Guayule

An Alternative Source of Natural Rubber

NATIONAL ACADEMY OF SCIENCES

Guayule:

An Alternative Source of Natural Rubber

Report of an Ad Hoc Panel of the
·Board on Agriculture and Renewable Resources
·Commission on Natural Resources
and ·Advisory Committee on Technology Innovation
Board on Science and Technology for International Development
·Commisson on International Relations

Con Resumen en Español

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Panel on Guayule

REED C. ROLLINS, Director, Gray Herbarium, Harvard University, Cambridge, Massachusetts, *Chairman*

PAUL J. ALLEN, Department of Botany, University of Wisconsin, Madison, Wisconsin (Deceased. November 13, 1976)*

HARRIS M. BENEDICT, Stanford Research Institute, Menlo Park, California (Retired)

DAVID H. BLANK, Commodity Industry Specialist, Bureau of Domestic Commerce, Department of Commerce, Washington, D.C.

JAMES F. BONNER, Professor of Biology, California Institute of Technology, Pasadena, California

FRANK A. BOVEY, Head, Polymer Research Department, Bell Telephone Laboratories, Murray Hill, New Jersey

ENRIQUE CAMPOS-LÓPEZ, Director, Centro de Investigaciones en Química Aplicada, Saltillo, Coahuila, Mexico

HAROLD E. DREGNE, Director, International Center for Arid and Semi-Arid Land Studies, Texas Tech University, Lubbock, Texas

RALPH EMERSON, Professor of Botany, University of California, Berkeley, California

WALTER T. FEDERER, Professor of Biological Statistics, Cornell University, Ithaca, New York

IRVIN C. FEUSTEL, Head, Natural Rubber Extraction and Processing Investigations, U.S. Natural Rubber Research Station, Salinas, California, U.S. Department of Agriculture (Retired)

HOWARD SCOTT GENTRY, Research Botanist, Desert Botanical Gardens, Phoenix, Arizona

A. J. HAAGEN-SMIT, Department of Biochemistry, California Institute of Technology, Pasadena, California

OMER J. KELLEY, Codirector, Crop Improvement Research Center, Office of Rural Development, Suweon, Korea

C. S. MARVEL, Professor of Chemistry, University of Arizona, Tucson, Arizona

MARTIN A. MASSENGALE, Vice Chancellor, University of Nebraska–Lincoln, Lincoln, Nebraska

WILLIAM G. McGINNIES, Director Emeritus, Office of Arid Lands Studies, University of Arizona, Tucson, Arizona

*In the final stages of the preparation of this report, we were saddened to learn of the death of Paul Allen. From his experiences with guayule during the 1940's he brought wide practical knowledge and technical insight to the deliberations of the panel. His contributions are inherent in this report.

ROBERT M. PIERSON, Assistant to the Director of Research, Goodyear Tire and Rubber Company, Akron, Ohio

JOEL SCHECHTER, Director, Research and Development Authority, Ben Gurion University of the Negev, Beer-Sheva, Israel

H. M. TYSDAL, Principal Geneticist, Head, Guayule Improvement, U.S. Natural Rubber Research Station, Salinas, California, U.S. Department of Agriculture (Retired)

LAWRENCE A. WOOD, Rubber Consultant, Polymers Division, National Bureau of Standards, Washington, D.C.

NOEL D. VIETMEYER, Board on Science and Technology for International Development, National Academy of Sciences, Washington, D.C., *Staff Study Director*

MARY JANE ENGQUIST, Board on Science and Technology for International Development, National Academy of Sciences, Washington, D.C., *Staff*

* * *

JULIEN ENGEL, Board on Science and Technology for International Development, National Academy of Sciences, Washington, D.C., *Head, Special Studies*

Contributors

THOMAS BAUER, Donner Laboratory and Pavillion, University of California, Berkeley, California

BENITO CANALES LÓPEZ, Subdirector Industrial, Comisión Nacional de Las Zonas Áridas, Mexico, D.F., Mexico

HUNG YU CHEN, Research Scientist, Goodyear Tire and Rubber Company, Akron, Ohio

JAMES K. CLARK, Senior Research Chemist, B. F. Goodrich Research Center, Brecksville, Ohio

KENNETH EMERSON, Professor of Chemistry, Montana State University, Bozeman, Montana

GEORGE P. HANSON, Senior Biologist, Los Angeles Arboretum, Arcadia, California

J. NEIL HENDERSON, Research Scientist, Goodyear Tire and Rubber Company, Akron, Ohio

ROBERT C. HIRST, Senior Research Chemist, Goodyear Tire and Rubber Company, Akron, Ohio

JOGINDER LAL, Manager, Basic Research, Goodyear Tire and Rubber Company, Akron, Ohio

ROLAND H. MAYOR, Assistant Manager, Synthetic Rubber Research, Goodyear Tire and Rubber Company, Akron, Ohio

WILLIAM P. MILLER, Intergovernmental Relations Officer, Office of Tribal Resources Development, Bureau of Indian Affairs, Department of Interior, Washington, D.C.

VIRGIL D. MOCHEL, Research Associate, Central Research Laboratory, The Firestone Tire and Rubber Company, Akron, Ohio

RICHARD C. OLDACK, Senior Chemist, Natural Rubber and Latex Company, The Firestone Tire and Rubber Company, Akron, Ohio

CLAY PARDO, Research Chemist, Western Regional Research Center, U.S. Department of Agriculture, Albany, California

EVERETT R. SANTEE, JR., Research Associate, Institute of Polymer Science, The University of Akron, Akron, Ohio

EMANUEL SCHOENBERG, Section Head, Natsyn Rubber, Goodyear Tire and Rubber Company, Akron, Ohio

HOWARD L. STEPHENS, Professor of Chemistry and Polymer Science, Institute of Polymer Science, The University of Akron, Akron, Ohio

ELEANOR C. TAYLOR, Taylor Nursery, Aromas, California

KENNETH W. TAYLOR, Taylor Nursery, Aromas, California

COE W. WADELIN, Section Head, Spectroscopy, Goodyear Tire and Rubber Company, Akron, Ohio

DAVID S. WINKLER, Research Associate, Institute of Polymer Science, The University of Akron, Akron, Ohio

Preface

This report examines the state of knowledge and the future promise of guayule *Parthenium argentatum* Gray, a little-known shrub native to the desert of southwest Texas and northern Mexico that was a commercial source of natural rubber during the first half of this century. The report is the product of the Panel on Guayule,* an international panel of botanists, agronomists, engineers, chemists, rubber technologists, and a rubber economist.

Although most members of the panel had worked with some aspect of guayule rubber production, some were invited to serve because of their knowledge of natural rubber (from the rubber tree *Hevea brasiliensis*), or synthetic rubber, arid land agriculture, Indian (Native American) economic development, or developing countries. Some persons unfamiliar with guayule—or skeptical of its possibilities—were included in the panel to provide perspective and to ensure critical evaluation of the plant's potential.

The panel's mandate was to analyze guayule's strengths and limitations as a modern, commercial crop, to identify areas of uncertainty, and to judge the wisdom of renewed development and research. The panel was specifically charged to consider the potentialities of guayule for providing employment and enabling better use of land on Indian reservations in Texas, New Mexico, Arizona, and California.

The panel prepared this report at a meeting in Tucson, Arizona, November 20–21, 1975, following a guayule conference sponsored by the University of Arizona. There were more than 100 participants in the conference, almost half of whom had worked in guayule cultivation or processing in a large, federally financed guayule project during World War II, the Emergency Rubber Project (ERP).

The panel also gathered information from a pilot facility at Saltillo, Mexico,† that is scaled to extract rubber from one ton of guayule shrubs

*The panel was convened jointly by the Board on Agriculture and Renewable Resources (Commission on Natural Resources) and by the Advisory Committee on Technology Innovation of the Board on Science and Technology for International Development (Commission on International Relations). Both boards are units of the National Research Council, which operates under the auspices of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

†Built by the Comisión Nacional de las Zonas Áridas (CONAZA) and based on research supported by CONAZA and Consejo Nacional de Ciencia y Tecnología (CONACYT).

daily. Much of the data on guayule rubber quality in this report comes from samples extracted and purified by Dr. Enrique Campos-López and his colleagues at Saltillo and analyzed by Professor Howard Stephens and his staff at the University of Akron, Akron, Ohio. In addition, just prior to the panel's meeting a 50-lb (23-kg) block of deresinated guayule rubber produced in 1951 by the U.S. Department of Agriculture was located at the Federal Records Center near Washington, D.C. Despite its age it was well-preserved. Samples were analyzed at Goodyear Tire and Rubber Company, Akron, Ohio, and at Bell Telephone Laboratories, Murray Hill, New Jersey. The results are included in this report.

The panel hopes that this report will demonstrate to the research community the ways in which the application of modern knowledge and modern technology could help develop this plant into a commercial crop once again. However, although the report is addressed to researchers and potential guayule growers and users, it is not primarily a technical treatise; it is also written for administrators in government, private industry, and funding agencies, since their decisions will ultimately determine whether funds will be available for guayule development.

A short list of readily available documents that complement this report with additional details is given in Appendix A. One is the report of an earlier National Research Council panel* that selected guayule as one of 36 neglected plants showing special promise as crops for the future.

The present study was made possible by funding from five government agencies: Bureau of Indian Affairs (Department of the Interior); Office of Native American Programs (Department of Health, Education, and Welfare); Economic Development Agency (Department of Commerce); Agricultural Research Service (Department of Agriculture); and the Office of Science and Technology (Agency for International Development). The panel is impressed by, and grateful for, this splendid example of interdepartmental cooperation.

A special debt of gratitude is owed to William P. Miller, Bureau of Indian Affairs, who initiated and coordinated the procurement of funds needed for the study. The panel is also indebted to Dr. William McGinnies for handling local arrangements in Tucson; to Dr. Frank A. Bovey and Robert M. Pierson for analyzing the block of guayule rubber from the federal archives; to Dr. Enrique Campos-López for making available unpublished data from the Mexican government's guayule-processing facility; and to the Goodyear Research Laboratories, Akron, Ohio, for sponsoring a meeting where panel

*The panel's report *Underexploited Tropical Plants with Promising Economic Value*, is available, without charge, from the Commission on International Relations (JH215), National Academy of Sciences-National Research Council, 2101 Constitution Avenue, Washington, D.C. 20418, USA.

members could meet with rubber technologists from the Akron area to review the panel's findings. The final report was edited and prepared for publication by F. R. Ruskin.

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1 Introduction and Conclusions

Of some 2,000 species of plants known to contain rubber,* only a few have ever produced it in substantial quantities for commercial use. Two of these, the rubber tree *Hevea brasiliensis* (grown principally in Southeast Asia) and the guayule shrub *Parthenium argentatum* Gray (which grows wild in some semiarid regions of North America), have been continuing sources of commercial rubber. In contrast to the majestic *Hevea* tree, guayule (a Spanish corruption of an Aztec word, usually pronounced wy-*oo*-lee) is an inconspicuous shrub less than 3 ft (1 m) tall. The two plants also have contrasting climatic requirements: *Hevea* is native to equatorial lowland rainforest regions in the Amazon basin; guayule comes from upland plateaus in Mexico and Texas with subtropical–temperate climates, where rainfall is low and erratic.

However, the rubber industry has long known that the two plants, despite these differences, produce a similar rubber. Indeed, in 1910 guayule provided 10 percent of the world's natural rubber and continued to be a minor source of commercial natural rubber for almost 40 years more. However, after World War II–during which a giant guayule-growing program, The Emergency Rubber Project, was conducted by the U.S. Forest Service (see Chapter 3)–cultivation of the plant was abandoned. The consensus in 1946 was that there was little need for another rubber source; hevea rubber was in good supply and under no threat from a hostile enemy. Furthermore, it was erroneously believed that man-made elastomers would make natural rubber obsolete.

But the outlook has since changed and the following conditions now obtain:

- Hevea rubber† shows no likelihood of being rendered obsolete by man-made rubber and, in fact, has retained its position as one of the world's most important commodities. There is an ever-increasing demand for natural rubber; it is now predicted that by 1980 the production of hevea rubber will be about 5 million tons, or one-third of the world's total rubber needs.

*There is no universal definition of rubber. In this report "rubber" refers to *cis*-polyisoprene rubbers (the normal kind) and not to balata, guttapercha or non-isoprenoid synthetic elastomers.

†This report uses "hevea rubber" to refer to the rubber from *Hevea brasiliensis*: both it and guayule are "natural" rubbers.

Moreover, there is wide belief that in the 1980s and 1990s the demand for natural rubber will exceed the expected production from *Hevea* plantations, thereby resulting in a worldwide shortage.*

Natural rubber is still preferred in applications that demand elasticity, resilience, tackiness, and low heat buildup. It is indispensable for bus, truck, and airplane tires, and where heat buildup under severe conditions could cause a failure.

- Petroleum, our major source of hydrocarbons, is dwindling and is now widely predicted to run out within a few decades. Thus, today, a plant that produces hydrocarbons—as guayule does—is particularly worthy of investigation.
- The increasing price of petroleum has lowered the competitiveness of synthetic elastomers, which are produced from petroleum-based feedstocks. Guayule is an alternative source—a renewable source—for petroleum-derived polyisoprene rubbers. It seems likely that in coming decades there will be markets for all the "natural" rubber that can be produced, whether hevea or guayule.
- *Hevea* can be cultivated only in a limited tropical zone; political, economic, or biological† changes in this area could endanger the world's supply of natural rubber.
- Today, with increasing population growth, there is a heightened universal need to utilize marginal lands productively, especially arid lands; to find crops adapted to harsh desert environments; and to provide jobs and income to desert dwellers living where farming conventional crops is risky or impossible. These needs, too, cast new light on the cultivation of guayule, for experiments have shown that "guayule could be grown successfully on many lands where the supply of irrigation water was insufficient for the successful production of most agricultural crops."‡

We live in a general economic climate quite different from the one existing when guayule rubber was last produced commercially. But guayule is worth cultivating only if its rubber has the technical quality to meet commercial needs.

*See Chapter 8.
†In Southeast Asia the *Hevea* tree leads a somewhat precarious existence. There, it has escaped the South American leaf blight that so devastates it in its Brazilian homeland that commercial rubber cultivation has not been feasible. Were leaf blight spores to be introduced to Southeast Asia the results could be catastrophic.
‡McGinnies and Haase. 1975. See Selected Readings.

CONCLUSION 1

Quality of Guayule Rubber

GUAYULE RUBBER AND HEVEA RUBBER HAVE CHEMICAL AND PHYSICAL PROPERTIES THAT ARE VIRTUALLY IDENTICAL.

Both guayule rubber and hevea rubber are hydrocarbons, both are polymers of isoprene, both have double bonds with a *cis* configuration (this gives the rubber its "bounce"), both are approximately the same in molecular length and weight. Both have very similar, or identical, microstructure: studies have not detected any differences even with techniques that can detect as little as 0.5 percent of structural difference. In both guayule rubber and hevea rubber the isoprene units are extremely regular: they are all joined end to end. There is no evidence for any aberrant connections in which an isoprene is not joined at its ends or in which the double bonds have *trans* configuration.

No difficulties are expected in manufacturing goods from guayule rubber; standard equipment can be used. It vulcanizes like hevea rubber, it has properties that allow it to flow properly in molds and extruders, and like hevea rubber, it has the natural tack crucial for tire manufacture.

CONCLUSION 2

Commercial Potential for Guayule Rubber

THE DEMAND FOR ALL RUBBERS IS EXPECTED TO INCREASE WORLDWIDE, AND A MARKET FOR GUAYULE RUBBER IS ASSURED IF IT CAN BE SOLD AT A COMPETITIVE PRICE.

Both hevea and guayule rubbers are excellent polymers and, provided their prices are competitive, will be preferred over synthetic elastomers in many cases. For example, most hevea rubber is used in tire carcasses because it resists heat buildup and thus suffers less heat-induced degradation.

Natural rubber prices are limited by synthetic rubber prices for, though a loss in quality may result, manufacturers can substitute synthetic for natural rubber in their products if necessary. Nonetheless, it is almost universally predicted by rubber economists that hevea rubber (and synthetic polyisoprene rubbers) will continue to command premium prices over other

elastomers. Guayule rubber's ability to match hevea rubber's properties confirms that it, too, can be a highly marketable commodity.

There appears to be plenty of room for adding guayule rubber to the markets of the future, and it should not be considered as a displacement for hevea rubber. If, during the next decade, present growth rates continue, the world's demand for isoprene-type rubber is expected to almost double.*

CONCLUSION 3

Research

USING AGRICULTURAL TECHNIQUES AND RUBBER EXTRACTION METHODS IN USE WHEN GUAYULE RUBBER WAS LAST PRODUCED 30 YEARS AGO, IT IS DOUBTFUL IF THE PLANT WOULD BE A COMMERCIALLY VIABLE CROP TODAY.

However, the application of modern technology can change this. There is a high probability that given research guayule can be made commercially viable once more.

In the 1930s and 1940s, resinous guayule rubber sold profitably at prices comparable to those of hevea rubber. But the methods used then are inadequate to produce guayule rubber on a competitive basis today. Nonetheless, the panel is confident that, with research, guayule can again become commercially viable. Although improvements should be made, no technical breakthroughs are required. Research is needed for improving upon the old agricultural and processing techniques, not for surmounting fundamental biological or technical barriers.

Guayule has the qualities necessary for a domesticated crop plant. It grows well under plantation conditions, is amenable to genetic improvement, and exists in an abundance of strains that can provide the necessary diversity.

In the past 30 years there have been major advances in plant genetics, agricultural technology (pest control, weed control, mechanization, etc.), chemical instrumentation, chemical engineering, and rubber technology. There are now techniques, unknown when guayule was last produced three decades ago, that could revolutionize production. Before any new production is begun, the older methods must be reviewed in the light of modern knowledge.

*Projections based on model calculations by the Malaysian Rubber Research and Development Board are diagrammed in Figure 28, page 55.

Recent scientific advances have been applied to the production of both of guayule's competitors: hevea rubber and synthetic polyisoprene. In the 1940s the per-acre yield of guayule rubber was slightly higher than that of hevea rubber,* but, since then, research has increased hevea yields tenfold—and even greater increases are predicted. When guayule was last produced, a synthetic "duplicate" (*cis*-polyisoprene) rubber was barely an organic chemist's dream; now it is a commercial reality.

Therefore, guayule now faces strong competition. Yet advances in science, so helpful to hevea and synthetic rubber, also make guayule more amenable to commercial utilization. Researchers have barely scratched the surface of scientific disciplines that could markedly improve guayule economics. Many research areas that promise improvements are mentioned in this report (see especially Chapter 9).

CONCLUSION 4

Implications for the United States

GUAYULE HAS POTENTIAL TO BECOME IMPORTANT TO THE NATION'S ECONOMY AND SECURITY.

Hevea rubber is a major commodity in American life. Each year the nation absorbs one-fifth of the world's supply. Because of its special properties, many types of tires are manufactured with a large proportion of hevea rubber. Hevea rubber is the fourth largest import in the category of inedible crude materials (behind iron ore, wood pulp, and lumber). In 1974 the United States imported 719,000 tons at a cost of over $500 million.

On the other hand, guayule is an American plant, found growing naturally in the Big Bend area of Texas (see Figure 1). Although other rubber-producing plants could be grown in the United States, guayule has the most immediate promise because much is already known about its cultivation and processing.

Guayule's qualities recommend it for development in the semiarid southwestern states. In 1942, the Emergency Rubber Project surveyed some 32

*In the early 1950s, a small breeding program demonstrated the possibilities of genetically improving guayule rubber production. Plant breeders developed strains that doubled the yield of the standard variety growing during World War II. Moreover, this was obtained in the warmer areas of California's San Joaquin Valley, which were not considered to have ideal climates for the guayule strains used. Unfortunately, termination of the whole guayule project precluded further development.

