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Final Report

SCARCITY, RECYCLING AND SUBSTITUTION OF POTENTIALLY CRITICAL MATERIALS USED FOR VEHICULAR EMISSIONS CONTROL

Prepared for

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INTRODUCTION AND SUMMARY

Technologies currently being employed in the United States to control vehicular emissions require large expenditures on imported platinum-group metals, and smaller expenditures on other materials sometimes characterized as "critical." There is considerable concern about the reliability of foreign supplies of many of these materials, and also about implications for the U.S. balance of trade. In order to carry out its regulatory functions efficiently, the U.S. Environmental Protection Agency must weigh these concerns appropriately, which involves quantifying the important costs and benefits to the United States that are associated with materials consumption. It is important to recognize all the costs imposed by the potential unreliability of foreign sources of materials supply, but it is also important not to overestimate the importance of these costs (as some parties may attempt to do when it is in their interest). In this study we explain how EPA can quantitatively estimate the criticality of materials, and factor those estimates directly into decisions about regulations controlling vehicular emissions.

As groundwork for our analysis, subcontractor Rath and Strong projects the quantities of platinum-group metals and other potentially critical materials that will be used for vehicular emissions control in the United States during the 1980s. In order to obtain a full assessment of the issue, we also consider in some detail two further topics. The first topic is the current extent of recycling of platinum-group metals and stainless steel scrap from catalytic converters; we also give particular attention to the extent of recycling that is likely in the future. The second topic is the technological possibilities for using emissions control technologies that require smaller amounts of platinum-group metals.

The basic contents of this study are organized into five chapters following this introductory chapter. Chapter 2 develops our main conclusions and recommendations regarding how the Environmental Protection Agency can factor into its policy decisions their effects on material markets. Our main conclusion is that EPA must estimate compliance costs carefully, taking into account likely increases in prices of materials due to EPA-induced demands, and also include some adjustment for the probability of large (but usually temporary) increases in prices of materials due to future market contingencies such as foreign supply disruptions. By and large, however, it is not reasonable to expect EPA to do more than estimate likely future costs of compliance as these depend on likely future costs of materials. Detrimental effects on the U.S. balance of trade from increased importation of materials to satisfy EPA regulations is a minor consideration that can usually be given low priority by EPA.

U.S. policymaking in response to the criticality of materials is more efficiently undertaken at the national level, if it is justified at all. National tariffs and stockpiles are the appropriate policy instruments, not ad hoc decisionmaking by each individual government agency whose decisions affect total U.S. consumption of materials.

Chapter 2 defines a "critical material" simply as one for which contingency planning is worthwhile. If the contingency is a military conflict, then the material is also "strategic." Chapter 2 then presents a comprehensive list of nonmilitary contingencies that may justify preparatory planning, that is, nonmilitary contingencies that may be the basis for considering a material critical. Contingencies that are potentially important from the perspective of consumers include mine disasters, labor strikes, equipment failure, depletion of reserves, new competing demands for a material, or just processing bottlenecks due to unexpectedly large total demand for the material. However, the type of contingency that most often makes a material highly critical is the threat of foreign supply disruptions.

Our analysis of the criticality of platinum-group metals and other materials used for vehicular emissions control in fact concentrates upon the unreliability of imported supplies. The seven materials for which we quantitatively estimate criticality are:

- Platinum;
- Palladium;
- Rhodium;
- Chromium;
- Manganese;
- Nickel; and
- Titanium metal.

Only in the case of titanium metal are we more concerned about problems other than foreign supply disruptions.

The quantitative measure of a material's criticality is the expected future cost per year due to the contingencies threatening the market, averaging out years in which the contingencies do and do not occur. We provide illustrative estimates for each of the materials listed above. In principle, the expected cost of contingencies can be multidimensional, and include noneconomic costs such as greater U.S. pollution from increased domestic production of materials, or even from relaxation of vehicular emissions standards, were that to be deemed likely. However, for this study we concentrate on the strictly economic costs associated with contingencies in material markets, usually disruptions in foreign supplies. Thus, we measure criticality strictly in terms of expected dollar losses per year.

Criticality of a material can be measured from the perspective of a particular end use, such as control of vehicular emissions, or from the perspective of the nation as whole. When criticality is calculated from a national perspective, it must be recognized that the same contingencies that inflict costs on U.S. consumers of materials will often benefit U.S. producers of those materials. This is generally the case where foreign supply disruptions are the contingency of concern, so that some balancing of criticality from the perspectives of consumers versus producers is required. For purposes of illustrative calculations, we assume a dollar gained by U.S. producers of a material compensates for a dollar lost by U.S. consumers.

For a contingency such as a foreign supply disruption, the key parameters of the criticality estimation that we explicitly recognize in our calculations are as follows:

- The severity of contingencies that threaten U.S. consumers (or producers) of a material, as measured by price increases (decreases) that occur;
- The expected time between occurrences of these contingencies;
- The duration of these contingencies;
- The quantity of the material consumed in the United States under normal conditions;
- The quantity of the material produced in the United States under normal conditions, both from primary and secondary sources;
- The extent to which U.S. consumption can be reduced when prices rise (the "elasticity" of short-run U.S. demand);
- The extent to which U.S. primary and secondary production can be increased when prices rise (the "elasticity" of short-run U.S. supply); and
- The size of normal U.S. inventories and stockpiles.

The most important determinants of the criticality that we estimate for the seven materials listed earlier are subjective estimates of the severity, frequency, and duration of a "representative" contingency for each market (that is, the first three of the items listed above). Unlike the other parameters of the criticality estimates, it is unfortunately not possible to estimate these parameters with any precision from historical data or engineering analysis.

Not surprisingly, from the perspective of consumption for vehicular emissions control it turns out that platinum is the most critical of the materials we consider, by more than an order of magnitude. However, the criticality penalty is very small relative to the apparent disadvantages of alternative emissions control technologies, as described later in the report. Thus, the criticality of platinum-group metals to the United States is not a strong reason to discourage use of these materials for emissions control.

Moreover, our simplified methodology for calculating illustrative measures of materials criticality does not take into account the fact that current consumption of platinum-group metals for emissions control creates a "rolling stockpile" of the material that will increasingly be available through recycling in the future. If this consideration were factored into the analysis, using a more sophisticated economic model, the criticality of platinum-group metals used for emissions control would be considerably less. (The same is true of the alloying metals used in the 409 stainless steel of catalytic converters, since most of that material will be recycled in the future as well.)

The analysis in Chapter 2 summarized above draws on background information presented in Chapters 3 through 6. Chapter 3 summarizes projections of U.S. materials consumption for vehicular emissions control developed by subcontractor Rath & Strong. Consumption of platinum and palladium is projected to drop off somewhat from the high rates of 1980 and 1981, but still represent a very sizable share of total U.S. consumption of those metals. U.S. consumption of rhodium is projected to rise substantially by the mid-1980s. Consumption for vehicular emissions control of other materials is very small, both relative to total U.S. consumption of those materials, and in terms of the share of compliance costs for which it accounts (or might plausibly account in during future times of shortages and high prices).

Chapter 4 presents extensive information on the markets for platinum-group metals, particularly platinum, palladium, and rhodium. The most important considerations for this study are U.S. reliance on potentially unreliable exports from South Africa and the Soviet Union, and the very large price increases necessary to induce most users of these materials to reduce consumption to any significant extent. Ameliorating U.S. vulnerability to foreign supply disruptions are substantial stockpiles maintained by most consumers, and very high rates of secondary recovery, making most applications of platinum-group metals interpretable as "stocks in use" (rather than "consumption").

Chapter 5 assesses publicly available information about the young industry recycling platinum-group metals from obsolete catalytic converters in the United States. Taking into account the cost of gathering and processing used converters, and the losses and contamination that occur during use, recovery of platinum-group metals from this source appears to be only moderately profitable at 1980 prices for platinum-group metals. Decreases in the prices of platinum-group metals which would be large by historical standards, but are conceivable, could make recovery at least temporarily uneconomical.

Finally, Chapter 6 discusses possible substitutes for platinum-group catalysts in vehicular emissions control. There is no published evidence that a catalyst system using only base metals could match the performance of the present three-way catalyst system, leaving aside the question of durability. It probably would be possible to design an oxidizing catalyst system using only base metal catalysts that would meet 1980 standards for emissions of carbon monoxide and hydrocarbons, but it would almost certainly not meet 1981 standards. The unit would have to be somewhat larger than present emissions converters using noble metals, and might well be more costly at normal prices for materials. Most avenues for using base metal catalysts in place of noble metal catalysts were investigated in the early 1970s and found (with a high degree of assurance) to be too unpromising to justify further research. General Motors continues to support research on zeolite catalysts by Professor Hall at the University of Wisconsin, but results are much too preliminary to warrant optimism.

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MATERIALS CRITICALITY AND EPA POLICYMAKING

This chapter contains the main conclusions of our study, drawing on background information presented in later chapters. We first define what a "critical" or "strategic" material is, and then describe market contingencies that can justify such a designation. We explain how criticality can be measured in terms of expected dollar losses per year, from the perspective of consumption for vehicular emissions control or from the perspective of the nation as a whole, and actually perform illustrative calculations for seven elemental materials. We describe how the criticality measure can be factored into EPA policymaking, particularly through its role in estimation of compliance costs for EPA regulations. We also draw out implications for more general EPA policy issues such as the likely adequacy of research on emissions control undertaken by U.S. vehicle manufacturers, and possible inadequacies in auto manufacturers' stockpiling of critical materials used for emissions control.

CRITICAL MATERIALS AND STRATEGIC MATERIALS

The term "strategic and critical material" was institutionalized in 1939 by the original legislation that established the U.S. National Defense Stockpile. (See Appendix 2-A.) The currently effective version of that legislation (as amended in 1979) defines strategic and critical materials as those that "(A) would be needed to supply the military, industrial, and essential civilian needs of the United States during a national emergency, and (B) are not found or produced in the United States in sufficient quantities to meet such a need."

The more general term "critical material" has been used in a variety of contexts by many different commentators and analysts. Webster's New Collegiate Dictionary defines "critical" in this context to mean: "indispensable for the weathering, solution, or overcoming of a crisis," and in fact gives "the stockpiling of strategic and critical materials" as an illustrative application of the term. Operationally, a material tends to be described as "critical" for national policymaking if future events threaten to inflict serious damage on the United States, and current planning and policies can reduce the expected costs associated with the threat. If the threatening event is a military conflict, the material is also described as "strategic." Webster's New Collegiate Dictionary defines "strategic" in this context to mean: "required for the conduct of war," and again gives "strategic material" as an illustrative application of the term.

Our usage of the terms "critical" and "strategic" is entirely compatible with general usage, as expressed in the above dictionary definitions. Since we will mainly be concerned with nonmilitary contingencies in material markets, we will focus on the "criticality" of materials. Our primary objective is to provide an operational, quantitative definition of materials criticality, that is as decisive as possible for determining what materials should be used for vehicular emissions control, and also for assessing the likelihood that the private sector will make the appropriate choices. (Alternative definitions of materials criticality, and methods of measuring it, are briefly surveyed in Appendix 2-C and in the Bibliographic Note at the end of this chapter.)

The reader should be warned that terminology tends to be variable and changing in this area. Currently, much publicity has been generated about schemes through which private individuals can readily invest in stockpiling of "strategic metals." In this context, a strategic metal tends to be an imported metal with defense applications whose market volume is not large and whose market price is volatile.

MARKET CONTINGENCIES THAT MAY BE THE BASIS FOR CONSIDERING A MATERIAL CRITICAL

For the U.S. Department of the Interior, CRA is currently conducting a study of methods for detecting and evaluating emerging problems in material markets.* One early output of that study was a comprehensive categorization of issues, problems, and contingencies in material markets that might inflict losses on U.S. citizens, and thus be of concern to the Department of the Interior or other federal agencies. The discussion that follows draws on this related project to describe general types of market contingencies,

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*See Charles River Associates (forthcoming).

preparations for which may benefit from special planning by private firms and government agencies. In other words, we now categorize and describe market contingencies that can be the basis for considering a material "critical."

Despite the potentially broad applicability of the concept of materials criticality, there is one type of nonmilitary contingency that outstrips the others in prominence, namely disruptions in foreign supplies of materials that the United States imports. This preeminence of foreign supply disruptions as the market contingency of concern is particularly true for the materials of central interest in this study: platinum-group metals are supplied to western markets predominantly by South Africa and the Soviet Union, neither of whose reliability is unquestioned, though the nature of the contingencies of concern is quite different for the two countries. Other materials used in vehicular pollution control equipment, such as chromium for stainless steel, are also obtained from potentially insecure foreign sources. (For example, South Africa is the largest exporter of chromium as well as platinum; the Soviet Union was an important exporter of chromium before 1975, and Albania is now an important supplier to the West.)

We now systematically review all the major types of market contingencies, the threat of which could conceivably be the basis for considering a material "critical."

DISRUPTED FACTORS OF PRODUCTION

Production of minerals, like other goods and services, is interpreted by economists to depend ultimately on the use of three main types of inputs or "factors of production": land, labor, and capital. In addition, other materials, transportation services, etc. are purchased from other firms (who themselves use land, labor, and capital). Disruption of any essential factor of production can stop production or delivery of a material, though disruption of some factors are considerably more likely than others. (Foreign producers, particularly those in less developed countries, are considerably more prone to disruptions of this type than are domestic producers; we distinguish problems with foreign production as a separate category below.)

The most notable "land" used in the production of materials is of course the mineral deposits from which metals and other materials are produced. Deposits can be made suddenly unavailable through natural disaster, mine accidents, or even sabotage. However, this type of disruption has not been very important historically in the United States.

By far the most common contingency affecting the availability of labor for mineral production is the deliberate strike, often organized by labor unions. One can conceive of other contingencies, such as disease, having an effect, but such events have not been important historically.

Once capital equipment is installed, it can break down and disrupt production. For major metals, this type of risk is spread so widely as to render it unimportant. For materials produced from only a few sources, it can be a problem from time to time, though usually one that is only temporary and modest in proportions.

Materials and services purchased from other firms can also disrupt producers of materials. Transportation routes can be severed by landslides or breakdown of equipment. There may just be sudden competition for cargo space from highly valued commodities that can afford to pay more for transportation. For example, in South Africa, platinum is sufficiently valuable as to justify transportation of refined material by airplane if necessary. However, other minerals produced in South Africa, such as chromium ore, are much more bulky, and shipments have at times been significantly delayed by the priority shipment of other goods, such as agricultural commodities in season.

Sharp increases in the prices of some inputs can be as disruptive to mineral production as cutoffs in other inputs. The most prominent example in recent years has been the sharp increase in the prices of petroleum and other forms of energy. OPEC has claimed at times that it was embargoing the United States and other regions of the world, but there is little evidence that this strategy has ever been effective (in the sense of imposing much greater costs on the embargoed regions compared to other importing countries). Energy availability may also be subject to more localized disruptions. For example, hydroelectric production of energy can be disrupted by low rainfall.

INADEQUACY OF RESERVES AND RESOURCES IN THE LONG RUN

For a few materials, published estimates of reserves and resources are sufficiently low so there might appear to be some chance of "running out" in a decade or two, before its use to meet EPA regulations has terminated. (A "resource" qualifies as a "reserve" if production therefrom is economically viable.) This fear is usually misplaced, because exploration can expand reserves, and new technologies can make economical the exploitation of previously uneconomical deposits. Because it generally emerges so slowly, this problem is usually not included in the calculation of materials criticality, though it should be considered when estimating the likely future cost of complying with EPA regulations. Thinking in terms of "contingency planning" is usually not that useful in this case.

TECHNOLOGICAL SHOCKS

The technological contingency of greatest concern to current consumers of a material is usually the possibility that a very large new use will emerge, resulting in an escalation of price. Fortunately, consumption of materials for new technologies tends to grow sufficiently slowly, or with sufficient warning, so that major price increases can usually be avoided through development of new productive capacity. The use of platinum as a catalyst for pollution-control equipment is a case in point. On the other hand, rhodium is produced as a byproduct, and has experienced relatively greater price increases because supply is limited by the amount of platinum production. Like inadequacy of reserves, this type of problem tends to emerge sufficiently slowly so that it is usually not explicitly included in the calculation of a material's criticality, though it should be factored into the analysis of materials costs at some point, as we discuss further below.

DISRUPTED FOREIGN SOURCES OF SUPPLY

Foreign producers of materials, particularly those in less developed regions, are subject to all the contingencies described above, often to a considerably greater extent than domestic producers. Localized military conflicts and sabotage can cause major disruptions. Also, foreign producers of materials are often not constrained by law from acting in a glaringly monopolistic fashion, and their governments may even attempt to use their exports as a political weapon.

There was concern during the 1970s that foreign exporters of minerals and metals would use OPEC as a model and form effective cartels. Foreign producers of metals such as aluminum and copper have attempted to increase their joint monopoly power by forming producers' associations, but these organizations have had very limited success. (For an extensive analysis of the difference between OPEC and mineral producers, and the limited ability of the latter to collude, see Charles River Associates (1976).) If foreign producers of a mineral or metal organize effectively, there is a theoretical possibility of "price gouging," where prices are raised very high, very rapidly, in order to catch consumers before they can change their consumption patterns. However, most foreign producers appreciate sufficiently the detrimental long-term effects of such a policy, so that it has not been common.

Most monopoly power in mineral markets is due to "natural" monopoly power, stemming from the fact that one country has low production costs and a dominant market share. This situation is often not too damaging to consumers over time, since the dominant producer must keep prices low enough to preclude entry by major competitors. Also, this situation tends to be quite stable, as the low-cost dominant producer is greatly interested in encouraging consumption of his material. Monopoly power can be exercised by private companies or by foreign governments. One of the neatest ways for a foreign government to accomplish this objective is simply to impose tarrifs on exports of a mineral, which raises the world price, and funnels monopoly profits directly into the national treasury. Caribbean producers of aluminum ores have favored this technique. (The U.S. Constitution forbids export tariffs in this country.)

Moderate collusion among foreign producers is often tacit rather than overt. This is probably the case in the platinum market. South African producers are not explicitly organized, but each realizes that an attempt to expand its market share may invite retaliatory expansion by its competitors. As a group, they are better off if capacity expansions are planned conservatively.

If, as is often the case, monopolistic aspects of foreign production are stable over time, they may not give rise to sudden contingencies (such as price gouging) and criticality planning of the type we develop below may not be necessary. Monopolistic world prices will be continually somewhat higher than they would be in a competitive environment, but consumers may rationally come to accept that situation as a fact of life, rather than a contingency subject to sudden reversal that requires planning.

Petroleum exports have in recent years been used with some success as a tool of foreign policy, but there is no analogous example among mineral markets. The value of world petroleum imports dwarfs trade in even major metals such as iron, copper, and aluminum. The Soviet Union stopped exporting metals to the United States prior to the Korean War, but no serious damage was inflicted on this country. The United Nations attempted to impose an embargo on Rhodesian chromium during the 1960s, but it was not enforceable.

THE BUSINESS CYCLE

The rate of economic activity in western market economies fluctuates considerably, inducing large changes in the consumptions and prices of materials. High prices (or even unavailability) of materials due to booming competing demands can seriously affect some consumers in much the same way as a foreign supply disruption. However, consumers with long-term contracts with suppliers of materials may be somewhat protected. Materials whose consumption is particularly sensitive to the rate of economic activity are sometimes considered "critical," but this is far from a universal practice. (We later consider the criticality of titanium metal from this viewpoint.)

DEFENSE

The premier contingency making a material "critical" is war. As discussed above, the material is called "strategic" in that case. The costs imposed on the United States by most of the contingencies described above are predominantly economic, and so the resulting criticality can be analyzed using economic theory. The costs of losing a war cannot be measured in purely economic terms, so determining the extent to which a material is strategic involves other considerations with which we do not attempt to deal. Our analysis of materials used to meet EPA regulations will concentrate upon peacetime contingencies.

PRINCIPLES OF MEASURING MATERIALS CRITICALITY AND IMPLICATIONS FOR EPA POLICYMAKING

Regulations implemented by the Environmental Protection Agency affect U.S. material markets in a variety of ways. The most widely publicized effects on material markets involve direct regulation, such as those telling producers of materials the maximum amounts of specified air pollutants they are allowed to emit. However, EPA rulemaking can also affect material producing industries more indirectly, simply by increasing the demand for materials which other industries need to meet EPA regulations. This study deals with this latter issue, in particular increased demands for platinum-group metals and other materials used by motor vehicle manufacturers to meet EPA emissions standards.

Obviously, some important aspects of the availability of materials for EPA regulations are normally factored into EPA's rulemaking processes, in particular the prices of materials as they affect projected costs of complying with the rules. Once EPA standards have been set, the regulated industry has a continuing incentive to minimize the cost of compliance, taking into account the prices of materials. The key question we consider in this chapter is whether there is some aspect of the availability of materials, beyond the inclusion of their price in estimated compliance costs (such as their "criticality"), that EPA should take into account when making rules and regulations. Our ultimate conclusion to this question in most cases is "no." However, there can be exceptions, and in any case there is often controversy surrounding decisions on this issue. Thus, in the remainder of this chapter we construct a fairly elaborate rationale for our conclusions, and also describe the possible exceptions.

MATERIALS PRICES AND COMPLIANCE COSTS

Predicting future compliance costs for a new or proposed EPA regulation, as it depends on material prices, should not be a matter of simply referring to the most recent price quote in Metals Week or the Chemical Marketing Reporter. The current price of a material may be significantly above or below the long-run market equilibrium, often because general economic activity in the industrialized consuming countries (as measured by their GNPs, for example) happens at the moment to be significantly above or below the historical trend. Or there may be some transient supply problem, such as a labor strike or a transportation bottleneck, causing current prices to be significantly above prices that are likely in the future.

Usually, the most relevant basis for predicting future compliance costs is the long-run equilibrium price of a material, where producers are earning an adequate, but not excessive, rate of return. Predicting long-run equilibrium prices for materials under normal market conditions is not a trivial task, if the highest possible degree of accuracy is required. However, it is a manageable problem. Here, we concern ourselves with whether these are important further issues for EPA to consider, beyond simply accepting the normal cost of materials implied by the methods of compliance chosen by the regulated private sector.

Where EPA regulations will require relatively large increases in world production of a material, one obvious complication is the effect of EPA induced demands on the long-run equilibrium price of the material. For most materials, long-run supply is very "elastic" in its response to price incentives. In economists' jargon, that means that a very modest increase in the market price of a material will eventually be a sufficient incentive for its producers to increase greatly their output, allowing a number of years for unrushed capacity expansions, and perhaps even additional time to explore for new reserves. It may even be possible to increase greatly the production of a material and eventually to have a lower market price than previously, if expanded production allows increased economies of scale or induces advances in processing technologies. The most notable exceptions to the above generalization (that materials are available in very elastic supply in the long run), occur when a material is produced as a byproduct of another material. In that case, increased market prices may lead to very little additional production. This consideration is particularly relevant for the more minor of the platinum-group metals, most notably rhodium.

In addition to setting regulations to be met in the "long run," EPA must also decide upon how quickly to impose standards of a given stringency. More rapid imposition of a standard may lead to more rapid increases in the demand for materials and short-run increase in their prices. These short-run price increases will recede after capacity to produce the materials has expanded, but they do imply temporarily higher compliance costs from faster implementation of regulations. For simplicity in the following discussion, we usually abstract away from the additional difficulties associated with analyzing the speed of implementing EPA regulations, and consider only the costs of regulations after they have been in effect for a while. However, our conclusions about the adequacy of considering materials criticality only to the extent that compliance costs are affected, also generally hold true when evaluating the overall costs (and benefits) of different possible speeds of implementation.

A final consideration relevant for predicting the costs of materials used to comply with EPA regulations is the probability of contingencies such as major foreign supply disruptions, that can greatly increase the price of a material for a number of months, or even years. As discussed above, significant susceptability to such contingencies qualifies a material to be considered "critical." We now consider how such considerations should in principle be included in the normal course of predicting compliance costs for EPA regulations, which requires analyzing how private firms include these considerations in their choices among alternative methods for complying with EPA regulations. This same analysis will be the basis for quantifying the criticality of a material.

COMPLIANCE COSTS AND THE CRITICALITY OF MATERIALS USED TO MEET EPA REGULATIONS

Figure 2-1 presents a concrete example of the materials component of compliance costs, in terms of the amount of an imaginary material "catalystium" used to meet EPA vehicular emissions standards. The illustrated catalystium "demand curve" assumes that when the market is in a normal undisrupted state, the world market price is $100 per ounce, and 10,000 ounces per year are purchased to meet EPA regulations. However, we suppose that there is a threat that the producers of catalystium located in a foreign country will be disrupted by a localized military conflict. For the sake of simplicity, we assume we know that the world market price rises from $100 per ounce to $300 per ounce during such disruptions, and that the disruptions last exactly one year. We further assume that the probability of a disruption occurring in any future year is 0.1.

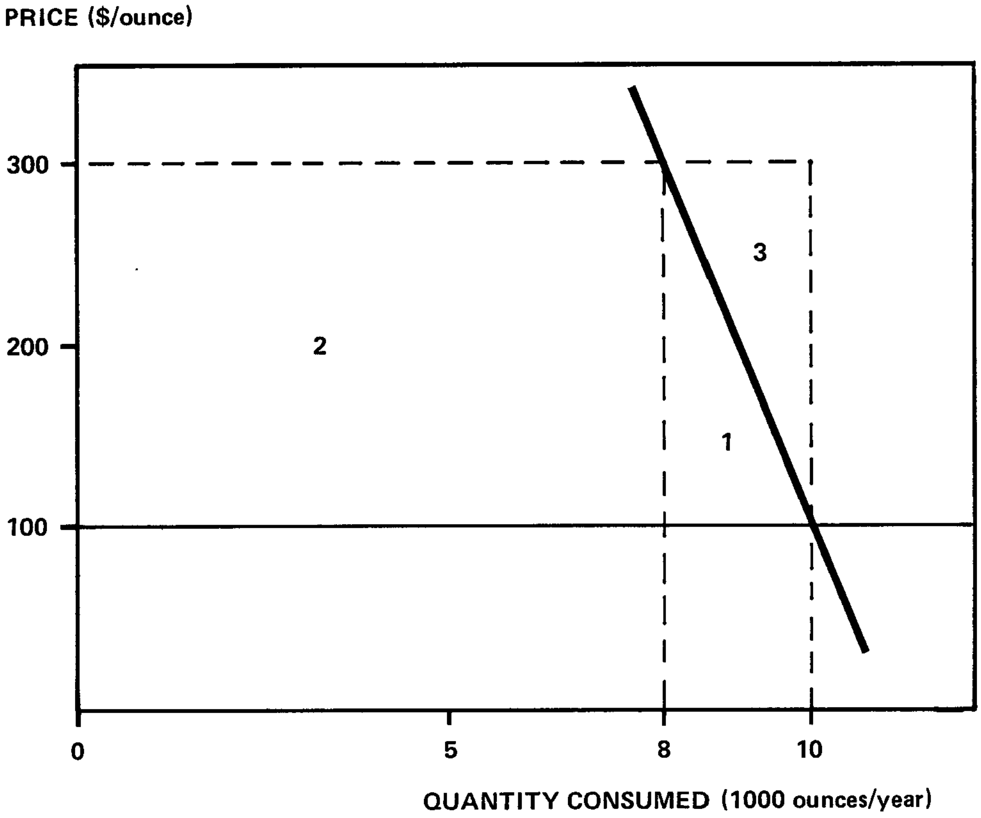
If producers of emissions control equipment continued to purchase 10,000 ounces of catalystium per year during disruptions, then it is very easy to include the effect of the supply disruptions in the calculation of average expected compliance costs in future years. The expected future price of catalystium would be 0.9($100) + 0.1($300) = $120 per ounce, averaging out years in which supply disruptions do and do not occur.

However, the example illustrated in Figure 2-1 is a bit more realistic. It assumes that producers of emissions control equipment can cut back somewhat on the use of catalystium when its price rises suddenly. A variety of design changes may allow reductions in the use of catalystium, but for simplicity we can assume here that simply using a greater proportion of another material in the equipment allows EPA regulations to be met. Using this greater proportion of the alternative material is not economical (i.e., does not minimize compliance costs) when catalystium costs $100 per ounce, but it is economical when catalystium costs $300 per ounce, and (we suppose) the switch in technologies can be made rapidly after such a price increase occurs.

How can the calculation of compliance costs take into account disruptions in the supply of catalystium in this more complicated case? One straightforward

Figure 2–1

CONSUMPTION OF "CATALYSTIUM" TO COMPLY WITH EPA STANDARDS, AND ECONOMIC LOSSES FROM SUPPLY DISRUPTIONS
(A HYPOTHETICAL EXAMPLE)



way to proceed would be to calculate costs for each of the alternative technologies separately, then weight the cost using less catalystium by 0.1, and the cost of the normal technology by 0.9. (That is, weight by the relative frequencies of a disruption occurring and not occurring.) However, it is also possible to infer the effect of disruptions in the supply of catalystium on compliance costs, just using the demand curve for catalystium illustrated in Figure 2-1.

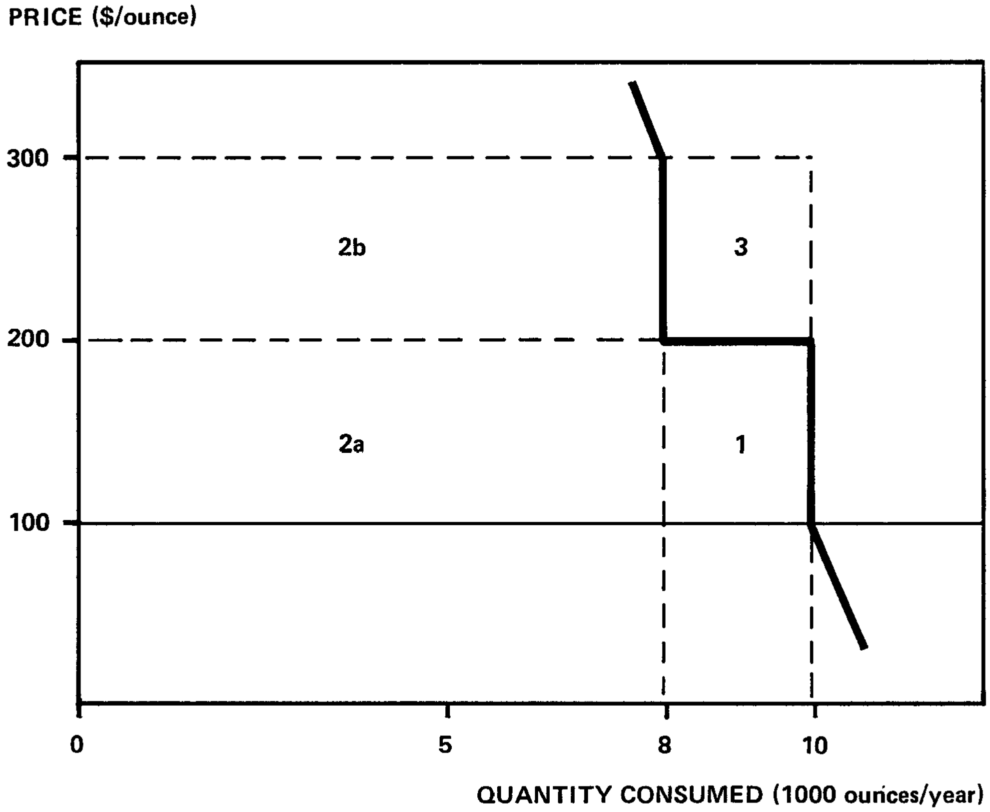
In order to appreciate how this is done, consider the more artificial demand "curve" for catalystium illustrated in Figure 2-2, which assumes that at a catalystium price of exactly $200 per ounce it is economical to switch entirely from the normal technology to the alternative using less catalystium. The resulting demand curve is a step function. (The more realistic smooth demand curve in Figure 2-1 assumes that the switch away from catalystium occurs gradually as prices rise from $100 per ounce to $300 per ounce.) In Figure 2-2, $200 per ounce of catalystium represents a "break-even" price at which it is equally economical to use either of the two technologies to meet EPA standards. We can tell from the diagram that the normal technology costs in total ($200-$100)(10,000) = $1,000,000 more per year, when the catalystium price is $200 rather than $100. Thus, at the catalystium price of $200 per ounce, the alternative technology using less catalystium must also cost $1,000,000 more than the normal technology with catalystium at $100 per ounce. Of this $1,000,000, additional costs for the 8,000 ounces of catalystium used with the alternative technology are ($200-$100)(8,000) = $800,000 per year. Thus, the cost of changing technologies, apart from the effect of an increase in the price of catalystium, is $1,000,000 - $800,000 = $200,000 per year.

This line of reasoning is probably clearer in the geometric terms of Figure 2-2. When the catalystium price rises from $100 to just below $200, the regulated industry continues to buy 10,000 ounces at an additional cost for the year of almost $1,000,000. This loss is represented geometrically in Figure 2-2 as the area of the rectangle made up of the two smaller rectangles labeled 2a and 1. When the catalystium price rises from just below $200 to just above $200, the total cost of compliance does not increase significantly, but switching to the alternative technology causes the costs to be broken down into

- the additional $200,000 cost of the alternative technology, represented as Area 1 in Figure 2-2, plus
- the additional $800,000 cost of the remaining amount of catalystium that is purchased, represented as Area 2a in Figure 2-2.

Figure 2–2

CONSUMPTION OF "CATALYSTIUM" TO COMPLY WITH EPA STANDARDS: ARTIFICIAL CASE WHERE DEMAND IS A STEP FUNCTION



If the catalystium price then rises from $200 per ounce to $300 per ounce, the remaining 8,000 ounces of catalystium that are purchased will cost an additional ($300-$200)(8,000) = $800,000 per year, represented in Figure 2-2 as Area 2b. (We are assuming in Figure 2-2 that no further reductions in the use of catalystium are economical in this price range.) Thus, the total increase in the cost of compliance caused by the catalystium price rising from $100 to $300 during supply disruptions is $200,000 in adjustment costs (represented by Area 1), plus $1,600,000 in additional costs for 8,000 ounces of catalystium (represented by Areas 2a and 2b). The cost savings achieved by switching to the alternative technology (rather than just continuing to buy 10,000 ounces of catalystium at $300 per ounce), is represented in Figure 2-2 as Area 3, amounting to $200,000 for the year of the disruption.

The above line of reasoning generalizes readily to the case where adjustment away from consumption of catalystium is gradual, as its price rises from $100 per ounce to $300 per ounce during supply disruptions. This more realistic case is illustrated in Figure 2-1. Again, Area 1 ($200,000) represents adjustment costs and Area 2 ($1,600,000) represents the additional cost of purchasing the remaining 8,000 ounces of catalystium during disruptions. Area 3 ($200,000) represents the cost savings achieved by adjusting to alternative technologies, rather than just continuing to consume 10,000 ounces per year during supply disruptions.

We now have sufficient information about the much simplified example of catalystium to illustrate the preferred approach to measuring its criticality for vehicular emissions control, due to the threat of foreign supply disruptions. Remember our earlier assumption that the disruptions are expected to occur on average in one year out of ten. Relative to the situation where normal price $100 occurs with certainty, the expected additional costs due to supply disruptions are (0.1) ($1,800,000) + (0.9) ($0) = $180,000 in each future year. (That is, additional costs of $1,800,000 are borne on average in one year out of ten, and no additional costs are borne in nine years out of ten.) This expected economic cost per year is the quantitiative measure of the criticality of catalystium consumption for vehicular emissions control.

It is clear from the above catalystium example that there are at least five basic determinants of the criticality of a material from the point of view of consumption for vehicular emissions control. (We will discuss other considerations in more general terms later.) The five determinants are:

- the severity of contingencies that threaten U.S. consumers, as measured by price increases that occur;
- the probability of the contingencies occurring;
- the duration of the contingencies;

- the quantity of calatystium consumed in the United States at normal prices; and
- the extent to which U.S. consumption can be reduced when prices rise (the "elasticity" of short-run U.S. demand).

It is interesting to note that the normal price of catalystium does not directly enter the calculations, except as a base from which to calculate plausible price increases during disruptions. Thus, for example, simply examining the cost share of various materials used for vehicular emissions control may not be a reliable guide to their respective criticalities, though there is some relationship between cost shares and criticality, as we explain further below.

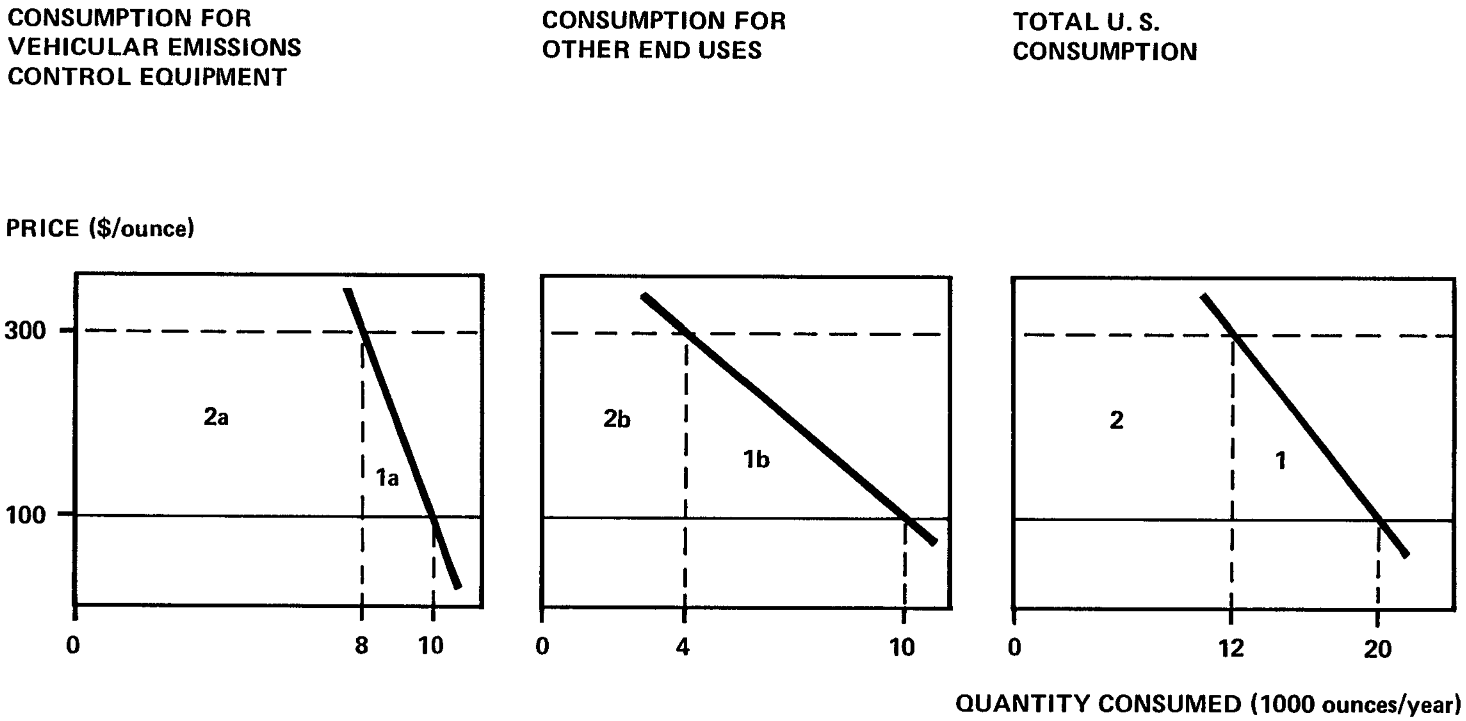
The above calculation of criticality was simplified in a number of important respects, notably in ignoring the effects of inventories and recycling. We allowed the producers of emissions control equipment to switch to more economical alternate technologies when the price of catalystium jumped, but we did not allow them to accumulate an economical level of inventories in preparation for disruptions. Also, we did not allow them to use recycled scrap to a greater extent. These considerations deserve further discussion, but it is convenient to discuss first criticality from a national perspective, rather than just from the perspective of producers of emissions control equipment.

THE CRITICALITY OF MATERIALS FROM A NATIONAL PERSPECTIVE

For other consumers of catalystium, criticality is measured in exactly the same fashion as for producers of vehicular emissions control equipment. In Figure 2-3, the demand curve for producers of vehicular emissions control equipment is reproduced on the left, and another (also hypothetical) demand curve for other consumers is given in the middle of the figure. The example assumes that it is economical for other consumers of catalystium to cut back on their consumption by 60 percent in response to tripled prices during supply disruptions, in contrast with producers of vehicular emissions control equipment, who find it economical to cut back consumption by only 20 percent. As a result, adjustment costs for other consumers during supply disruptions, represented as Area 1b in Figure 2-3, are larger than corresponding Area 1a for producers of vehicular pollution control equipment. Triangular Area 1b represents adjustment costs of (1/2)($300-$100)(10,000-4,000) = $600,000 per year, while Area 1a represents adjustment costs of only $200,000 per year (as previously calculated). But, of course, "other" consumers of catalystium benefit from their greater flexibility by having to pay much less for catalystium during supply disruptions: Area 2b represents additional costs of only ($300-$100)(4,000) = $800,000 per year, as opposed to Area 2a for producers of vehicular emissions control equipment, which was previously calculated to be $1,600,000 for the year of a disruption.

Figure 2–3

U. S. CONSUMPTION OF "CATALYSTIUM" FOR ALL END USES, AND TOTAL ECONOMIC LOSSES FROM SUPPLY DISRUPTIONS



CONSUMPTION FOR VEHICULAR EMISSIONS CONTROL EQUIPMENT

CONSUMPTION FOR OTHER END USES

TOTAL U. S. CONSUMPTION

On the right side of Figure 2-3, total U.S. consumption of catalystium is obtained by summing (horizontally, at each price) consumption for vehicular control equipment and consumption for other end users. (Note that the quantity scale on the total consumption graph has been compressed.) The reader can easily confirm that costs during disruptions are additive across all end uses. That is, the national adjustment cost, represented by Area 1, is the sum of Areas 1a and 1b ($800,000), and the remaining national expenditure for catalystium consumption during disruptions, represented by Area 2, is the sum of Areas 2a and 2b ($2,400,000). Total national costs borne by U.S. consumers during disruption years are thus $800,000 + $2,400,000 = $3,200,000.

If the United States produces no catalystium, and could not do so even when the price of imports triples for a year, then sufficient information on the above example has been given to calculate the criticality of catalystium from a national perspective. Remembering that disruptions are assumed to occur on average in one year out of ten, expected U.S. losses from disruptions are (0.1)($3,200,000) = $320,000 per year.

However, suppose that the United States produces catalystium in normal times, and could expand output somewhat during disruptions in foreign supplies. In that case, the criticality of catalystium will be less from a national perspective, though consumers will still face the same expected losses (assuming the probability and severity of price increases from disruptions are as before). The calculation of national criticality in terms of expected losses yields this result, by recognizing that U.S. producers benfit greatly from foreign supply disruptions, thus facing negative criticality from the threat of this particular contingency. We now describe how the "criticality calculus" described above can be extended to yield this result.

Figure 2-4 gives a hypothetical U.S. supply curve for catalystium, showing production of 4,000 ounces per year at the normal price of $100 per ounce, and production of 5,000 ounces during years in which supply disruptions occur, when the price on the world market is assumed to be $300 per ounce. How much additional benefit do U.S. producers receive as a result of producing 5,000 ounces at $300, rather than 4,000 ounces at $100? It is clear revenues rise from ($100)(4,000) = $400,000 to ($300)(5,000) = $1,500,000, but the additional cost of producing 1,000 more ounces must be netted out.

This additional cost to producers can be calculated by estimating how much additional production would occur at prices between $100 and $300 (in a way analogous to measuring additional costs to consumers in Figure 2-2). Figure 2-5 gives a more artificial U.S. supply curve, specifying that the additional U.S. production of 1,000 ounces per year all kicks in at $200 per ounce. According to this supply curve, the additional labor, materials, energy, and other factors of production required to produce an additional 1,000 ounces of catalystium cost $200 per ounce produced, so it is economical (profitable) to produce the additional quantity when the market price is above $200 but not when it is below $200. Thus, the total cost of producing

Figure 2—4

U. S. PRODUCTION OF "CATALYSTIUM," AND ECONOMIC GAINS FROM FOREIGN SUPPLY DISRUPTIONS

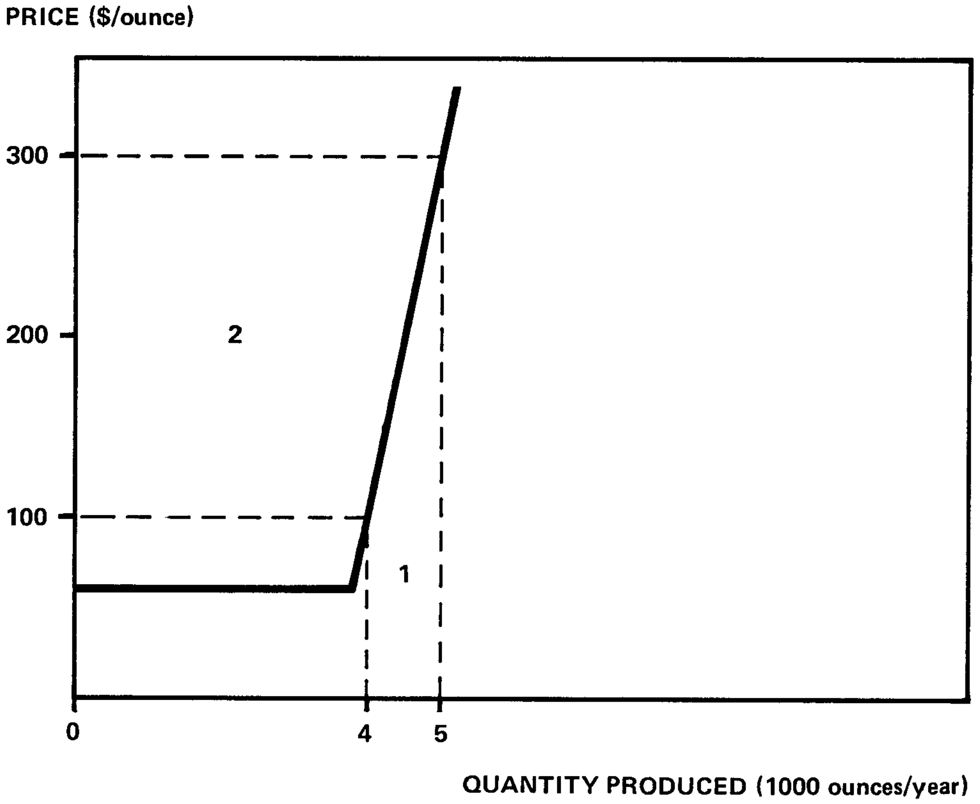
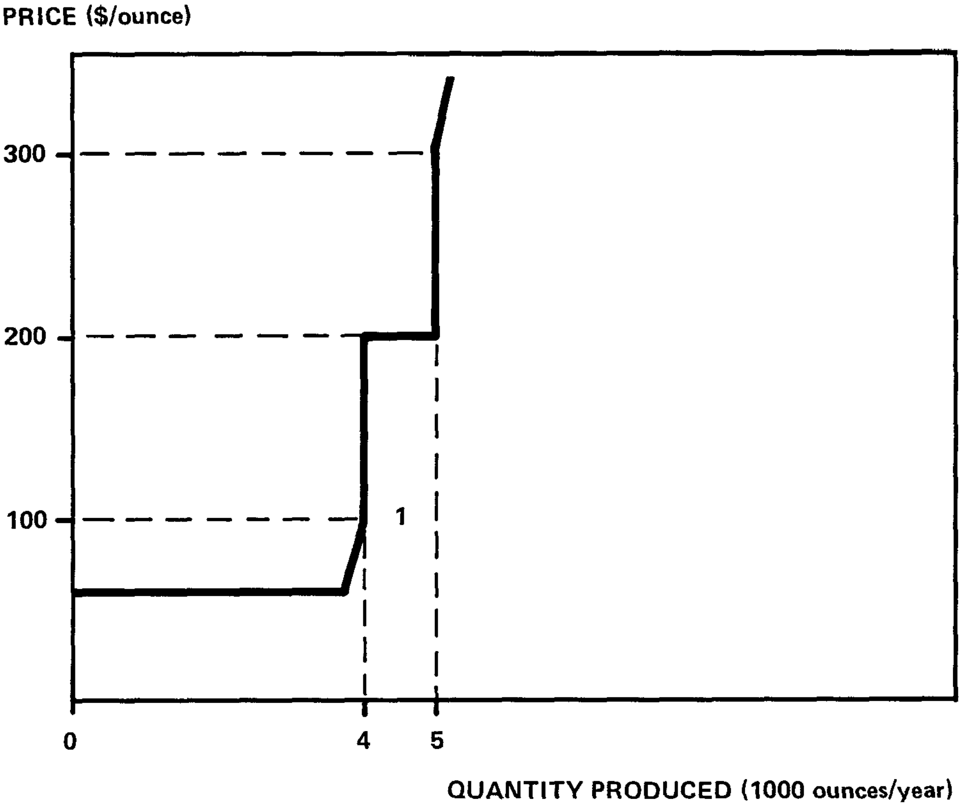


Figure 2–5

U. S. PRODUCTION OF "CATALYSTIUM": ARTIFICIAL CASE WHERE SUPPLY IS A STEP FUNCTION



the additional 1,000 ounces is ($200)(1,000) = $200,000 for the year of the disruption.

In general, even for the more realistic smooth supply curve in Figure 2-4, the cost of additional production can be estimated as the area under the supply curve, out to the point at which production occurs. Thus, in Figure 2-4 the cost of additional production is represented as trapezoidal Area 1, equal to (1/2)($100 + $300)(5,000 - 4,000) = $200,000. U.S. producers thus gain Area 2 in Figure 2-4, equal to ($1,500,000 - $400,000) - $200,000 = $900,000, during years in which the price of catalystium rises to $300 per ounce. (If producers just continued to produce 4,000 ounces during a disruption year, they would only gain $800,000.)

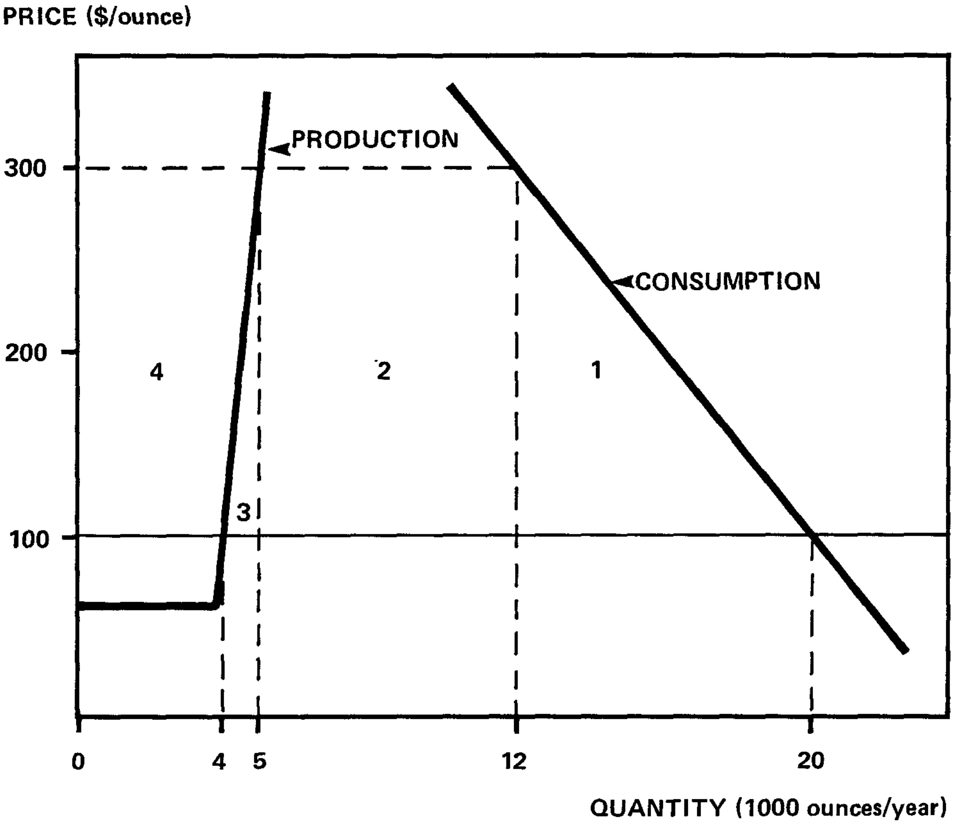
We are now in a position to recalculate U.S. losses during years in which foreign supplies of catalystium are disrupted, recognizing the fact that U.S. production will expand. Figure 2-6 combines the total U.S. demand curve of Figure 2-3 and the U.S. supply curve of Figure 2-4. When the world market price is at the normal level of $100 per ounce, U.S. consumption is 20,000 ounces and U.S. production is 4,000 ounces, requiring net imports of 16,000 ounces per year (the horizontal distance between the supply curve and the demand curve). At the disruption price of $300 per ounce, U.S. consumption is 12,000 ounces and U.S. production is 5,000 ounces, requiring net imports of 7,000 ounces per year.

