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MIT REPORT

Making Nuclear Power Work:

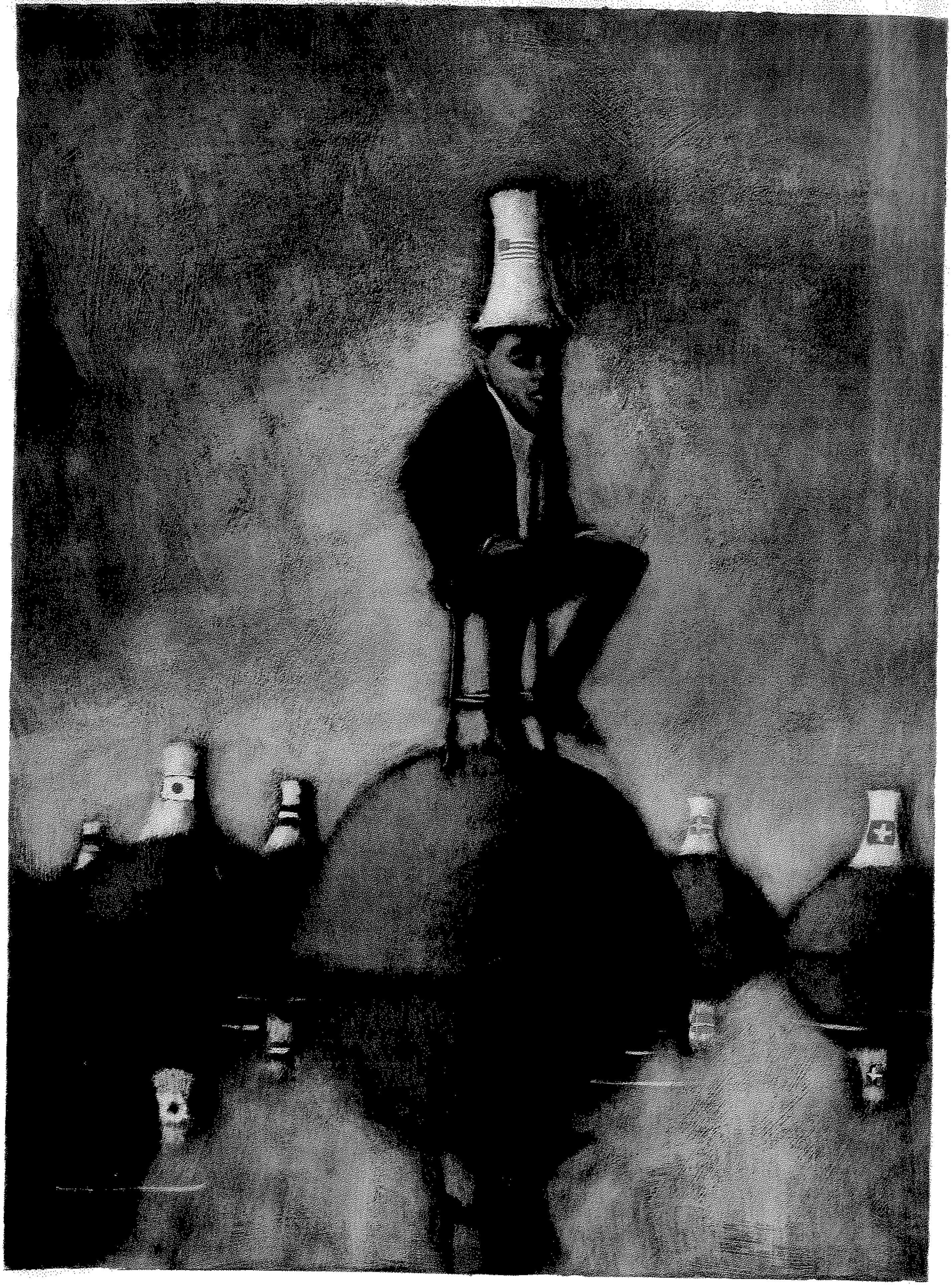
Lessons from Around the World

UTILITY managers and outside analysts alike often say that the U.S. nuclear industry is in trouble because of the grave disadvantages it faces compared with its counterparts abroad. In this view, overzealous safety regulators and public critics hamper U.S. managers' ability to run their plants. The large number of utilities, reactor vendors, and suppliers results in a fragmented industry that prevents operators from learning from one another's mistakes.

Our study of nuclear operations from 1975 to 1984 shows that these factors are not unique to the United States. Utilities in Japan, Sweden, France, Switzerland, and West Germany outperformed those in the United States despite strict regulatory climates as well as great variety in reactor design, utility ownership, and relationships with suppliers. And although public opinion

