# MATERIAL SUBSTITUTION: LESSONS FROM THE TIN-USING INDUSTRIES

John E. Tilton
*International Institute for Applied Systems Analysis, Laxenburg, Austria*

RR-84-9
May 1984

Reprinted from John E. Tilton, editor, *Material Substitution: Lessons from Tin-Using Industries*. Washington, D.C.: Resources for the Future, Inc. (1983)

**INTERNATIONAL INSTITUTE FOR APPLIED SYSTEMS ANALYSIS**
**Laxenburg, Austria**

---

Reprinted by permission of Resources for the Future and Johns Hopkins University Press from John E. Tilton, editor, *Material Substitution: Lessons from Tin-Using Industries*, pages 1–11.


---

Printed by Novographic, Vienna, Austria

## FOREWORD

The substitution of relatively abundant and cheap raw materials for scarce and expensive resources has since the Industrial Revolution helped the world satisfy its voracious appetite for material inputs and cope with the problem of resource depletion. Despite its importance, however, there is still much we need to learn about the substitution process. To what extent, for example, is substitution intertwined with technological change? How important are material prices in stimulating substitution? How quickly can substitution normally take place? How does it affect our ability to forecast mineral consumption; to apply conventional economic principles in analyzing mineral markets; to constrain monopoly or oligopoly power in these markets; to alleviate mineral shortages?

This report is a reprint of the first part of a study undertaken in the hope of providing some insights into such questions. It provides an overview or summary. The second and much larger part, which is not reprinted here, contains three in-depth case studies of substitution – on beverage containers by F.R. Demler, on solder applications by P.D. Canavan, and on tin chemical stabilizers and the pipe industry by D.G. Gill.

The original study, conducted under my direction at the Pennsylvania State University with the financial support of the U.S. National Science Foundation, is similarly entitled *Material Substitution: Lessons from Tin-Using Industries*. It was published in 1983 by Resources for the Future in Washington, D.C.

JOHN E. TILTON
*Leader*
Mineral Trade and Markets Project

# 1

# Material Substitution: Lessons from the Tin-Using Industries

*John E. Tilton*

Historically, the United States and other industrialized countries have substituted relatively abundant materials for increasingly scarce materials. This has alleviated—some would even say, postponed indefinitely—the upward pressure on material costs resulting from the depletion of high-grade, readily available, and easy to process mineral deposits.

Forest products, as Rosenberg (1973) has shown, provide a dramatic illustration from the past of this benefit of material substitution. The abundance of timber in nineteenth century America led to its widespread use, both as a fuel and as a building material. By the end of the century, however, the once seemingly endless tracts of forest land were gone, and many feared that shortages of this essential resource would soon curtail the country's economic development. The substitution of coal, petroleum, and natural gas for wood as a fuel, and iron and steel, aluminum, cement, and plastics for wood as a material, however, averted a shortage, and the country's economy continued to grow rapidly during the twentieth century. As for the future, Goeller and Weinberg (1976), Skinner (1976), and others contend that material substitution will have to play an even more critical role, if the adverse effects of dwindling mineral resources on economic growth and living standards are to be avoided.

While material substitution is an essential weapon in society's arsenal for holding the long-run problem of resource depletion at bay, it is important for other, more immediate reasons as well. Material substitution may, at least in some applications, soften the blow of abrupt and unexpected interruptions in mineral trade, whether these interruptions arise from wars, civil disturbances, strikes, natural disasters, or embargoes. During World War II, Germany, the United States, and other countries managed to replace tin, tungsten, and other restricted materials with more available alternatives in many end uses (Eckes, 1979, chap. 4). In recent years, interest in material substitution as a cushion against supply interruptions has grown as the political situation in southern Africa and other mineral producing regions has become more turbulent.

Despite its importance, we still have much to learn about the nature of material substitution. For example, just how important a factor is substitution in shaping short-run and long-run trends in material consumption? Are its effects generally evolutionary and continuous, or abrupt and discontinuous? Is the replacement of one material by another primarily motivated by shifts in relative prices, or are changes in government regulations, consumer preferences, technology, and other factors typically more influential? Where substitution does occur in response to shifts in material prices, what is the nature of the time lag between the two? What kinds of substitutions can be made quickly, and what kinds require years or decades to accomplish?

## Approach

To provide insights into such questions, material substitution was examined in three tin-using industries—beverage containers, solder, and tin chemical stabilizers used in the production of plastic pipe. In these case studies, which are found in part II, material substitution is defined to encompass a number of different types of events that may substantially alter material use.

The first is material-for-material substitution, where one material is used in place of another. Examples include the use of an aluminum beer can for a glass bottle, the installation of plastic rather than copper pipe, and using aluminum rather than copper-brass radiators to cool automobile engines.

The second is other-factors-for-material substitution, where consumption is reduced by increasing nonmaterial inputs, such as labor, capital, and energy. The hand soldering of radios, televisions, and other electronic products, for example, requires less solder than more automated production using printed circuit boards. As indicated in part II, however, producers have favored printed circuit boards despite their higher material intensity because they lower labor costs.

The third is quality-for-material substitution, where material is saved by reducing the quality or performance standards of the final product. For example, the lightweight, nonreturnable bottles produced during World War II had relatively high breakage rates. These bottles could have been strengthened by using more glass to make them thicker.

The fourth is interproduct substitution, whereby a change in the mix of goods used to satisfy a given need alters the demand for one or more materials. Television may reduce the need for movie houses, public transportation for private automobiles, and the telephone for letters or visits. This type of substitution, unlike others, does not affect the manufacturing process or the materials used in the production of individual goods, but instead influences material use by changing the composition of the goods and services produced. It includes what Chynoweth (1976) and others call functional substitution, which occurs when a product (along with the materials it embodies) is replaced by an entirely different means of achieving the same end. The use of satellites instead of underground cables to transmit long-distance telephone messages is an example.