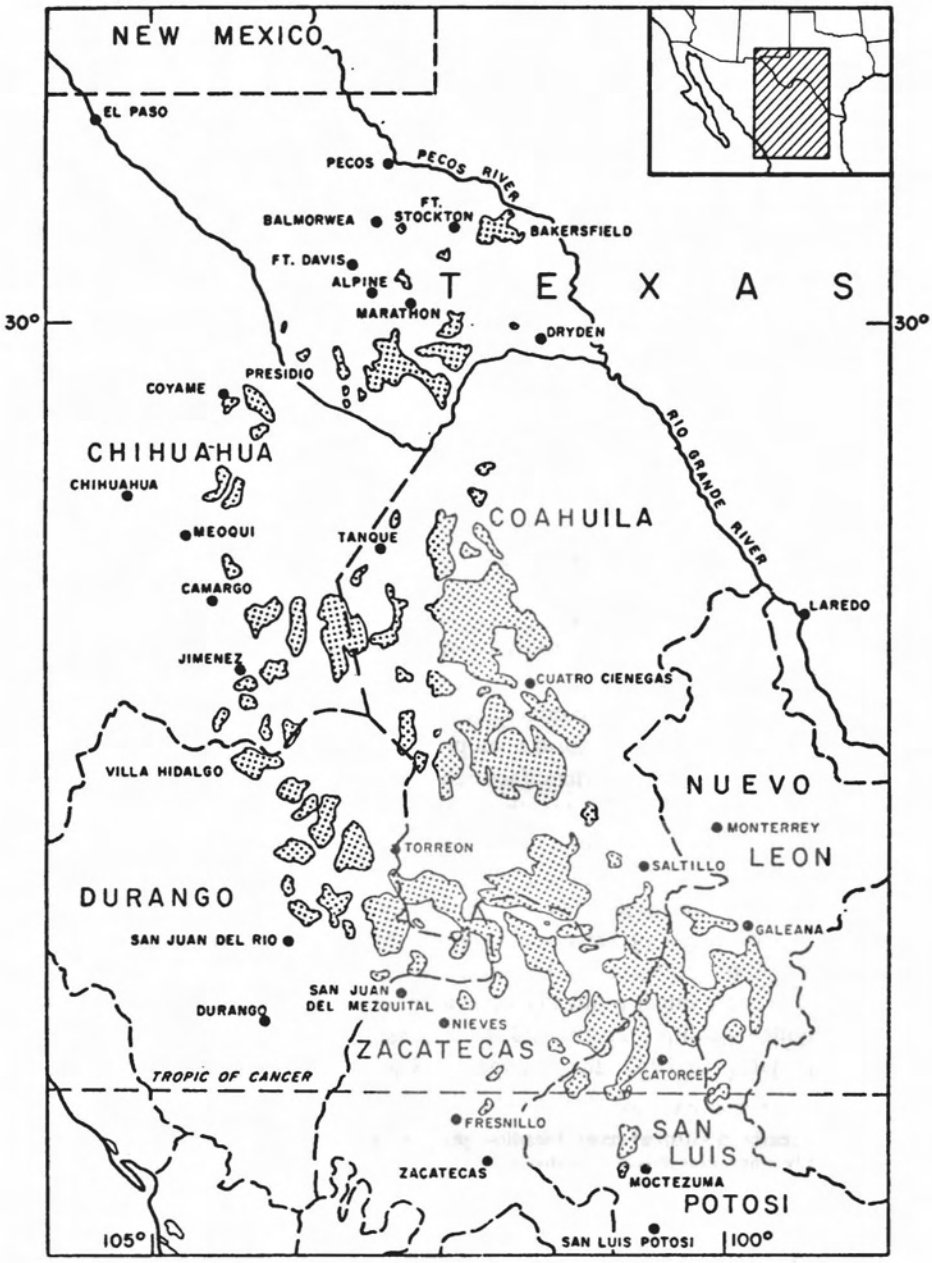

Figure 1. Distribution of native guayule in Mexico and Texas.

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million acres of land and classified 5 million acres in California, Arizona, New Mexico, and Texas as suitable for guayule culture (see Figure 2).

Because the guayule plant is native to a semiarid environment, it has relatively low water requirements. However, whether it can be economically cultivated in arid regions without irrigation is not yet clear, although the amount of irrigation water it needs annually is less than the requirement for most crops (see Figure 3). Also, the plant can be grown where the supply of rainfall or irrigation water is unreliable: As available moisture is used up,

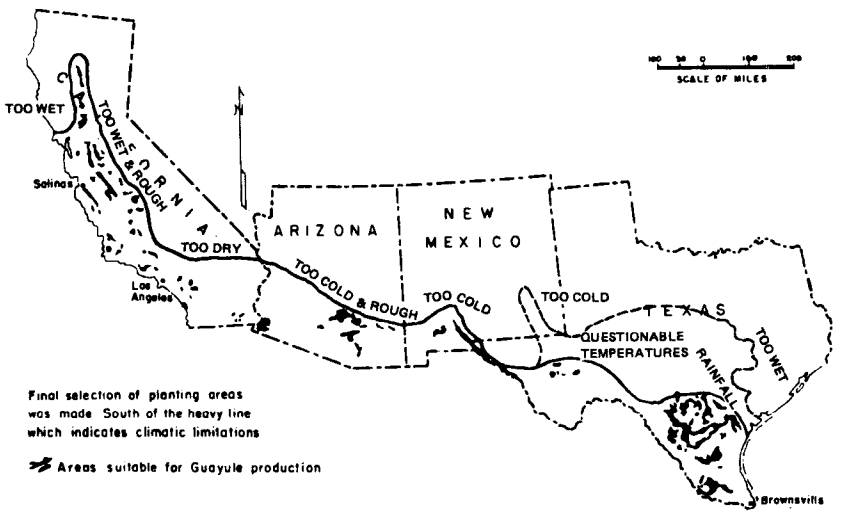

Figure 2. Areas in the United States with climate considered suitable for the cultivation of guayule (as reported by the Emergency Rubber Project, 1944).

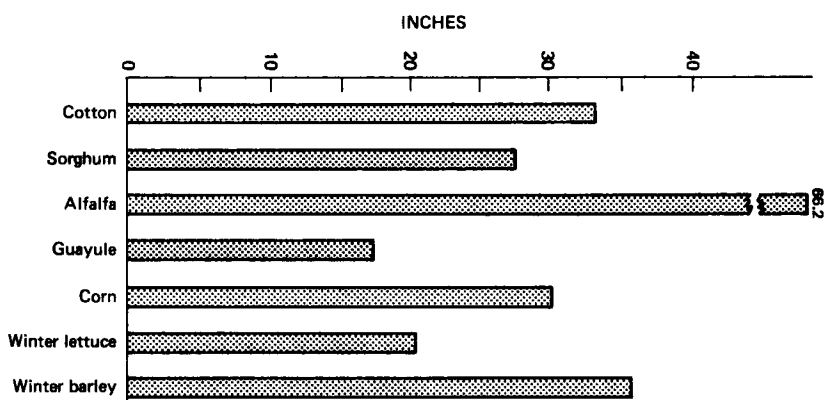

Figure 3. Estimated consumption of water by guayule compared with selected irrigated crops grown at El Paso, Texas.

guayule enters a resting state and remains semidormant until moisture returns.

In the long run, as the nation's petroleum disappears, guayule's greatest value may be as an alternative to the synthetic polyisoprene rubbers that are produced from petroleum. The guayule plant could become a renewable domestic source of polyisoprene rubber for the nation.

CONCLUSION 5

Implications for Native Americans

GUAYULE CULTIVATION MIGHT EVENTUALLY HELP INDIANS IN THE SOUTHWEST TO DEVELOP AN ECONOMIC BASE FOR THEIR RESERVATIONS.

Indian reservations comprise more than one-sixth of the land area of Arizona and New Mexico and are among the most poverty-stricken areas in the nation. Despite the availability of land, the reservations have never approached their potential for agricultural production. Unemployment is high; the only jobs available on most reservations are connected with the cattle industry; even off-reservation jobs are closed to the inhabitants because of their lack of skills and the cost of transportation.

According to the Bureau of Indian Affairs, approximately 39 percent of the total reservation labor force (137,000) were unemployed in 1974 and another 19 percent were employed only on a seasonal or part-time basis. This seriously affects the quality of reservation life. Further, with the Indian population of the reservations growing annually by 3.5 percent, it is likely that not only will unemployment continue, it will increase.

Indian tribes, particularly in the Southwest, are heavily dependent upon a federal bureaucracy that performs services for them and subsidizes most of their health and welfare services, education, and the maintenance of roads and community buildings. The reservations cannot generate enough income to support these costs themselves.

Conventional crops are not providing the reservations with an economic viability; perhaps an arid-land plant like guayule can. If so, a guayule agribusiness could reduce the funds with which the federal government now supports tribal governments in the guayule zone.

Much Indian land appears suitable for growing guayule. The belt that includes much of Texas, New Mexico, Arizona, and California, and encompasses more than a score of reservations and small Indian rancheros, is

thought to have promise for the plant (see Figure 2). The bulk of Indian land in this area is only marginally suited to conventional crops such as cotton.

Guayule production could be a means for educating and training Indians in agriculture. Such training would be relevant to the reservations' needs and would help counter the migration to the cities that less-relevant education fosters.

(The Mexican government has a guayule development program based on similar principles. Guayule bushes grow on some of the poorest lands in Mexico—lands that cannot be used for conventional agriculture. The guayule region was relatively prosperous during World War II, when approximately a dozen rubber mills operated there. Today it is poverty stricken. Guayule exploitation is seen as one way to give opportunity to the people of the region, and the government is providing the research and support needed to redevelop the industry.)

Nevertheless, despite guayule's promise as a crop for reservations there is too little information at this time to justify anything more than small experimental plantings on Indian lands. The Bureau of Indian Affairs and other agencies involved in Indian economic development should await research developments before expanding guayule cultivation on reservations. They should, however, keep abreast of technical developments in guayule so that Indians can fully capitalize on the plant when research has reduced the uncertainties and the risks of commercial failure.

CONCLUSION 6

Guayule's Promise for Semiarid Regions

GUAYULE HAS POTENTIAL TO BECOME AN IMPORTANT CROP IN SEVERAL REGIONS OF THE WORLD OUTSIDE ITS INDIGENOUS AREAS IN MEXICO AND THE UNITED STATES.

Today, many countries are striving to exploit their own raw materials. Yet, for most, rubber must remain an import.

Commercial *Hevea* cultivation is restricted to a humid tropical zone within 10 degrees of the equator having about 100 in. (254 cm) of annual rainfall. On the other hand, the production of synthetic polyisoprene rubbers is restricted to just a handful of highly industrialized countries. Guayule cultivation may therefore interest many nations that lie outside the equatorial tropics and that lack the industry and markets to warrant synthetic polyisoprene production.

The Government of Mexico is already launching guayule production. Mexico is the only country with enough *wild* stands to support an industry; elsewhere, guayule will have to be a cultivated crop. Fortunately, it is not a weedy plant* and can be introduced to new regions with little risk of becoming a pest.

Guayule's ability to adapt to different geographic regions is uncertain. However, it has been successfully grown in small plots in Spain, Turkey, Israel, Argentina, South Australia, and the Soviet Union. The plant does not appear much affected by latitude or altitude, but its growth is very dependent on frost and on rainfall.

Trial guayule plantings are recommended in countries with Mediterranean climates; for example, the region of South America that includes Chile and Argentina, southern Africa, southwest Australia, and the Mediterranean region itself. Other areas where experiments seem justified are: Africa's Sahel region (as well as Ethiopia, the Sudan, and Somalia), semiarid areas of East Africa, Pakistan, northwestern India, and northeast Brazil, and also the Campo Cerrado (central Brazil) and Llanos (Colombia) areas, where most crops grow poorly because of the long dry season.

Although agronomic trials are justified, countries (especially developing countries) should await the results of guayule's evolution in Mexico and the United States before proceeding beyond small-scale experiments.

*For example, it is nothing like *Parthenium hysterophorus L.*, a weed that is a serious problem in parts of Asia, North America, and Australia.

2 Recommendations

In the light of its conclusions, the panel deliberated on what actions should be taken to capitalize on guayule's potential and made the following recommendations.

RECOMMENDATION 1

United States Initiatives in Guayule Development

THE UNITED STATES GOVERNMENT SHOULD INITIATE A PROGRAM OF RESEARCH AND DEVELOPMENT LEADING TO COMMERCIALIZATION OF THE GUAYULE PLANT.

Guayule has national implications for industry, agriculture, defense, and emergency preparedness. It also relates well to government policies on energy independence, improving the balance of trade, increasing agricultural production on marginal lands, and raising the living standards of Indians. *A national commitment to guayule research and development is needed.*

Guayule development should begin with a well-planned, well-coordinated research program aimed at applying modern technology and science: A detailed evaluation of production, performance, and economics is needed. Therefore, it is recommended that the federal government initially fund a feasibility study, technology assessment, and environmental-impact analysis of guayule. These studies could then become the foundation for a budgetary appropriation specially earmarked for guayule or for funding from existing budgets in such relevant agencies as:

- Department of Agriculture;
- National Science Foundation (since there is much need for basic research into guayule's genetics, biochemistry, rubber chemistry, etc.);
- Department of Commerce (because of the importance of rubber to the nation's business);

- Energy Research and Development Agency and the Federal Energy Administration (because of the potential for guayule to replace petroleum-derived synthetic polyisoprene rubbers);
- Department of Defense and the Federal Preparedness Agency (because of the strategic importance of natural rubber to the manufacture of large tires, especially aircraft tires);
- Department of Transportation (because most natural rubber is used to manufacture tires); and
- Bureau of Indian Affairs (because of guayule's potential as a crop for reservations in the Southwest; see page 8).

Although it is important to continue testing the quality and performance of guayule rubber, the current bottleneck lies in the earlier stages of agricultural production. Guayule's development into a viable modern product will require the combined skills of plant geneticists, plant physiologists, pulp and paper technologists, organic chemists, and chemical engineers.

The work of each researcher complements that of the others; therefore, to reduce delay, duplication, and inefficiency, a program that coordinates the various activities is important. For example, the plant breeder should have continuing information from an organic chemist as to the quantity and composition of the rubber and resin in the plants he grows. They, in turn, must be coordinated with the rubber technologist and the rubber industry, who are the ultimate users. To maintain such coordination, the panel recommends a guayule development program somewhat like those established to apply modern science to rice production (at the International Rice Research Institute, IRRI, in the Philippines) and to corn and wheat (at the Centro Internacional de Mejoramiento de Maíz y Trigo, CIMMYT, in Mexico).

Although the development of guayule necessitates close coordination, no new major research facility is envisaged. Instead, the research can be done at existing institutions, with a central office set up to coordinate the efforts. It is recommended that the program have the ability to contract for assistance from research personnel at institutions throughout the nation. The project should have an advisory board made up of outstanding scientists and administrators from industry, government, and academic institutions.

Interdisciplinary agricultural research centers (e.g., IRRI and CIMMYT) have annual budgets of about $7–$10 million. Guayule research does not warrant as large a staff as IRRI and CIMMYT (at least initially) but for a strong program 15–30 full-time researchers could be needed to cover the relevant disciplines from botanical, agricultural, engineering, and polymer sciences. Allowing for construction of a pilot guayule processing facility, the funding level required could be in the range of $2–$4 million annually.

RECOMMENDATION 2

International Cooperation

THE GOVERNMENT OF THE UNITED STATES AND THE GOVERNMENT OF MEXICO SHOULD COLLABORATE IN GUAYULE RESEARCH AND DEVELOPMENT.

The Mexican government began seriously to explore the economic potential of guayule early in 1974. Its inventory showed that Mexico has 2.6 million tons of wild guayule shrubs (containing more than 250,000 tons of rubber) that are amenable to harvest. As a result, a pilot facility was constructed at Saltillo in northern Mexico to study the technical feasibility and costs involved in exploiting this natural resource.

This facility has to use wild, nonuniform guayule bushes with fairly low rubber content. However, both in Mexico and elsewhere, the rational and long-term development of a guayule industry requires that the plant be brought under plantation control. This is especially true in the United States. Our native stands of guayule are much smaller than Mexico's and are insufficient to support a modern mill.

Most advances in guayule cultivation have been made in the United States. It is the combination of Mexican expertise in guayule processing and United States expertise in guayule cultivation that would make a cooperative program profitable.

In addition, a collaborative program would avoid duplication in several research and development fields. The facility in Saltillo already has the equipment for milling the shrubs and might be made available for assessing the processing characteristics of guayule strains selected in breeding programs in the United States. The Mexican facility could supply American industry (the world's largest rubber buyer) with samples to analyze and test in their products.

Collaboration would also facilitate the collection of seeds from the wild guayule stands in both countries. This is particularly important, because when large-scale harvest of guayule begins in Mexico in the next few years, much potentially valuable germ plasm will be lost unless seed collections are made in advance. It is recommended that a cooperative arrangement with Mexico be worked out immediately to facilitate the collection and maintenance of seed stocks to mutual advantage. Several other *Parthenium* species are also important potential sources of germ plasm because they can be hybridized with guayule to produce bigger shrubs. Seeds of these species, which occur principally in Mexico, also need to be collected for breeding purposes.

RECOMMENDATION 3

Varietal Selection and Improvement

GUAYULE BREEDING PROGRAMS SHOULD COMMENCE IMMEDIATELY.

Improvement of the guayule plant through breeding and selection is essential for commercial production. Today, guayule research is hamstrung because only small amounts of the seed of commercially useful strains are available. It is recommended that new collections of guayule seed from wild populations in Texas and Mexico be made immediately, with particular attention paid to those strains that are high rubber producers.

The panel recommends that a stockpile of guayule seed be developed. The seed should be classified and stored in a facility such as the National Seed Storage Center at Fort Collins, Colorado. Seeds of promising varieties should be supplied to persons wishing to embark on guayule research.

Guayule breeding projects should focus on:

- Increasing rubber yield by increasing the percentage of rubber within the plant and by developing a more rapidly growing shrub;
- Developing new techniques to determine the amount and quality of the rubber in the plant—especially techniques that can be taken into the field to screen wild populations and individual plants; and
- Establishing a wider range of adaptation to cold and drought.

It is extremely important to increase seed stocks and to improve the strains already available in the United States (from the Emergency Rubber Project). Projects toward this end should be funded immediately.

RECOMMENDATION 4

Experimental Plantings

EXPERIMENTAL PLANTINGS OF GUAYULE SHOULD BE ESTABLISHED IN AREAS OF CALIFORNIA, ARIZONA, NEW MEXICO, AND TEXAS THAT APPEAR TO BE APPROPRIATE.

To develop guayule into a crop for the United States, we need to know how the plant performs in a wide variety of climates, soil types, and loca-

tions. It is not certain that guayule can be grown in marginal lands, even though its native habitat is a semiarid desert. Some members of the panel feel that as a commercial crop it may have to compete with cotton for better quality land.

One important question about guayule cultivation is whether it can be profitably grown where the supply of irrigation water is insufficient for the successful production of other agricultural crops. Experimental plantings can help provide the answer. They will indicate whether the future for guayule will be as a crop that competes with existing irrigated agriculture or as one that grows in areas now largely unproductive.

These plantings will:

- Provide new information on growing guayule;
- Reintroduce guayule to researchers unfamiliar with the plant;
- Provide comparative analyses of the suitability of different areas of the country for guayule production;
- Provide agronomists and agricultural engineers with plants for testing agricultural methods and machinery; and
- Provide plant geneticists, plant physiologists, and organic chemists with sites at which to test their improved varieties.

To introduce the plant to Indians, some of the experimental plantings should be on Indian reservations.

RECOMMENDATION 5

Archives of Old Guayule Projects

THE FEDERAL GOVERNMENT SHOULD CENTRALIZE ITS GUAYULE RECORDS AT A LOCATION IN THE SOUTHWEST ACCESSIBLE TO RESEARCHERS.

The federal government spent more than $30 million on guayule between 1942 and 1945. Hundreds of researchers were involved and, as a result, more technical information is available on this plant than on any other not now under cultivation. The information is contained in documents long out-of-print, in unpublished reports, and in correspondence. Several hundred cubic feet of these records are stored at the Federal Records Center at Suitland, Maryland, at the National Archives in Washington, D.C., and elsewhere. The

panel recommends that these records be transferred to a single institution, which should be convenient to researchers spearheading the revival of guayule.

Furthermore, a number of the old studies should be reprinted. They contain much information that is still relevant today.*

*Examples include:

Feustel, I.C. *Natural Rubber Extraction and Processing Investigation.* 1953. Final Report: US Natural Rubber Research Station, Bureau of Agriculture and Industrial Chemistry, Salinas, California. 221 pp.

Hammond, B. L. and L. G. Polhamus. 1965. *Research on Guayule* (Parthenium argentatum) *1942-1959.* U.S. Department of Agriculture Technical Bulletin 1327. 157 pp.

Taylor, C. A. 1946. *The Propagation of Guayule: Studies Covering Seed, Nursery, and Direct Seeding Practices.* U.S. Department of Agriculture (Forest Service, Emergency Rubber Project). 85 pp.

Roberts, P. H. 1946. *Final Report, The Emergency Rubber Project: A report on our Wartime Guayule Program.* U.S. Forest Service, Los Angeles. 234 pp.

Dortignac, E. G. and G. A. Mickelson. 1945. *Dry-Farming Possibilities for Guayule in California.* U.S. Forest Service, Emergency Rubber Project. 85 pp.

Artschwager, E. 1943. *Contribution to the Morphology and Anatomy of Guayule* (Parthenium argentatum). U.S. Department of Agriculture Technical Bulletin 842. 33 pp.