The U.S. loss areas described in earlier figures are renumbered in Figure 2-6. Area 1 ($800,000) is adjustment costs suffered by U.S. consumers in order to reduce consumption from 20,000 ounces to 12,000 ounces. Areas 2, 3, and 4 together ($2,400,000) represent extra payments by U.S. consumers for the remaining 12,000 ounces that are purchased at the high $300 price rather than at the normal $100 price. Of that total additional transfer to (all) suppliers by U.S. consumers, Area 4 ($900,000) accrues to U.S. producers as increased profits and Area 3 ($100,000) represents additional revenues of U.S. producers used to cover increased production costs (beyond the $100 per ounce that consumers normally pay). Loss Area 2 ($1,4000,000) accrues to foreign producers as extra payment for the 7,000 ounces of catalystium that are still imported.

We should mention that the method described above for measuring the cost imposed by a large increase in the price of a material may require supplementation where adjustment to the disruption involves dismissal of workers. The standard assumption implicit in the above methodology is that these workers can find alternative employment at comparable wages. Where this assumption is significantly overoptimistic, the additional cost of unemployed labor should be added when calculating the criticality of a material from a national perspective.

Figure 2–6

TOTAL U. S. CONSUMPTION AND PRODUCTION OF "CATALYSTIUM," AND NET ECONOMIC LOSSES FROM FOREIGN SUPPLY DISRUPTIONS



It may have already occurred to the reader that if the United States started off as a net exporter of catalystium, rather than a net importer, then the gains accruing to U.S producers from a foreign supply disruption will be larger than the losses suffered by U.S. consumers, as U.S. producers export more onto the world market at much higher prices. Thus, a material can be quite critical to U.S. consumers, and yet have "negative" criticality from a national perspective. This balancing of gains and losses by various groups within the United Sates requires closer examination, to which we now turn.

INCOME REDISTRIBUTION AND NONECONOMIC DIMENSIONS OF MATERIALS CRITICALITY

Netting gains of U.S. producers against losses of U.S. consumers, each calculated in dollar terms, is a common procedure, but it may be preferable for purposes of national policymaking to keep separate accounts of these gains and losses. For example, as a value judgment, legislators may feel that a dollar gained by U.S. producers is not as important as a dollar lost by U.S. consumers. The implied value judgment is that a redistribution of income from U.S. consumers to U.S. producers is undesirable, rather than being the neutral consideration that the netting procedure would require.

If the analyst keeps separate accounts of losses and gains by U.S. consumers and producers, then a "multi-dimensional" measure of criticality results. The user of the multi-dimensional measure can then apply his or her own weights to losses suffered by various groups of consumers and producers, in order to calculate a single summary measure of the criticality of various materials (as is generally required to make final policy decisions). But, of course, this summary measure will generally be somewhat different from that which results from applying another person's "weights" (value judgments).

Other, noneconomic effects of disruptions in material markets may make it desirable to measure the criticality of materials in additional dimensions that are not even denominated in dollar terms. Continuing with our earlier example, suppose that increases in the world price of catalystium from $100 to $300 causes Congress to relax vehicular emissions standards. In that case, consumption of catalystium would decrease during disruptions more than previously, and, as our earlier diagrams indicate, the direct economic losses from disruptions measured in dollar terms would be less. However, the noneconomic effects of increased vehicular emissions due to relaxed standards would be considered a cost of the disruption by most of the U.S. populace. Some estimate of increased air pollution would then be an appropriate additional dimension for a criticality measure used for national policymaking. The prime example of a noneconomic dimension of materials criticality concerns its usefulness for military contingencies (that is, the extent to which it is "strategic"). Obviously, the cost to the United States of being less well prepared for war cannot be measured entirely in dollar terms.

It is necessary to understand that a measure of materials criticality can be extended to include noneconomic dimensions, but we cannot explore all such possibly useful generalizations here. Hereafter we will simply assume that all costs imposed on U.S. citizens by contingencies of concern in the catalystium market are strictly economic, and that a dollar gained by a U.S. producer compensates for a dollar lost by a U.S. consumer. Under these assumptions, we can conclude that the criticality of catalystium in the case allowing for U.S. production (as illustrated in Figure 2-6) equals expected annual loss (0.1)($3,200,000 -$900,000) = $230,000 per year (that is, averaging out years in which disruptions do and do not occur).

ROLE OF SECONDARY PRODUCTION AND INVENTORIES

Two important activities occurring in U.S. material markets that we chose, for simplicity, not to include explicitly in the above illustrative calculations for the catalystium market are inventory adjustments and secondary recovery (recycling). It is straightforward to include secondary recovery in the analysis in a roughly appropriate way, by simply including secondary production with primary production (from mines) in the supply curves illustrated in Figures 2-4 and 2-6. Just as for primary U.S. production, the criticality of a material from a national perspective is reduced the greater the amount of recycling in normal times, and the greater the extent to which recycling can be expanded when prices suddenly rise. (This description of the role of secondary recovery is qualitatively correct, but it ignores the linkage between past consumption and the pool of scrappable items from which secondary production can come during disruptions. More sophisticated market models that explicitly recognize this linkage should ideally be used to calculate the criticality of materials.)

Business firms faced with the threat of disruptions in the supply of an input such as catalystium normally maintain inventories or stockpiles to be used when supply disruptions occur. It is clear from the above analysis how the existence of normal business inventories and stocks can decrease expected costs from supply disruptions (that is, decrease the criticality of a material), by reducing the amount of material that must be purchased on the world market at very high prices during disruptions. On the other hand, holding inventories imposes costs of its own that should also be attributed to the disruption threat, and included in the measure of criticality. Administering and maintaining a stockpile requires the time of a firm's managers and employees, and involves other out-of-pocket expenses as well, even after the inventories have been acquired.

The original cost of the stockpiled material is not counted by economists as a cost to the firm (or nation) at the time of acquisition, since one kind of asset (money) has just been transformed into another kind (stockpiled catalystium, in our example). The transformation could be reversed, if desired (except for transaction costs, such as transportation and brokerage charges). However, holding assets in the form of catalystium over time, rather than in plant and equipment, in other immediately productive assets, or even in a financial instrument earning interest, does impose costs on the firm (and the nation). These costs are usually approximated by the estimated interest costs of financing the stockpile (even if the stockpiler did not actually borrow to finance his inventories). Many metals and other materials do not cost much (out of pocket) to store, relative to their market value, so the dominant cost of stockpiling is in fact the interest expense. As a general rule, U.S. firms increase their stockpiles, held in anticipation of market contingencies, until the next unit stockpiled is not expected to be salable during the next disruption for enough to cover its expected holding costs (recognizing that the dates, severities, and duration of disruptions are uncertain events).

In summary, U.S. consumers of a material generally make two major types of adaptations to the threat of supply disruptions (and other contingencies as well). Before the disruption they acquire inventories, and after it occurs they switch to alternative technologies, as summarized in market demand curves for the material (such as Figure 2-3). (Having the capability to switch quickly to alternate technologies during disruptions may, of course, also require advance planning.)

For purposes of measuring the economic criticality of a material from a national perspective, we can now lengthen the list of determinants (developed earlier for particular consumers) as follows:

- the severity of contingencies that threaten U.S. consumers or producers, as measured by price increases that occur;
- the expected time between these contingencies;
- the duration of these contingencies;
- the quantity of the material consumed in the United States under normal conditions;
- the quantity of the material produced in the United States under normal conditions, both from primary and secondary sources;
- the extent to which U.S. consumption can be reduced when prices rise (the "elasticity" of short-run U.S. demand);
- the extent to which U.S. primary and secondary production can be expanded when prices rise (the "elasticity" of short-run U.S. supply); and
- the size of normal U.S. inventories and stockpiles.

In addition to privately held inventories, the U.S. National Defense Stockpile contains platinum-group metals and other materials that could conceivably be used for vehicular emissions control during a nonmilitary emergency. Appendix 2-A considers this possibility, and concludes that an act of Congress would probably be required to authorize such releases. We do not assume these stockpiles will necessarily be available during the nonmilitary contingencies upon which we base the illustrative criticality estimates given at the end of this chapter.

ADEQUACY OF PRIVATE ADAPTATIONS TO THE THREAT OF SUPPLY DISRUPTIONS AND OTHER CONTINGENCIES

Recognizing the adaptations that private firms make in response to the threat of contingencies in material markets, key questions are whether the U.S. government should make additional preparations and adaptations with respect to critical materials, and, more particularly, whether the Environmental Protection Agency should weigh the criticality of the material in its decisionmaking, beyond including the effects of the underlying contingencies on the usual calculation of expected future compliance costs (as we described that process earlier). Under certain circumstances, which can be approximately satisfied in some material markets, general government policies (such as stockpiling, tariffs, quotas, or subsidies to domestic producers) are not needed. In these circumstances, private firms can be expected to do the amount of stockpiling, and choose the production technologies, that are efficient from a national perspective. In these cases EPA only must consider the effect of materials prices on expected compliance costs when choosing among policy options.

We cannot analyze in detail here the conditions under which private adaptations to market contingencies are efficient from a national perspective. (Charles River Associates has filled many volumes analyzing these issues, particularly for materials criticality stemming from the threat of foreign supply disruptions. See the Bibliographic Note and References.) However, we can state the most important of these conditions and give some indication of their relevance.

The first of the conditions under which private firms would prepare sufficiently for market contingencies is that there be no expectation of price controls, material allocation, or other government interference with the market, even during serious disruptions. For example, if firms expect inventories to be reallocated from "have" firms to " have not" firms (as actually occurred in the post-OPEC U.S. petroleum market), then they will have reduced incentive to accumulate contingency stocks, and private holdings will be less than is justified by benefits (and costs) measured from a national perspective. Expectation of price controls (perhaps instituted with the rationale of "moderating the inflationary impact of a supply disruption") can have the same unfortunate consequences.

A second condition is as follows: The preparations for contingencies by individual U.S. firms must not reduce the likelihood or severity of the contingency faced by other U.S. firms. This condition is likely to fail to some extent. For example, when an individual U.S. firm holds an additional unit of inventories, it must bear the entire cost of holding that unit, but some of the benefit generally accrues to other firms. This "external" benefit to other U.S. firms occurs during disruptions, when the firm with the additional stockpiled unit needs to buy one unit less on the world market, tending to decrease the price at which other U.S. firms obtain their imports. One can imagine an artificial situation where this mechanism would not operate, for example where a cartel of foreign producers threatens to suddenly form and double the existing market price, no matter how much the resulting rate of demand is reduced due to U.S. buyers consuming out of stocks. However, it is much more likely that the cartel would set a lower price, at least initially, if U.S. stocks are higher. This mechanism is referred to in CRA studies as the "price deterrence" benefit of U.S. stockpiling. Reductions in U.S. consumption during disruptions due to use of alternative technologies can also have price deterrence benefits that are external to the individual U.S. firm actually adopting the alternative.

In general, whenever a U.S. firm bears all the cost of some action preparing for a disruption, or all of the cost of an adjustment made during the disruption, but other firms reap some "external" benefit, private preparations and adjustments tend to be less extensive than is desirable for the nation as a whole. All of the costs of an additional increment of preparation or adjustment are recognized by the private decisionmaking unit, but all of the benefits to the nation are not. The private firm stops preparing or adjusting when the incremental private cost equals the incremental private benefit, whereas, from a national viewpoint, the firm should continue preparing and adjusting until the incremental private cost equals the incremental national benefit.

Another mechanism of the same nature can be relevant when a material market is threatened by a disruption that is deliberately decided upon by foreign producers of a material, or by their governments. In that case, greater U.S. preparations, particularly larger U.S. stockpiles, can decrease the probability of a disruption occurring in the first place. In CRA studies this mechanism is called the "probability deterrence" benefit of U.S. stockpiling. (See for example the appendix to Klass, Burrows, and Beggs (1980).)

Depending on the types of threats facing a particular market, price deterrence and probability deterrence can make private preparations and adjustments much less than would be desirable from a national perspective. In these situations, a strong case can be made for government policies, such as tariffs or stockpiling, that will manipulate or augment private preparations and adjustments.

Other conditions can cause preparations for market contingencies by U.S. firms to fall short of the national optimum. One such condition involves the way private firms compare present costs and benefits with future costs and benefits. Generally, decisionmakers "discount" costs and benefits occurring in the future relative to current costs and benefits; that is, a dollar gained tomorrow justifies the expenditure of something less than a dollar today. But makers of public policy may conclude that private firms discount future costs of disruptions too much, thus incurring insufficient costs for preparations today. (Economic theory does not offer a definitive answer to the question of what rate of time discount is most appropriate for national policymaking.)

The above discussion assumed, as is often the case, that U.S. firms consuming a critical imported material are individually small relative to the world market, but together account for a sizable proportion of world consumption. On the other hand, if a single U.S. firm accounts for most of U.S. consumption, then the importance of price deterrence effects and probability deterrence effects, as discussed above, may be considerably less. Most of the benefits of preparation for, and adjustments to, disruption will accrue to that single U.S. firm, rather than being "external," so the extent of private preparations and adjustments will tend to be much closer to the national optimum. In Japan, it is common for firms to coordinate decisions about critical imported materials, thus gaining benefits that otherwise would be possible only in the case of a single importing firm. However, in the United States such coordination would run afoul of antitrust regulations. (There are many competing considerations in deciding the desirability of the Japanese institutional arrangement versus the U.S. arrangement, and this consideration is very probably not the deciding one.)

One circumstance that can lead to <u>more</u> private preparations for disruption (relative to the national optimum) rather than less, is "risk aversion" on the part of private firms. This situation can be explained with reference to our earlier sample calculation of criticality for consumers of the imaginary material catalystium. We calculated the criticality of catalystium to consumers by averaging losses that could be expected to occur over many years. Since disruptions were assumed to occur in one year out of ten, the average expected loss to consumers was (0.1)($3,200,000) = $320,000 per year. Contrast this expected loss with that which would occur if a disruption loss of $640,000 occurred in one year out of two. In that case, expected losses are again $320,000 per year, and the criticality of the material is as before.

This procedure for evaluating losses of different sizes occurring with different frequencies is entirely appropriate for policymaking at the national level, where losses in a given year of $640,000 or $3,200,000 are miniscule relative to the size of the entire U.S. economy. However, consider a small U.S. firm for which catalystium accounts for a major proportion of production costs, and suppose there is stiff competition from other firms whose product does not require catalystium. For that small firm, a tripling of the price of catalystium, sufficient to inflict costs of $3,200,000 on U.S. consumers over one year, might be sufficiently severe to cause bankruptcy. The fact that losses will "average out," over many succeeding years, is small comfort if the firm has gone bankrupt in the meantime. In this case, where the possible loss is catastrophic for the decisionmaking unit, it is rational to be "risk averse," and undertake more stockpiling and other preparations for disruptions than would be justified by average expected costs alone.

In addition to stockpiling on its own, a small firm can also reduce the risk of an increase in the price of catalystium by buying "forward" contracts for future delivery of catalystium on a commodity exchange. In that way the risk is spread among a great many speculators, who can individually diversify their speculations so that they are not catastrophically affected by a disruption in the catalystium market. In this way private risk aversion can be reduced, which is beneficial to the individual firm, but may reduce preparations for disruptions that they would otherwise undertake. Another strategy for reducing risks of supply disruptions is to enter into long-term, fixed-price contracts with reliable suppliers who are unlikely to be disrupted.

IMPLICATIONS FOR EPA POLICYMAKING

We have described above a number of conditions in material markets that can cause private firms' preparation and adjustments for market contingencies, particularly supply disruptions, to be different from (usually less extensive) those that would be justified by the costs and expected benefits measured from a national perspective. In those circumstances, a case can be made for government policies such as tariffs and national stockpiles, which modify or augment private preparations or adjustments made in response to the threat or occurrence of a contingency such as a supply disruption. A material must be "critical," that is, threatened with serious contingencies such as a major foreign supply disruption, to justify government actions in addition to the private actions that profit-maximizing U.S. firms undertake naturally. However, government actions such as tariffs and national stockpiles are not necessarily justified for all critical materials. That is, criticality is a necessary condition, but not a sufficient condition, to justify general government policies such as tariffs and stockpiles.

With this analysis of criticality and general government policymaking in material markets as a background, we can now address directly the principle question that this chapter asks: how should the Environmental Protection

Agency factor the criticality of materials into its decisionmaking, beyond recognizing the effects of contingencies on prices of materials when calculating average future compliance costs? We presume that any effect of EPA decisions on the long-run equilibrium price of a material (roughly speaking, its "normal" price) is taken into account. (The usual example is where increased demands induced by EPA regulations raise the normal price of the material somewhat.) We also presume that any operative, or likely, general government policies in the material market (such as tariffs) are taken into account by EPA when calculating compliance costs.

Our answer to the question of appropriate EPA policymaking procedures is particularly easy to justify if general government policies in the material market, such as stockpiles and tariffs, are presumed to adequately recognize the material's criticality. In that case, the price paid for the material by producers of vehicular emissions control equipment respresents the material's true cost to society, and no special EPA policymaking, beyond careful forecasting of compliance costs, is required. This conclusion can be justified in great detail, using elaborate versions of the type of economic cost-benefit analysis that we described above as a basis for measuring the criticality of materials. However, the conclusion is sufficiently plausible on its face (and we have sufficiently burdened noneconomists reading this chapter with unfamiliar concepts) so that we forgo its full development. It is basically just one application of very general economic theories showing how the price system can efficiently allocate resources in a free market economy.

It is, of course, true that EPA decisions can greatly change the quantities of a material that are consumed in the United States, as well as other conditions affecting its criticality, thus changing the general government policies that are appropriate. To take an obvious example, increased U.S. consumption to meet EPA regulations would presumably increase the optimal size of government stockpiles. In order to facilitate better and more timely government policymaking for materials markets, it certainly could be worthwhile in principle for the EPA to inform other government agencies, particularly those with direct responsibility for policymaking in material markets, concerning EPA decisions that will significantly affect material markets. (We hope circulation of this study outside EPA will serve this purpose to some degree.) In return, EPA might learn of possible changes in general government policies that would affect the forecasting of compliance costs and hence potentially affect EPA decisions.

The above line of reasoning might sound a trifle artificial to those familiar with U.S. policies toward material markets, because in fact such policies have been designed almost exclusively in response to the threat of military contingencies. As we discuss further in Appendix 2-A, the U.S. National Defense Stockpile is currently reserved exclusively for defense related applications, unless an act of Congress authorizes release for other purposes (which has never happened in the forty-plus years of the stockpile's existence). The United States has modest tariffs on the importation of a number of raw and processed materials. The policy debate on such tariffs often centers around the desirability of having secure domestic sources of supply during wartime (though the political power of special interest groups sometimes seems the more important consideration). Certainly, U.S. tariffs have not been adjusted as the types of nonmilitary contingencies that we identified earlier threaten and recede, in the way in which economic theory suggests would be optimal.

On the other hand, there are a number of government policies aimed at the structural causes of certain nonmilitary contingencies in material markets. Government sponsored R&D is often aimed at reducing U.S. dependence on imports of materials, for example, by making it profitable to exploit previously uneconomical U.S. deposits. The U.S. Department of the Interior is the lead agency in this area. U.S. government agencies such as the National Labor Relations Board are concerned with settling domestic labor disputes, including those affecting material markets. The U.S. Department of State and other U.S. agencies are concerned with international relations that may affect the conditions under which this country imports materials. Nevertheless, it is still relevant to note that the United States in most cases has not generally employed market-specific policy instruments, such as tariffs and "economic" stockpiles, to counteract the threat of nonmilitary contingencies such as foreign supply disruptions.

Is this lack of fine-tuned U.S. policies aimed at nonmilitary contingencies a serious problem? In most cases, probably not. In many material markets, it can plausibly be argued that the private sector undertakes sufficient preparations for, and adjustments to, nonmilitary contingencies in material markets so that the benefit of even theoretically optimal government policies on tariffs and stockpiling would diminish expected national losses only moderately. Moreover, when decisions are finally made in the real world about such national policy instruments as tariffs and public stockpiles, it must be recognized that they are often in practice more costly than analysis of their theoretical optimality would indicate. Administering tariffs and stockpiles can be much more costly than originally estimated, particularly when vested economic interests and political realities intrude into the management process. Recognizing these facts of political life reduce considerably the potential scope for beneficial government policymaking, and makes historical practice in the United States more understandable.

Suppose then that the EPA is contemplating policy options that will greatly affect the market for certain materials (such as increasing demand for the platinum-group metals), and it suspects that national policies (such as tariffs and economic stockpiles) do not adequately recognize the criticality of the materials. What should EPA do? The first observation we make, which is easy to understand in the light of discussions above, is that it is often difficult to determine whether national policies "adequately" recognize the criticality of materials, given private efforts to ameliorate that criticality. To say the least, it would be very ambitious for EPA to analyze conditions in material markets in sufficient depth to make such a determination, particularly where government agencies with direct responsibility for these issues have not done so. In fact, EPA can hardly be held responsible for such policy analysis, and doubtless it is a responsibility whose lack EPA does not regret.

Furthermore, any actions EPA could take to reduce consumption of a critical material -- for example by requiring compliance through one technology rather than another -- would fall into a category that economists call "second-best solutions." It is more efficient from a national perspective to have national policies that discourage all consumers from using a critical material, if that is indeed called for because some condition exists in the market that makes private policies otherwise inadequate.

The two main conclusions we reach regarding the role of materials criticality in EPA decisionmaking are thus as follows: first, in almost all cases the EPA need only calculate compliance costs in a comprehensive manner that recognizes the likelihood of market contingencies temporarily raising market prices in the future. (The effect of EPA induced demands for materials on compliance costs should also be recognized, both during possibly rapid implementation, and during the "long run" thereafter.) Second, where the EPA anticipates its policies will have major impacts on material markets, it should coordinate with the Department of the Interior and other federal agencies with more direct responsibility for policies affecting material markets.

In order to implement these suggestions, it can still be useful for EPA to estimate roughly the criticality of materials required for compliance with its regulations. Estimating criticality from the perspective of consumption for vehicular pollution control equipment is very closely related to estimating how much expected future compliance costs will be raised due to the contingencies that threaten the market, which is something EPA should do anyway. Estimating criticality from a national perspective suggests the possible importance of EPA coordinating policies affecting materials markets with other government agencies. The last part of this chapter pursues both of these conclusions by developing rough estimates of the criticality of platinum-group metals and four other materials required for vehicular emissions control equipment.

SHOULD EPA SPONSOR R&D ON VEHICULAR EMISSIONS CONTROL?

Our discussion above considered decisions by private firms about amounts of critical materials to use, when there exists a range of different technologies for complying with EPA standards on vehicular emissions. A further, related question is whether private research and development on new compliance technologies is sufficiently extensive, or whether government sponsored research of some sort is called for.

Research is of course an uncertain process, and there is always the chance that a government sponsored program will discover a new technology that private investigators overlooked. However, there appears to be no general evidence that government sponsored research tends to be more productive per dollar spent. If anything, conventional wisdom asserts just the opposite, that private R&D tends to be more efficient. There are horror stories about ill advised and unsuccessful government supported research, but there are other cases as well, where government research was successful where private research was not successful, or was deemed too unpromising even to pursue. A classic case in the history of material markets is the development by the U.S. Bureau of Mines of technologies to process deposits of the low-grade iron ore taconite.

We reach no conclusions here concerning the comparative cost effectiveness of private versus government research and development. Rather, we simply examine the general circumstances under which private decisions about R&D expenditures in this area are made, to see if there are strong reasons to suspect that the total amount spent would be inadequate.

The usual cause of inadequate private research (and hence the usual justification for government sponsorship of research) involves reasoning much like that we described above to analyze the adequacy of private stockpiling and other preparations for contingencies in material markets. An individual private firm bears all of the expenses of research it undertakes on its own. If there are large "external" benefits to other firms from successful research by one firm, which that one firm cannot substantially capture through licensing fees and other arrangements, then the firm contemplating research will tend to spend less than is justified by the expected benefits of its research to the nation as a whole. So-called "basic" research tends to have the most extensive external benefits, which cannot be appropriated by the successful researcher. Thus, government sponsorship of research is typically most justified for basic research.

How do the circumstances of private research and development on vehicular emissions control stack up against the usual justification for government sponsorship? By and large it appears that the private level of effort in this area should be roughly appropriate. Most of the research is specific to emissions control, and has limited usefulness outside the motor vehicle industry. To be more specific, much of the benefit of research in this area undertaken by General Motors will accrue to General Motors. Moreover, licensing fees for technologies patented at General Motors should allow GM to appropriate some of the benefits received by other motor vehicle manufacturers. The general case for government sponsorship of research in this area appears quite weak.

In Chapter 6 we review research on alternatives to conventional catalytic converters (containing platinum-group metals) that has taken place to date. Certainly there is no direct indication that promising avenues of research to develop more cost effective compliance technologies have been left unexplored.

A MAJOR QUALIFICATION AND A POSSIBLE POLICY PRESCRIPTION

The relatively optimistic conclusions reached above about the adequacy of private R&D and private preparations for contingencies such as supply disruptions, are applicable to all industries, whether their consumption of a critical material stems from the nature of consumers' demands in the marketplace or from the need to satisfy government regulations. However, there is one further major consideration where consumption of a material is based predominantly on the need to satisfy a government regulation.

The main qualification we would make to our general case for the adequacy of private R&D on vehicular emissions control technologies concerns private expectations about the stringency of future emission standards. If U.S. firms do not expect a future standard to be actually in effect and enforced, then they may well not undertake adequate research on ways to meet that standard in the manner least costly to themselves and the nation. EPA is undoubtedly in a better position than we to assess the credibility of scheduled future vehicular emissions standards.

This same type of issue can arise when assessing the adequacy of the preparations that the U.S. auto industry makes for contingencies such as foreign supply disruptions. If the U. S. auto industry believes that it will be able to arrange relaxation of emissions standards whenever the price of platinum, palladium, and rhodium rises greatly during a supply disruption, then the industry will probably undertake less extensive preparations than they would otherwise. In particular, they would stockpile much less of these metals for such contingencies.

It is easy to see why a politically persuasive case for relaxation of emissions standards could be made during a major supply disruption in the platinum-group markets. It would probably be virtually impossible for U. S. vehicle manufacturers to obtain enough of these metals on the spot market if they had no inventories and supplies from South Africa and the Soviet Union were cut off. As discussed further below, the prices of the required platinum-group metals could become "astronomical" in this case.

It would be very interesting in this regard to know the size of the inventories of platinum, palladium, and rhodium that the U. S. auto industry currently maintains. However, as discussed further in Chapter 4, consumers' stocks of these metals are not officially estimated in the United States. If stocks in the auto industry are quite low in comparison with other industries (such as petroleum refining or glass manufacturing) where continuing use of platinum-group metals is mandated by technology rather than by government regulation, then a case could be made that the auto industry has some expectation of throwing itself on the mercy of the regulatory and legislative processes in the event of a major disruption in platinum-group supplies from South Africa. (In fact, stocks of these critical materials in the auto industry should be considerably greater than those "on the shelf" in the petroleum and glass industries, because those other industries have control over material obtained by secondary recovery (after a few years' use), whereas the auto industry has no special access to material obtained from obsolete catalytic converters.)

The obvious solution to this problem, if it is indeed a problem, would be to require documentation from U. S. auto manufacturers that they have a specified minimum level of inventories on hand at all times, unless given an explicit exemption by EPA. We have not investigated the legal or practical aspects of implementing such a new regulation. In setting the appropriate level for such inventories, it would be important for EPA to decide whether very large increases in the price of platinum-group metals could in fact eventually justify some relaxation of emissions standards. (One interesting aspect of such a policy is that it would probably be about as effective with foreign vehicle manufacturers as with U.S. manufacturers, even though they would not be directly subject to the stockholding requirement; the reason is that they would fully expect EPA vehicular emissions standards to be maintained as long as U.S. vehicle manufacturers could consume platinum, palladium, and rhodium out of required inventories.)

MATERIAL IMPORTS AND BALANCE OF PAYMENT PROBLEMS

The reader may have noticed in the preceding discussions that, despite its references to general policymaking in materials markets, no explicit mention was made of the effect of increased material imports on the U.S. balance of trade or balance of payments. This omission was purposeful, since the issue tends to be largely a red herring for efficient government policymaking in markets for particular goods such as materials. It is relatively straightforward to estimate the increased dollar value of U.S. material imports that would result from increased consumption for vehicular emissions control. However, in themselves, increased imports usually do not signal significant national losses --and certainly not losses of the same magnitude as the dollar value of increased imports.

It would be too time consuming to develop fully the rationale for the above conclusion here, but the general idea is as follows. International trade benefits all countries that participate, by allowing them to import goods in whose production they are relatively inefficient, and export goods in whose production they are relatively efficient. Imports are a necessary part of this process, and as such they benefit the United States rather than harming it.

Nevertheless, though it may at first seem paradoxical in view of the above general truths, it is possible in theory to benefit the United States by reducing U. S. imports. This can be done for all imports most easily by imposing a general tariff, or for imports of a particular good (such as a material) by imposing a specific tariff or quota. Where reduced imports of a particular material are planned, the rationale is generally that the United States is a large importer on the world market, and reduced U.S. imports can reduce the price at which the remaining imports are obtained. In effect, implementing such policies allows the United States to act monopolistically ("monopsonistically," to be more precise) with respect to its foreign suppliers. The United States does benefit, but foreign exporters lose even more than the United States gains.

The biggest problem with policies such as tariffs, particularly a general tariff on all imports, is that they invite retaliation. If other trading countries also reduce their imports, then all countries will typically be worse off than with no tariffs at all, simply because the greater international productive efficiency allowed by trade has been diminished. Recognizing these facts, the United States has often been a world leader in attempting to reduce international trade barriers, so that all countries benefit from more free trade. U. S. tariffs on material imports can be a useful response to the threat of particular market contingencies (as discussed earlier in this chapter), particularly where retaliation by foreign suppliers is not a problem. However, simply imposing trade barriers to improve the U. S. balance of trade largely represents a "beggar-thy-neighbor" policy that runs counter to the U. S. tradition of supporting free trade (continually threatened by special interest groups though the tradition may be).

Some of the same effect as a tariff on imports of materials could be achieved by EPA requiring that compliance with its regulations be achieved with less of an imported material, such as the platinum-group metals. It is unlikely such actions would invite retaliation in the way a tariff can, so, from a narrow perspective, some small economic gain to the United States could accrue. However, in order to obtain such monopolistic (monopsonistic) benefits, foreign prices for the remaining amount of U. S. imports must be driven down. The first requirement is that EPA decisions affect a large proportion of U. S. imports of the material. As we show later, EPA has this "leverage" only in the market for platinum-group metals. Moreover, in most major material markets, world supply is usually very price elastic in the long run, which means that a reduction in U. S. consumption (or in the growth of U.S. consumption) will cause only a very small decrease in the world price of the material, after suppliers have had a chance to ajust to the new situation. Thus, for example, the monopsonistic benefit to the United States of reducing platinum consumption would be very small because of the elasticity of supplies from South Africa.

There are exceptions to the above generalizations, however, particularly by product materials where demand reductions can lead to sizable price decreases. Among materials used for vehicular pollution control in the United States, the outstanding example is rhodium, which is a byproduct of platinum. Rhodium production is essentially at the limit imposed by current world platinum production, and rhodium is usually the most expensive commercial metal (per unit weight). If EPA eliminated U.S. rhodium consumption for vehicular emissions control, there would be a significant decrease in its price on the world market. It would be possible to do a careful calculation of the optimal extent to reduce U.S. rhodium consumption in order to realize the maximum monopsonistic gain for the United States. (If EPA decisions determined all of U.S. rhodium consumption, then the maximal monopsonistic gain to the United States would be obtained simply as a result of EPA recognizing the effect of its decisions on the price of rhodium when calculating compliance costs, as we have recommended.) However the gain to the United States would still be very modest, and it seems almost certain that EPA has more important policy concerns to occupy its attention. Moreover, regulating rhodium consumption downward would indirectly violate the U.S. tradition advocating free trade. (An interesting further aspect of the case of rhodium is that the parties most harmed by a reduction in U.S. imports would be platinum producers in South Africa.)

We have attempted above to make the most reasonable case we can for EPA being concerned with the implications of its policies for U.S. material imports and the balance of trade. However, in the final analysis we do not think it is of sufficient importance to warrant inclusion as a separate consideration in EPA policymaking. It will be hard enough for EPA simply to take into account such vagaries of international trade as changes in exchange rates among the U.S. dollar and other world currencies, as these affect the dollar cost of U.S. material imports, and hence compliance costs for EPA regulations. It is not really reasonable to expect EPA to design optimal monopsonistic importing policies as part of its decisionmaking.

A SIMPLE ECONOMIC MODEL FOR ESTIMATING CRITICALITY DUE TO FOREIGN SUPPLY DISRUPTIONS

The economic model we use in this chapter to estimate the criticality of materials used in vehicular emissions control equipment, is a slightly generalized version of the simple analysis of U.S. supply and demand curves that we described earlier in numerical terms for the imaginary material "catalystium." As in that example, we concentrate on materials criticality due to the threat of foreign supply disruptions, and calculate criticality from both the national perspective and the perspective of consumption for vehicular emmissions control.

KEY PARAMETERS AND FORMULAS

Figure 2-7 displays, with general algebraic motation, the linear supply and demand curves that are assumed to be relevant to each of the materials we consider. Key parameters of the criticality measurement, whose roles are explicitly indicated in Figure 2-7, are as follows:

P_0 = the normal world market price of the material

XP_0 = the world market price during disruption

Q_d = U.S. consumption at normal price P_0

Q_p = U.S. primary production at normal price P_0

Q_r = U.S. secondary production at normal price P_0

ε_d = the price elasticity of U.S. consumption

εp = the price elasticity of U.S. primary production

εs = the price elasticity of U.S. secondary production.

Other key parameters in the criticality measurement are the following:

D = the duration of disruptions, and

T = the time interval between (starts of) disruptions

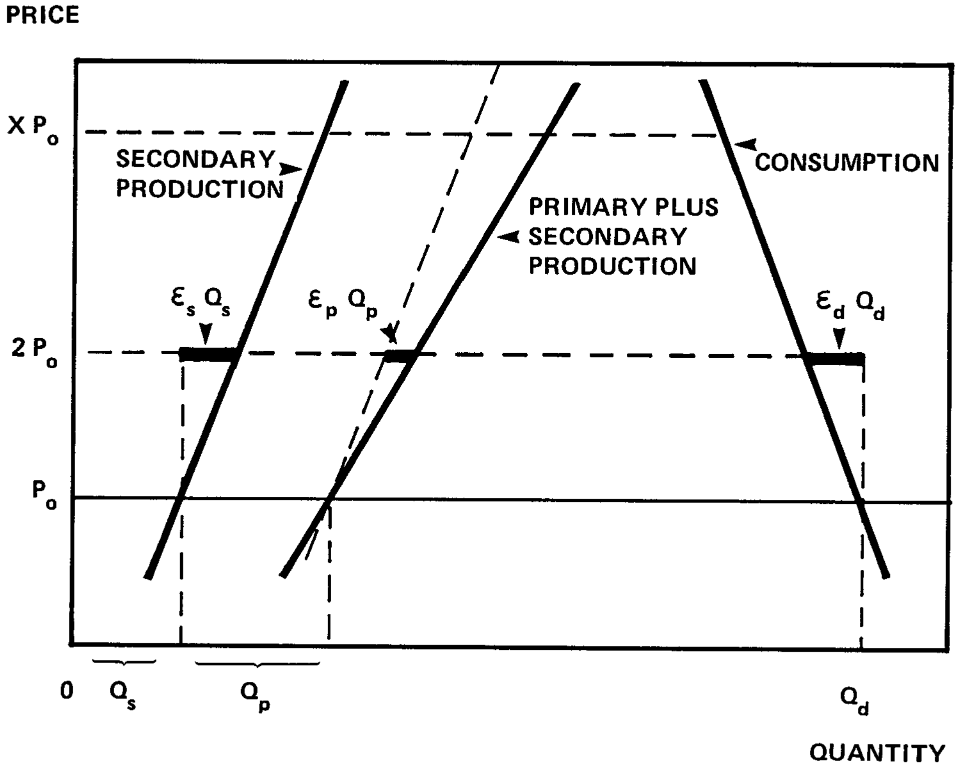
When we consider later the possible role of stockpiling, we must also specify

r = the "real" rate of interest (difference between observed nominal rates and the rate of inflation), and

e = the out-of-pocket expenses of stockholding, measured relative to the value of the material stockpiled.

Figure 2–7

MARKET MODEL FOR ESTIMATING CRITICALITY OF IMPORTED MATERIALS THREATENED WITH FOREIGN SUPPLY DISRUPTIONS



The price elasticity of U.S. consumption is the relative decrease in U.S. consumption that results from a doubling of the price. Thus, if a doubling of price causes a 10 percent decrease in consumption (as was the case for producers of emissions control equipment in the "catalystium" example dicussed earlier), $\varepsilon_d = 0.1$. Since we are assuming all demand (and supply) curves are linear, decreases in consumption resulting from larger price increases are proportionately greater. Thus, an X-fold increase in price during disruptions causes U.S. consumption to decrease to $Q_d [1-(X-1)\varepsilon_d]$.

The price elasticity of U.S. primary or secondary production is the relative increase in U.S. primary or secondary production that results from a doubling of price. Along linear supply curves, an X-fold increase in price causes U.S. primary production to increase to $Q_s [1-(X-1)\varepsilon_s]$.

Figure 2-8 reproduces the total U.S. demand and supply curves from Figure 2-7 and labels the loss areas that were explained in numerical terms for the catalystium example. Triangle 1 is the net cost consumers incur from reducing consumption by fraction $(X-1)\varepsilon_d$. The rectangle made up of Areas 2, 3, and 4 is the additional payment (or "transfer") consumers make to domestic and foreign suppliers due to the price increase. Rectangle 2 is the additional transfer to foreign suppliers. The rectangle made up of areas 3 and 4 is the additional transfer to domestic producers, of which Triangle 3 represents the additional cost of production (beyond the cost of importing the material at normal price P_0).

The first column of Table 2-1 translates the loss areas in Figure 2-8 into algebraic formulas convenient for performing the actual calculations. These formulas take into account the duration (D) and frequency (1/T) of disruptions, to give average expected losses per year. All losses are expressed as multiples of market values observable in normal times. For example, U.S. consumers' losses are a multiple of the value of their consumption in normal times (P_0Q_d). "Losses" of primary and secondary producers are generally negative (that is, "gains"), because the transfer (a negative cost) is bigger than the adjustment cost by an amount represented in Figure 2-8 as Trapezoid 4. The losses of primary and secondary producers are expressed in Table 2-1 as multiples of the values of their production in normal tmes (P_0Q_p and P_0Q_s, respectively).

Average expected U.S. losses per year, netting gains by U.S. producers against the larger losses by U.S. consumers, are obtained by adding up the losses in the first column of Table 2-1. The result is our measure of the criticality of the material from a national perspective. We do not present

Figure 2–8

U. S. ECONOMIC LOSSES (AND GAINS) FROM
FOREIGN SUPPLY DISRUPTIONS

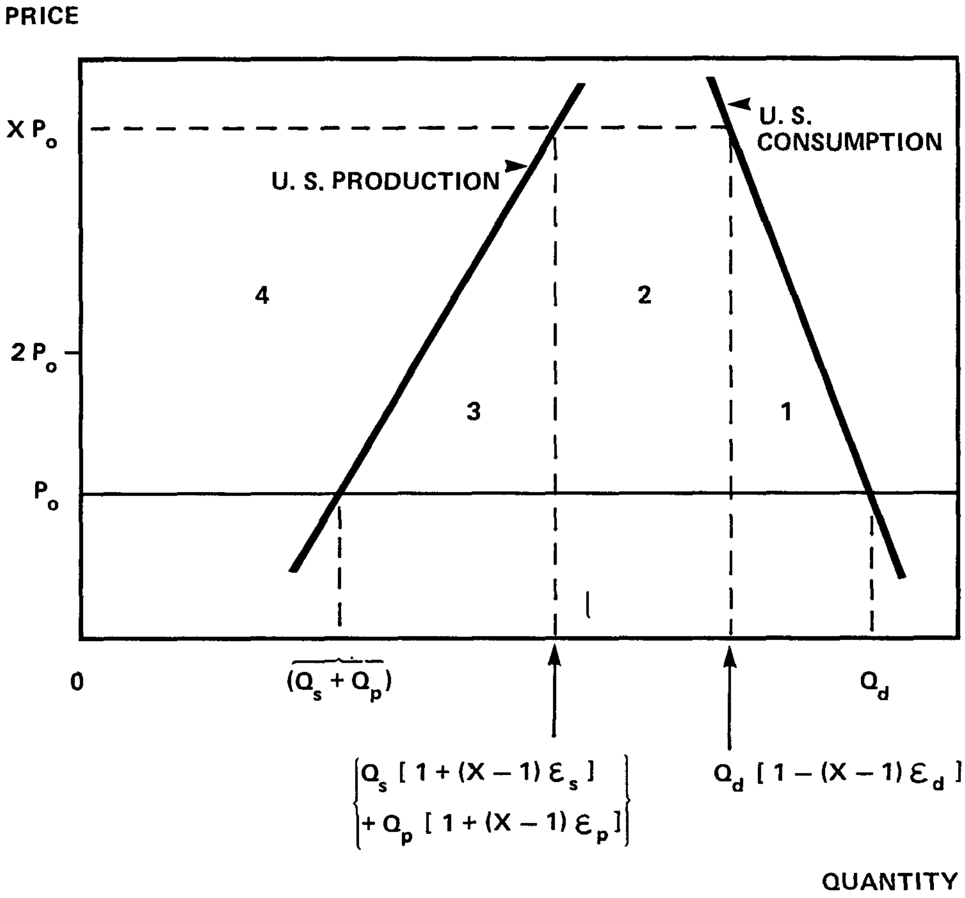


Table 2-1

FORMULAS FOR AVERAGE EXPECTED ANNUAL U.S. ECONOMIC LOSSES FROM FOREIGN SUPPLY DISRUPTIONS*

Economic Groups	No Stockpiling	Import-Eliminating Stockpile**	Comprehensive Stockpile
Consumers			
Adjustment (1)	$[P_oQ_d \frac{(X-1)^2}{2} \varepsilon_d]$ D/T	←	0
Transfer (2,3 and 4)	$\{P_oQ_d[(X-1)-(X-1)^2 \varepsilon_d]\}$ D/T	←	0
Primary Producers			
Adjustment (3, part)	$[P_oQ_p \frac{(X-1)^2}{2} \varepsilon_p]$ D/T	←	0
Transfer (3 and 4, part)	$\{-P_oQ_p[(X-1)+(X-1)^2 \varepsilon_p]\}$ D/T	←	0
Secondary Producers			
Adjustment (3, part)	$[P_oQ_s \frac{(X-1)^2}{2} \varepsilon_s]$ D/T	←	0
Transfer (3 and 4, part)	$\{-P_oQ_s[(X-1)+(X-1)^2 \varepsilon_s]\}$ D/T	←	0
Stock Holders			
Holding Cost	0	$(r+e)\ Po \left\{\begin{matrix} Q_d\ [1-(X-1)\ \varepsilon_d] \\ -Q_p\ [1+(X-1)\ \varepsilon_p] \\ -Q_s\ [1+(X-1)\ \varepsilon_s] \end{matrix}\right\} D$	$(r+e)\ Po\ (Q_d-Q_p-Q_s)\ D$
Acquisition Cost, Less Revenues	0	$-(X-1)\ Po \left\{\begin{matrix} Q_d\ [1-(X-1)\ \varepsilon_d] \\ -Q_p\ [1+(X-1)\ \varepsilon_p] \\ -Q_s\ [1+(X-1)\ \varepsilon_s] \end{matrix}\right\} D/T$	0

Table 2-1

FORMULAS FOR AVERAGE EXPECTED ANNUAL U.S. ECONOMIC LOSSES FROM FOREIGN SUPPLY DISRUPTIONS*

(Continued)

SOURCE: Charles River Associates, 1981.

*Appendix 2-B describes a simple computer program that performs these calculations.

**Arrows indicate that formulas are unchanged from the column to the left.

separate formulas for calculating economic losses from the persective of U.S. consumption for vehicular emissions control, because they are a special case of the formulas in Table 2-1. All that is required is setting U.S. primary and secondary production (Q_p and Q_s) equal to zero, and setting U.S. consumption (Q_d) equal to consumption for vehicular emissions control equipment, with the appropriate price elasticity (ε_d).

TREATMENT OF STOCKPILING

The economic model we are using is too simple to provide an adequate explanation of the holding of inventories and stockpiles. As discussed earlier, U.S. stockpiles can reduce U.S. losses during a disruption by reducing the amount of imports required. Stockholding of a material can be undertaken by U.S. producers, consumers, dealers, brokers, commodity exchanges, or in fact any private party that wishes to bear the expense of doing it, generally with the expectation of selling at some time in the future at a significantly higher price that covers holding costs. In Table 2-1 we treat U.S. stockpiling as a separate activity, even though it may be undertaken by consumers, primary producers, or secondary producers. (Consumers holding stocks can be considered to sell to themselves during disruptions.)

Table 2-1 allows the calculation of U.S. economic losses using three different assumptions about stocks. None of these three oversimplified assumptions about stocks will be exactly appropriate, but they provide useful perspective in the area where our analysis of materials criticality would otherwise be weakest. The formulas in the first column of Table 2-1, which we discussed above, calculate average expected U.S. economic losses per year assuming there is no U.S. stockpiling at all.

The formulas in the second column of Table 2-1 assume that the U.S. stockpile is sufficiently large so that the United States need not import any of the material during disruptions, but the domestic price is still equal to the world market price (XP_0) during disruptions. Thus, U.S. consumers and producers experience the same losses and gains as they did with no stockpile. (The arrows in the second column of Table 2-1 indicate where loss formulas are unchanged from the first column.) The difference between the two cases is that additional revenues that accrued to foreign suppliers during disruptions when there was no U.S. stockpile now accrue to U.S. stockpilers.

As explicitly indicated in the labeling of the quantity axis in Figure 2-8, the amount of U.S. imports during disruptions, measured at annual rates, is

$$\text{Annual Rate of Imports During Disruptions} = Q_d\,[1-(X-1)\varepsilon_d] - Q_p\,[1+(X-1)\varepsilon_p] - Q_s\,[1+(X-1)\varepsilon_s]$$

If disruption duration D is a half year, for example, the actual quantity of imports during the disruption will be half of the amount determined by the above formula, which we assume to be the quantity stockpiled in the second column of Table 2-1.

The "real" cost of holding a dollar of assets in the form of stockpiles (rather than in a form earning interest) is the "real" interest rate r, which we specify to be 6 percent ($r = 0.06$) for results reported in this chapter. The real interest rate is estimated as the difference between the "nominal" interest rate actually observed in money and capital markets, and the rate of inflation. Our use of an estimated real interest rate, to calculate the costs of holding stockpiles for a year, implies the reasonable assumption that the value of stockpiled material will rise at the same rate as the general rate of inflation in the U.S. economy, even in the absense of any supply disruption. All prices, values, and economic losses that we report in this chapter are in terms of constant 1981 dollars, that is, dollars deflated to adjust for future inflation (which raises the "nominal," but not the "real," prices of materials and most other goods.) (A real interest rate of 6 percent is approximate by historical standards. However, in 1981 real interest rates were unusually high in the United States. Nominal interest rates were nearly 20 percent per year, while general inflation was running at less than 10 percent per year, implying a real interest rate closer to 10 percent. Since the analysis we are doing here bears on policies over many future years, estimating future costs of holding stocks on a more normal historical basis seems appropriate.)

In addition to the real interest cost of holding stocks, there are out-of-pocket costs for management, warehousing, etc., that should in principle be included. For most materials, the interest cost is considerably larger, but we also allow for an annual out-of-pocket cost (e), per dollar value of stockpiled material. We generally just assume $e = 0.005$ for results reported in this chapter. The annual cost of holding the "import-eliminating" stockpile is thus

$$(r+e)\,P_0 \quad \begin{array}{c}\text{Annual Rate of Imports}\\ \text{During Disruptions}\end{array} \quad D$$

as entered under "Stock Holding Costs" near the bottom of the second column in Table 2-1.

In addition to holding costs, stockpilers of course also acquire the material during normal times at price P_0, and sell it during disruptions at price XP_0. The cost of acquiring stocks, net of revenues received from sale during disruptions, is

$$-(X-1)\,P_0\;\begin{array}{c}\text{Annual Rate of Imports}\\ \text{During Disruptions}\end{array}\;D$$

which will generally be negative because prices rise during supply disruptions (X>1). This negative cost, adjusted for the fact that it only occurs every T years, is entered under "Acquisition Cost, Less Revenues" at the bottom of the second column in Table 2-1. This amount would accrue to foreign suppliers if there were no U.S. stockpile, as assumed in the first column of Table 2-1, but with an import-eliminating stockpile it accrues to U.S. stockholders instead. If the acquisition costs, less revenues from sales during disruptions (on an annual average basis), is more *negative* than the holding cost per year is *positive*, then holding stocks in *anticipation* of the contingency is profitable, and U.S. economic losses are reduced by stockpiling. (If disruptions are sufficiently mild or infrequent, it may not be profitable to stockpile, in which case total U.S. economic losses would not be reduced by stockpiling.)

A U.S. stockpile that would be sufficiently large to replace completely normal imports during foreign supply discriptions, and hence prevent any domestic price increases, clearly could not be profitable for private stockpilers. It would also be larger than the optimum stockpile that minimizes national losses (assuming it is not possible for the United States to export stockpiled material). Nevertheless, such a stockpile may be closer to the appropriate size than the "import-elminating" stockpile considered in the second in second column of Table 2-1. Thus, in the third column of Table 2-1 we consider a "comprehensive" stockpile, sufficient to make up for normal U.S. imports of $(Q_d\text{-}Qp\text{-}Q_s)D$ during the disruption. The cost of holding the stockpile is indicated in the third column of Table 2-1. All other entries in the third column are zero because there is no price increase during disruptions in the U.S. market. (U.S. consumers suffer no losses, U.S. producers experience no gains, and the revenue from sale of U.S. stockpiles just equals the acquisition cost.)

(There would be some justification for estimating U.S. materials criticality using estimates of actual U.S. stocks, rather than the hypothetical stock sizes considered in Table 2-1. However, available data on U.S. stocks are often incomplete, notably for the platinum-group metals, as discussed in Chapter 4. There are also theoretical reasons for considering the hypothetical stock sizes in a simple model that does not recognize any relationships between stock sizes and the severity of price increases during the specified foreign supply disruptions.)

A computer program to perform the simple calculations described in Table 2-1 is presented in Appendix 2-B.

MEANINGFULLNESS OF RESULTS FROM THE MODEL

It has undoubtedly occurred to the reader, before reaching this point in the analysis, that estimating the criticality of materials is a highly inexact science, particularly as regards specifying the severity, duration and frequency of disruptions threatening material markets. It can be instructive to review the history of supply disruptions and other contingencies in the markets of interest. But situations and threats change too rapidly for historical analysis to provide definitive results. For example, historically South Africa has been a quite reliable source of platinum-group metals, chromium, and other materials often identified as critical. And yet its reliability into the 1990s and beyond has been a source of concern to U.S. policymakers. Clearly we must often rely on quite subjective estimates of the likely severity, duration, and frequency of contingencies threatening particular markets in order to obtain the most relevant measures of materials criticality.