The fifth is technological substitution, in which an advance in technology allows a product to be made with less material. The introduction of electrolytic tinplating during and after World War II greatly reduced the tin requirements for beer and soft drink cans, and provides a good example of this type of substitution. New technology can also create new products, as the aluminum can illustrates, and thus increase the opportunities for interproduct substitution.

In short, material substitution may result from the introduction of new technology, from shifts in the composition or quality of final goods, and from changes in the mix of factor inputs used in producing these goods. This is clearly a broader and more encompassing definition than the common perception of material substitution, which often is restricted solely to material-for-material substitution. A broad definition, however, is more appropriate and useful if ultimately one is concerned with alleviating material shortages or forecasting future mineral requirements.

There are, of course, other ways to study material substitution than the case study approach followed here. One possibility entails the estimation of production or cost functions for entire industries, economic sectors, or even the economy as a whole. Such efforts, which Slade (1981) has recently reviewed, generally treat materials as a single factor of production, and assess the extent to which they can be replaced by other inputs such as capital, energy, and labor. Their findings vary greatly, depending on how the production or cost functions are specified, how technological change is treated, and how other issues are resolved. They also tend to suffer from the use of aggregate input data and from their static nature (Kopp and Smith, 1980; Slade, 1981).

A second alternative involves more micro investigations that consider individual materials and often focus on specific end uses. These efforts specify and estimate formal models, the most common of which are econometric supply and demand models, such as the Fisher, Cootner, and Baily model of copper (1972) and the Woods and Burrows model of aluminum (1980).

These models typically assess the effects of material substitution by including in their demand equations price variables for close substitutes, and so implicitly assume that material prices are the primary driving force behind substitution. The specification of such models also normally presumes that the relationship between demand and material prices adheres to a particular lagged structure that remains fixed over time, and that this relationship is continuous and reversible. The latter implies that the demand lost when a material's price increases is recovered when price returns to its original level. While they are perhaps plausible in certain instances, such assumptions are open to question. Even more important, in making them, these models are assuming away many of the interesting questions associated with material substitution.

The decision to concentrate on a limited number of in-depth case studies was taken in the belief that this was the most promising approach given the current state of understanding and knowledge about the material substitution process. Like other approaches, it has its limitations. In particular, since material substitution occurs constantly in literally thousands of products throughout the economy, only tentative conclusions about the general nature of material substitution can be drawn on the basis of such a limited sample of actual situations.

The focus on tin-using industries was motivated by two considerations. First, the price of tin rose substantially during the 1970s, both in real terms and in relation to the prices of most of the alternative materials with which it competes. In this regard, there is some concern that the depletion of known, high-quality deposits and the failure to discover new deposits of comparable quality will continue to force prices up in the future. Second, the United States and other industrialized countries rely almost entirely on imports from developing countries for their primary tin requirements. These imports come in large part from Malaysia and other countries in Southeast Asia. The lengthy sea routes over which they travel could easily be interrupted during military or other emergencies.

While all of the case studies examine uses of tin, they are not concerned exclusively with tin. Indeed, by its very nature one cannot study material substitution without considering more than one material. In its many applications, tin competes with a variety of materials, including chromium, steel, glass, aluminum, cast iron, copper, antimony, lead, plastic, and silver. In certain applications steel, plastics, lead, and other materials are complementary products in the sense that they are used with tin in producing a product. As a result, a reduction of their price tends to increase the demand for tin.

The three sectors of the tin industry selected for study—beverage containers, solder, and tin chemicals used in the manufacture of plastic pipe—were chosen for different reasons. As every consumer of beer or soft drinks knows, the beverage container market has been a lively battlefield for competing materials over the last two decades. The sturdy returnable glass bottle, the lighter one-way bottle, the tinplate can, the aluminum can, the tin-free steel can, and recently the plastic bottle have all fought for this market. The variety of competing materials and the dramatic speed with which their fortunes may rise and fall make the container market of particular interest.

In contrast, it is widely assumed that little material substitution has occurred in the solder market, and that little is possible. Indeed, solder by definition is an alloy of tin and lead, with other materials added in minor amounts in certain applications. Moreover, for technical reasons the tin content of solder cannot be varied without seriously affecting its performance in certain uses, particularly electronic equipment. So solder provides an opportunity to examine the extent and nature of material substitution in applications where substitution is generally presumed difficult. As solder is consumed in a multitude of products, this case study concentrates primarily on its use in can seams, new motor vehicle radiators, and fillers for automobile bodies. Other important applications of solder in the electronics and plumbing industries are considered in less detail.

Tin chemicals, and particularly organotin chemicals used as stabilizers in the production of plastic pipe, have grown substantially over the last two decades. In contrast, as table 1-1 shows, most sectors of the tin industry have been stagnant or decreasing. Consequently, an investigation of tin chemicals provides an opportunity to examine why material substitution may not always reduce the demand for a commodity whose price is rising rapidly. Due to the many uses of tin chemicals, the focus is restricted to organotin chemicals and their use in plastic pipe production.

The scope of the case studies is further limited in three respects. First, although many of the trends in U.S. tin consumption are also found in other countries, in a number of instances important differences do exist between the United States and other countries. While some of these differences are noted in passing, the emphasis is on material substitution in the United States.