3 Background

When the conquering Spaniards, in the 1500s, reached what is now Mexico they discovered Aztecs playing a game similar to basketball, with a bouncing ball and a stone ring for a goal. Rubber for the balls was extracted from latex-containing plants. In the northern semidesert highlands, the stems of guayule bushes were used. The Indians chewed them, spitting out the rubber and vegetable matter separately.

For several centuries guayule was no more than a curiosity, although, because its rubber and resin burned fiercely, it was often used to fire smelters extracting silver from rich ores in northern Mexico's Chihuahuan desert region. During the first decade of this century, however, the guayule bush attracted attention as a source of natural rubber. Scores of patents were issued to would-be entrepreneurs and more than a dozen rubber-extraction factories were built in Mexico and Texas.

In 1910 about 50 percent of U.S. rubber was extracted from wild guayule shrubs. A number of the industrial leaders of the day (led by Bernard Baruch and including John D. Rockefeller, Thomas Fortune Ryan, Nelson W. Aldrich, and Daniel Guggenheim) invested 30 million dollars in a guayule company, the Continental-Mexican Rubber Company (see Figure 4).

As a result, Mexico became a rubber-exporting country. Francisco Madero, scion of one of the wealthiest guayule-growing families, became president of Mexico in 1911. From 1910–1946 the United States imported more than 150 million pounds (68 million kg) of Mexican guayule rubber. For example, in 1912 16 million pounds (7 million kg) were imported at a price of 48.5¢ per pound ($1.07 per kg). About 1910, when it was thought that guayule fortunes were soon to be made, there was a boom in desert land in the United States and Mexico.

But the wild stands, though extensive, could not endure such sustained harvesting. No replanting, cultivation, or rotational cropping was then practiced, and the reckless exploitation resulted in the complete devastation of the wild guayule stands. By 1912, therefore, many mills had been forced to close. Then revolution broke out across northern Mexico, causing abandonment of the remaining mills.

The Revolution, for example, forced the Continental-Mexican Rubber Company to retreat across the border. In Arizona, and later in California, the company began to produce guayule as a cultivated crop. Its efforts received

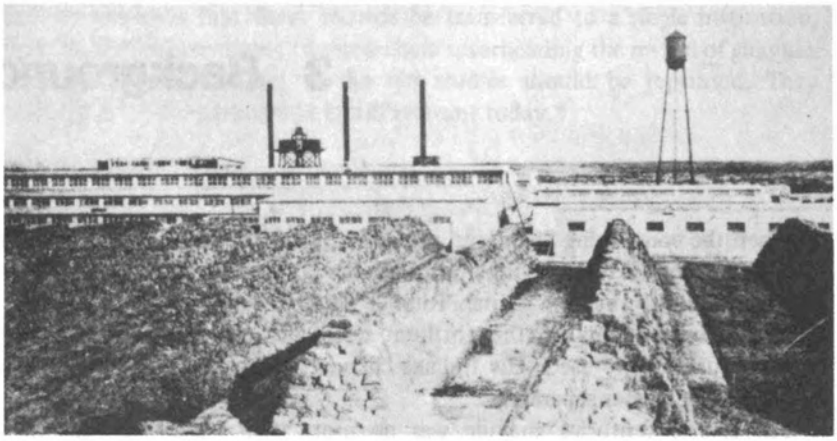

Figure 4. Stacks of guayule in bales. Continental-Mexican Rubber Company, Torreón, Mexico 1910. This factory provided a significant fraction of the rubber used in the United States at that time.

a large boost in the 1920s when the British government restricted the amounts of rubber it would sell to the rest of the world. Using the rubber from its giant plantations in the crown colony of Malaya (now Malaysia) as an economic lever, the British unilaterally increased rubber prices threefold. With this incentive, the company planted 8,000 acres (3,240 ha) of guayule in California and, during the late 1920s, over 3 million pounds (1.4 million kg) of rubber were extracted. The rubber sold profitably at prices competitive with those of hevea rubber. But the onset of the Depression tumbled rubber prices to 2¢ per lb (4.4¢ per kg), ruined the British scheme,* and arrested guayule development.

In 1930, the War Department recognized the danger that the United States could be cut off from rubber supplies. Dwight D. Eisenhower, then a major, was assigned to study the use of guayule as an alternative. His report urged that guayule plants growing in the United States be protected and reserved for strategic emergencies and that guayule development be supported by the federal government. However, the advice was ignored, and in December 1941 the United States and its allies lost more than 90 percent of their rubber supply when Japanese forces invaded Southeast Asia.

*In the 1930s a cartel of rubber-producing countries (including Malaya, Ceylon, the Dutch East Indies, and French Indochina) was more successful and controlled natural rubber supplies and dictated prices until World War II. The history of rubber economics during the 1920s and 1930s is given in Smith, G. B. 1972. *Rubber for Americans: The Search for an Adequate Supply of Rubber and the Politics of Strategic Materials 1934-1942.* Ph.D. Dissertation, Bryn Mawr College. Available from University Microfilms, Ann Arbor, Michigan (order #73-9111).

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A massive "Emergency Rubber Project" (ERP) was initiated in February 1942. More than 1,000 scientists and technicians were assigned to guayule production and research. In 3½ years, supported by a work force of 9,000 workers, the ERP planted almost 32,000 acres (13,000 ha) of guayule at 13 sites in 3 states. It produced one billion guayule seedlings (see Figure 5) and 3 million pounds (1.4 million kg) of resinous rubber for the war effort (see Figures 6–8). Toward the end of the program, 15 tons of rubber were produced daily in factories at Salinas and Bakersfield, California. Four guayule mills were constructed in Mexico; by the end of 1942, they were processing 180 tons of shrub in a 24-hour day.

However, in 1943, as a result of government investments of several hundred million dollars, synthetic elastomers began to be produced in commercial quantities. This industry quickly expanded. At war's end, with the presence of the synthetic elastomer industry and with surplus stocks of hevea rubber in Southeast Asia, the economic and strategic justification for continued guayule production seemed to have disappeared. The fields in which the ERP planted guayule had been leased in 1942. But by 1946

Figure 5. Salinas, California 1942. The scope, magnitude and accomplishments of the Emergency Rubber Project go unrecognized today. The nursery required to provide the billions of seedlings for California's guayule plantations contained over 45,000 seedbeds (each 4 ft wide and 400 ft long). Over 5 million linear feet of redwood boards were laid between seedbeds for convenience during rainy weather. (U.S. Department of Agriculture).

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Figure 6. Irrigated guayule grown by the Intercontinental Rubber Company near Salinas, California circa 1941. These plants have been in the field less than 4 months. For 20 years the crop was commercially produced in this temperate, winter-rainfall region. During the period 1942–46 the federal government operated this plantation: 8,000 acres (3,000 ha) of guayule were grown to harvestable size. (U.S. Department of Agriculture)

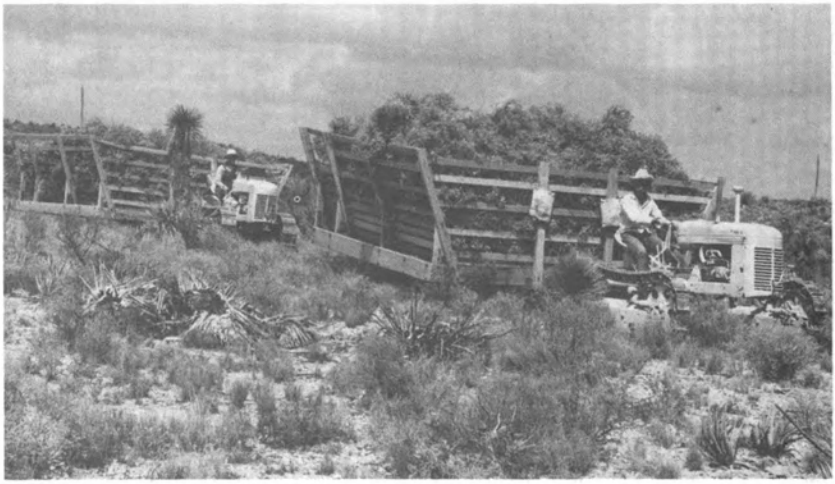

Figure 7. On the "02" Ranch near Alpine, Texas, 1943. Harvesting wild guayule to provide rubber for the war effort. The arid landscape is typical of the Big Bend area where guayule is native. (U.S. Department of Agriculture)

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Figure 8. First guayule rubber tire–Secretary of Commerce Jesse Jones receives first automobile tire made entirely of rubber produced from guayule, January 15, 1942. (Wide World Photos)

wartime inflation had made the rents paid by the ERP totally inadequate, and the farmers pressured the Congress to return their land. Accordingly, in 1946 the 77th Congress terminated funding for the ERP and ordered that the guayule bushes already planted be destroyed. An estimated 21 million pounds (10 million kg) of rubber in 27,000 acres (11,000 ha) of guayule plantations that were reaching maturity were burned or disked into the ground (see Figure 9). Further, most of the seed from the genetic improvement program was destroyed along with hundreds of millions of seedlings.

After 1946, the U.S. Department of Agriculture continued to investigate guayule, but its efforts were inadequately funded. Nevertheless, promising genetic improvements and breakthroughs in processing and rubber quality were made. Following up research advances made by Japanese-Americans interned during the war at Manzanar Relocation Center in the Owens Valley, California (see Figure 10), machinery designed to pulp wood for paper production was used experimentally to mill guayule shrubs. Also, new techniques were developed for leaching out the resins that lower guayule rubber's quality. Deresination and the use of wood-pulping mills greatly improved the quality of the rubber produced and, in road tests in 1953, heavy-duty truck tires made from deresinated guayule showed properties equivalent to those made from hevea rubber.

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Figure 9. Burning guayule shrub on the James Nelson farm in the Beaumont area of Southern California. In 1946 the 77th Congress legislated that the Emergency Rubber Project be liquidated. All 30,000 acres of guayule then in plantations were burned or disked into the ground. An estimated 10,000 tons of rubber were destroyed. (W.G. McGinnies)

Nonetheless, in 1953 the federal guayule research program (at the U.S. Natural Rubber Research Station, Salinas, California) was terminated. The Continental-Mexican Rubber Company (then known as the Intercontinental Rubber Company) was purchased–for its New York Stock Exchange listing–by Texas Instruments Incorporated, and its rubber production also ceased.

Concurrent with the U.S. efforts, attempts to cultivate guayule were made in Australia, Argentina, Mexico, Spain, Turkey, and the Soviet Union. These continued through the 1950s, but the world rubber situation continued to militate against guayule and the plantations were abandoned. Currently, there are no commercial guayule plantations anywhere in the world, though experimental plots have recently been established in Israel, Arizona, and California.

Only in Mexico did guayule development continue, and as a result of knowledge accumulated during recent decades two agencies of the Mexican government (the Consejo Nacional de Ciencia y Tecnología and the Comisión Nacional de las Zonas Áridas) are now embarking on rubber production from what they estimate is 2.6 million tons of adult guayule shrub growing wild in about 10 million acres (4 million ha) in the States of Coahuila, Zacatecas,

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Figure 10. Unirrigated guayule, Manzanar, California circa 1943. In this barren, semi-arid, winter-rainfall location in the Owen's Valley guayule was grown as a dryland crop during the period 1942–44. The work was done by Japanese-Americans forcibly detained in a relocation camp. Guided by Professor Robert Emerson of the California Institute of Technology they greatly advanced guayule technology by pioneering the use of wood-pulping machinery for milling guayule shrubs. (C. Emerson)

Chihuahua, Nuevo León, and San Luis Potosí (see Figure 1). The plan is to harvest 300,000 tons annually in order to produce 30,000 tons of deresinated guayule rubber. A pilot plant to process one ton of shrub daily was completed in March 1976 (see Figure 17). Incorporating advanced technology from the synthetic rubber industry, this facility produces guayule rubber that is deresinated and of far higher quality than that previously produced. In August 1976 tires were manufactured from guayule rubber and are now undergoing testing.

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4 The Plant

Guayule is a member of the sunflower family, Compositae, and belongs to the genus *Parthenium*. There are 16 species of *Parthenium*: guayule is *Parthenium argentatum*, so named because of a silvery sheen on its gray-green leaves. It is the only *Parthenium* species known to produce rubber in any quantity.

A bushy perennial shrub (Figure 11), guayule has narrow leaves, covered in a drought-protecting white wax, that alternate along the stem, and a canopy of small flowers borne on exceptionally long stems (Figure 12). Usually only about 2 feet (60 cm) high, it is long-lived and hardy; it may survive 30 or 40 years under desert conditions where annual rainfall may be less than 10 in. (250 mm).

Native to a semiarid area in north-central Mexico and southern Texas, guayule occurs in stands scattered throughout 130,000 sq mi (337,000 sq km) of the Chihuahuan Desert and surrounding regions. In the United States, the shrub is found wild in the Trans Pecos area (Stockton Plateau and Big Bend region) of southwestern Texas (see Figure 1).

Guayule's native habitat is a semiarid plateau 4,000-7,000 ft (1,200-2,100 m) high. In this area it withstands temperature between 0° and 120°F (-18° and 49°C). Heat appears not to affect this desert-adapted plant, but at temperatures below 60°F (16°C) its growth rate slows; below 40°F (4°C) it becomes semidormant; freezing temperatures sometimes kill it.

The plant develops a taproot that may penetrate the soil more than 20 ft (6 m), supplemented by extensive fibrous roots that may spread up to 10 ft (3 m) laterally. This root network allows guayule to absorb moisture from a large volume of desert soil and thus to withstand periodic drought. For severe and extended droughts the plant has another survival mechanism: it becomes dormant. In some parts of Mexico, guayule has survived by this means, despite the virtual absence of rainfall for several years.

In guayule's native habitat, 9-16 in. (230-400 mm) of rain falls annually (mainly in the summer months). The plant grows best in well-drained soils and cannot tolerate waterlogging. In nature it grows in a wide variety of shallow, stony, calcareous, and friable soils.

Unlike the rubber in *Hevea* and other latex-producing plants, guayule rubber is not contained in ducts, but in single, thin-walled, cells (Figure 13).

Figure 11. Guayule growing wild in Zacatecas State, Mexico. Rubber is found in thin-walled cells throughout the stems, branches, and roots. Leaves contain no rubber. Some strains have yielded up to 26 percent rubber (dry weight basis). (N. D. Vietmeyer)

These rubber-filled cells are mainly in the outer layers (in the cortical tissues and the medullary rays) and mostly in new-grown tissues, but the old cells of the inner xylem and pith produce rubber for several years. Two-thirds of the rubber is in the stems and branches, the remainder in the roots. There is no rubber in the leaves.

The rubber is suspended in cell sap to form a latex as in other rubber-producing plants. Unlike *Hevea*, however, guayule produces no natural antioxidant and the rubber in its latex rapidly degrades upon contact with air.

In native guayule bushes rubber constitutes, on the average, about 10 percent of the total weight of the plant (dry weight). But guayule has considerable genetic variability: in the wild it exists in a large number of strains—indeed almost every plant is a separate strain. Some of these contain much rubber, others almost none. In the 1940s, strains containing up to 26 percent rubber were found. However, the strains that were widely cultivated had been selected prewar and were able to produce about 20 percent rubber (dry weight) after 4 years' growth.

The rubber yield depends not only on genetic makeup but also on environmental conditions. When guayule grows actively it produces little or no

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Figure 12. Guayule branch showing leaves, inflorescences, and general appearance. (U.S. Department of Agriculture)

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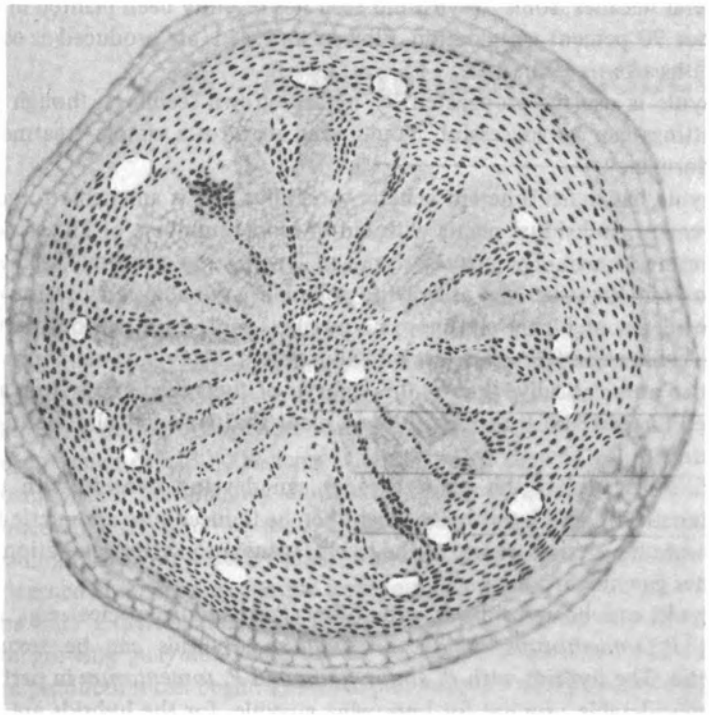

Figure 13. Guayule stem cross-section. The stained rubber shows up as black dots, the resin ducts as white holes. (F.T. Addicott)

rubber. If the plant is stressed, growth slows and the products from photosynthesis are diverted into rubber production. Thus when growth slows during cool weather or because of reduced moisture supply, the rubber content begins to increase.

Apparently rubber is not used or metabolized by the plant because it continues to accumulate for at least 10 years; plants can remain in the field for even longer periods without serious loss of rubber. Experiments have shown also that if guayule plants are deprived of all carbohydrates and other energy sources, they still fail to utilize their rubber as an energy source.

Resin ducts are found throughout the shrub, and resins (which include terpenes, sesquiterpenes, diterpenes, glycerides, and low molecular-weight polyisoprene hydrocarbons) constitute 10–15 percent of the plant (dry weight).

Guayule flowers are pollinated by wind and by insects. The tiny seeds are produced at a prolific rate; a plant can yield several thousand after a single rainfall. Vigorously growing plants bloom and set seed continuously throughout summer and fall. If stored carefully the seeds can remain viable

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for several decades; some 20-year-old seed has recently been planted in Israel with over 90 percent germination. Flowers and seeds are produced as early as six months after germination.

Guayule is usually propagated by nursery-grown seedlings, though grafts and cuttings can be successful. Young seed requires a simple treatment to break dormancy.

Guayule has much inherent genetic variability and is amenable to genetic improvement. Individual plants with chromosome numbers of 2n=36 to 100 or more are known. The guayule types of 2n=36 are completely sexual and reproduce in the usual way, involving pollination (double fertilization). The guayule plants of higher chromosome numbers reproduce without requiring double fertilization (these are termed "apomicts"). Many guayule populations reproduce apomictically, that is, the embryo of their seed arises from a non-fertilized nucleus and thus reproduces a plant that is genetically identical to the parent.

With sexual types the plant breeder can develop hybrids with useful characteristics. These hybrid plants can then be induced into apomictic forms to replicate the characteristics of the hybrid, generation after generation. This facilitates guayule breeding.

Guayule can be hybridized with other *Parthenium* species, e.g., *P. incanum, P. tomentosum*, and *P. stramonium*. Hybrids can be sexual or apomictic. The hybrids with *P. stramonium* and *P. tomentosum* in particular show considerable promise for improving guayule, for the hybrids are much bigger plants than guayule and some of them contain rubber. Crosses with *P. incanum* offer opportunities for greater cold tolerance (see Chapter 9). Crosses with other *Parthenium* species still remain to be attempted.

5 Agricultural Production

For a crop that is not now produced, guayule's agriculture is remarkably well-known; almost a thousand scientific papers have been written about the plant, including excellent manuals for germinating seed, caring for seedlings, transplanting, fertilizing, irrigating, and harvesting. This knowledge is based largely on empirical observations made during 40 years of commercial production and during the period when the Emergency Rubber Project was active, in which over 30,000 acres (12,000 ha) of guayule were cultivated in California.* Wartime urgency demanded that good-quality agricultural land and adequate irrigation be used. Thus, the work of the ERP is perhaps a misleading model for a desert plant, but basic features of guayule agriculture were learned and many agronomic techniques developed.

The ERP experience showed that there were no insurmountable difficulties in growing guayule. There are no fundamental barriers to be overcome before production can begin. The ERP plantations and experimental plantings provide guidelines for producing rubber under a wide variety of soil and climatic conditions.

Climate Needs and Irrigation

Moisture is perhaps the most important determinant in guayule growing. Although the plant can produce rubber in very dry climates, it is not clear that it can be *economically* cultivated in regions as arid as much of its native habitat. This is because where rainfall is deficient and drought common, the plant is hard to establish and may take more than 7 years to develop commercially useful quantities of rubber.

