avoid financial turbulence like that of 19 October 1987.

Competitiveness is not purely a matter of being able to price exports favorably on the world markets. Competitiveness on the side of import restraint is equally important, and shifts toward a more moderate propensity to consume (higher propensity to save) and higher levels of investment activity are needed.

Fiscal prudence should be blended with technical competitiveness (cost effectiveness) in order to achieve an overall balanced degree of competitiveness among the world economies. There are ways and policies of doing this all together, but it requires a high degree of government support, activity, and guidance. Given the precarious state of economic imbalance that has developed, a total recuperation of American competitiveness will not come about in a passive way by waiting for market forces to carry out the full adjustment.

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Technology and Competitiveness: A Key to the Economic Future of the United States

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The United States still is a leader in technology and innovation, but American industry has been slow to translate that advantage into commercial success. A major contributing factor is the low status accorded manufacturing in this country and a lack of teamwork among scientists, engineers, and managers. However, there are encouraging signs that these key players in the innovation cycle are recognizing the need to work together to improve products and manufacturing processes and to restore the competitive position of the United States.

AFTER DECADES OF UNQUESTIONED LEADERSHIP IN INDUSTRY, science, trade, and other endeavors, the United States is confronted with a painful new reality. A new group of competitors, equipped with strong manufacturing and marketing skills, are eager to challenge the U.S. position in the global marketplace.

Evidence of a decline in U.S. competitiveness is all around us—in trade deficits that have continued to rise despite the drop in the dollar, in slow productivity growth, in stagnant real wages, and in a declining share of world markets, even for high-technology products. These ominous trends have added new urgency to the national quest for competitive renewal. The stakes are high. They are nothing less than the continued ability to provide a rising standard of living.

That was one of the main points that the Commission on Industrial Competitiveness made in a report submitted to President Reagan in 1985 (*1*). The commission cited four causes for the decline of American competitiveness: (i) failure to develop our human resources as well as other nations; (ii) inadequate incentives for savings and investment; (iii) trade policies that do not address the new realities of international commerce; and (iv) shortcomings in our commercialization of new technology.

In this article, I focus on the technology issue—the area that most directly concerns the science and engineering community—by exploring how U.S. industry can become more competitive through better development and deployment of technology. My discussion will revolve around four key points.

- How America's competitive decline is eroding our standard of living
- The link between technology and productivity—the cornerstone of competitiveness
- The importance of manufacturing in the innovation cycle
- The key role scientists, engineers, and industry can play in bringing about a competitive renaissance in the United States

Competitiveness and Standard of Living

The Commission on Industrial Competitiveness defined competitiveness as "the degree to which a nation, under free and fair market conditions, produces goods and services that meet the test of international markets while simultaneously maintaining and expanding the real incomes of its citizens" (*1*, p. 6). How effective has U.S. industry been in meeting the test of international markets? Trade statistics present a sobering picture. The United States did not register a merchandise trade deficit in this century until 1971. Since then, the deficit has risen dramatically, and despite the decline of the dollar, it has remained high. In 1987 alone, it was $171 billion—a deficit of more than $700 for every person in this country.

Deterioration was most pronounced in manufactured products, which account for three-fourths of U.S. trade. However, even high-tech products, which currently account for 40% of U.S. trade in manufactures, posted a deficit in 1986—the first ever (*2*). And in 1987, despite another drop in the exchange value of the dollar, the United States posted only a modest surplus ($590 million) in high-tech trade.

As a result of the trade imbalance, the United States has gone from a current account surplus of $6.3 billion in 1981 to a deficit of $140 billion only 5 years later. In 1982, we were a net creditor, with $150 billion of foreign assets. By 1986, we had become a net

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debtor, with $263 billion of foreign debt. It is estimated that U.S. foreign debt could increase to between $500 and $800 billion by 1990 (*2*, p. x–xi).

The United States also has fallen short of meeting the other criterion of competitiveness cited above—"maintaining and expanding the real incomes of its citizens." The U.S. standard of living has been growing much more slowly than in the past, and real wages have actually declined. Indeed, from 1973 to 1986, real average hourly wages of production and nonsupervisory workers fell by 10%. This decline has been masked, in part, by a steep rise in nonlabor income (such as interest and transfer payments) and by a rise in two-paycheck families (*3*).

And the decline in real wages is still continuing. According to the *Wall Street Journal*, average weekly earnings, adjusted for inflation, were lower in 1987 than in any year since 1982, a time of deep recession. The same is true of hourly earnings (*4*).