**Table 1-1. Tin Consumption in the United States by End Use Sector, 1955 and 1978**

| | 1955 | | 1978 | |
|---|---|---|---|---|
| End Use Sector | Thousands of Tons[a] | Percent | Thousands of Tons[a] | Percent |
| Tinplate | 34.1 | 37 | 17.3 | 27 |
| Solder | 22.6 | 25 | 18.3 | 29 |
| Bronze and Brass | 20.0 | 22 | 10.4 | 17 |
| Chemicals[b] | 1.9 | 2 | 7.6 | 12 |
| Other[c] | 13.3 | 14 | 9.5 | 15 |
| Total | 91.9 | 100 | 63.1 | 100 |

*Source:* American Bureau of Metal Statistics (various years).
[a]Metric tons are used throughout this study.
[b]Includes tin oxides and miscellaneous.
[c]Includes terne plate, babbit, collapsible tubes, tinning, pipe and tubing, type metal, bar tin, miscellaneous alloys, and white metal.

Second, the case studies do not cover all the important tin consuming industries. Table 1-1, which shows the major end use sectors for tin in the United States for the years 1955 and 1978, indicates that over two-thirds of the country's supplies are used to make tinplate, solder, and bronze and brass. Beverage containers are part of the tinplate sector, but so are fruit and vegetable, meat, soup, and other cans. Beer and soft drink cans have accounted for only between 10 and 20 percent of total U.S. tinplate consumption. The case studies also examined important uses of solder and chemicals, but as noted already, coverage of these sectors is far from complete.

Third, the studies concentrate on explaining the past, primarily the period since 1950, rather than predicting the future. The past can be documented with data, and the factors causing material substitution identified more or less. The future is far more uncertain, and detailed information on material consumption, prices, and other relevant variables is not available. Thus, the analyses carried out here are designed to enhance knowledge of the nature and determinants of material substitution by improving our understanding of events that have taken place. Of course, it is hoped that this information will ultimately prove useful in assessing the role that material substitution may play in the future.

The case studies are similar in that they all follow three analytical steps. In the first, the pounds or tons of tin consumed in specific applications, such as soft drink containers, are quantified for the years covered in the analysis.[1]

In the second step, what are called the apparent determinants of tin consumption are identified and measured. These determinants are directly related to tin consumption by an identity, and basically indicate how tin usage has

[1]Metric tons are used throughout this study.

changed over time. For example, the amount of tin in the solder used to produce new motor vehicle radiators has varied over time as a result of changes in (1) the number of new motor vehicles and hence radiators produced; (2) the proportion of radiators made from copper and brass, rather than aluminum, and so requiring soldering; (3) the pounds of solder used per copper-brass radiator; and (4) the tin content of the solder used for this purpose. Any change in tin consumption from one year to another in radiator solder must result from a change in one or more of these apparent determinants.

Although the apparent determinants vary from one end use to another, they contain in all instances one variable that reflects the change over time in the output of the end use. In the preceding example, it is the number of new motor vehicle radiators. This apparent determinant may change over time for reasons other than material substitution. The number of new motor vehicles and in turn radiators produced in the United States, for instance, may increase simply because population and per capita income are growing. Changes in all the other apparent determinants, however, are the result of one or more of the five types of material substitution identified earlier. Moreover, while the apparent determinant reflecting changes in the output of the end product can change for other reasons, it too may be affected by material substitution, particularly interproduct substitution. The growth of mass transit systems in metropolitan areas, for example, may slow the growth of new automobile radiators.

By identifying the apparent determinants and empirically assessing their effects, one can dissect the change in tin consumption into its component parts. The reasons why these parts change can then be assessed.

This is done in the third step, which identifies and evaluates the major underlying factors responsible for the changes in the apparent determinants, and thus ultimately in tin consumption. These factors include the price of tin, the price of alternative materials, technological developments, government regulations, and a host of other considerations. At this step, the analysis cannot be as empirically rigorous. Assessing the relative importance of the major underlying factors involves some judgment, even after weighing the available information from industry and other sources. Surprisingly, however, in many instances, due largely to the level of disaggregation on which the analyses are conducted, the important underlying factors are readily apparent.

## Findings

In all of the end uses studied—beer and soft drink containers, can seams, motor vehicle radiators, automobile body solder, and chemical stabilizers used in the production of the PVC plastic pipe—material substitution greatly affected tin consumption over the longer run, a period of ten years or more. Moreover, in many instances, it sharply altered or reversed trends in tin usage even in the short run.

The tinplate can, for example, after years of increasing its share of the beer container market, abruptly found itself during the late 1960s being pushed out of this market by aluminum and tin-free steel cans. Even with solder, often considered immune to material substitution, the introduction of low-tin alloys, produced by substituting lead and minute amounts of other metals for tin, substantially reduced the need for the latter in can seams and automobile body solder. More recently, the trend away from large automobiles has decreased the size of the average motor vehicle radiator and in turn the need for solder and tin in this use.

Two types of material substitution are especially prevalent. The first is material-for-material substitution. The beverage container market in particular has experienced substantial changes over time in the number and quantity of materials it consumes. A wide variety of materials also compete for the pipe market. Indeed, much of the growth in tin chemicals for this industry has come about as a result of the substitution of plastic for copper, cast iron, steel and other kinds of pipe. In solder, material-for-material substitution has occurred on a modest scale with the appearance of aluminum radiators, and on a more significant scale with the widespread adoption of low-tin alloys for can seam and body solder.

Technological substitution is the second type often encountered. New technology reduced the tin content of the average size tinplate beverage container by 93 percent between 1950 and 1977. Similarly, in the plastic pipe industry, the introduction of second and third generation organotin stabilizers caused their tin content to fall by nearly 50 percent.

Other types of material substitution, though apparently less common, also occur. The growing distribution of soft drinks in bulk containers, due in large part to the rise in fast food chains, slowed the penetration of the tinplate can in this market. Another example of functional substitution is found in the electronic industry where the miniaturization of components greatly reduced the number of electrical connections requiring soldering.