In its native habitat, annual rainfall can be less than 9 in. (230 mm), but ERP researchers concluded that 11-25 in. (280-640 mm) annually is needed for commercial rubber production. About 16-18 in. (410-460 mm) was recommended for production on a long rotation (4-8 years).

*Salinas area, 8,000 acres (3,200 ha); Tracy-Newman, 12,000 acres (5,000 ha); Bakersfield, 9,000 acres (3,600 ha); and Southern California (Indio, Carlsbad, and San Clemente) 2,000 acres (800 ha).

The guayule plant can survive arid conditions, but if annual rainfall is less than 14 in. (356 mm) supplemental irrigation is needed to give a worthwhile yield of rubber in a reasonable time. When annual moisture exceeds 25 in. (640 mm) excessive vegetation growth, rather than rubber formation, may occur.

The highest yields recorded for cultivated guayule have been obtained with irrigation. Irrigation allows the farmer to control the moisture that the plants receive; it can force growth, shorten the production cycle, and extend guayule production into areas where rainfall is unreliable.

To meet guayule's peculiar need for stress periods that cause it to produce rubber, both irrigation and rainfall must be unevenly distributed year-round. Definite dry seasons appear necessary and of course with irrigation these can be induced at will in arid regions.

Wild guayule bushes have survived temperatures well below freezing, but in plantations the plants (especially young seedlings) are frost sensitive. For survival, guayule planted in frost-prone areas requires careful tending. A frost of 20°F (-7°C) can injure tender plants, but those previously induced into dormancy ("hardened off") by exposure to gradually decreasing temperatures or by reduced irrigation are not harmed by much lower temperatures.

Soils

To produce guayule successfully, a soil's moisture-retention characteristics are most important. Well-drained soils are needed and the ERP project concluded that sandy loam was best. The plant does not grow well in compacted and poorly drained soils.

Guayule appears to need little fertilizer, will grow well in moderately fertile soils, and is not a serious soil-depleting crop. While fertilizer improves vegetative growth it does not necessarily increase the amount of rubber produced. The optimum fertilization for maximum rubber production is yet to be determined.

Guayule does not appear to be very salt tolerant. Because of high evaporation, salt buildup could cause problems if the plant is grown with irrigation in arid regions.

Field Production

Several years are needed for guayule to attain an economic size and rubber content. Irrigation is the most important factor in hastening the growth rate and, with irrigation, guayule can be brought to economic harvest size in 3

years. In experiments, productive harvests have even been made at the end of the second year. Under dry-land farming it is generally thought that much longer periods are required for economic production.

Guayule is suited to highly mechanized agriculture; engineers in the ERP developed and used machinery to handle each step in production from seed gathering to baling the harvested shrubs. Guayule lends itself to many modern agricultural implements: conventional tillage equipment to prepare the land; mechanical tree planters to plant seedlings; corn or cotton cultivators, digger-harvesters, and hay balers to bale the shrubs for easy transportation.

All commercially cultivated guayule has been produced from seedlings grown in a nursery and transplanted to the field. Toward the end of the ERP some researchers found that, with special care, seeds could be planted directly in the field. But guayule seeds are tiny—the size of lettuce seeds—and they must be carefully planted in light soil very close to the surface. Here they are vulnerable; both wind and sand splash (from sprinkler irrigation) can bury them too deep for successful germination, or leave them uncovered—with fatal results. Furthermore, during the first 5 weeks, weeds can completely smother the tiny, tender seedling. A nursery allows better control of these difficulties.

During the ERP, guayule seedlings were grown in nursery beds 4 ft (1.2 m) wide and 400 ft (120 m) long. Over 45,000 of these were planted during 1942.* Serious losses were encountered during transplanting unless the seedlings were first induced into a near-dormant state by cold or drought.

The plantation's first year is a critical time, since the small seedlings are easily smothered by weeds.† In later years, less cultivation is needed, and a point is quickly reached where guayule shades out weeds and robs their roots of moisture; then little or no further weeding or cultivation is needed.

Pest Control

In the wild, guayule appears remarkably free of disease and insect pests, but under cultivation the plants are susceptible to both. Although few plants

*The final report of the Emergency Rubber Project gives some concept of the magnitude of the project. Describing establishment of the initial lot of seedbeds, the report (page 47) states: "One of the first purchases made at Salinas involved the procurement of 3,500 tons of [specially dried] sand. Since 11,786 seedbeds, each 400 feet long, were sown, and each bed contained seven rows of seed, the 3,500 tons of sand was eventually deposited in bands which, if joined end to end, would extend from Salinas, California eastward across North America and the Atlantic Ocean to Gibraltar!"

†Today, weed problems should not be as serious as those reported in the literature. All the previous guayule plantations were established before the discovery of organic herbicides. Preliminary observations suggest that modern herbicides will reduce weed infestations dramatically.

died from disease or pests in the huge areas of plants cultivated in the ERP, infestations were found nonetheless. The diseases are the common ones that affect other crops such as cotton and lettuce. Some are quite serious, such as cotton root-rot, charcoal rot, dieback, and wilt. A few days in standing water encourages *Phytophthora* rot on guayule roots. Irrigation must always be carefully managed to avoid waterlogging.

Guayule is reportedly highly resistant to root-knot nematode.

Plantation guayule can be damaged by several insects (grasshoppers were the worst insect pests in the ERP), particularly during the seedling stage. Today these insects can undoubtedly be controlled with insecticides.

Harvesting

Guayule is normally harvested, roots and all, with a tractor-drawn digger (see Figure 14). The shrubs are then baled for transport to an extraction mill.

Important research advances have been made with pollarding guayule. In this method (also known as coppicing) the bushes are mowed off about 2 in. (5 cm) above the ground so that only the trunk, branches, and leaves are harvested. The roots (containing about one-third of the plant's rubber) are left in the ground to produce new growth. Most roots resprout and grow into

Figure 14. Guayule is adapted to mechanized agriculture. All the operations involved in producing it (for example, seeding, transplanting, cultivating, harvesting, and baling) have been mechanized. Here a combine harvester picks up shrub, chops and blows it into a waiting truck for transport to a baler or factory. (Intercontinental Rubber Company, Salinas, California, January 1931)

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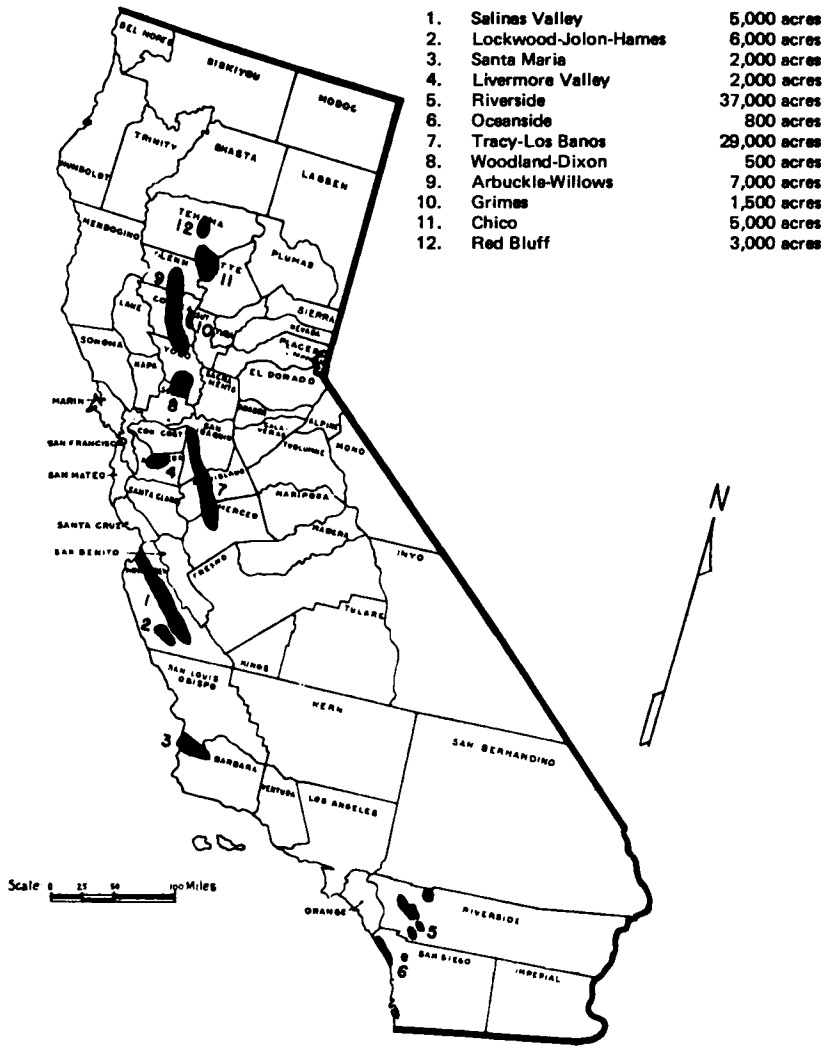

Figure 15. Areas in California judged as suitable for dryland (unirrigated) guayule cultivation. The figures quoted represent the specific areas judged as suitable for producing "moderate to high" yields of rubber when compared with irrigated guayule production in the Salinas Valley. (Source: Dortignac, E.G., and G. A. Mickelson. 1945. *Dry-Farming Possibilities for Guayule in California*. U.S. Forest Service, Emergency Rubber Project.)

new shrubs so fast that a one-year-old pollarded bush becomes as large as a two-year-old seedling. Comprehensive analysis still remains to be done, but in principle this method rapidly produces two crops while avoiding the expensive replanting normally required. Whether more than two crops can be harvested without replanting is unknown.

Dry-land (Nonirrigated) Production

Guayule's water requirements are not well-enough known for us to accurately predict what a rubber yield will be in a given location. Yet a major hope for the future is that guayule can be grown in land that is not now used for conventional crops. In this way it would not compete with food production.

As a native of desert regions, guayule has potential to be grown where rainfall is too sparse or too unreliable for other crops. But though guayule will grow in such areas, it is not known whether dry-land farming can be profitable. To determine this more accurately is one of the main research needs in guayule production (see Chapter 9).

A detailed analysis of the possibilities for growing unirrigated guayule in California was made in the 1940s (the results are given in Figure 15). It was shown that under dry-land conditions guayule roots are able to penetrate porous soils (if devoid of thick strata of gravel and coarse sand) to depths of 8-10 ft. (2.4-3 m) during the first growing season, and to depths of 14-16 ft (4-5 m) during the second season. A reservoir of moisture often accumulates below the root zone of conventional crops—such as grains—and is unavailable to their roots. This was found to be the case in areas of California where grain crops (with roots 5-6 ft [1.5-2 m] deep) were grown. But with its deeper root system guayule could obtain the moisture that existed from 5-20 ft (1.5-6 m) deep in the soils.*

*Dortignac, E. G. and G. A. Mickelson. 1945. *Dry-Farming Possibilities for Guayule in California.* U.S. Forest Service, Emergency Rubber Project.

6 Rubber Extraction

As already noted, the latex in guayule shrubs is found in the roots, stems, and branches; to obtain it the whole plant is processed.* The latex is contained in microscopic cells, which are not connected; hence guayule plants cannot be tapped like rubber trees. The rubber must be physically or chemically separated from other components in the harvested shrub: dirt and rocks (caught on the roots), leaves, woody vegetable matter, cork, cellular juices and resins (see Table 1).

This complicated separation can be accomplished with up to 95 percent rubber recovery. It can be done with a sequence of fairly standard and continuous processes (see Figure 16).

Guayule plants, unlike *Hevea*, contain no antioxidant, nothing to retard oxidative degradation of the rubber once the cells are exposed to air. Thus the shrub must be kept intact and processed within a few days of harvest. In addition, each processing step must be conducted without excessive delay.

TABLE 1. Components of harvested guayule shrubs

Moisture	45 - 60 percent
Rubber	8 - 26 percent*
Resins	5 - 15 percent*
Bagasse	50 - 55 percent*
Leaves	15 - 20 percent*
Cork	1 - 3 percent*
Water Solubles	10 - 12 percent*
Dirt and Rocks	Variable

*dry weight basis

*Guayule could, in theory, be extracted using several different approaches (solvent extracting the uncoagulated latex, for example) but this chapter largely describes the process now in pilot stage at Saltillo, Mexico (see Figure 17). It is a process that integrates modern technology from the synthetic-rubber industry and from the pulp and paper industry with the most advanced techniques developed for guayule by U.S. engineers during the 1940s and 1950s. All of the steps have been in operation since March 1976, and one ton of shrub is being processed daily.

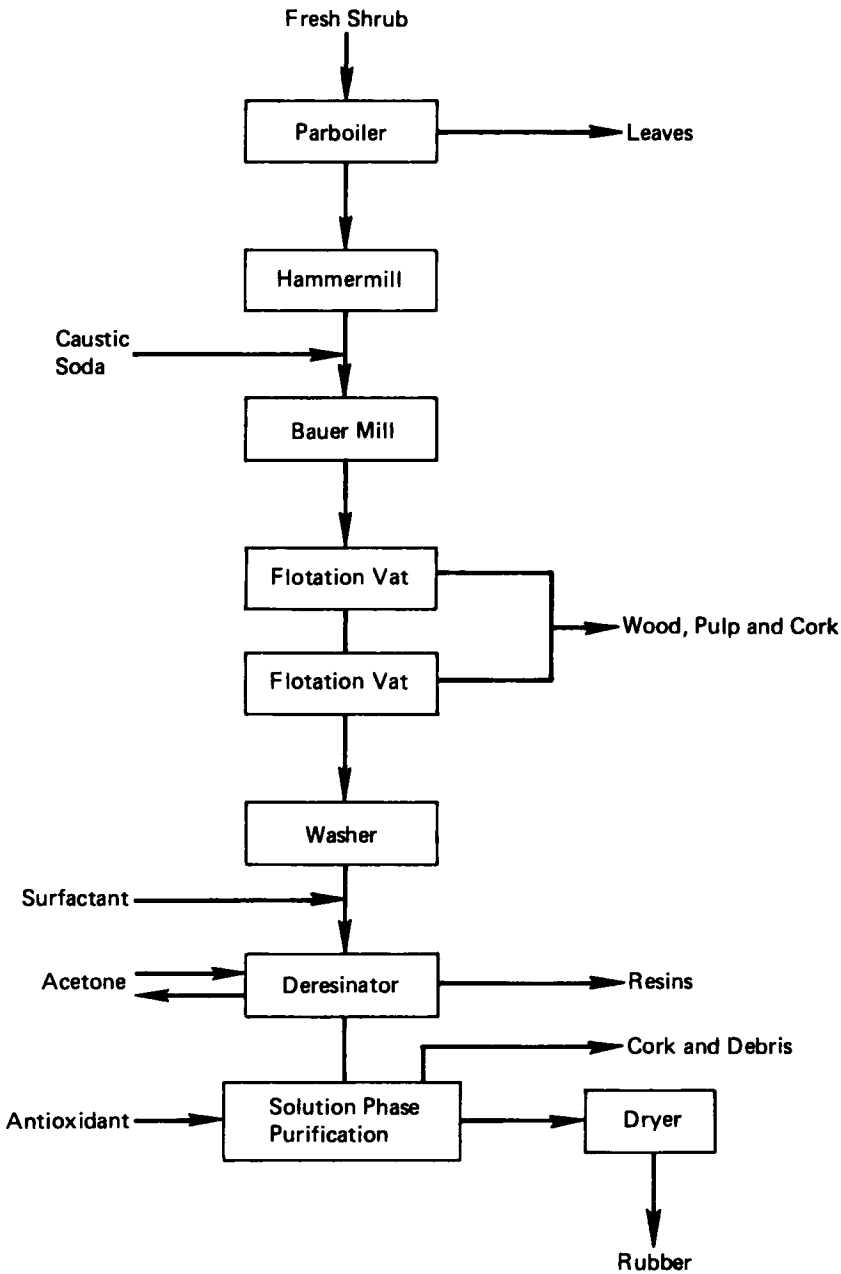

Figure 16. The method for commercially extracting rubber from guayule shrubs recently developed in Mexico.

Figure 17. A section of the Government of Mexico's pilot guayule-processing mill at Saltillo, Coahila. Scaled to handle 1 ton of shrub daily, the facility has been constructed to optimize the processing methods developed in recent years by Mexican researchers. Current plans call for scaling up to large production (300,000 tons of shrub per year) by 1979. On the right are seen parts of the Bauer mill and flotation vats; in the background is the unit for removing resins from the crude rubber. (N. D. Vietmeyer)

Parboiling

In the first step, the shrubs are dipped in hot water (10 minutes at 75°C [167°F]). This coagulates the rubber in the latex cells, which decreases its deterioration during processing and simplifies its separation from the vegetable matter. Parboiling also removes much of the soil from the roots, but perhaps most important, it removes the leaves, which contain no rubber. Defoliation greatly benefits processing by reducing (up to 20 percent) the bulk of material to be handled and increasing mill capacity. It also improves the final product, for the leaves contain copper, manganese, and resinous compounds that contaminate the rubber and catalyze its degradation.

Milling

To release the rubber from the cells the plant tissue must be separated and disintegrated. Although older processes used equipment designed for ore crushing, research has shown the superiority of pulping machinery designed

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to separate wood fibers and release lignins in paper manufacture. At Manzanar and in the final phases of the U.S. guayule project a Jordan Mill was used; the current Mexican project uses a Bauer Mill. Both of these mills are used in the paper industry for making pulp. Prior to pulping, guayule shrubs are coarsely hammer milled. Caustic soda is added because during the pulping process it helps break open the rubber-filled cells and promotes separation of the rubber from the vegetable matter.

The pulping is done in water, which causes the rubber and brown, pungent resins to agglomerate into a spongy form known as guayule "worms" (see Figure 18).

Rubber Separation

In a large slurry tank (as used in manufacturing wood pulp) the slurry of pulped shrub separates: the waterlogged bagasse sinks, the worms float and are skimmed from the surface (see Figure 19). In a second tank the crude worms are again stirred in a slurry tank, the rubber skimmed from the surface, and residual bagasse separated.

The tacky, resinous worms are then rinsed to remove caustic soda. They are difficult to handle and gum together, trapping water, cork, and fiber

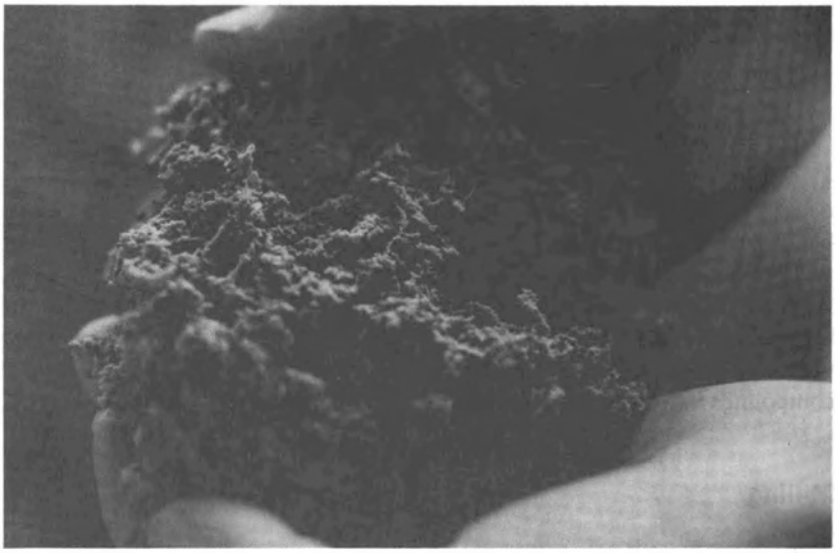

Figure 18. Guayule rubber "worms," the crude form in which the rubber separates from the wood pulp. (N. D. Vietmeyer)

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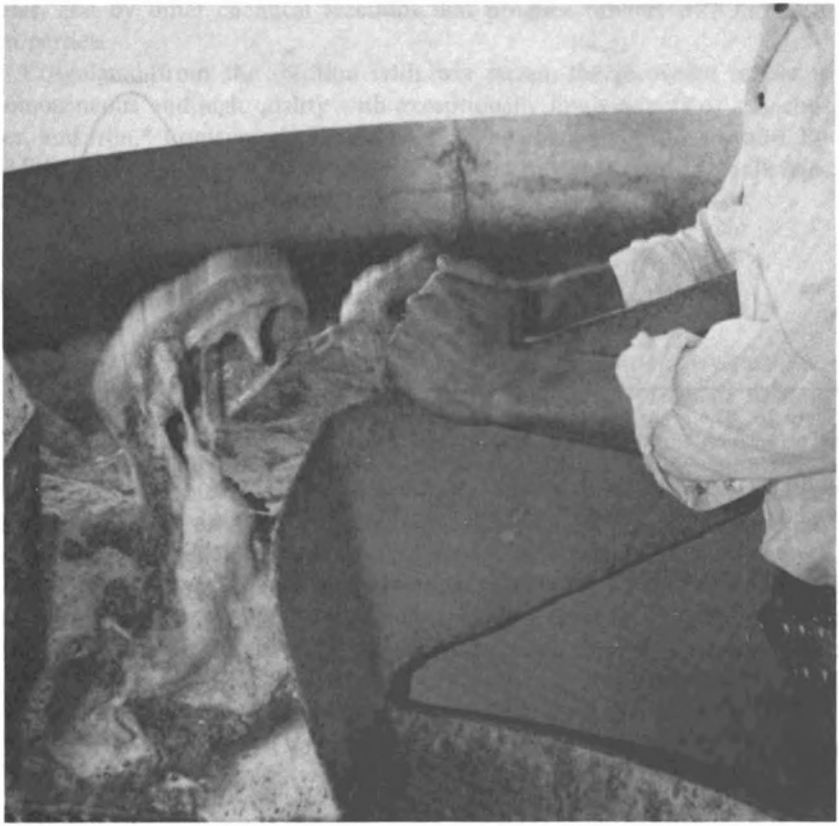

Figure 19. In the main step in extracting guayule rubber the pulp of disintegrated shrubs is stirred in a vat; the rubber floats to the surface and is skimmed off, the waterlogged pulp sinks and is pumped away. Saltillo, Mexico, 1976. (N. D. Vietmeyer)

between them. To keep them small, manageable, and easy to deresinate, the worms are next warmed in water containing a little surfactant (detergent).