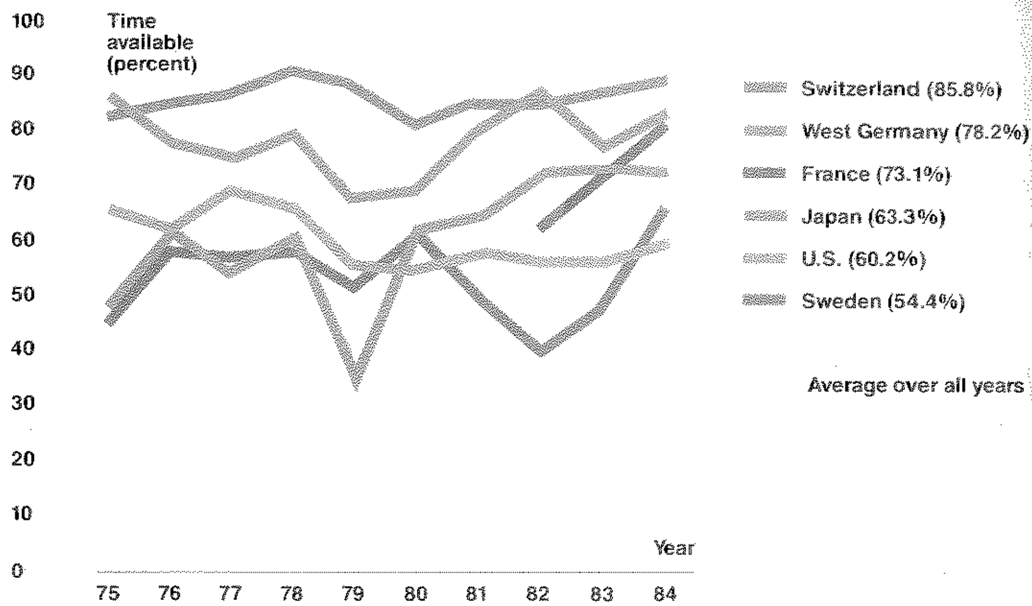
An international study shows that the key to improving the performance of U.S. nuclear plants lies in managerial reform.

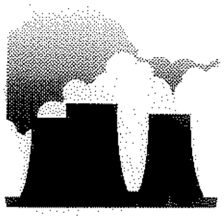
BY KENT HANSEN, DIETMAR WINJE, ERIC BECKJORD, ELIAS P. GYFTOPOULOS, MICHAEL GOLAY, AND RICHARD LESTER



ILLUSTRATIONS: KEVIN HAWKES

How Pressurized-Water Reactors Performed





	SWITZERLAND			WEST GERMANY			FRANCE			JAPAN			SWEDEN			UNITED STATES		
	% Avail.	σ	Plants	% Avail.	σ	Plants	% Avail.	σ	Plants	% Avail.	σ	Plants	% Avail.	σ	Plants	% Avail.	σ	Plants
1975	82.5	0.8	2	85.9	3.3	3				47.5	36.3	4	45.2		1	66.4	13.2	27
1976	84.9	1.7	2	77.8	16.4	4				62.1	12.5	5	58.4		1	62.3	15.0	30
1977	86.5	1.5	2	75.4	10.4	5				54.9	28.3	6	57.3		1	69.6	10.4	36
1978	90.2	0.1	2	79.2	8.2	5		N/A		60.7	10.3	6	58.4		1	67.0	16.8	39
1979	87.7	0.7	2	68.1	13.1	6				34.5	15.7	8	51.6		1	56.3	20.9	40
1980	81.1	5.6	3	69.5	13.7	6				62.4	15.4	8	61.3		1	55.0	20.8	41
1981	85.3	4.0	3	80.0	5.2	6				64.3	17.9	9	49.8	14.9	2	58.0	21.3	46
1982	84.7	3.5	3	86.8	4.6	7	63.1	20.1	19	72.8	13.2	10	40.3	24.6	2	56.6	22.0	47
1983	87.1	3.2	3	77.4	9.4	7	72.4	11.1	19	73.6	17.3	10	48.5	11.5	3	56.8	23.6	49
1984	89.0	0.2	3	83.1	6.8	7	81.6	7.3	24	72.9	12.9	11	67.0	6.3	3	60.2	23.4	52

Many countries have had difficulties with their pressurized-water reactors, but most have improved their records. The exception is the U.S., whose overall performance has remained poor. The charts show what percentage of time the average reactor in each country was available to produce power. The middle column shows the standard deviation, or spread of results about the average, among each nation's plants. The U.S. also compares badly using this measure of consistency.

can affect the overall climate for nuclear power, public opposition is not unique to the United States and did not influence reactor performance during the decade of our study.

We found that the best U.S. reactors performed as well as any of their counterparts abroad. But the worst did significantly worse, dragging down the overall average performance of the U.S. industry. Moreover, many other countries experienced difficulties with their reactors and were able to turn their records around.

These findings suggest that the key to improving the U.S. nuclear industry lies not in changing the system within which utilities operate, but rather in implementing managerial reforms that have proven crucial to success elsewhere.

To better understand the roots of the U.S. industry's problems, we compared reactor performance in six nations with major nuclear programs. We analyzed figures provided by national organizations in each country and interviewed members: utility managers and operators, suppliers, and regulators.

Our study included every light-water reactor—the world's dominant nuclear technology, one that uses

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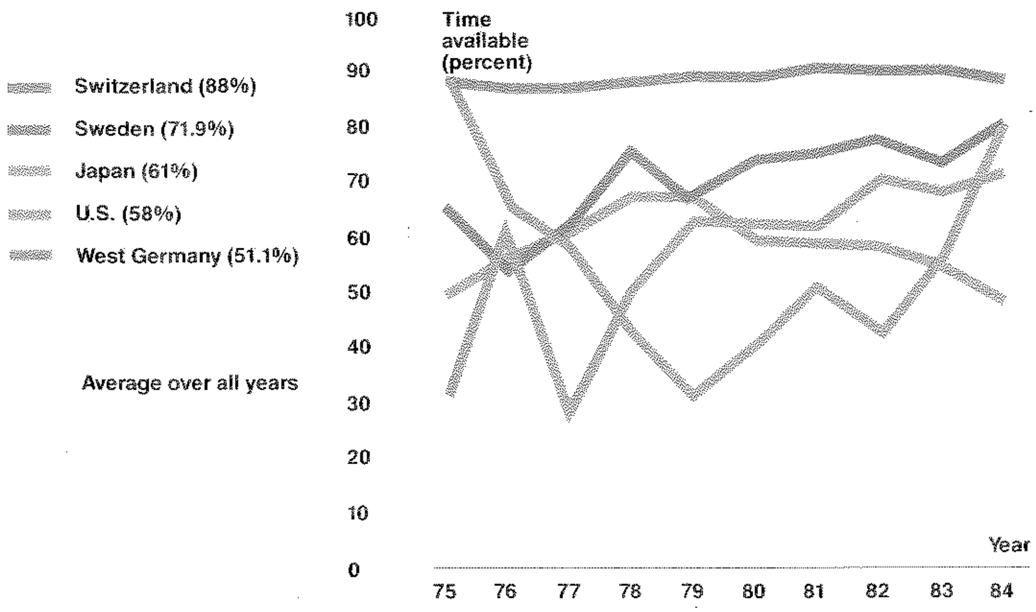
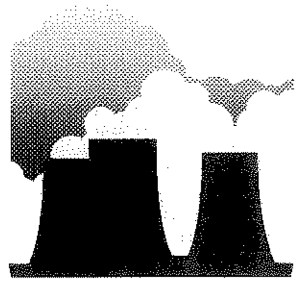
How Boiling-Water Reactors Performed