The case studies also strongly suggest that intermaterial competition and substitution are becoming more intense and prevalent over time, as the number of materials increases and the properties of existing materials are enhanced, allowing them to penetrate new markets. This tendency is clearly found in the beverage container market. In the early 1950s, the glass bottle basically monopolized both the packaged beer and soft drink markets. The only competition came from the tinplate can, in which a modest amount of beer was shipped. Starting in the 1960s and continuing in the 1970s, however, the bottle encountered increasing competition from the tinplate can, the aluminum can, the tin-free steel can, and recently the plastic bottle. While the glass bottle continues to be the most popular packaged container (if the returnable and one-way bottle are considered together), its share of the soft drink market dropped from 100 to 62 percent between 1950 and 1977. In beer, it fared even less well, retaining only 40 percent of the market by 1977.

Growing material competition is found in other sectors as well. Polyvinyl chloride (PVC) plastic did not enter any of the pipe markets examined until the early or mid-1960s. Antimony stabilizers as an alternative for organotin first appeared in the late 1970s. Solder, once required to seal the side seams of all cans, had its monopoly of this market broken by the development of welded and cemented seams, and by the introduction of the two-piece can, which has no side seam.

The factors responsible for material substitution are numerous and their significance tends to vary over time and by end use. However, three factors—relative material prices, technological change, and government regulations—are of particular importance in all of the case studies. In examining their influence, it is useful to start with material prices, since economists and others often assume that they are the principal motivation or incentive for material substitution. On this, the evidence is mixed; or more correctly, it supports the proposition that material prices are important but that several qualifications or corollaries to this conclusion are necessary.

There is no doubt that the high and rising price of tin has discouraged its use. As table 1-1 indicates, total tin consumption in the United States, in contrast to that of nearly all other metals, has declined over the postwar period. Moreover, it is not difficult to document specific examples of substitution away from tin that is motivated at least in part by its price, as is illustrated by the development of second and third generation tin stabilizers, low-tin alloy solders for can seams and automobile body fill, and the declining tin content of tinplate.

Still, material substitution has in many instances increased, and increased substantially, the use of tin. Such substitutes take place, despite the high price of tin, for two reasons. First, in some uses tin provides superior quality or performance that outweighs its higher cost. For example, electronic manufacturers, after experimenting with solders containing 50 percent tin and 50 percent lead, reverted back to 63 percent tin solders because the latter's lower melting temperature resulted in less damage to printed circuit boards during the manufacturing process.

Second, substitution takes place on many levels. In the pipe industry, for example, it occurs in the production of stabilizers, plastic compounds, and pipe.[2] Since tin constitutes between 18 and 35 percent of the final cost of producing organotin stabilizer, producers are strongly motivated to reduce or eliminate their use of tin. However, at subsequent stages of production, tin becomes an increasingly smaller fraction of total cost, finally accounting for 1 percent or less of the final price of PVC plastic pipe. At this stage, the price of tin has much less of an effect on the type of pipe purchased.

So, it is not surprising that the price of tin has its greatest impact on material substitution at relatively early stages of production, where tin costs constitute a significant portion of total costs. It is here that substitution has with considerable consistency reduced tin usage. In plastic pipe, for example, the tin content of stabilizers has dropped substantially as a result of the development of second and third generation tin stabilizers and the recent appearance of antimony stabilizers. This contrasts with the material substitution at later stages of production, which has significantly increased the use of tin. At the compound stage, polyvinyl chloride, which requires a stabilizer, has replaced other types of plastic; and at the pipe stage, plastic has replaced pipe made of copper, cast iron, and other materials. At both of these stages, the price of tin has had a small impact on final cost, and has been easily offset by other considerations.

When tin prices do stimulate material substitution, three possible time dimensions or lagged responses are found. First, where existing technology and equipment permit the use of one material for another in the production process, substitution can respond immediately to changes in material prices. In such situations, when the price of a material rises above a certain threshold level, producers switch away from it. When the price falls below this threshold, they switch back again. Not only is the response fast, but it is reasonably predictable. The case studies of containers, solder, and tin chemical stabilizers uncovered a few instances of this type of response. The dual canmaking line, introduced about 1976, can substitute between aluminum sheet and tinplate in 4 hours. Also, plastic pipe producers can switch from one plastic resin to another quite quickly since the same equipment is used. However, the opportunities for such a rapid response to changes in material prices or other conditions are limited.

Second, where the technology for substitution exists but equipment must be altered or completely replaced, material substitution occurs only after some delay. Moreover, the lag normally exceeds the minimum period required to build new facilities or modify old ones, for producers hesitate to make such changes, in light of the costs, until they are

[2]The production of plastic pipe involves the melting and extruding of a plastic compound, which is composed of a plastic resin, such as polyvinyl chloride (PVC) or acrylonitrile-butadiene-styrene (ABS), plus several chemical additives. The latter include lubricants to prevent the compound from sticking to the extruder, impact modifiers to increase resilience, and flame retardants. In addition, compounds made from PVC resins must contain a stabilizer to prevent decomposition and other undesirable effects caused by heat during production. Organic tin chemicals or organotins are the most commonly used stabilizers, though lead and antimony stabilizers are also available. The stages of plastic pipe production are described in more detail in part II.

reasonably certain that the change in material prices is not temporary. The expense of switching also means that the threshold price at which substitution occurs is higher than would otherwise be the case, and that once a change is made, the price of the replaced material must fall appreciably below the original threshold level before producers will switch back again. This type of substitution has occurred from time to time in the beverage container and pipe markets. Though not all that prevalent, it is more frequently encountered than the first type of response.