If anything, figures denominated in dollars understate the seriousness of the situation because they do not truly reflect the dollar's reduced purchasing power within a global context. Edward Hyman, chief economist for the investment firm of C. J. Lawrence, Morgan, Grenfell Inc., was quoted as saying that in relation to strong currencies such as the Japanese yen, Americans are enduring "a major recession in purchasing power" (*4*). That is a key consideration in view of the increasing globalization of economic activity. The fact is, a truly domestic U.S. economy has ceased to exist. Today, imports and exports represent about 10% of our gross national product, twice as much as they did just two decades ago. Almost one-fifth of our industrial production is exported, and 70% of the goods we produce compete directly with merchandise from abroad (*1*, p. 9).

The globalization of the economy has been accompanied by rapid worldwide dissemination of industrial technology. Innovation knows no boundaries in today's world. Multinational companies diffuse research throughout the countries in which they operate rather than confine it to a national base. Furthermore, other countries have become major investors in R&D. Measured in constant 1982 dollars, the United States spent $62.2 billion on R&D in 1970, whereas the combined expenditures of Japan, West Germany, France, and the United Kingdom were $38.1 billion. In 1985, the United States spent $96.7 billion on R&D; the combined total of these other four industrial nations was $79.8 billion (*5*).

Globalization can be viewed as a threat or an opportunity. If we attempt to isolate ourselves from the world around us by drawing our wagons into a circle of protectionism, then a continued decline in competitiveness—and hence our standard of living—is inevitable. But if we squarely face the challenges of the new world order, we will find rich rewards by active participation in the global marketplace.

The total dollar volume of world trade has grown sevenfold since 1970, much faster than the U.S. economy. This represents tremendous growth opportunities for U.S. companies that are prepared to compete (*5*, p. 9). But capturing a share of this dynamic market will not come easy. U.S. firms must contend with high capital costs. Trade laws often work against our interests, and our high wages are a disadvantage we would like to keep. That leaves us with the imperative to work more productively and more effectively than our competitors.

Technology's Contribution to Productivity

Better use of technology can help U.S. industry improve productivity. For products that compete on the basis of quality, serviceability, and innovation, technological improvements in process or product design are of overriding importance. Indeed, some economists consider technological innovation an even more important factor in increased productivity than capital and labor stocks (*6*).

Technology played a key role in building U.S. competitiveness long before "high tech" entered our vocabulary. Leading economists argue that the single biggest factor behind productivity growth is innovation. They have demonstrated that two-thirds, and perhaps as much as 80%, of U.S. productivity growth since the Depression can be directly or indirectly attributed to innovation (*7*). Today, technology-based sectors generate an estimated 50% of our GNP—twice the percentage of just a generation ago.

Moreover, the benefits of advanced technology extend far beyond the realm of high-tech products. They permeate all aspects of industry, agriculture, and service. For example, advanced technology currently is helping rejuvenate the industrial heartland of the United States by retooling and inventory costs, increasing productivity, and enhancing product quality. Through genetic engineering plant varieties are being developed that better withstand pests and drought and that require less fertilizer. And new technology is having a revolutionary impact on services such as health care, banking, and transportation (*6*, pp. 11–12).

Technology is one area in which the United States has a competitive advantage. In fact, as a nation, it is probably our greatest strength. In scientific and engineering knowledge, our nation is second to none (*8*). Our research university system has provided the country with the highest proportion of R&D scientists and engineers in the Western world. Most major technical breakthroughs since World War II originated in the United States. And no other country offers entrepreneurs such ready access to venture capital and a large equity market.

Yet, the competitiveness of U.S. industry is seriously handicapped by shortcomings in our ability to commercialize technology to develop both the products and manufacturing processes that today's markets demand. As a result, foreign companies have made inroads in a number of high-tech sectors pioneered and previously dominated by the United States, such as semiconductors. Some product lines—especially video cassette recorders, compact disk players, and other consumer electronics—have been completely taken over by foreign competitors.

This loss of market share—or entire markets—did not happen overnight. The United States began to fall behind major competitors in productivity performance and the application of technology in the late 1960s. During the past two decades, U.S. industry's substantial productivity advantage has narrowed considerably or disappeared altogether in a number of key sectors, such as steel, automobiles, machine tools, and semiconductors (*2*).

U.S. productivity has grown at an average rate of only 0.8% per year in the past 10 years, compared with more than 3% annually in the 1950s and 1960s. During the same period, productivity was growing at four times that rate in the rest of the industrial world (*8*).

Moreover, we are not making the necessary investments in research and training to keep us on the leading edge of technology. U.S. spending on nondefense R&D, both by government and by the private sector, has increased far more slowly than nondefense R&D spending in rival nations. Today, Japan spends nearly 3% of GNP on nondefense R&D whereas the United States spends about 1.9% (*5*). And U.S. government funding for university research plant and facilities declined by 95% in real terms from the 1960s to the 1980s (*9*). That gap cannot be filled by private, state, or university resources.