	SWITZERLAND			SWEDEN			WEST GERMANY			JAPAN			UNITED STATES		
	% Avail.	σ	Plants	% Avail.	σ	Plants	% Avail.	σ	Plants	% Avail.	σ	Plants	% Avail.	σ	Plants
1975	86.9		1	64.7	4.9	2	88.7		1	28.1	33.0	3	49.4	17.7	18
1976	85.9		1	53.0	12.9	4	65.4		1	61.9	13.6	5	55.4	17.6	19
1977	86.3		1	61.2	7.4	4	75.3	7.8	2	25.8	21.5	5	60.1	12.9	21
1978	87.3		1	74.8	6.2	5	41.7	7.0	2	49.7	26.7	9	67.5	12.5	21
1979	88.0		1	66.0	12.6	5	30.1	28.7	3	62.5	9.6	10	67.1	14.7	22
1980	87.9		1	73.6	6.3	5	39.2	23.6	4	61.7	12.3	10	59.2	13.0	22
1981	89.5		1	75.0	6.3	7	50.0	21.0	4	61.4	13.6	10	58.7	14.2	22
1982	89.9		1	77.7	8.5	7	41.9	19.4	4	70.2	14.5	11	58.5	19.0	22
1983	90.1		1	73.1	10.3	7	56.4	28.0	4	68.2	8.1	11	54.8	21.3	23
1984	88.5		1	80.9	5.1	7	78.8	3.6	4	72.1	13.8	13	48.3	26.1	25

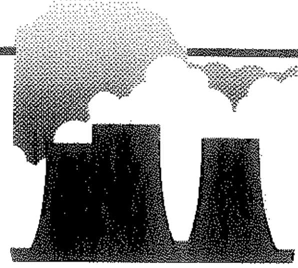
Results for boiling-water reactors vary, with Switzerland again posting the best record. Japan revamped its preventive-maintenance plan for all reactors to improve its record. The United States, with as many reactors as the other nations combined, shows a downward trend. (France has no reactors of this type.)

ordinary water for cooling—of at least 300 megawatts operating from 1975 to 1984 in these countries. The plants come in two versions: pressurized-water reactors (PWRs) and boiling water reactors (BWRs). What we found was a remarkable variation in performance. Different countries achieved different results with the two kinds of reactors, and these results changed over time.

Reactor designers originally expected that nuclear plants would be easy to operate, and that they would therefore be used almost continuously at full power. This was considered important because the capital cost of nuclear power is high. Both reactor designers and utility managers realized the need to close a plant for refueling, and they planned six weeks per year for this process plus maintenance. Thus, they expected that a plant would operate at full power for about 88 percent of the year.

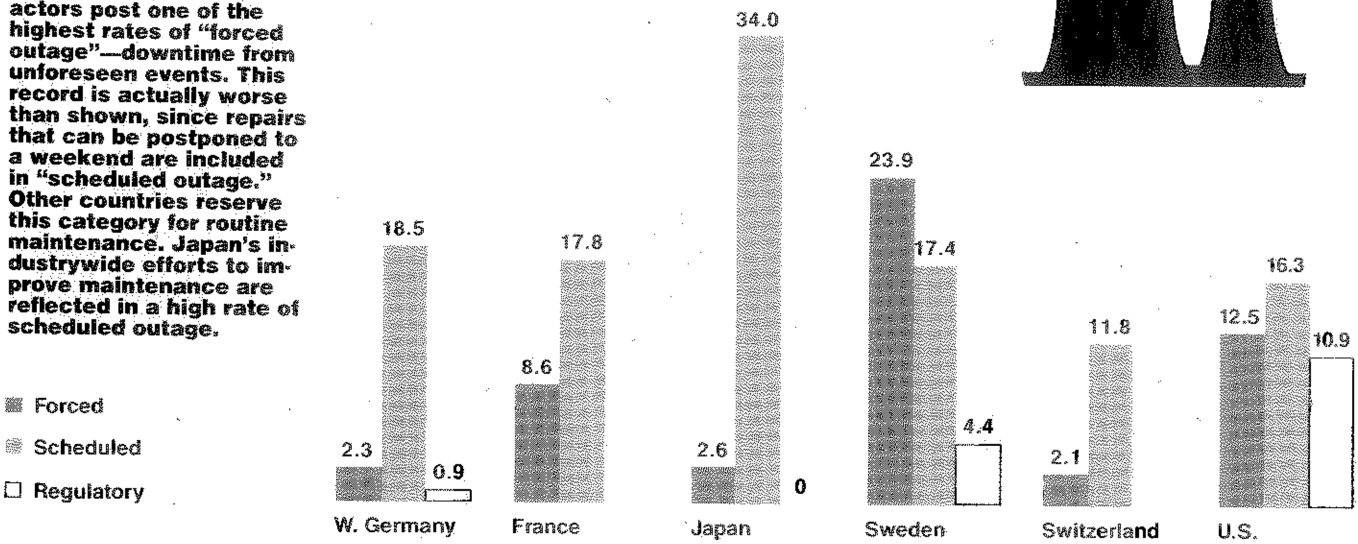
Our study reveals that pressurized-water reactors in only one country—Switzerland—came close to this goal, recording "energy availability" levels of more than 80 percent over 10 years. (Availability measures how much power reactors actually *can* produce as opposed to the amount they *do* produce, since some plants may be on line but not in use.) The Swiss, who operate only 3 PWRs (*see the charts on this page*), are also the most consistent performers, with the difference between their best and worst plants averaging only 8 percentage points during the time of the study. This small difference year after year suggests that all the plants