Third, where new technology must be introduced before substitution occurs, the response to a change in material prices takes even longer. In this case, there is also greater uncertainty and variation regarding both the size of the response and the length of its time lag. Once substitution away from a material does occur, a decline in its price is even less likely to result in the recapturing of a lost market than in the second situation.

It is this third type of response that has consistently had the greatest impact on tin usage. In beverage containers, for instance, tin prices have encouraged the introduction of electrolytic plating, differential and lighter tin coatings, the tin-free steel can, and the tin-free steel bottom used on all tinplate cans—all major developments reducing tin usage. In solder, the experiments that led to the use of low-tin alloys for can seams and automobile body finishing have been particularly important. In the pipe industry, tin consumption has been cut by about 50 percent from what it would otherwise have been by the development of superior tin stabilizers and the introduction of antimony stabilizers. Thus, the relatively high price of tin, when it has effected material substitution, has often done so indirectly by stimulating new tin-conserving technologies.

This conclusion is part of a broader finding. In all of the end uses examined, technological change appears as the dominant factor affecting material substitution. The use of tin in beer and soft drink containers, for example, was made possible by the development of the tinplate can. Its competitiveness over time has been enhanced by electrolytic plating, the easy-open aluminum top, the cheaper tin-free steel bottom, two-piece production techniques, and a host of other innovations. Conversely, the development of the one-way bottle, the aluminum can, the tin-free steel can, and subsequent improvements in these containers have reduced tin consumption in this market.

The use of solder in electronics was first stimulated by the introduction of printed circuit boards, and then reduced by the trend toward miniaturization. In cans, it declined substantially after welded and cemented seams were developed and two-piece canmaking technology was introduced. In motor vehicle radiators, the appearance of the sweat-soldered tube and corregated fin core for the dip-soldered cellular core used in the early postwar period substantially reduced solder and in turn tin usage.

The use of tin as a stabilizer for the production of PVC plastic was originally made possible by new technology. The rapid penetration of PVC in the pipe market that followed was stimulated by advances in extruder techniques, the development of superior tin stabilizers, and other innovations. After this rapid ascent, tin consumption in PVC plastic pipe may decline as quickly as it rose due to another new development, antimony stabilizers.

These are but a few of the many developments identified in part II. Technological change has been a powerful force shaping the use of tin in all of the applications examined. Moreover, its impact has often been abrupt and uneven, at times stimulating and at other times curtailing tin use. This random and discontinuous character of technological change makes it difficult to foresee its effects.

Government regulations have also influenced material substitution. While less important than technological change, the influence of this factor appears to be growing over time. Recent container deposit legislation, for example, has favored the returnable glass bottle; and among metal containers, the aluminum can, whose homogeneous composition makes it cheaper to recycle. During military emergencies the government has restricted the use of tin containers in the domestic market, and encouraged tin-conserving new technologies, such as electrolytic plating and low-tin solder alloys. Tin consumption in solder for cans has been influenced by the regulations of the Food and Drug Administration, in automobile radiators by the fuel efficiency standards of the Environmental Protection Agency, and automobile body finishing by the lead exposure standards of the Occupational Safety and Health Administration. In the pipe industry, the ubiquitous building codes imposed by thousands of local authorities have encouraged the use of tin by inhibiting lead stabilizers and slowing the growth of antimony stabilizers. They have also impeded tin consumption by delaying the use of plastic pipe.

While government regulations, material prices, and particularly technological change are the more prevalent and influential factors responsible for material substitution, other considerations have also been important in certain applications. For example, changes in customs, causing the decline of the local tavern and the rise of fast food chains, have altered the mix of packaged and bulk containers in the beer and soft drink markets. The popularity of the vinyl-roofed automobile has reduced the consumption of body solder, while the desire for quieter plumbing systems has favored heavier materials over plastic.

## Implications

The findings described in the preceding section point toward several general conclusions regarding the nature of material substitution. First, such substitution may, and often does, substantially alter material requirements. This is particularly true over the long run, but applies at times in the short run as well. Second, material-for-material and technological substitution are the easiest types of substitution to identify and appear more prevalent than other types. Third, a major cause, perhaps the major cause, of substitution is technological change. Fourth, changes in material prices typically have little effect on the mix of materials in the short run because producers are constrained by existing technology and equipment. Over the long run, they have more of an impact. Indeed, the major influence of material prices apparently is exerted indirectly over the long run by altering the incentives to conduct research and development on new material-saving technologies. Finally, government activities and regulations often motivate material substitution.

These conclusions, of course, are tentative. As pointed out earlier, material substitution is taking place continuously in a multitude of products throughout the economy, and so there are dangers in drawing general conclusions on the basis of only a few cases. It is important to keep this caveat in mind in examining the implications of the findings.

### *The Demand Curve*

The downward sloping demand curve, a conceptual tool widely used by economists, business analysts, and others, indicates the quantities of a commodity that the market will demand at various prices over a particular period, such as a year, on the assumption that all other determinants of demand remain unchanged. Although the curve is formally derived in microeconomics from the theories of the firm and consumer behavior, the nature of the curve and in particular its downward slope seem reasonable. As the price of a good goes up, less will be demanded, first because consumers will substitute other goods whose prices have not risen (the substitution effect) and second because consumers will have less real income to spend on all goods and services (the income effect).

Materials are rarely desired for their own sake, but rather their demand is derived from the demand for final goods and services. Moreover, the proportion of total costs contributed by any particular material in the production of most finished products is small. This means that changes in material pieces generally do not produce major shifts in the output of final goods and services. Nor do they cause significant changes in real consumer income. As a consequence, the reduction in material demand resulting from an increase in price comes about entirely, or almost entirely, as a result of material substitution.