At the same time, we are witnessing a decline in the proportion of U.S. undergraduates majoring in science and engineering and the number of Americans receiving advanced degrees in these fields. The fraction of U.S. freshmen choosing science and engineering majors

in college has been declining since 1972. This trend has been reflected in the number of engineering doctorates awarded to U.S. citizens, which has dropped by approximately half since 1970, while the number awarded to holders of temporary visas has more than tripled (*10*).

Foreign students currently represent approximately 40% of U.S. graduate engineering enrollments and receive more than half of new U.S. Ph.D.'s in engineering. Further, half of all U.S. engineering faculty under the age of 35 are foreign, and this proportion is increasing. In fact, without foreign students and professors, there would be severe shortages of qualified engineering personnel in the United States (*10*).

Why are not more American students interested in engineering and science? No doubt, they are influenced in some part by the priorities of businesses that hire graduates. When Fortune 500 executives were asked what functional area offered the greater opportunities for advancement, one-third said marketing, one-fourth said finance, and one-fourth said general management. In contrast, less than 5% considered production or manufacturing a logical choice.

Manufacturing: Innovation's Missing Link

Many companies accord manufacturing a low status, and this is a key contributor to our nation's sagging productivity in comparison with Japan and other major industrial nations. Our culture has been quick to celebrate the dramatic breakthrough, the bold idea, and the brilliant concept. It has been far less inclined to praise incremental improvements and painstaking execution.

We seem to be laboring under a delusion that the United States can adopt what Teece calls "a 'designer role' in international commerce while letting independent firms in countries such as Japan, Korea, Taiwan, or Mexico do the manufacturing"—a dangerous strategy in the light of recent experience. As an example, Teece adds, "One reason why U.S. manufacturers did not capture the greatest part of the profits from the development of color TV, for which RCA was primarily responsible, is that RCA and its U.S. licensees were not competitive at manufacturing" (*11*).

This view is shared by Vincent Russo, head of the Air Force's manufacturing technology program, which is managing government funding for the National Center for Manufacturing Sciences. He was quoted as saying, "When it comes to manufacturing, the one place we have an edge is in technology. But we haven't been aggressive enough as a nation in applying it" (*12*).

In contrast, manufacturers in Japan, Taiwan, and Korea have proven extremely adept at adopting innovative processing technologies, embedding them in new capital equipment, and creating the skilled work forces that can effectively use them. This has led to dramatic improvements in manufacturing efficiency and quality that have made the countries of East Asia such formidable competitors in world markets.

Since manufacturing is the most costly component in the innovation process in most sectors, it is vital that American industry elevate it from the ranks of poor country cousins to its rightful status at the head of the table. It does us little good to design state-of-the-art products if our foreign competitors can replicate them within a matter of months—and at a lower cost. Failure to capitalize on the original R&D investment decreases the ability to make future investments and leads to a rapidly declining ability to compete.

In today's world, shortening the time between idea stage and finished product often makes the difference between success and failure. The high costs of developing new products, the brief time before copies appear, and rapid obsolescence make for a short innovation cycle—often 3 to 5 years (*6*). A study by the consulting firm McKinsey & Company demonstrated that for a typical product with a 5-year life span, a 6-month delay in shipping would reduce after-tax profits by one-third. A 50% development-cost overrun, by contrast, would reduce after-tax profits by only 3.5% (*13*).

And proper attention to manufacturing confers more than cost advantage. Often it leads to systematic continuing improvements in products and processes that improve the quality of a product, make it easier to service or use, and enhance its competitiveness in other ways. Such refinements often have more impact on a product's commercial success than research breakthroughs or radical innovations.

One Company's Experience

In order to make day-to-day adaptations and mid-course corrections in production, there must be continued communication between engineers and workers and between the design and manufacturing arms of the company. We learned this lesson at Hewlett-Packard a decade ago when we embarked on a campaign to improve product quality and lower production costs.

It soon became obvious that we needed to make some basic changes in the way we interacted with one another. For example, our manufacturing engineers used to play a somewhat passive role in the innovation process. They assumed that whatever the design engineers threw over the fence, manufacturing would build. Today, manufacturing engineers are part of the product design team from day one of a project. Product and process design go on in parallel. And the collaboration between R&D and manufacturing has changed both functions for the better.

In breaking down these organizational barriers, we have broadened our idea of what good design is. It is not just advancing the state of the art or adding new features—though those will always be extremely important to us. There are added considerations—such as the fewest possible parts, product cost, the ability to automate production, reliability, and serviceability. We probably would not have gained those insights without encouraging more give-and-take between design and manufacturing staffs and making them equal members of the same team.

Hewlett-Packard's experience with quality control has taught us that improvements in manufacturing can produce an enormous competitive advantage. For example, when we started our campaign nearly a decade ago, we discovered that fully 25% of our manufacturing costs were involved in responding to quality problems—that is, not doing things right the first time. In 1979, I asked that our product failure rates be cut to one-tenth the then current levels by the end of the decade of the 1980s.