The results we report below are of course also limited by the simplicity of our economic model, and the fact that we are only specifying one type of market contingency. Clearly there is in fact some probability of any of a wide range of disruptions, characterized by different severities and durations. Nevertheless, our specification of a single, representative disruption (severity, duration, and frequency) for each market can still be a roughly valid basis for comparisons among markets. These specifications distill considerable CRA experience in analyzing contingencies in material markets using more sophisticated models. The results we report here are probably in the same ballpark as criticality estimates that would be obtained with much more extensive applications of much more sophisticated models. Moreover, the results reported here have the advantage that they clearly indicate the reasons that the criticality of materials used for vehicular emissions control equipment differ so markedly.

For the U.S. Department of the Interior, CRA has been working on a quite sophisticated model specifically designed to simulate reliably much more severe disruptions in the platinum and palladium markets than have occurred historically. Elements of this model are discussed in Chapter 4. The model is dynamic, so that, for example, the longer a disruption lasts the more consumers can adjust away from materials that have become more costly. The linkage between past consumption of plantium and palladium and current secondary recovery is explicitly recognized. Supply and demand conditions abroad, as well as in the United States, are recognized so that, for example, it is possible to estimate the extent to which greater U.S. stockpiles will

Table 2-2

MATERIALS USED FOR VEHICULAR EMISSION CONTROL:
CRITICALITY FROM A NATIONAL PERSPECTIVE.

Material (form)	Value of Normal U.S.			Price Elasticity of U.S.		
	Consumption P_oQ_d (\$ million)	Primary Production P_oQ_p (\$ million)	Secondary Production P_oQ_s (\$ million)	Consumption ε_d	Primary Production ε_p	Secondary Production ε_s
Platinum - Group						
Platinum (metal)	729.0	1.4	315.0	0.03	1.3	0.015
Palladium (metal)	123.0	1.3	47.5	0.045	0.3	0.015
Rhodium (metal)	76.0	0.2	23.8	0.03	0.4	0.015
Other Materials						
Chromium (ferro)	686.0	0	56.4	0.07	0	0.05
Manganese (ferro)	792.0	14.4	0	0.04	0.1	0
Nickel (metal)	1,590.0	200.0	100.0	0.08	0.08	0.02
Titanium Metal (sponge)	253.0	0	11.0	0*	0*	0.01

*For titanium, the price elasticities of demand and primary supply are set equal to zero, as an (imperfect) adjustment for the fact that the specified contingency of concern involves an increase in demand creating a processing bottleneck. See the discussion in the text.

Table continued on following page.

Table 2-2 (continued)

MATERIALS USED FOR VEHICULAR EMISSION CONTROL:
CRITICALITY FROM A NATIONAL PERSPECTIVE.

	Supply Disruption			Expected annual U.S. losses ($ million/year) with		
Material (form)	Severity (Proportional Increase in World Price) X	Duration D	Expected Time Between Disruptions T	No Stockpiling	Import-Eliminating Stockpile	Comprehensive Stockpile
Platinum - Group						
Platinum (metal)	7	2.5	20	246.0	103.0	67.0
Palladium (metal)	6	2.5	20	36.0	17.0	12.1
Rhodium (metal)	7	2.5	20	32.9	11.9	8.5
Other Materials						
Chromium (ferro)	5	2	20	211.0	96.1	81.8
Manganese (ferro)	4	1.5	20	164.0	77.3	75.8
Nickel (metal)	3	1	15	152.0	84.4	83.9
Titanium Metal (sponge)	3	1	15	32.3	15.7	15.7

SOURCE: Charles River Associates, 1981.

Table 2-3

MATERIALS USED FOR VEHICULAR EMISSION CONTROL: CRITICALITY FROM THE PERSPECTIVE OF THAT END USE

	Vehicular Emission Control		Supply Disruption		
Material (form)	Value of U.S. Consumption $P_oQ_d^*$ ($ million)	Price Elasticity of Consumption ε_d^*	Severity (Proportional Increase in World Price) X	Duration D (years)	Expected Time Between Disruptions T (years)
Platinum - Grown					
Platinum (metal)	280.0	.03	7	2.5	20
Palladium (metal)	18.7	.03	6	2.5	20
Rhodium (metal)	18.0	.03	7	2.5	20
Other Materials					
Chromium (ferro)	10.0	0.25	5	2	20
Manganese (ferro)	0.3	0.33	4	1.5	20
Nickel (metal)	2.0	0.5	3	1	15
Titanium Metal (sponge)	3.8	0.5	3	1	15
TOTAL	332.8	-	-	-	-

Table continued on following page.

Table 2-3 (continued)

MATERIALS USED FOR VEHICULAR EMISSION CONTROL:
CRITICALITY FROM THE PERSPECTIVE OF THAT END USE

	Expected Annual Consumers Losses ($ million/year) With		
Material (form)	No Stockpile	Import-Eliminating Stockpile	Comprehensive Stockpile
Platinum - Grown			
Platinum (metal)	191.0	56.2	45.5
Palladium (metal)	10.8	3.5	3.0
Rhodium (metal)	12.3	3.6	2.9
Other Materials			
Chromium (ferro)	2.00	2.00	1.30
Manganese (ferro)	0.03	0.03	0.03
Nickel (metal)	0.13	0.13	0.13
Titanium Metal (sponge)	0.25	0.25	0.25
TOTAL	216.51	65.71	53.11

SOURCE: Charles River Associates, 1981.

diminish the severity of price increases on the world market during disruptions. We had hoped to be able to report results from these sophisticated platinum and palladium models in this study, but unfortunately appropriate results are not yet available.

On the other hand, there are definitive advantages to applying the same simple model to all markets. The model used here, though simple, recognizes all of the potentially crucial determinants of materials criticality. Moreover, these determinants can be tabulated to indicate readily why expected economic losses are much different in one case versus another. For present purposes, clarity and organized analysis of the issues are undoubtedly more important than refined estimates of the second digit of the criticality measure.

SAMPLE ESTIMATES OF THE CRITICALITY OF PLATINUM, PALLADIUM, RHODIUM, CHROMIUM, MANGANESE, NICKEL, AND TITANIUM METAL

As explained in some detail above, the most useful measure of the criticality of a material is expected losses (usually predominantly economic) associated with the threat of various market contingencies, the most important of which often involves disruptions of foreign sources of supply. Expected economic losses can be calculated from the perspective of the nation as a whole, netting gains and losses of domestic producers and consumers, or from the perspective of a particular end use, such as control of vehicular emissions.

Table 2-2 presents sample estimates of the criticality -- from a national perspective -- of seven elemental materials used for vehicular emissions control in the United States, using the economic model described in Table 2-1. The required parameter estimates are presented on the first page of Table 2-2, and expected economic losses (calculated under three different assumptions about stockpiles that will be available during the contingency) are presented on the second page.

Table 2-3 presents the corresponding criticality estimates calculated from the perspective of consumption for vehicular emissions control. The severity (X), duration (D), and frequency (1/T) of the market contingency are repeated from Table 2-2.

In the following discussion, we first explain our projections of the values of consumption and production for the seven raw materials. Then we specify price elasticities of consumption and production, and the severity, duration, and frequency of a representative contingency threatening each market. Given these parameters of the criticality calculation, we finally interpret the resulting estimates of expected economic losses given in the last three columns of Tables 2-2 and 2-3, and draw out the policy implications for EPA.

NORMAL CONSUMPTION, PRODUCTION, AND PRICES

The parameter estimates in Tables 2-2 and 2-3 are designed to be roughly appropriate for the mid-1980s in the United States. Trend projections of total U.S. consumption and production under normal conditions were obtained from *Mineral Trends and Forecasts*, U.S. Bureau of Mines (1979). Appropriate *estimates of other parameters are* much more uncertain than these quantities, so any reasonable projections of total U.S. consumption and production are adequate for our purposes.

Total U.S. primary production (Q_p) includes only production from domestic raw materials. Total U.S. secondary production (Q_s) includes only production from *old* or *obsolete* scrap. Production from new scrap, generated by *processing before materials* are sold in final goods (to consumers, investors, or the government), is not explicitly considered because its supply can usually not be expanded significantly, even under the incentive of much higher prices for the material. Correspondingly, total U.S. consumption (Q_d) includes consumption out of primary production and old scrap, but consumption of new scrap is netted out. (For platinum, palladium, and rhodium, the estimates of secondary production (Q_s) and total consumption (Q_d) from U.S. Bureau of Mines (1979) have been roughly adjusted upward by CRA to include "toll refining" of the metal, where secondary refining of used metal is undertaken on a fee-for-service basis, with the consuming industry retaining ownership.)

The values of materials reported in Tables 2-2 and 2-3 are based upon the following market prices, projected to be roughly appropriate for normal market conditions in the mid-1980s:

- Platinum : $450 per troy ounce of metal
- Palladium : $95 per troy ounce of metal
- Rhodium : $475 per troy ounce of metal
- Chromium : $940 per short ton of elemental chromium contained in ferrochromium
- Manganese : $480 per short ton of elemental manganese contained in ferromanganese
- Nickel : $5,700 per short ton of metal
- Titanium Metal : $11,000 per short ton of metal in the form of sponge.

These prices (labeled P_0) are measured in constant 1981 dollars, so that inflation has no direct effect on the values reported in Tables 2-2 and 2-3. (For simplicity, these values (that is, price P_0 times quantity produced or consumed) are calculated as though *all* of U.S. production or consumption is processed through the indicated form of the material; this assumption is least appropriate for chromium, where a majority of U.S. consumption indeed requires production of ferrochromium or similar ferroalloys, but a substantial proportion of U.S. consumption does not.

The first column of Table 2-3 estimates the value of U.S. consumption of each of the seven elemental materials for vehicular emissions control in 1985 to 1987. The prices specified above (P_0) are applied, while quantities consumed (Q_d^*) were projected by Rath & Strong, as described in Chapter 3. We should note one limitation of the Rath & Strong estimates for the purposes of this study. Regulations imposed by the U.S. Environmental Protection Agency significantly affect consumption of platinum-group metals and other critical materials by *foreign* manufacturers who export vehicles to the U.S. market, as well as consumption by U.S. manufacturers. It is very likely that increased costs of critical materials would be largely passed on to U.S. consumers, so that our methodology for measuring the criticality of materials should in principle be extended to recognize U.S. imports of materials already in automobiles or parts. Unfortunately, neither the data from Rath & Strong, nor general market data provided by the Bureau of Mines and other federal agencies, are readily adaptable to this purpose, so we do not perform those calculations here.

The value of U.S. consumption for vehicular emissions control ($P_0Q_d^*$) projected in Table 2-3, and the value of total U.S. consumption (P_0Q_d) projected in Table 2-2, indicate the "leverage" that decisions by the Environmental Protection Agency could have on various material markets. Consumption for vehicular emissions control, as a percentage of total projected U.S. consumption is as follows for each of the markets:

- Platinum : 38.4 percent
- Palladium : 15.2 percent
- Rhodium : 23.7 percent
- Chromium : 1.5 percent
- Manganese : 0.04 percent
- Nickel : 0.13 percent
- Titanium Metal : 1.5 percent

Clearly leverage is greatest in the market for platinum, and is negligible for the four alloying elements.

CONTINGENCY THREATS AND PRICE ELASTICITIES

We now consider briefly major contingencies threatening the markets for the seven elemental materials used for vehicular emissions control, and specify the severity, duration, and frequency of a representative contingency (usually a foreign supply disruption) threatening each. The parameter estimates are reported in Tables 2-2 and 2-3. As discussed earlier, specification of a single contingency can only begin to characterize the range of possible events in various material markets. Our main concern is that the relative sizes of the single disruption threats be roughly appropriate when comparing one market with another, and that the resulting measure of expected U.S. economic losses be in the right ballpark. In the following discussion of each market we also specify all elasticities that characterize the responsiveness of U.S. consumption and production to much higher market prices.

PLATINUM, PALLADIUM, AND RHODIUM

As discussed at greater length in Chapter 4, western consumption of the platinum-group metals is supplied predominantly by South Africa and the Soviet Union. There is clearly the potential for a very severe cutoff in primary world supplies. Almost all platinum-group mining outside South Africa is a byproduct of nickel and copper which implies that output from alternative sources would not expand significantly in response to larger increases in the price of platinum-group metals.

Moreover, the demand for platinum-group metals tends to be very unresponsive to price increases. We estimate in Chapter 4 that a five-fold price increase would only cut platinum and rhodium consumption by 12 percent, and palladium consumption by 18 percent. That is,

$$\varepsilon_d = (0.12/4) = 0.03 \text{ for platinum and rhodium}$$

and

$$\varepsilon_d = (0.18/4) = 0.0045 \text{ for palladium}$$

The major consideration mitigating the severity of disruptions in world supplies of platinum, palladium, and rhodium is secondary recovery. There are very large quantities of these metals currently in use as catalysts, and in other applications where a very high percentage can be recycled. During disruptions in primary supplies, the natural operation of the price system would redirect some of this recycled material toward the most critical end uses (that is, to those uses that are willing to pay the most for the material). However, because secondary recovery is already so extensive in the platinum-group markets, there are only very modest opportunities to expand recyling during emergencies. We specify secondary recovery elasticity ε_S= 0.015 for all three platinum-group metals under consideration.

For purposes of the sample criticality measurements in Tables 2-2 and 2-3, we specify a seven-fold price increase (X=7) for platinum and rhodium during disruptions. We specify the probability of a disruption to be sufficiently high so that the expected time between disruptions is T = 20 years. Because South Africa or the Soviet Union could be cut off from the United States for a long time, we specify disruption duration D = 2.5 years. For palladium we specify a somewhat less severe price increase during disruptions (X=6) because, worldwide, price responsiveness is somewhat greater on the demand side (and perhaps even on the supply side) of the market.

There may be significant mining of platinum-group deposits at the Stillwater complex in the United States by the 1990s, but we do not factor that possibility into our analysis. It would not be possible to create entirely new underground U.S. capacity quickly enough after a supply disruption has started to produce much during the first two or three years of the disruption, but existing or abandoned sources, especially placer deposits and the old mine at Goodnews Bay, Alaska, could be expanded or activated fairly quickly. The Goodnews Bay deposit yields almost entirely platinum, and its reactivation justifies a large primary supply elasticity for platinum in the United States. We specify ε_p = 1.3 for platinum. There is actually more rhodium than palladium in the Goodnews Bay deposits, justifying a slightly higher overall U.S. supply elasticity for rhodium. We specify ε_p = 0.3 for palladium and ε_p = 0.4 for rhodium. These price elasticities of primary supply are quite large, but they have relatively little effect on the calculations because normal U.S. primary production is so low.

CHROMIUM

South Africa is the dominant producer of chromium for western markets. Neighboring Rhodesia produces substantial quantities of high-grade ores suitable for metallurgical applications. Turkey and the Phillippines also produce substantial quantities. The Soviet Union formerly exported large amounts of chromium to the West, but in recent years Albania has become the important Communist exporter to the West. A complete disruption in southern

Africa (South Africa and Rhodesia) would eliminate a large proportion of western supplies and cause substantial, sustained price increases on the world market. We specify disruption severity X = 5 for common grades of ferrochromium, and disruption duration D = 2 years. We specify the time between disruptions to be T = 20 years, the same as for the platinum-group metals, which are also obtained from South Africa and Communist countries.

The United States does not produce significant amounts of primary chromium under normal market conditions. A severe disruption such as that specified in Tables 2-2 and 2-3 would induce some production from small U.S. deposits in California and elsewhere, but our results would not be changed significantly by recognizing this complication, so we simply specify $\varepsilon_p = 0$. (A slightly generalized version of the economic model would be required to recognize zero production at normal prices, with significant production beginning at some higher price.)

Chromium is used predominantly for stainless steel and other steel alloys. It is also used for refractories and in chemicals without first being processed into ferrochromium. Consumption for chemicals is most responsive to price changes, while consumption for stainless steel is least responsive. There are very limited opportunities for reducing the chromium content of stainless steels while still retaining the corrosion resistance at higher temperatures required for the most demanding applications of stainless steel. However, less than 20 per cent of stainless steel consumption is for demanding applications such as turbines, while many other end uses could substitute coated steels, plastics, and other materials. A five-fold increase in the price of ferrochromium corresponds to roughly an 80 per cent increase in the price of stainless steel, which would lead to substantial conservation of stainless steels. Such a large price increase would reduce chemical consumption of chromium by considerably more than half. We specify the overall U.S. price elasticity of demand for chromium (valued in the form of ferrochromium) to be $\varepsilon_d = 0.07$.

Approximately eight per cent of U.S. chromium consumption is from secondary sources, predominantly scrapped stainless steel used to make new stainless steel. There are modest opportunities for increasing stainless scrap recovery, for example by more carefully sorting stainless scrap from the more common types. (A CRA pundit once remarked that there might also be significantly increased recovery of stainless steel hubcaps through illicit channels.) We specify the price elasticity of secondary supply to be $\varepsilon_s = 0.05$.

MANGANESE

The Soviet Union produces more manganese than any other country by a considerable margin, but uses the material intensively in its domestic steel industry, and exports little to the West. South Africa is by far the largest exporter to the industrialized western countries, followed by Brazil, Gabon, Australia, and India. Southern Africa is not as important in the manganese market as in the chromium market, and there are a larger number of alternative suppliers with more extensive possibilities for expanding production. Thus, we specify the disruption severity to be less (X = 4) and the disruption duration less (D = 1.5 years). We keep the same disruption frequency as for the other materials obtained from South Africa (time between disruptions T = 20 years).

Well over 90 percent of U.S. consumption of manganese is for steelmaking, where it is an indispensable constituent of virtually all steels. There is a small amount of flexibility in the quantity of manganese used per ton of steel, and there could be a small amount more if manganese specifications for steels were modified to reflect technologically minimal needs under the current state of the art of steelmaking. Also, manganese that occurs naturally in many iron ores and in steel scrap, and is normally lost in processing, can be conserved by such procedures as slag recycling. We specify the overall U.S. demand elasticity to be $\varepsilon_d = 0.04$.

Projected 1985 U.S. primary production of manganese is very modest, though it could probably be expanded substantially during a sustained serious disruption of foreign supplies. (The Bureau of Mines may be assuming some production from ocean nodules.) We specify the domestic price elasticity of supply to be $\varepsilon_s = 0.1$.

NICKEL

The most common cause of supply disruptions in the world nickel market has been labor strikes at Canadian mines, particularly at the dominant Canadian producer INCO. The Canadian market share has dropped greatly over the last two decades, to less than 40 per cent, so such labor unrest is less critical to the United States and other nickel importing nations than was earlier the case. Newer producers, such as Australia and the island of New Caledonia (an "overseas department" of France, in the southwestern Pacific Ocean) have been more stable, and in any case represent alternative sources of supply . (Canadian production of nickel is discussed briefly in Chapter 4, because Canadian production of platinum-group metals is predominantly as a byproduct of nickel.)

Strikes tend not to last for very long, in comparison with other sorts of contingencies, such as civil wars, so we specify disruption duration D = 1 year. Price increases during strikes will affect purchasers forced to go to the spot market more than those under undisrupted long-term contracts, so we specify the relative price increase to U.S. consumers to be only X = 3. However, we specify somewhat more frequent disruptions occurring on the average of every T = 15 years.

Nickel is used in stainless steels, alloy steels, nonferrous alloys, and is also used for electroplating. Limited substitution is possible, either through use of different alloys, or use of different types of materials altogether. We specify the U.S. price elasticity of demand to be ε_d = 0.08. (The appropriate elasticity would be somewhat greater if the disruption lasted longer than one year.)

U.S. primary production of nickel is modest, normally accounting for between 10 and 15 percent of U.S. consumption. There has been a fair amount of excess capacity in recent years, and production could probably be expanded significantly over the course of a year. We specify the U.S. price elasticity of supply to be ε_s = 0.08.

There is modest secondary production of nickel from obsolete scrap, with limited possibilities for expanding this recovery during periods of high nickel prices. We specify the price elasticity of secondary U.S. supply to be ε_s = 0.02

TITANIUM

The criticality of titanium is unlike that for the other metals we have considered, in that disruptions in supplies of the elemental raw material are not a serious threat, but processing bottlenecks can be. Most titanium is mined from deposits of the ore ilmenite, and is used in very mundane applications as a white pigment. Less than five percent of titanium is processed into a metallic "sponge" and then metal, the majority for applications in aerospace hardware. Some is also used in steel alloys. (Most metal is produced from the ore rutile, rather than ilmenite, though it is possible at slightly higher cost to make metal from ilmenite if the appropriate processing capacity has been constructed.)

The most likely bottleneck in the production of titanium metal is in the capacity to make sponge from rutile. In fact, world production was seriously constrained by sponge capacity in 1980 and 1981, causing a substantial increase in prices over long-run equilibrium levels. Under incentives of very high prices, new sponge plants can be built in a year or a year and a half. Thus, disruptions in the supply of titanium metal are not likely to last a long time. We specify duration D = 1 year. Consumers under long-run contracts with producers may not suffer a great deal, which affects our specification of a relatively low disruption severity X = 3.

By far the most common cause of insufficient sponge capacity is difficulty in predicting the demand for titanium metal, as determined by such factors as the rate of macroeconomic activity in industrialized countries and decisions about military spending. As discussed earlier, there is some question whether the threat of such common commercial contingencies truly qualifies a material to be considered "critical." Most of the same issues arise, but our very simple economic model is not really set up to analyze situations where the U.S. demand curve will likely be shifting outward when the contingency occurs. We ignore this analytical complication for the present analysis, except (as an imperfect adjustment) we specify negligible price elasticities of domestic demand and supply, $\varepsilon_d = 0 = \varepsilon_s$. In recent years the United States has imported increasing amounts of titanium sponge from Japan and the Soviet Union. Disruptions in these imports could also impose costs on the United States.

Only modest amounts of titanium metal scrap are generated from obsolete aircraft and chemical processing equipment. In most cases, scrappage of obsolete titanium equipment would not be accelerated simply because of higher scrap values, since titanium values are typically very small relative to the total value of the equipment. Thus, we specify a very small price elasticity of secondary production, $\varepsilon_s = 0.01$.

PRICE ELASTICITIES OF CONSUMPTION FOR VEHICULAR EMISSIONS CONTROL

We have not investigated in any detail the efficiency of substituting for 409 stainless steel and other alloys in emissions control systems. Substitution of materials such as aluminized steel has been proposed. The main cost imposed by such a substitution would apparently be reduced durability, necessitating replacement costs borne by car owners. EPA durability requirements might have to be relaxed to allow such a substitution. It is said that aluminized steels tested to date lasted less than half as long as 409 stainless steel in catalytic converters.

Under the price incentives that we assume to exist during disruptions (see Table 2-2), we suppose for purposes of calculations that use of any of these alloying materials can be eliminated (not necessarily simultaneously, however). The implied elasticities of demand for vehicular emissions control (ε_d) are as follows:

- Chromium: 0.25
- Manganese: 0.33
- Nickel: 0.5
- Titanium metal: 0.5

The above elasticity estimates should be regarded as illustrative rather than definitive.

For platinum, pallodium, and rhodium, we assume only very modest reductions in usage would be possible in response to six- and seven-fold price increases. For purposes of illustrative calculations, we specify price elasticity $\varepsilon_d = 0.03$.

ILLUSTRATIVE CRITICALITY ESTIMATES AND CONCLUSIONS

Having explained all the parameters required for the calculations, we can now compare the "criticality" (average annual ecoomic losses) for the seven elemental materials described in Table 2-2 (national perspective) and Table 2-3 (vehicular emissions control only). From a national perspective, platinum is the most critical of the materials considered, but chromium, manganese, and nickel have average annual losses that are of the same order of magnitude. The severity of the supply disruption threatening the platinum market is ameliorated considerably by the extensive secondary recovery of old material that takes place in the United States.

The value of normal U.S. nickel consumption is more than double that of any of the other materials, but the severity and duration of disruptions is not as great as for the other materials considered, and U.S. production, both from primary and secondary sources, is significant. Also, the price elasticity of demand is greater for nickel than for the other materials considered.

The value of U.S. manganese consumption is somewhat greater than the value of U.S. chromium consumption, but the greater severity of the disruption threat for chromium makes it the more critical material.

The criticality of palladium, rhodium, and titanium metal from a national perspective, is less than that of the other materials, largely because the value of U.S. consumption in normal times is less. The criticality of palladium and rhodium is substantially reduced by secondary recovery, while the representative contingency threatening the market for titanium metal ties with nickel for being the least severe of those specified.

The above conclusions about the relative criticality of the various materials hold whether losses are calculated assuming no stockpiling or very large stockpiles. (A comprehensive stockpile is usually only moderately larger than an "import-eliminating" stockpile, and both are large relative to the disruption threat.)

From the perspective of consumption for vehicular emissions control, platinum is the most critical material by more than an order of magnitude relative to any other material considered here. The value of platinum consumption dwarfs that for the other materials, and no other material faces a more severe disruption threat. The criticality of palladium, rhodium, and chromium is potentially significant but relatively low. The criticality of manganese, nickel, and titanium is negligible. The criticality of the alloying materials (chromium, manganese, nickel, and titanium metal) is lessened considerably by large price elasticities of consumption (ε_d), reflecting our assumption that alternative alloys (such as aluminized steels) could be used during such a truly severe supply disruption.

As noted earlier, the above calculations of the criticality of platinum, palladium, and rhodium, do not explicitly recognize the linkage between current consumption of the material and possibilities for future secondary recovery. In the case of platinum-group metals used for vehicular emissions control, consumption taking place in the late 1970s and 1980s will develop into a "rolling stockpile" of material that could considerably reduce U.S. vulnerability to foreign supply disruptions in the 1990s. When this consideration is fully taken into account, the criticality of platinum could be considerably less than estimated above. We have not projected the size of the U.S. rolling stockpile of platinum-group metals in this study. It will be a simple exercise with the model mentioned earlier that CRA has designed for the U.S. Department of the Interior.

The average annual losses from contingencies calculated in Tables 2-2 and 2-3 are much more illustrative than definitive, for reasons indicated throughout the discussions above. However, these calculations clearly provide the right types of information to guide policy decisions by the Environmental Protection Agency. We finish our discussion in this chapter assuming the criticality estimates in Table 2-3 are appropriate. It will be clear how to use any revised estimates that become available.

Consider in particular the menus of materials required for the currently projected emissions control technology as specified in Table 2-3. The total annual cost for that menu, where all the indicated material markets are in a normal state, is approximately $330 million per year. Expected annual losses from contingencies in the various material markets are approximately $50 million per year, assuming large stockpiles. (Private inventories are in fact typically substantial for the more critical materials; Chapter 4 describes stockpiles for the platinum-group metals.) Total expected annual costs for the menu of materials, including disruption costs, is thus approximately $380 million per year.

Suppose that an alternative emissions control technology presented itself, which was equally effective and otherwise like that described in Table 2-3, except that total expected annual costs for a substitute menu of materials (including expected losses from market contingencies) was less than $380 million per year. That alternative technology would have a lower overall expected cost than the currently projected technology using platinum-group catalytic converters.

We confirm in Chapter 6 that no new technology currently on the horizon has much promise of being more cost effective than platinum-group catalytic converters. The critical materials penalty of approximately $50 million per year constitutes only a very modest additional expected cost over the normal cost of $330 million for the indicated menu of materials, particularly when all the disadvantages of alternative control technologies are considered.

If a new, more cost-effective technology should be developed, we have reasonable confidence that the U.S. auto industry would choose that technology in a way that appropriately weighs the criticality of the required materials. The reasons for this conclusion were discussed earlier in the chapter. They can be summarized by saying that, in this case, there appears to be little reason for a significant discrepancy between the cost to private firms of complying with EPA regulations, and the cost to society. (This fortunate situation is not always the case for other EPA regulations.)

Moreover, assuming the U.S. auto industry believes that EPA emissions standards of a given stringency will be in effect for many years into the future, the industry should have sufficient incentive to undertake the amount of research and development that is appropriate to that stringency. The reason is analogous to that made above concerning appropriate private decisions about which materials to use: The cost reductions made possible by a new, lower cost emissions control technology would benefit the firm developing the new technology to an extent comparable to the total national benefit from reduced control costs. This optimistic conclusion, that U.S. firms will undertake the amount of research and development approximately appropriate for a given EPA standard, will, however, not hold if U.S. firms seriously doubt that the standard will be maintained into the future.

The preparations that the U.S. auto industry has made for disruptions in foreign supplies of platinum-group metals, particularly the size of stockpiles they maintain, may be inadequate if they expect that relaxation of EPA emissions standards can be arranged during those disruptions. As protection against this possibility, EPA might consider requiring U.S. vehicle manufacturers to hold specified minimum levels of inventories of platinum, palladium, and rhodium.

The fact that we can directly use our definition of materials criticality to choose compliance technologies having the lowest expected costs in the future shows that we are using the appropriate concept. The concept of materials criticality is designed to facilitate decisions about what materials to use and what policies (such as stockpiling and tariffs) to pursue, to protect that rate of consumption of critical materials which is deemed efficient. In this chapter we have emphasized the choice of materials to consume, but extensions of the same methodology are appropriate for choosing efficient stockpiles and tariffs. Earlier investigations have summarized appropriate variables for determining materials criticality, but few have fashioned a quantitative measure of criticality appropriate for direct inclusion in the decisionmaker's balancing of economic (and noneconomic) costs and benefits. Appendix 2-C, which is extracted from a 1978 CRA study, briefly surveys some of these alternative analyses. Other work in this area, particularly more recent work, is summarized briefly in the following Bibliographic Note.

BIBLIOGRAPHIC NOTE

To our knowledge, no other study has specifically addressed in any detail the issue of how a line agency of the federal government, without direct responsibility for materials policymaking, should factor the criticality of materials into its policymaking, for example where consumption of those materials could be greatly increased by the agencies' decisions. However, many other studies have treated in great detail more general aspects of the problem, such as what contingencies threaten what markets, and what national policies are most effective in reducing expected costs from contingencies. We briefly survey here (and in Appendix 2-C) studies that are particularly prominent, recent, unusual, or closely related to the analysis we have presented in this chapter.

The Office of Minerals Policy and Research Analysis at the U. S. Department of the Interior has taken important steps in recent years toward implementating the type of methodology that we recommend for measuring the criticality of materials. See Adams, White, and Grichar (1979), who consider the criticality of bauxite, cobalt, copper, iron, and nickel. The analysis by Adams, White, and Grichar is notable for considering a range of disruption severities and for formally surveying (by "modified Delphi" techniques) market experts to estimate disruption probabilities. An earlier methodological and empirical study by the same group at the Department of the Interior estimated expected economic costs from potential disruptions in the markets for aluminum, chromium, platinum, and palladium. See U.S. Department of the Interior (1975). This work was reviewed and revised in Charles River Associates (1977). Two shorter articles summarizing basic methodologies and conclusions are Adams (1977), and Burrows and Beggs (1977).

The CRA study that treats methodologies for estimating the criticality of materials in most general terms is Charles River Associates (1978). The chapter from that report which summarizes alternative methodologies for measuring the criticality of materials is reproduced as Appendix 2-C to this chapter. The most comprehensive CRA study in this area is the multi-volume Charles River Associates (1976), which estimated economic costs from problems in the markets for platinum, palladium, chromium, manganese, and three other non-energy materials, as well as the market for petroleum. Other CRA studies treating the criticality of materials which the United States imports, and appropriate policy responses at the national level, include: Charles River Associates (1977a), Charles River Associates (1976b), Charles River Associates (1976a), and Charles River Associates (1975). Much of the CRA work referred to above is summarized in the book Klass, Burrows, and Beggs (1980), which specifically treats the same material markets as Charles River Associates (1976).

Since World War II, a number of landmark studies of problems and contingencies affecting U.S. material markets have been conducted by government-sponsored commissions. Among the most prominent were the U.S. President's Materials Policy Commission (1952) and the National Commission on Materials Policy (1973). Most studies by major government commissions focused on general issues in mineral markets (such as resource depletion, possibilities for more recycling, appropriate amounts of research and development, and control of pollution from domestic mineral production), rather than specifically on the types of contingencies that make a material "critical." In the 1970s, several major government studies appeared that focused more particularly on those types of contingencies, particularly disruptions of foreign supplies. A short but useful example is the Special Report on Critical Imported Materials by the Council on International Economic Policy (1974).

The most sophisticated of the government studies undertaken in the 1970s was that by the National Commission on Supplies and Shortages (1976), which went into considerable depth on ways of improving federal policymaking on material markets at the national level. Also notable for breadth in covering issues affecting material markets, and appropriate policymaking at the national level, are drafts produced by the recent Domestic Policy Review of Nonfuel Minerals. See U.S. Department of the Interior (1979).

The third volume of U.S. Department of the Interior (1979) is entitled A Compendium of Issues, Options, and Recommendations Contained in Major Post-War Nonfuel Mineral Policy Studies. It is available through the Superintendent of Documents of the U.S. Government Printing Office. This large volume provides a comprehensive bibliography and a collection of key quotes from most of the significant studies of national policymaking for nonfuel minerals undertaken since 1945. It includes many references that we do not mention here because they are less directly relevant, less prominent, less incisive, or representative only of special interests. We recommend this source if more extensive bibliographic information than we provide here is desired.

The Brookings study by Tilton (1977) is to be recommended for sensible economic analysis of a broad range of contingencies and problems currently facing minerals industries.

A recent study conducted at Resources for the Future, Inc. evaluates contingencies in the markets for cobalt, chromium, manganese, aluminum, copper, lead, and zinc, concluding that only for chromium does the United States clearly face "undue vulnerability ... to contingencies that might either seriously disrupt supplies or cause sharp upward movement of prices, with consequent serious economic impact." No quantitative estimate of economic costs or the criticality of the various materials is developed, however. See Fischman (1979), p. 1, and also an abridged version issued in book form, Fischman (1980).

A study by Zabrowski and Lyle (1978) at the old Federal Preparedness Agency (now the Federal Emergency Management Agency) investigates certain characteristics of the input-output matrix for an economy that bear on the criticality of its material industries, as we would recommend measuring it. However, the analysis appears incomplete as a basis for choosing materials to utilize, or policies to ameliorate supply disruptions, in part because it does not consider the likelihood of contingencies of various severities.

A recent report by Kern O. Kymn (1980) at the U.S. Federal Emergency Management Agency is notable for assessing criticality of a material (steel is used as an example) stemming from labor strikes, rather than foreign supply disruptions.

It is worth noting that planning for contingencies affecting the price and availability of materials can be considerably more unwieldy than the situation faced by EPA in planning for vehicular emissions control. The principal investigator of this study recently participated in a panel for the National Materials Advisory Board, leading to the short report entitled Identification of Critical and Strategic Materials for Naval Combat Systems, NMAB (1981). Navy systems are so complex that it is inordinately costly to trace all the materials used back through third and fourth level vendors to the suppliers of the original raw materials, despite the fact that military purchases of components are much better documented than most commercial purchases. As a result, production bottlenecks can spring up in unexpected places in the chain of materials supply.

There are, of course, a multitude of sources of information and data on the markets for individual materials. Those for the platinum-group markets are reviewed in Chapter 4. Similar sources of information are available for chromium, manganese, nickel, titanium, and other potentially critical materials. Publications of the U.S. Department of the Interior provide particularly useful summaries of relevant information. The Annual Report of the Secretary of the Interior Under the Mining and Minerals Policy Act of 1970 usually provides a useful summary of policy issues in minerals markets that are considered most pressing at the national level. The U.S. Federal Emergency Management Agency (FEMA) makes quarterly (National Defense) Stockpile Reports to Congress, describing the operative legislation, the current status of the stockpile, goals for the future size of the stockpile, and recent activities (including a separately bound statistical supplement).

APPENDIX 2-A

AVAILABILITY OF MATERIALS FROM THE U.S. NATIONAL DEFENSE STOCKPILE

APPENDIX 2-A

AVAILABILITY OF MATERIALS FROM THE U.S. NATIONAL DEFENSE STOCKPILE

In this appendix we consider possible avenues by which materials can be released from the National Defense Stockpile for non-military contingencies. Our general conclusion is that an act of Congress would almost certainly be required to authorize release of materials required for vehicular emissions control during a non-military emergency.

The U.S. National Defense Stockpile was established just prior to World War II. Its sole objective is to "serve the interest of national defense." It is "not to be used for economic or budgetary purposes." The enabling legislation for the stockpiling, amended in 1979, further requires that the quantities of material stockpiled are to be "sufficient to sustain the United States for a period of not less than three years in the event of a national emergency." Stockpile goals are estimated by the Federal Emergency Management Agency (FEMA) as the difference between requirements for materials in wartime and the amount likely to be available, assuming some austerity in non-military consumption.

The Strategic and Critical Materials Stockpiling Act (as amended July 30, 1979) allows disposal of materials only under specified authorities, the most general of which is an act of Congress. The President can authorize disposals under more narrowly defined conditions. Perishable materials are to be "rotated" out of the stockpile to prevent deterioration. With prior notification of the Committees on Armed Services of the Senate and House of Representatives, the President can dispose of materials that are in excess of stockpile requirements, or that may deteriorate in value if not sold.

Beyond the above described types of stockpile releases, which are primarily designed for routine management of the stockpile, Section 7 of the Strategic and Critical Materials Stockpiling Act also grants the President more discretionary authority. In time of war declared by Congress, or in time of a declared national emergency, the President or his delegate may release materials specifically required for the national defense. The President also has the power during times other than declared emergencies or wars to release material specifically required for purposes of the national defense.

Historically, there have been 28 releases authorized by the President under Section 7; all but three of these were made during World War II, the Korean Conflict, or the Viet Nam Conflict. All releases under Section 7, including those made during wartime, have been made directly by the President, rather than through delegated authority. The three releases made at other times consisted of mercury (in 1956 and 1959) and asbestos (in 1979). The critical consideration in all these releases was that the material would be used directly for defense purposes. Since use of material for control of vehicular emissions ostensibly does not constitute application to national defense, it is highly doubtful that releases under Section 7 could be made by the President for that purpose.

It is conceivable that platinum-group metals or other material required for vehicular emissions control, might be available from the stockpile, because amounts held in excess of requirements are due to be sold. (There is no excess currently.) However, in this case the President is required to use competitive negotiation and formal advertising, unless prior explanation is made to Congress. In the usual case of competitive bidding, producers of emissions control equipment would have to vie with other consumers for the materials they wish to obtain.

There is one further avenue under which the President has in the past authorized releases from the National Defense Stockpile. Section 101(b) of the Defense Production Act of 1950 (as amended August 20, 1980), gives the President general authority to allocate materials in the civilian market when he finds:

> (1) that such material is a scarce and critical material essential to the national defense, and (2) that the requirements of the national defense for such material cannot otherwise be met without creating a significant dislocation of the normal distribution of such material in the civilian market to such a degree as to create appreciable hardships.

In two cases, historically, it has been found that operation of the defense priorities system has created sufficient "hardships" in the civilian market that releases from the national stockpile were justified. The materials released were argon gas and titanium. Since contingencies <u>other than</u> operation of the defense priorities system seem most likely to affect materials required for vehicular emissions control, this avenue for arranging releases from the National Defense Stockpile also does not promise to be very useful for meeting EPA related materials consumption in a non-military emergency.

The general conclusion that emerges from the above review of peacetime releases from the national stockpile is that almost certainly an act of Congress would be required to respond to the types of non-military contingencies that appear most likely in the market for platinum-group metals. This conclusion is particularly clear if EPA were to wish that the material be specifically allocated for use in vehicular emissions control equipment, rather than being put up for competitive bids among all consumers in the market. A FEMA official with whom we discussed the matter concurred with this conclusion.

APPENDIX 2-B

COMPUTER PROGRAM TO CALCULATE AVERAGE ANNUAL ECONOMIC LOSSES FROM CONTINGENCIES IN MATERIAL MARKETS

APPENDIX 2-B

COMPUTER PROGRAM TO CALCULATE AVERAGE ANNUAL ECONOMIC LOSSES FROM CONTINGENCIES IN MATERIAL MARKETS

This appendix lists a simple computer program designed to calculate the economic losses determining the criticality of a material. The very simple economic model upon which the program is based is described in the text of the chapter. The formulas applied are described fully in Table 2-1. The required criticality calculations can be performed by hand without difficulty, but the program is a convenience, particularly where one is interested in disaggregating losses according to whether they are suffered by U.S. consumers, primary producers, secondary producers, or stockholders. The numbers displayed in the following listing of the program and its output are for the "catalystium" example explained in the early part of the chapter.

The program is written in the BASIC language for the Tektronix 4052 computer, but should be readily adaptable to most other minicomputers. The program requires less than 8,000 bytes of core.

```
LIST
100 REM--PROGRAM TO CALCULATE MATERIALS CRITICALITY (EXPECTED ANNUAL
110 REM--ECONOMIC LOSSES FROM CONTINGENCIES)
120 REM--SAMPLE CALCULATIONS FOR IMAGINARY "CATALYSTIUM" MARKET
130 REM--VERSION 1, AUGUST 15, 1981, S. BEGGS
140 REM--PARAMETERS
150 REM--VALUE OF NORMAL U.S. CONSUMPTION FOR VEHICULAR EMISSION
160 REM--CONTROL ($ MILLION)
170 V1=1
180 REM--PRICE ELASTICITY OF U.S. CONSUMPTION FOR VEHICULAR EMISSION
190 REM--CONTROL
200 E1=0.1
210 REM--SUPPLY DISRUPTION SEVERITY (PROPORTIONAL INCREASE IN WORLD
220 REM--PRICE)
230 X=3
240 Z=X-1
250 REM--EXPECTED TIME BETWEEN (STARTS OF) DISRUPTIONS (YEARS)
260 T=10
270 REM--EXPECTED DURATION OF DISRUPTIONS (YEARS)
280 D=1
290 REM--VALUE OF TOTAL NORMAL U.S. CONSUMPTION ($ MILLION)
300 V2=2
310 REM--PRICE ELASTICITY OF TOTAL U.S. CONSUMPTION
320 E2=0.2
330 REM--VALUE OF NORMAL U.S. PRIMARY PRODUCTION ($ MILLION)
340 V3=0.1
350 REM--PRICE ELASTICITY OF U.S. PRIMARY PRODUCTION
360 E3=0.125
370 REM--VALUE OF NORMAL U.S. SECONDARY PRODUCTION ($ MILLION)
380 V4=0.3
390 REM--PRICE ELASTICITY OF U.S. SECONDARY PRODUCTION
400 E4=0.125
410 REM--STOCKHOLDING COST, PER $1 MILLION OF MATERIAL PER YEAR
420 REM--($ MILLION, AT NORMAL PRICES)
430 C=0.065
```

```
440 REM--CALCULATIONS FOR CONSUMERS PRODUCING VEHICULAR EMISSION
450 REM--CONTROL EQUIPMENT
460 I1=V1*E1*Z↑2/2/T*D
470 I2=V1*(Z-Z↑2*E1)/T*D
480 I0=I1+I2
490 REM--CALCULATIONS FOR THE UNITED STATES
500 J1=V2*E2*Z↑2/2/T*D
510 J2=V2*(Z-Z↑2*E2)/T*D
520 J0=J1+J2
530 K1=V3*E3*Z↑2/2/T*D
540 K2=-V3*(Z+Z↑2*E3)/T*D
550 K0=K1+K2
560 L1=V4*E4*Z↑2/2/T*D
570 L2=-V4*(Z+Z↑2*E4)/T*D
580 L0=L1+L2
590 H1=0
600 H2=0
610 H0=0
620 M0=J0+K0+L0+H0
630 M1=J1+K1+L1+H1
640 M2=J2+K2+L2+H2
650 PAGE
660 PRINT "EXPECTED U.S. ECONOMIC LOSSES FROM MARKET CONTINGENCIES"
670 PRINT "        ($ MILLION, AVERAGE PER YEAR)"
680 PRINT " "
690 PRINT " "
700 PRINT "ADDITIONAL COSTS FOR PRODUCERS OF VEHICULAR EMISSION"
710 PRINT "CONTROL EQUIPMENT (NO STOCKHOLDING)"
720 PRINT "    TOTAL = ";I0
730 PRINT "         ADJUSTMENT = ";I1
740 PRINT "         TRANSFER = ";I2
750 PRINT " "
760 PRINT " "
770 PRINT "U.S. LOSSES WITH NO STOCKPILE"
780 GOSUB 800
```

```
790 GO TO 1010
800 REM--SUBROUTINE TO PRINT OUT LOSS DISAGGREGATION
810 PRINT "     CONSUMERS"
820 PRINT "          SUBTOTAL = ";J0
830 PRINT "               ADJUSTMENT COST = ";J1
840 PRINT "               TRANSFER COST = ";J2
850 PRINT "     PRIMARY PRODUCERS"
860 PRINT "          SUBTOTAL = ";K0
870 PRINT "               ADJUSTMENT COST = ";K1
880 PRINT "               TRANSFER COST = ";K2
890 PRINT "     SECONDARY PRODUCERS"
900 PRINT "          SUBTOTAL = ";L0
910 PRINT "               ADJUSTMENT COST = ";L1
920 PRINT "               TRANSFER COST = ";L2
930 PRINT "     STOCKHOLDERS"
940 PRINT "          SUBTOTAL = ";H0
950 PRINT "               HOLDING COSTS = ";H1
960 PRINT "               ACQUISITION COST, LESS REVENUES = ";H2
970 PRINT "     U.S. TOTAL = ";M0
980 PRINT "          ADJUSTMENT & STOCKHOLDING COSTS = ";M1
990 PRINT "          TRANSFER (TO FOREIGNERS) = ";M2
1000 RETURN
1010 STOP
1020 PAGE
1030 PRINT "U.S. LOSSES WITH IMPORT-ELIMINATING STOCKPILE"
1040 H2=-M2
1050 M2=0
1060 H1=(V2*(1-Z*E2)-V3*(1+Z*E3)-V4*(1+Z*E4))*C*D
1070 H0=H1+H2
1080 M1=J1+K1+L1+H1
1090 M0=M1
1100 GOSUB 800
1110 STOP
1120 PAGE
1130 PRINT "U.S. LOSSES WITH COMPREHENSIVE STOCKPILE"
```

```
1140 J1=0
1150 J2=0
1160 J0=0
1170 K1=0
1180 K2=0
1190 K0=0
1200 L1=0
1210 L2=0
1220 L0=0
1230 H1=(V2-V3-V4)*C*D
1240 H2=0
1250 H0=H1
1260 M1=H1
1270 M2=0
1280 M0=M1
1290 GOSUB 800
1300 END
```

```
EXPECTED U.S. ECONOMIC LOSSES FROM MARKET CONTINGENCIES
         ($ MILLION, AVERAGE PER YEAR)


ADDITIONAL COSTS FOR PRODUCERS OF VEHICULAR EMISSION
CONTROL EQUIPMENT (NO STOCKHOLDING)
     TOTAL = 0.18
          ADJUSTMENT = 0.02
          TRANSFER = 0.16



U.S. LOSSES WITH NO STOCKPILE
     CONSUMERS
          SUBTOTAL = 0.32
               ADJUSTMENT COST = 0.08
               TRANSFER COST = 0.24
     PRIMARY PRODUCERS
          SUBTOTAL = -0.0225
               ADJUSTMENT COST = 0.0025
               TRANSFER COST = -0.025
     SECONDARY PRODUCERS
          SUBTOTAL = -0.0675
               ADJUSTMENT COST = 0.0075
               TRANSFER COST = -0.075
     STOCKHOLDERS
          SUBTOTAL = 0
               HOLDING COSTS = 0
               ACQUISITION COST, LESS REVENUES = 0
     U.S. TOTAL = 0.23
          ADJUSTMENT & STOCKHOLDING COSTS = 0.09
          TRANSFER (TO FOREIGNERS) = 0.14

STOP IN LINE 1010 PRIOR TO LINE 1020
```

```
U.S. LOSSES WITH IMPORT-ELIMINATING STOCKPILE
     CONSUMERS
          SUBTOTAL = 0.32
               ADJUSTMENT COST = 0.08
               TRANSFER COST = 0.24
     PRIMARY PRODUCERS
          SUBTOTAL = -0.0225
               ADJUSTMENT COST = 0.0025
               TRANSFER COST = -0.025
     SECONDARY PRODUCERS
          SUBTOTAL = -0.0675
               ADJUSTMENT COST = 0.0075
               TRANSFER COST = -0.075
     STOCKHOLDERS
          SUBTOTAL = -0.0945
               HOLDING COSTS = 0.0455
               ACQUISITION COST, LESS REVENUES = -0.14
     U.S. TOTAL = 0.1355
          ADJUSTMENT & STOCKHOLDING COSTS = 0.1355
          TRANSFER (TO FOREIGNERS) = 0

STOP IN LINE 1120 PRIOR TO LINE 1130
```

```
U.S. LOSSES WITH COMPREHENSIVE STOCKPILE
     CONSUMERS
          SUBTOTAL = 0
               ADJUSTMENT COST = 0
               TRANSFER COST = 0
     PRIMARY PRODUCERS
          SUBTOTAL = 0
               ADJUSTMENT COST = 0
               TRANSFER COST = 0
     SECONDARY PRODUCERS
          SUBTOTAL = 0
               ADJUSTMENT COST = 0
               TRANSFER COST = 0
     STOCKHOLDERS
          SUBTOTAL = 0.104
               HOLDING COSTS = 0.104
               ACQUISITION COST, LESS REVENUES = 0
     U.S. TOTAL = 0.104
          ADJUSTMENT & STOCKHOLDING COSTS = 0.104
          TRANSFER (TO FOREIGNERS) = 0
```

APPENDIX 2-C

EARLIER APPROACHES TO MATERIALS CRITICALITY

APPENDIX 2-C

EARLIER APPROACHES TO MATERIALS CRITICALITY

The following survey of earlier analysis of materials criticality is taken from Charles River Associates (1978). A few more recent studies are discussed briefly in the Bibliographic Note. The chapters preceding the following discussion (in its original report), discussed materials criticality in more general terms, including the application of more sophisticated economic models to the determination of materials criticality. However, the text of the present chapter is sufficient introduction to understand all important issues that are raised in this appendix.

Earlier studies of materials criticality have in the main had the same concerns which motivated the analysis we have presented above. In this chapter we discuss some of the more prominent of these earlier studies in light of the basic principles and economic modeling recommended in the previous two chapters. Examining the strengths and weaknesses of these earlier efforts from such a perspective also allows us to elaborate upon our earlier discussions and provide further examples.

Import Dependence

The most prominent area of policy analysis for which criticality measurements have been developed is undoubtedly that of foreign supply disruptions. This emphasis has been particularly pronounced since the formation of OPEC and the subsequent Arab oil embargo.

The typical first step toward investigating the criticality of imported materials is to rank the materials by the percentage of U.S. import dependence which each accounts for. A bar chart of such a ranking for the year 1972 is reproduced below as Figure 4-1.[1] U.S. import dependence for platinum group metals, chromium and cobalt was nearly complete, whereas only a moderate percentage of U.S. copper consumption had to be imported.

Although such a ranking of materials is useful, it obviously has limitations as a measure of criticality. The most obvious limitation of Figure 4-1 is the omission of information on the absolute size of the market. For example, although U.S. import dependence was slightly greater for tantalum than it was for aluminum (ores and metal), the absolute value of the aluminum ore imports is so much greater than the absolute value of the tantalum imports that there can be little doubt that aluminum is the more critical material.[2]

Chapter 3 of the present study is a good general guide to the many further relevant considerations which need to be included in a measurement of criticality, such as the probability of a disruption occurring and the existence of substitutes. It is worth reiterating a point previously made about the use of policy models for measuring materials criticality. If materials markets to be compared are assumed to be identical in all respects except the value of imports -- the same normal inventory/consumption ratio, the same price elasticities, the same disruption severity, the same disruption probabilities and so on -- then the resulting criticality loss measures are simply proportional to import dependence in absolute dollar terms.

