLD LEVELS--		7.	10.	400.	300.	60.	300.	200.	50.	50.
BAUXITE	1.	5.	0.	2691.*	364.*	31.	15.	10.	0.	91.*
BAUXITE, BY PROD	28829.	6.	2.	2762.*	374.*	31.	15.	10.	0.	91.*
FLUORSPAR ORE	0.	5.	0.	1004.*	168.	19.	255.	140.	0.	79.*
GOLD ORE	43.	2.	0.	187.	100.	58.	94.	60.	0.	76.*
MANGANESE ORE	0.	3.	0.	100.	8.	22.	15.	8.	0.	98.*
PETROLEUM	4.	2.	0.	565.*	185.	18.	104.	34.	0.	39.
SILVER ORE	71.	4.	0.	277.	73.	14.	208.	56.	0.	50.*
TANTALUM ORE	0.	10.*	0.	100.	1865.*	39.	59.	13.	0.	96.*
ZINC BYPROD.	70.	3.	0.	166.	100.	20.	125.	81.	0.	59.*
ZINC ORE	2.	3.	0.	166.	100.	20.	125.	81.	0.	59.*

APPENDIX C

PRIMARY INDIUM MINERALS

Mineral	Chemical Comporition
Indite	$FeIn_2S_4$
Dzhalindite	$IN\ (OH)_3$
Roquesite	$CuInS_2$

MINERALS KNOWN TO CONTAIN INDIUM

Mineral	Chemical Composition
Sphalerite	$(Zn,Fe)S$
Stamnite	Cu_2FeSnS_4
Chalcopyrite	$CuFeS_2$
Galena	PbS
Pykrhotite	$Fe_{1-x}S$
Chalcocite	Cu_2S
Cassiderite	SnO_2
Smithsonite	$ZnCO_3$
Siderite	$FeCO_3$

APPENDIX D

INDIUM OCCURENCES IN ALASKA SELECTED ORE DEPOSITS[1]

NOTABLE AMOUNTS OF INDIUM DETECTED[2]

Property	Location
Silvertone Corporation	Fairbanks District

TRACES OF INDIUM DETECTED[2]

Property	Location
Mt. Parker Mine	Glacier Bay
"1967 Silver Vein"	Fish Crrek
Rock Mountain Creek	Seward Peninsula
Alamo Prospect	Walker Cove
Mt. Jefferson Coolidge	Hyder Area
Sealevel Mine	Revilla Island
Heckla Prospect	Hyder Area
Seal Cove	Gravine Island
A. L. & S. Mine	Revella Island
Niblack Mine	Prince of Wales Island
Danzinger Prospect	California Creek
Bessie and Mable Mine	Lost River
Winfield Shaft	Lost River
Eureka Lodge	Potato Mountain
Grounding Basin	So. Fork Porterfield River
Tin Creek Mine	Lost River
Portland Croop	Endicott Arm
Lost River Mine	Lost River
Loken Prospect	Chichagof Island
Windy Creek	Susitna River
Maki #1	Skagway
Antler River	Berners Bay
Silver Dollar	California Creek
Cache Mountain	White Mountain
Ricks Nickel	Salcha River

Source: Field samples taken by the U.S. Bureau of Mines, Janeau Field Office, Juneau, Alaska.

1. Samples were analyzed between 1960-1973 in the U.S. Bureau of Mines Juneau Lab.

2. Because analysis was by qualitative spectroscopic examination, quantitative values are not available.

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John Abelson
Solar Energy Research Institute
1617 Cole Boulevard
Golden, Colorado 80401

John Benner
Solar Energy Research Institute
1617 Cole Boulevard
Golden, Colorado 80401

David Benson
Solar Energy Research Institute
1617 Cole Boulevard
Golden, Colorado 80401

J. Richard Burke
Solar Energy Research Institute
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Wilmington, Delaware 19898

Robert Ferber
Jet Propulsion Laboratory
4800 Oak Grove Drive
Building 506
Pasadena, California 91103

Dennis Flood
NASA Lewis Research Center
21000 Brookpark Road
Cleveland, Ohio 44135

Firoze Katrak
Charles River Associates
200 Clarendon Street
Boston, Massachusetts 02116

K. M. Koliwad
Jet Propulsion Laboratory
Building 506
4800 Oak Grove Drive
Pasadena, California 91103

Fred Koomanoff
U.S. Department of Energy
Solar Power Satellite
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Paul Moskowitz
Building 475
Brookhaven National Laboratories
Upton, New York 11973

Richard Stirn
Jet Propulsion Laboratory
4800 Oak Grove Drive
Mail Stop 512 103
Pasadena, California 91103

Edward Pagor
Alusuisse Metals, Inc.
15910 Ventura Boulevard
Encino, California 91436

Dr. Alan Postlewaite
Dept. of Energy, Photovoltaic Systems Branch
600 E Street, N.W., #404
Washington, D.C. 20585

Allen White
Northeast Solar Energy Center
70 Memorial Drive
Cambridge, Massachusetts 02142

John Wollam
NASA Lewis Research Center
M.S. 302-1
21000 Brookpark Road
Cleveland, Ohio 44135

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