DIAGRAMS: TOM BRIGGS DESIGN



PWR Downtime (%)

U.S. pressurized-water reactors post one of the highest rates of "forced outage"—downtime from unforeseen events. This record is actually worse than shown, since repairs that can be postponed to a weekend are included in "scheduled outage." Other countries reserve this category for routine maintenance. Japan's industrywide efforts to improve maintenance are reflected in a high rate of scheduled outage.



are well designed, built, operated, and maintained.

West German PWRs also performed well. Reactor ratings in that country declined to under 70 percent in the late 1970s, when utilities decided to strengthen safety systems across the board. After completing these upgrades, the industry boosted energy availability above 80 percent and shrank the difference between the best and worst PWRs from a high of 16 percentage points in 1976 to just under 7 percentage points in 1984.

Japan has posted the most dramatic improvement. Pressurized-water reactors there posted an energy availability of only 35 percent in 1979. In response, the entire industry—utilities, vendors, engineering firms, and government—developed a plan for improving preventive maintenance. This policy paid off in consistently good performance, with energy availability averaging more than 70 percent in the early 80s. The Japanese appear to have continued their improving trend over the past five years.

Sweden, which ran only two PWRs, averaged a low 55 percent availability over 10 years. Problems with steam generators, which other countries also experienced, meant that much of its nuclear capacity was shut down at any given time.

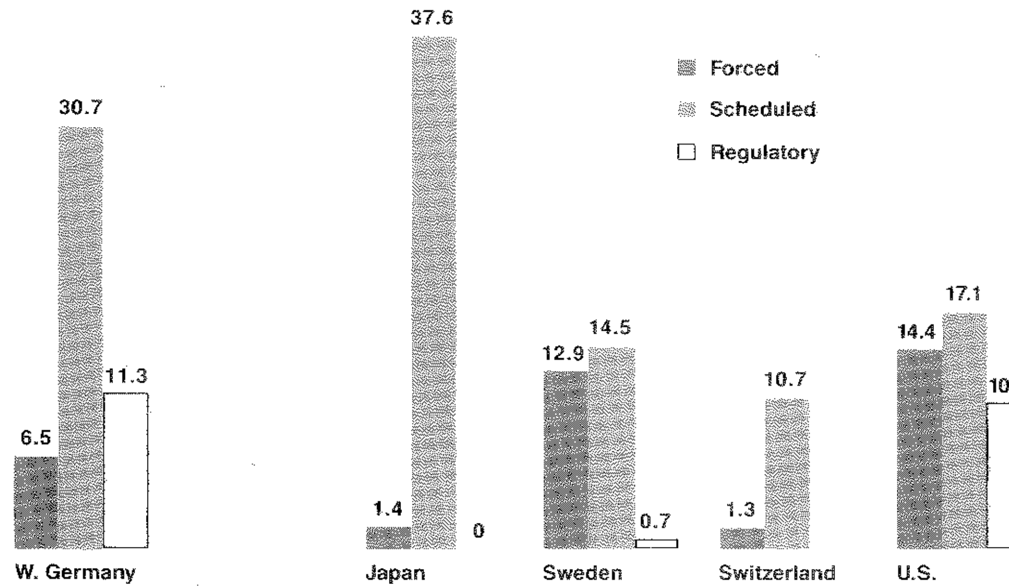
The most striking aspect of the U.S. industry—which had as many pressurized-water reactors (over 50) as the other nations combined—was its great variation in performance. Some plants performed as well as the Swiss plants year after year, others fluctuated from excellent to poor and vice-versa, and some performed consistently badly. Some 6 plants on line for at least 10 years posted a lifetime availability of over 75 percent, while 6 other plants with similar experience functioned in the 40 percent range. Overall U.S. PWRs posted a relatively poor record, averaging only 60 percent energy availability in 1984—the worst of any of the six nations that year. And unlike reactors in the other countries, U.S. nuclear plants did not show an improving trend during the early 80s. This record does not appear to have improved during the past few years.

Results for boiling-water reactors also varied from country to country (*see the charts on page 33*), with Switzerland again achieving the most outstanding results. Sweden's BWRs showed a steadily improving performance second only to Switzerland's. The Germans, in contrast, had more trouble with this type of reactor than with their PWRs.

As with pressurized-water reactors, the U.S. utilities ran over half of the world's boiling-water reactors but posted the weakest energy availability—as low as 50 percent in 1984. Performance showed a general downward trend during the decade.