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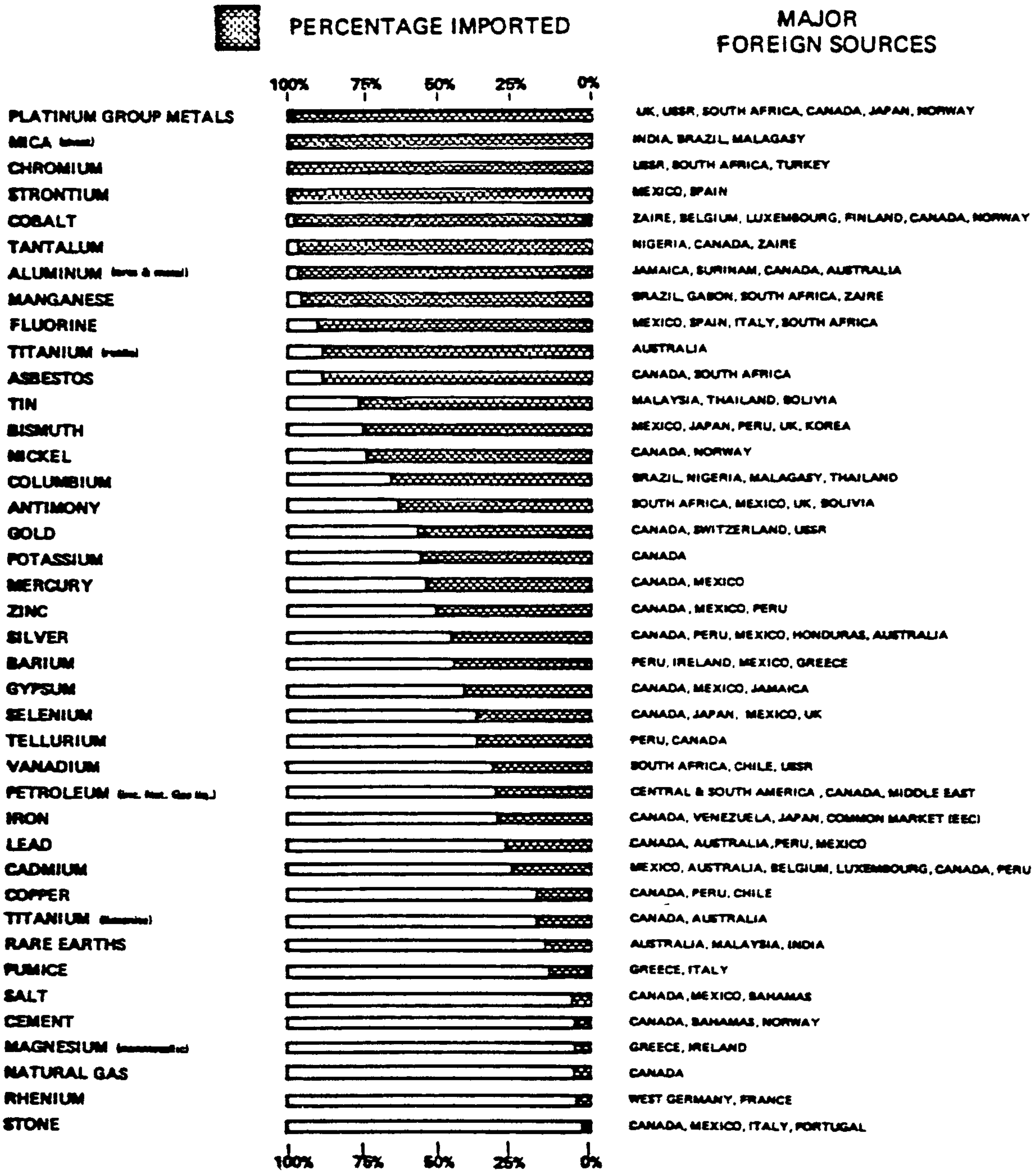
[1] This particular diagram is from National Commission on Materials Policy, *Material Needs and the Environment Today and Tomorrow*, Final Report (Washington, D.C.: U.S. Government Printing Office, June 1973), pp. 2-25. Similar charts have been produced by other investigators.

[2] On the other hand, measuring import dependence as a percentage of consumption does have the great advantage of indicating whether there are domestic producers who might expand production when foreign supplies are cut off.

Figure 4–1

PERCENTAGE OF U.S. MINERAL REQUIREMENTS IMPORTED DURING 1972



SOURCE: National Commission on Materials Policy, *Material Needs and the Environment Today and Tommorrow* (Washington D.C.: U.S. Government Printing Office, June 1973), p. 2–25.

Measuring Criticality Without Economic Models

Even if one's basic definition of materials criticality is much less explicit and detailed than that developed above in Chapter 2, it is not particularly difficult to identify many of the factors which determine such criticality. A number of studies have compiled comprehensive lists of determinants on a subjective basis, without constructing a formal economic model. Typically, cross tabulations of characteristics for various materials have been prepared, with summary index values calculated for each material by arbitrarily weighting the characteristics.

We will now review a few of the more important studies which have developed measures of materials criticality without the use of an economic model

Study by King and Cameron

One of the more detailed and formal efforts along these lines has been done by Alwyn King and John Cameron at the U.S. Army War College.[1] The list of observable factors which they considered relevant to determining U.S. vulnerability to foreign supply disruptions is reproduced below as Table 4-1.

In order to compute a summary measure of criticality, King and Cameron first assigned arbitrary numerical weights to large (L), medium (M) and small (S) effects on the materials' vulnerability for the factors listed in Table 4-1. Then the direction and magnitude of the factor's effect on the vulnerability of particular materials were also characterized by arbitrary weights. The two weights were multiplied in each cell of Table 4-1 and then added, first for "economic, political and military" considerations separately, and then for all three together. Each material investigated was treated in this fashion in turn.

---

[1] Alwyn H. King and John R. Cameron, "Materials and the New Dimensions of Conflict" (Carlisle Barracks, Pa.: U.S. Army War College, Strategic Studies Institute, May 15, 1974); Alwyn H. King, "Materials Vulnerability of the United States -- An Update" (Carlisle Barracks, Pa.: U.S. Army War College, Strategic Studies Institute, April 30, 1977).

Table 4-1

FACTORS AFFECTING COMMODITY RELATIVE VULNERABILITY INDEX, AS COMPILED BY KING AND CAMERON

L = Large
M = Medium
S = Small

Factor	Effect on Vulnerability		
	Economic	Political	Military
Domestic reserves:			
Availability	L	L	L
Cost of developing	L	L	S
Domestic production industry:			
Present capability	L	L	L
Cost of augmenting	L	L	S
Substitute materials:			
Present availability	L	L	L
Cost of research to develop	L	L	S
Time required to develop	L	L	L
Additional domestic resources:			
Present availability	L	L	L
Cost to develop suitable processes	L	M	M
Time to develop suitable processes	M	M	M
Probability of discovery if not available	M	M	S
Cost of additional exploration	M	M	S
Foreign suppliers:			
Number of controlling companies	L	S	M
Number of supplier countries	M	L	M
Political stability of supplier countries	M	L	M
Ideology of supplier countries	L	L	L
Productive capacity of supplier countries	L	L	L
Economic sufficiency of supplier countries	L	L	S
History of political relations with US	S	M	S
US dollar involvement in supplier country	M	M	S
Accessibility of supplier countries (supply routes)	S	S	L
US Stockpile:			
Present US stockpile objective	L	L	L
Actual quantity in US stockpile	M	M	M
Customary industry stockpile	M	M	M

Table continued on following page.

Table 4-1 (Continued)

FACTORS AFFECTING COMMODITY RELATIVE VULNERABILITY INDEX, AS COMPILED BY KING AND CAMERON

	Effect on Vulnerability L = Large M = Medium S = Small		
	Economic	Political	Military
Trend in usage of critical material	M	M	S
Proportion of national consumption directly related to military requirements	S	S	L
Importance of secondary sources (recycling)	M	M	M

SOURCE: Alwyn H. King, *Materials Vulnerability of the United States - An Update* (Carlisle Barracks, Pa.: U.S. Army War College, Strategic Studies Institute, April 30, 1977), p. A-2.

King and Cameron have only reported results for a truncated version of the above methodology based on a consideration of the following five factors: availability of domestic reserves; availability of substitutes; number of foreign suppliers; ideology of foreign suppliers; and U.S. stockpile objective. Also, they considered only eleven of the materials most likely to have high criticality ratings. Results, in rank order with their "vulnerability index ratings," were chromium (34), platinum group (32), tungsten (27), manganese (23), aluminum (22), titanium (20), cobalt (20), tantalum (16), nickel (14), mercury (11) and tin (6).[1] These results are intuitively plausible. However, applying the methodology to many more materials using all 27 factors in Table 4-1 could easily lead to questionable results since there is no overall economic theory underlying the analysis.

Relative Inclusiveness of the CRA Policy Model

It is interesting to compare King and Cameron's list of determining factors and subjective approach to materials criticality with the use of the CRA economic policy model described in Chapter 3. Both approaches are concerned primarily with foreign supply disruptions. Use of an economic model makes much heavier demands on the analyst when new factors are to be formally included in the methodology. However, the economic modeling approach described in Chapter 3 in fact includes explicitly or implicitly virtually all of the observable factors listed in Table 4-1. Furthermore, application of the economic model greatly enhances the value of this basic information by utilizing as accurate a quantitative specification as possible, and by translating this information into dollar loss figures, broken down by who gains and who loses. Thus, groups with differing interests and values have information in the most useful possible form for

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[1] King and Cameron, *op. cit.*, p. 17.

ordering their own priorities and for participating in the process of determining a national consensus on priorities and policies. The complexity and scope of the materials criticality problem is reduced in the most meaningful possible way by applications of an economic model.

In the remainder of this section we will consider the factors listed in Table 4-1 and evaluate how adequately they can be incorporated in the economic model described in Chapter 3. In some cases, a generalization of the model in Chapter 3 would allow somewhat fuller recognition of relevant circumstances (e.g., the depletion of reserves), but in general the available policy models can be very comprehensive if careful analyses precede specification of their parameters.

Domestic Reserves

U.S. reserves of the commodity under study should be important determinants of the domestic supply curve in the CRA policy model; however, it is not possible to infer directly the flow of domestic production from the stock of reserves. If reserve estimates were accurate and inclusive, it might be desirable to allow explicitly for backward shifts in the U.S. supply curve as the domestic resource base is depleted. However, reserve estimates only reflect the state of knowledge at a particular point in time, and historically depletion has been more than offset by discovery and technological change in most cases. Thus, the fact that the existing CRA policy model ignores depletion is usually not a serious omission, though it may be so in cases such as petroleum where the size of domestic reserves is relatively well known.

Domestic Production Industry

The present capability of the domestic production industry is indicated by the position of the short-run domestic supply curve. The cost of (gradually) augmenting domestic production capacity is indicated by the position of the long-run domestic supply curve relative to the short-run curve.

The intersection of the short-run and long-run domestic supply curve occurs at a single rate of production which can be referred to as the "capacity" of the domestic industry, though capacity in this sense represents an optimal adaption of industrial capital to the existing rate of production, not an upper bound on production.

Substitute Materials

The availability of substitutes under current technology is usually the primary determinant of the short-run and long-run price elasticities of demand in the CRA policy model. In many cases important "substitutes" for a material whose criticality is being investigated will be factors of production other than alternative materials. For example, labor may be substituted for a material such as manganese by increasing the attentiveness of workers controlling its consumption in steelmaking.[1]

Substitutions may also be made by consumers of final goods and services; when the price of a potentially critical material rises, consumers may decide to decrease their purchases of goods requiring its use. All these considerations

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[1] When the price of a material input shifts upward, an economist considers any factor of production which is consequently used in greater amounts to be a "substitute" for the material input. The engineer's definition of a "substitute" is much less general.

affect the "derived demand curve" for a raw material which enters the policy model. The demand curve for the raw material is characterized as "derived" because it can be determined from the demand curve for the final good and information about the substitutions which producers can make.

In the standard market model underlying the CRA policy model, changes in U.S. technology, such as development of new substitute materials, are theoretically represented as shifts in the demand curves. In practice, movements along a demand curve are often interpreted to include some minor predictable technological innovations and some efficiencies due to "learning by doing." The dynamic implications of such processes are captured in their relevant form in the CRA model by the short-run and long-run supply and demand curves, and by solving for the intersections of short-run and long-run curves which maximize firms' profits over time.

Domestic Resources

U.S. "resources," as opposed to "reserves," would become economical to exploit only at prices higher than normal. Thus, the shape of the domestic long-run supply curve is strongly affected by the existence of resources. However, unless a market disruption (such as the formation of OPEC) is expected to endure, it may not be efficient to exploit such resources because of the long lags between substantial investments and actual domestic production. If exploitation requires significant research and development, the same distinctions between dynamic adjustments in short-run curves and shifts of underlying long-run curves must be made on the supply side of the domestic market as were discussed above for the demand side of the market.

Foreign Suppliers

The number and nature of foreign suppliers of an imported material determine the probability of supply disruptions of various lengths and severities. There is in practice no reliable relationship between readily discerned characteristics of supplier countries and the probability of disruptions. The characteristics listed in Table 4-1 are suggestive in particular cases, but expert assessment of the overall disruption probability is undoubtedly much more reliable than subjective weighting of the tabled characteristics.[1]

Plausible disruption scenarios involving various producer countries can often be translated into effects on the world market price using econometric market models prior to application of a policy model; the effect of stock releases on the world market price during the disruption should also be estimated. The particular approach chosen depends on the market structure both in normal times and during the disruption. For example, the structure of the chromite market was fairly competitive in the 1950s and early 1960s, but some collusion among producing countries has occurred during the 1970s. A sharp cut-off of supplies from southern Africa would today encourage much greater collusion than that which has occurred since 1974. Thus, predicting world prices during such a disruption involved both constructing a cartel pricing model utilizing historical behavior patterns for consumers and suppliers who were assumed

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[1] One characteristic not explicitly mentioned in Table 4-1 involves distinguishing sources of supply as to whether or not they are controlled by less developed countries. Some investigators have made this distinction an important element in their analysis of materials criticality, but, as with the other characteristics, it is only part of the broader situation which determines the probability of disruptions of various severities and durations.

to remain competitive, and utilizing hypothetical behavior patterns leased on profit maximization for the suppliers who were assumed to collude.[1]

The situation described above for the chromite market in which there is a competitive market structure in normal times and monopolistic pricing during the supply disruption is typical. However, in analyzing a cutoff of cobalt supplies from Zaire due to the recent military conflict in Shaba Province, it was appropriate to reverse this pattern. Zaire normally exercises considerable monopolistic power as the price setter in the cobalt market. However, during a complete disruption of Zaire the "fringe" of competitive suppliers would become the only sources of supply and the market structure would hence become fully competitive. Determining a competitive price which clears the disrupted market by utilizing historical behavior patterns captured by the CRA econometric model then became appropriate.[2]

Before applying the policy model discussed in Chapter 3, it is appropriate to utilize formal market models in the manner illustrated above to determine the severity of plausible disruption scenarios in terms of world price increases. This formal modeling approach contrasts with the approach recommended earlier for determining the probability of a disruption beginning and continuing, when this probability must generally rely on a subjective evaluation of a multitude of relevant factors,

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[1] See Charles River Associates Incorporated, *The Report of the U.S. Department of the Interior on the Critical Materials Aluminum, Chromium, Platinum and Palladium: A Review and Revision* (Cambridge, Mass.: CRA, July 1977), Chapter 6.

[2] See Charles River Associates Incorporated, *Implications of the War in Zaire for the Cobalt Market* (Cambridge, Mass.: CRA, June 1977).

like those characteristics of foreign suppliers which are listed in Table 4-1. Expert opinions on probabilities are likely to differ significantly. However, the probabilities are readily interpreted intuitively and discussion of whether the chance of a disruption is one chance in four or one chance in forty over the next decade is much more incisive than an arbitrary weighting of a mixed bag of relevant considerations.

U.S. Stockpile

The size of industry and government stocks which are available during an economic disruption directly enters the determination of materials criticality when the CRA policy model is applied. Moreover, the specified size of stocks held by other consuming nations can be of crucial importance, though it is not listed in Table 4-1. In general, the preparedness of foreign consumers determines how aggressively they bid for remaining world production during a disruption, and hence affects the price at which imports can be obtained by the United States.

One of the significant advantages of applying a formal economic model to the determination of materials criticality is simply the identification of relevant considerations which may be overlooked if the structure of the problem is delineated more informally. Remembering to include the stocks of foreign consumers is a case in point.

In general, there is a vast economic literature on such problems as estimating supply and demand curves which can be drawn upon to improve criticality measurements. For example, the smaller the proportion of the cost of final goods which is accounted for by a potentially critical raw material, the less price elastic its demand will tend to be and hence the greater its criticality; formulas precisely specifying such relationships are often very useful for studies such as those we are recommending for determining materials criticality.

Trend in Usage

As importation of a material increases, the expected dollar loss which measures its criticality will generally increase as well. If the domestic quantities demanded, supplied, and stocked at the normal price increase proportionately, and if the price elasticities and other parameters remain constant, then expected dollar losses calculated with the CRA policy model will also increase proportionately. In general, of course, trends in various categories of end users can affect the price elasticity of demand for all categories combined, which appropriately summarizes the information required by the policy model; criticality loss measures would then not increase precisely proportionately with the quantity of total consumption.

At any time, the fact that there has recently been an unexpected change in the trend of usage can make an important difference in criticality ratings. A sharp increase in usage can leave world producers above the capacity point (where their short-run supply curve intersects their long-run supply curve), thereby limiting their ability to respond if other segments of the market are disrupted. On the other hand, an unexpected trend decrease in consumption can result in worldwide excess capacity and considerably lower estimates for criticality loss measures. As circumstances change, naturally criticality estimates should be periodically updated.

Military Consumption

The U.S. military does not consume large amounts of raw materials directly. However, its purchases of fabricated items do indirectly require sizable quantities of raw materials. If the military demand is to be considered a fixed requirement, e.g., because there is no suitable substitute for a critical application, then all of the elasticity in the U.S. demand curve will be due to decreases in civilian demand. Such a demand curve can be utilized in the usual fashion when the CRA policy model is applied to analyzing foreign supply disruptions. If a foreign supply disruption of concern is in fact a major military conflict involving the United States, then further issues are involved, as discussed elsewhere in this study.

Secondary Recovery

Secondary recovery decreases the amount of U.S. primary demand at each price, which is the appropriate input for the CRA policy model. In fact there are further ramifications to secondary recovery which can be of great importance in a few cases where rates of secondary recovery are very high and the lags between consumption and recovery are short. The prime example is platinum, which is largely used as a catalyst in petroleum refining and in chemical production.[1] In this case the amount of platinum in use is essentially a sizable stock which can be reallocated during disruptions.

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[1] The recovery rate for platinum used in catalytic converters for automobiles and in electrical equipment is also very high, but recovery lags are longer for this end use than for the other uses.

A special policy model has been designed at CRA for application to the platinum and palladium markets, where the most important precaution in the face of threatened foreign supply disruptions need be only some extra metal held "in use."[1] This platinum or palladium held "in use" is "extra" in the sense that using more of the metal as catalysts has benefits; however, these benefits would normally not justify the cost of purchasing the metal unless there was also a significant probability that the market price would increase after purchase (due to a foreign supply disruption in the present instance).

A BOM Tabulation

The study by King and Cameron is similar in format to a number of other cross tabulations of materials' characteristics relevant for measuring criticality. Not all such tabulations attempt to push the analysis so far toward subjective quantification of characteristics and computation of summary indices as do King and Cameron. One of the more graphic and authoritative of such cross comparisons has been constructed by John Morgan of the U.S. Bureau of Mines. It is reproduced below as Figure 4-2.[2]

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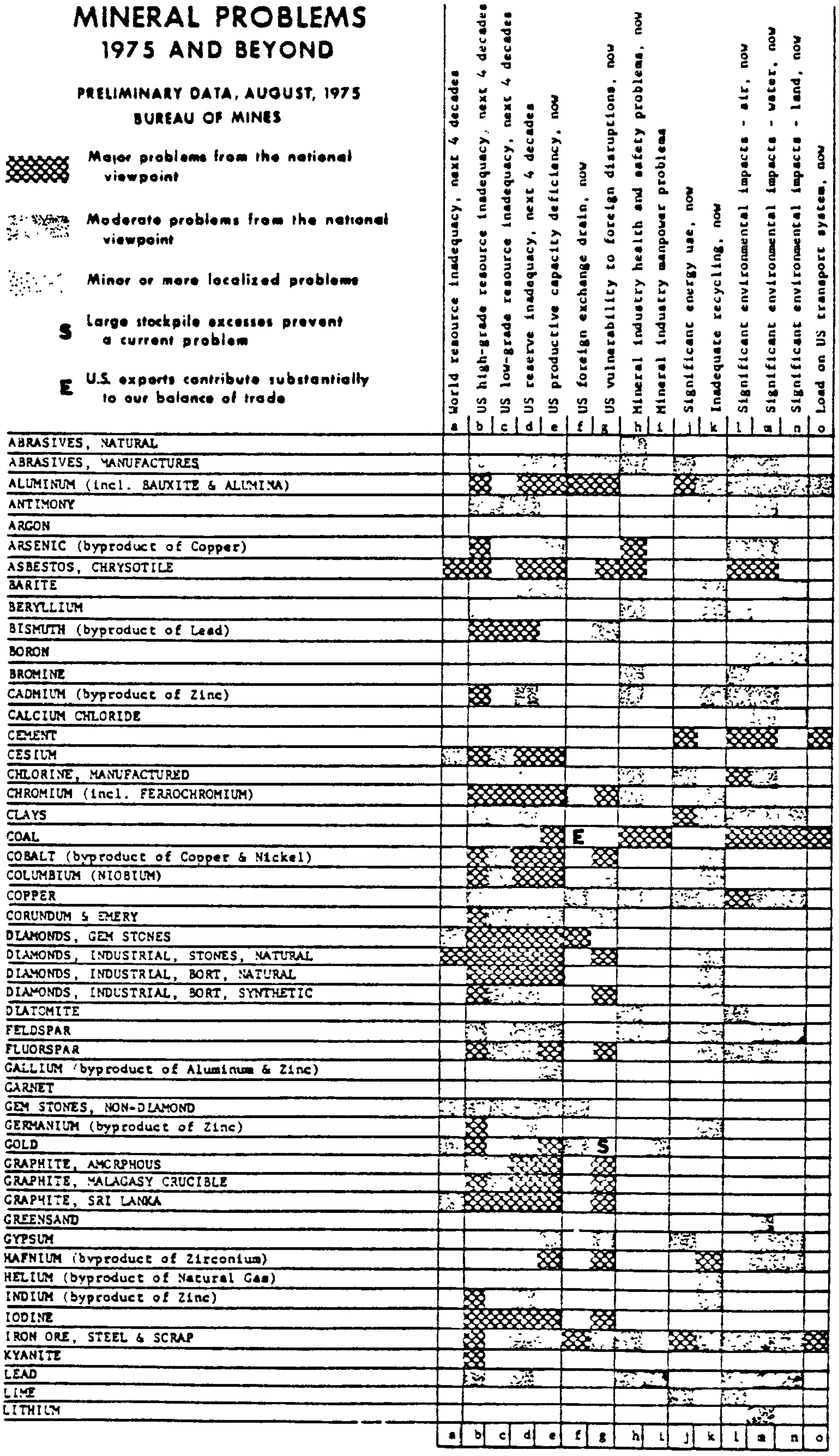
[1] See Charles River Associates Incorporated, *The Report of the U.S. Department of the Interior, op. cit.*, Chapters 9 and 10.

[2] See John D. Morgan, "Mineral Data Improvements and Critical Materials R&D at the U.S. Bureau of Mines," *Proceedings of the Workshop on Government Policies and Programs Affecting Materials Availability* (Columbus, Ohio: Metals and Ceramics Information Center, February, 1976), pp. 319-344. This same paper was presented before the National Symposium on Ceramics in the Service of Man in June 1976, and was reproduced as a Bureau of Mines Publication entitled *National Considerations of Strategic and Critical Materials.*

Figure 4–2

BOM CROSS TABULATION OF MINERAL PROBLEMS



MINERAL PROBLEMS
1975 AND BEYOND

PRELIMINARY DATA, AUGUST, 1975
BUREAU OF MINES

▩ Major problems from the national viewpoint

▨ Moderate problems from the national viewpoint

░ Minor or more localized problems

S Large stockpile excesses prevent a current problem

E U.S. exports contribute substantially to our balance of trade

a World resource inadequacy, next 4 decades
b US high-grade resource inadequacy, next 4 decades
c US low-grade resource inadequacy, next 4 decades
d US reserve inadequacy, next 4 decades
e US productive capacity deficiency, now
f US foreign exchange drain, now
g US vulnerability to foreign disruptions, now
h Mineral industry health and safety problems, now
i Mineral industry manpower problems
j Significant energy use, now
k Inadequate recycling, now
l Significant environmental impacts - air, now
m Significant environmental impacts - water, now
n Significant environmental impacts - land, now
o Load on US transport system, now

ABRASIVES, NATURAL
ABRASIVES, MANUFACTURES
ALUMINUM (incl. BAUXITE & ALUMINA)
ANTIMONY
ARGON
ARSENIC (byproduct of Copper)
ASBESTOS, CHRYSOTILE
BARITE
BERYLLIUM
BISMUTH (byproduct of Lead)
BORON
BROMINE
CADMIUM (byproduct of Zinc)
CALCIUM CHLORIDE
CEMENT
CESIUM
CHLORINE, MANUFACTURED
CHROMIUM (incl. FERROCHROMIUM)
CLAYS
COAL — E
COBALT (byproduct of Copper & Nickel)
COLUMBIUM (NIOBIUM)
COPPER
CORUNDUM & EMERY
DIAMONDS, GEM STONES
DIAMONDS, INDUSTRIAL, STONES, NATURAL
DIAMONDS, INDUSTRIAL, BORT, NATURAL
DIAMONDS, INDUSTRIAL, BORT, SYNTHETIC
DIATOMITE
FELDSPAR
FLUORSPAR
GALLIUM (byproduct of Aluminum & Zinc)
GARNET
GEM STONES, NON-DIAMOND
GERMANIUM (byproduct of Zinc)
GOLD — S
GRAPHITE, AMORPHOUS
GRAPHITE, MALAGASY CRUCIBLE
GRAPHITE, SRI LANKA
GREENSAND
GYPSUM
HAFNIUM (byproduct of Zirconium)
HELIUM (byproduct of Natural Gas)
INDIUM (byproduct of Zinc)
IODINE
IRON ORE, STEEL & SCRAP
KYANITE
LEAD
LIME
LITHIUM

Figure 4–2 (cont.)

BOM CROSS TABULATION OF MINERAL PROBLEMS

MINERAL PROBLEMS
1975 AND BEYOND

PRELIMINARY DATA, AUGUST, 1975
BUREAU OF MINES

- ▓ Major problems from the national viewpoint
- ▒ Moderate problems from the national viewpoint
- ░ Minor or more localized problems
- **S** Large stockpile excesses prevent a current problem
- **E** US exports contribute substantially to our balance of trade

	a World resource inadequacy, next 4 decades	b US high-grade resource inadequacy, next 4 decades	c US low-grade resource inadequacy, next 4 decades	d US reserve inadequacy, next 4 decades	e US productive capacity deficiency, now	f US foreign exchange drain, now	g US vulnerability to foreign disruptions, now	h Mineral industry health and safety problems, now	i Mineral industry manpower problems	j Significant energy use, now	k Inadequate recycling, now	l Significant environmental impacts - air, now	m Significant environmental impacts - water, now	n Significant environmental impacts - land, now	o Load on US transportation system, now
MAGNESIUM										░	░				
MANGANESE (incl. FERROMANGANESE)		▓		▓	▓										
MERCURY								▓				░	░		
MICA, SCRAP & FLAKE															
MICA, SHEET		▓		▓	▓										
MOLYBDENUM						E							░		
NATURAL GAS				▓	▓	▓				▓					▓
NICKEL		▓		▓	▓							░			
NITROGEN, ELEMENTAL												░			
NITROGEN, FIXED				▓								░	░		
OIL SHALE					▓								▓	▓	
OXYGEN															
PEAT															
PERLITE															
PETROLEUM		▓		▓	▓	▓	▓			▓		▓	░		▓
PHOSPHATES		▓		▓		E						▓	▓	▓	
PLATINUM GROUP PLATINUM, PALLADIUM, OSMIUM, RHODIUM, RUTHENIUM, IRIDIUM		▓		▓	▓		▓					░			
POTASH				▓	▓									░	
PUMICE & VOLCANIC CINDER															
QUARTZ CRYSTALS (LASCA for synthetic)		▓		▓	▓		▓					░			
RADIUM															
RARE EARTHS															
RHENIUM (byproduct of Copper-Molybdenum Ore)															
RUBIDIUM (byproduct of Lithium & Cesium)															
SALT										░			░	░	
SAND & GRAVEL								░				░	▓	▓	▓
SCANDIUM (byproduct of Uranium & Phosphate)															
SELENIUM (byproduct of Copper)		▓			▓										
SILICON (METAL & FERROSILICON)															
SILVER		▓			▓				░						
SLAG - IRON & STEEL								░				░			
SODIUM CARBONATE & SULFATE	░												░		
STAUROLITE (byproduct of Titanium minerals)															
STONE								░				░		░	▓
STRONTIUM					▓		▓								
SULFUR											▓	▓	▓	▓	
TALC								▓				▓			
TANTALUM	░	▓		▓	▓		▓								
TELLURIUM (byproduct of Copper)		▓													
THALLIUM (byproduct of Zinc)								░							
THORIUM															
TIN		▓	▓	▓	▓		S				░				
TITANIUM (incl. ILMENITE & RUTILE)		▓		▓	▓		▓			░	░		░		
TUNGSTEN							S								
URANIUM	░	▓		▓				░		▓	▓		░	░	
VANADIUM		▓													
VERMICULITE		░		░											
WOLLASTONITE				░											
YTTRIUM (byproduct of Rare Earths)															
ZEOLITES															
ZINC		▓			▓	░		░	░						
ZIRCONIUM (incl. ZIRCON)					▓		▓				▓	░	░		
	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o

SOURCE: Dr. John D. Morgan, "Mineral Data Improvements and Critical Materials R & D at U.S. Bureau of Mines," *Proceedings of the Workshop on Government Policies and Programs Affecting Material Availability* (Columbus, Ohio: Metals and Ceramics Information Center, February 1976), pp. 342–343.

Many of the problem areas identified in Figure 4-2 have already been discussed in terms of our theoretical framework and the application of policy models to determination of materials criticality. However, other of these problem areas deserve a brief comment.

A mineral is apparently considered a "U.S. foreign exchange drain" (problem area f) if the net imports of the United States have a high value. If there is an opportunity for this country to develop domestic resources of a particular mineral, say through investment in developing new recovery technologies, then such a mineral does present an opportunity for beneficial government R&D programs. In cases such as petroleum, large expenditures on imports may be partially the result of collusion among foreign suppliers. However, in general international trade greatly benefits the United States, and the theory of comparative advantage explains why it is good that we import some goods and services in exchange for those we export. Thus, large U.S. expenditures for imports are not a sufficient condition for criticality; such expenditures may or may not be a symptom of some problem or indicate the need for revised government policy.

Health, safety, and environmental problems (areas h, l, m, and n) are included in Figure 4-2, in contrast to studies restricted to criticality stemming from actual or potential foreign supply disruptions. As we noted in the general theoretical discussion of Chapter 2, a restricted viewpoint is quite workable as long as the national policies designed to treat each problem area are relatively distinct. For example, stockpiles counteract the threat of foreign supply disruptions but have little direct impact on health, safety, and environmental problems. The reverse is true of pollutant taxes or job safety regulations.

Another set of problem areas identified in Figure 4-2 relates to a fairly distinct set of national policies, and thus can often be usefully treated apart from criticality due to foreign supply disruptions. Manpower, energy, and transport (problem areas i, j, and o) are inputs into the U.S. minerals extraction and processing industries which are particularly prone to problems requiring national attention. Examples of relevant policies would be forced arbitration of strikes or regulation of the price of natural gas. Materials which are considered a "load on the U.S. transport system" are apparently simply voluminous and heavy, which may or may not indicate criticality.

"Inadequate recycling" (problem area h) can be an important element in the analysis of many policy problems, from foreign supply disruptions to occupational health regulations. However, it can be an area of concern simply on the grounds of economic efficiency. Depletion allowances in the tax system, discriminatory freight rates, and other institutional characteristics of the U.S. economy appear to bias consumption toward primary sources of materials and away from secondary scrap. Economic losses due to these inefficiencies could in principle be included in a materials criticality rating if the perspective were to be broader than a concern only with foreign supply disruptions.

It is clear that cross tabulations of market characteristics like that in Figure 4-2 are a useful way of organizing information. When the CRA policy model is applied to materials criticality, cross tabulations of the inputs into the model should be constructed as well as cross tabulations of outputs. Such an input tabulation would be in many ways a particularly incisive substitute for the type of presentation we have been discussing.

Measuring Criticality With Input-Output Models

There have been a number of studies of the effects of shortages on the U.S. economy based on input-output models. Such models explicitly consider all sectors of the economy simultaneously; this inclusiveness is an advantage when one wishes to consider simultaneous shortages of most materials, as would occur for example during a war. The Federal Preparedness Agency routinely uses such models in planning stockpile objectives. Unfortunately, adding to an input-output model all the features which the CRA policy model incorporates for measuring materials criticality would be an extremely complex project which is not likely to be undertaken soon. In any case, a policy model based on a model of a single market implicitly recognizes the interrelationships among markets to a greater extent than may be immediately apparent.

A recent study done at the Stanford Research Institute is representative of the results which an input-output model generates when shortages are analyzed.[1] Moreover, the study explicitly addressed the issue of determining criticality of materials in terms of prescreening those which were worth careful consideration using the formal model. We will use this report as the basis for most of our discussion of the application of input-output models to materials criticality.

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[1] See the following publications: Mark D. Levine and Irving W. Yabroff, *Department of Defense Materials Consumption and the Impact of Material and Energy Resource Shortages* , prepared for the Defense Advanced Research Projects Agency by the Stanford Research Institute, November 1975; Evan E. Hughes, *et al.*, *Strategic Resources and National Security: An Initial Assessment*, prepared for the Defense Advanced Research Projects Agency by the Stanford Research Institute, April 1975; Mark D. Levine and Irving W. Yabroff, "Strategic Resources and National Security," Paper I in *Proceedings of the Department of Defense Materials Shortage Workshop*, Metals and Ceramics Information Center, January 1975.

Prescreening of Materials

The prescreening of materials for the SRI study was done on a formal basis which is similar to other subjective weighting schemes we have already discussed.[1] Seven criteria were used to rate commodities on a scale of 1 to 10:

(1) Percent of U.S. consumption for defense purposes.[2]
(2) U.S. reserves.
(3) Percent of U.S. consumption imported.
(4) Vulnerability of sources.
(5) Difficulty of substitution.
(6) Value of consumption ("economic importance").
(7) Leverage of industry (high value of final good output per dollar of raw material input).[3]

Results for 74 potentially critical raw materials are reproduced in Table 4-2. A rating of 10 for a particular criterion is the maximum contribution to criticality which is allowed; a rating of zero indicates a lack of data. A

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[1] The methodology is described below only in enough detail that the summary table of results can be roughly interpreted. For a complete discussion, see Hughes and others, pp. 191-212. Data utilized for criteria (1), (2), (3) and (6) were explicitly for the year 1972. Criteria (4), (5) and (7) were evaluated subjectively.

[2] The first criterion reflects the fact that the study was done for the Department of Defense; in terms introduced in Chapter 2, the perspective of this study is somewhat less general than "national concensus," though introducing specialized interests in such an *ad hoc* fashion is open to criticism.

[3] The "leverage" of a raw material is directly taken into account in the CRA policy model when the U.S. price elasticity of demand for the raw material is derived from the price elasticity of demand for finished goods.

Table 4-2

PRIORITIES OF MATERIALS: RANKING ON NATIONAL SECURITY AND ECONOMIC CRITERIA

	Name of Material	(1) DoD Use	(2) U.S. Reserves	(3) Imports	(4) Vulnerability of Sources	(5) Difficulty of Substitution	(6) Economic Importance	(7) Industrial Leverage	Geometric Mean Columns 2-8
[6]*	1. Aluminum	5	10	10	3	6	6	5	6.0
	2. Iron	8	7	2	3	8	10	9	5.9
	3. Manganese	7	10	8	6	7	1	8	5.7
	4. Graphite	5	10	9	6	5	0	2	5.5
[7]*	5. Copper	10	5	2	4	6	6	7	5.2
	6. Yttrium	4	9	4	0	0	0	0	5.2
[5]*	7. Chromium	7	10	7	7	5	1	5	5.1
[2]*	8. Platinum-Group	5	10	10	6	8	1	3	4.9
[10]*	9. Tungsten	8	9	5	7	7	1	4	4.9
	10. Mica-Sheet	10	10	10	7	4	1	2	4.8
[9]*	11. Nickel	7	10	7	4	4	2	4	4.8
	12. Antimony	8	10	5	6	7	1	3	4.7
[3]*	13. Cobalt	10	4	7	6	7	1	4	4.7
	14. Fluorine	6	10	8	5	6	1	3	4.6
	15. Mercury	7	9	6	7	7	1	2	4.5
[8]*	16. Silver	5	9	4	6	8	1	4	4.5
	17. Tantalum	6	10	8	6	6	1	2	4.5
[4]*	18. Tin	8	10	9	4	3	1	3	4.3
	19. Lithium	7	5	0	3	6	0	2	4.2
	20. Asbestos	3	9	9	5	5	1	2	3.8
	21. Columbium	6	6	7	6	4	1	2	3.8
	22. Cesium	0	0	8	5	5	0	1	3.8
	23. Bismuth	4	8	5	3	7	1	3	3.7
	24. Potassium	1	7	6	4	8	1	6	3.6
	25. Cadmium	9	6	4	3	4	1	3	3.6

Table continued on following page.

Table 4-2 (Continued)

PRIORITIES OF MATERIALS: RANKING ON NATIONAL SECURITY AND ECONOMIC CRITERIA

	Name of Material	(1) DoD Use	(2) U.S. Reserves	(3) Imports	(4) Vulnerability of Sources	(5) Difficulty of Substitution	(6) Economic Importance	(7) Industrial Leverage	Geometric Means Columns 2-8
	26. Thallium	10	1	10	0	5	0	1	3.5
	27. Indium	0	7	0	4	5	0	1	3.4
[11]*	28. Zinc	8	6	5	3	2	1	4	3.4
	29. Beryllium	10	1	4	6	6	1	3	3.3
	30. Thorium	10	1	4	7	4	0	1	3.2
	31. Gold	4	9	7	2	5	1	1	3.1
[12]*	32. Lead	8	2	2	4	5	1	4	3.1
	33. Vanadium	5	9	2	3	4	1	2	3.0
	34. Germanium	10	6	2	5	3	1	1	2.9
	35. Sulfur	5	8	1	1	7	1	5	2.8
	36. Selenium	6	1	4	3	7	1	2	2.7
	37. Arsenic	1	3	0	6	4	0	2	2.7
	38. Hafnium	0	1	10	3	5	0	1	2.7
	39. Strontium	5	1	9	4	4	1	1	2.6
	40. Barium	6	1	4	3	4	1	3	2.6
	41. Rubidium	0	10	1	5	5	1	1	2.5
	42. Zirconium	5	1	0	3	6	0	1	2.5
	43. Corundum	4	10	0	0	2	1	1	2.4
	44. Gypsum	1	6	4	2	3	1	3	2.4
[1]*	45. Titanium	4	1	5	3	4	1	2	2.4
	46. Chlorine	4	1	1	1	7	2	8	2.4
	47. Sand and Gravel	2	1	1	2	6	3	7	2.4
	48. Iodine	3	4	10	1	3	1	1	2.3
	49. Stone-Crush	3	1	1	1	6	3	7	2.3
	50. Tellurium	3	1	4	4	6	1	1	2.2

Table continued on following page.

Table 4-2 (Continued)

PRIORITIES OF MATERIALS: RANKING ON NATIONAL SECURITY AND ECONOMIC CRITERIA

Name of Material	(1) DoD Use	(2) U.S. Reserves	(3) Imports	(4) Vulnerability of Sources	(5) Difficulty of Substitution	(6) Economic Importance	(7) Industrial Leverage	Geometric Means Columns 2-8
51. Rhenium	0	1	5	4	6	1	1	2.2
52. Boron	0	1	1	6	7	1	3	2.2
53. Molybdenum	9	1	1	3	3	1	3	2.2
54. Nitrogen	3	1	1	1	8	2	6	2.2
55. Phosphorus	2	1	1	2	8	1	6	2.1
56. Clays	3	1	1	2	7	1	4	2.1
57. Silicon	9	1	1	1	6	1	3	2.1
58. Garnet	10	3	1	2	2	1	1	2.0
59. Rare Earths	2	1	1	8	7	1	1	2.0
60. Talc	4	1	1	3	5	1	2	2.0
61. Gallium	1	1	10	2	3	0	1	2.0
62. Magnesium	5	1	1	2	4	1	3	2.0
63. Sodium	5	1	1	1	6	1	5	2.0
64. Calcium	0	1	1	1	7	1	9	2.0
65. Bromine	4	1	1	2	5	1	2	1.9
66. Diatomite	4	1	1	3	3	1	2	1.8
67. Feldspar	3	1	1	2	5	1	2	1.8
68. Kyanite	0	1	0	3	3	0	1	1.7
69. Mica-Scrap	4	1	1	2	3	1	2	1.7
70. Pumice	3	2	1	2	3	1	1	1.7
71. Stone-Dimen	4	1	1	1	3	1	3	1.7
72. Vermiculite	3	1	1	2	3	1	1	1.5
73. Perlite	3	1	1	2	2	1	1	1.4
74. Scandium	0	1	0	0	0	1	0	1.0

*Ranking by effect of shortage on GNP. See text.

SOURCE: Evan E. Hughes, *et al.*, *Strategic Resources and National Security: An Initial Assessment*, prepared for the Defense Advanced Research Projects Agency by the Stanford Research Institute, April 1975, pp. 202-205.

summary measure for the seven criteria is calculated simply by taking a geometric average of all positive ratings. The materials are listed in Table 4-2 by their rank according to this summary measure.[1]

The 12 nonfuel materials which were studied intensively by Levine and Yabroff with their input-output model were titanium, platinum, cobalt, tin, chromium, aluminum, copper, silver, nickel, tungsten, zinc and lead. These materials are indicated on the left side of Table 4-2 by an asterisk and by an alternative ranking which will be explained below. The lack of close correspondence between the formal prescreening rank and the materials which were eventually deemed worthy of further study is a pointed commentary on the weakness of subjective weighting schemes. Considerations such as vulnerability of supply sources and substitution possibilities are undeniably important in determining materials criticality, but their relative importance differs in complicated ways from material to material; a formal economic model is generally required to clarify such issues.

The point is not that prescreening of materials before detailed construction of criticality ratings is infeasible or undesirable. Rather, given that there are only roughly a hundred candidate raw materials, it is relatively easy to select the most useful ones to analyze in depth according to the principles presented in Chapter 2 of this study. The same materials are the major candidates in most studies of criticality, assuming the results from formal weighting

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[1] There is no weighting of the relative importance of the various criteria, as was done by Cameron and King.

procedures are applied with good judgment. The criticality of less major materials should also be analyzed in time, but just using roughly conservative assumptions will often show quickly that the criticality of a material such as dimensional stone is not as great as for materials of more immediate interest.

Consider the case of sheet mica, which Levine and Yabroff did not study intensively in spite of its having a high rating (10) in Table 4-2. Despite the high rating, good substitutes exist, consumption is declining steadily, and use of natural sheet mica is expected to be very low by the year 2000. The United States has very few reserves of sheet mica, but resources which could be exploited at considerably higher prices are sizable.[1] Moreover, the U.S. strategic stockpile contains a very large quantity of the material, some of which would very probably be available to U.S. industry during any major disruption of imports. The criticality of sheet mica would almost certainly be much lower than indicated in Table 4-2 if it were analyzed according to the principles we have recommended in this study.

The Cost of Disruptions

The last report from the SRI study applied a 150-sector input-output model to gas, petroleum, coal and the twelve nonenergy materials listed above. Although this final stage of the study does not explicitly consider the relative criticality of materials, some basic results are generated which indicate what one can expect from utilizing an input-output model to determine materials criticality.

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[1] Producing sheet mica is labor-intensive, so the cost of U.S. labor (relative to that in less developed countries where production occurs) makes it uneconomical to exploit U.S. resources.

The ultimate results reported in the SRI study are reproduced in their graphical form in Figure 4-3. Shortages of individual raw materials are measured on the horizontal axis as a percent of normal consumption, and the percent reduction in attainable GNP is measured on the vertical axis.[1] Reductions in gas, petroleum and coal availability quickly cause catastrophic reductions in GNP according to results generated by the input-output model. However, quite conceivable shortages of the 12 nonenergy materials are also represented as having disastrous effects on GNP.

It is important to put the results in Figure 4-3 into perspective before critiquing them. First, input-output models have intrinsic limitations which are very difficult to avoid and which were quite familiar to the authors of the study. Thus, results for shortages beyond certain points are considered unrealistic and are so indicated by using dashed lines in the figure; even the more reliable results represented with solid lines are artificial enough that they probably should not be interpreted literally (as we discuss further below). Second, the results in Figure 4-3 are not intended by the authors to indicate complete criticality ratings, since they do not consider such obviously relevant factors as the probability of a disruption occurring.[2]

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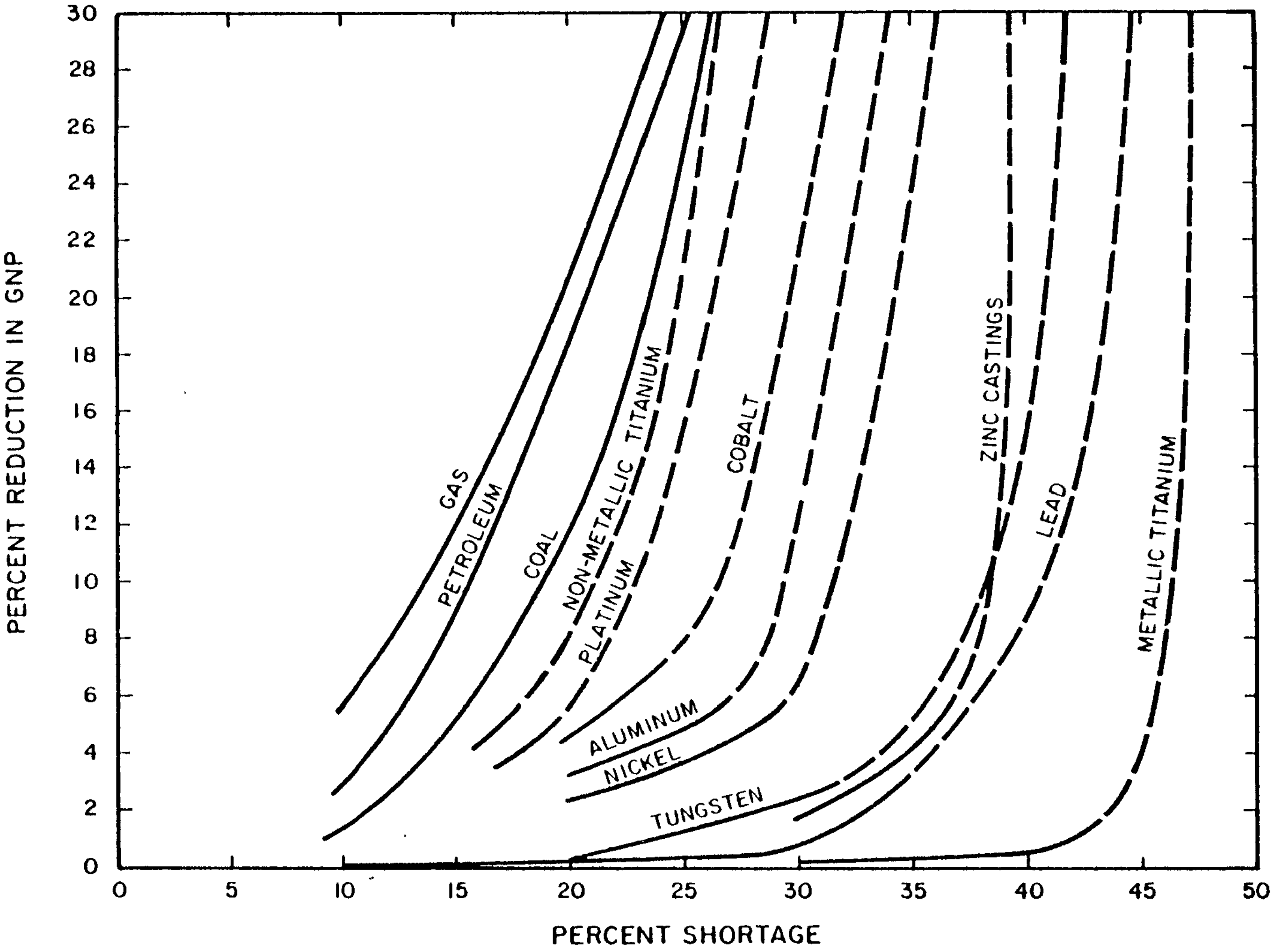
[1] A linear programming algorithm was used to maximize GNP given the resource shortage. Because of unrealistic fixed coefficients production functions and unrealistic constant values of unit outputs, artificial constraints on industrial capacities and on final demands had to be imposed in order to obtain results which were not obviously unreasonable.

[2] Based partially on their formal analysis, the authors do venture the tentative recommendation that chromium, aluminum, tin and platinum may be the most critical commodities for economic stockpiling by the United States. See Levine and Yabroff, *Department of Defense Materials Consumption, op. cit.*, p. 12. Additional study is also recommended.

Figure 4—3

EFFECTS OF ENERGY AND MATERIAL SHORTAGES ON GNP ESTIMATED BY SRI



SOURCE: Mark D. Levine and Irving W. Yabroff, *Department of Defense Materials Consumption and the Impact of Material and Energy Resources Shortages* (Menlo Park, Ca.: Stanford Research Institute, November 1975), p. 78. Report prepared for the Defense Advanced Research Projects Agency.

Nevertheless, the ranking of materials from left to right in Figure 4-3 is highly suggestive of the type of results which a full input-output analysis of criticality would generate. This ranking of nonenergy materials was indicated above in Table 4-2 by the bracketed numbers and asterisks at the left side.[1]

Comparing the rankings for nonmetallic titanium and metallic titanium in Figure 4-3 is a revealing way to indicate some of the most important limitations of input-output models. It is suggested that a given percentage reduction in GNP can be caused by a relatively small shortage of the nonmetallic titanium but that the same percentage reduction requires a much larger shortage of metallic titanium. According to our interpretation of Figure 4-3, nonmetallic titanium ranks first among the nonenergy materials in what we might call potential criticality, while metallic titanium ranks last.

Metallic titanium popularly has a high-technology image because of its use in aerospace applications. However, nonmetallic uses account for the bulk of titanium consumption; most goes into white pigments for very mundane usage in paints, paper and plastics. The wide usage of titanium pigments as an intermediate good throughout industry accounts for its apparent importance in Figure 4-3. As the availability of titanium decreases, buildings would not be built and appliances would not be manufactured because of a shortage of white paint, at least according to an input-output model which allows for no substitutions.

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[1] Four materials are omitted from Figure 4-3 for clarity, but are included in Table 4-2 : tin and chromium fall between cobalt and aluminum; copper and silver fall between aluminum and nickel.

It is possible at considerable expense to modify input-output models to take substitution possibilities into account in a rudimentary fashion. However, adding to an input-output model all the features which make the policy model in Chapter 3 very well suited to determining materials criticality would be an unrealistically complicated job at the present time. In particular, the input-output model is static and does not take into account the successive adaptions which the economy can make over time. A related difficulty is that the GNP loss measures generated by an input-output model are generally less satisfactory than the economic surplus measures used in the policy model of Chapter 3; the surplus measures recognize that successive unit reductions in the availability of a good inflict larger and larger economic costs on society.

