same technology, which uses a natural fiber and produces no wastewater, is being tested in a widening range of product applications, including absorbent mats.

The Kenaf Demonstration Project began in early 1986 specifically to conduct activities that would lead to commercialization of kenaf fibers. The resulting series of collaborative activities with industry either directly or indirectly helped to build today's foundation of 8-10 kenaf businesses in the United States and kenaf research programs in USDA and universities. The successes are attributable largely to creative and innovative partnerships between public and private interests, which combine resources, ideas, and people to overcome major technical, economic, and institutional barriers.

Over time, USDA has invested more than $15-20 million of public funds into efforts to support the research, development, and commercialization of kenaf as a new fiber source for industry. While it is difficult to quantify the contributions, it is safe to estimate that the various private cooperators involved have matched USDA on at least a 3-to-1 basis. Given the projects already in operation and those soon to leap off the drawing board, it looks as though taxpayer investment in kenaf has been rewarded. ❑

15 Guayule Has Real Rubber in It, and It Grows in the United States

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North and South America have two plants, hevea and guayule, that provide natural rubber for use in commerce. Many of us are familiar with the hevea tree (*Hevea brasiliensis*), a native of the Amazon region that is now grown primarily in Southeast Asia, because at present, this plant provides all of the natural rubber used in the world.

History of Guayule

The lesser known guayule shrub (*Parthenium argentatum*) is a native of north-central Mexico and southwestern Texas. In fact, the Spanish explorers saw Indians in Mexico playing with a bouncing ball made from guayule rubber. Rubber production in those days was a community undertaking; the Indians chewed the bark to separate the rubber from the rest of the plant.

The chemical composition and properties of the rubber from guayule and hevea are similar. Though guayule makes about the same quantity of resin-type compounds that have potentially valuable industrial uses, rubber removal from guayule requires special extraction procedures. The guayule plant, unlike hevea, makes and stores rubber in individual cells of the stem instead of in the stem sap.

From the early 1900's through the 1930's, guayule provided a significant amount of the rubber used to make automobile tires. During World War II, the United States made a major effort to produce guayule rubber to replace the then-unavailable overseas source of hevea. This emergency project produced large amounts of guayule rubber, reaching 10 percent of the Nation's supply and use.

The abrupt closure of the project at the end of the war resulted in the abandonment of the plant nurseries, fields, and processing facilities. Germplasm selections, breeding stock, and supplies of rubber and seeds were also destroyed. The present outlook for the commercialization of guayule is clouded because of its cyclical history of sudden spurts of interest followed by complete neglect.

Why Natural Rubber?

Modern transportation depends heavily on natural rubber, as it is the basic ingredient of tires. Natural rubber is also the ingredient of many elastic products that require high tensile strength, durability, and low heat buildup when flexed. So synthetic rubber from petroleum cannot completely replace natural rubber. In addition, natural rubber is a renewable resource, whereas petroleum reserves are not.

Properties of Rubber

Natural rubber is a polymer with a chain of thousands of isoprene molecules (C_5H_8) linked together. Plants such as goldenrod, dandelion, and milkweed manufacture a short-chain-length polymer, averaging 4,000 or fewer isoprene units. By comparison, the hevea and guayule plants can synthesize long-chain polymers of 25,000 or more units. Only the long-chain polymers have the elastic strength and durability for making tires and rubberbands.

A rubber tire encircling the desert shrub guayule symbolizes the plant's potential as a primary source of natural rubber for the United States.
Jack Dykinga/USDA 0584X711-28