Deresination

Guayule worms contain about 17–25 percent of resins (see Figure 20). To remove resins, the small (1 mm diameter in the surfactant-treated Mexican product), highly porous worms are extracted with warm acetone, a common industrial solvent. A fluid-bed process is used, and in only minutes the acetone carries away about 95 percent of the resins together with much water.

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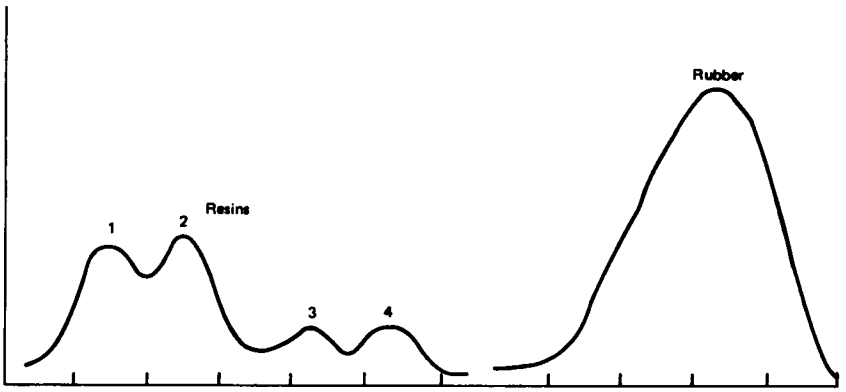


Figure 20. The resins that contaminate freshly extracted guayule rubber appear in this gel permeation chromatograph: Peaks 1 and 2 contain monoterpenes, sesquiterpenes, and diterpenes; peaks 3 and 4 contain saponifiable material (fats), principally triglycerides of lineoleic, oleic, stearic, and palmitic acids. (E. Campos-López)

The acetone then is distilled from the resin/water mixture and recycled. After steam sparging to remove residual acetone, the grey-white guayule rubber contains about 2 percent resins, as well as cork and debris that failed to sink in the slurry tanks.

This method produces a uniformly deresinated rubber, which can be dried with standard equipment: a screw press followed by a hot-air drier.

Final Purification

The Mexican government's guayule project incorporates an ultimate-purification step that takes advantage of modern developments in the synthetic-rubber industry. The deresinated rubber is dissolved in solvent.* This solution can be readily filtered to remove residual insolubles (cork, fiber, dirt). The filtered solution is homogeneous and the rubber can be bleached, protected with antioxidants, or treated with other reagents to give a high-quality, uniform product.

But perhaps more important is the power that the solution phase gives the manufacturer to chemically modify the rubber. In solution the rubber can be altered by polymerization, chlorination, copolymerization with methacry-

*Unlike hevea rubber, guayule rubber contains little gel and dissolves satisfactorily in hexane or cyclohexane (see Chapter 7). In the Mexican process the solution used contains about 5 percent rubber.

lates, and by other chemical reactions that produce rubbers with different properties.

Coagulated from the solution with wet steam, the recovered rubber is homogeneous and high quality with exceptionally low amounts of ash, copper, and iron.* Constant-viscosity rubber can be obtained by this method. By adding surfactant during coagulation, a powdered rubber suited to bulk handling can be obtained, unthinkable with the tacky guayule of the past.†

Alternative Methods

In the 1950s the U.S. Natural Rubber Research Station developed an alternative method for separating the rubber from small pieces of floating debris that accompany the worms from the slurry tank. A pressure vessel was used to waterlog the debris (cork and cellulosic waste) which in a subsequent slurry tank would sink, leaving only the worms floating. The worms were then deresinated, using acetone, as in the Mexican process.‡ The product, though not equaling the quality of the Mexican rubber (e.g., it contains about 3 percent benzene-insoluble material), nonetheless can probably fill many of the commercial end uses that now employ hevea rubber, and it may be cheaper because it avoids the costs of solution-phase purification.

*Furthermore, the solvent is washed, distilled, and recycled.

†Information supplied by E. Campos-López.

‡A partial deresination method called "retting" was used on a small scale in the 1930s and '40s. In this process the harvested shrubs were moistened and stored in the air. Under these conditions molds and bacteria decompose some of the resins that most seriously lower rubber quality. The rubber is then milled out of the retted shrub in the normal manner.

7 Rubber Quality

Freshly extracted guayule rubber contains about 20 percent clove-scented liquid tars, called resins. Almost all the guayule rubber sold in the past was in this tarry form. It was inferior to hevea rubber (which has only 2 percent nonrubber content), its physical properties were poor and nonuniform, and the rubber degraded rapidly. It was also difficult to handle, impossible to dry, and contained dirt, flint (from the rock-filled mill used to macerate the shrubs), and vegetable matter. This resinous rubber gave guayule a bad reputation, which still persists in the rubber industry.

Guayule rubber's poor performance was caused by the impurities resulting from inadequacies inherent in the extraction process used, a method that during 40 years changed little from its original design. However, a breakthrough was made in the late 1940s when it was found that resin could be easily removed. Unfortunately, the discovery came too late; no deresinated rubber was produced for commercial use because the guayule program was then being terminated.

Since it is unlikely that the resinous guayule rubber will ever again be marketed, this chapter outlines the properties of guayule rubber purified of resins.

Nonrubber Constituents

Because guayule rubber is extracted from the whole shrub including the roots, dirt and rocks are potential contaminants; so too are cork and bagasse. In the Mexican process for solution-phase purification (see Chapter 6) these are largely removed. Although the ash content recorded in Table 2 is higher than allowed in the best grades of hevea rubber, it is not excessive.

There are, however, some beneficial nonrubber constituents in hevea rubber that are not present in guayule rubber. These include small amounts of nitrogen-containing materials, notably proteins, amino acids and polypeptides, which accelerate vulcanization and save time for the rubber processor. These are also absent in synthetic polyisoprene elastomers and it seems probable that, as in the case of synthetic polyisoprenes, compounds can be added to guayule rubber to overcome this lack.

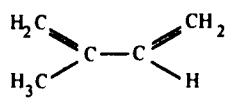
Table 2. Nonrubber constituents in a typical sample of rubber produced by the Mexican government at the Saltillo guayule extraction mill

	Guayule	*Hevea (SMR-5)**
Dirt (percent)	.007	0.05
Nitrogen (percent)	0.16	0.7
Ash (percent)	0.79	0.5
Copper (ppm)	trace	8
Manganese (ppm)	0	10
Volatile matter (mainly moisture)	1.0	1.0

*Allowable maximum figures

Chemical Structure

Like hevea rubber, guayule rubber is a polymer of the simple 5-carbon molecule, isoprene (1). The isoprene units are joined together end to end to form a giant molecule containing tens of thousands of carbon atoms in a



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linear chain identical to that of hevea rubber and with similar molecular weight (Figures 21 and 22). As a result, guayule rubber has the same stretch, bounce, and general properties as hevea rubber.

Today, the technical requirements of rubber products have become extremely precise. If a few percent of the isoprene units differ from the rest in their geometry, then the rubber can be inadequate for use in tires and other products used under severe conditions. The geometry and attachment of the isoprene units within a molecule are termed the molecule's microstructure.

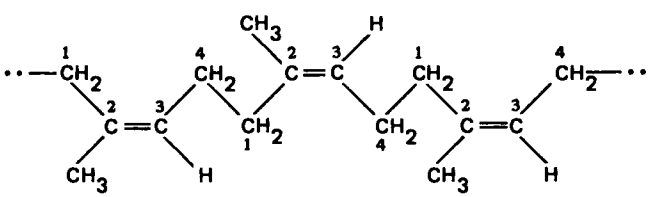


Figure 21. Guayule rubber consists of thousands of isoprene units joined end to end (i.e., carbon atom 4 of each is connected to carbon atom 1 of the next). In both guayule rubber and hevea rubber all the double bonds have *cis*-stereochemistry (the carbon chain at each end, i.e., at carbon atom 2 and carbon atom 3, is connected to the same side of the double bond).

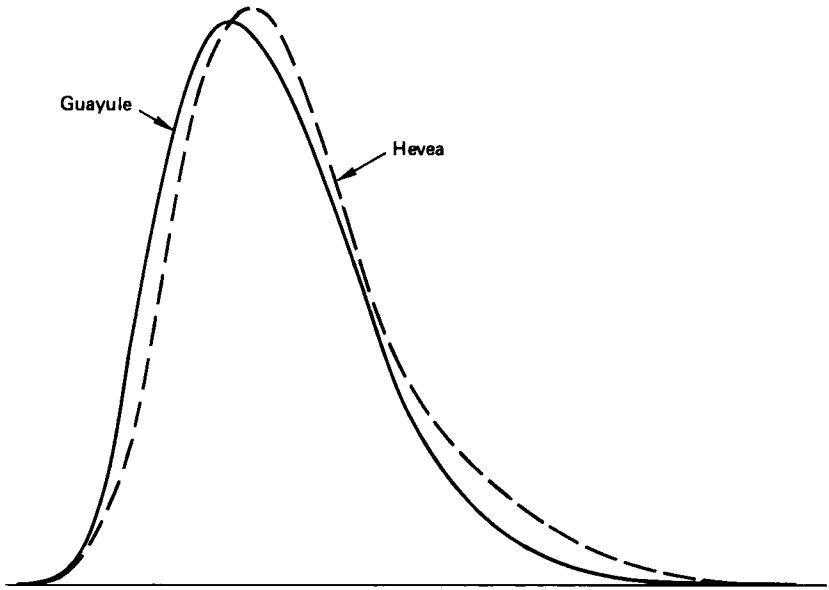
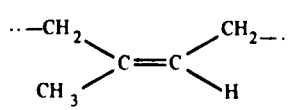


Figure 22. The distribution of the molecular weights of the polyisoprene chains in guayule rubber is similar to that in hevea rubber. Gel permeation chromatograms of guayule stem rubber and hevea latex rubber were run in tetrahydrofuran (40°C) using Styragel columns measuring 10^7, 10^6, 10^5, and 10^4 Å. (Redrawn from a paper by E. Campos-López and J. L. Angulo-Sánchez. See Selected Readings page 70.)

In collecting data for use in this report, several modern techniques for determining small inhomogeneities in microstructure have been applied to guayule. Nuclear magnetic resonance spectroscopy (proton NMR at 60 MHz and 300 MHz, and Carbon-13 NMR at 25 MHz) have shown that the microstructures of guayule rubber and of hevea rubber are identical. The instruments could have detected differences if only a few tenths of a percent of the isoprene units were different in the two rubbers.

Within the limits of detection of the sensitive nuclear magnetic resonance measurements, every isoprene unit in guayule rubber is attached at its ends and every double bond has *cis* stereochemistry (Figures 23 and 24). They all have the *cis*-1,4 shape and attachment shown in (2). No other type of isoprene structure, (such as *trans*-1,4 or 1,2 or 3,4 bonded isoprenes)



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is present. This contrasts with synthetic polyisoprenes, which may contain from 1 to 8 percent of isoprene units that are not *cis*-1,4. Although this difference appears small, it affects certain performance characteristics (e.g. hot tear strength) out of all proportion, since ability to crystallize rapidly on elongation is destroyed by these inhomogeneities. The precise stereochemistry of isoprene rubbers is becoming an increasing concern in modern uses such as radial tires.

The identity of structure between hevea and purified guayule rubbers is confirmed by infrared and x-ray measurements as well as by differential thermal analysis (DTA). Both rubbers show a sharp break corresponding to the glass transition at exactly the same temperature. Furthermore, if each rubber is first chilled (2 days at -20°C), a high degree of crystallinity

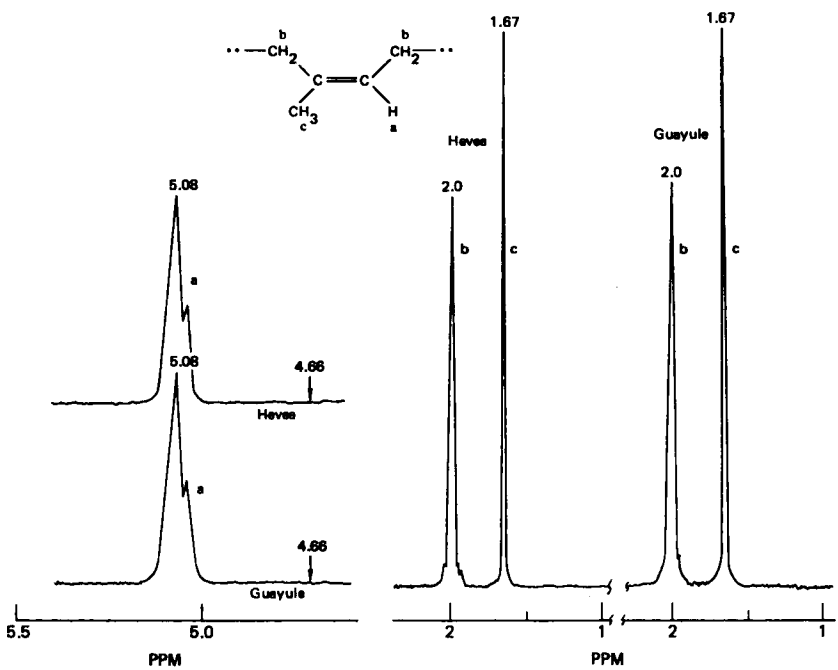

Figure 23. Both guayule and hevea rubbers show identical proton magnetic resonance spectra, even when measured on a 300-MHz spectometer, one of the most sensitive tools for structural elucidation. The spectra show a complete absence of peaks attributable to stereo or structural isomers, demonstrating that guayule rubber is a highly stereoregular polymer composed entirely of *cis*-1,4 isoprene units. (Spectra run at 300 MHz, in carbon tetrachloride solution, measured in ppm vs TMS.) (E. Campos-López and J. Palacios)

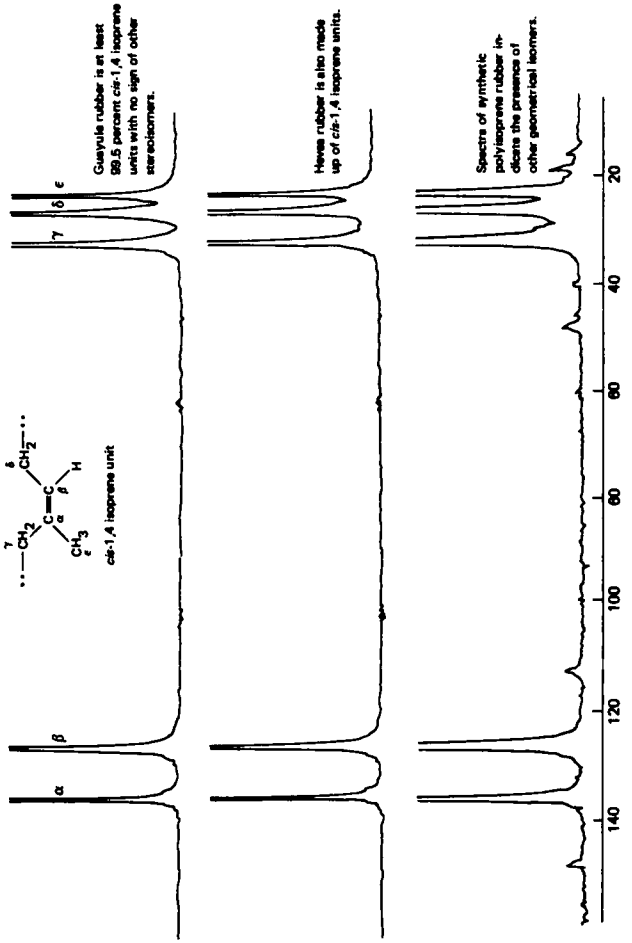

Figure 24. Carbon-13 nuclear magnetic resonance spectra confirm the structural and geometrical purity of guayule rubber, and that guayule and hevea rubbers are, to the limits of detection (0.5 percent), identical. (Solid samples measured in D_2O, at 25 MHz, each spectrum, measured in ppm vs TMS, 4000 scans. The synthetic rubber is Li-Pi-50.) (F. A. Bovey and E. R. Santee Jr.)

becomes apparent in the DTA plots. This only occurs when the microstructure is highly uniform. The hevea and guayule rubbers perform similarly in this very sensitive measurement (see Figure 25), providing strong confirmation that the two have the same structure.

The amount of branching and cross-linking between guayule rubber molecules has not been defined quantitatively, though the ease with which

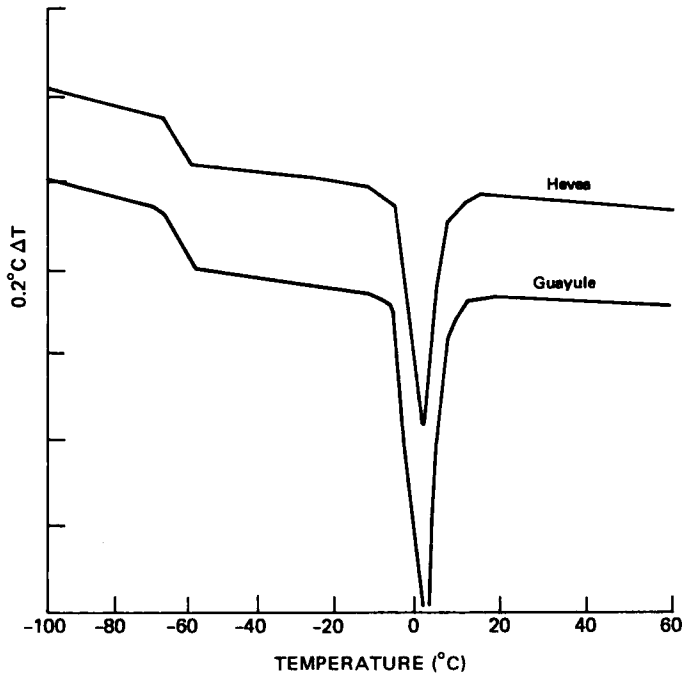

Figure 25. Crystallization of hevea rubber (pale crepe) and of guayule. This sensitive test can identify molecular differences between the two rubbers. Because there are no meaningful differences in curve shape or in melting point, this test shows that both rubbers have identical microstructure. Both show an identical glass transition, between -60° and 70°C. (Measurements courtesy of R. M. Pierson and J. Lal)

the rubber dissolves in solvent suggests that it is low. Guayule does not appear to be a highly cross-linked species. Little gel is produced during formation of rubber in the plant and little forms after extraction. In fact, the Mexican pilot plant relies on dissolving the rubber in aliphatic solvent as a step in the purification process.*

Mechanical Properties

A summary of the mechanical properties of guayule rubber that shows the similarity to the properties of hevea rubber is given in Table 3.

*Panel member E. Campos-López reports that the gel content (a measure of branching and cross-linking) is never more than 4 percent (measured in cyclohexane), and that it does not increase upon standing.

Table 3. Properties of Raw Guayule Rubber

	*Guayule**	*Hevea (SMR-5)*
Mooney Viscosity (ML-1+4 at 212°F/[100°C]	105	85
Antioxidant (percent BHT)	0.6	
Acetone solubles (percent)	2	2.8
Wallace Rapid Plasticity (Po)	47.5	
Plasticity Retention Index (percent)	41	60
Tack†		
Rubber to rubber (psi)	9.5	8.5
Rubber to metal (psi)	4.25	5.0
Rubber-black masterbatch (psi)	8.25	11.5
Rubber-black masterbatch to metal (psi)	5.25	4.0
Green Strength (psi at 100 percent elongation)	20±0.05	20±0.05

*These figures are based on early samples from the pilot plant at Saltillo, Mexico. They are likely to change as the extraction and purification methods are refined.
†Determined using a Monsanto Tel-Tak apparatus. Table courtesy of H. L. Stephens.