Analysis of Two or More Markets With a Policy Model

As mentioned earlier, the sectoral inclusiveness of input-output models makes them an important tool when analyzing simultaneous shortages in many markets, as would occur during a war. However, even in planning mobilization for a war, models which are sophisticated in other ways can be useful for analyzing certain problems.

For analyzing disruptions in *one* market or *several* markets, the advantages of models like those discussed in Chapter 3 of this study are compelling. Most importantly, such models allow a realistic *dynamic* treatment of the adjustments the economy can make during a disruption, including substitution of alternative materials and the optimal allocation of available inventories. The simpler structure of the underlying microeconomic models also means that other aspects of materials criticality, such as the probability of disruptions of various lengths and severities, can be treated in a more satisfactory manner.

The policy model discussed in Chapter 3 does assume in its basic form that prices for inputs other than the potentially critical material are relatively stable during supply disruptions. Such an assumption may be significantly unrealistic for certain closely related markets. However, generalizing the policy model to take account of several closely related markets, such as iron and manganese (complements) or bauxite and copper (substitutes) would only be moderately costly. More ambitious generalizations of the policy model would allow treating simultaneous disruptions in multiple markets, as long as *most* of the markets in the economy were relatively unaffected. Fortunately for ease of analysis as well as for peace of mind, it is very unlikely that disruptions of nonfuel minerals would massively disrupt the U.S. economy to the extent that such microeconomic analysis would be an insufficient tool for analysis. In any case, the microeconomic policy model could be nested inside a macroeconomic model if this were considered necessary for analyzing cataclysmic cases.

Because it ignores, or at best oversimplifies the substitution possibilities and other dynamic adjustments which the economic system can make, an input-output model can easily consider simultaneous disruptions of many materials. However, in most cases a microeconomic approach to analyzing widespread disruptions offers more realistic and reliable results.

Other Studies of Criticality

In the remainder of this chapter we briefly discuss interesting aspects of other studies bearing on the criticality of materials.

NMAB Study

The National Materials Advisory Board (NMAB) recently completed a study of critical materials which utilized definitions different from those which we have proposed: "Critical materials are those that are necessary to manufacture the products required for a national emergency and its accompanying essential civilian needs."[1] "Criticality" thus does not necessarily imply that a serious disruption of supplies is probable; however, "strategicness" is used to connote unreliable foreign sources. In terms of the basic concepts developed in Chapter 2 of the present study, the definition of criticality used in the NMAB study appears to be more closely related to the total utility gained from a material than to expected losses of utility.

In any case, the actual selection of materials in the NMAB study is not closely tied to the formal definition of criticality. In fact, the selection process is only described in general terms as a subjective weighting of many relevant factors, with the details omitted. The materials selected for detailed study were chromium, germanium, iridium, rhenium,

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[1] National Materials Advisory Board, Committee on the Technical Aspects of Critical and Strategic Materials, *A Screening for Potentially Critical Materials for the National Stockpile*, Publication NMAB-329 (Washington, D.C.: National Academy of Sciences, 1977), p. iv. Critical and strategic materials are discussed in this study specifically in the context of decisionmaking for the U.S. national stockpile.

zirconium, hafnium and vanadium. Chromium was identified as the most critical of these materials.

C.O.I.E.P. Study

A task force of federal agencies under the direction of the Council on International Economic Policy and the National Security Council produced a useful overview of critical materials in 1974.[1] The basic explicit criterion of criticality employed was U.S. import dependence, but other considerations relating to the threat of foreign supply disruptions were weighted qualitatively; there was no attempt to rank materials by their criticality. This study illustrates the type of prescreening of materials which can be usefully done before the more formal and ambitious approach we have proposed is implemented.

OTA Study

A recent study of stockpiling policies by contractors for the Office of Technology Assessment has a short section on criteria for selecting materials.[2] The analysis is somewhat unwieldy, involving consideration of separate stockpiles for each of five objectives: to discourage or counteract cartel or unilateral political actions affecting price or supply; to cushion the impact of nonpolitical import disruptions; to assist in international materials market stabilization; to conserve scarce domestic materials; and to provide a market for temporary surpluses and to ease temporary shortages. In a

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[1] Council on International Economic Policy, *Critical Imported Materials* (Washington, D.C., December 1974).

[2] U.S. Congress, Office of Technology Assessment, *An Assessment of Alternative Economic Stockpiling Policies* (Washington, D.C., August 1976), pp. 52-57.

rough way this approach does recognize that materials criticality depends on the type of conditions which exist and the type of contingencies which threaten. Selection of materials related to the above problem areas was finally done by a survey and consensus of expert opinion, formalized as a "modified Delphi technique."

NCSS Study

The National Commission on Supplies and Shortages did not specifically recommend implementation of a system for measuring criticality of materials. However, the approach to criticality which we have proposed here is logically a preliminary part of the process of policy analysis, most obviously for determination of stockpile levels. The Commission's discussion of stockpiling in fact recognizes the usefulness of the type of policy model discussed in Chapter 3, and earlier versions of the CRA policy model are explicitly examined.[1] The Commission's report also recognizes the importance of the cost measurements which we have emphasized and it delves in depth into many closely related issues, such as improving data collection for policy analysis.

NSF Study

The National Science Foundation sponsored a methodological study of materials criticality by International Research and Technology Corporation in 1974.[2] This study alludes to many of the ideas which we have earlier identified as important,

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[1] National Commission on Supplies and Shortages, *Government and the Nation's Resources* (Washington, D.C., December 1976), pp. 131-140.

[2] International Research and Technology Corporation, *Critical Materials: A Problem Assessment*, prepared for the National Science Foundation (Arlington, Va., May 1974).

but it has no unifying theory of criticality and in particular fails to take full advantage of economic concepts and theory. In the final analysis it simply lists many relevant considerations without relating them to an explicit economic model explaining losses from disruptions.

AFL-CIO Study

The AFL-CIO commissioned a study of imported raw materials and their importance for U.S. workers and consumers.

> Nine commodities were considered of major significance in terms of use by U.S. industry, import dependency, vulnerability to price and supply manipulation, and impact on U.S. employment . . . aluminum, copper, lead, zinc, tin, nickel, manganese, iron ore and chromium.[1]

This study did not consider the measurement of materials criticality in any depth. It is interesting for current purposes only because the materials of greatest concern to the most prominent U.S. labor organization are no different from those selected by other investigators, despite a perspective arguably narrower than a national concensus.

DOD Workshops

The proceedings of two workshops sponsored by the Department of Defense in 1975 and 1976 are interesting for expressing a broad range of concerns relating to and merging with the issue of measuring materials criticality. Shortages of fabricated items due to inadequate capacity, OSHA and EPA regulations, and even scheduling difficulties are discussed

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[1] Jocelyn Gutchess and Stanley Ruttenberg, *Raw Materials for America: A Program to Assure Meeting Future Needs*, prepared for the Industrial Union Department of the AFL-CIO (July 1975), p.10.

in the various papers.[1] The most frequent complaint is a lack of timely and reliable forecasts of materials availability. We have considerably narrowed the focus of our present inquiry so that these important issues must be treated elsewhere.

Admittedly, we have had relatively little to say directly about how to determine materials which are most critical for defense purposes, beyond showing in Chapter 2 how such considerations can be made conceptually compatible with criticality stemming from nonmilitary considerations. For some materials, such as germanium (which is used in infrared optical technology), nonmilitary criticality may be small relative to other materials, while military criticality is great.[2]

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[1] The following *Proceedings* volumes were published by the Metals and Ceramics Information Center, a Department of Defense Information Analysis Center: *Workshop on Government Policies and Programs Affecting Materials Availability* (February 1976); *Materials Shortage Workshop* (January 1975). Edward Dyckman, "Review of Government and Industry Shortages," Item A in the 1975 volume, is a useful overview of some earlier work on materials criticality which we have also discussed.

[2] See "Demand of New Technology on DOD Material Supply -- Initial Findings," Item C in the 1975 DOD *Workshop Proceedings* volume.

CHAPTER 2 REFERENCES

1. Adams, Robert L. 1977. "Evaluative Methods -Some Basic Concepts and Tools of Analysis." In conference proceedings on Contingency Planning for Materials Resources. Sponsored by The Engineering Foundation and The National Science Foundation, Edward B. Berman, ed. New York: United Engineering Center.

2. Adams, Robert L., Barbara A. White and James S. Grichan. 1979. "Developing a Critical Minerals Index: A Pilot Study." Office of Minerals Policy and Research Analysis, U.S. Department of the Interior. July.

3. Burrows, James C. and Steven D. Beggs. 1977. "Policy Implications of Producer Country Supply Restrictions: Approach and Conclusions." In conference proceedings of Contingency Planning for Materials Resources. Sponsored by The Engineering Foundation and The National Science Foundation, Edward B. Berman, ed. New York: United Engineering Center.

4. Charles River Associates. 1978. "Measuring Materials Criticality for National Policy Analysis." Prepared for the General Accounting Office. March.

5. __________. 1977a. "Implications of the War in Zaire for the Cobalt Market." (Revised). Prepared for the Office of Minerals Policy and Research Analysis, U.S. Department of the Interior. June.

6. __________. 1977b. "The Report of the U.S. Department of the Interior on the Critical Materials Aluminum, Chromium, Platinum and Palladium: A Review and Revision." Prepared for the Office of Minerals Policy and Research Analysis, U.S. Department of the Interior. July.

7. __________. 1976a. "Policy Implications of Producer Country Supply Restrictions." Prepared for Experimental Technology Incentives Program, National Bureau of Standards, U.S. Department of Commerce. Vol. I-V. August-December.

8. __________. 1976b. "Public Policy in the Chromium Market." Prepared for the Office of Minerals Policy and Research Analysis, U.S. Department of the Interior. October.

9. __________. 1976c. "Public and Private Stockpiling for Future Shortages." Prepared for National Commission on Supplies and Shortages. August.

CHAPTER 2 REFERENCES (continued)

10. ___________. 1975. "Economic Issues Underlying Supply Access Agreements: A General Analysis and Prospects in 10 Mineral Markets." Prepared for the Bureau of International Labor Affairs, U.S. Department of Labor.

11. Council on International Economic Policy. 1974. "Critical Imported Materials." Special Report, Washington, D.C.: December.

12. Dyckman, Edward. 1975. "Review of Government and Industry Shortages."

13. Fischman, Leonard L. 1980. "World Mineral Trends and U.S. Supply Problems." Prepared by Resources for the Future. Washington, D.C..

14. ___________. 1979. "Major Mineral Supply Problems." Prepared by Resources for the Future. Prepared for the Office of Science and Technology Policy, Executive Office of the President. Washington, D.C.: September.

15. Gutchess, Joceyln and Stanley Ruttenberg. 1975. "Raw Materials for America: A Program to Assure Meeting Future Needs." Prepared for the Industrial Union Department of the AFL-CIO, July.

16. Hughes, Evan E. et al. 1975. "Strategic Resources and National Security: An Initial Assessment." Prepared for the Defense Advanced Research Projects Agency by the Stanford Research Institute, April.

17. International Research and Technology Corporation. 1974. "Critical Materials: A Problem Assessment." Prepared for the National Science Foundation, Arlington, Va., May.

18. King, Alwyn H. and John R. Cameron. 1974. "Materials and the New Dimensions of Conflict." Carlisle Barracks, Pa.: U.S. Army War College, Strategic Studies Institute, May 15.

19. King, Alwyn H. 1977. "Materials Vulnerability of the United States -- An Update." Carlisle Barracks, Pa.: U.S. Army War College, Strategic Studies Institute, April 30.

20. Klass, Michael W., James C. Burrows, and Steven D. Beggs. 1980. "International Minerals Cartels and Embargoes: Policy Implications for the United States." Praeger: N.Y.

21. Kymm, Kern O. 1980. "Development of an IDEAS (Industrial Disruptions Economic Analysis System) Critical Industries Strike Impact Assessing System." June.

CHAPTER 2 REFERENCES (continued)

22. Levine, Mark D. and Irving W. Yabroff. 1975. "Department of Defense Materials Consumption and the Impact of Material and Energy Resource Shortages." Prepared for the Defense Advanced Research Projects Agency by the Stanford Research Institute, November.

23. ________. 1975. "Strategic Resources and National Security: Paper I in Proceedings of the Department of Defense Materials Shortage Workshop, Metals and Ceramics Information Center, January.

24. Materials Shortage Workshop. 1975. Metals and Ceramics Information Center, Department of Defense Information and Analysis Center. January.

25. Morgan, John D. 1976. "Mineral Data Improvements and Critical Materials R&D at the U.S. Bureau of Mines." Proceedings of the Workshop on Government Policies and Programs Affecting Materials Availability. Columbus, Ohio: Metals and Ceramics Information Center, February: 319-344.

26. National Commission on Materials Policy. 1973. "Materials Needs and the Environment Today and Tomorrow." U.S. Government Printing Office, June.

27. National Commission on Supplies and Shortages. 1976. "Government and the Nation's Resources." December.

28. National Materials Advisory Board (NMAB). 1981. "Identification of Critical and Strategic Materials for Naval Combat Systems." Commission on Sociotechnical Systems, National Research Council. April.

29. ________. 1977. "A Screening for Potentially Critical Materials for the National Stockpile." Committee on the Technical Aspects of Critical and Strategic Materials. Washington, D.C.: National Academy of Sciences.

30. Tilton, John E. 1977. "The Future of Nonfuel Minerals." The Brookings Institution, Washington, D.C.

31. U.S. Congress. 1976. "An Assessment of Alternatives Economics Stockpiling Policies." Office of Technology Assessment, Washington, D.C.: 52-57.

32. U.S. Department of the Interior. 1979a. "Domestic Policy Review of Nonfuel Minerals." Draft report, Vol. I-II. Volume III prepared by the Department of Mineral Economics, Pennsylvania State University for the U.S. Bureau of Mines.

CHAPTER 2 REFERENCES (continued)

33. U.S. Department of the Interior. 1979b. "Mineral Trends and Forecasts."

34. U.S. Department of the Interior. 1975. "Critical Materials: Commodity Action Analyses (Aluminum, Chromium, Platinum and Palladium). Prepared by the Office of Minerals Policy Development. March.

35. U.S. Department of the Interior. <u>Mining and Minerals Policy</u>. Issued annually.

36. U.S. Federal Emergency Management Agency. <u>Stockpile Report to the Congress</u>. Issued quarterly.

37. Webster's New Collegiate Dictionary. 1976. G. & C. Merriam Co.

38. Workshop on Government Policies and Programs Affecting Materials Availability. 1976. The Metals and Ceramics Information Center, Department of Defense Information Analysis Center. January.

39. Workshop Proceedings, Department of Defense. 1975. "Demand of New Technology of DOD Material Supply -- Initial Findings." Item C.

3

PROJECTIONS OF MATERIALS CONSUMPTION FOR CONTROL OF VEHICULAR EMISSIONS

Rath & Strong projected consumption of materials for U.S. vehicular emissions control for this study. Only projected consumption for the platinum-group metals is reported in detail here, because, as confirmed in Chapter 2, these are by far the most critical materials from the perspective of vehicular emissions control. However, order of magnitude estimates for other potentially critical materials, as used in Chapter 2, are also presented below.

Tables 3-1 through 3-3 project consumption of platinum, palladium, and rhodium by the four significant U.S. auto manufacturers, for emissions control on cars and light trucks. These projections are based upon assuming a constant volume of U.S. production over the reported time horizon from 1980 to 1987. Assumed production by U.S. manufacturers, in thousands of vehicles per year, is as follows:

	Cars	Light Trucks	Total
General Motors	5,700	1,382	7,082
Ford	2,090	916	3,006
Chrysler	950	272	1,222
American Motors	285	154	439
Total	9,025	2,724	11,749

The projections in Tables 3-1 through 3-3 recognize differences in the technologies used for emissions control by the four U.S. manufacturers, and the effect of future mixes of engine types. One important reason for

Table 3-1

U.S. CONSUMPTION OF PLATINUM FOR VEHICULAR EMISSIONS CONTROL, 1980-1987
(1000 grams per year)

Year	Cars	Light Trucks	Total
1980	20,096	6,301	26,397
1981	19,060	5,976	25,036
1982	15,651	4,936	20,587
1983	14,780	4,723	19,503
1984	13,980	4,507	18,487
1985	14,244	4,561	18,805
1986	15,595	4,857	20,452
1987	14,468	4,535	19,003

SOURCE: Rath & Strong, 1981.

Table 3-2

U.S. CONSUMPTION OF PALLADIUM FOR VEHICULAR EMISSIONS CONTROL, 1980-1987
(1000 grams per year)

Year	Cars	Light Trucks	Total
1980	8,534	2,676	11,210
1981	8,115	2,543	10,658
1982	6,025	1,847	7,872
1983	4,661	1,506	6,167
1984	4,414	1,434	5,848
1985	4,493	1,449	5,942
1986	4,871	1,537	6,408
1987	4,553	1,435	5,988

SOURCE: Rath & Strong, 1981.

Table 3-3

U.S. CONSUMPTION OF RHODIUM FOR VEHICULAR EMISSIONS CONTROL, 1980-1987
(1000 grams per year)

Year	Cars	Light Trucks	Total
1980	25.2	7.2	32.4
1981	13.5	3.9	17.4
1982	339.1	140.5	479.6
1983	947.1	291.7	1,238.8
1984	851.9	266.1	1,118.0
1985	858.4	266.2	1,124.6
1986	964.5	291.2	1,255.7
1987	877.7	268.1	1,145.8

SOURCE: Rath & Strong, 1981.

projected declines in platinum and palladium consumption between 1980 and 1987, is assumed reductions in the size of gasoline engines and greater usage of diesel engines. Rath & Strong assumed that diesel engines will be equipped with a monolithic substrate contained in a clamshell particulate trap largely made of 409 stainless steel, in which particles are burned using hot exhaust gases. No use of noble metals in the particulate traps is assumed.

The Rath & Strong subproject report for this contract contains a detailed description of the assumptions underlying their projections, and a wealth of data beyond that required for the immediate purposes of this study (such as a disaggregation of platinum-group consumption by vehicle manufacturer). Thus, their report is included with this study as a separately bound appendix.

Appendix 3-A presents alternative estimates, by the Environmental Protection Agency, of consumption of platinum-group metals for control of vehicular emissions in 1981. The EPA estimates differ considerably from those presented for 1981 in Tables 3-1 through 3-3, particularly for rhodium.

The detailed projections of platinum-group consumption provided in Tables 3-1 through 3-4 are of some interest in their own right. However, such detail and accuracy is not really required for the rough estimation of materials criticality performed in Chapter 2. For that purpose, we simply round off projected annual consumption for the period 1985-1987 roughly as follows (in thousands of grams per year):

- Platinum: 20,000
- Palladium: 6,000
- Rhodium: 1,200

Other potentially critical materials used in vehicular systems for emissions control, fuel management, and related purposes, are chromium, manganese, nickel, and titanium. These materials are mostly contained in the stainless steel (type 409) used in the catalytic converter. The following very rough estimates of annual consumption of these materials by U.S. vehicle manufacturers, for emission control and related purposes on cars and light trucks, were provided by Rath and Strong (in short tons per year):

- Chromium: 10,600
- Manganese: 730
- Nickel: 360
- Titanium: 350

As explained in the preceding chapter, these quantities are small proportions of total U.S. consumption of these metals, and their criticality from the perspective of U.S. vehicle manufacturers and EPA is much less than the criticality of the platinum-group metals. (We confirmed for this project that consumption for emissions control of several other metals, including molybdenum and vanadium, is nonexistent or entirely inconsequential.)

3A

EPA ESTIMATES OF CONSUMPTION OF PLATINUM-GROUP METALS FOR CONTROL OF VEHICULAR EMISSIONS IN 1981

Tables 3-1 through 3-3 in the text provide Rath & Strong estimates of U.S. consumption of platinum, palladium and rhodium for vehicular emissions control in 1980 and 1981, as well as for the 1985-1987 time frame considered by Charles River Associates in Chapter 2. The Rath & Strong estimates for 1981 differ substantially from best estimates produced internally by the Control Technology Assessment and Characterization Branch of EPA's Office of Air, Noise and Radiation. The EPA estimates are given in Table 3A-1.

Time did not allow us to investigate the reason for the large discrepancies between Tables 3-1 through 3-3, and the EPA estimates for 1981. In any case, the Rath & Strong estimates for 1985-1987 are much more compatible with the EPA estimates for 1981, and the 1985-1987 projections were the basis for the work in Chapter 2.

Table 3A-1

U.S. CONSUMPTION OF PLATINUM, PALLADIUM AND RHODIUM FOR VEHICULAR EMISSIONS CONTROL, EPA ESTIMATES FOR 1981

Number of Light-Duty Gasoline Vehicles Produced in the United States: 8,864,444

Grams of Platinum-Group Metals Consumed per Vehicle:

Platinum:	1.957
Palladium:	0.653
Rhodium:	0.184
Total:	2.794

Implied Total U.S. Consumption of Platinum-Group Metals, in Thousands of Grams:

Platinum:	17,350
Palladium:	5,790
Rhodium:	1,630

Equivalent Total U.S. Consumption of Platinum-Group Metals, in Troy Ounces

Platinum:	557,700
Palladium:	186,000
Rhodium:	52,400

SOURCE: Environmental Protection Agency, Office of Air, Noise and Radiation, Control Technology Assessment and Characterization Branch. August 5, 1981.

4

PLATINUM-GROUP METALS

INTRODUCTION

This chapter focuses on the platinum-group metals (PGMs) used in vehicular emissions control systems. As discussed in another chapter, there is currently no economical alternative to the noble-metal catalytic converter which uses platinum, palladium, and rhodium. Supplies of these materials thus become an important issue when contemplating the costs of auto emission regulations.

The supply elasticity of PGMs is discussed in this chapter by time-frame of response. Stockpiles of PGMs are first analyzed in terms of their ability to bridge a short-term demand/supply gap. Following the stocks discussion is an analysis of world primary production elasticity by country, a discussion of total world PGM reserves, and an analysis of world supply reliability.

Following the primary production section, other PGM-using industries are examined, focusing on the response of consumption and secondary recovery in each industry to PGM price rises. The chapter concludes with a discussion of the role of speculation in PGM markets.

STOCKS

The most immediate possible supply response to any increase in demand for platinum group metals would come from stocks. The key questions then become what government and private stocks of PGMs exist, how large they are, and what the immediate supply elasticity of the stocks is. The secretive nature of the platinum industry makes these questions difficult to answer precisely; nevertheless, much information is public and discussions with industry personnel have revealed additional information. The industry secrecy often has good cause; one firm recently told the U.S. Bureau of Mines that it would not be reporting any PGM stocks during the current period due to forced removal by armed robbery.

There are several different types of PGM stocks. Table 4-1 categorizes PGM stocks in the United States and indicates whether reliable data are regularly reported on each of them.

The following sections discuss each kind of stock and available information about their size.

U.S. NATIONAL STOCKPILE

Currently, the U.S. government maintains stockpiles of three platinum-group metals -- platinum, palladium, and iridium. As Table 4-2 indicates, current inventories of each metal are well below stated goals of the General Services Administration (GSA), which is in charge of maintaining stockpiles of U.S. critical materials. The current total PGM inventory of 1,725,000 troy ounces has not changed since 1971.

There is industry speculation that the GSA may soon purchase PGMs. One mechanism that would facilitate this purchase is the proposed National Defense Stockpile Transaction Fund. Monies entering the fund through sale of commodities in excess of their goals can be used to purchase other commmodities in deficit. Silver and tin are two excess commodities, although recent GSA efforts to sell silver have been stopped in Congress.

The anticipated military buildup under the Reagan administration, according to industry sources, is expected to lead to primary focus on platinum-group metals and cobalt for stockpile acquisition. (See American Metal Market, 1981.) It is too early to tell how much of the PGM stockpile deficit will be eliminated and, of course, planning of GSA activities in commodity markets is kept secret in order to avoid speculative reaction.

REFINER, IMPORTER, AND DEALER STOCKS

U.S. Bureau of Mines data on stocks of PGMs held by refiners, importers, and dealers from 1975 to 1980 are reproduced in Table 4-3. The figures show a squeezing down of inventories starting in 1978 due to higher metals prices and strong demand. Figure 4-1 plots the changing composition of refiner, importer, and dealer stocks among the PGMs during the 1970s.

Table 4-1

PLATINUM GROUP METAL STOCKS

Type	Regular Data Reported?
U.S. National Stockpile	Yes
Refiner, Dealer, and Importer Stocks	Yes
Industry Shelf Stocks	No
Industry Stocks in Use	No
Private Speculative/Investment Stocks	No

SOURCE: Charles River Associates, 1981.

Table 4-2

CURRENT STATUS OF U.S. NATIONAL DEFENSE STOCKPILE
(Thousands of Troy Ounces)

Material	Goal	Current Inventory
Platinum	1,310	453
Palladium	3,000	1,255
Iridium	98	17
Total	4,408	1,725

SOURCE: U.S. Bureau of Mines, 1981, Mineral Commodity Summaries, Washington, D.C.: U.S. Government Printing Office.

Table 4-3

REFINER, IMPORTER, AND DEALER STOCKS OF PLATINUM GROUP METALS, 1975-1980*
(Troy Ounces)

Year	Platinum	Palladium	Rhodium
1975	420,770	335,621	53,847
1976	536,318	459,765	47,769
1977	438,045	475,358	48,392
1978	369,823	369,937	51,322
1979	305,605	323,865	47,678
1980**	493,000	293,831	46,421

*Includes metal in depositories of the New York Mercantile Exchange.

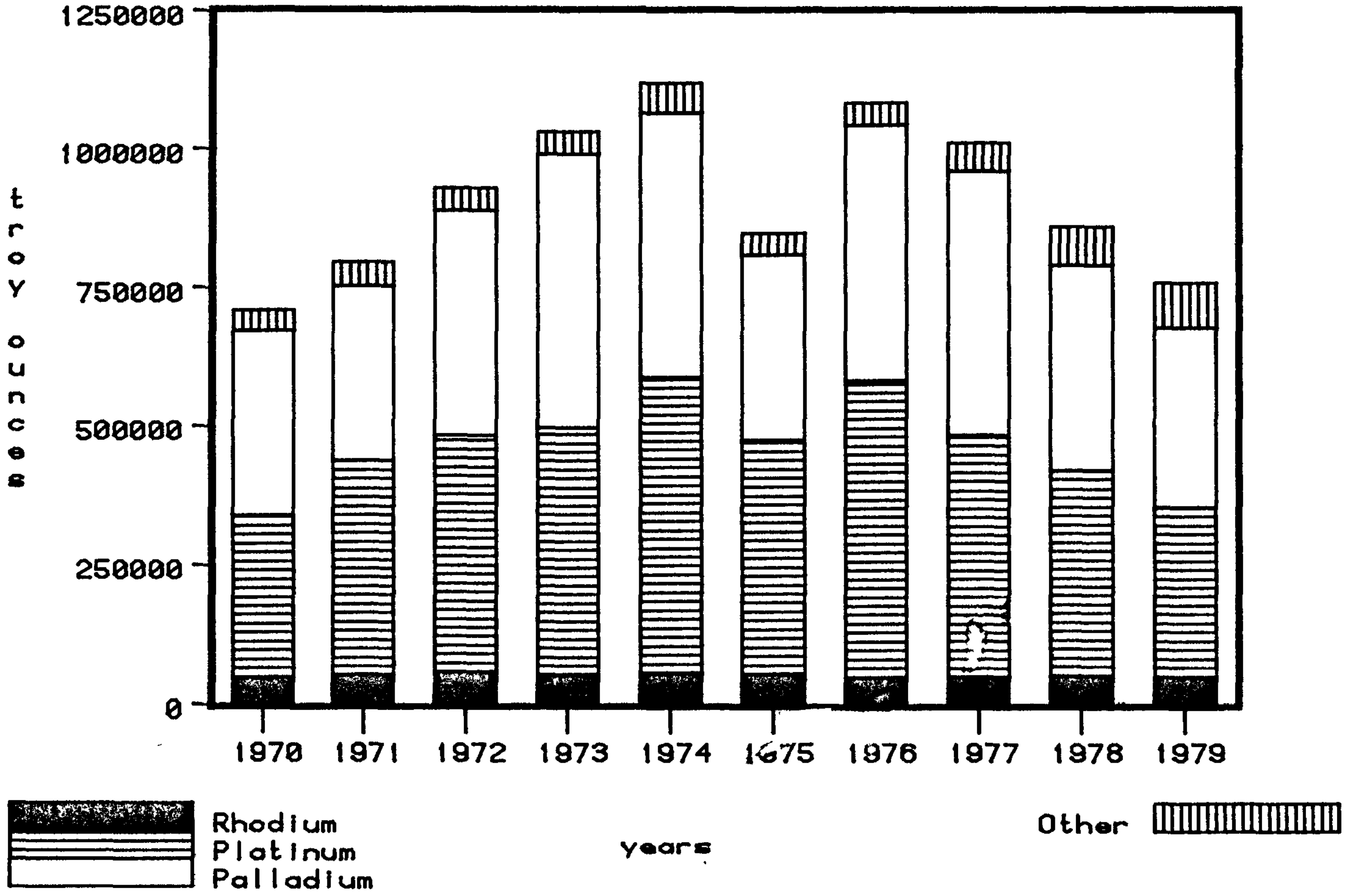
**As of December 31, 1980.

SOURCE: U.S. Bureau of Mines, various issues, *Minerals Yearbook* and *Mineral Industry Surveys*, various issues, Washington, D.C.: U.S. Government Printing Office.

Figure 4—1

Platinum Group Metal Stocks held by Refiners, Importers, & Dealers

(Prepared By: Charles River Associates)



SOURCE: U.S. Bureau of Mines, Minerals Yearbook,
Mineral Industry Surveys, various issues, Washington, D.C.

The U.S. Bureau of Mines (U.S. BOM) collects these data by sending out a questionnaire to all U.S. domestic refiners, dealers, and importers. U.S. BOM sources indicate that the returned questionnaires capture about 90 percent of the firms. A U.S. BOM telephone survey revealed that the less than ten percent of firms that did not respond dealt with minute quantities of PGMs. Hence, it can be safely concluded that the U.S. BOM reports capture well over 95 percent of refiner, importer, and dealer PGM stocks.

INDUSTRY SHELF STOCKS

There exist no published data on the amount of platinum-group metals held in inventory for future use by industries in the United States or abroad. Firms generally will not disclose information of this nature, so knowledgeable industry observers willing to talk are one of the few readily available sources of information on industry PGM shelf stocks.

The National Materials Advisory Board (NMAB) in their recent report on government PGM stockpiling strategies stated that the chemical, petroleum, and glass industries hold large inventories of PGMs. (See NMAB, 1980.) However, the NMAB did not provide any order of magnitude estimates of industry shelf stocks. The only bit of quantitative information in their report on shelf stocks is that from 1971 to 1977 the petroleum industry added an estimated 350,000 to 450,000 troy ounces of platinum to its shelf stockpiles.

Discussions with knowledgeable industry observers have tended to corroborate the NMAB claim that the petroleum, chemical, and glass industries maintain large PGM inventories. One source stated that the chemical industry probably has over one year's supply of replacement needs, and the source "firmly believed" that the glass industry has one year's supply as well. Another source stated that petroleum companies sometimes lease their PGM stocks and usually have one year's supply as shelf stocks.

Applying this one-year estimate to data on sales to consuming industries data, one can arrive at lower bound estimates for PGM shelf stocks for the chemical, petroleum, and glass industries (Table 4-4). (See Tables 4-21 and 4-23 for basic data.)

The U.S. automobile industry, the largest domestic user of platinum and rhodium, and the third largest user of palladium (in 1979), is completely secretive about its PGM inventories. It is reported, however, that the automobile companies purchase PGMs directly from primary producers, and in turn sell them back to catalyst manufacturers such as Engelhard or Johnson-Matthey. Auto company personnel interviewed would not divulge the size of their PGM inventories.

Table 4-4

LOWER-BOUND ESTIMATES OF PLATINUM GROUP METAL SHELF STOCKS, BASED ON 1979 RATES OF CONSUMPTION
(Troy Ounces)

Industry	Platinum	Palladium	Rhodium
Chemical	98,600	199,743	11,684
Petroleum	170,013	24,588	1,223
Glass	88,594	1,729	15,276

SOURCE: Order of magnitude estimates by Charles River Associates, 1981.

INDUSTRY STOCKS IN USE

Platinum-group metals actually being used in production processes are referred to as PGM "stocks in use," because in many industries (e.g., chemical, glass, and petroleum) PGMs are used as catalysts or otherwise indirectly, and loss rates are quite low. In petroleum refining, for example, platinum is used as a catalyst and thus not consumed by the production process, but it must be periodically recycled because of high temperatures and contamination; the loss rate is around 3 percent during recycling. For the chemical industry the recycling loss rate is about 18 percent, and for the glass industry about 3 percent.

In a 1976 report, (CRA, 1976) CRA used these loss rates, data on industry growth, and current annual industry PGM consumption data to arrive at order of magnitude estimates of stocks in use. Very rough estimates of 1979 stocks in use can be generated from these original estimates and the ratio of current to previous annual PGM consumption by industry. These estimates are provided in Table 4-5.

There are dangers inherent in this estimation methodology, however. First, Bureau of Mines consumption data are not comprehensive, but are based on reported sales to consuming industries. In its annual Mineral Commodity Summaries, the Bureau of Mines calculates "apparent consumption" with an accounting formula based on imports, and this figure is always well above reported sales to consuming industries.* A second difficulty with an estimation method of this nature is that industries purchase PGMs not only to replenish stocks in use, but also to adjust shelf stocks. If in a given year an industry's shelf stocks are being increased, consumption would be high and so would the subsequent stock-in-use estimates.

In late 1980 CRA designed, for the U.S. Department of the Interior, a new model of platinum and palladium consumption and production that focused on engineering estimates of the speed and extensiveness with which consumption of the two metals could be reduced after supply disruptions so severe that their price would rise to five or ten times normal levels (which is considerably beyond the range of historical experience).

Part of this modeling effort involved estimating the typical holding period prior to recycling of stocks in use, and estimating recovery rates. This

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*The accounting formula is:

> Mine Production + Secondary Refining Production + (Imports - Exports) + (Beginning Stocks - Ending Stocks).

Table 4-5

ESTIMATES OF PLATINUM AND PALLADIUM STOCKS IN USE, 1979
(Troy Ounces)

Industry	Platinum	Palladium
Petroleum	1,787,500	849,940
Chemical	1,158,168	1,874,896
Glass	1,098,900	24,040
Electrical	1,653,106	5,027,132
Other*	1,895,528	3,924,000

*Includes jewelry, medical, dentistry, and miscellaneous.

SOURCE: Charles River Associates estimates, based on U.S. Bureau of Mines, Minerals Yearbook, various issues, Washington, D.C.: U.S. Government Printing Office.

model will provide more sophisticated estimates of platinum and palladium stocks in use, which would largely overcome the two difficulties described above. Unfortunately, this platinum-palladium model has not yet been fully implemented for computation.

The stock-in-use estimates shown in Table 4-5 are rough order of magnitude numbers, and the confidence intervals are unknown. They serve as a useful reference point, however.

PRIVATE SPECULATIVE/INVESTMENT STOCKS

Platinum-group metals have recently become an object of private speculative investment, probably due in large measure to the realization that the United States is extremely import dependent and industrial use is rising. The New York Mercantile Exchange sponsors trade in platinum futures contracts, in response to this interest by investors outside the chain of producers and consumers.

Absolutely no estimates are published on the amount of PGMs in the hands of private investors. The Bureau of Mines omits sales to private investors from the "miscellaneous sales" category in its publications, because of confidentiality problems due to the small number of buyers. Bureau personnel have indicated that these undisclosed numbers have been quite small to date, however.

In commodities futures trading, only a small percent of the contracts are actually consummated by delivery, because an investor's long or short position is usually nullified with an offsetting contract before the specified delivery date. At that point, profits or losses are counted and the trader is out of the market, for richer or poorer. Hence, the amount of existing valid platinum futures contracts or "open interest" is not the proper indication of how much metal is actually trading hands through the futures market. In general, it seems unlikely that much platinum is being held by individuals who fear economic or political chaos, and consequent depreciation of paper currency. Such individuals seem much more likely to hold traditional media of exchange, such as gold or silver. Indications are, therefore, that the stock of PGMs in the hands of private investors is quite small relative to other kinds of stocks discussed in this section.

STOCKS AND INCREASED DEMAND IN THE SHORT RUN

The above order of magnitude estimates of various PGM stocks allow us to address the question of how large a gap between demand and supply they could bridge, given a one or two year lag in any response of primary production.

U.S. auto manufacturers could perhaps buy a small percentage of shelf stocks held by other industries at a moderate premium. However, astronomical prices probably would be required to induce sale of anything like a majority of shelf stocks held by other industries, particularly at times when market conditions were perceived to be more uncertain than usual.

Simple arithmetic demonstrates that, except for rhodium, U.S. government stockpiles could help meet increased PGM demand for the auto industry (Table 4-6). However, such action is highly uncertain due to the fact that government stocks are reserved for emergencies, unless compelling reasons lead to special Congressional action. No shipments from U.S. government PGM stockpiles have occurred in recent years.

Table 4-7 presents current refiner, importer, and dealer stocks as a percent of 1979 auto industry consumption. It is physically possible for these stocks to meet substantial percentage increases in auto industry PGM demands. However, evidence indicates that flows from this source can be price-inelastic. For example, while the dealer price for platinum increased 70.5 percent in 1978, refiner, importer, and dealer stocks of platinum fell by only 17.4 percent during that year. Similar price-inelastic behavior occurred for palladium and rhodium. These figures suggest that PGM prices might have to increase dramatically to encourage flows from stocks held by refiners, importers, and dealers in the United States. The price required to call forth these private stocks could be more moderate than these numbers suggest if the demand/supply gap is expected to be only temporary.

STATISTICAL OVERVIEW OF SUPPLY AND DEMAND

In this section, a brief outline of PGM supply and demand is presented to set the stage for subsequent analysis. First, data on world primary production are presented, and then industrial use of PGMs in the United States is described.

SUPPLY

Due to lags in data gathering and publication, country-specific estimates of world primary PGM production have been published by private sources only through 1977. More current production data, where available, are discussed in producer country profiles below. Tables 4-8 through 4-10 present world estimates by country of primary production for platinum, palladium, and rhodium, respectively. These tables reflect the central fact that over 98 percent of the world's primary production of platinum-group metals is

Table 4-6

U.S. NATIONAL STOCKPILES AS A PERCENT
OF 1979 AUTO INDUSTRY PLATINUM METAL GROUP CONSUMPTION
(Nominal Data in Troy Ounces)

	1979 Auto Industry Consumption	U.S. Stockpiles November 30, 1980*	Stockpiles as a Percent of Consumption (Column 2/Column 1)
Platinum	803,229	453,000	56.4
Palladium	222,156	1,255,000	565.00
Rhodium	26,136	0	0

*As of November 30, 1980.

SOURCE: U.S. Bureau of Mines, 1979, Minerals Yearbook, and 1981, Mineral Commodities Profiles, Washington, D.C.: U.S. Government Printing Office.

Table 4-7

RECENT U.S. REFINER, IMPORTER, AND DEALER STOCKS OF PLATINUM GROUP METALS AS A PERCENT OF 1979 AUTO INDUSTRY CONSUMPTION
(Troy Ounces)

	1979 Auto Industry Consumption	Refiner, Importer, and Dealer Stockpiles September 30, 1980	Stockpiles as a Percent of Consumption (Column 1/Column 2)
Platinum	803,229	402,310	50.1
Palladium	222,156	321,065	144.5
Rhodium	26,136	50,021	191.4

*As of August 30, 1980.

SOURCE: Charles River Associates Incorporated, 1981.

Table 4-8

ESTIMATED WORLD PRODUCTION OF PRIMARY PLATINUM BY COUNTRY, 1971-1977
(Thousands of Troy Ounces)

	1971	1972	1973	1974	1975	1976	1977
Australia	-	-	0	0	0	0	0
Canada	219	187	163	177	184	198	216
Colombia	26	24	26	21	23	26	25
Ethiopia	0	0	0	0	0	0	0
Japan*	3	4	4	4	5	9	10
Philippines	1	3	2	1	1	-	-
South Africa	750	870	1,416	1,700	1,559	1,680	1,740
USSR	690	705	735	750	795	840	840
United States*	10	4	6	4	5	-	-
Total	1,701	1,799	2,354	2,658	2,572	2,753	2,831

*Production of refined metal, some from imported ores and crude palladium.

SOURCE: U.S. Bureau of Mines, Minerals Yearbook, various issues, Washington, D.C.: U.S. Government Printing Office; and Roskill Information Services, Ltd., 1979, The Economics of Platinum Group Metals, London.

Table 4-9

ESTIMATED WORLD PRODUCTION OF PRIMARY PALLADIUM BY COUNTRY, 1971-1977
(Thousands of Troy Ounces)

	1971	1972	1973	1974	1975	1976	1977
Australia	-	-	1	1	1	2	2
Canada	190	162	142	154	160	172	188
Japan*	5	6	6	11	14	18	20
Philippines	2	5	4	2	1	-	-
South Africa	438	508	826	991	909	980	1,015
United States*	10	11	13	9	11	6	5
USSR	1,380	1,410	1,470	1,500	1,590	1,680	1,680
Total	2,026	2,103	2,463	2,669	2,687	2,859	2,910

*Production of refined metal, some from imported ores and crude palladium.

SOURCE: U.S. Bureau of Mines, various issues, Minerals Yearbook, Washington, D.C.: U.S. Government Printing Office; and Roskill Information Services, Ltd., 1979, The Economics of Platinum Group Metals, London.

Table 4-10

ESTIMATED WORLD PRODUCTION OF PRIMARY
RHODIUM BY COUNTRY, 1971-1977 (Thousands of Troy Ounces)

	1971	1972	1973	1974	1975	1976	1977
Canada	14	12	11	11	12	14	14
South Africa	44	51	83	99	91	98	101
U.S.A.	0	0	0	0	0	0	0
U.S.S.R.	46	47	49	50	53	56	56
Total (countries listed)	104	110	143	160	156	168	171

SOURCE: Estimates by Roskill Information Services, Ltd.

obtained from only three countries -- South Africa, the Soviet Union, and Canada. Canada is a junior member of the "big three"; clearly the Soviet Union and South Africa dwarf other PGM producing countries. South Africa predominates in platinum with 61.5 percent of world production in 1977, while the Soviet Union dominates in palladium with 57.7 percent of world production in 1977. South Africa accounted for 59.1 percent of 1977 world rhodium production, as reported by Roskill; the corresponding percentages for the Soviet Union and Canada were 32.7 and 8.2, respectively.

These tables also indicate that U.S. production of PGMs is inconsequential; we are almost completely import-dependent. This situation is expected to be mitigated in the future, however, with the development of U.S. PGM deposits discussed below.

Tables 4-11 through 4-14 indicate the countries upon which the United States is directly import dependent. Countries that are important exporters to the United States differ somewhat from the primary producing countries, because ores and concentrates are often exported to other countries for refining. In the long run, the distribution of output among the primary producing countries is by far the more important consideration. However, in the short run, trade patterns can be difficult to redirect due to long-term contracts between producers, refiners, and users, the location of processing facilities, and similar considerations. Thus, existing trade patterns are of some importance for analyzing the short-run effects of supply disruptions.

Table 4-11 contains data for all platinum-group metals, while Tables 4-12, 4-13, and 4-14 pertain to platinum, palladium, and rhodium, respectively. The importance of the United Kingdom as an exporter of PGMs to the United States is clear from the tables. The United Kingdom is important because of refining done there by companies like Johnson-Matthey, which owns part of Rustenburg Platinum Mines, South Africa's largest platinum mine. Other countries that export sizable amounts of PGMs to the United States include Japan and Switzerland. Figures 4-2 through 4-5 aid in the interpretation of the import data for platinum, palladium, and rhodium. These graphs trace major countries' changing shares of the U.S. import market throughout the 1970s. Two related trends emerge clearly: the increasing importance of South Africa and the decreasing importance of the Soviet Union in the 1970s.

U.S. refining of platinum-group metals throughout the 1970s is outlined in Tables 4-15 through 4-18. Data are presented on primary and secondary toll and nontoll refining for all platinum group metals. Data are presented separately for platinum, palladium, and rhodium.

U.S. primary refining has sharply fallen over the 1970s. These data in part reflect South African efforts to refine more metal within that country, rather than exporting ores or concentrates.

Table 4-11

U.S. IMPORTS FOR CONSUMPTION OF PLATINUM METALS BY COUNTRY,[1] 1970-1980

(Troy Ounces)

Country	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980
Australia	6,093	5,099	8,352	4,904	--	6,476	6,280	1,600	--	--	10,396
Belgium-Luxembourg	14,184	24,466	15,917	21,807	37,056	30,418	31,416	26,249	49,472	34,783	102,246
Canada	24,745	51,365	39,605	33,281	57,972	57,962	93,648	88,510	90,305	80,668	98,330
Chile	--	--	--	1,761	--	--	--	--	1,608	--	--
Colombia	27,547	26,856	25,535	27,210	20,165	21,588	18,201	7,989	14,550	15,707	3,988
France	--	5	--	953	2,205	2,244	11,985	7,074	--	--	5,735
Germany, Federal Republic of	10,320	9,684	19,676	10,957	12,731	22,490	36,014	25,370	--	--	54,140
Italy	--	1,240	--	--	--	350	5,409	2,800	33,408	7,723	15,194
Japan	25,628	24,170	111,875	164,468	208,119	51,567	19,864	18,581	29,597	35,002	22,388
Mexico	6,411	4,624	15,669	12,935	25,980	12,132	20,424	152,402	106,780	31,867	41,997
Netherlands	10,021	781	1,428	49,649	6,206	6,000	6,130	10,602	29,014	33,068	59,304
Norway	11,676	12,553	23,361	38,287	74,974	36,137	28,103	19,480	13,798	32,085	17,629
Romania	--	--	--	--	--	--	--	2,680	--	--	--
South Africa, Republic of	115,500	165,672	237,697	245,411	1,016,458	837,081	1,241,669	1,267,191	1,591,925	2,083,209	1,908,325
Sweden	--	4,067	2,807	4,253	8,077	9,531	7,679	4,067	--	--	8,929
Switzerland	1,671	470	2,099	29,149	9,381	11,547	13,641	20,440	23,178	40,324	31,096
USSR	494,978	407,628	736,264	882,267	1,012,321	331,267	652,112	617,215	552,666	693,215	376,747
United Kingdom	651,895	558,009	589,711	806,423	734,458	362,168	455,193	226,657	343,503	305,522	503,321
Yugoslavia	--	--	--	--	--	1,225	4,862	3,876	--	--	3,247
Other	131,138	91,354[3]	62,188[4]	168,918[5]	14,502[6]	20,101[7]	14,429[8]	7,591	41,607	85,955	242,930[9]
Total	1,531,807	1,388,043	1,892,184	2,502,633	3,240,605	1,820,284	2,667,059	2,510,374	2,921,411	3,479,128	3,505,942

Table continued on following page.

Table 4-11 (Continued)

U.S. IMPORTS FOR CONSUMPTION OF
PLATINUM METALS BY COUNTRY[1], 1970-1980
(Troy Ounces)

[1] Includes unwrought and semimanufactured platinum-group metals, unspecified combinations, platinum-group metals from precious metal ores, sweeping, waste, scrap, and materials not elsewhere specified.

[2] January-December 1980.

[3] Includes Argentina, Austria, Brazil, Denmark, Finland, Panama, Peru, Surinam, and New Zealand.

[4] Includes Botswana, Brazil, Costa Rica, Finland, Ghana, Malawi, Netherlands-Antilles, New Zealand, Panama, Turkey, Venezuela.

[5] Includes Brazil, Costa Rica, El Salvador, Finland, Ireland, Panama, New Zealand, Uruguay, and Venezuela.

[6] Includes Republic of Korea.

[7] Includes Costa Rica, Finland, and Panama.

[8] Includes Costa Rica, Finland, Peru, and Portugal.

[9] Includes Argentina, Costa Rica, Finland, Hong Kong, and Namibia.

SOURCE: U.S. Bureau of Mines, Minerals Yearbook and Mineral Industry Survey, various issues, Washington, D.C.: U.S. Government Printing Office.

Table 4-12

PLATINUM IMPORTS FOR CONSUMPTION IN THE UNITED STATES BY COUNTRY,[1] 1970-1980

(Troy Ounces)

Country	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980[2]
Australia	--	--	--	--	--	--	240	--	--	--	--
Belgium-Luxembourg	1,004	150	220	--	1,467	2,180	1,181	--	7,187	4,768	12,187
Canada	2,957	2,061	2,647	278	2,128	1,810	1,620	3,462	6,328	1,815	33,452
Colombia	22,163	22,027	17,220	23,496	12,300	12,600	--	--	1,252	--	119
France	--	5	--	953	--	--	7,873	2,770	--	--	225
Germany, Federal Republic of	3,140	9,260	9,253	5,150	2,296	1,976	14,034	8,273	--	--	17,085
Italy	--	1,240	--	--	--	302	5,409	--	20,178	9,231	13,551
Japan	12,840	18,503	37,316	49,706	45,246	10,011	8,170	2,498	10,019	19,090	15,471
Mexico	37	--	269	112	15	112	--	2,313	347	--	--
Netherlands	5,309	150	--	305	--	2,252	1,199	3,309	3,451	1,452	13,754
Norway	4,707	6,713	8,237	7,234	13,601	9,229	8,369	4,801	4,556	10,842	6,611
Romania	--	--	--	--	--	--	--	2,680	--	--	--
South Africa, Republic of	97,541	116,818	107,339	89,294	597,569	412,166	693,994	675,010	933,411	1,199,601	1,059,512
Sweden	--	--	--	--	--	--	550	--	--	--	193
Switzerland	1,017	12	--	11,079	5,669	6,554	3,510	8,100	9,770	16,912	24,331
USSR	31,078	69,241	169,394	86,757	108,580	33,642	50,430	10,432	20,210	25,640	15,892
United Kingdom	306,705	224,176	260,697	399,768	313,726	189,589	195,336	95,955	158,175	130,369	219,493
Yugoslavia	--	--	--	--	--	--	482	--	--	--	643
Other	1,709	375[3]	3,795[4]	--	1,034[5]	926[6]	7,900[7]	3,277	9,331	14,491	4,705[8]
Total	490,207	470,731	616,387	674,132	1,103,631	683,349	1,000,297	822,880	1,174,215	1,434,211	1,436,338

Table continued on following page.

Table 4-12 (Continued)

PLATINUM IMPORTS FOR CONSUMPTION
IN THE UNITED STATES BY COUNTRY,[1] 1970-1980
(Troy Ounces)

[1] Includes unwrought platinum grains, nuggets, sponge, and semimanufactured platinum. Excludes small amounts of platinum contained in sweepings, waste, scrap, and unspecified combinations.

[2] January-December 1980.

[3] Includes Denmark.

[4] Includes Botswana, Brazil, Costa Rica, Finland, Ghana, Malawi, New Zealand, Panama, and Turkey.

[5] Includes Republic of Korea.

[6] Includes Costa Rica and Panama.

[7] Includes Peru and Portugal.

[8] Includes Argentina, Costa Rica, Finland, Hong Kong, Namibia, Cyprus, and Israel.

SOURCE: U.S. Bureau of Mines, Minerals Yearbook and Mineral Industry Survey, various issues, Washington, D.C.: U.S. Government Printing Office.