As commonly drawn, the demand curve presumes that the functional relationship between price and demand is reversible. Frequently, however, commodity analysts claim, if a material loses a particular market, that market will be lost forever. Such statements imply that an industry may not be able to recapture a market lost during a price rise even if its price subsequently returns to its previous level. In other words, if a commodity moves up its downward sloping demand curve, it may not be able to reverse itself and move back down the same curve, as the conventional demand curve implies. Such concerns, it is even suggested, help explain the restraint that molybdenum, nickel, aluminum, and other material producers exercise in raising their prices during boom conditions.[3] As is well known, many material producers charge less than the market clearing price at such times.

In assessing the reversibility assumption, it is useful to distinguish among short-run, medium-run, and long-run demand curves. The short-run demand curve indicates how demand responds to a change in price during a time period that permits neither plant and equipment nor technology to change. The medium run covers a period sufficiently long to allow plant and equipment to change, and the long-run demand curve for technology as well as plant and equipment to change.

The assumption of reversibility seems most plausible for the short-run demand curve. The material substitution that can take place in the short run, such as the use of aluminum sheet for tinplate on a dual canmaking line, involves changes that can be made quickly with little cost or disruption. When these conditions govern the switch from one material to another, they are also likely to hold for a switch back to the original material. While the number of such substitution opportunities is limited, causing the short-run demand curve to be relatively steep, the possibilities that do exist and that can be quickly exploited tend to be easily reversible.

Reversibility appears more questionable over the medium run. Material substitution is in such instances likely to entail considerable expense. New equipment may have to be ordered, personnel retrained, and production lost during the changeover period. Once a firm has incurred such conversion costs, it will not find it worthwhile to switch back to a material unless the latter's price drops considerably below the level at which the original substitution became attractive.

In the long run, the assumption of reversibility appears particularly doubtful. Within this time frame, price-induced innovations may substantially alter the underlying technical and economic conditions governing the use of a material in a number of its applications. The introduction of better

[3]The argument that producers keep prices below what the market will bear during economic booms to prevent substitution is not by itself very convincing. Since demand exceeds supply when price is held below the market-clearing level, producers must allocate or ration their customers. This means that once a firm has received its quota, the price of additional supplies is infinitely high. This presumably should encourage customers as much or more to search for possible alternative materials. The argument becomes more plausible if producers while restraining prices also discriminate in their rationing in favor of those customers with the greatest substitution possibilities. The extent to which producers actually engage in such discrimination, however, is unknown. Normally, it appears they allocate supplies on the basis of their customers' past purchases.

products can prevent a resurgence of consumer demand for older, traditional products even when the raw material costs of the latter fall sharply. Who, for example, would return to mechanical calculators even if the cost of their embodied materials were zero? Such uncertainty surrounding the generation of new technology makes it most unlikely that the demand induced by a fall in price will exactly offset the demand lost by an equivalent rise in price.

The demand curve is also often assumed to be continuous. The importance and nature of material substitution, however, suggest that this too may not be very realistic, particularly for those materials whose use is concentrated in a few major applications. Price may rise over a range, with little or no effect on demand. Then, once a particular threshold is crossed, making the use of an alternative material attractive, demand may fall sharply. Such discrete jumps may be found in both short- and medium-run demand curves. They are even more likely to distinguish the long-run demand curve, since innovations, such as the antimony stabilizer or the aluminum can, by their nature are discrete events that either do or do not occur. When they do occur, their impact can be substantial.

A third questionable but common assumption concerns the stability of the relationship between demand and price over time. While the demand curve is often assumed to shift in response to changes in income, the prices of substitute materials, and other factors affecting demand, once the influence of these variables is taken into account or controlled for, the relationship between the price of a material and its demand is presumed to be reasonably stable from one period to the next. Efforts to estimate demand curves, or entire demand functions, on the basis of time series data must make such an assumption, at least implicitly.[4] The use of demand functions, however estimated, for forecasting or assessing future market conditions also requires this assumption.

The importance of price-induced technological change, however, suggests that such stability may not exist. The occurrence of innovations inherently involves a certain random or chance element. In addition, their effect on demand varies greatly. In short, there is not a stable relationship between price and the number of induced innovations, or between the number of induced innovations and their cumulative effect on demand. Yet both of these conditions are needed if the response of demand to a change in price is to remain stable over time.

Since the demand curve is defined as the relationship between the demand for a commodity and its price, assuming all other factors remain unchanged, one way of trying to preserve the assumptions of reversibility, continuity, and intertemporal stability is simply to exclude the effects of price-induced technological change. By definition, one might argue, such developments involve a change in one of the other factors (technology) which the construction of a demand curve can presume remains constant. This approach is certainly feasible, and it increases the plausibility of the three assumptions. Unfortunately, if the principal effect of a change in price on material demand occurs indirectly via induced technological change, as the studies here suggest, this approach reduces the demand curve to a sterile academic concept with little practical use. Indeed, by ignoring the major impact of price, it may even be misleading.

### *Material Shortages*

In assessing the role that material substitution can play in mitigating or eliminating shortages, two very different types of shortages must be distinguished. The first is due to the depletion of high quality mineral deposits, and imposes upon society the necessity of procuring its mineral needs from increasingly costly sources. This type of shortage comes about slowly with considerable warning, as the real price of a material climbs persistently over time and in the process gradually constricts demand. Although examples are hard to find because the real costs of most materials have actually fallen over the last century, there is concern that this type of shortage may become a serious problem some time in the future.

The second type of shortage, in contrast, is quite common. It tends to be temporary, rarely lasting for more than three to five years, and often arises quickly with little warning. It can be caused by a variety of factors, including war, embargoes, cyclical surges in demand, strikes, accidents, natural disasters, and inadequate investment in mining and processing. It may manifest itself in the form of sharply higher real prices, or where a few major firms maintain a relatively stable producer price, in the form of actual physical shortages.