To get us moving in the right direction, we sent key functional managers to a variety of different sites to gain practical insight into how we could improve quality. For example, our team spent time studying the quality control program at our Japanese joint venture, Yokogawa Hewlett-Packard (YHP).

YHP is a case study in the benefits of quality control. During a 5-year period, it managed to cut manufacturing costs on its own products by 42% and inventory by 64%. Failure rates went down by 60%, and R&D cycle time was cut by more than a third. At the same time, productivity almost doubled, and profits and market share improved by about a factor of 3.

By synthesizing what we learned from YHP and other successful manufacturing operations, we have been able to dramatically improve quality at Hewlett-Packard plants in the United States and abroad. As a result, our field failure rates have been decreasing more than 20% a year, which puts us well on track in meeting our goal of

cutting failure rates to one-tenth by the end of the decade. In fact, many parts of our business have already exceeded that ambitious goal.

The aggregate result of thousands of incremental improvements is, indeed, significant. Because of improved quality, we no longer need to carry the inventory margin of error we used to need. We have earned the right to do "just-in-time" manufacturing. As a result, we have been able to reduce our inventory levels from 20.5% of sales in 1979 to 13.8% last year. That works out to a savings of $542 million for the period.

This is just one example of what can be accomplished if the entire company is motivated to work together as a team toward the common goal of building a better mousetrap at lower cost. There are encouraging signs that a growing number of U.S. companies are focusing on manufacturing as a key element of the competitive equation.

For example, beleaguered automobile manufacturers are fighting back with multibillion-dollar investments in plant modernization. In the eight states bordering the Great Lakes, there are 16,000 companies producing high-tech equipment, including robotics, optics, biomedicine, computer software, and electronics. This manufacturing renaissance is being encouraged by state governments using a variety of incentives, including access to universities and state funds.

The Department of Commerce credits increased investments and accompanying improvements in manufacturing processes and technology with recent increases in worker output per hour—a key productivity indicator. Output per hour of all U.S. manufacturing workers increased 3.7% in 1986, and during the first three quarters of 1987, the rate of increase was 3.2%, much faster than during the 1960s and 1970s. These changes offer hope that the nation's prolonged productivity slump has been arrested and that industry is regaining its competitive vigor.

It is also encouraging to note that U.S. manufactured exports were up 15.3% in 1987 and have continued to rise in 1988. However, a significant portion of that improvement can be attributed to a lower priced dollar. The long-term competitiveness of U.S. industry hinges on making real gains in quality and productivity as the dollar moves toward purchasing power parity.

Our Role in Restoring Competitiveness

The private sector is the logical starting point for a renaissance of competitiveness in the United States. In our society, industry has the primary responsibility for training and motivating workers, investing capital, serving markets, and managing assets. But successful innovation also requires the involvement of scientists, engineers, and the academic community.

Such cooperation benefits all parties concerned. A prime example is the Center for Integrated Systems (CIS) at Stanford University, a symbiosis of university and industry research in computer science, integrated circuit engineering, solid-state physics, and other disciplines. CIS represents a special partnership that joins together private industry, academia, and government in an Americanized version of the cooperative spirit that has given Japanese industry an international edge. This arrangement is mutually beneficial because it promotes collaboration between academic and industrial communities in the basic research needed to keep the United States in the forefront of technology.

Twenty high-tech corporate sponsors each pledged $750,000 for construction of the $15 million CIS facility and $100,000 in annual contributions to support research at the center. Participating companies benefit from the opportunity to rub shoulders with Stanford faculty and students and to get a preview of CIS research results. The university, on the other hand, gains capital for support of scientific research facilities and valuable insight into new developments in computer science and microelectronics. Without such exposure, it is virtually impossible for universities to keep abreast of latest equipment and processes and thereby provide education that matches modern job requirements.

Opportunities for cross-pollination between academic and industrial research efforts abound. High-energy physicists face subtle problems of measurement. Company researchers encounter similar obstacles in their drive for increased miniaturization and precision. Both groups can profit by exchanging notes.

Another indication of increased attention to manufacturing is the support being extended by the National Science Foundation to centers of excellence in our research universities that include process technologies in their charter. These centers are serving to raise the level of manufacturing expertise in their fields and to provide an opportunity for academics and practicing engineers to pool their insights.

All of us—whether we call ourselves scientists, engineers, academics, managers, or public servants—have key roles to play in improving our nation's ability to compete in the world arena. In order to maintain and expand the real income of our citizens, we must do more than match the productivity increases of competing nations. What is required is a concerted and sustained effort on our parts to make renewed competitiveness a goal in all of the decisions we make. And we all have a stake—a rising standard of living—in removing the institutional and attitudinal barriers that prevent us from restoring the nation's competitive advantage.

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