Table 4-13

PALADIUM IMPORTS FOR CONSUMPTION IN THE UNITED STATES BY COUNTRY,[1] 1970-1980

(Troy Ounces)

Country	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980[2]
Australia	--	--	974	--	--	1,124	--	--	--	--	--
Belgium-Luxembourg	24	8,525	--	--	665	2,725	2,744	6,592	32,337	12,573	51,053
Canada	2,275	18,279	13,512	5,092	18,955	11,739	16,773	21,840	20,821	23,800	25,736
Colombia	--	--	--	--	--	--	--	--	--	--	--
France	--	--	--	--	1,905	1,979	3,363	1,000	--	--	200
Germany, Federal Republic of	4,538	--	6,840	5,718	4,882	16,604	16,305	6,334	--	--	32,885
Italy	--	--	--	--	--		--	--	--	--	--
Japan	502	--	34,310	5,496	57,628	8,920	260	15,730	6,286	2,534	4,549
Mexico	--	--	--	--	8	--	--	--	--	5	91
Netherlands	3,252	631	520	42,366	750	2,609	2,436	3,387	4,119	18,866	37,759
Norway	6,969	5,840	15,124	6,950	7,390	11,555	9,304	8,962	6,454	14,657	5,925
South Africa, Republic of	10,637	39,163	111,920	137,615	319,854	294,481	444,119	486,639	498,786	690,439	648,987
Sweden	--	888	--	--	--	4,500	650	--	--	--	--
Switzerland	28	458	2,098	16,450	1,502	4,447	8,431	2,330	11,233	19,812	2,003
USSR	456,206	332,909	523,112	668,737	763,343	75,076	427,102	514,249	503,438	602,307	339,570
United Kingdom	287,457	254,643	193,819	265,881	160,172	117,118	187,152	81,416	121,134	95,002	164,231
Yugoslavia	--	--	--	--	--	1,225	3,922	3,198	--	--	2,604
Other	1,929	2,012[3]	--	--	1,033[4]	--	750[5]	--	19,485	24,439	995[6]
Total	773,817	663,348	902,229	1,154,305	1,338,087	554,102	1,123,311	1,151,677	1,224,093	1,504,434	1,316,588

Table continued on following page.

Table 4-13 (continued)

PALADIUM IMPORTS FOR CONSUMPTION
IN THE UNITED STATES BY COUNTRY,[1] 1970-1980
(Troy Ounces)

[1] Includes unwrought and semimanufactured palladium. Excludes small amounts of palladium contained in sweepings, waste, scrap, and unspecified combinations.

[2] January-December 1980.

[3] Includes Austria and Denmark.

[4] Includes Republic of Korea.

[5] Includes Peru.

[6] Includes Namibia.

SOURCE: U.S. Bureau of Mines, Minerals Yearbook and Mineral Industry Survey, various issues, Washington, D.C.: U.S. Government Printing Office.

Table 4-14

RHODIUM IMPORTS FOR CONSUMPTION IN THE UNITED STATES BY COUNTRY,[1] 1970-1980
(Troy Ounces)

Country	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980[2]
Australia	--	--	--	--	--	--	--	--	--	--	--
Belgium-Luxembourg	68	39	--	--	1,210	--	--	--	1,044	725	57
Canada	3,500	--	428	--	467	897	2,272	2,191	510	1,186	230
Colombia	4,160	2,932	--	--	--	--	--	--	--	--	--
France	--	--	--	--	300	--	628	2,946	--	--	--
Germany, Federal Republic of	1,465	323	27	3	1,406	3,028	1,548	947	--	--	643
Italy	--	--	--	--	--	--	--	--	--	--	129
Japan	1,320	--	3,213	--	6,567	12,831	--	353	106	866	128
Mexico	--	--	6	113	8	--	--	--	53	--	--
Netherlands	--	--	--	262	96	300	--	342	2,495	1,559	914
Norway	--	--	--	--	--	--	--	132	77	699	1,007
South Africa, Republic of	714	335	2,524	2,045	8,622	15,810	26,208	33,690	53,041	65,157	81,891
Sweden	--	--	--	--	--	--	--	--	--	--	64
Switzerland	--	--	1	--	--	100	1,200	1,288	750	250	50
USSR	7,694	5,478	7,139	34,344	34,646	37,977	12,699	19,743	23,453	17,310	8,482
United Kingdom	22,091	25,555	37,078	56,444	45,285	11,025	19,306	18,308	20,893	19,610	15,387
Other	--	--	388[3]	--	--	61[4]	263	--	516	1,656	1,295[5]
Total	41,012	34,662	50,804	93,211	98,607	82,029	64,124	79,940	102,938	109,018	110,277

Table continued on following page.

Table 4-14 (Continued)

RHODIUM IMPORTS FOR CONSUMPTION
IN THE UNITED STATES BY COUNTRY,[1] 1970-1980
(Troy Ounces)

[1] Includes unwrought and semimanufactured rhodium. Excludes small amounts of rhodium contained in sweepings, waste, scrap, and unspecified combinations.

[2] January-December 1980.

[3] Includes Botswana, Brazil, Costa Rica, Finland, Ghana, Malawi, Netherlands-Antilles, Panama, Turkey, and Venezuela.

[4] Includes Finland.

[5] Includes Finland and Namibia.

SOURCE: U.S. Bureau of Mines, Minerals Yearbook and Mineral Industry Survey, various issues, Washington, D.C.: U.S. Government Printing Office.

Table 4-15

TOTAL PRIMARY AND SECONDARY PLATINUM-GROUP METALS REFINED IN THE UNITED STATES, 1970-1979

(Troy Ounces)

	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979
Primary Metal:										
Nontoll Refined	19,822	21,184	15,380	19,916	13,234	16,571	7,101	5,199	8,303	8,392
Toll Refined	270,335	233,850	84,219	38,566	20,107	17,174	10,232	1,083	1,354	476
Total	290,157	255,034	99,599	58,482	33,341	33,745	17,333	6,282	9,657	8,868
Secondary Metal:										
Nontoll Refined	350,176	278,175	255,641	265,901	325,216	270,101	215,355	195,219	257,191	309,022
Toll Refined	1,451,535	1,218,988	1,277,404	1,000,623	1,067,915	1,158,294	859,432	1,003,940	1,021,960	1,090,202
Total	1,801,711	1,497,163	1,533,045	1,266,524	1,393,131	1,428,395	1,074,787	1,199,159	1,279,151	1,399,224

SOURCE: U.S. Bureau of Mines, Minerals Yearbook, various issues, Washington, D.C.: U.S. Government Printing Office.

Table 4-16

PRIMARY AND SECONDARY PLATINUM
REFINED IN THE UNITED STATES, 1970-1979
(Troy Ounces)

	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979
Primary Metal:										
Nontoll Refined	8,036	10,198	3,708	5,560	4,103	5,292	2,748	831	1,081	1,980
Toll Refined	183,264	156,599	54,773	32,883	16,293	14,619	8,676	466	177	56
Total	191,300	166,797	58,481	38,443	20,396	19,911	11,424	1,297	1,258	2,036
Secondary Metal:										
Nontoll Refined	118,298	103,429	75,942	94,884	95,999	103,623	64,901	50,838	75,585	75,038
Toll Refined	896,472	625,649	787,697	581,005	654,156	635,148	494,069	620,848	630,961	585,932
Total	1,014,770	729,078	863,639	675,889	750,155	738,771	558,970	671,686	706,546	660,970

SOURCE: U.S. Bureau of Mines, Minerals Yearbook, various issues, Washington, D.C.: U.S. Government Printing Office.

Table 4-17

PRIMARY AND SECONDARY PALLADIUM REFINED IN THE UNITED STATES, 1970-1979
(Troy Ounces)

	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979
Primary Metal:										
Nontoll Refined	10,322	10,237	10,836	13,121	8,634	10,968	4,025	4,300	7,222	6,412
Toll Refined	74,953	66,467	23,752	3,972	2,784	2,002	1,063	610	1,177	420
Total	85,275	76,704	34,588	17,093	11,418	12,970	5,088	4,910	8,399	6,832
Secondary Metal:										
Nontoll Refined	208,555	161,099	162,718	150,019	213,416	149,552	134,747	134,086	166,371	220,639
Toll Refined	494,758	527,375	431,248	373,396	365,779	437,809	311,000	327,450	344,022	446,189
Total	703,313	688,474	593,966	523,415	579,195	587,361	445,747	461,536	510,393	666,828

SOURCE: U.S. Bureau of Mines, Minerals Yearbook, various issues, Washington, D.C.: U.S. Government Printing Office.

Table 4-18

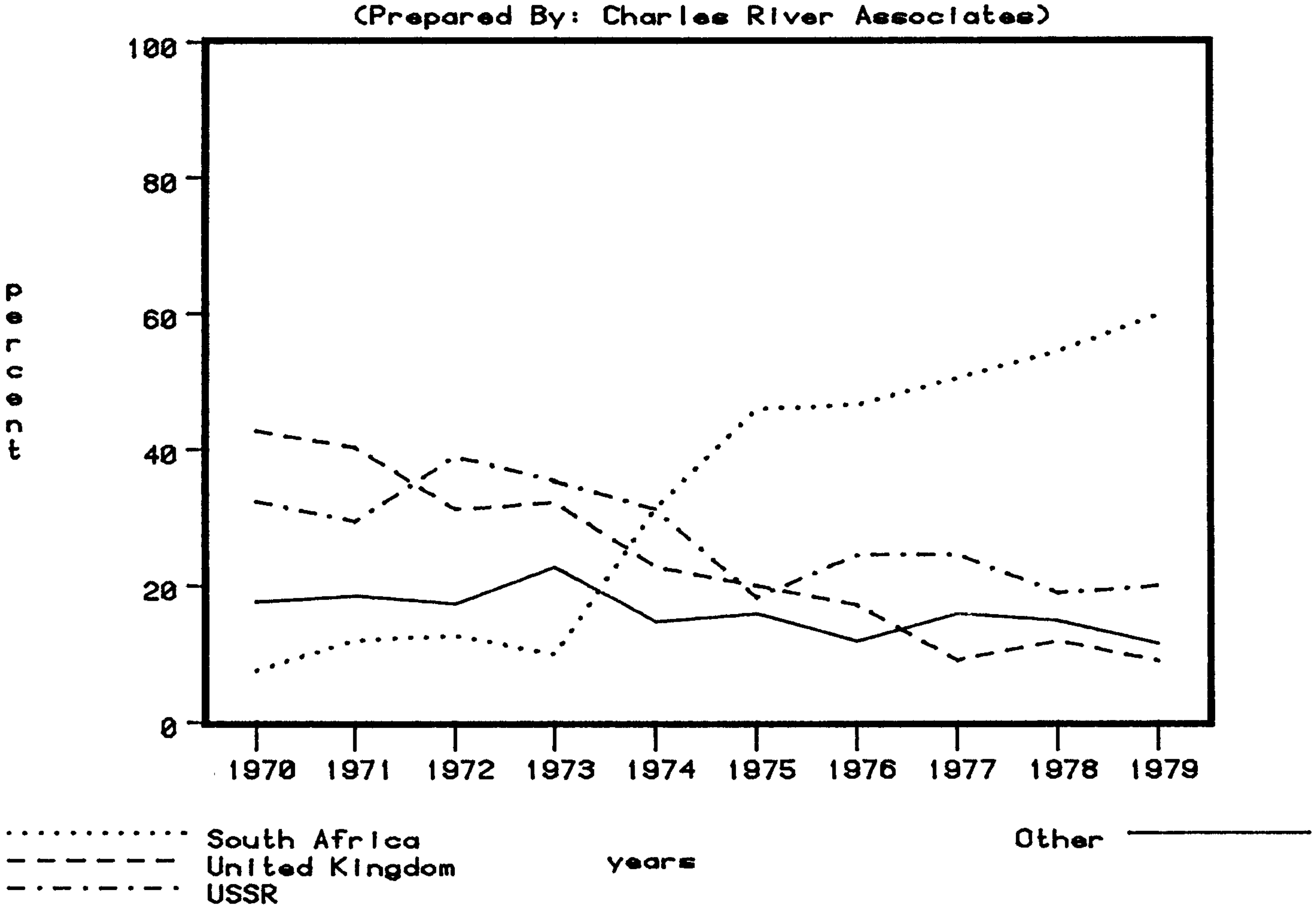
PRIMARY AND SECONDARY RHODIUM
REFINED IN THE UNITED STATES, 1970-1979
(Troy Ounces)

	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979
Primary Metal:										
Nontoll Refined	64	83	62	88	38	28	35	6	--	--
Toll Refined	8,885	8,118	3,354	381	185	164	95	3	--	--
Total	8,949	8,201	3,416	469	223	192	130	9	--	--
Secondary Metal:										
Nontoll Refined	13,394	8,837	11,390	11,561	11,127	13,683	8,058	5,011	8,266	7,964
Toll Refined	47,861	43,173	44,065	36,865	36,196	49,063	34,035	42,178	35,914	38,875
Total	61,255	52,010	55,455	48,426	47,323	62,746	42,093	47,189	44,180	46,839

SOURCE: U.S. Bureau of Mines, Minerals Yearbook, various issues, Washington, D.C.: U.S. Government Printing Office.

Figure 4–2

Percentage of Total U.S. Platinum-Group Metal Imports from Various Countries

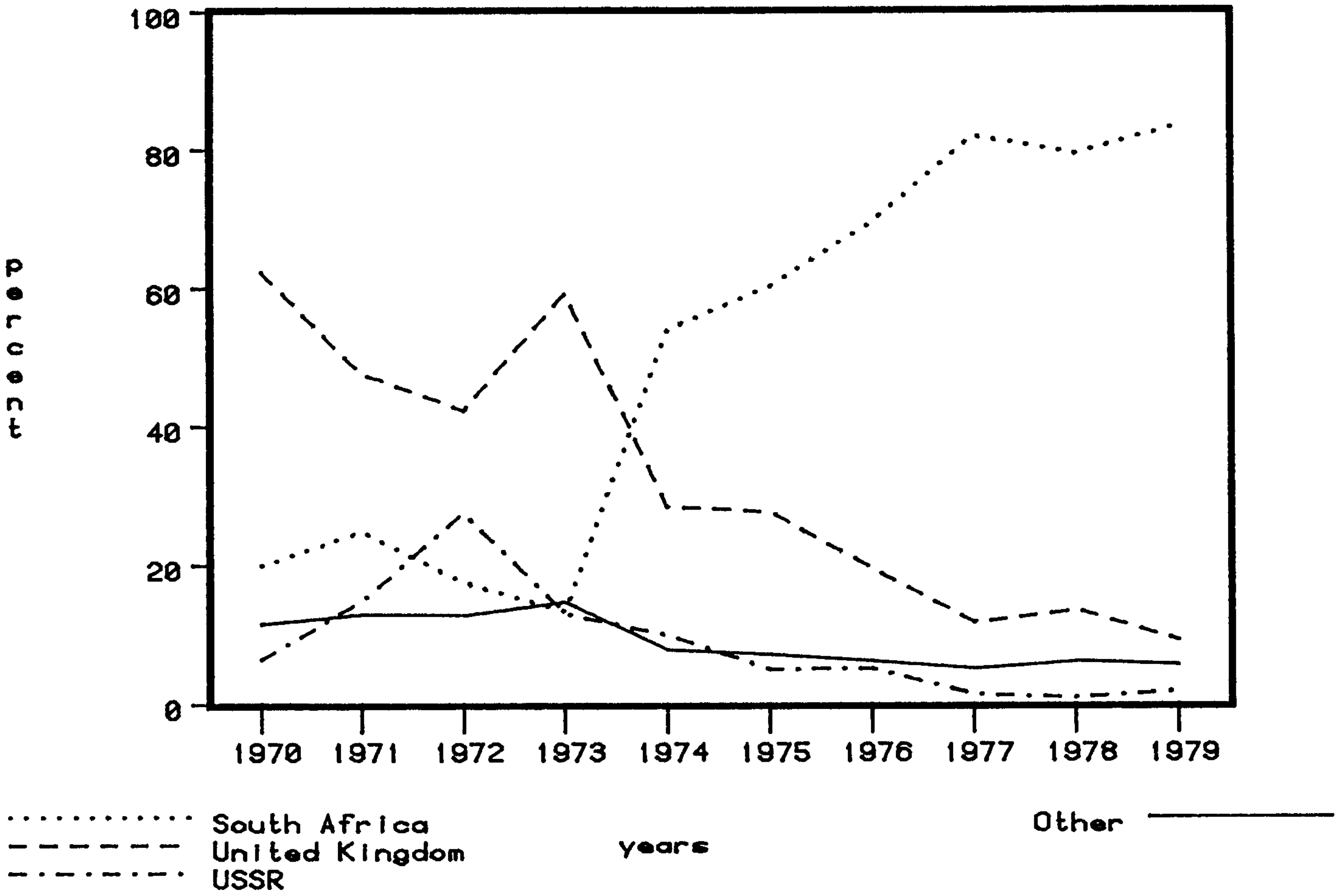


SOURCE: U.S. Bureau of Mines, Minerals Yearbook, Mineral Industry Surveys, various issues, Washington, D.C.

Figure 4—3

Percentage of Total U.S. Platinum Imports from Various Countries

(Prepared By: Charles River Associates)

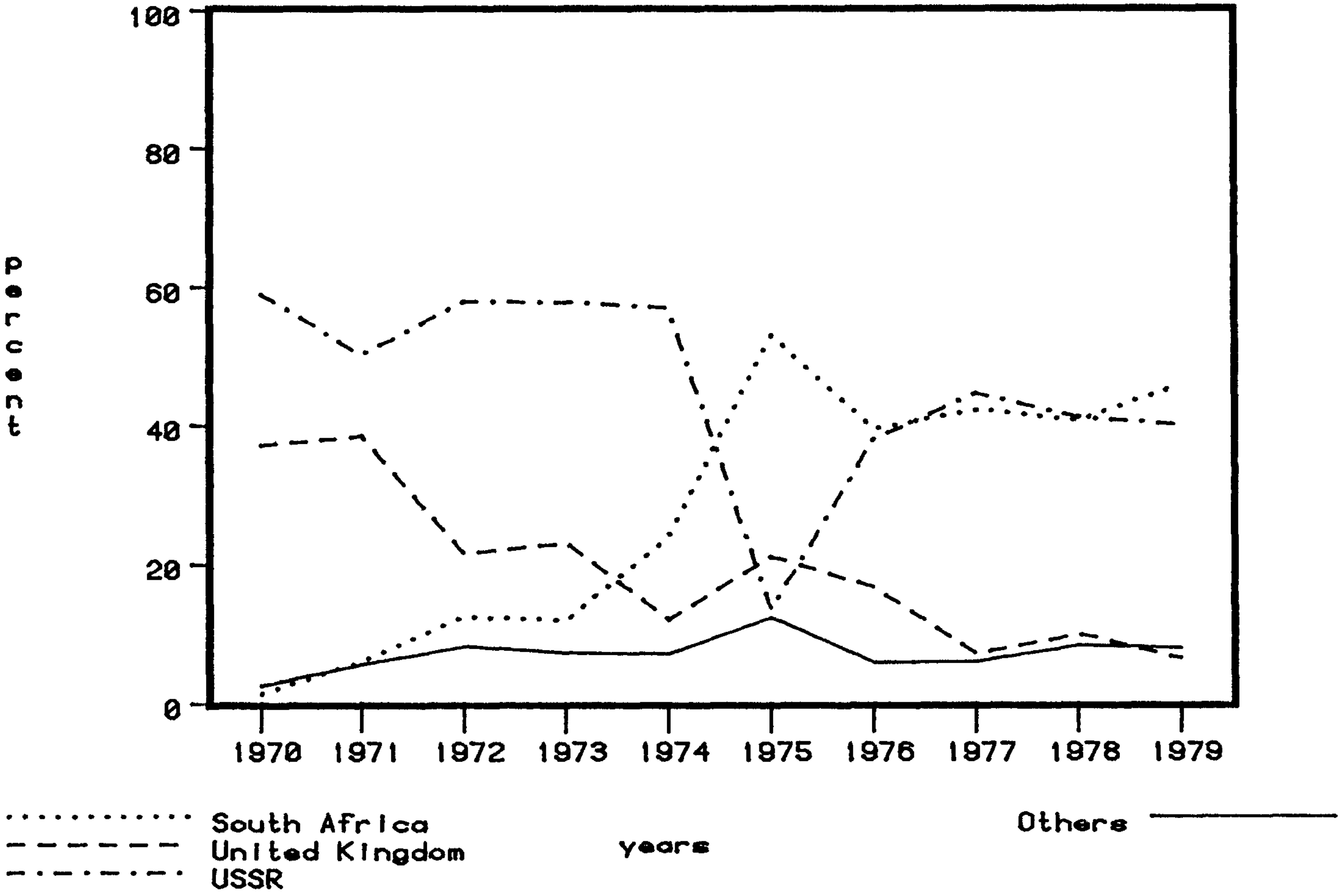


SOURCE: U.S. Bureau of Mines, Minerals Yearbook,
Mineral Industry Surveys, various issues, Washington, D.C.

Figure 4–4

Percentage of Total U.S. Palladium Imports from Various Countries

(Prepared By: Charles River Associates)

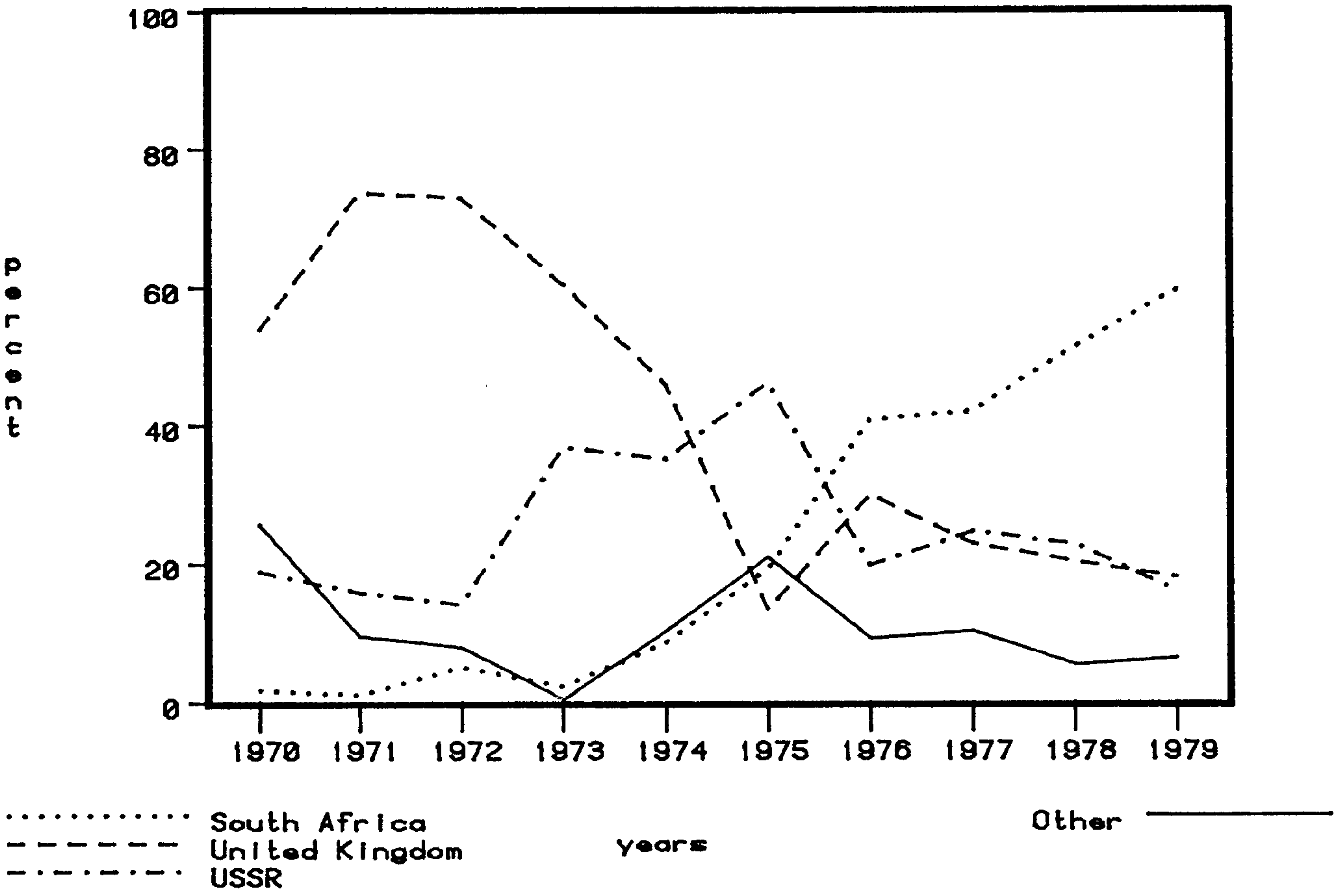


SOURCE: U.S. Bureau of Mines, Minerals Yearbook,
Mineral Industry Surveys, various issues, Washington, D.C.

Figure 4–5

Percentage of Total U.S. Rhodium Imports from Various Countries

(Prepared By: Charles River Associates)



SOURCE: U.S. Bureau of Mines, Minerals Yearbook, Mineral Industry Surveys, various issues, Washington, D.C.

Refining of secondary metal for all PGMs in the United States throughout the 1970s fluctuated within the 1.0 to 1.5 million ounce range, except for 1.8 million ounces in 1970 (Table 4-15). Individually, platinum, palladium, and rhodium secondary refining followed this fluctuating behavior throughout the last decade, with no readily discernable upward or downward trend (Tables 4-16 through 4-18).

Table 4-19 identifies trends in U.S. exports of PGMs throughout the 1970s. The data reveal that exports to Japan, Canada, and the United Kingdom have increased significantly, while exports to West Germany have trended downward.

DEMAND

Demand for PGMs fluctuates considerably, due to the overall level of economic activity, technological changes, and government policy actions (such as auto emission and lead-free gasoline mandates). This section presents a brief discussion of PGM industrial uses. In many applications PGMs operate like capital goods, the purchase of which often can be deferred. This fact exacerbates fluctuations in demand due to changes in economic activity (a phenomenon economists refer to as the "acceleration principle"), but also implies consumption can be forgone during supply disruptions.

CATALYTIC USES

A catalyst is a substance that initiates or speeds up a chemical reaction, while not being consumed itself. Platinum-group metals are excellent catalysts that are cost effective for many uses, even compared to other much less expensive metals such as nickel. A case in point is use of PGMs in catalytic converters. Currently, no alternative base-metal catalytic converter appears economical, as discussed at length in a later chapter. Catalytic uses of various types comprise by far the majority of U.S. PGM demand. Major catalytic applications are discussed below by consuming industry.

PETROLEUM INDUSTRY. Platinum metals are used as catalysts in the refining of petroleum products in three processes: catalytic reforming, hydrocracking, and isomerization. Reforming is generally the largest use of the three, and it has recently grown considerably. The platinum catalyst eventually fails due to high temperatures and contamination; it is then recycled, with about a 3 percent loss rate.

Table 4-19

U.S. EXPORTS OF PLATINUM-GROUP METALS, BY COUNTRY, 1970-1980
(Troy Ounces)

	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980[1]
Argentina	673	1,055	126	--	--	--	--	--	1,391	640	936
Australia	2,154	1,932	2,990	8,906	--	1,780	3,489	2,255	1,109	10,008	799
Belgium-Luxembourg	24,818	40,204	45,117	69,594	49,864	38,812	53,342	54,406	36,370	37,841	32,283
Brazil	7,644	1,490	5,289	6,057	--	6,351	--	1,176	10,147	6,816	4,634
Canada	11,299	18,506	10,069	20,358	30,666	39,607	47,854	33,263	51,606	62,396	72,399
Colombia	--	--	--	--	--	--	--	--	11,505	1,802	--
Finland	--	--	--	--	--	--	--	--	6,140	2,574	4,684
France	32,842	35,084	4,386	--	9,263	10,284	10,026	6,279	11,609	18,753	11,838
Germany, Federal Republic of	155,222	90,616	120,685	103,880	181,553	135,754	74,716	66,821	73,533	98,876	111,175
Hong Kong	157	1,015	1,235	--	--	--	--	--	2,906	1,487	984
Italy	16,770	10,934	19,221	--	--	20,387	7,007	1,718	1,721	8,774	6,393
Japan	70,811	94,265	254,460	310,940	247,432	168,774	118,857	110,547	225,222	328,889	237,963
Mexico	4,158	1,926	2,967	5,327	--	--	2,631	3,431	58,099	55,004	6,144
Netherlands	12,076	15,831	9,715	19,669	24,453	28,389	3,097	3,311	7,838	10,610	11,786
Norway	--	--	--	--	--	--	--	--	3,897	3,180	3,967
South Africa, Republic of	--	1,585	1,106	--	25,213	55,722	11,190	1,053	2,307	6,320	3,252
Sweden	--	--	--	--	--	--	--	--	15,951	17,739	4,249
Switzerland	8,415	4,437	4,964	7,819	95,053	43,238	32,785	38,875	26,963	48,710	67,194
Taiwan	--	--	--	--	11,267	--	5,985	1,979	1,643	116	--
United Kingdom	64,212	80,201	52,105	27,901	103,913	97,656	132,251	90,303	146,197	154,284	173,741
USSR	--	--	--	--	--	--	1,603	--	--	--	--
Other	2,515	5,529	4,559	47,075[2]	57,077[3]	19,131[3]	7,574[4]	11,114[5]	6,393	22,599[6]	10,543[7]
Total	413,766	404,610	538,994	627,526	835,754	665,885	512,407	426,631	702,547	899,598	764,964

Table continued on following page.

Table 4-19 (Continued)

U.S. EXPORTS OF PLATINUM-GROUP METALS, BY COUNTRY, 1970-1980
(Troy Ounces)

[1] January-December 1980.

[2] Includes People's Republic of China, Israel, and Spain.

[3] Includes Israel

[4] Includes Venezuela.

[5] Includes Ireland, Republic of Korea, and Peru.

[6] Includes Greece, Republic of Korea, Singapore, Spain, and Venezuela.

[7] Includes Greece, Ireland, Republic of Korea, Singapore, and Venezuela.

SOURCE: U.S. Bureau of Mines, Minerals Yearbook and Mineral Industry Survey, various issues, Washington, D.C.: U.S. Government Printing Office.

Catalytic reforming is the most efficient way known to raise the octane rating of gasoline without adding lead. The increasing use of lead-free gasoline in the United States insures that reforming will continue to be a major use of platinum metals, though sales to the petroleum industry for reforming may be considerably lower during the 1980s, after initial loadings of required increased reforming capacity have been completed (the economists' "accleration principle" in operation). Modern technology in newer plants, however, can reduce the platinum intensity of petroleum refining.

CHEMICAL INDUSTRY. The chemical industry is a major consumer of platinum, palladium, and rhodium for catalysis and pollution control. Nitric acid production is a major component of chemical industry consumption of platinum-group metals, accounting for about 30 percent of industry use of PGMs in an average year. Processing losses for PGMs used in nitric acid production are much higher relative to initial loadings than is the case for most other chemical uses.

AUTOMOTIVE INDUSTRY. The automotive industry is, in the early 1980s, by far the largest user of PGMs in the United States, predominantly for use in catalytic converters. New, highly sophisticated emission-control systems also make use of platinum in the coating of an exhaust gas oxygen sensor. The exact amount of platinum used in each sensor is proprietary, but the amount is much less than is found in convertors.

Previously, oxidation catalysts were used to reduce emissions, but with tighter standards for nitrogen oxide emissions, most U.S. car makers have switched to the new three-way catalyst. The oxidation catalyst uses approximately 0.05 troy ounces of platinum and palladium in a roughly 2 to 1 ratio. The three-way catalyst uses platinum, palladium and rhodium.

NONCATALYTIC USES

ELECTRICAL END USES. Platinum, palladium, and rhodium have high electrical conductivity and hence are used in the electrical equipment industry. Platinum is used in thermocouples, electrical contacts, and electroplating of printed circuits, while palladium is used for relays and metal contacts in telecommunications equipment.

The Bell System uses large amounts of palladium in its switching equipment. Most contacts are now a silver-palladium alloy rather than all palladium. Conversion from mechanical to electronic switching by the Bell System is decreasing its demand for palladium. By the mid-1980s it is anticipated that the Bell System will be able to meet all its internal needs for palladium from its own recycling of obsolete equipment.

GLASS PRODUCTION. Platinum group metals are used in the manufacture of glass and glass fiber because of high corrosion resistance, ability to withstand high temperatures, and compatible expansion coefficients. The glass industry consumes relatively minor quantities of platinum and palladium, but in 1979 it had the third largest reported sales figures for rhodium of any industry in the United States.

MEDICAL, DENTAL, AND JEWELRY USES. Very little rhodium is consumed in dental and medical uses, but substantial amounts of platinum and palladium are used. In 1979, reported sales of palladium were second highest in the dental and medical categories. Application of PGMs in dental work include dental crowns, caps, and bridges. Medical uses for PGMs are quantitatively minor. They are used in cancer chemotherapy, heart pacemakers, and hypodermic needle tubing.

On the whole, U.S. consumers have not been as much enamored with platinum jewelry as with gold and silver jewelry, and U.S. reported sales to this industrial category are relatively low. Japanese jewelry consumers have historically favored platinum jewelry, but the relative demand for platinum in jewelry apparently may be fading there.

CONSUMPTION TRENDS IN THE 1970S

Table 4-20 gives a percentage breakdown of world platinum-group metal consumption by end use. The figures are estimated by private publications through 1977, and are probably not as reliable as similar figures for the United States alone. Two readily discernible worldwide trends from Table 4-20 are that electrical use has declined relatively and that automotive use began and climbed rapidly in the mid-1970s. Relative world shares for petroleum, dental and medical, and glass have remained fairly constant, while chemical and jewelry shares were erratic from 1972 to 1977.

Tables 4-21, 4-22, and 4-23 and Figures 4-6, 4-7, and 4-8 provide an overview of U.S. consumption of platinum, palladium, and rhodium. As discussed in the previous section, the U.S. Bureau of Mines PGM consumption data are not comprehensive, but are the sum of sales reported to consuming industries. Total "apparent consumption" figures, based on net import and production data, are consistently above reported sales, but are not reported on an industry-specific basis. Reported sales, despite being less than comprehensive, still can be used reliably to examine changing patterns of interindustry PGM consumption.

As mentioned in the previous section, sales data reflect not only usage of PGMs directly or indirectly in production, but also possible changes in shelf stocks. For example, if the chemical industry embarked on a plan to increase its PGM shelf stocks in a particular year, reported sales data might look

Table 4-20

WORLD ESTIMATED CONSUMPTION OF PLATINUM GROUP METALS BY END USE, 1972-1977
(Percent)

End Use	1972	1973	1974	1975	1976	1977
Electrical	33.8	33.5	26.5	19.1	20.8	22.6
Chemical	27.5	25.2	23.0	22.4	21.4	23.4
Jewelry	18.4	19.8	19.4	27.4	20.8	20.5
Automotive	-	-	11.2	11.3	16.7	12.7
Petroleum	5.7	5.8	6.4	5.9	4.3	5.1
Dental and Medical	6.4	6.7	6.7	6.5	8.4	6.3
Glass	3.8	3.6	4.0	3.0	2.7	3.7
Others	4.4	5.4	2.8	4.4	4.9	5.5
Total	100.0	100.0	100.0	100.0	100.0	100.0

SOURCE: J. Aron and Roskill estimates from Roskill Information Services, Ltd., 1979, The Economics of Platinum Group Metals, London.

Table 4-21

PLATINUM SOLD TO CONSUMING INDUSTRIES IN THE UNITED STATES, BY END USE,[1] 1970-1980

(Troy Ounces)

	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980[2]
Automotive	--	--		--	350,000	273,000	480,965	354,338	597,538	803,229	517,143
Chemical	148,289	135,112	225,895	238,974	215,663	148,813	83,560	84,414	149,696	98,600	116,609
Dental and Medical	18,302	23,097	30,462	27,887	25,513	17,097	26,858	27,083	44,139	27,053	26,191
Electrical	103,318	51,940	92,381	117,352	98,608	73,624	89,319	90,217	106,422	115,775	142,442
Glass	46,687	40,703	26,970	72,543	74,398	33,813	41,683	59,995	98,094	88,594	51,843
Jewelry and Decorative	29,203	18,577	20,655	22,433	22,968	22,900	23,371	34,650	25,751	27,712	38,360
Petroleum	202,015	141,800	98,847	123,649	139,519	107,988	59,103	74,772	108,365	170,013	141,197
Miscellaneous	18,555	19,859	50,089	55,695	17,020	21,318	46,246	64,350	66,336	77,949	56,372
Total	566,369	431,088	545,299	658,533	943,689	698,553	851,105	789,819	1,196,341	1,408,925	1,090,157

[1] Includes primary and nontoll-refined secondary metals.

[2] Excludes companies reporting annually.

SOURCE: U.S. Bureau of Mines, Minerals Yearbook and Mineral Industry Surveys, various issues, Washington, D.C.: U.S. Government Printing Office.

Table 4-22

PALLADIUM SOLD TO CONSUMING INDUSTRIES IN THE UNITED STATES, BY END USE,[1] 1970-1980
(Troy Ounces)

	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980[2]
Automotive	--	--	--	--	150,000	97,000	194,496	125,010	198,809	222,156	176,518
Chemical	184,618	218,651	292,710	259,959	163,205	142,975	128,229	161,234	146,352	199,743	116,515
Dental and Medical	47,583	61,594	94,274	135,060	124,074	114,970	139,279	112,473	206,312	243,627	174,8321
Electrical	429,032	431,505	425,081	524,056	390,237	132,247	152,312	223,748	286,574	392,372	289,797
Glass	21,147	237	2,250	1,439	9,549	17,633	2,989	907	2,757	1,729	1,121
Jewelry and Decorative	17,329	18,752	19,375	23,052	21,701	23,026	5,700	15,567	12,570	11,766	12,874
Petroleum	15,494	2,916	14,499	3,761	14,877	1,755	7,291	8,507	18,909	24,588	21,391
Miscellaneous	24,140	26,451	27,835	65,157	12,420	11,942	26,766	53,023	45,645	36,640	21,320
Total	739,343	760,106	876,024	1,012,484	886,063	541,548	657,062	700,469	917,928	1,132,621	814,368

[1] Includes primary and nontoll-refined secondary metals.

[2] Excludes companies reporting annually.

SOURCE: U.S. Bureau of Mines, Minerals Yearbook and Mineral Industry Surveys, various issues, Washington, D.C.: U.S. Government Printing Office.

Table 4-23

RHODIUM SOLD TO CONSUMING INDUSTRIES IN THE UNITED STATES, BY END USE,[1] 1970-1980
(Troy Ounces)

	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980[2]
Automotive	--	--	--	--	--	--	391	871	2,939	26,136	37,012
Chemical	26,445	14,910	15,358	23,772	23,328	15,440	19,225	20,245	19,397	11,684	5,174
Dental and Medical	51	31	48	297	373	41	75	275	232	45	42
Electrical	9,056	9,084	7,867	13,187	15,538	8,252	9,062	10,758	14,329	16,923	6,646
Glass	7,138	3,362	13,923	16,689	7,464	4,471	3,828	13,986	16,605	15,376	8,420
Jewelry and Decorative	5,343	5,419	6,593	12,526	10,460	4,932	5,170	5,011	9,950	7,458	9,588
Petroleum	59	176	149	3,057	1,239	114	1	--	281	1,223	650
Miscellaneous	805	1,384	2,157	3,987	3,200	3,598	3,123	4,070	5,907	4,625	1,665
Total	48,897	34,366	46,095	73,515	61,602	36,848	40,875	55,216	69,640	83,470	63,197

[1] Includes primary and nontoll-refined secondary metals.

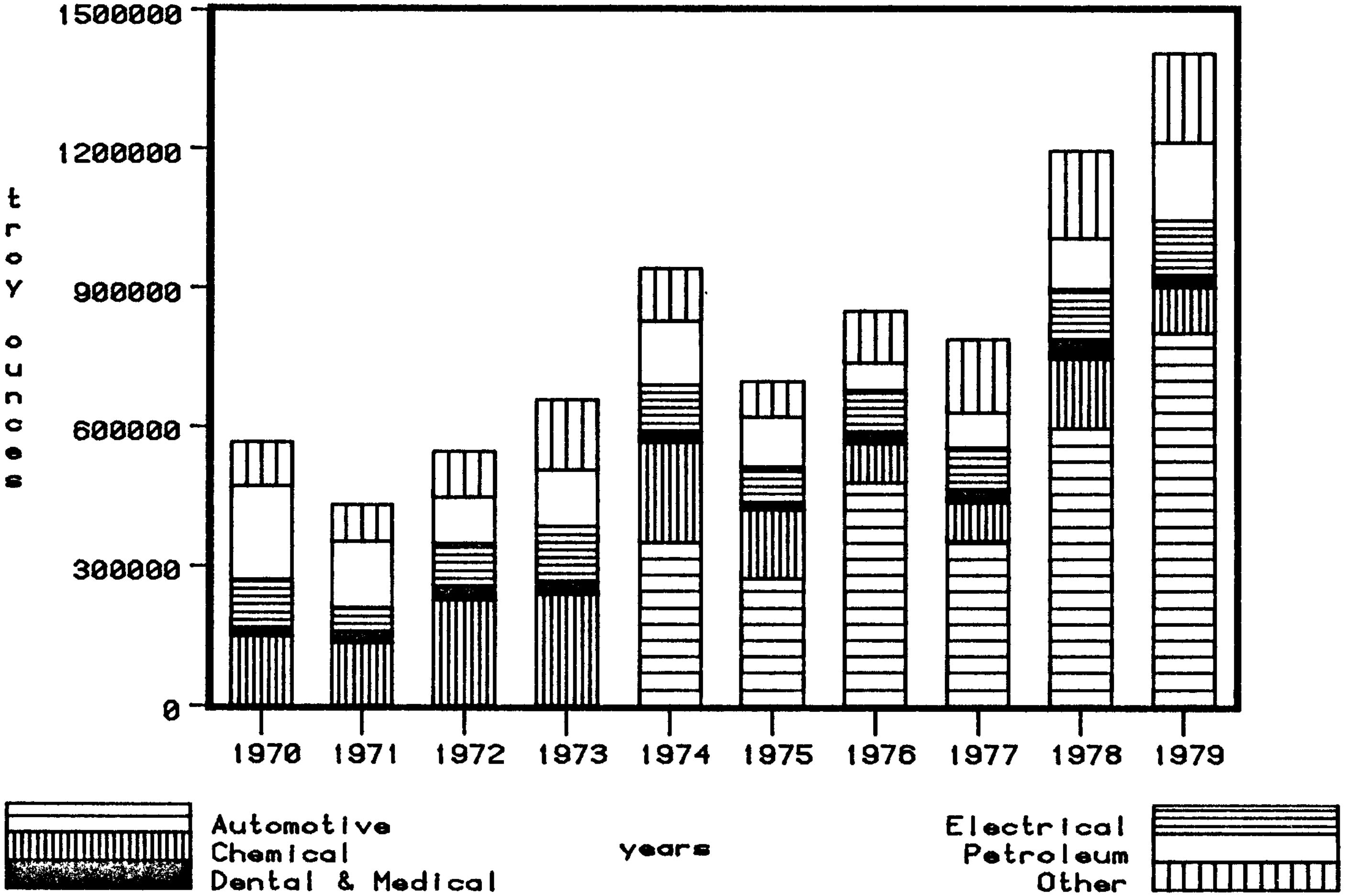
[2] Excludes companies reporting annually.

SOURCE: U.S. Bureau of Mines, Minerals Yearbook and Mineral Industry Surveys, various issues, Washington, D.C.: U.S. Goverment Printing Office.

Figure 4–6

Platinum Sold to U.S. Consuming Industries

(Prepared By: Charles River Associates)

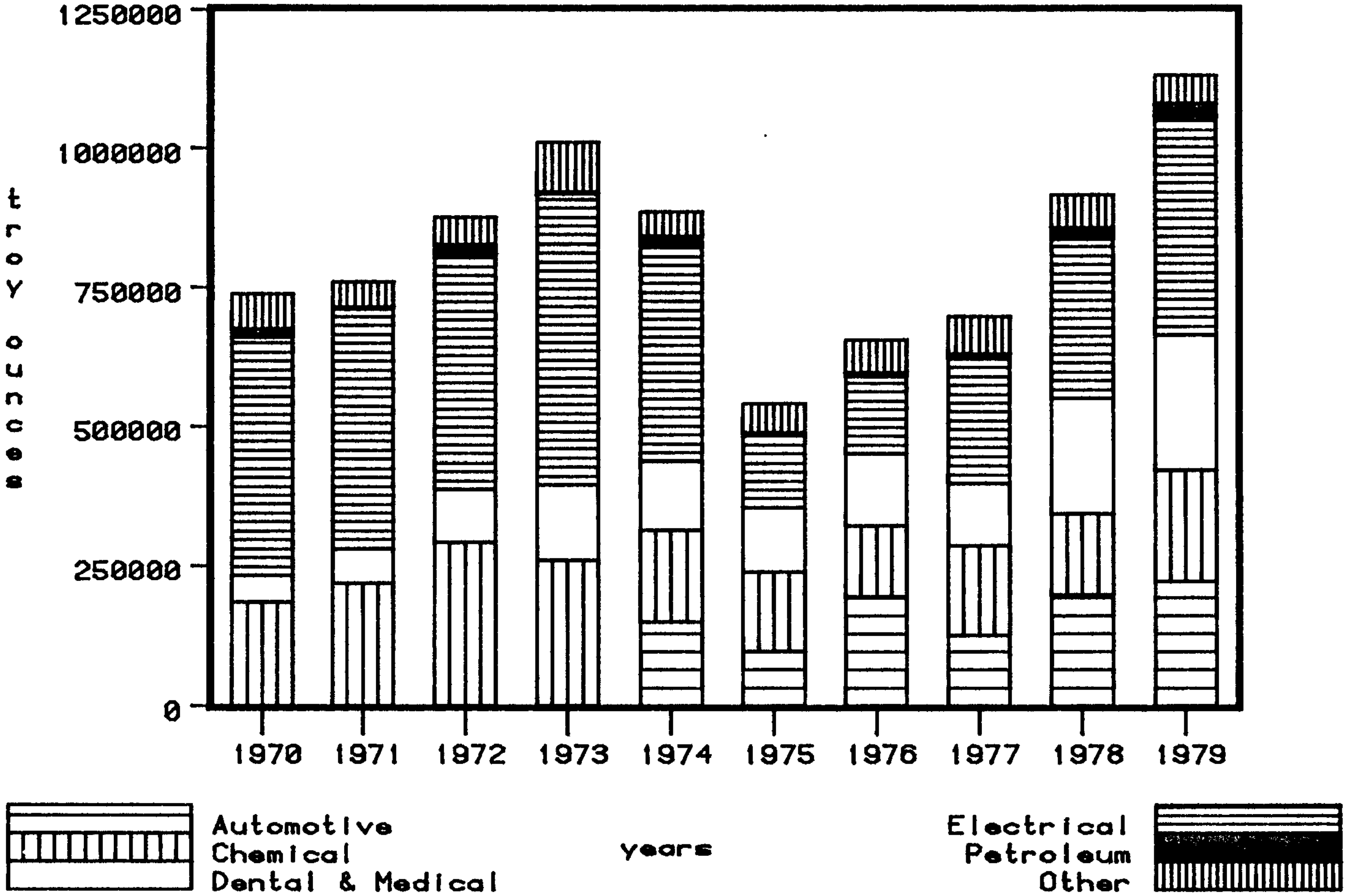


SOURCE: U.S. Bureau of Mines, Minerals Yearbook, Mineral Industry Surveys, various issues, Washington, D.C.

Figure 4–7

Palladium Sold to U.S. Consuming Industries

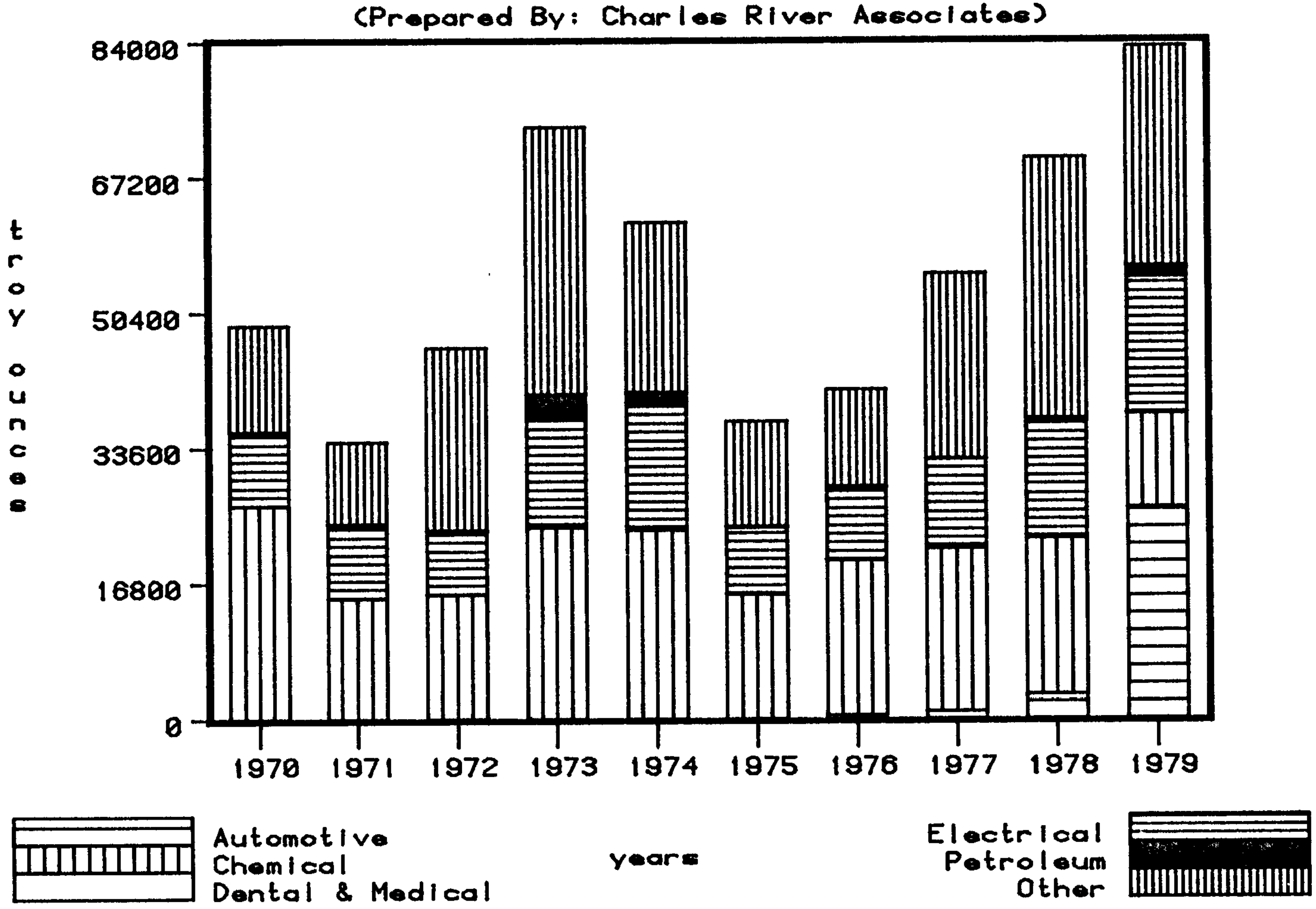
(Prepared By: Charles River Associates)



SOURCE: U.S. Bureau of Mines, Minerals Yearbook,
Mineral Industry Surveys, various issues, Washington, D.C.

Figure 4—8

Rhodium Sold to U.S. Consuming Industries



SOURCE: U.S. Bureau of Mines, Minerals Yearbook,
Mineral Industry Surveys, various issues, Washington, D.C.

abnormally large relative to changes in the production of the chemical industry.

Figure 4-6 shows the upward trend in U.S. reported platinum consumption throughout the 1970s. Figures 4-7 and 4-8 indicate that U.S. reported palladium and rhodium consumption has been more erratic; stock adjustments may account for part of this.

From Table 4-21, it can be seen that the industries to whom the largest sales of platinum were reported in 1979 are automotive, petroleum, electrical, and chemical. For palladium, reported sales were highest in 1978 to the electrical, dental and medical, automotive, and chemical industries (Table 4-22). For rhodium, reported sales were highest in 1979 to the automotive, electrical, glass, and chemical industries (Table 4-23).

PRICES

The market for PGMs has a two-tier pricing structure. In broad terms, there is one price which primary producers charge their regular contractual customers, called the producer price, and there is another price that others must pay on the spot market, called the dealer price.