Regulatory Zeal

Despite complaints by the U.S. industry about the excess zeal of safety regulators, we found that this factor can account for only a small fraction of the poor U.S. performance. Strict safety standards are not unique to the United States. All six countries maintain an independent agency much like the U.S. Nuclear Regulatory Commission (NRC) to set op-



BWR Downtime (%)
Like PWRs, U.S. boiling-water reactors post a high rate of forced downtime. "Regulatory" shutdowns, which result from complying with safety standards, are also high here. The U.S. industry cites this as evidence that regulators are too strict. But safety standards are just as tight elsewhere. Other countries usually consider such shutdowns "forced."

erating guidelines—known as "tech specs," or technical specifications. Tech specs determine, for example, how much radioactive water can leak from a reactor's primary cooling loop to its secondary loop before a plant must shut down. Regulators in all six countries have unambiguous authority to require utilities to close their reactors if they violate tech specs.

What is unique to the United States is a highly antagonistic relationship between regulators and utilities. Many industry people think NRC staff members are technically inept or promoting a hidden agenda. Conversely, regulators often believe that utilities managers are less than forthright in responding to requests and orders, and that some do not make safety a priority. Both regulators and utility managers deplore members of Congress who second-guess every decision, usually garnering a great deal of media attention, and lament a legal process that permits indefinite delay in attempts obtain an operating license.

In other countries, relationships between regulators and utilities may become strained at times, but all parties report that communication is open and forthright, with no group withholding information or acting secretively or vindictively. Regulators do not usually need to prove their strength and independence, and they analyze differences of opinion carefully before taking strong action. Nor do politicians attempt to interfere in regulatory decisions. And the public generally considers regulators responsible and competent, and so makes little attempt—and has little opportunity—to intercede on the grounds that regulators are failing to represent the public interest.

U.S. regulators do occasionally take actions that their counterparts abroad would not. For example, the NRC ordered five plants shut down for several months around the time of the Three Mile Island accident because of concern that some pipes could not withstand serious earthquakes. Later analyses showed the concern was invalid, and the NRC admitted that the shutdown had been unnecessary.

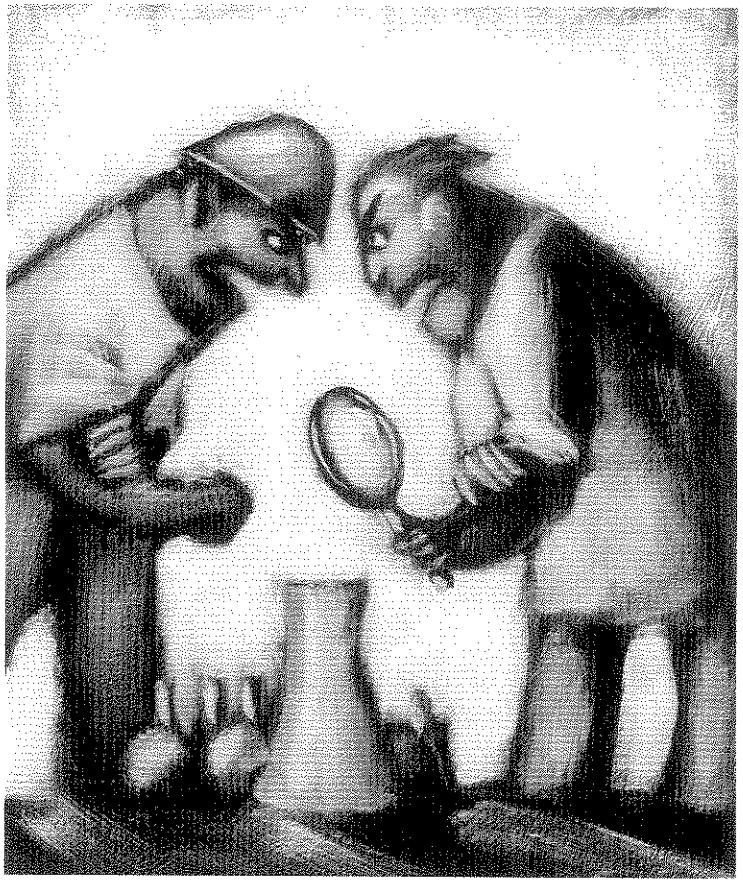
This problem would undoubtedly have been treated differently in other countries. However, we did not find such instances common. Nor did we find that public opinion—another supposed bane of the U.S. industry's existence—affected reactor performance, either in the United States or abroad. The average citizen has little opportunity to intervene after a nuclear plant has begun operating.

U.S. utilities did post one of the highest rates of "outage" caused by safety regulators, losing an average of 10 percentage points of capacity per year. (*See the charts on these pages.*) But these figures may overstate the problem, since they include violations of tech specs.

Other nations define this category differently. They see violations of tech specs as cases where good engineering practice means plants *should* close, and therefore report them as "forced shutdowns"—the category reserved for unforeseen events. France and Switzerland do not even recognize the concept of regulatory loss. In West Germany and Sweden, shutdowns are considered regulatory only when a utility and a regulator do not agree on the need for it.

Not surprisingly, given the overall success of their nuclear programs, Switzerland, Japan, and West Germany show low rates of forced outage—an average 2.5 percentage points of their total PWR capacity per year. The French lost an average of 9 percentage points of capacity annually to forced outage but showed an improving trend in the early 1980s. Sweden's disappointing 24 percent figure for PWRs reflects its problems with steam generators; the country does better with BWRs.

The U.S. industry averages a high rate of forced outage—13 percentage points for PWRs and 15 percentage points for BWRs, and these figures have been high from the beginning of the nuclear program. But the problem may be even worse, since the industry calls repairs that can be postponed to the next weekend "scheduled outages"—the label other countries reserve for plant refueling and maintenance.



One hurdle U.S. utilities face that their overseas counterparts do not is heavy financial scrutiny from state and local regulators.

How Ownership Affects Results

A look at the ownership patterns in different countries reveals that the U.S. nuclear industry does not operate in a uniquely fragmented atmosphere. Some other countries achieve success with almost equally diffuse structures. And different ownership patterns can produce good performance.