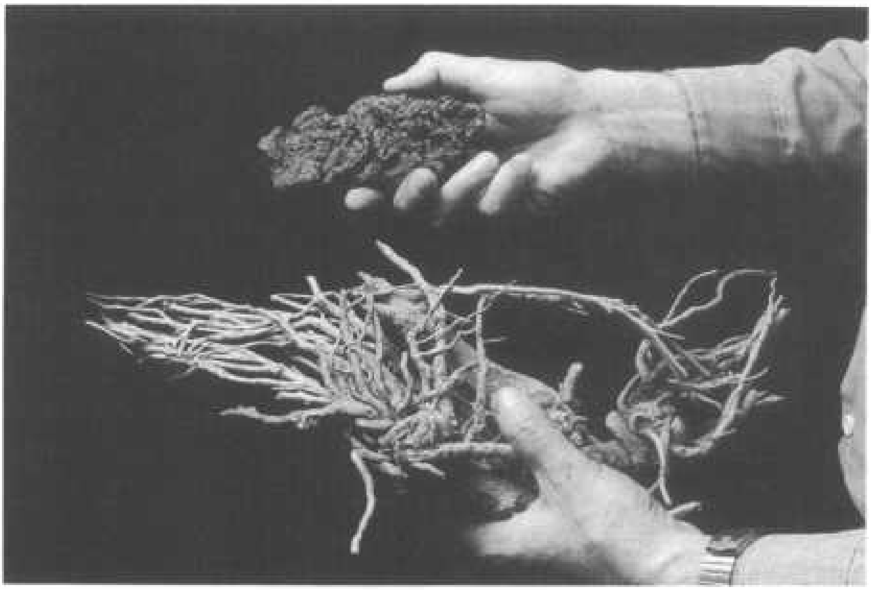
Processing of Rubber

When mass production of automobiles began in the early 1900's, rubber tire manufacturing became a major industry. Guayule rubber was obtained by grinding the shrub in water and skimming off the floating rubber "worms." This flotation procedure was used during the World War II production of guayule rubber. Unfortunately, the rubber from this process contains resinous impurities that make the rubber tacky, soft, and likely to break down with time.

Efforts to improve guayule rubber quality were rekindled in the 1970's, when the petroleum crisis occurred. In the new process, resin in the worms was removed by solvent extraction. Rubber produced in this way can make high-performance aircraft tires.

Further improvement in rubber quality and efficiency of production came about with the sequential extraction procedure. The sequential process used two different solvents: one to dissolve and remove the resin, and the other to dissolve and separate the rubber. In Salinas, CA, and Peoria, IL, USDA researchers evaluated a variety of such processes.

The latest extraction process uses only one solvent to dissolve both the rubber and the resin. Dissolved rubber in the mixture is then removed by selective coagulation and precipitation. In the late 1980's, Bridgestone/ Firestone, Inc., built a pilot facility in



Rubber (top), extracted from dried guayule (bottom), at the Northern Regional Research Center, Peoria, IL. Guayule now yields about 5 pounds of rubber per 100 pounds of shrub.

Jack Dykinga/USDA 1284X1802-10

Sacaton, AZ, for extracting rubber with this process. The facility produced 5 metric tons of rubber for tire production and testing before it was closed. Resin and low-molecular-weight rubber fractions from this operation are also undergoing development and testing for possible coproduct applications.

This selective coagulation procedure can separate rubbers of different molecular weights that have different physical properties. Thus, the processor can tailor the end product to the needs of the customer.

Applications of Rubber

The demand for rubber continues to grow. Natural rubber now accounts for 31.5 percent, or 4.7 million tons annually, of the total rubber market worldwide. Petroleum-based synthetic rubber meets the remaining needs. In 1990, the United States imported over 800,000 metric tons of natural rubber, costing nearly $1 billion. About two-thirds of this natural rubber is used for tires and related products. This is not surprising, because a passenger tire is made up of 30 percent natural rubber and an aircraft tire 100 percent. The remaining one-third of natural rubber goes into making other rubber products such as V-belts, conveyor belts, storage tank linings, and hoses. A small amount ends up in footwear and adhesive products.

As expected, performance tests of guayule rubber are primarily directed to transportation. These include light- and heavy-duty truck tires, aircraft tires, military tank track pads, and motor mounts. The tensile-strength, wear, and heat-resistance characteristics of guayule products have met or exceeded those of similar products manufactured from hevea rubber.

Other nontransportation market products are available. Guayule rubber makes a nonstick base for chewing gum. Blending guayule rubber with polyolefins produces a polymer for making extruded or injection-molded products. Finally, chemical modification of guayule rubber has produced new types of polymers. These polymers have properties similar to those of existing thermoplastic elastomers for making various types of molded goods.

Guayule Coproducts

Resin-like compounds derived from the rubber extraction process add to the coproduct value of the guayule shrub. Initially, these incidental materials were considered nuisances and waste products. Now they appear to have special uses that may give them considerable value in their own right.

The coproducts of guayule consist of (1) low-molecular-weight rubber (LMWR), (2) organic and water-soluble resins, and (3) bagasse (plant residue). Some of these materials, especially LMWR, are ideal raw materials in polymer synthesis. They serve as building blocks for making more complex compounds that are useful in industry.

LMWR is a short-chain polymer averaging about 4,500 isoprene units and is thus not suitable for making tires. However, chlorinating the LMWR forms tough, flexible, and chemically resistant compounds. Be-

Performance tests of guayule rubber are directed primarily toward transportation and related products. Guayule passes a tire-scorching test at 145 miles an hour in simulated carrier landings at the Patuxent Naval Air Test Center in Maryland.
Anita Daniels/USDA 0684W917-12A

cause chlorinated rubber products resist abrasion and water, they are used in making highway stripes and marine and pool paints. Floor coating containing this material is hard and resistant to abrasion, chemicals, and impact.