The case studies suggest that material substitution can make a major contribution toward alleviating the first type of shortage, but much less of a contribution toward the second type. Substitution has substantially reduced tin consumption in a number of end uses, and the high and rising price of tin appears to have been a significant factor, at least indirectly, in motivating this shift. However, the response to changing material prices is typically small in the short run, for rarely is one material substituted for another while the same equipment, the same technology, and the same production processes continue in use. At a minimum, material substitution normally involves at least the replacement or modification of existing equipment, and more commonly, the development of new technologies. Since such changes take time, the major impact of a price rise on the con-

[4]The demand function indicates the relationship between demand and all factors influencing demand. It is thus more encompassing than the demand curve which portrays the relationship between a commodity's price and its demand, assuming that income and other factors affecting demand remain constant at some prescribed level.

sumption pattern of a material is not realized for a number of years. By then, the second type of shortage is usually over.

*Market Power and Producer Cartels*

In assessing the market power of the major material producers, most research has emphasized market concentration, which reflects the number and size distribution of the firms in an industry. Since many metal and other material industries are fairly concentrated, this approach often leads to the conclusion that firms do possess market power and the ability to earn excess profits. Moreover, in these oligopolistic industries the major producers frequently quote or set a producer price, rather than simply accept a price determined on a competitive exchange. This behavior is often cited as collaborating evidence for the conclusion that these firms possess market power.

During the 1970s, concern over the possible exercise of monopoly power expanded to encompass the governments of mineral producing countries, as well as the multinational mining corporations and other major producing firms. The success of OPEC in raising the price of oil in 1973 led many to conclude that other mineral-producing countries would also attempt to form producer cartels and artificially raise material prices.

Material substitution, however, can severely limit market power even in highly concentrated industries. Collusive efforts by established producers to raise prices substantially are likely to stimulate new technological activity, and eventually end in failure, with markets irretrievably lost. While higher prices may have little effect on material substitution in the short run, permitting a cartel to succeed for a while, the adverse consequences over the longer term are likely to far outweigh the short-term benefits. This discourages collusive activities except where firm managers or government officials have unusually short time horizons or are ignorant of the long-term consequences.

This conclusion, coupled with the findings that intermaterial competition is growing more intense over time as new materials are developed and traditional ones expand into new markets, suggests that the conventional view of market power in the material industries, based primarily on considerations of market concentration and pricing behavior, may be twenty years out of date. It also suggests that Schumpeter (1950, pp. 84–85), writing in the early 1940s, correctly described the nature of competition in the material industries today, if not then:[5]

> . . . It is still competition within a rigid pattern of invariant conditions, methods of production and forms of industrial organization in particular, that practically monopolizes attention. But in capitalist reality as distinguished from its textbook picture, it is not that kind of competition which counts but the competition from the new commodity, the new technology, the new source of supply, the new type of organization (the largest-scale unit of control for instance)—competition which commands a decisive cost or quality advantage and which strikes not at the margins of the profits and the outputs of the existing firms but at their foundations and their very lives. This kind of competition is as much more effective than the other as a bombardment is in comparison with forcing a door, and so much more important that it becomes a matter of comparative indifference whether competition in the ordinary sense functions more or less promptly; the powerful lever that in the long run expands output and brings down prices is in any case made of other stuff.
>
> It is hardly necessary to point out that competition of the kind we now have in mind acts not only when in being but also when it is merely an ever-present threat. It disciplines before it attacks. The businessman feels himself to be in a competitive situation even if he is alone in his field or if, though not alone, he holds a position such that investigating government experts fail to see any effective competition between him and any other firms in the same or a neighboring field and in consequence conclude that his talk, under examination, about his competitive sorrows is all make-believe. In many cases, though not in all, this will in the long run enforce behavior very similar to the perfectly competitive pattern.

[5]Reproduced with permission from J. E. Schumpeter, *Capitalism, Socialism, and Democracy*, Harper and Row, New York, 1950.

*Forecasting Material Requirements*

Government agencies, private firms, international organizations, independent consulting firms, and others forecast future material requirements. These forecasts are needed to formulate sound public policies in the resource field, as well as for private investment decisions.

Although many different types of forecasting procedures are used, these techniques can be separated into three generic groups. The first encompasses a variety of statistical procedures that differ greatly in their complexity, but basically involve analyzing past trends and projecting them into the future. One such technique is simply extending into the future the linear trend of past consumption. Far more complicated is the Box-Jenkins procedure, which employs a mathematical model to identify various functional trends present in past consumption and to estimate the parameters of these trends. It then uses these estimated trend functions to project consumption into the future.

The second group of forecasting methods is comprised of models that specify causal or behavioral relationships. Traditional supply and demand analyses fall into this category. In these models, demand is typically assumed to be a function of the price of the commodity, an income or activity variable, and perhaps the prices of complementary and substitute products as well. Since the full effect of a change in price on demand may not occur immediately, various types of lag responses may be built into such functions. Once the causal equations are identified, their parameters must be estimated. This is usually done on the basis of past data and behavior using econometric techniques, though parameters may be determined on the basis of known technical relationships or other a priori information.

The third group includes forecasting techniques that are qualitative or judgmental in nature, and less quantitative. The Delphi method in which the views of a number of experts are solicited and then integrated to produce a forecast falls into this category. So too do forecasts based on the informed judgment of analysts who have adjusted current trends in consumption or the predictions of causal models for the effects of anticipated changes in public policies, consumer preferences and habits, technology, and other factors whose future influence on consumption cannot be measured with precision.