Private utilities own most of the U.S. nuclear units. One utility usually heads up a consortium, playing a lead role in management and operations. In 1986 some 54 lead utilities operated nuclear facilities, nearly half of which were responsible for only one unit. The 3 largest utilities of this group—Tennessee Valley Authority, Commonwealth Edison of Chicago, and Duke Power Co.—operated 25 percent of U.S. nuclear capacity.

The Swiss have achieved their impressive record with a diverse system in which four large private utilities own the country's nuclear plants. In Japan, nine private utilities own all the nuclear units. But France has achieved its excellent results with Electricité de France (EDF), a monolithic utility owned by the government.

Swedish ownership of nuclear capacity divides about evenly between public and private utilities, with some municipal and cooperative utilities owning stock in the privately run companies. Similarly, nine large private utilities own most of the nuclear plants in West Germany, although public authorities may hold stock in them.

The relationship of outside contractors to utilities also varies widely among the countries, with no one setup guaranteeing or ruling out success. For example, three countries—France, West Germany, and Sweden—achieved different results using a simple vendor system. One French company, Framatome, designed and built the nuclear steam supply systems (NSSSs) for that country while the utility itself did the rest of the engineering and construction. Kraftwerk Union AG (KWU) or its parent organizations built all the West German plants in our sample, managing the projects from beginning to end. One steam-system vendor, ASEA-ATOM, a Swedish company, dominates the relatively small Swedish market. Both the State Power Board and the various private utilities have done some of their own engineering and construction as well as contracting with ASEA-ATOM.

Utilities in Switzerland, Japan, and the United States all have fragmented relationships with contractors yet produce much different results. None of the three NSSS vendors in Switzerland are Swiss, and a variety of indigenous and foreign suppliers provide engineering and construction services and other major components. In Japan, three companies, part of the industrial consortia Mitsubishi, Hitachi, and Toshiba, provide the NSSS as well as other components and design. Various firms provide engineering and construction services. In the United States, four vendors supply the NSSS. Engineering and construction arrangements span the entire spectrum from, on one extreme, nine firms providing design work to, on the other, eight utilities managing their own construction programs.

Finally, the internal organizations of the utilities themselves vary widely. The depth and breadth of competence within France's monolithic EDF is great, and the central organization makes for ease of communication. The French practice of typically siting four plants at each site also aids in sharing experience and simplifying planning. Typically 900 people operate the plants at each site while more than 700 staff members plan maintenance and refueling from Paris.

Hundreds of employees at the German, Swedish, and Swiss sites not only run the plants but also plan downtime for maintenance and repairs. Headquarters exert relatively little control. Instead, one employee, the site manager, maintains full responsibility and authority for keeping reactors running smoothly and safely. Conversely, the Japanese tend to maintain relatively small utility staffs, relying on contractors for services and supervision. This system reflects the long-lasting relationships between utilities and suppliers.

The U.S. situation is highly varied. Large integrated utilities such as Duke Power and Commonwealth Edison maintain their own operations staffs at the plants while large central staffs deal with engineering, licensing, and planned outages. The smaller utilities often rely heavily on outside contractors for many of these functions.

Clearly, good plant performance does not hinge on any one system.

How Economics Affect Performance

One hurdle that U.S. utilities face and their overseas counterparts generally do not is heavy financial scrutiny from state and local regulators. The oil price shocks of the 1970s had a profound effect on the attitudes of state public utility commissions, or PUCs, which set electricity rates. Today these commissions are under great pressure to keep rates low. They are therefore delving deeper and deeper into utility decision making, questioning the prudency of plant costs and sometimes removing large amounts of money from calculations used to determine rates. The commissions have also begun to look at plant operations as a potential source of inefficiency and excess cost.

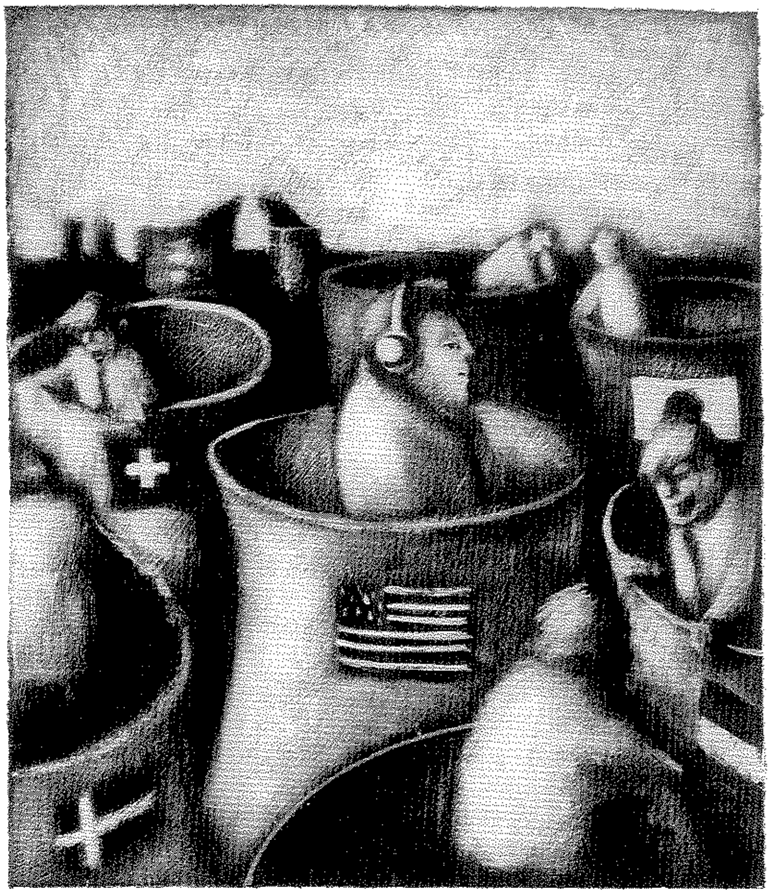
However, we found little evidence that such economic regulation influenced plant performance during the time of the study. This could change as more and more U.S. regulators encourage utilities to pursue "least-cost planning," forcing them to trade long-range performance for short-term savings. If it continues, we believe least-cost planning will prove uneconomical.