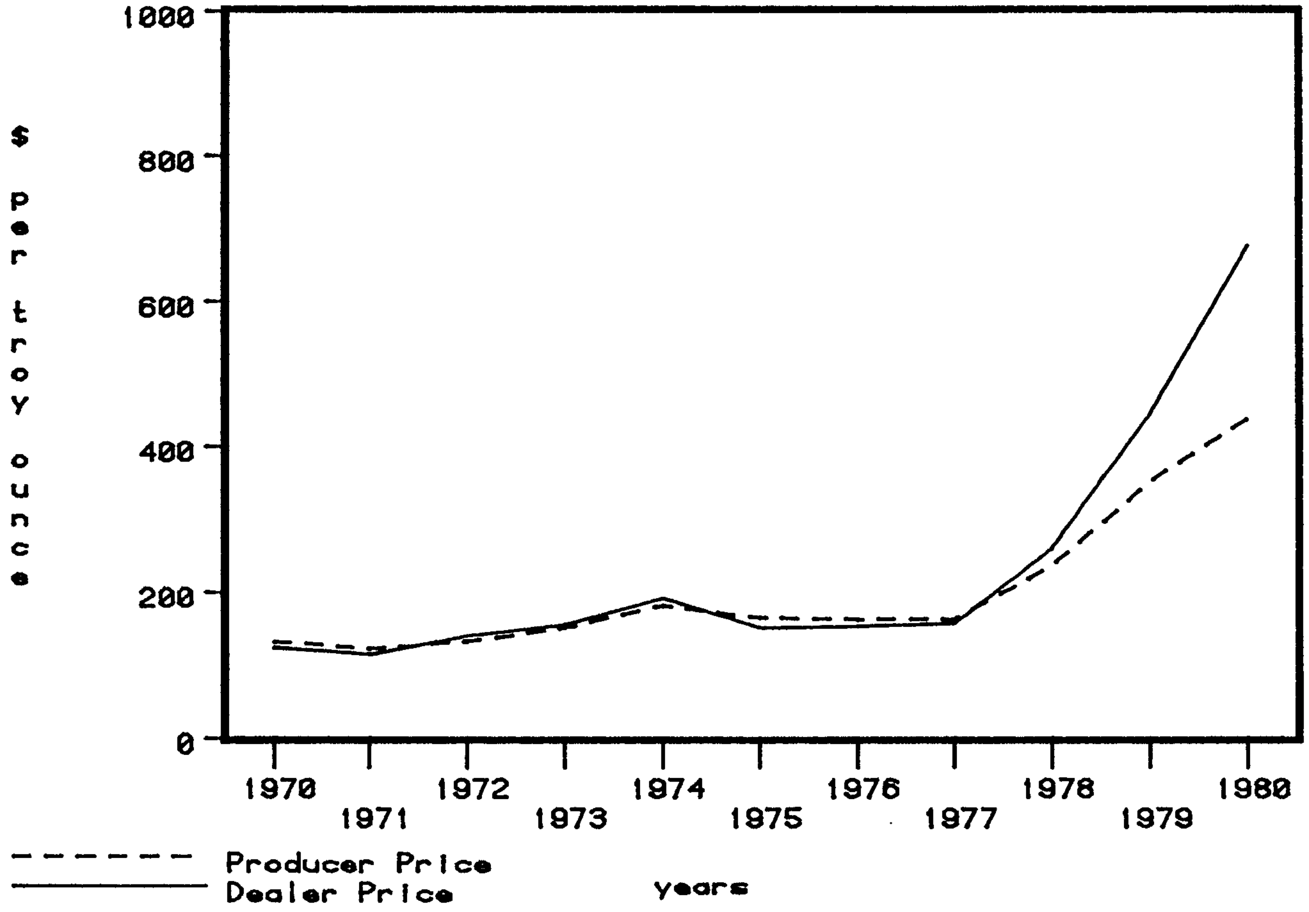
As Figures 4-9, 4-10, and 4-11 demonstrate, producer and dealer prices for platinum, palladium, and rhodium have closely tracked one another throughout the 1970s. This is because the economic forces of supply and demand, which typically first influence the spot price, are also taken into account during producer negotiations with the contractual consumers. Occasionally, short-term forces cause the spot price to deviate substantially from the producer price.

Figures 4-12, 4-13, and 4-14 plot 1980 monthly producer and dealer prices for platinum, palladium, and rhodium. Dealer prices are more variable, reacting constantly to market events that will only slowly influence contractual arrangements. Especially noticeable is the large excess of dealer prices over producer prices for platinum in early 1980, which many industry observers attributed to speculative activity. The producers of platinum-group metals have kept prices to traditional industrial consumers at more stable levels so that long-run consumption and profitability for the platinum producers are not damaged for short-run gains.

Figure 4–9

Average Annual Platinum Producer & Dealer Prices, 1970-1980

(Prepared By: Charles River Associates)

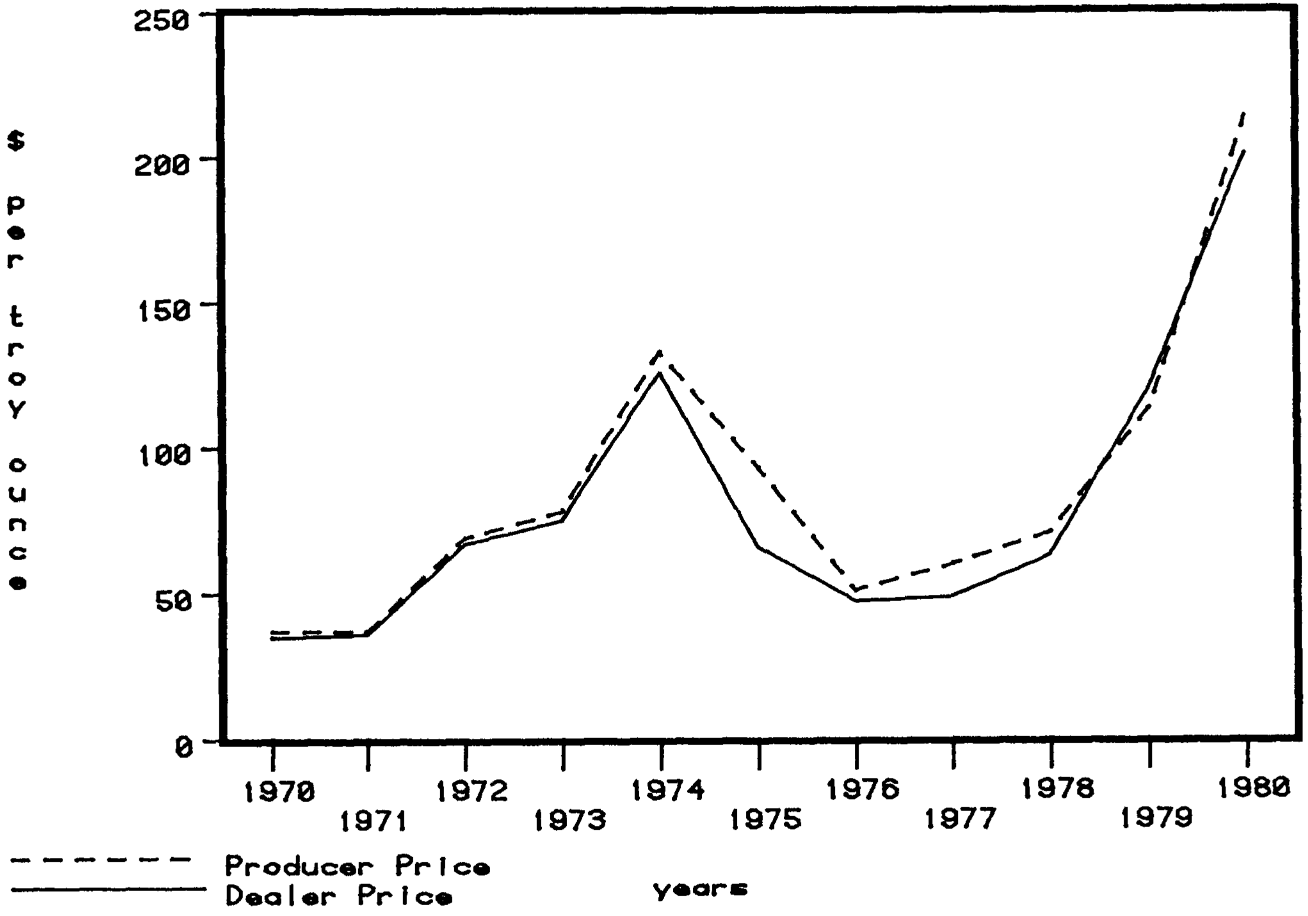


SOURCE: U.S. Bureau of Mines, Minerals Yearbook,
Mineral Industry Surveys, various issues, Washington, D.C.

Figure 4-10

Average Annual Palladium Producer & Dealer Prices, 1970-1980

(Prepared By: Charles River Associates)

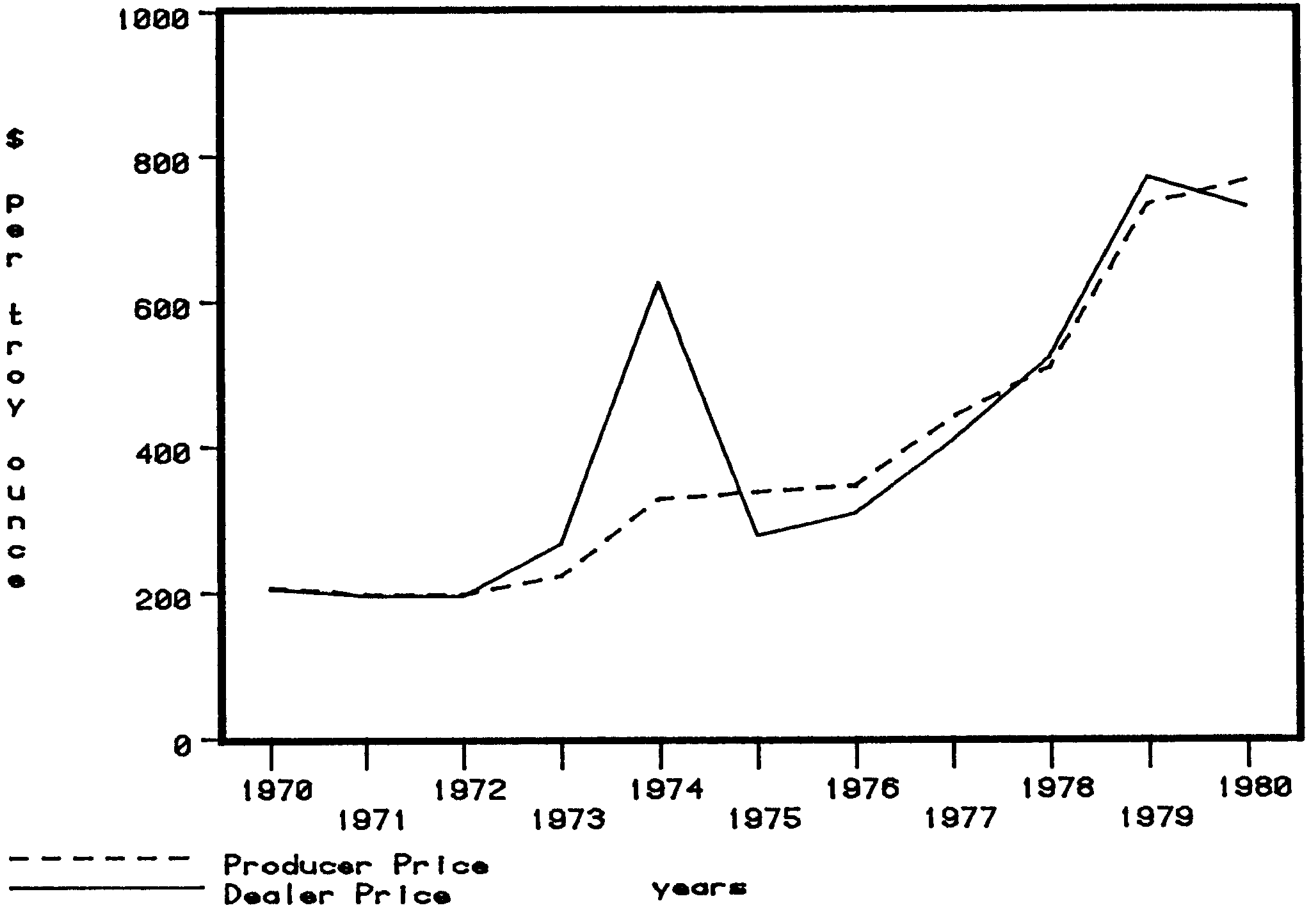


SOURCE: U.S. Bureau of Mines, Minerals Yearbook,
Mineral Industry Surveys, various issues, Washington, D.C.

Figure 4-11

Average Annual Rhodim Producer & Dealer Prices, 1970-1980

(Prepared By: Charles River Associates)

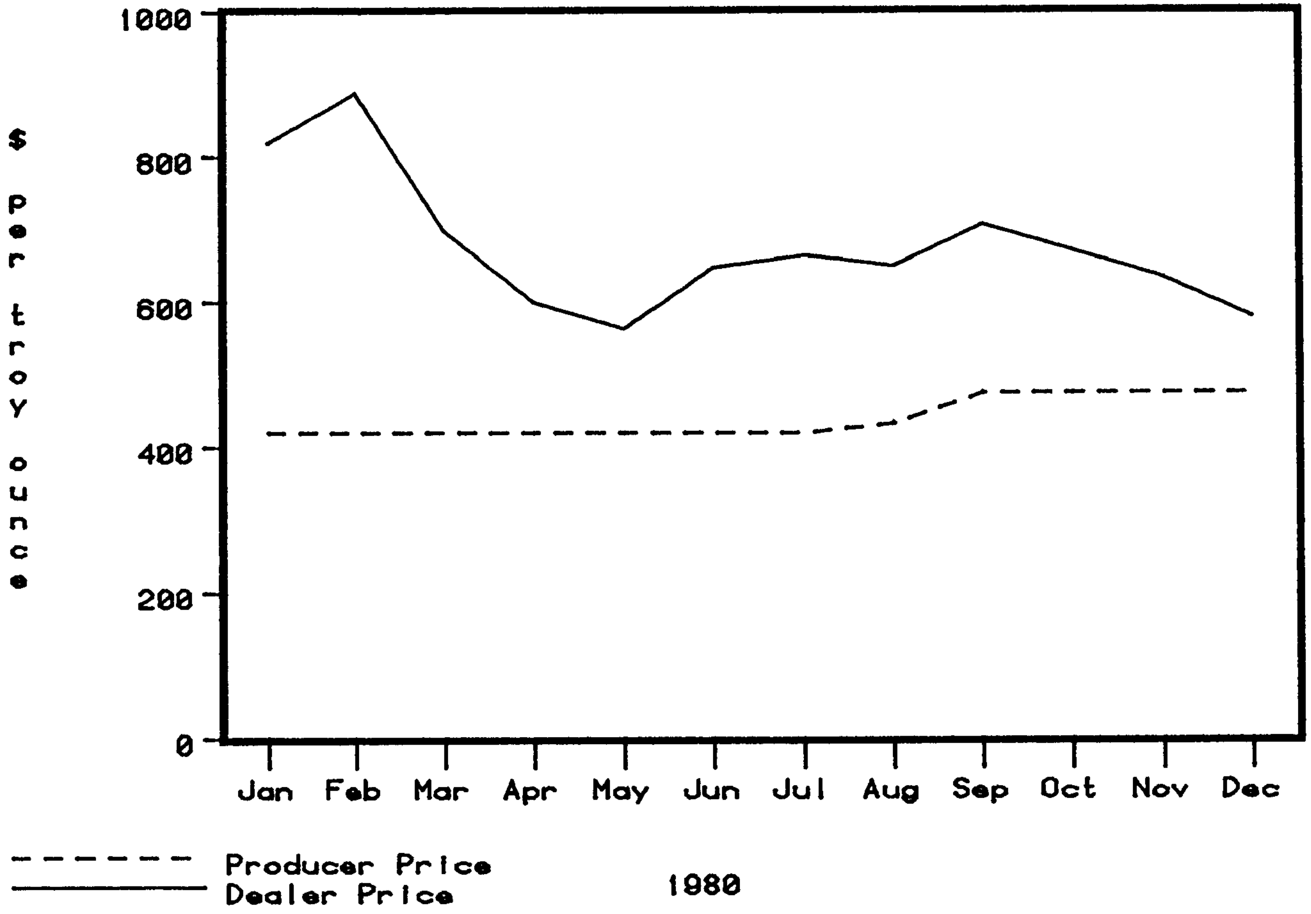


SOURCE: U.S. Bureau of Mines, Minerals Yearbook,
Mineral Industry Surveys, various issues, Washington, D.C.

Figure 4–12

Monthly Platinum Producer and Dealer Prices, 1980

(Prepared By: Charles River Associates)



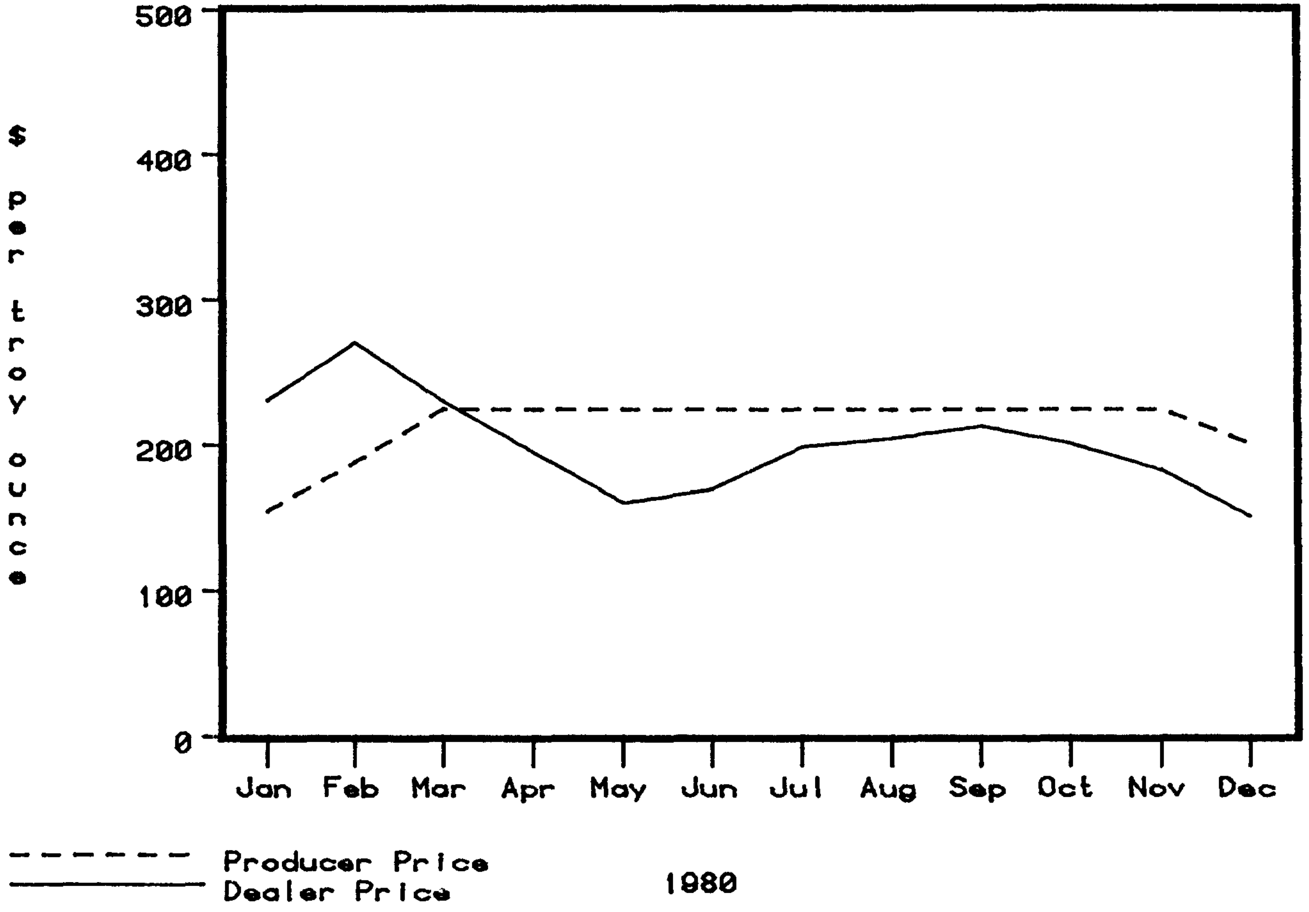
SOURCE: U.S. Bureau of Mines, Minerals Yearbook,
Mineral Industry Surveys, various issues, Washington, D.C.

Charles
River
Associates

Figure 4—13

Monthly Palladium Producer and Dealer prices, 1980

(Prepared By: Charles River Associates)

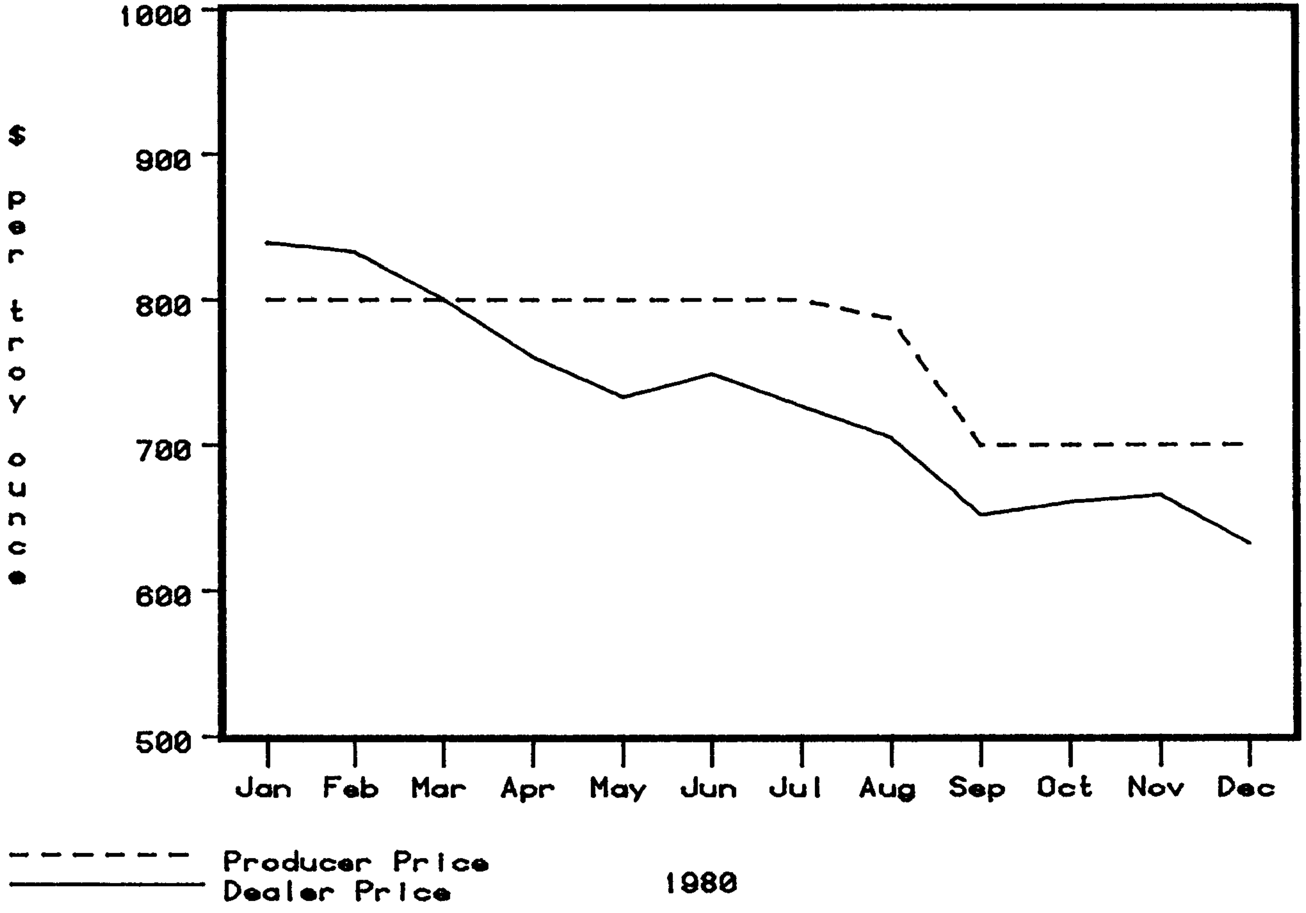


SOURCE: U.S. Bureau of Mines, Minerals Yearbook, Mineral Industry Surveys, various issues, Washington, D.C.

Figure 4–14

Monthly Rhodium Producer and Dealer Prices, 1980

(Prepared By: Charles River Associates)



SOURCE: U.S. Bureau of Mines, Minerals Yearbook,
Mineral Industry Surveys, various issues, Washington, D.C.

PRIMARY PRODUCERS

This section describes capacity, production, and supply elasticities of countries mining platinum-group metals. Current conditions are analyzed, focusing on how each country could respond to increased PGM demand, whether due to increased consumption for vehicular emissions control or some other cause.

SOUTH AFRICA

CURRENT PRODUCTION

As Tables 4-8, 4-9, and 4-10 indicate, South Africa produces most of the world's primary platinum and rhodium, and a significant amount of palladium. More recent 1979 platinum production figures for the "big three" South African producers are: Rustenburg Platinum Mines, 1.3 million troy ounces; Impala Platinum Mines, 900,000 troy ounces; and Western Platinum, 80,000 troy ounces. Total South African 1979 production of palladium was 906,000 troy ounces; 1979 rhodium production was 108,000 troy ounces.

South African PGMs come predominantly from the Merensky Reef in the Bushveld Complex. About two-thirds of the PGMs in the Merensky Reef by weight is platinum. The ore grade is approximately 8.1 grams of PGMs per metric ton of ore. The Merensky Reef is one of the few deposits in the world, and by far the largest, where PGMs are the principle product. In the Soviet Union and Canada, PGMs are byproducts from the mining of other metals, mostly nickel. This fact is important, because the supply of PGMs from byproduct operations responds more strongly to changes in production of the parent metal than to changes in PGM prices. Byproduct supply is discussed further below.

Current production technologies in South Africa and elsewhere involve significant time lags between mining and delivery of refined metal. At present it requires about seven months after mining to deliver refined platinum or palladium, and about 16 months for other PGMs. In part, these lags are due to ores, concentrates, and slimes being shipped to other countries for refining. In 1978, the Bureau of Mines estimated the cost of refining platinum and palladium at $7 to $8 per troy ounce, and two to three times this for other PGMs (Mineral Commodity Profiles, 1978).

New production technologies are being developed which should reduce these production lags. Texasgulf, Inc. is testing a new plasma smelting process to obtain PGMs from concentrates containing high amounts of chromite. (See Engineering and Mining Journal, 1979.) The South African National Institute for Metallurgy has already developed a new PGM extraction process from high chromite ores which Western Platinum will use to mine the UG2 seam, a high chromite deposit below the Merensky Reef.

The UG2 seam's rhodium concentration is almost three times that of the Merensky Reef. One source (Buchanan, 1980) puts the rhodium proportion (percent of PGMs accounted for by rhodium) at 8 percent for UG2 versus 3 percent for Merensky. Consequently, both the platinum/rhodium and palladium/rhodium ratios are lower for UG2 than for Merensky. The platinum/rhodium ratio is 5.25 for UG2 and 19.66 for Merensky, while the palladium/rhodium ratio is 4.375 for UG2 and 8.33 for Merensky.

The high rhodium concentration in UG2 is important because three-way catalytic converters in 1980 used platinum and rhodium in roughly a 10 to 1 ratio, and there is concern about this ratio being much higher than the current mining ratios from Merensky of 19 to 1. However, Ford's three-way catalyst reportedly utilizes rhodium, palladium, and platinum in proportions "not very far off" from those in which they are currently mined.

As the UG2 deposit comes on stream, platinum/rhodium mining ratios could approach the 10 to 1 usage ratio. CRA communications with mining companies in South Africa indicate that Impala and Rustenburg Mines, the two largest producers, are not planning to mine the UG2 seam in the near future. However, Western Platinum, due to its smaller holdings in the Merensky Reef, is planning to recover about 110,000 troy ounces of PGMs annually from UG2. This quantity, however, is small when compared to total 1979 South African PGM production of 2.28 million ounces by Rustenburg, Impala, and Western.

Despite the fact that the UG2 deposit lies only 100 to 350 meters under the Merensky Reef, and the two could be simultaneously mined from a vertical shaft, Rustenburg and Impala have indicated little interest in developing UG2. Impala personnel have indicated, however, that should auto emission standards become tighter and drive up the relative demand for rhodium, they would consider mining UG2.

It is likely that higher rhodium production would have to come from UG2 due to rhodium's relative scarcity in Merensky deposits. Working with October 1979 producer prices, Buchanan calculated that platinum accounts for 61.7 percent of PGM dollar revenues from the Rustenburg area of Merensky, compared to 6.6 percent for rhodium (Buchanan, 1979). The current platinum/rhodium producer price ratio is higher than in 1979 (0.679 versus 0.475), so revenue from platinum would now account for an even higher percentage relative to rhodium.

The economics of increased rhodium production are thus clear. Platinum prices and not rhodium prices currently control PGM production decisions in Merensky Reef deposits. To significantly increase the rhodium/platinum production ratio, the UG2 seam will have to be exploited by more than the planned 110,000 ounce annual production by Western. To entice development of UG2 by Rustenburg and Impala, relative rhodium prices probably will have to rise; long-term contracts would maximize the incentive effects of any given price increase. Because UG2 lies directly below Merensky and could be simultaneously mined from vertical shafts, additional incentives would not have to be great to encourage development of UG2, but development could still require several years.

In 1978 the U.S. Bureau of Mines published data on South African PGM refinery (as opposed to mining) capacity: 2.1 million troy ounces for Rustenburg; 1.5 million troy ounces for Impala; and 135,000 ounces for Western. Rustenburg's output is refined by Matthey Rustenburg refiners in South Africa and England. Impala refines all of its material in South Africa, while Western platinum ships its concentrate to Falconbridge Nickel's refinery in Norway for removal of nickel and copper, and then back to South Africa for removal to PGMs. According to recent news reports, Impala undertook a 10 to 20 percent increase in refinery capacity from 1978 to 1980, and Western hopes soon to increase its refinery capacity to 245,000 troy ounces at a cost of $32.7 million.

T. P. Mohide has published estimated 1978 mining (as opposed to refining) capacity for South African producers (in troy ounces) (Metal Bulletin Monthly, 1980) : Rustenburg, 1,516,781 for platinum and 564,383 for palladium; Impala, 1,093,493 for platinum and 423,288 for palladium; Western, 105,822 for platinum and 56,438 for palladium. While Mohide does not estimate rhodium capacities, they can be estimated by dividing the platinum figures by 19.66, the platinum/rhodium production ratio in the Merensky Reef. Using this method, we arrive at 1978 mining capacity figures for rhodium (in troy ounces) of 77,151 for Rustenburg, 55,620 for Impala, and 5,383 for Western.

SUPPLY ELASTICITY

Long-term purchase contracts can play a very important role in inducing South African producers to increase capacity and production. Increasing mining capacity is a lengthy and expensive process, and inherently risky from a business viewpoint since demand may suddenly fall after the expansion. The price incentives required to induce expansion may not be nearly so large if long-term contracts allow consumers to share risks with producers.

For PGM producers in South Africa and elsewhere, two facts make mining expansion particularly risky. First, PGM demand, whether for catalytic converter, petroleum, chemical, or electronic uses, is largely dependent on macroeconomic activity in the United States, Japan, and Western Europe. A second variable in PGM markets is Soviet behavior. While the data discussed above showed that Soviet PGM sales to the West are declining, South African producers are still reluctant to expand capacity when large Soviet PGM supplies could begin flowing to the West again. In addition, the Soviets are thought to have large stockpiles of platinum and palladium (but no substantial rhodium stockpile). Mohide estimated that in 1979 the Soviets had 20 metric tons, or 705,479 troy ounces of platinum, and 50 metric tons, or 1,763,698 troy ounces of palladium stockpiled. These stockpiles loom large as platinum and palladium sold to U.S. consuming industries in 1979 were 1,408,925 and 1,132,621 troy ounces, respectively.

Currently, most major U.S. PGM users, including General Motors, Ford, and Chrysler, have long-term contracts with South African producers. General Motors has a ten-year contract with Impala, while Rustenburg supplies Ford under long-term contract. The GM contract reportedly includes annual delivery of 300,000 troy ounces of platinum.

While details of these contracts are proprietary, they generally call for an annual amount of PGMs to be purchased at a fixed price, usually the producer price or lower. Often there is an inflation clause in the contract. These long-term contracts for fixed annual deliveries shift the burden of fluctuating demand to the auto companies. When auto sales and hence PGM demand are down, the auto companies incur inventory storage and holding costs, while the South African producers maintain their revenue flows to cover production and amortized expansion costs. One implication of this practice is that auto company stocks of PGMs are presumably inversely related to sales, allowing for lags involved in routing PGMs through catalytic converter manufacturers.

According to industry sources, large chemical and petroleum refining firms often have long-term contracts as well with the South African producers. Long-term contracts are also common for the electronic industry. This leaves the jewelry, medical and dental, and miscellaneous other industries to buy mainly on the spot market, although there also may be some contracting in these industries. Overall, it appears that approximately 70 percent of platinum, palladium, and rhodium consumption (not counting reuse of toll-refined material) is typically sold under long-term contract in the United States. One implication of this situation for the Environmental Protection Agency is that it will generally be quite costly to implement new regulations so quickly that the regulated industry is forced onto the spot market, without allowing time for long-term contracts and capacity expansion by South African producers.

The degree to which capacity and production expansion decisions are dictated by long-term contracts and not short-term PGM prices is illustrated by the historical behavior of South African producers. Two instances are particularly illustrative. The first occurred during the 1979 slump in auto sales. Despite the slump, Rustenburg, with the security of long-term contracts, undertook to increase output from 1 to 1.2 million troy ounces, and to aim for 1.4 million ounces for 1981. A company executive stated that the expansion was undertaken to meet perceived future increased demand from the auto industry (see _American Metal Market_, 1979a).

A second example illustrates the extent to which production and producer stocks of PGMs are tied to long-term contracts and thus unavailable on the spot market. Recently, a major U.S computer manufacturer attempted to contract for a two-year supply of platinum at producer prices and was unable to do so, allegedly because all producer inventory was committed in long-term contracts. One industry observer commented that South African producers would not increase production for a two-year contract, because this was not considered a long-term commitment compared to more common ten-year contracts (see American Metals Market, 1979b). The cost of capacity expansion could not be amortized over so short a time span.

Under normal circumstances, substantial demands for PGMs are best met from primary production by the major producers in South Africa, through long-term contracts of more than two years. Producers are fond of emphasizing this consideration in press reports or negotiations with potential new customers. Furthermore, since the above example indicates that producer stocks are likely to be committed in long-term contracts, a potential purchaser on the spot market in the United States would have to rely largely on refiner, importer, and dealer stocks. Earlier analysis of these stocks in the United States revealed that while physically they could meet a substantial increase in PGM demand, past behavior suggests that these inventories would be released only for large price increases.

A further advantage of long-term contracts is that they insulate platinum producers somewhat from competition with their own material, when it is recycled. This could be a particularly relevant concern during the 1980s, should large amounts of PGMs be recycled from vehicular emissions control devices.

Given the key role of long-term contracts, the question then becomes the extent and speed with which South African PGM production could be expanded with such contracts. Discussions with industry sources ,and CRA analyses of South African production technology, indicate that increases in auto industry platinum demand on the order of 20 to 40 percent (160,045 to 321,291 troy ounces over 1979 demand) could be readily met in two to three years without substantial platinum price increases. Substantially larger production increases could be implemented over longer periods of time without substantial increases in the (deflated or "real") price of platinum.

The Merensky Reef is situated such that expansion of capacity and production is not very difficult. In the past, when platinum demand has increased, the length and shallowness of the reef have made it possible to increase production quickly. To extract the ore, surface adits, or openings sloping down along the reef, are used. In the Rustenburg area, the slope is generally only 10 degrees, in which case simple incline haulage tracks are used to remove the ore.

Deeper deposits in the reef are opened by sinking vertical shafts from 500 to 3,000 feet down. One difficulty with the vertical shafts and deeper operations is that the temperature gradient in the Merensky Reef is quite steep, about one degree Fahrenheit for each 90 feet (compared, for example, to one degree for each 200 feet in South African gold mines).

One factor that would tend to mitigate price increases in response to higher PGM demand is the threat of Soviet production and stockpiles entering the supply stream. Soviet behavior as a PGM supplier is analyzed below.

It was noted above that platinum, palladium, and rhodium accounted for 61.7, 8.2, and 6.6 percent, respectively, of the 1979 revenue generated from Rustenburg area ores (Buchanan, 1980.) In 1980, palladium's share was up a bit and rhodium's down due to higher and lower current producer prices, but the point is the same: increased platinum (not just palladium or rhodium) demand and prices is usually necessary to encourage increased South African production from the Merensky Reef.

For South African PGM production ratios to move toward rhodium (and palladium) and away from platinum, the UG2 seam will have to be mined in conjunction with the Merensky Reef. On the demand side, a solution is to produce three-way catalytic converters that utilize platinum, palladium, and rhodium in a manner more consistent with their mining ratios. GM converter technology apparently utilizes rhodium more intensively than its current mining ratio, while Ford has indicated that their three-way catalyst PGM ratios are not very far from current mining ratios. Given this apparent flexibility in the ratio in which rhodium and platinum are used, it may not take large changes in relative prices to induce equilibrium in the platinum, rhodium, and palladium markets, even if more extensive use of three-way catalytic converters is required.

The key to increasing South African production of PGMs for emissions control without undue price disruptions is to announce regulatory changes two or three years in advance, so the auto companies can negotiate higher output long-term contracts, and producers can implement expansion plans in an orderly fashion.

THE SOVIET UNION

Until 1971, the Soviet Union was the world's leading supplier of PGMs, but conditions have changed throughout the 1970s. Soviet sales to the West of platinum alone steadily increased from 225,000 troy ounces in 1970 to 631,000 ounces in 1976, then steadily decreased to 300,000 ounces in 1979. PGM proportions in Soviet production are platinum, 25 percent; palladium, 71 percent; and other PGMs, 4 percent. Soviet PGM production is thus heavily skewed toward palladium.

PGM production in the Soviet Union is largely a byproduct of nickel operations, and hence responds to decisions concerning nickel production. Soviet production of PGMs in 1979 can be estimated by applying ore grades and PGM proportions to estimated Soviet nickel production. Buchanan arrives at estimates of 757,000 troy ounces of platinum and 2,130,000 troy ounces of palladium. Extending this methodology, estimated 1979 Soviet production of rhodium is 90,000 troy ounces.

PGMs are found in three major deposits in the Soviet Union: Norilsk, Petsama, and the Ural Mountains. Norilsk, located in the north-central part of the Soviet Union in the Krasnoyarsk Territory, is by far the most important deposit, accounting for 85 percent of Soviet PGM production.

U.S. imports for consumption of platinum, palladium, and rhodium from the Soviet Union have displayed a more erratic trend over the 1970s than total Soviet shipments to the West. From Table 4-15 it can be seen that 1979 U.S. imports of PGMs from the Soviet Union totaled 693,215 troy ounces, down from a 1974 high of 1,012,321 ounces. The 1979 figure of 693,215 troy ounces was 20 percent of the 3,479,128 total ounces imported from all countries for consumption that year in the United States.

Tables 4-12, 4-13, and 4-14 focus respectively on platinum, palladium, and rhodium imports by the United States. Platinum imports from the Soviet Union have fallen from the mid-1970s, and in 1979 they accounted for only 1.8 percent of total U.S. platinum imports. Palladium imports from the the Soviet Union have been erratic, but in 1979 they accounted for a significant 40 percent of total U.S. palladium imports for consumption. Likewise, rhodium imports from the Soviet Union have been erratic, but accounted for 15.9 percent of 1979 U.S. rhodium imports for consumption.

From these calculations it can be seen that palladium is the only PGM for which Soviet imports are of much importance to the United States. Late in 1980, the Soviets virtually halted palladium exports to the West for reasons which are unclear. Despite the cutoff, analysts quoted in press reports were sanguine about adequate compensatory supplies from South Africa, albeit at a higher price. The Soviet palladium embargo in 1980 demonstrated that, while the dealer price of palladium is significantly influenced by Soviet sales, supplies from South Africa can take up much slack and large increases in the price of palladium are not required to equilibrate the market. Figure 4-13 shows that the dealer price rose from around $165 an ounce in early June, to around $220 in mid-September.

SUPPLY ELASTICITY

Having seen that U.S. dependence on imports of platinum, palladium, and rhodium from the Soviet Union is now quite low, we still must consider the elasticity of Soviet supplies of these three metals should U.S. demand increase. Soviet actions in PGM markets are difficult to predict. One theory with some historical merit holds that the Soviets sell metal to the West mainly to earn foreign exchange funds, so sales are inversely related to Soviet grain harvests and other determinants of net exports. Soviet export behavior has followed this pattern less clearly in the 1970s than in earlier years. In any case, Soviet production of PGMs, and hence potential exports, are bound by decisions about nickel production. A rough consensus of industry sources is that Soviet PGM flows to the United States will remain quite insignificant during the 1980s and will not approach higher historic levels, unless there is a drastic improvement in East-West relations.

CANADA

Although Canada ranks third in world PGM production, it is dwarfed by South Africa and the Soviet Union. In 1979, Canada produced 327,000 troy ounces of PGMs, 44 percent of which was platinum, 46 percent palladium, and 10 percent other PGMs. By comparison, in 1979 the Soviet Union produced an estimated 3 million troy ounces of PGMs, and South Africa produced almost 3.5 million troy ounces.

Canada has not played an important direct role in U.S. PGM imports; Tables 4-11 through 4-14 show that throughout the 1970s, Canada supplied only a very small fraction of U.S. imports of PGMs for consumption.

Canadian production of PGMs, like that of the Soviet Union, comes as a byproduct of nickel operations, principally by International Nickel (INCO) in Sudbury, Ontario. Other mining operations are found in Quebec, British Columbia, and Pickle Lake, Ontario. The PGM concentration in the nickel ore at Sudbury is quite low, averaging only 0.8 to 0.9 grams per metric ton of ore.

A deposit that could come on line at much higher PGM prices is Lac des Iles, 88 kilometers north of Thunder Bay, Ontario. The deposit contains 3 million tons of ore with 4.450 grams of PGMs per metric ton, and a platinum/palladium ratio of 1:8. In close proximity to Lac des Iles is the Roly zone, containing 7 million tons of ore with a PGM concentration of 5.5 grams per metric ton. However, for these deposits to be profitable, PGM prices would have to increase by several times current levels. At the Roly zone, PGM prices would have to increase to 5 to 10 times their current level to make production profitable.

Because PGMs are produced in Canada as a nickel byproduct, output is predominantly dependent on events in the nickel market.

UNITED STATES

Heretofore, primary production of PGMs in the United States has been quite insignificant (Tables 4-8 to 4-10). However, PGM deposits have been discovered in Montana, Minnesota, and Alaska, and it is possible that in 5 to 10 years the majority of U.S. palladium requirements, and a significant portion of platinum requirements, could be met domestically.

The most promising U.S. deposit, in Stillwater, Montana, is currently being explored jointly by the Johns-Manville and Chevron corporations. Based on public announcements by Johns-Manville and Chevron executives, the deposit can be profitable at 1980 PGM prices, but a delay of three to five years to set up operation is required. Potential annual production has been estimated at 643,000 ounces of palladium and 225,057 ounces of platinum.

Total PGM reserves at Stillwater are estimated to be around 35 million ounces. There are three zones in the Stillwater complex: the Basil, Ultramafic, and Banded. According to a 1978 press release by Johns-Manville, the Banded zone has a strike length of 18,000 feet and an average grade of 2 grams of PGMs per metric ton of ore, with minor amounts of nickel and copper across a seam width of 7 feet. There is another section in the Banded zone with an average grade of 24.7 grams of PGMs per metric ton of ore. In both sections, the platinum/palladium ratio is 1 to 3.5. In the Ultramafic zone, PGM occurs from traces up to 8.9 grams platinum and 2 grams palladium per metric ton.

The Minnamax project, about 60 miles north of Duluth, Minnesota, is being explored by Amax, Inc. and is believed to contain about 4.4 billion tons of copper-nickel mineralized rock. Tests on a 120-ton bulk sample by the U.S. Bureau of Mines found 0.7 to 1.2 grams of platinum , 4.1 to 4.4 grams of palladium, and small concentrations of other PGMs per metric ton of ore. Using values from a sample tested by International Nickel Co. (0.037 grams platinum and 0.1 grams palladium per metric ton of ore), estimated total PGM resources at Minnamax are 18 million troy ounces. The National Materials Advisory Board estimated PGM reserves there to be 50 million troy ounces.

In Alaska, the Crillion-La Perouse Complex contains an estimated 100 million tons of copper-nickel ore with a PGM grade of 0.17 grams per metric ton. The platinum/palladium ratio is 0.8. Goodnews Bay, Alaska, produced over 500,000 troy ounces of PGMs between 1927 and 1976, but is currently not actively mined.

In the United States, only the Stillwater and Goodnews Bay deposits could be mined independently of nickel and copper values. Only Stillwater appears potentially profitable at 1980 PGM prices. Plans now call for an annual output at Stillwater of 55,000 troy ounces of platinum, 190,000 of palladium, 22,000 of rhodium, and 2C,000 of other PGMs. It is economically viable to quadruple these figures at current prices, given enough development time. Goodnews Bay could produce around 10,000 troy ounces of platinum a year, but only if prices were to increase tenfold.

If test reports are accurate, the United States for the first time could meet significant portions of its PGM demand from domestic primary production. Quadrupling the annual output plans stated above would yield 220,000 troy ounces of platinum, 760,000 ounces of palladium, and 88,000 ounces of rhodium. Considering total PGMs sold to consuming industries in the United States in 1979 (Tables 4-21 through 4-23), the above figures represent 15.6 percent of the platinum demand, 67.1 percent of the palladium demand, and 105.4 percent of the rhodium demand. Of course, the estimated quadrupled output should be compared with higher future consumption in most end uses.

Output of the magnitudes discussed above would put the United States squarely in competition with established South African producers. Whether Stillwater is developed to the extent discussed above depends not only on the accuracy of U.S. production cost estimates, but also on the price and production decisions in South Africa. South African PGM production costs are believed to be somewhat lower than those projected at Stillwater.

COLOMBIA

Production of PGMs in Colombia is a byproduct of gold mining. Currently 25,000 ounces of platinum are produced yearly from placer deposits in Colombia. Reserves are estimated to be under 1 million troy ounces of platinum. There is virtually no palladium production in Colombia. Due to the byproduct nature of PGM productiuon, Colombia would not be a significant factor in meeting increased PGM demand, short of a price rise to many times current levels.

OTHER COUNTRIES

Over 98 percent of the world's PGM primary production currently comes from South Africa, the Soviet Union, and Canada. There is only byproduct PGM production from nickel-copper ores in Australia, Indonesia, the Philippines, Zimbabwe, and Finland. At much higher prices, China could produce small amounts of platinum as a byproduct of copper-nickel production in the Garsu province.

WORLD RESERVES

Table 4-23 summarizes estimated world PGM reserves by country, with data on ore grades and proportions for each PGM. The huge reserves in South Africa indicates that long-run supply response should be very price elastic, as long as this source of supply remains available.

The importance of the South African UG2 seam in terms of world reserves is clear. Moreover, the table facilitates analysis of the proportions of various platinum group metals in each deposit. For instance, rhodium is seen to be in high proportion at UG2 and Stillwater.

It is also important to remember that PGMs are primary products in South Africa. Unike Canada and the Soviet Union, where PGMs are nickel-copper byproducts, production in South Africa should respond primarily to events in PGM markets.

SUPPLY RELIABILITY

Any discussion of the reliability of U.S. platinum and palladium supplies must, of course, begin with South Africa. Rustenburg and Western Platinum Mines operate in South Africa, whereas Impala's mines, concentrator, and smelter are in Bophuthatswana, which became a quasi-independent state in 1977, under the South African Homelands policy. Impala's head office and refinery are in South Africa proper, however. The fact that much of Impala's operations are in Bophuthatswana is not necessarily a cause for concern, since Impala is the country's principal industry and relations with the homeland government generally have been cordial. A portion of Rustenburg's ore bodies are also in Bophuthatswana.

Labor conditions in the Republic of South Africa actually may be somewhat more uncertain than those in Bophuthatswana, at least in the short run. The most recent labor incident in South Africa affecting mining occurred in March 1979 when the South African Mine Workers Union called on all of its 18,000 members to walk out one week after one-third of its miners struck. The major issue was removal of job reservations for whites only. The strike ended after six days, after reasonably organized negotiations among mining companies, union leadership, and the union rank and file. The South African Chamber of Mines, which can act as an intermediary in labor disputes, did not have to intervene in the 1979 incident.

The South African mining industry naturally has been sensitive to concern about its reliability as a long-run source of supply, and it can present a persuasive case for confidence. On a recent tour of South Africa, U.S. Representative James D. Santini (D-Nev.), an advocate of an expanded U.S. national minerals stockpile policy, found little cause for supply concern in South Africa (American Metal Market, 1980). Santini serves as chairman of the House Mines and Mining Subcommittee. He stated after his tour that "South Africa's Achille's Heel is resolving their racial problems," and he found that the mining companies themselves were on the cutting edge of social change.

It is certainly outside the scope of the present project to forecast the likelihood of civil unrest in South Africa comparable to that which has occurred in outlying areas such as Rhodesia. However, it is worth noting that in most cases where such unrest has taken place in Africa, mining operations have not been direct targets for catastrophic sabotage, presumably because any of the parties vying for power strongly prefer to have the mines' revenues, should they be successful. However, such historical precedents are hardly conclusive, and there would be many imponderables even if we had a great deal more time to give to the issue. We have no immediate reason for great concern about supplies of PGMs from South Africa.

Canada has experienced rather severe labor problems at the Sudbury nickel operations. Most recently, in 1979 INCO (Canada's largest producer of PGMs), reduced customer deliveries to 40 percent of 1978 levels due to an eight-month strike. Regular INCO customers had to turn to the spot market and pay premium prices.

The Soviet Union cannot of course be considered a reliable source of supply. It has cut off supplies of metals to the United States in the past, both for political reasons (e.g., prior to the Korean War) and for possible economic gain (e.g., to support much higher export prices for palladium). Even without such identifiable motivations, Soviet actions on export markets can seem capricious to Western consumers. The moderate market response to the cessation of Soviet exports of palladium in 1980, in part because of compensating supplies from South Africa, is encouraging.

CONSUMPTION ELASTICITY AND SECONDARY RECOVERY

In addition to increased primary production, secondary recovery could help meet increased demand for PGMs due to tighter emissions standards. Furthermore, other industries could reduce their consumption if PGM prices increase sufficently. The central issues then become by how much would demand by other industries fall and secondary recovery increase, after a given increase in PGM prices.

CRA has recently designed an engineering-based model of demand elasticity and secondary recovery for PGMs in each major industrial end use. This analysis for the U.S. Department of Interior is for the purpose of specifying a complete model of the platinum and palladium industries. The results of this work are utilized for an analysis of industry-specific demand elasticities and secondary recovery below. Analyses of these issues for PGM consumption by the U.S. automotive industry are treated in some detail in another chapter of this report.

PETROLEUM REFORMING

The demand for PGMs in petroleum processing exhibits low demand elasticity (and then only after substantial lags) due to lack of substitutes. Our estimates of the long-run price response in petroleum reforming is tabulated below:

Relative Price Increase	1	2	5	10
Long-Run Relative Consumption Decrease	1	0.967	0.867	0.700

As the numbers indicate, a doubling of PGM prices would result in less than a 4 percent decrease in quantity demanded even in the long run. Moderate additional reductions in PGM demand could be obtained from petroleum reforming only with a 5- or 10-fold price increase. The recycling recovery rate for petroleum reforming is quite high, perhaps 97 percent.