Material substitution greatly complicates the task of forecasting mineral requirements, and is likely to render any technique regardless of the category to which it belongs vulnerable to wide margins of error when forecasting over the longer term, ten to twenty years into the future. In the short run, the effects of material substitution may be small or relatively continuous, and so more predictable. Yet even this is not certain. Within a year the strong upward market penetration of a product can be accelerated or completely reversed by material substitution. Moreover, the growing intensity of material competition over time makes this type of volatility increasingly likely.

The first group of forecasting techniques implicitly assumes that material substitution is either a relatively unimportant factor shaping consumption, or that it is continuous and evolutionary so that its future influence can be projected from its past effects. Neither of these assumptions is reasonable over an extended period of time, and as just noted, may not even be valid in the short run.

The second group of forecasting techniques, when it considers material substitution explicitly, generally assumes that it is motivated or caused by a shift in relative material prices. This is the case, for example, when the demand functions within a supply and demand model include price variables for major substitute commodities. Moreover, although such models do not necessarily assume that a change in material prices immediately affects demand, as they can specify a lagged response, they do normally assume that the structure of this response follows a stable pattern over time and that it reflects a continuous and reversible functional relationship between prices and demand.

These assumptions can be questioned for reasons that have already been discussed. In particular, since the major impact of changes in material prices occurs indirectly through the development of new technology, neither the magnitude of the response to a change in price nor its lagged structure remains constant over time. On some occasions the response is negligible, while on others price changes provoke innovative activity that drastically alters consumption patterns. In addition, complete reliance on the use of material prices to capture the effects of substitution is certain to miss the impact of those substitutions that are motivated by considerations of performance and quality or that occur at later stages of production where material costs are trivial. In tin-using industries such substitutions have often been important, and have at times substantially increased the use of tin despite its rising price.

Thus, only the last of the three groups of forecasting techniques appears to offer any hope of adequately accounting for the effects of substitution in predicting future mineral requirements, at least over the longer term. This is the only approach that can take full account of the abrupt and inconsistent, yet major, effects of material substitution that are caused not only by shifts in material prices, but also by changes in technology, government regulations, and other factors as well. Even here, in light of the inherent uncertainties involved in predicting the future course of new technology, government regulations, and the other factors affecting substitution, wide margins of error should be expected.

To some extent this pessimistic assessment can be modified when forecasting the requirements for a material in all of its end uses together, rather than requirements in specific end uses. Aggregation in this situation may lead to better results, because the large distortions in consumption caused by material substitution in individual end uses may to some extent cancel out. This is particularly likely to be the case for materials used in many applications. Still, given the pervasive influence of material substitution, the reliability of forecasting techniques that do not explicitly consider material substitution and take account of its discontinuous and abrupt nature must be questioned.

In summary, an examination of various uses of tin over the past several decades in the United States suggests that substitution, when defined broadly, is a major force shaping and altering material consumption patterns. Substitution, in turn, is driven primarily by technological change, and to a somewhat lesser extent by relative material prices and government actions. Material prices influence substitution largely by encouraging the development of new technologies that conserve or replace materials whose price is high and expand the uses of materials whose price is low.

These findings, to the extent that they reflect the nature of material substitution in general, have a number of implications. They call into question the common assumptions regarding the reversibility, continuity, and intertemporal stability of the demand curve, and suggest that the relationship between the demand for a material and its price is much more complex than is often assumed. In this regard, they raise the possibility that some of the methods now being used to estimate material demand functions and to analyze commodity markets may not be appropriate.

In addition, the findings imply that substitution greatly complicates the forecasting of future material requirements. If reliable long-term predictions are possible at all, they require that the future effects of material substitution be explicitly assessed. This cannot be done on the basis of past trends of historical relationships between material prices and demand. The findings also indicate that material substitution is a major constraint on the exercise of market power. Substitution can force firms in even highly concentrated industries to behave in a competitive manner. It also undermines the viability of cartels that the governments of mineral exporting countries might wish to create, and thus reduces the prospects for such collusive efforts. Finally, while cautioning that substitution may respond too slowly to changes in material prices to alleviate temporary shortages due to war, embargoes, cyclical demand surges, and strikes, the findings suggest that material substitution has a major contribution to make in the long-run struggle to prevent persistent shortages caused by the depletion of mineral resources.

# References

American Bureau of Metal Statistics, annual, *Non-Ferrous Metal Data*, New York.

Chynoweth, A. G., 1976, "Electronic Materials: Functional Substitutions," *Science*, vol. 191, no. 4228, pp. 725–732.

Eckes, A. E., Jr., 1979, *The United States and the Global Struggle for Minerals*, Austin: University of Texas Press.

Fisher, F. M., P. H. Cootner, and M. N. Baily, 1972, "An Econometric Model of the World Copper Industry," *Bell Journal of Economics*, vol. 3, pp. 568–609.

Goeller, H. E., and A. M. Weinberg, 1976, "The Age of Substitutability," *Science*, vol. 191, no. 4228, pp. 683–689.

Kopp, R. J., and V. K. Smith, 1980, "Measuring Factor Substitution with Neoclassical Models: An Experimental Evaluation," *Bell Journal of Economics*, vol. 11, pp. 631–655.

Rosenberg, N., 1973, "Innovative Responses to Materials Shortages," *American Economic Review*, vol. 63, no. 2, pp. 111–118.

Schumpeter, J. A., 1950, *Capitalism, Socialism and Democracy*, 3rd ed., New York: Harper & Row.

Skinner, B. J., 1976, "A Second Iron Age Ahead?," *American Scientist*, vol. 64, pp. 258–269.

Slade, M. E., 1981, "Recent Advances in Econometric Estimation of Materials Substitution," *Resources Policy*, vol. 7, pp. 103–109.

Woods, D. W., and J. C. Burrows, 1980, *The World Aluminum-Bauxite Market*, New York: Praeger, pp. 184–230.