Individual plants abroad do not face such economic review, largely because nuclear power is often much cheaper than electricity from fossil fuel. Consumers have long been used to paying high prices for electricity, and authorities set rates for nuclear power that give utilities a good return on their investment.

In France, the government actually makes money for the national treasury from electricity rates. MITI sets electric rates in Japan such that utilities have not had trouble funding new plants or avoiding financial distress. In West Germany, state authorities establish electricity rates based on overall cost to residential and small commercial users, not on the records of individual plants. In Switzerland, local distribution companies buy their electricity from the large suppliers at unregulated prices.

Sweden is the exception to this general rule. Hydropower is much less expensive than nuclear power there, but water supplies vary from year to year. When water is plentiful, the State Power Board sets low electric rates, and private nuclear utilities lose money. When water is scarce, rates go up and nuclear becomes economical.

The cost of electricity from nuclear power versus fossil fuel may help explain the performance gap between U.S. and foreign utilities. This is because the cost of power affects the amount of money utilities can invest in their plants. Owners abroad who spend a lot on the initial plant design will still have an economical source of electricity. U.S. owners, facing close competition from coal, may try to limit their capital investment. Such short-term savings may translate into long-term problems. Unfortunately, since each country keeps track of plant costs differently, we were unable to compare them on a common basis.



Nuclear experts abroad are baffled by the late start the U.S. utility industry has made in exchanging information, improving equipment, and criticizing itself.

Cooperation Beats Antagonism

The foreign experience nearly eliminates external factors as the major cause of the U.S. nuclear industry's woes. It also suggests internal mechanisms for improvement. A key factor in allowing foreign utilities to boost performance has been industry-wide cooperation. Utilities, suppliers, and regulators all work together on what they view as common problems. Nuclear experts in these countries are baffled by the late start the U.S. utility industry has made in exchanging information, improving equipment, and criticizing itself.

In 1980 U.S. utilities took an important first step by creating the Institute of Nuclear Power Operations (INPO), which works with utilities to improve plant performance and safety and maintains a database on these efforts. This database has already helped the industry reduce radiation exposure among workers as well as cut the amount of radioactive waste from reactors. The Electric Power Research Institute has also long coordinated utility R&D. However, neither organization includes suppliers and regulators as members, so the base of information is limited. Given the deep distrust between utilities and regulators, competition among suppliers, and public concern about potential collusion in the industry, cooperation among all parties will not be easy. Nevertheless, experience suggests that it is crucial.

Closer ties between utilities and suppliers would also help. Managers abroad rely on long-term relationships with suppliers for help in planning major changes in plant design and operation. Because support people are often nearby and familiar with a plant, operators can respond quickly to forced outages. The potential benefit is enormous: a 1 percent loss in capacity at a 1,000-megawatt plant costs about $10 million per year in replacement power. Ties with suppliers also allow managers to learn from these firms' experiences at other plants.

Encouraged by public utility commissions, U.S. managers typically solicit competitive bids from many different suppliers to keep operating costs down. This practice undoubtedly achieves short-term savings at the expense of long-term gains.

Our study has convinced us of one other conclusion that is also the most difficult to prove: utilities both here and abroad that show consistently good results operate with a high level of managerial involvement in day-to-day problems. We found that when managers expect top performance from employees and foster an esprit de corps, staff members respond. Others have noticed the same effect. One expert remarked that he could walk into a plant and estimate its performance after five minutes of observation.

Managers can boost their plants' records by maintaining high-quality components, thorough spare-parts inventories, up-to-date instruments for testing and diagnosis, and extensive contacts within the industry. They can also invest in a plant's intellectual resources. U.S. operators must meet certain training levels, but no similar requirements exist for professional staff. Staff members who travel to other utilities are usually top management, not plant operators. Foreign utilities are much more likely to enroll their employees in short, in-house training courses and academic-degree programs, and to exchange employees with other organizations. A similar effort among U.S. utilities is overdue.

Managers would also do well to look to their foreign counterparts for help in solving problems. We sensed little if any interest among U.S. managers in establishing relationships with utilities abroad. Most seemed to feel that the new database created by INPO could provide any information they needed.

We believe that the U.S. industry should merge INPO's efforts with those of similar databases in other countries. Working contacts between middle-level managers in the United States and abroad would also help. Foreign engineers we spoke with professed an admirable willingness to share information and experience. These experts thought highly of INPO's staff and goals, but they did not have frequent or prolonged contacts with the agency. Since foreign nuclear experts believe they are doing a better job than their American counterparts, they are puzzled by the lack of interaction.

Finally, managers in the United States must take vigorous steps to pressure operators of the weakest plants to improve their performance. Many executives seem unwilling to criticize their colleagues. Very often the attitude is one of sympathy in the face of poor results. This is understandable. However, the entire industry is hostage to its worst performers. As long as some plants fail to meet expectations, people will argue that nuclear power is unreliable and expensive.