PETROLEUM CRACKING

Most platinum purchased by the petroleum industry is used for petroleum reforming, but moderate amounts used for cracking (a recent development, about which the industry is still quite secretive) are unusual because there is no secondary recovery and consumption is more responsive to price increases than is typical for PGMs. Price responsiveness of demand is estimated in the table below.

Relative Price Increase	1	2	5	10
Long-Run Relative Consumption Decrease	1	0.70	0.44	0.31

NITRIC ACID PRODUCTION

Nitric acid production, which uses platinum in a catalytic process, currently accounts on average for about 30 percent of U.S. platinum purchases for chemical processing. (Palladium is used in very small quantities relative to platinum in nitric acid production; the elasticity figures below refer to platinum.)

Higher platinum prices can reduce PGM demand in nitric acid production by encouraging better recycling and usage of the so-called "random pack" technology, which uses platinum less intensively.

Relative Price Increase	1	2	5	10
Long-Run Relative Consumption Decrease	1	0.74	0.49	0.37

The table above indicates that a doubling of platinum prices will decrease platinum consumption in nitric acid production by approximately 26 percent in the long run.

CHEMICAL PROCESSES OTHER THAN NITRIC ACID

In most chemical applications other than nitric acid production there is no significant loss of platinum or palladium, hence little room to improve PGM recovery rates. The following very low demand elasticity estimates apply to both platinum and palladium.

Relative Price Increase	1	2	5	10
Long-Run Relative Consumption Decrease	1	0.997	0.992	0.989

TELEPHONE SWITCHING EQUIPMENT

Our estimates for price elasticity of demand for palladium in telephone switching equipment is given below.

Relative Price Increase	1	2	5	10
Long-Run Relative Consumption Decrease	1	0.92	0.67	0.25

For a price increase of 100 percent, demand for palladium would decrease by only 8 percent, but would diminish by 75 percent for a 10-fold price increase. This is possible because electronic switching, which will be used for most new switching by the 1990s, could be used immediately in place of palladium (electromechanical) switches if price incentives were sufficient.

Between 1955 and 1974, the Bell System was the largest purchaser of palladium in the United States, accounting for around 60 percent of palladium sales reported by the U.S. Bureau of Mines for the electric category. In 1975 a silver-palladium alloy was substituted for pure palladium contacts. By 1980 the installation of electronic switching instead of electromechanical relays was common. By 1980, Bell System purchases of nontoll-refined palladium were down to around 100,000 ounces per year.

Our estimates are that the amount of recycled palladium from scrapped Bell equipment throughout the rest of the century will be roughly 100,000 troy ounces annually. Gross consumption of palladium by the Bell System is projected to decline from 200,000 ounces in 1980 to 100,000 ounces in 1985, and 50,000 ounces in 1990. Thus, after 1985, the Bell System will be a net supplier of palladium.

DENTAL AND MEDICAL USES

Gold is the most generally competitive substitute for platinum and palladium in dental work. If the price of gold were to remain constant, substitution away from palladium or platinum in response to increases in their prices would be rapid and extensive:

Relative Price Increase	1	2	5	10
Long-Run Relative Consumption Decrease	1	0.15	0.01	0

(If increased prices for platinum and palladium were caused by a countrywide disruption in South Africa, it is plausible that gold prices would also increase, in which case substitution away from platinum and palladium would be much less extensive.)

ELECTRICAL -- OTHER THAN TELEPHONE SWITCHES

Platinum and palladium are used in "electronic inks" which dry into conductive paths in miniature electronic components. Our estimates for price elasticity of demand for these two platinum metals are given below:

Relative Price Increase	1	2	5	10
Long-Run Relative Consumption Decrease	1	0.78	0.59	0.50

Even if PGM prices were to increase 10-fold, PGM consumption in electrical uses (other than telephone switching) would decrease only 50 percent. It is not anticipated that recovery of PGMs from scrapped electronic gear will be profitable unless prices increase greatly.

GLASS

Platinum and rhodium are used extensively in the glass industry, in glass handling and forming equipment, because of its tendency not to react with other agents. There are no close substitutes for PGMs in glass production, and as a consequence price responsiveness is low:

Relative Price Increase	1	2	5	10
Long-Run Relative Consumption Decrease	1	0.97	0.93	0.90

PRICE ELASTICITIES FOR CALCULATING THE CRITICALITY OF PLATINUM, PALLADIUM, AND RHODIUM

The above estimates of the responsiveness of platinum and palladium consumption to large price increases were specifically developed for analysis of severe supply disruptions. Thus, they are designed for the type of analysis of materials criticality that we carried out in the preceding chapter.

The only category of platinum and palladium consumption not discussed above is vehicular emissions control. The concluding chapter of this study discusses the limited possibilities for reducing consumption of platinum and palladium, assuming currently promulgated emissions standards are maintained. For purposes of estimating the criticality of platinum, palladium, and rhodium, we suppose conservatively that a five-fold increase in the prices of platinum, palladium, and rhodium would make efficient only a 12 percent decrease in quantities consumed (beyond decreases that would occur anyway, due to technological advances, decreases in engine sizes and so on). We assume the same price responsiveness for rhodium consumption. We do not yet regard this price responsiveness to be a definitive estimate, but we use it as a placeholder until further work can be done.

Finally, weighting the price responsiveness of all the categories of platinum and palladium consumption by their expected relative importance in the mid-1980s (not discussed here), we obtain the following price elasticities of U.S. demand that were used in the national criticality measurement in the second chapter:

- Platinum 0.03
- Palladium 0.045

Without similarly detailed analysis, we specify the price elasticity of U.S. demand for rhodium to be the same as that for platinum.

SPECULATION AND INCREASED DEMAND FOR PLATINUM GROUP METALS

In recent years speculating in platinum-group metal spot and futures markets has become more pronounced. Among the platinum-group metals, only platinum and palladium are traded in futures contracts on the New York Mercantile Exchange.

Speculating in platinum can be simply defined as buying and selling by those who otherwise have no use for the metal in anticipation of future price changes. While speculation more immediately affects the spot price of platinum, it can also affect the producer price, since underlying forces of supply and demand are eventually reflected in the provisions of long-term contracts as well as in spot prices. One industry observer has ventured that the speculative factor is on average equal to about 25 percent of the activity in the spot market (see American Metals Market, 1980).

The reasons for speculation in platinum, just as in other metals, vary with the speculator. Some investors may reason that future demand or supply events which the current price does not reflect may increase platinum prices, in which case they can purchase on the spot market and hold the metal, or buy a futures contract for platinum delivery at a later date at a specified price. Engaging in a futures contract to buy is referred to as "going long." On the other hand, if the speculator believes that future market events are likely to decrease platinum's price relative to the currently quoted futures trading price, he can "sell short", i.e., engage in a contract to deliver platinum at a future date at a fixed price. If the speculator has guessed correctly, he can purchase the platinum to deliver at the future date when the spot price is lower than the previously contracted price, hence earning a profit. Only two to three percent of the platinum futures contracts at the New York Mercantile Exchange are ever consummated with actual physical delivery of the metal. In most cases, traders cancel their positions on a daily basis by entering futures contracts on both the buying and selling sides, incurring either a profit or loss on the difference.

In addition to speculators who engage in the above-described activity, there are those who desire to hold platinum as security for future severe economic or political instability, where "hard" currency like gold and silver would be a more viable medium of exchange. It appears however that currently most speculators in platinum are there purely for the possibility of short-run economic gains.

At times, platinum prices follow the speculative trends in gold and silver prices, allegedly because of concern over the value of paper currency in inflationary times. Often, however, platinum does not move in tandem with gold or silver, in part because platinum demand, unlike gold, is predominantly determined by industrial consumption.

Speculation is often responsible for discrepancies between dealer and producer prices. As Figures 4-9 through 4-14 indicate, the discrepancies are usually short-lived but sometimes sharp. The speculative sector in the platinum market today is credited by some observers with causing the clear divergence of platinum dealer prices over producer prices during the late 1970s and early 1980s (Figure 4-9). Primary producers of PGMs have kept prices to their industrial customers significantly below those on the spot market so as to stabilize demand (and thereby presumably maximize profits in the long run, if not the short run).

The reaction of speculators can be a significant consideration for evaluating any proposed regulatory policy that would be implemented so quickly as to force auto manufacturers or their suppliers onto the the spot market to purchase platinum-grown metals. Even in the absence of speculative activity, demand and supply for platinum-group metals tend to be insensitive to price changes, so that relatively large price changes are required to equilibrate the market when a new demand for PGMs suddenly appears. With speculative activity, an unanticipated demand can destabilize the market and greatly exacerbate the resulting price variability.

In the long run, much more platinum and palladium can be supplied from South Africa and even deposits in the United States without greatly increasing the metals' prices. If at all possible, regulatory changes requiring sizable new amounts of PGMs should be planned and promulgated more than two years in advance, so that long term contracts can be signed with producers and the required new PGM capacity can be created.

Appendix

ANNOTATED BIBLIOGRAPHY AND GUIDE TO SOURCES OF INFORMATION ON PLATINUM-GROUP METALS

To keep abreast of the PGM market at a general level, or to analyze policy impacts, there is a nucleus of publications which serve quite well. Below are listed organizations that publish PGM information, followed by a discussion of which aspects of the market are adequately covered and which aspects are poorly covered. Finally, an annotated bibiliography is provided.

U.S. government publications are readily available and very useful. The U.S. Bureau of Mines (US BOM) regularly publishes PGM data and market analyses; these publications are often cited in other PGM reports. The Canada Ministry of Natural Resources occasionally publishes reports on PGM world markets. Also, the Mineral Bureau of South Africa publishes regular information.

There are also many private sources of PGM information. Roskill Information Services in London provides regular newsletters as well as periodic publications that bring together data from around the world. J. Aron and Co., New York, is also a source of information on PGM markets.

A variety of journals and newsletters publish regular PGM information. Some, like American Metal Market, provide daily price statistics, while others, like Engineering and Mining Journal, provide information of a more technical nature.

Other organizations provide irregular but sometimes very useful publications on PGMs. The International Precious Metals Institute seminars generate publications often containing PGM information. Also, the National Material Advisory Board has published monographs on PGM supply and use patterns.

The increased importance of PGMs has led to publication of increasingly comprehensive data. Primary production data are generally good, except, of course, for the Soviet Union. Reasonably reliable data exist for consumption in industralized countries. In the United States, the Bureau of Mines estimates "apparent consumption" to compensate for the underreporting of actual consumption. Trade of PGMs among industrialized countries is fairly well captured; data on trade with less developed countries are not as good.

The most obvious deficiency is data on PGM stocks. The U.S. Bureau of Mines publishes data on refiner, dealer, and importer stocks, but these do not include consumer shelf and in-use stocks, or private investor stocks. Only unofficial estimates are available for other countries and other kinds of private stockpiles.

ANNOTATED BIBLIOGRAPHY

U.S. BUREAU OF MINES

1. Mineral Commodity Profiles, Platinum Group Metals, No. 22, September 1978, 23 pages. An excellent general reference for the structure of PGM markets, and discussion of major supply and demand issues. U.S. and world coverage is provided. Price, world production and trade, and consumption data are included.

2. Mineral Commodity Summaries, annual, Platinum Group Metals chapter. A brief (usually two page) update of important events in PGM markets. Data provided include percent breakdowns of U.S. consumption, U.S. production and recycling, U.S. government stockpiles, and world mine production and reserves. In addition to these data, a general discussion of trends and issues is provided. Publishing is prompt.

3. Minerals Yearbook, annual, Platinum Group Metals chapter. This is the most comprehensive yearly US BOM publication on PGMs. Data are provided on producer and dealer prices, U.S. consumption by end-use and type of production, foreign trade by country, and world primary production. Also included are general discussions on recent trends in many aspects of the PGM market, including technological changes in the use and production of PGMs. Publication lags are significant, however.

4. Mineral Industry Surveys, quarterly, Platinum Group Metals. A pamphlet with quarterly U.S. data on PGMs. Included are data on PGMs recovered by refiners; refiner, importer and dealer stocks; consumption by end use; imports and exports by country; and producer and dealer prices.

5. Mineral Trade Notes, monthly. This publication compiles PGM trade data obtained in part from the State Department.

6. Minerals and Materials, monthly edition on Platinum Group metals. Two or three pages of charts and tables are provided. Coverage includes domestic consumption, primary and secondary production, trade, and prices.

ONTARIO, CANADA MINISTRY OF NATURAL RESOURCES

1. Platinum Group Metals --Ontario and the World by Thomas P. Mohide, Minerals Resources Branch, March 1979, 162 pages. Description of each of the PGMs, with emphasis on how they are used. For each PGM, a complete analysis of where and how primary and secondary production occurs is included. A good general reference or "textbook."

MINERALS BUREAU OF SOUTH AFRICA

1. The Bureau periodically publishes memoranda and reports dealing with PGMs. Some relevant publications are Internal Memoranda No. 8, "Platinum Group Metals in Canada," and No. 25, "Platinum Group Metals in the People's Republic of China."

ROSKILL INFORMATION SERVICES, LTD. (LONDON)

1. Roskill's Letters from Japan, monthly. Periodic information on PGM demand by category in Japan, and dealer and producer price is reported. Also, information is provided on ore content and deposits of leading world PGM producers.

2. The Economics of Platinum Group Metals, Second Edition, 1979. Useful compendium of worldwide PGM data. Among the hundreds of tables are end-use for the world and major countries, voluminous primary and secondary production data by country, and international trade data. One difficulty, however, is that the 1979 (second) edition reports data only through 1978.

J. ARON COMMODITIES CORPORATION

1. J. Aron's Precious Metals Research Department periodically publishes reports on supply and demand characteristics of PGM markets.

INTERNATIONAL PRECIOUS METALS INSTITUTE

1. The IPMI conducts regular seminars and publishes the papers from these seminars. Often papers are presented on the economics and metallurgy of PGMs.

NATIONAL MATERIALS ADVISORY BOARD

1. While the NMAB does not publish regular PGM reports, "Supply and Use Patterns for the Platinum Group Metals" (1980) discusses the criticality of PGMs and recommends stockpiling objectives.

JOURNALS

1. American Metals Market (daily) and Metals Week (weekly) provide PGM price and market information. Several other journals periodically contain PGM information of a more technical nature: Engineering and Mining Journal, Mining Journal (London), and World Mining.

CHAPTER 4 REFERENCES

1. American Metal Market. 1979a. Statement by Albert Robinson, Chairman, Rustenberg Platinum Holdings, Ltd. Sept. 28, 1979: 12.

2. ___________. 1979b. December 6.

3. ___________. 1980. Feb. 15: 1.

4. Buchanan, D.L. 1980. "Platinum: Great Importance of Bushveld Complex." World Mining. (August.)

5. ___________. 1979. "Platinum-Group Metals Production from the Bushveld Complex and Its Relationship to World Markets." University of Witwaterstrand, Bureau of Mineral Studies, Johannesburg.

6. Charles River Associates Incorporated. 1976. "Policy Implications of Producer Country Supply Restrictions: The World Platinum and Palladium Markets." National Bureau of Standards, U.S. Department of Commerce.

7. "Cobalt, Platinum Scene Stockpile Focus." 1981. American Metal Market Feb. 5: 1.

8. Engineering and Mining Journal. 1979. September: 38.

9. Mohide, T.P. 1980. Metal Bulletin Monthly. February: 55 (Converted from metric tons to troy ounces by Charles River Associates).

10. National Materials Advisory Board. 1980. Supply and Use Patterns for the Platinum Group Metals. Washington, D.C.: 109.

11. U.S. Bureau of Mines. 1978. "Platinum." Mineral Commodity Profiles. No. 22.

5

RECYCLING OF PLATINUM-GROUP METALS FROM CATALYTIC CONVERTORS

Since 1975, catalytic convertors have been fitted onto the exhaust systems of American automobiles to reduce the level of hydrocarbon and carbon monoxide emissions. The convertors contain small quantities of platinum-group metals (PGMs) deposited on a substrate that facilitate the chemical breakdown of exhaust pollutants into harmless components such as carbon dioxide and water vapor. The PGM content of each catalytic convertor is quite small, approximately 0.05 troy ounces worth about $20 at 1981 prices. 1981 PGM prices are relatively high by historical standards, and there is some question whether market forces will be sufficient to induce recycling of these metals from spent convertors.

Consumption of platinum by the automobile industry beginning in 1974 is shown in Table 4-21, taken from U.S. Bureau of Mines data. Catalytic convertors purchased by the auto industry in 1980 accounted for approximately 40 to 45 percent of total U.S. consumption of platinum and palladium. By way of contrast, the chemical and electrical industries each consumed approximately 15 percent of these precious metals. No major reductions in the use of platinum-group metals have occurred through 1980. The 1981 model year employs a "three-way" catalyst nationwide (instituted in 1980 in California) which contains rhodium in addition to platinum and reduced quantities of palladium.

The recovery and recycling of PGMs from the chemical, petroleum, electrical, glass and other industries have well-established technologies that can recover more than 95 percent of the precious metals in scrap residues. On the other hand, recovery technologies for catalytic convertors are still being developed. We will analyze these issues further after a preliminary discussion of the functions of catalytic convertors in automobiles.

BACKGROUND ON THE FUNCTION OF THE CATALYTIC CONVERTOR

Exhaust gases from the internal combustion engine contain, in the absence of any controls, four environmentally hazardous components: unburned hydrocarbons, carbon monoxide, oxides of nitrogen, and lead. The first three can be controlled using the catalytic convertor and the fourth by changing to unleaded gasolines. There is a clear distinction between catalytic systems for the oxidation of carbon monoxide and unburned hydrocarbons and systems for the reduction of the oxides of nitrogen. Problems in developing exhaust catalyst systems lie not only with the catalyst itself, but also with support systems and reactors capable of withstanding engine exhaust conditions as well as thermal shock, vibration, and general misuse. Emissions are worst at start-up, when the catalyst is cold and below its effective operating temperature.

THE CHARACTERISTICS OF CATALYST MATERIAL

PGMs are the crucial catalysts being employed in convertors. The PGMs are deposited in a very thin layer onto one of two forms of inert substrate, either a monolithic honeycomb or pellets. To obtain effective performance as rapidly as possible after engine start-up, the density of the support material is kept as low as is practical. Recently, a stainless steel honeycomb has been developed. The entire catalyst is contained in a stainless steel casing which is placed into the exhaust system between the exhaust manifold and the muffler. The casing directs the exhaust flow through the catalyst bed and protects the catalyst from mechanical damage. The harmful components in the exhaust gases are converted to carbon dioxide and water vapor in the convertor.

The PGM loading in each convertor manufactured by GM from 1975 to 1979 was about 0.05 troy ounces of platinum and palladium, combined in a 5:2 ratio, amounting to 0.036 troy ounces platinum and 0.014 troy ounces palladium. Prior to 1980, the total catalyst (including substrate) weighed between 4 and 6.4 pounds. In 1980, the density of the substrate was reduced, lowering the range of weights to between 2.8 and 4.4 pounds. In 1981, GM began using the three-way catalyst with a loading of about 0.05 troy ounces platinum, 0.02 troy ounces palladium, and 0.005 troy ounces rhodium per convertor, which amounts to about $30 worth of PGMs at 1981 prices: ($475 per troy ounce platinum, $140 per troy ounce palladium, and $700 per troy ounce rhodium). The total weight of the catalyst system averages 5 pounds in the latest convertors. We present below a breakdown of the costs of a catalytic convertor when it is new and another breakdown of the scrap value of the same convertor after 50,000 miles of use.

COST BREAKDOWN FOR NEW AND USED CONVERTORS

The breakdown of the components of a typical new 1980-1981 three-way pellet convertor are given below:

Part	Material	Manufactured Costs
Convertor Assembly	--	$ 1.92
Outer Wrap	409 Stainless Steel	5.42
Shell	409 Stainless Steel	3.00
Input/Output pipes	409 Stainless Steel	1.68
Bed Support	409 Stainless Steel	2.86
Insulation	Fiberglass	1.85
Pellets	Alumina + PGMs	30.05
TOTAL		46.75
Total "aftermarket" selling cost, including markup by auto parts dealer		$204.00

SOURCE: Rath & Strong, 1980.

The value of materials in a spent three-way convertor after 50,000 miles of operation (not counting recovery costs) is approximately as follows:

Part	Material	Convertor	Value of Material After Processing Losses
Convertor can and support structures	409 Stainless Steel	$ 1.25*	$ 1.25
Pellets	PGMs	$30.05	$24.04**
		$31.30	$25.29

SOURCE: Charles River Associates, 1980.

From the above table, it can be seen that what remains of value from a spent convertor is the can and the PGMs. The can is 409 stainless steel which, because of contamination, will only be worth about $0.05 per pound. This 409 stainless is not high-quality scrap, especially after contamination by exhaust gases.

New convertors of the major automakers were sold by auto parts dealers ("aftermarket") for approximately $200 in 1980. (See Chiltons, 1980.) GM had the following choices of pellet systems in 1980:

Oxidizing catalysts only	$188
Oxidizing and reducing catalyst (Cadillac)	$204

For renewing spent convertor catalysts, GM had a repair kit containing new pellets for $38, with a labor charge of $20, bringing the total cost for replacement to $58.

Ford had a range of honeycomb convertor prices ranging from $172 to $320 (on the Maverick and Granada models). Ford also charged $20 for labor to replace a spent convertor, so the cost of putting in a whole new honeycomb catalyst totaled between $192 and $340.

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*Convertor can weighs approximately 25 pounds, and 409 stainless steel scrap from this source is valued at approximately $0.05 per pound.

**80 percent PGM recovery assumed (10 percent loss from abrasion during operation and 10 percent loss during processing). There is not yet an industry concensus on these loss percentages; these assumptions are a compromise among industry sources with which CRA talked.

Chrysler had honeycomb convertors that ranged in price from $176 to $196. Replacement of a spent convertor required about 1.2 hours and cost $24 for labor, bringing the total for convertor replacement to $200 to $220 for an automobile.

The above prices were typical in 1980. The manufacturing/vendor cost is from one fifth to one quarter of the $200 selling price, or $40 to $50. The corresponding actual plant manufacturing cost would be roughly $27 to $34 per convertor. There is, of course, a significant markup over manufacturing costs by the time the convertor reaches the customer. However, a spent convertor, after 50,000 miles of use, will contain scrap metals worth at most only about $31, including the value of the stainless steel can, which in 1980 was worth about $.05 per pound. If the recovery rate for PGM processing and recycling is 80 percent, the total scrap value of contained metals drops from $31 to $25 per convertor. (See the table above.)

RECYCLING CATALYTIC CONVERTORS

There are three phases in the lifetime of a catalytic convertor when it may be scrapped, allowing recovery of contained PGMS: 1) after failure to meet original specifications; 2) after usage makes the performance of the convertor on an operational vehicle unsatisfactory; and 3) when the vehicle is scrapped. We now consider each of these cases in turn.

PHASE I: REJECTED CATALYSTS

This category consists of calatysts in the form of beads, pellets, monoliths, honeycomb or biscuits which are supplied by the manufacturers to the automotive industry, but do not meet specifications for insertion into convertors. For this classification of scrap, the total amount produced through 1980 was about 4 million pounds, with roughly an additional 2 million pounds being generated in 1981.

PHASE II: REPLACEMENT AFTER 50,000 MILES

Catalytic convertors are guaranteed for only 50,000 miles of vehicle operation. The material from failed convertors scrapped prior to scrappage of vehicles will be a particularly important source of supply in states with inspection programs.

The amount of automotive catalyst which will become available will be solely dependent upon mandatory replacement of spent catalysts after 50,000 miles. Sebastian Musco of Gemini Industries, a new catalyst recycling company, estimates this market will eventually be 8 million pounds per year, containing approximately 50,000 troy ounces of platinum and 21,000 troy ounces of palladium. (See Musco, 1979.) (Replacement catalytic convertors will likely be taken off of late model wrecked cars where the convertor is relatively new and undamaged and resold at prices ranging from $35 to $65 each.)

PHASE III: AUTO CATALYST FROM SALVAGED AUTOS

This phase represents the largest resource for recycled PGMs. Musco at Gemini Industries has estimated that by 1984, 4 million cars containing 18 million pounds of catalyst will become available. He feels that catalysts from automobiles in California will begin to surface in significant amounts by 1981. He projects by 1988 approximately 8.5 million convertor equipped cars will be scrapped, containing 45 million pounds of catalyst, or approximately 300,000 troy ounces of platinum and 125,000 ounces of palladium; by 1998, he maintains these figures will double.

Phase I and II convertor recovery has been going on for several years, but Phase III is very much in an embryonic state. Phase III presents a more complex problem, involving dismantling the convertors from salvaged auto wrecks.

Discussions with several large auto scrap handling companies and precious metal producers, who are entering the business of PGM recycling from convertors, have indicated that the removal of the convertors is quite easy and fast in most cases. Either the convertors are torched off, which takes a couple of minutes, or a hydraulic cutter is used, which can remove three convertor cans per minute. One scrap yard, when removing the gas tank before shredding the auto wrecks, uses a fork lift to remove the convertor along with the whole exhaust system in about thirty seconds. There was early concern that recovering convertors is too labor-intensive to be cost effective. However, we have uncovered no evidence that this is in fact the case.

One major precious metals producer has estimated that 60 percent of all PGMs in convertors going to scrap yards in 1981 are being recycled in the last two phases.

AMC and GM convertors, containing loose beads or pellets, are simple to open. The beads are removed easily by a vacuum suction hose and shipped to PGM processors in drums. The Ford monolithic convertor can is more difficult to shear open, since a torch is not used. The whole convertor is usually shipped to the processor. Probably because of the difficulty with Ford convertors (and the probability of getting some empty cans), Gemini Industries, a leader in the field, has stopped processing monolithics and now only handles the beads.

The convertors being recovered in 1980 came predominantly from 1975 through 1979 model autos, which used the oxidation catalyst only. The typical loading was a total of 0.05 troy ounces of PGMs in a platinum: palladium ratio of 5:2, that is, 0.036 ounces platinum and 0.014 ounces palladium. (The PGM loading varied with model year and engine size, but this was the average loading level.) At 1980 PGM prices (producer prices) of $475 per troy ounce for platinum and $140 per troy ounce for palladium, the total value of PGM in a typical two-way convertor was $19.15. Johnson-Matthey, a large PGM refiner which is getting into convertor catalyst recycling, has reported their refining costs, including PGM losses, to be $8.35 per convertor. This leaves only $10.80 per convertor for the purchase and transportation of used catalysts from the scrap dealers, which, as will be shown below, is near the breakeven point that makes this activity at all profitable.

Used convertors usually pass through several hands before ending up at the refinery. The convertors are first recovered from salvaged autos at scrap yards and auto dismantlers, of which there are estimated to be between 15,000 and 20,000 in this country. (See McKinnon, 1978.) Auto dismantlers typically buy wrecked cars from individuals, auto insurance companies, and municipal governments. The convertors, as well as other major auto parts, then enter the "core-exchange" market through a core buyer. The core buyer typically drives a truck around to various scrap yards and picks up barrels of used convertors. He then may sell to a scrap broker, who then sells to refiners like Gemini, Engelhard, or Johnson-Matthey. If the dismantler is large enough, he may deal directly with the refiner.

Cohen quoted the following operating cost breakdown for gathering and processing scrap and catalytic convertors (Cohen, 1979):

Stage of Recycling	Range of Cost (dollars)
Auto dismantler	4.00-5.50
Intermediary stages (core buyer and/or core supplier)	1.50-2.50
Transportation to refinery	0.05-0.12
Refining	0.73-1.22
TOTAL COST	$6.28-9.34

We now consider more recent information on this issue.

Information from a 1980 ADRA* survey of scrap dealers in various states has indicated that dismantling time, the availability of dry storage areas for 300 or more convertors, and shipping costs will be the major costs determining the profitability of recycling PGMs. If the convertors were picked up, then $4 per unit would make the activity profitable for scrap dealers. But if the convertors had to be shipped, then $7 or $8 would be required in the case of a Michigan dealer shipping to Gemini Industries in California. In general, from a survey of Massachusetts auto dismantlers, as well as the ADRA respondents, prices ranging from $8 to $11 per convertor for bulk quantities delivered to the refiner were found prevailing. Gemini, for instance, is offering $7.86 for pellet convertors and $5.70 for honeycomb convertors at existing platinum prices of $475 per troy ounce. Gemini will buy only in minimum orders of 1,000 pounds. This is the price for the catalyst alone. If the can also is bought for its chromium value, another $1.50 to $2.00 is paid per convertor. A Louisiana firm, Southern Scrap Materials Corporation, now entering the business of refining convertor catalysts, is offering $12.00 to $13.50 per convertor.

Transportation costs quoted by Engelhard** are $0.05 per pound of catalyst, just for shipping from Tennessee to their New Jersey plant, which translates to $0.30 per pellet convertor with 6 pounds of catalyst and $0.20 per monolithic convertor. Assuming 4 pounds for the catalyst system, and using the refining costs of Johnson-Matthey noted earlier, a revised table of gathering and processing costs would be as follows for 1980 prices:

Stage of Recycling	Pellet Convertor		Honeycomb Convertor	
	1	2	1	2
Auto Dismantler	$4.00-6.00	$7.36-13.50	4.00-6.00	$5.70
Intermediary Stages (core buyer or supplier)	1.50-2.50	--	1.50-2.50	--
Transportation to Refinery	0.20-0.30	--	0.20-0.30	--
Refining+	8.35	8.35	8.35	8.35
Total Cost	$14.05-17.15	$16.21-21.85	14.05-17.15	14.05

1 = Selling to intermediaries from dismantler.

2 = Selling direct to refineriers from dismantler.

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*ADRA - Automotive Dismantlers and Recyclers of America, Washington, D.C.

**Personal communication with Englehard Corp., New Jersey.

+See Warwick, 1980.

These are average costs. Costs for more specific situations depend on the origin of the scrapped convertor shipment, the location of the refinery, and the quality of shipped catalyst material. Moisture, iron, lead, and other contaminants can reduce the price that refiners will ultimately pay for spent convertor catalysts.

SPENT CATALYST PGM REFINING

The convertor recyling business is clearly in its infancy, and details on how the refining companies process the catalyst to recover PGMs is very much proprietary information right now. However, there are two possible processing routes that could be taken, which have been discussed publicly in general terms. The first is by smelting the spent catalyst material, slagging off impurities, and separating out the PGMs. The second route is by chemically leaching the PGMs from their alumina substrate and applying standard recovery methods now being used for primary production of PGMs.

The smelting route appears quite costly in terms of energy consumption, since platinum melts at 1769°C. Rhodium melts at 1966°C, and the substrate melts at over 2000°C. It appears that smelting would be the less efficient processing route.

Chemical leaching of the PGMs leaves behind the substrate. It could be performed with a number of industrial acids. The spent catalyst would likely be ground to finer particle size to expose more surface area for more effective leaching. While no information was obtained on process details, the outline of a plausible method is as follows: Platinum and palladium are readily dissolved in aqua regia -- a mixture of hydrochloric and nitric acids, and HNO_3, while rhodium will not dissolve and is left behind. This separates platinum and palladium into a solution where platinum could be precipitated with ammonium chloride solution, as the impure platinum salt. Several more steps of redissolving and precipitating platinum would be required for purification. Subsequently, a pure platinum chloride salt would be roasted in muffle furnaces at 1000°C to give platinum sponge of 99.99 percent purity.

The palladium remaining in solution after platinum removal might be precipitated in a manner similar to that for platinum, and ultimately roasted to form palladium metal sponge.

The insoluble rhodium in the catalyst could be removed with molten sodium trisulfate at 500°C. From the rhodium sulfate solution, rhodium hydroxide can be precipitated and then dissolved in hydrochloric acid to form rhodium chloride. Several more redissolving and precipitating stages would be used to purify the chloride before it goes to a glass lined vessel to be boiled with formic acid, forming "rhodium black" precipitate. This is then ignited in a muffle furnace to produce 99.9 percent pure rhodium powder.

This is a hypothetical chemical leaching process based on the current techniques used in primary PGM production by Johnson-Matthey, INCO, Engelhard and others. Recovery rates for PGMs from spent catalysts upon processing are estimated to be approximately 90 percent of the PGMs that physically remain after use. However, buildup of lead on the catalyst can complicate the recovery process and reduce the yield. Other losses have been identified by the PGM refiners, attributed to abrasion of the beads, which removes some of the PGM surface coating. It apparently is difficult to discern whether loss is due to abrasion or chemical reactions during operation of the convertor. Some spokesmen for vehicle manufacturers still claim that very little loss of PGMs occurs, by either volatization or by abrasion. Another type of PGM loss can occur, called afterburn, which is initiated by the high operating temperatures inside the convertor (over 1000"F). If the engine is run with a rich fuel mix, unburned gases in the exhaust can ignite in the convertor and even melt down some of the catalyst material, which can make PGM recovery very difficult or impossible.

The current leader in the technology of recycling PGMs from convertors is generally acknowledged to be Gemini Industries in California. It is a small company that was retained by General Motors to review the problem of expensive existing recovery processes and low yields. Gemini claims it has developed a new, less expensive process to recover the PGMs, and the company anticipates no difficulties in recovering PGMs from the three-way catalytic convertors going into new automobiles in 1981 (Musco, 1979). Gemini, as of February 1980, was processing 2 million pounds of catalyst material per year, and had capacity to process 3.5 million pounds per year. A planned $2 million capital improvement would expand capacity to 10 million pounds per year (see Chemical Week, 1980).

Available data on PGM recycling technologies is insufficient to evaluate independently the summary analyses of their costs provided by refiners such as Johnson-Matthey. Our best judgment is that industry claims about the cost of refining convertor material are plausible, and improved technologies such as those claimed by Gemini Industries could indeed determine whether recycling PGMs in obsolete catalysts would be profitable at PGM prices lower than those existing today. We do not forecast such substantial decreases in PGM prices, but they are a possibility, for example, if the Soviet Union begins exporting much more extensively. At 1981 PGM prices, recycling appears at least marginally profitable even with "traditional" refining methods.

FUTURE AVAILABILITY OF PGMS FROM SCRAPPED CONVERTORS

During the first three years of substantial catalytic convertor use, from 1975 to 1977, approximately 1.1 million troy ounces of PGMs were consumed. (See Roskill, 1978.) By the end of 1980, the cumulative total had risen to 1,500,000 troy ounces of platinum and 600,000 ounces of palladium (see Musco, 1979). By the early 1980s, 550,000 troy ounces of this PGM content had become available, according to Sebastian Musco of Gemini Industries. Engelhard has characterized 1985 as the "kick off" year for PGM recycling, because at that time most scrapped automobiles coming into auto dismantlers will have catalytic convertors. A significant fraction of new demand for PGMs by the automotive industry could then be supplied from recycling catalytic convertors.

CHAPTER 5 REFERENCES

Chiltons 1980 Labor Guide and Parts Manual. Chilton Book Co., Radnor, Pa.

Chemical Week. 1980. February 17.

Cohen, Mark A. 1979. "Recycling of Catalytic Convertors." Draft. EPA, Washington. April.

McKinnon, R.F. 1978. "Panel on Trends in the Use of Platinum Group Metals." Presentation Before the National Academy of Science, Washington, D.C.: August 30.

Musco, S.P. 1979. "Reclaiming of Precious Metals From Automobile Catalytic Convertors." Third International Precious Metals Institute, Chicago. May: 178.

Roskill. 1978. "Platinum Group Metals." 118.

Wernick, N. 1980. Paper presented at ADRA Annual Convention. Johnson-Matthey Corp., Honolulu, Hawaii, November.

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SUBSTITUTES FOR PLATINUM-GROUP CATALYSTS IN VEHICULAR EMISSIONS CONTROL

BACKGROUND

The requirements of the Clean Air Act of 1967, together with the amendments in 1970 and 1977, provide the framework for the establishment of emissions standards from automobile engines. These basically set maximum permissible emission levels for three pollutants, CO, hydrocarbons, and NO_x, in terms of grams per mile, as determined by a standardized test procedure that averages the representative modes of operation of an automobile.

The emissions standards in effect until 1974 could be met by engine modifications, but those for the 1975 and later model years required the use of a catalyst for most cars. For the period of 1975 to 1979, the standards for NO_x (3.1 to 2.0 gm/mile, except for California) could be met by engine modifications, so the catalyst was an oxidizing catalyst only, designed to oxidize most of the CO and hydrocarbons in the exhaust to CO_2 and water.

The standards for 1980 model cars required a further reduction in permissible CO and hydrocarbon levels. The standards for the 1981 model year reduced the allowable CO emissions further. The reduction in allowable NO_x emissions was of great importance technically, since it could not be met on all cars by engine modifications but required the development of a new catalyst system. The situation with respect to CO emissions is in a state of flux. EPA has waived the 3.4 g/mile standard for many 1981 and 1982 model cars, allowing the 7.0 g/mile standard to remain for this period.

OXIDIZING CATALYSTS

During the research and development leading to the oxidizing catalyst used during the period 1975 to 1980, literally thousands of catalyst compositions were developed and tested by chemical companies, oil companies, catalyst manufacturers and automobile companies. It was found that no catalyst compositions could begin to meet the requirements of activity and durability with the use of gasoline containing lead compounds and the accompanying halogenated additives (such as ethylene chloride) required to prevent the buildup of lead deposits in the engine. Hence it was necesesary to require the use of a lead-free fuel.

Designing catalyst systems to meet mandated emissions standards is a very intricate matter. The main factors involved are basically the following:

1. Catalyst durability;

2. Emissions before the catalyst reaches operating temperature, that is, the "cold start" problem; and

3. Intrinsic catalyst activity and response to poisoning from sulfur in the gasoline.

These factors interact with each other in a complicated manner. An enormous amount of technical literature exists on various ramifications of the problem. For example, an excellent, critical and recent review by Kummer of the Ford Motor Co. (1980) cites 168 references. The key points are the following:

1. Catalyst Durability

The catalyst is required to meet the required emission levels specified by the Federal Test Procedure after completing 50,000 miles of driving over a prescribed route in a specified manner. The catalyst may fail because of (i) sintering, that reduces active area, (ii) loss of active catalyst by attrition or spalling, or (iii) deactivation by poisons, especially sulfur. Catalyst durability is also determined by engine durability. A variety of engine malfunctions can cause excessive amounts of unburned fuel in the exhaust that can lead in a short time to excessive catalyst temperatures that permanently destroy its activity.

2. "Cold Start"

Much of the CO and hydrocarbons that are emitted in the Federal Test Procedure escape before the catalyst reaches operating temperature, and the problem is exacerbated by the necessity to choke the engine for start-up, which unfortunately increases hydrocarbon and CO emissions from the engine.

Thus it is vitally important that the catalyst be brought up to operating temperature as rapidly as possible, a process termed "light-off."

3. Intrinsic Activity

A. Oxidation Catalysis

The best base-metal oxide catalysts, such as copper oxide (CuO) or cobalt oxide (Co_3O_4), show activities (per unit surface area) for CO oxidation comparable to that of noble-metal catalysts, but they are less active for hydrocarbon oxidation, especially for saturated hydrocarbons. Moreover, these oxides in an unsupported form sinter readily. When supported on alumina, which increases the available catalytic area, they tend to react with the alumina at high temperatures to form less active species, but alumina is still considered the best available, reasonably economic support.

Non-leaded gasoline contains about 150-600 parts per million of sulfur, which is converted to SO_2 during combustion. All base-metal catalysts become gradually deactivated by SO_2 in the exhaust, at the temperature range of 400-600°C, as a result of adsorbed sulfate species (Yao, 1975). Those catalysts containing copper or chromium are least affected and the situation can be alleviated to some degree by operating at temperatures above about 600°C. The presence of a small amount of noble metal on the surface of a base metal oxide can also help suppress sulfur poisoning (Gallagher, et al., 1975). However, supported noble metal catalysts are much less deactivated than base metal catalysts by SO_2 at temperatures below about 500°C. Probably the poisoning of base-metal oxide catalysts could be prevented if the catalyst were occasionally heated to above 700°C (Fishel, 1974), but temperatures of 1000°C or so can cause their rapid, irreversible sintering.

In summary, U.S. car manufacturers have gone completely to the use of platinum or a mixture of platinum and palladium for oxidation catalysts. No catalysts consisting only of base metals are used. The reasons are as follows:

- These noble metals are less deactivated by sulfur compounds at temperatures below 500°C;
- They are more active for hydrocarbon oxidation than base metal oxides; and
- They are more thermally resistant to sintering.

Development of suitable automobile catalysts requires enormous expense to demonstrate durability. (It has been estimated that each 50,000 mile durability test of one car may cost between $50,000 and $100,000.) Therefore there are very strong incentives to test only those catalysts that clearly have the potential for the required durability. By about 1973 it had become evident that base metal systems were noncompetitive, and catalyst suppliers and the automobile companies turned completely to optimizing the performance of noble metal catalyst systems.

NO_x REMOVAL CATALYSTS

The commitment to noble metal catalysts by car manufacturers was further reinforced by the necessity to develop a new catalyst system to reduce NO_x levels for the 1981 model cars. No known catalyst of requisite activity is available to decompose NO to N_2 and O_2. However, by operating a suitable catalyst within a narrow gas composition range, termed the "window," at essentially the stoichiometric value* it is possible to markedly lower the emissions of all three pollutants. This is termed a "three way" catalyst (TWC), because all three pollutants -- CO, hydrocarbons, and NO_x -- react simultaneously. In effect, the exhaust is brought very close to a mixture of only H_2O, CO_2, and N_2.

The three-way plus oxidation catalyst system may also be used. It consists of one bed operated as a three-way converter to reduce NO_x, after which secondary air is added and the mixture passed through an oxidizing converter. Removal of CO and hydrocarbons is somewhat improved, but NO_x conversion is not as good as with the three-way system, largely because some NH_3 is formed in the first bed and is reoxidized to NO_x in the second. However, it can be operated satisfactorily over a wider range of air-fuel ratios than the TWC. A three-way catalyst is apparently becoming the preferred system by U.S. car makers. The fuel-air ratio to the engine is carefully controlled to essentially the stoichiometric value by use of an oxygen sensor on the engine exhaust.

The reduction of NO_x to nitrogen by CO or H_2 is readily catalyzed by base metal oxide catalysts such as NiO, CuO, or $CuCr_2O_4$, although some of the NO_x may be converted to NH_3. NiO is of particular interest in that, in the presence of H_2 or H_2O, conversion of NO to NH_3 is quite low (Shelef and Gandhi, 1971), and the Ford three-way catalyst used in California in 1979 incorporates NiO as well as Pt and Rh (see the discussion below). However, these base metal catalysts are severely poisoned by surface sulfides which are formed under reducing conditions, in contrast to sulfates formed under oxidizing conditions. Deactivation by sulfur can be lessened by operating at temperatures above 650°C, but thermal degradation can then be severe.

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*The stoichiometric ratio is that ratio of air to fuel at which the oxygen present is just sufficient to convert the fuel to CO_2 and H_2O if it were burned completely. If the air-fuel ratio is less than this it is termed "fuel-rich" operation; if the air-fuel ratio is greater than this it is termed "fuel-lean" operation.

For removal of NO_x by reduction, the noble metal catalysts are again superior to the base metal catalysts. Rhodium is more active than platinum or palladium and produces less NH_3, but because of its scarcity and high cost, a mixture of rhodium with platinum, or with platinum and palladium, is usually used.

With three-way catalysts, the closed-loop system that controls the air-fuel ratio to the engine operates essentially by an on-off method that causes this ratio to oscillate at a frequency that varies moderately above and below about one Hertz (sec^{-1}). The catalyst thus operates under transient conditions, the exhaust gas alternately being net oxygen-rich (fuel lean) and then net oxygen deficient (fuel rich). The performance of noble-metal catalysts is improved by incorporating an additional component such as cerium oxide, which is usually described as having an "oxygen storage capacity." In an oxidized state this component provides oxygen for CO and hydrocarbon oxidization during the fuel-rich portion of the cycle, when the catalyst is simultaneously reduced. When the cycle changes to the fuel-lean portion, the catalyst component is reoxidized from O_2 or by NO_x; the latter process aids in NO_x removal. The effects are still only partly understood and the water gas shift reaction, $H_2O + CO \rightarrow H_2 = CO_2$, may also play a role in CO removal (Schlatter and Mitchell, 1980; Hegedus and Gumbleton, 1980).

The monolith three-way catalyst used by the Ford Motor Co. in California in 1979 contained about 14 percent Al_2O_3, 1.6 percent NiO_2, 0.7 percent CeO_2, 0.15 percent platinum and 0.015 percent rhodium. The pelleted catalyst used by General Motors in California in 1978 contained noble metals at about 0.05 percent of total weight, with a platinum/rhodium ratio of about 2 in one type of vehicle and about 15 in another (R. Canole, et al., 1978). The noble metal catalysts can be further improved, at least in principle, by depositing the noble metal in layers slightly displaced below the outside surface of the porous support, which gives added protection from poisons such as phosphorus compounds that come from lubricating oil (Hegedus, et al., 1979; Summers and Hegedus, 1979; and Hegedus, 1981). The additional expense for development of the three-way catalysts represents a very large sunk cost that in effect commits the automobile manufacturers even more deeply to the use of noble-metal catalysts. (The Japanese car makers have followed essentially the same path as U.S. car makers, but with slightly different mechanical methods of controlling the air-fuel ratio with the use of a three-way catalyst.)

BASE-METAL CATALYST RESEARCH

During recent years, a modest research effort on base metal catalysts has been maintained at General Motors and by Professor W. Keith Hall (University of Wisconsin, Milwaukee, Wisconsin), working with G.M. (Hall, 1981). This work has focused on zeolite catalysts which were not considered in the early 1970s. (A zeolite is a crystalline alumino-silicate containing a very fine pore structure. A large variety are known and several are currently used commercially as catalysts, primarily in petroleum processing. Some are quite stable at high temperatures and in the presence of water vapor.) Of a large variety of compositions considered by Hall and co-workers, a Fe-Y zeolite was the most attractive (Fu, et al., 1980). It can be reversibly oxidized and reduced between Fe^{2+} and Fe^{3+}, and it shows reasonable activity for reaction of NO_x with CO, although not as good activity as that exhibited by a standard GM oxidizing catalyst. Nonetheless many questions remain, including actual thermal stability and resistance to poisoning by SO_2. Hall speculates that it is possible that SO_2 may be excluded by its size from reaction sites accessible to CO, so that SO_2 might not be an effective poison in this case, but this possibility remains to be demonstrated.

A new class of catalysts having strong interactions between a supported metal and the support have been developed by researchers at Exxon (Tauster, et al., 1981) (so-called S.M.S.I. catalysts). They consist primarily of group VIII metals dispersed on transition metal oxides. (Group VIII includes Fe, Co, and Ni, as well as the six noble metals.) They have not been studied as automobile catalysts, but they have been shown to have unusual chemisorption properties which suggests that some members of the class might possibly adsorb sulfur compounds less readily and hence be more resistant to poisoning. It is to be emphasized that this possibility is speculative and no experimental studies have been done. However, it is another direction that could be explored in the future.

Kummer (1980) emphasizes that one of several requisites for development of a solely base-metal oxide catalyst is improved stability at high temperatures and in the presence of water vapor. Some work at Ford Motor Co. was done with ZrO_2 as a support, which has a high melting point. New silicalite-type zeolites developed by Union Carbide (Flanigan, et al., 1978) are stable to very high temperatures and might be interesting in this regard.

SUMMARY ON POSSIBLE REPLACEMENT OF PLATINUM-GROUP METALS

The above history of the development of automobile catalysts to date shows the great complexities that have been overcome in order to develop noble-metal catalyst systems that meet the presently-mandated requirements for emissions standards and durability. With the present state of the art, it probably would be possible to design a solely base-metal oxidizing catalyst system that would at least initially meet (Federal Test Procedure) standards for emissions of carbon monoxide and hydrocarbons. This system would have to be somewhat larger than present units utilizing noble metals and there might be some difficulty with achieving sufficiently fast warm-up. However, because of sulfur poisoning such a unit could almost certainly not meet present durability standards and it would not remove NO_x, so it could only meet pre-1981 NO_x emissions standards.

Technology exists for reducing the sulfur in gasoline to a very low level, which could substantially prolong the life of a base-metal catalyst. We are not aware, however, of any analysis of how costly this desulfurizaton would be. It would probably vary considerably from refiner to refiner and would depend on the sulfur content of the crude oil. Low sulfur crude oil is even today a premium material that commands a higher market price than lower quality, higher sulfur crudes. Unfortunately, crude oils being imported into the United States increasingly contain higher sulfur contents.

There is no published evidence that a solely base-metal catalyst could match the performance of the present three-way catalyst system, even initially. The Ford three-way monolith catalyst incorporating NiO and CeO_2 still uses approximately the same quantity of platinum that is required for a solely oxidizing catalyst designed to meet 1980 CO and hydrocarbon emission standards. The very high prices of platinum-group metals of course provide car makers with a very strong incentive to reduce the cost of their catalyst units by substituting base metals. Most promising avenues for such substitutions have been extensively explored.

To reduce the use of platinum significantly further would apparently require the relaxation of present emissions standards, either with respect to allowable rates of emission or durability. Exploratory work on certain zeolite catalysts by General Motors and Professor Hall is interesting, but much further effort would be required to determine if these catalysts truly have potential. Considering the fact that all previous base-metal catalysts have proved inadequate, the likelhihood of new, solely base-metal catalysts becoming practical for meeting present standards of durability and emissions must be considered slight. We have searched the literature and talked to a number of people knowledgeable in the field of catalysts in general and auto catalysts in particular, but there appear to be no other leads to solely base-metal catalysts that would meet present auto emission standards.

CHAPTER 6 REFERENCES

1. Canole, R., et al. 1978. S.A.E. Paper 780205.

2. Fishel, N.A., et al. 1974. Environmental Science and Technology, 8, 260.

3. Flanigan, E.M., et al. 1978. Nature, 271.

4. Fu, C.M., M. Deeba and W.K. Hall. 1980. Industrial Engineering & Chemistry, Product Research and Development, 19, 299.

5. Gallagher, P.K., et al. 1975. Materials Research Bulletin 10, 623.

6. Hall, W.K. 1981. Personal communication.

7. Hegedus, L.L. 1981. Personal communication.

8. Hegedus, L.L., and J.J. Gumbleton. 1980. Chemtech, 10, 630.

9. Hegedus, L.L., et al. 1979. Journal of Catalysis, 56, 321.

10. Kummer, J.T. 1980. Progress in Energy and Combustion Science, 6, 177.

11. Schlatter, J.C. and P.J. Mitchell. 1980. Industrial Engineering & Chemistry, Product Research and Development. 19, 288.

12. Shelef, M. and H.S. Gandhi. 1972. Industrial Engineering & Chemistry, Product Research and Development, 11, 2.

13. Summers, J.C. and L.L. Hegedus. 1979. Industrial Engineering & Chemistry, Product Research and Development. 18, 318.

14. Tauster, S.J., et al. 1981. Science, 211, 1121.

15. Yao, Y.Y.F. 1975. Journal of Catalysis, 39, 104.

Peer Reviewers' Comments on Report Number EPA 460/3-82-012

Larry C. Landman, Project Officer, CTAB

Readers of this Report

Due to the timing of the writing of this final report and the implementation of EPA's peer review process, it was not possible to incorporate the reviewers' comments into the final report entitled "Scarcity, Recycling and Substitution of Potentially Critical Materials Used for Vehicular Emissions Control."

The following corrections are applicable to the above cited report which was prepared under EPA contract number 68-03-2910 and dated February 1982:

Page 2-62

The report now reads as follows:

> "...EPA might consider requiring U.S. vehicle manufacturers to hold specified minimum levels of platinum, palladium, and rhodium."

EPA has no authority to require manufacturers to do this.

Page 3-5

The report now reads as follows:

> "Thus, their [Rath & Strong subproject] report is included with this study as a separately bound appendix."

At the recommendation of EPA, this subproject report was not included with this study.

Page 3A-2

The report now reads as follows:

> "Grams of Platinum-Group Metals Consumed per Vehicle:"

Page 4-35

The authors state:

> "Currently, no alternative base-metal catalytic converter appears economical, as discussed at length in a later chapter."

While base metal catalysts have a number of problems, economics (i.e., cost) does not appear to be a major difficulty.