The Mooney viscosity, which tests the "plasticity" of a rubber, has been measured at 95-105 in modern guayule samples. This is in the same range as hevea rubber's plasticity and means that guayule rubber should not exceed hevea rubber in the amount of softening needed during milling. But guayule rubber, like hevea rubber, will probably be more difficult to process than synthetic isoprene-type rubbers.

The plasticity-retention index is an indication of a rubber's resistance to aging or breakdown. Although the guayule sample tested fell short of the standards of the highest quality hevea rubber (i.e.,SMR-5 where PRI is about 60),it is in the range of the hevea rubber used in tires (SMR 20, whose PRI is about 40).

"Green strength" measures the strength of the raw rubber during processing. Without good green strength, a tire hung on a hook during manufacture will sag out of shape before it is vulcanized. Indeed, a primary reason why synthetic polyisoprenes are not more widely used is because their green strengths are inferior to that of hevea rubber. Imperfections in the microstructure are believed to be a major factor contributing to reduction in the green strength of a polyisoprene rubber. However, as can be seen in Table 3, guayule rubber's green strength is equivalent to that of hevea rubber.*

*The similarity of microstructure is expected to result in similar green strengths between the two rubbers. But comprehensive analyses (done as this report went to press) suggest that guayule's green strength is intermediate between that of synthetic polyisoprene and hevea rubber. If this proves to be a true feature of guayule rubber (and not just that of early samples from a new pilot facility) it might limit the percentage of guayule that would be added to the blend of rubbers used for tire making by large manufacturers. Green strength is important only during fabrication (i.e., before vulcanization): It does not affect the quality of the final manufactured product, and it is important only in large factories that use sophisticated automated methods.

"Building tack" measures how well the layers of raw rubber stick together before they are vulcanized. It is a very important property in the fabrication of certain types of tires. Synthetic elastomers have less building tack than hevea. Both hevea and guayule rubber have good building tack and do not require the addition of ingredients to increase tack. The excellent flow and tack characteristics of guayule rubber should make it suitable for the manufacture of radial tires and large tires.

Processing Characteristics

Because of its structural similarity to hevea rubber, no difficulties are expected in processing guayule rubber with standard equipment. For example, it softens readily (see Figure 26) and is expected to extrude readily and flow properly in molds. Guayule rubber differs slightly from hevea rubber in the ratio of chemicals needed to compound it for adequate cure rates. This is due to the slightly different nonrubber impurities expected in commercial products. Both contain small amounts of moisture, dirt, terpenes, and triglycerides, but guayule lacks the protein "impurity" that is beneficial to the curing properties of hevea rubber.

Comparative data on vulcanizates of guayule and hevea rubber are given in Table 4. A standard formulation developed for comparing hevea rubbers was

Table 4. Properties of vulcanized guayule rubber*

	Hevea (SMR-5)	*Guayule*
Initial Viscosity (lbs.-in.)	5.5	5.0
Minimum Viscosity (lbs.-in.)	4.0	3.7
Maximum Viscosity (lbs.-in.)	35.0	25.0
T_ss, min.	7.0	10.5
T_c, (90), min.	19.0	25.0
Cure Rate (lbs.-in./min)	5.3	2.5
Cure time at 284°F (140°C), min.	19	25
Modulus at 300 percent (psi)	1,770	1,050
Modulus at 500 percent (psi)	–	2,455
Tensile Strength (psi)	4,050	3,645
Elongation (percent)	490	635
Set at Break (percent)	13	14
Bashore Rebound (percent)	48	40
Shore A Hardness	60	54
Swelling Index (g. benzene imbibed/g. rubber)	2.94	3.44
M_c	9,500	13,000
Tear Strength (ppi)	436	178

*Vulcanized using recipe 2A given in ASTM D 3184-71. The vulcanization characteristics of each stock were determined on a Monsanto Rheometer at 284° F (140°C) using ASTM D 2084-71T. Measurements courtesy of H. L. Stephens.

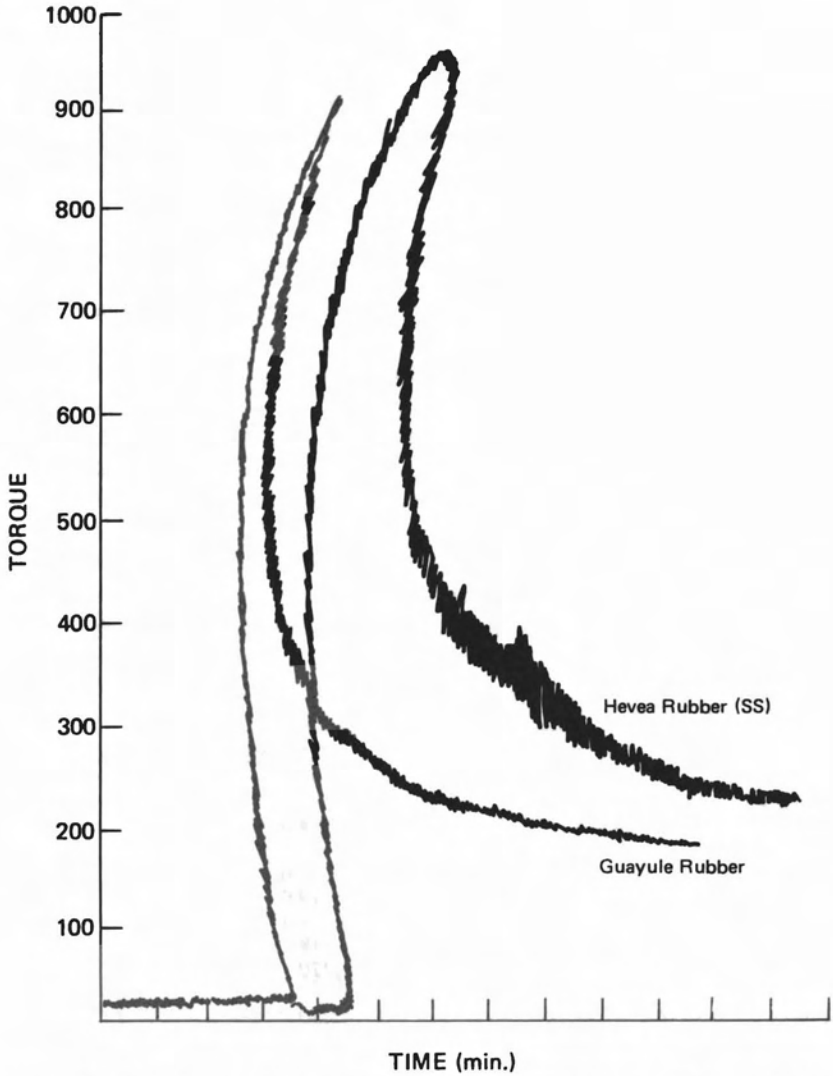

Figure 26. Preliminary analyses suggest that guayule rubber develops little cross-linking between molecules. As a result, processing guayule rubber appears to require less energy than hevea rubber. To soften the rubber by breaking up cross-links in a Brabender mill requires the same torque, but guayule rubber softens in much less time . . . .

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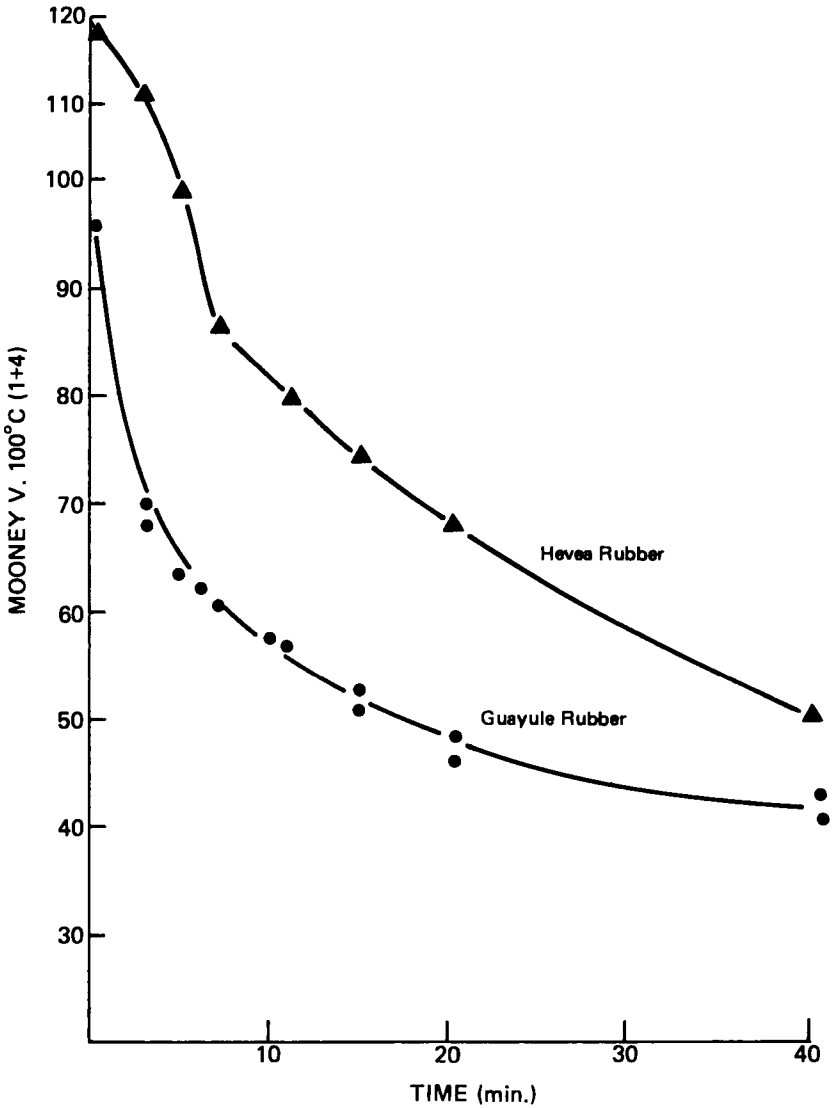

. . . The relative ease of processing guayule rubber is also apparent when masticating the two rubbers in an open mill. Guayule rubber seems to soften more rapidly. The results are further confirmed by molecular weight measurements that show more rapid decreases in guayule than in hevea rubber. (Data reported by Campos-López, E., Ponce V., Neavez and Canales. 1976. See Selected Readings.)

used. The results show that guayule's lack of vulcanization accelerators cause it to vulcanize more slowly than hevea rubber. By adding accelerators to the formulation this can undoubtedly be overcome.

Figure 27. This—the first successful truck tire ever built of guayule rubber—was made from rubber grown and processed by the U.S. Natural Rubber Research Station, Salinas, California. Carcass construction is 100 percent guayule rubber with tread made of synthetic rubber. Road tests, in which the tire was run continuously at 45 mph with approximately 40 percent overload, were made by the Office of Rubber Reserve, Camp Bullis, Texas. Guayule proved to be the equal of hevea rubber in these tests. This tire, one of a test lot, was fabricated in 1953 by the Firestone Tire and Rubber Company, Akron, Ohio. (U.S. Department of Agriculture)

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Performance

Almost nothing is known of guayule rubber's performance under full operating conditions. Virtually all the 120,000 tons of resinous rubber, purchased by rubber companies between 1903 and 1946, were blended with hevea rubber and may have been used as much for its tackiness as for its rubber.

While the federal guayule project was winding down in the early 1950s, several tons of deresinated guayule rubber were distributed to industry for performance testing. The results were erratic (not always attributable to the rubber) but in a federally supervised test, Firestone Tire and Rubber Company placed one guayule tire and one hevea tire on the back wheels of three gravel-laden trucks. To ensure equal wear, the tires were switched regularly. The guayule tires performed as well as the hevea tires. One survived 50,900 miles (82,000 km) without showing a body break (see Figure 27).

If production were resumed and guayule sought a place alongside hevea and the synthetic polyisoprenes in tire manufacture, it is likely to be used—initially at least—in blends with these rubbers and with the more widely used styrene-butadiene synthetic rubbers. Under such circumstances, slight differences from hevea in processing or properties become much less noticeable, a factor that could greatly facilitate commercial introduction of guayule.

8 Economics

Because no guayule has been produced commercially in recent decades, its economics are very uncertain. The available data are largely irrelevant and reflect wartime conditions of 30 years ago. They are based on obsolete production methods, on a low-quality resinous rubber, and do not take into account the potential sale of by-products. Nonetheless, some general conclusions can be drawn.

General Rubber Market

In a recent analysis* the World Bank projects that until the end of this decade the worldwide demand for rubber—both natural and synthetic—will grow at the rate of 5 percent per year. Furthermore, natural rubber is expected to retain its present share (30 percent) of the total rubber market.

In the past, growers have been able to increase production of hevea rubber to match increases in demand. During the 1960s, hevea rubber production increased at a rate of 3.9 percent per year. Because of recent breakthroughs that raise the yield per tree, the rate is expected to rise to 5.7 percent annually for the rest of this decade. However, yields cannot be increased indefinitely, and between 1980 and 1985 the world's supply of hevea rubber is expected to increase annually by only 3.8 percent. This is a serious concern, because during these years the world's rubber requirements are projected to grow annually by 5.9 percent. Thus, the World Bank concludes that after 1980 hevea rubber cannot retain the share of the market that it now has. Not enough will be produced and a shortfall will result. The probability of such a shortfall has also been reported by the Malaysian Rubber Bureau (see Figure 28).†

Worldwide recession depressed prices for the different grades of hevea rubber by 23 percent in 1975. But the World Bank expects prices "to increase (in current US dollars terms) to about 60 US¢ per lb. [$1.32 per kg] in 1980

*World Bank. June 1976. *Price Prospects for Major Primary Commodities*. Report No 814/76, Commodities and Export Projections Division, Annex II pages 1-10.
†Allen, Thomas and Sekhar. See Selected Readings.

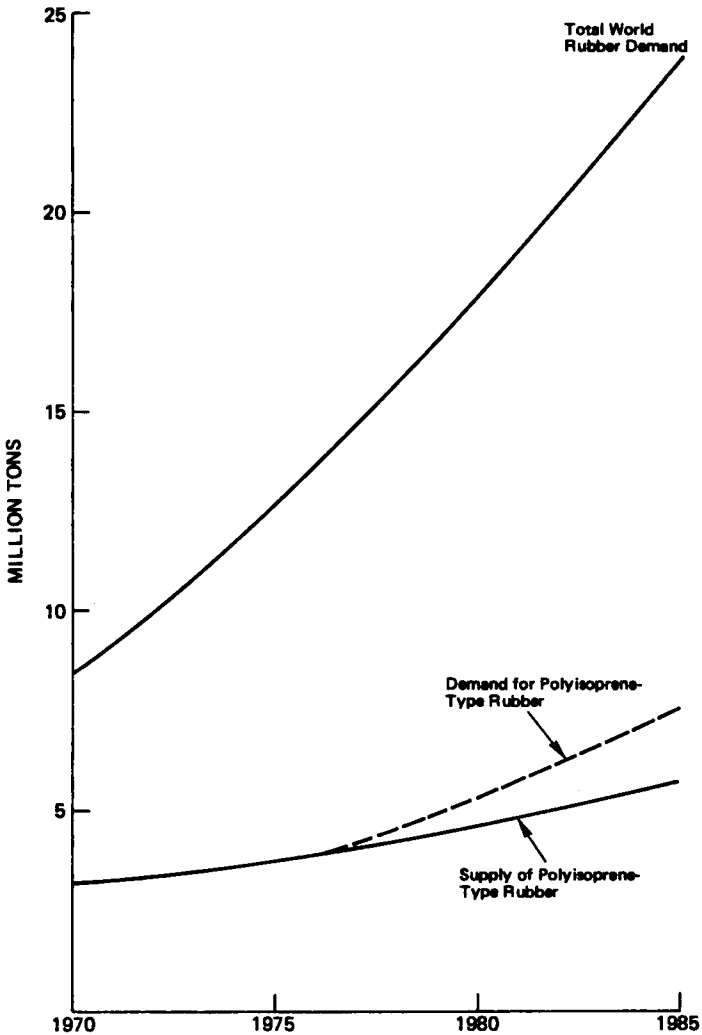

Figure 28. The shortfall in rubber production projected for the 1980s if present growth rates continue. Based on model calculations by the Malaysian Rubber Research and Development Board, which predicts that the world's requirements for all types of rubber will increase annually by 7 percent and that polyisoprene-type rubber will constitute 30 percent of all the rubber required. The supply of polyisoprene-type rubber is projected to increase at only 4 percent annually. (Taken from Allen, Thomas and Sekhar. See Selected Readings.)

and 78 US¢ per lb [$1.72 per kg] in 1985." The current price is 39 US¢ per lb (86¢ per kg).

The projected shortfall of hevea rubber and the large price increases expected during the 1980s provide economic incentive for urgent action to develop guayule once more into a commercial crop.

Synthetic Elastomers

Synthetic rubbers derive from the petrochemical industry. All but one—polyisoprene—have structure and properties different from natural rubber. Because of this, they are not always interchangeable with natural rubber in the major rubber products such as tires and industrial conveyor belts, where small differences in properties can be important.

With the petrochemical industry's rapid expansion in recent decades, synthetic rubber producers were able to increase their supplies rapidly. This was made possible by the seemingly unlimited supplies of petroleum—an assumption that has been shattered by the recent "energy crisis."

Petroleum's ready availability during the 1960s led to a drastic lowering of the prices of monomers (the "building blocks" from which synthetic rubbers are constructed), which was reflected in a sharp decline in synthetic rubber prices. Today the petroleum situation is much different, and it seems likely that petroleum prices will continue to rise in the future, increasing monomer prices and raising synthetic rubber prices.

Man-made polyisoprene and hevea rubber can be interchanged for some purposes. However, in the United States, it is produced by only two facilities whose annual production is only about 10 percent of the amount of hevea rubber imported each year. Isoprene is expensive and, with petroleum prices increasing, its price will rise.* These "synthetic natural rubbers" have been 3-4¢ per lb (7- 9¢ per kg) more expensive than hevea rubber—a premium that was paid by industry because they were more uniform and more easily masticated (the "softening up" that is usually the first step in the manufacture of rubber goods).

*It is possible that synthetic polyisoprene use could grow substantially in the future. Synthetic polyisoprene has been slow growing due to the high cost of isoprene monomer, which is manufactured from petroleum derivatives. Historically, the U.S. petrochemical industry has cracked natural gas or light feedstocks in order to obtain raw materials. New plants being designed, or under construction, will use naphtha or gas oil as a feedstock; the cracking of naphtha or gas oil yields isoprene as a by-product and the cost of by-product isoprene could be much less than the currently deliberately manufactured isoprene.

Tire Rubber

Seventy percent of the hevea rubber imported by the United States is used to manufacture tires; the remainder is used in latex products, in industrial conveyor belts and hoses, and in footwear (Table 5). The elasticity, resilience, tackiness, and low heat buildup that characterize the polyisoprene structure in hevea rubber are important in tire carcasses. Because of this, hevea rubber has retained a strong market in face of competition from the synthetic elastomers that are not polyisoprenes.

The market strength of polyisoprene rubbers is due to these technical qualities. Because the differences in quality derive from fundamental structural differences between polyisoprenes and the other polymers it seems unlikely that some technical improvement will change the competitive position of polyisoprene rubbers, at least in the near future.

The larger the tire, the higher the proportion of natural rubber it normally contains. Aircraft tires are made almost entirely of natural rubber; truck and bus tires contain at least 40 percent; automobile tires—which absorb the bulk of the natural rubber produced—contain about 20 percent. Radial tires, which are taking an increasingly large fraction of the automobile tire market (see Figure 29), require almost twice as much natural rubber as the older tire designs.

It seems likely that, in the United States at least, higher petroleum costs will increase the number of small, light cars and decrease the tire market's growth. However, the growing use of radial tires should produce additional demand for natural rubber, even though they are long-wearing. In other

Table 5. Estimated natural rubber consumption in the United States, 1973 (1,000 Long Tons)

Product	*Consumption*	*Percent*
Passenger car tires	192	26.6
Truck/bus tires	310	42.9
Other tires	50	7.0
Total for tires	552	76.5
Footwear	15	2.1
Hose and belting	30	4.2
Other fabricated goods	85	11.8
Other products	40	5.4
TOTAL	722	100.0

Information courtesy of D. H. Blank.