The industry is now debating whether to adopt "performance indicators" that would be monitored by utility commissions. These standards are controversial because they could infringe on management options, invite political misuse, and encourage trade-offs between safety and performance. Nevertheless, just as high expectations by senior managers influence staff performance, so peer pressure could prove of immense value in motivating specific companies. The U.S. nuclear industry has taken vigorous steps to improve safety via INPO. It should now move firmly to develop a constructive vehicle for candid self-criticism. ■

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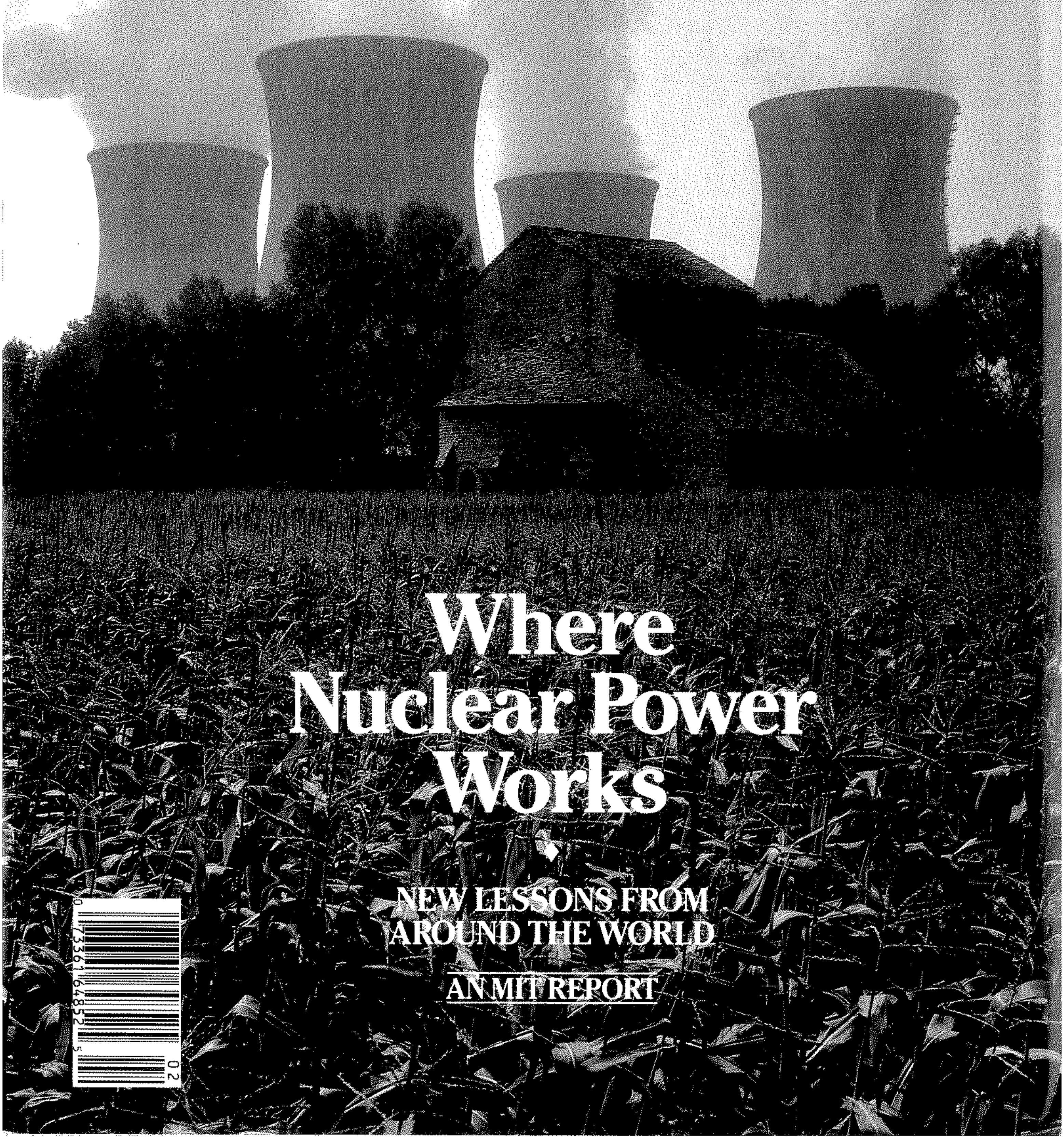

Where Nuclear Power Works

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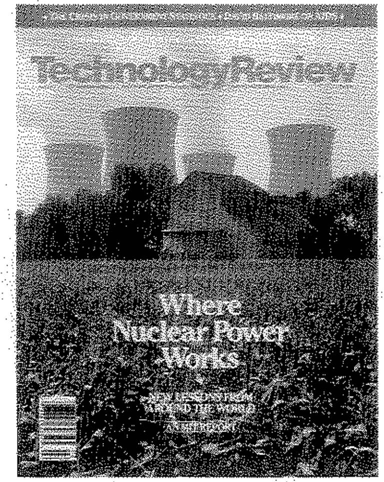

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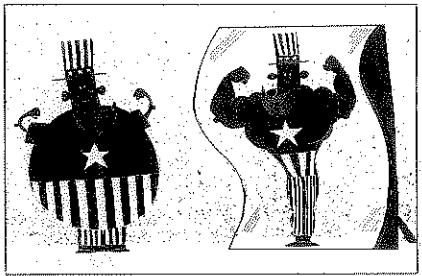

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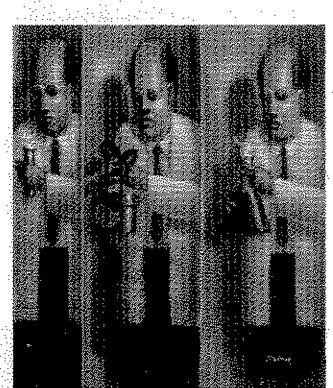

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