Epoxy compounds of LMWR are used as toughening aids in polymer formulations. In addition, the epoxidized rubber has potential in making thickeners, adhesives, and thermoplastic polymers. The low-molecular-weight fraction of guayule is less expensive than the LMWR derived from hevea.

Hydroxylated LMWR compounds make polymer-forming raw materials used in producing polyesters, polyethers, and polyurethanes. Currently, these important materials are manufactured from petroleum sources. Guayule provides an alternative, renewable source of these important and extensively used industrial chemicals.

By modifying the LMWR, water-stable polymers are formed. These waterborne particles are used in paints that do not require volatile organic solvents. Volatile organic compounds (VOC's) in paints are being discouraged, in order to reduce solvent pollution of the atmosphere. Polymer-modified, chlorinated rubber shows promise as powder coatings that do not involve any VOC's.

In contrast to the problems with crude resinous impurities in early processing, current nonrubber compounds of guayule resin have potential useful applications in industry. When resin is chemically modified and recombined with the guayule rubber itself, rubber with high tear resistance (a desirable property in tires) is produced.

Guayule resin can be used as a plasticizer for other high-molecular-weight polymers. It can stabilize the physical properties of synthetic rubber. Protective coatings made by mixing guayule resin with epoxy material are easily stripped from the surface when needed. These coatings are useful for the temporary storage and weather protection of aircraft and motor vehicles.

The organic soluble resin, when blended with marine coatings, produces an antifouling mixture that can prevent formation of barnacles on ocean buoys and ship hulls. The material should be less hazardous to the environment than existing paint and coating compounds.

Wood impregnated with organic soluble guayule resin resists attack by marine borer, termite, and soil fungi. The resin mixture is very complex, and studies to characterize its composition are just beginning. Because the resin coproduct is a natural product, it is considered to be environment-friendly.

The bagasse, which remains after rubber extraction, is convertible to furfural, an important chemical raw material for manufacturing industrial solvents, resins, and plastics. The bagasse can also be used to make hardboard siding. The guayule-bagasse hardboard overlay is highly water repellent.

Growing Guayule

A low-growing, desert-adapted shrub, guayule can withstand extreme water stress. However, it is sensitive to hard frost. Thus, the Southwestern United States would play a major role in the cultivation of guayule.

The cultivation of guayule is similar to that of current major crops. Guayule culture initially required a large labor force, but research application of modern technology has essentially mechanized the system and better planting and harvesting equipment is now available. In addition, improved seed treatment and direct planting techniques have enhanced plant establishment and the economics of growing guayule.

The guayule shrub can be grown under irrigated or nonirrigated culture. Information is available on the water requirements and method of irrigation of the existing crop varieties. Guayule can be grown under dryland conditions, but in this situation, it needs longer growing periods than the irrigated crop. However, dryland production will provide a natural living system for storing rubber, as these plants can be maintained at a low cost and harvested, as necessary, when a special emergency arises.

To further improve guayule's economic prospect, the rubber yield of existing genetic lines of guayule must be doubled. This can be achieved

Dale Bucks, ARS national technical advisor on guayule, measures guayule plant height as the crop, grown in a marginal soil of more than 95 percent sand, is irrigated by an automated sprinkler system.

Jack Dykinga/USDA 0584X707-11

through proper selection and breeding, as was done with hevea. Guayule, unlike many of our domestic crops, produces seeds without fertilization. This is both a hindrance and a help in germplasm improvement: Plant crosses are harder to make and identify; but once a good line is developed, it can be readily maintained.

Commercializing Guayule

As with all new, alternative crops, guayule commercialization faces the proverbial "chicken or egg" problem. Farmers won't grow the crop because the rubber-processing facility is not available, and industry won't build the facility because of the lack of a reliable source of the shrub.

Yet, guayule still has great potential to become an important source of natural rubber for the United States. Not only could guayule rubber production in the United States offset the annual import of almost 1 billion dollars' worth of hevea rubber, but economists have predicted a shortage of hevea rubber in the late 1990's. Increasing the yield, decreasing the production costs, and finding new

To increase the amount of rubber in guayule plants, ARS chemist Charles De Benedict sprays bioregulators on the plants. *0584X712-11A*

pro-ducts of guayule will improve and hasten its chance for commercialization.

Rubber production first started in the Americas. When guayule rubber is commercially produced in the United States, the natural-rubber source will have finally returned to its place of origin. ❑

Rapeseed and Crambe: Developing Useful Products From Oils That Are High in Erucic Acid

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The use of rapeseed oil dates back to antiquity. Ancient (2000 to 1500 B.C.) writing from Greece, Rome, India, and China refer specifically to oilseed rape, its medicinal value, and its use as a cooking oil. The focus of this chapter, however, is not on the edibility of oils but on the industrial use of high erucic acid (industrial) rapeseed and crambe oils.