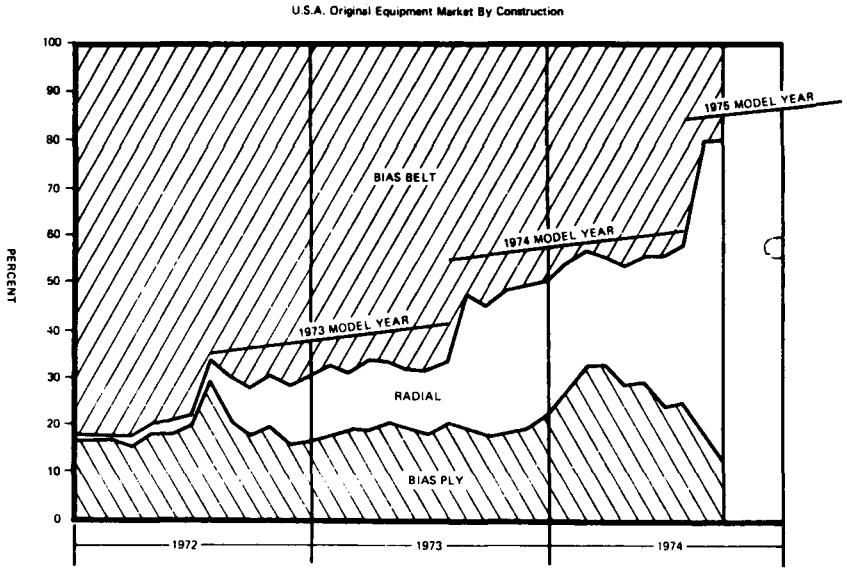

Figure 29. The radial tire is increasing in popularity. The figure illustrates their increasing demand by American automobile manufacturers. This is creating a corresponding increase in the use of natural rubber because radial tires contain about twice the amount that a bias ply or bias belted tire contains. (Goodyear Tire and Rubber Company)

countries a greater rate of increase in the numbers of motor vehicles should create relatively greater increases in natural rubber consumption than in the United States (see Figure 30).

Wild Stands of Guayule

The Government of Mexico has recently surveyed its wild guayule and charted over 10 million acres (4 million ha) of accessible, dense stands of native bushes suitable for commercial harvest. Averaging 10-17 percent per bush, it is estimated that these stands contain a living stockpile of 300,000 tons of guayule rubber. It has been judged economic to exploit this commercially, especially because the region is arid and largely unproductive; guayule promises jobs and income for many poverty-stricken peasants.

In the United States, native guayule stands are too small, and wage rates too high, for wild guayule to be a profitable rubber source. Thus, for the United States—and all countries outside Mexico—it must be developed as a cultivated crop.

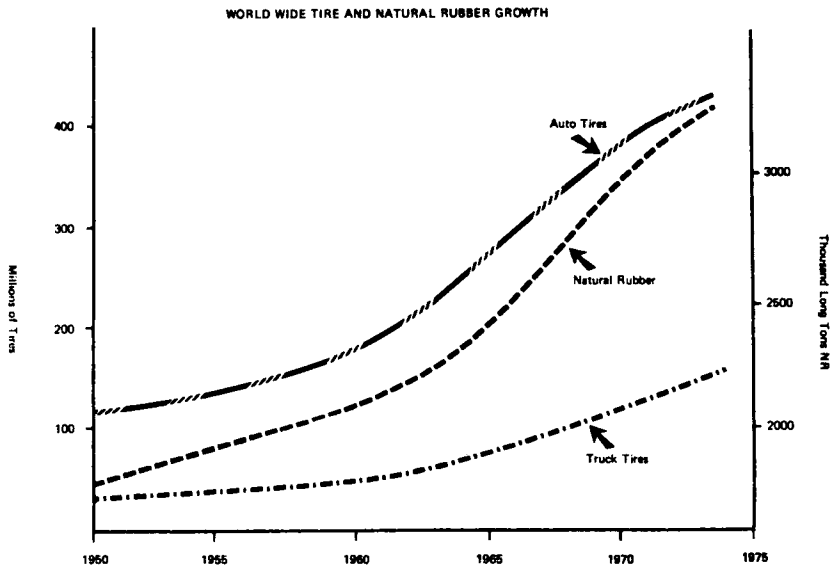

Figure 30. Growth of tire markets vs. natural rubber (NR). (R. M. Pierson)

Cultivated Guayule

Rubber yields have been measured only for a few guayule strains originally selected by W. B. McCallum, a guayule pioneer and chief scientist of the Intercontinental Rubber Company. Virtually all the guayule grown during World War II was based on McCallum's seeds (especially on a strain listed as Number 593). The vast wealth of guayule germ plasm in the wild (see Chapter 4) lies untapped.

The best yields yet reported* for cultivated guayule were from plants directly seeded in irrigated fields at Salinas, California. Two years after planting they yielded 1,200–1,500 lb of rubber per acre (1,300–1,700 kg per ha).

Using the more common method of growing seedlings and transplanting them to the field, rubber yields of 900 lb per acre (1,000 kg per ha) after 2 years were usual during World War II.† Generally, irrigated guayule will accumulate about 500 lb of rubber per acre (560 kg per ha) annually over a 3- to 5-year period. (Guayule plants continue to accumulate smaller amounts

*A. C. Hildreth. 1946. Recent advances in guayule growing. *India Rubber World* 114:55-59.

†Poage, W. R. 1945. Study of Rubber in the United States, Mexico and Haiti. *House Report # 2098, January 1945, 78th Congress, 2nd Session.*

throughout their lifetime, and a single harvest of 27,000 lb per acre [30,000 kg per ha] has been recorded.*)

These yields compare favorably with hevea rubber yields before World War II when, in Southeast Asia, for example, 16-year-old rubber trees produced about 200 lb of rubber per acre (340 kg per ha) annually.†

The Rubber Research Institute of Malaysia has improved *Hevea* yields dramatically since that time, and in 1974 Malaysia's average annual rubber yield was 1,200 lb per acre (1,300 kg per ha). Trials have shown that, by using special techniques, 3,000–6,000 lb per acre per year (3,400–6,700 kg per ha per year) are possible. Guayule has far to go to match these figures.

Production Costs

To compete with hevea rubber prices, guayule production in the United States must be mechanized. Wages in hevea rubber producing areas are about 20–30 cents per hour, while the minimum agricultural wage in the United States is $2.00 per hour. Fortunately, guayule is suitable for mechanized agriculture. *Hevea* on the other hand, is one of the most labor-intensive crops in the world. No method for cropping it mechanically has been devised, and rising labor costs may well affect its profitability in the future. During the ERP period, it was found that the season when labor was needed in California's guayule fields corresponded to the slack season for most farm workers. Thus, guayule helped provide them with year-round employment.

The United States contains huge areas of land that appear suited to guayule cultivation. It has been estimated that, in theory, there is ample land in Texas and the Southwest to grow enough guayule to fill the nation's annual rubber needs.

Although costs for producing guayule rubber today are uncertain, it would appear that no exceptional costs are involved for planting, cultivating, and harvesting the crop. Indeed, the costs are likely to be much like those of the same operations on other crop plants. The uncertainties lie mainly in the milling costs. The costs of milling in the 1940s are irrelevant today, but the Mexican government's pilot-sized mill should soon give a better idea of modern costs. Although the new mill simplifies several of the previously used steps, it does require solvent to deresinate the rubber and solvent will be lost in each

*The highest production rate ever recorded was a small experimental plot that produced over 100 lb of rubber per acre per month (over 100 kg per ha per month) during the second year of growth.

†Van Iterson, G. 1936, 37. *Hevea brasiliensis* as a producer of rubber. *Indian Rubber Journal*. 92:869-73 and 93:23-30, 60-65.

step. Moreover, the water needed in the flotation method used to separate rubber from pulped shrub may prove costly in arid areas.

An advantage of guayule is that it can be left in the ground without losing its rubber. The plant can be viewed as a living and growing stockpile, which, once established, requires little or no management or care and provides an economic "cushion." For example, the Intercontinental Rubber Company sold no rubber from 1931 to 1933 when rubber prices were disastrously low. They allowed the "stockpile" to grow and used it only when prices rebounded.

For the same reason, guayule may be an excellent crop for marginal semiarid regions on the fringes of conventional agriculture. It is a hardy plant and will survive drought for several years. Although it may not grow as vigorously, no rubber will be lost. It therefore offers a security that other crops cannot.

The ability to survive and accumulate rubber without maintenance may make guayule an excellent crop for stopping soil erosion, and even for grazing—both of which are important for increasing the productivity of semiarid wasteland. In arid regions with 8–14 in. (200–350 mm) annual rainfall, the conventional measures of yield per acre per year may be irrelevant. A guayule crop each 7 years may be preferable to no crop at all. This is the essence of the Mexican program, in which each wild stand will be harvested on a 7-year rotation and left to reseed itself between harvests.

By-Products

Guayule's by-products have never been capitalized on commercially. Indeed their composition and qualities are little known. Yet some seem to promise new importance. The wax from guayule leaves has a remarkable hardness and a melting point even higher than carnauba wax (generally acknowledged to be the best wax available). It is produced in large quantities by the leaves, appears easily extracted, and has a clear, white color that carnauba cannot match. With some grades of carnauba wax selling at over $2.00 per lb, guayule wax could become a financial asset to the processor.

Similarly, the mill's bagasse and cork appear to have commercial significance, though final analyses of their value for paper, cardboard, or construction materials are not yet complete.

The resins too may have commercial value. Although their structure is not known with certainty, they do contain some of the same terpenes produced by pine trees. Pine stump diterpene acids—often in short supply—are used for sizing in the paper industry, and volatile terpenes are the important ingredients in turpentine, a solvent widely used in the paint industry.

9 Research Needs

Wartime needs forced the Emergency Rubber Project to begin large-scale guayule rubber production without waiting for research, but today we have time to be more rational. We have powerful tools for investigating the genetics, physiology, and biochemistry of plants, which can provide the basic knowledge for developing guayule into a commercial source of rubber.

Genetics

Many aspects of guayule production are, at least in part, genetically controlled. In a given plant, genetics controls rubber content, rate and size of growth, resin content, disease resistance, ease of defoliation, ability to compete with weeds, and cold and drought tolerance. These are amenable to improvement, and guayule's unique bimodal reproduction (see Chapter 5) simplifies plant breeders' tasks and assures a more rapid rate of success than with other plants. Nonetheless, domesticating a wild plant involves the consideration of many characteristics, and long, patient manipulation will be needed to mold guayule into an optimized, scientifically engineered crop plant.

Plant breeding is the main key to unlocking guayule's potential; it is urgent to get guayule breeding studies under way because 2–4 years are required before a breeder can tell how good a rubber producer his "new" plant is. Many populations of wild plants seem to contain the required genetic diversity. The difficulty, if anything, is that the plants are too diverse, too scattered, and too numerous. A simple, rapid method for screening plants for rubber content would be extremely valuable. If portable, the breeder could use it to comb wild stands for desirable strains instead of growing thousands of seeds in a blind groping for desirable types. To measure rubber content is not easy—the microscopic rubber cells are hidden within the bark. But if analytical chemists can devise an instrument for determination of rubber content in the field* it would be a boon for selecting guayule shrubs with the

*Preferably by rapid microanalytical methods (such as pulsed NMR or density measurement) that does not involve extracting rubber.

highest rubber content. Their seeds would then become the genetic stocks from which to develop guayule plantations. Even a nonportable instrument for precise, rapid, rubber-content determination would be a major advance. Such instruments could also be invaluable in breeding studies by allowing geneticists to determine the best rubber-producing strains without having to wait years for the plant to mature.

Guayule breeding has scarcely begun; a small postwar breeding program indicated that yields could be expected at least to double those of the standard strain (Number 593) used during the war. Some researchers predict that the yield of strain 593 can be quadrupled. Such improvements could come from strains with a high proportion of rubber, strains that develop their rubber more rapidly, and strains that produce bigger plants. Research on hybridizing guayule with larger *Parthenium* species was very promising when all guayule research was abandoned in 1953. Some of the hybrids are 7 times guayule's size (see Figure 31) and some contain rubber (quantity yet unknown).

It is highly probable that plant breeders could select strains for increased cold tolerance (which could extend guayule cultivation into more temperate regions), for dry-land agriculture, and for other geographical conditions. Furthermore, strains could be selected for specific rubber qualities (for molecular weight or for zero gel-content, for example). The possibilities are clearly enormous.

Physiology

New research tools (phytotrons, radiotracers, gas chromatography, etc.) give immense assistance to the investigation of the peculiar physiology of guayule, enabling us now to learn the biochemical mechanisms that produce rubber. The factors that affect rubber yield and rubber quality (such as cold, moisture, temperature, dormancy, day length, fertilizer, age) can also be determined. Recognition of these factors will benefit guayule production, because at the moment the cultivation requirements are known imprecisely and are based largely on empirical observation.

Plant-growth regulators (such as 2,4,5-trichlorophenoxy acetic acid and 2-chloroethyl phosphonic acid) have revolutionized hevea rubber production. These and others may also benefit guayule, but possibly in different ways; for example, by defoliating the shrubs or by stimulating unstressed plants to produce rubber.

Figure 31. Guayule can be grafted to, or hybridized with, other *Parthenium* species. For example, guayule (left) can be hybridized with *Parthenium stramonium* (right). Some of the resulting hybrids contain rubber, are much larger than guayule, and may perhaps greatly improve rubber yields in the future. (U.S. Department of Agriculture)

Dry-land Agriculture

The ERP grew guayule almost entirely under irrigation. Although some shrubs were grown without irrigation near Riverside and Salinas, California, the experience has not been analyzed in the published literature. Also, some were grown, unirrigated, at Manzanar Relocation Center in the Owens Valley of California. In both these areas, rains are prevalent during winter months,

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rather than—as occurs in guayule's native habitat—during the summer, which is the normal growing season.

These experiences demonstrate that guayule can be produced as a dry-land crop in a Mediterranean-type climate, but the information is too fragmentary to determine its economics. Tests should be undertaken to determine the rubber yields obtainable from guayule grown nonirrigated in arid regions with annual rainfall less than 15 in. (380 mm).

The amount and distribution of rainfall during the year will influence the establishment, growth, and rubber accumulation. The climatic conditions under which dry-land production can compete with irrigated production should be determined, as should the plant density and cultural techniques needed to farm guayule as a desert crop. Tests should be carried out to determine its value as an intercrop grown together with food crops.

General Agronomy

Research should be initiated to shorten guayule's production cycle. With agronomic and genetic research, the optimum yields can probably be achieved in as little as 2 years, at least under intensive, irrigated agriculture.

But agronomic research is also needed on:

- Soil characteristics (physical and chemical) that maximize rubber yield;
- Weed control; and
- Insect and disease control.

Guayule is usually propagated by seedlings, although there have been some successes (and some failures) with planting seeds directly into the field. Research is needed to determine whether direct seeding (perhaps using modern techniques such as pelleting and precision planting in seed tapes) can be routinely accomplished and if it has advantages over planting nursery-grown seedlings.*

Harvesting

Research could make guayule harvesting more efficient than the methods previously used. Bulk handling is one research avenue. Another is pollarding,

*Nonetheless, it is probable that to establish guayule in marginal farmland nursery production will always prove necessary.

harvesting only the tops of the plants while leaving the roots to resprout. A third is defoliation of the plants while still in the field (sheep and goats have been suggested, but hormones may prove more useful).

Processing

The rubber-extraction process described in Chapter 6 is now operating satisfactorily in pilot-plant stage. However, alternative approaches still deserve testing; they may prove simpler and cheaper, or they may produce a better product. Among the alternatives worth testing are the following:

- Extracting latex from the shrub without coagulating it to rubber.
- Removing the resins from the shrubs before the rubber is removed. (This method may have advantages because during milling some rubber may be degrading while it is in contact with the resins.)
- Retting the shrubs before extracting the rubber. (Guayule retting is a spontaneous microbial process in which molds and bacteria are allowed to grow on the moistened shrubs. They selectively decompose the most deleterious resins, and thus produce rubber with improved physical properties. It is a simple, cheap process and, though not relevant for large-scale guayule processing, may prove suitable for small-scale rubber extraction in rural areas.)

Other research is needed to optimize each stage in the existing extraction method. Although much of this will be done at the Mexican pilot facility, research is needed to test different pulping mills, various deresination solvents, new extraction procedures, and methods other than parboiling for coagulating the rubber and defoliating the bushes.

By-Products

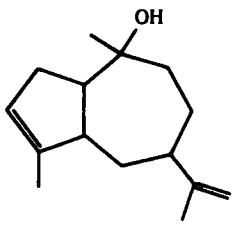
One of the most pressing research needs is to analyze guayule's by-products. Perhaps more than any other factor, their commercial utilization could affect the economics of guayule rubber production. Each ton of rubber extracted produces about 2 tons of wood fiber (bagasse), half a ton of resins, and about one ton of leaves. These by-products appear to have commercial potential.

In the Mexican pilot plant, guayule shrubs are comminuted in a mill that was designed to produce pulp for paper manufacture. The resulting bagasse has not yet been tested for use in paper, cardboard, or pressed-board, but it

seems to have promise at least for lower-quality uses. Returns from its sale could significantly lower the overall rubber-extraction costs.

So, too, could sale of resins, which contain volatile and nonvolatile terpenoids, a high melting wax, a shellac-like gum, drying oils, and cinnamic acid. (The chemical analysis reported by the U.S. Natural Rubber Research Station in 1953 is given in Figure 32.) Research is also needed to devise commercially feasible techniques for separating the resins into their saleable products. It is conceivable that the resins could prove more valuable than the rubber.

A volatile oil with a distinctive lingering, spicy odor can be separated from the resins and leaves (by steam distillation). The oil contains mono- and sesquiterpenes (including α and β pinene, limonene, cadinene, and partheniols 3 and 4*), and may be valuable to industry.



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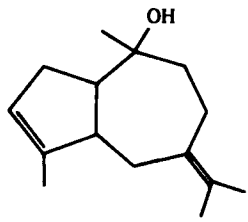

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Guayule leaves also contain 2.5 percent of their weight (dry matter basis) as a cuticle wax, which could become a useful commodity. It is a hard wax with one of the highest melting points (169°F, 76°C) ever recorded for a natural wax. This is particularly important today because hard waxes are in universal demand. Analysis of the wax and research on its extraction could lead to yet another valuable guayule by-product.

Because guayule plants take several years to reach harvesting age, it is important to test possible uses *while they are in the field*. One avenue worth research is to test guayule as an oilseed crop. It produces many seeds and seed-collecting and seed-processing equipment was designed during the 1940s; but the seed was used for propagation, and its composition has not yet been determined. Undoubtedly, guayule seed contains oil and protein, but its concentrations, chemical makeup, and potential use as human and animal food are unknown.

Animal feed is scarce in the semiarid regions where guayule grows wild and thus, even with their resins and wax, guayule leaves are grazed by sheep, goats, and rabbits. Palatability and nutritional studies are needed to see if

*Hendrickson and Rees. 1962. See Selected Readings.

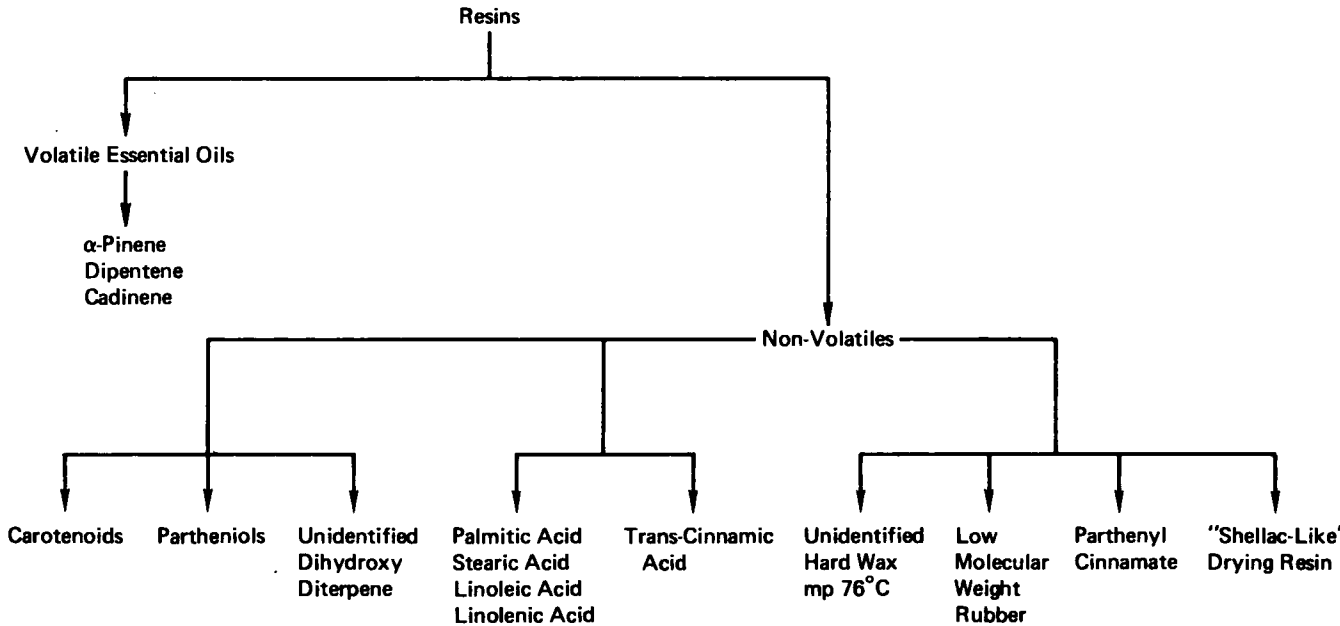

Figure 32. Components of guayule resins.

guayule could be a supplemental browse shrub. The growing shrub also has potential for windbreaks, controlling soil erosion, and landscaping, all of which are concerns in semiarid regions; research on these uses is encouraged. Guayule might also prove useful as an intercrop grown together with food crops.

Product Development

If guayule is to become a commercial crop, research must answer the following questions:

- How well do the "best" grades of guayule rubber compare with those of hevea rubber?
- What levels of unextracted resin and other impurities are permissible in guayule rubber for the most demanding uses—e.g., truck tires?
- How pure and uniform can guayule rubber be made economically?

Since uniform properties are particularly important, a major research goal should be to develop a standard guayule rubber, a product of known properties. To do this, standards will have to be set, and all stages in the milling controlled and standardized to assure a uniform product.

Research should also aim at producing guayule-crumb, a product similar to hevea-crumb, with dry, free-flowing rubber particles that can be bulk handled.

More extensive study of the mechanical properties of both raw guayule and its vulcanizates are needed. Initially they should use the purest material available, but tolerable levels of impurities should also be determined. Particularly needed are more extensive measurements of rates of crystallization, especially upon elongation and at elevated temperatures (194°–212°F, 90°–100°C).

Compounding is an area demanding research. Tests are needed of different formulations, fillers, reinforcements, softeners (including the use of guayule resins themselves), phenolic resins for high temperature curing, etc.

More work is needed to determine guayule rubber's sensitivity to ozone, oxygen, nitrogen oxides, sulfur oxides, and oils, as well as to humidity, sunlight, cold, and other climatic conditions.

Testing guayule rubber's compatibility in blends with other rubbers is also a promising research area, as is the formulation of graft copolymers.

Appendix A

Selected Readings

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Appendix B

Biographical Sketches of Panel Members

PAUL J. ALLEN was Professor of Botany and of Plant Pathology at the University of Wisconsin-Madison. He received a Ph.D. from the University of California, Berkeley, in 1941. During World War II he was involved in guayule research at the Eastern Regional Research Laboratories of the U.S. Department of Agriculture in Philadelphia, and from 1943-1946 was in charge of the Microbiology Section of the Guayule Rubber Extraction Research Unit at Salinas, California. Since that time he taught botany and plant and fungal physiology at the University of Wisconsin, and from 1965–70 he was Chairman of the Department of Botany. He specialized in research on the physiology of symbiotic associations (particularly those involving diseases of plants) and on the control of development in the rust fungi, and published numerous articles and contributed chapters to books on these subjects. Dr. Allen died on November 13, 1976.

HARRIS M. BENEDICT received an A.B. from the University of Cincinnati in 1929 and a Ph.D. in Plant Physiology from the University of Chicago in 1932. He served with the U.S. Department of Agriculture from 1934–1949, and was a Plant Physiologist with the Guayule Rubber Research Project from 1942–1949. Later he served as Staff Scientist and as Manager of the Plant Science Section of the Stanford Research Institute. His main interests have been centered on the effects of various environmental conditions on crop yield and growth, with emphasis in recent years on the effects of air pollutants and pesticides.

DAVID H. BLANK is a Commodity Industry Specialist (rubber and plastics) at the U.S. Department of Commerce, Washington, D.C. He graduated from Purdue University in 1952 with a B.S. in Science and did postgraduate work in economics at Hofstra College and the Foreign Service Institute of the Department of State. He was a compounder for the General Tire and Rubber Company prior to joining the Commerce Department in 1958. He is a member of the Rubber Division, American Chemical Society, and served as a Director from 1974 to 1976.

JAMES F. BONNER is Professor of Biology at the California Institute of Technology. He started guayule research in 1940 with the Continental Rubber Co. and worked with the U.S. Forest Service on the Emergency Rubber Project from 1942 to 1946. He then continued to work on guayule supported by the Office of Naval Research, the Quartermaster Corps of the U.S. Army, and finally, in connection with isoprenoid biosynthesis, by the National Institutes of Health. He has been involved in guayule agronomy, plant physiology, and biochemistry as well as in tracing the path of carbon in the biosynthesis of rubber both in guayule and in the rubber tree, *Hevea brasiliensis*. At present he is a consultant to The Rubber Research Institute of Malaysia. In 1950 Dr. Bonner was elected a Member of the National Academy of Sciences.

FRANK A. BOVEY is head of the polymer chemistry research department at Bell Laboratories, Murray Hill, New Jersey. He received a B.S. degree from Harvard University in 1940 and Ph.D. from the University of Minnesota in 1948. He was employed by Minnesota Mining and Manufacturing Company from 1948 to 1962 and by Bell Laboratories from 1962 to the present. He is an expert in the structure and properties of the large molecules that compose rubbers and plastics. In 1975 Dr. Bovey was elected a Member of the National Academy of Sciences.

ENRIQUE CAMPOS-LOPEZ is Director, Guayule Research, Centro de Investigación en Química Aplicada, in Saltillo, Mexico. Together with his staff and team of young colleagues he is involved in developing an economically feasible process for the industrial extraction of guayule rubber. Activities so far have concentrated on the chemistry, physico-mechanical properties, and rheological behavior of guayule rubber, the development of rubber-extraction techniques, and the construction of a pilot-scale mill. Dr. Campos received his Ph.D. from the University of Akron in 1970.

HAROLD E. DREGNE is Horn Professor and Director of the International Center for Arid and Semi-Arid Land Studies at Texas Tech University, Lubbock. He received a B.S. in Chemistry and Mathematics from Wisconsin State University in 1938 and a Ph.D. in Soil Chemistry from Oregon State University in 1942. He was on the faculty at the University of Idaho, Washington State University, and New Mexico State University before becoming Chairman of the Plant and Soil Science Department at Texas Tech in 1969. From 1970 to 1975, he was Chairman of the AAAS Committee on Arid Lands. He is the editor of *Arid Lands in Transition* and author of *Soils of Arid Regions.*

RALPH EMERSON is Professor of Botany at the University of California at Berkeley. He received his Ph.D. in 1937 from Harvard University. Dr. Emerson is a specialist on the biology of fungi. From 1944 to 1946 he was Microbiologist on the U.S. Department of Agriculture Emergency Rubber Project at Salinas, California. Together with Paul J. Allen (see above) and others he investigated the use of microorganisms to degrade resins and thus improve the quality of guayule rubber. He has co-authored an article on guayule retting and a book on thermophilic fungi and published a number of research papers and reviews on aquatic fungi. He has served on committees for the National Institutes of Health and the National Science Foundation and is a member of various scientific societies including the American Academy of Arts and Sciences. In 1970 Dr. Emerson was elected a Member of the National Academy of Sciences.

WALTER T. FEDERER is a Professor of Biological Statistics in the Department of Plant Breeding and Biometry, Cornell University. He is also Administrative Officer of the Biometrics Unit and the Statistics Center. He has published several books and over 100 research papers on statistical design, statistical analyses, and on assessing the correctness of statistical models applied to biological systems. He received his M.S. in Plant Breeding from Kansas State University in 1941 and his Ph.D. in Mathematical Statistics from Iowa State University in 1948. From July 1942 to November 1944 he was employed by the Emergency Rubber Project. Stationed at Salinas, California, he conducted statistical analyses of the guayule experiments then in progress. He is a Fellow of the American Statistical Society, and was elected a member of the International Statistical Institute.

IRVIN C. FEUSTEL is retired from the U.S. Department of Agriculture after nearly 40 years of service. He received a B.S. in Chemistry from Washington State University in 1927, an M.S. in Chemistry from George Washington University in 1929, and a Ph.D. in Chemistry from The American University in 1934. Dr. Feustel engaged in and directed a variety of research projects involving soils, plant growth, microbiology, and fruit and vegetable processing. From 1947 to 1953 he was Head of Natural Rubber Extraction and Processing Investigations at Salinas, California, which developed processes that produced high quality deresinated rubber from guayule. A USDA Superior Service Award was bestowed for this work.

HOWARD SCOTT GENTRY is a Research Botanist at the Desert Botanic Garden, Phoenix, Arizona. He received his B.A. in Zoology, University of California, Berkeley, in 1931, and a Ph.D. in Botany, University of Michigan, Ann Arbor, in 1941. Dr. Gentry has spent much of his career investigating the botany and ecology of Mexican plants, especially those of the northern desert regions. In working for the Emergency Rubber Project in 1942 and '43 he made experimental plantings of guayule in Mexico and investigated *Cryptostegia*, another little-known rubber-producing plant. From 1950 to 1971 he was Agricultural Explorer for the U.S. Department of Agriculture, making seed collections in more than 20 countries. His work on jojoba, another desert plant that, like guayule, has potential to become a valuable crop plant, is well-known. He is author of several books and numerous articles.

A. J. HAAGEN-SMIT is Professor Emeritus at the California Institute of Technology. He received a Ph.D. from the University of Utrecht in The Netherlands in 1929. He is a specialist in organic analytical studies of natural products, such as essential oils and plant hormones. During the war years he studied the volatile components of guayule oils. Later he turned to problems of environmental pollution and established the photochemical nature of Los Angeles smog. He served at different levels of government in numerous committees dealing with environmental matters. At present he is a member of the executive committee of the Environmental Protection Agency's Science Advisory Board. In 1971 Dr. Haagen-Smit was elected a Member of the National Academy of Sciences.

OMER J. KELLEY is Co-Director of the Crops Improvement Research Center, Office of Rural Development, Suweon, Korea. He received a B.S. in 1939 and an M.S. in 1940 from Colorado State University and a Ph.D. from Ohio State University in 1942. Dr. Kelley was head of the soil and water research program for the Guayule Emergency Rubber Project 1942–45. He was Chief of the Soil and Water Research Program of the USDA-Agriculture Research Administration, for the 17 Western States from 1946 to 61. Later he served as Director of the Agriculture Research Center for Stanford Research Institute and as Director of the Office of Agriculture for the Agency for International Development. Dr. Kelley's main fields of expertise and interest are in Research Administration, the Development of National Agriculture Research Programs in developing countries, and in the conservation and use of soil and water resources.

WILLIAM G. McGINNIES, Director Emeritus of the Office of Arid Lands Studies, University of Arizona, was in charge of Surveys and Investigations for the Emergency Rubber Project and served as liaison between research and operations. He thus became familiar with all phases of guayule rubber production. Since 1922 Dr. McGinnies has been connected with research, teaching, and operations in arid lands. He is one of the editors of, and a contributor to, the chapters in *Deserts of the World*, a 788-page review of knowledge of deserts published by the University of Arizona. He is also one of the editors of *Food, Fiber, and Arid Lands*, also published by the University of Arizona. Dr. McGinnies was also instrumental in getting production started on jojoba (an oil-producing plant) on Indian lands of the southwestern United States.

CARL S. MARVEL, a Professor of Chemistry at The University of Arizona, is particularly interested in synthetic polymer chemistry. He was a member of the Chemistry staff of the University of Illinois from 1920 to 1961. From 1941 to 1955 he participated in the government synthetic rubber program. He has continued active research in synthetic polymer chemistry since joining the faculty at the University of Arizona in February 1961. One of the most distinguished of American chemists, Dr. Marvel has received numerous national and international awards for his contributions to chemistry. In 1938 he was elected a Member of the National Academy of Sciences.

MARTIN A. MASSENGALE is Vice-Chancellor for Agriculture and Natural Resources at The University of Nebraska-Lincoln. For the previous seventeen and one-half years , he was a member of the faculty and administration at The University of Arizona where he became widely known for his work in crop physiology, water-use efficiency, and arid-lands agronomy. He received his B.S. in Agriculture from Western Kentucky University in 1952 and his M.S. and Ph.D. in Agronomy from the University of Wisconsin in 1954 and 1956, respectively.

ROBERT M. PIERSON is Assistant to the Director of Research at Goodyear Tire and Rubber, which he joined in 1941 at the beginning of the synthetic rubber program. He received a B.S.E. from Princeton in 1940, and—except for a year with a paper company—has been involved with synthetic rubber ever since. During his tenure as Manager of Synthetic Rubber Research his department developed the first synthetic cis-polyisoprene, an effort involving many analytical, structural, and performance comparisons with hevea rubber. Mr. Pierson is also involved with a foundation interested in technology for developing nations.

REED C. ROLLINS is Asa Gray Professor at Harvard University and Director of the Gray Herbarium. He received an A.B. from the University of Wyoming in 1933, an M.S.

from Washington State University in 1936, and a Ph.D. from Harvard in 1941. Dr. Rollins was successively Associate Geneticist and Geneticist in the Research Division of the Emergency Rubber Research Project during World War II. Later, he was Principal Geneticist of the Stanford Research Institute in charge of the genetics and breeding program on the guayule rubber plant. His research over the years
reproduction and population structure in higher plants and the systematics and evolution of the mustard family Cruciferae. He first recognized the role of interspecific hybridization in guayule diversity and was the first to prove the existence of apomixis in guayule. In 1972 Dr. Rollins was elected a Member of the National Academy of Sciences.

JOEL SCHECHTER is currently the Director of the Research and Development Institute of the Ben-Gurion University in Beer-Sheva, Israel. His institution has 25 varieties of guayule under experimental cultivation. From 1961 to 1973 he was Director of the Negev Institute for Arid Zone Research where extensive experience was obtained in the cultivation of desert plants. He holds degrees both in electrical engineering and in plant science and has been involved in many projects of arid-zone development both in Israel and in other arid and semiarid regions.

HEWITT M. TYSDAL retired from the Agricultural Research Service, U.S. Department of Agriculture, as Chief, Tobacco and Sugar Crops Research Branch. He received a Ph.D., majoring in Agronomy and Genetics, from the University of Minnesota. He was in charge of guayule breeding and production at the U.S. Natural Rubber Research Station at Salinas, California, for several years following World War II. He was invited by the Spanish government to spend several months in Spain as a consultant on guayule and rubber problems. Dr. Tysdal was the first to develop a commercial variety of alfalfa resistant to bacterial wilt. He was invited to give the Spragg Memorial Lectures at Michigan State University and was elected a Fellow of the American Association for the Advancement of Science, and of the American Society of Agronomy. He is also a Fellow of the American Scandinavian Foundation and has studied in Sweden.

LAWRENCE A. WOOD is Consultant on Rubber in the Polymers Division of the National Bureau of Standards, Washington, D.C. He received a Ph.D. in Physics from Cornell University in 1932 and was a member of the Rubber Section of the National Bureau of Standards from 1935 to 43 when he became Chief of the Section, a position which he held until 1962. In that capacity he was concerned with the evaluation and testing of all varieties of natural rubber, including guayule rubber. Members of the NBS Rubber Section developed a laboratory method for the rapid extraction of resins from chilte and guayule rubbers in 1950. Dr. Wood has been a U.S. Delegate to international rubber conferences in 1938, 1948, 1968, and 1974.

NOEL D. VIETMEYER, staff director for this study, is a Professional Associate of the National Academy of Sciences. Recipient of a Ph.D. in organic chemistry from the University of California, Berkeley, he has been staff officer for a number of NAS studies that have drawn attention to little-known plants that could well become future crops.

Resumen en Español

De las 2,000 especies de plantas que actualmente se conocen contienen hule,* unicamente dos lo han producido en cantidades comerciales. Éstas son el *Hevea brasiliensis*, el árbol del hule, que crece principalmente en el Sureste de Asia el *Parthenium argentatum* (el guayule) el cual es nativo de las regiones áridas de America del Norte (vea la Figura 1).

A diferencia del *Hevea*, el guayule es un arbusto poco impresionante, con semejanza a la artemisa y desde 1902 hasta 1946 fué explotado comercialmente como una fuente de hule. Sin embargo, el hule de guayule no ha sido producido en cantidades apreciables durante los últimos 30 años, el tiempo en su contra y en la mitad de los 40's, fué abandonado. Entonces, pareció no servir ningún propósito, pués se pensó que había poca necesidad de otra fuente de hule natural, la Segunda Guerra Mundial había terminado y aunque el hule de hevea fué un suministro, se pensó que al elaborar el hombre elastomeros sintéticos el uso del hule natural se volvería gradualmente absoleto.

Pero la prespectiva ha cambiado; hoy en día, el hule de hevea no tiene ni remotas posibilidades de ser desplazado, por el contrario, ha retenido su posición como uno de los artículos de consumo más importantes mundialmente. El aumento del precio del aceite se reduce la competitividad de los elastomeros sintéticos (los cuales son producidos básicamente de suministros del petróleo) y hay una demanda mundial creciente por el hule natural. Esta predicho que si no hubiera otra fuente natural de hule para 1980 la producción de hevea deberá alcanzar los 5 millones de toneladas, lo cual representará un tercio de hule consumido a nivel mundial (ver Figura 2).

El hule natural es empleado en aplicaciones que demandan elasticidad, resistencia, adhesividad y baja generación de calor. El hule natural es indispensable para la fabricación de llantas de autobuses, camiones, y aviones y usadas bajo condiciones severas donde la generación interna de calor no cause fallas.

Hoy en día, una planta que produce hidrocarburos es especialmente valiosa porque muestra mayor fuente, el petróleo, está disminuyendo y estará agotado en unas décadas.

El guayule es una fuente alternativa—una fuente renovable—para los hules polisoprenos derivados del petróleo. En las décadas venideras habrá mercado

Nota: No existe una definición universal del "hule." En este reporte "hule" se refiere al tipo *Cis* 1-4 polisopreno.

para todos los hules "naturales" que pueden producirse, ya sea de hevea ó guayule.

En la actualidad con una población en incremento tenemos la necesidad de utilizar productivamente las tierras marginales mundialmente, especialmente las tierras áridas, encontrar recursos adaptados a las frágiles pero ásperas condiciones del desierto y dar trabajo e ingresos a los moradores del desierto donde la convencional agricultura es imposible ó arriesgada. Esto coloca al guayule bajo una nueva prespectiva puesto que los experimentos han mostrado que "el guayule podría ser exitosamente cultivado en muchas tierras donde el suministro de agua irrigada es insuficiente para la producción de la mayoría de las cosechas agrícolas."*

El clima económico general en estos días es muy diferente aquel, cuando el guayule fué producido comercialmente. Pero el guayule es digno de la investigación y desarrollo solamente si el hule posee las características requeridas para las necesidades comerciales.

Dentro del contexto de este reporte se concluye que:

– No existen diferencias detectables entre las estructuras químicas del hule de guayule y el hule de hevea. Los dos tienen tales propiedades químicas que, dentro de los límites de los instrumentos corrientes, son idénticas.

– Existe un vasto mercado para el hule de guayule que pueda ser producto economicamente.

– Usando las viejas técnicas de producción y estracción de la planta sería dudoso que el guayule fuera viable de exportarse comercialmente. Sin embargo, la investigación y tecnología moderna podría, cambiar esta situación.

– Existen grandes posibilidades de que la investigación conduzca al guayule a un punto variable comercial en 5–10 años.

– El guayule tiene un potencial que ha llegado a ser muy importante para la economía y seguridad de los Estados Unidos.

– El cultivo del guayule puede ayudar, con el tiempo, a los indios emprobecidos del suroeste a desarrollar una base económica para sus reservaciones.

– El guayule ha llegado a ser potencialmente un importante recurso en varias regiones de las superficie de México y Estados Unidos donde crece naturalmente.

Basado en estas conclusiones este reporte recomienda que:

– El Gobierno de los Estados Unidos debería iniciar un programa de investigación y desarrollo aplicado, conducido hacia la comercialización de la planta de guayule.

– En sus proyectos de investigación sobre guayule el Gobierno de los Estados Unidos y el Gobierno de México deberían cooperar.

– Un programa de producción de guayule debe iniciarse inmediatamente.

Deberán Establecerse:

– Plantaciones experimentales de guayule en las áreas seleccionadas de California, Arizona, Nuevo México y Texas que sean apropiadas para su cultivo.

*McGinnies and Haase, 1975. (Vease Selected Readings.)

– El gobierno federal debería centralizar sus archivos sobre guayule en alguna localización en el suroeste de manera de hacerlos accesibles a los investigadores.

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