e-lab

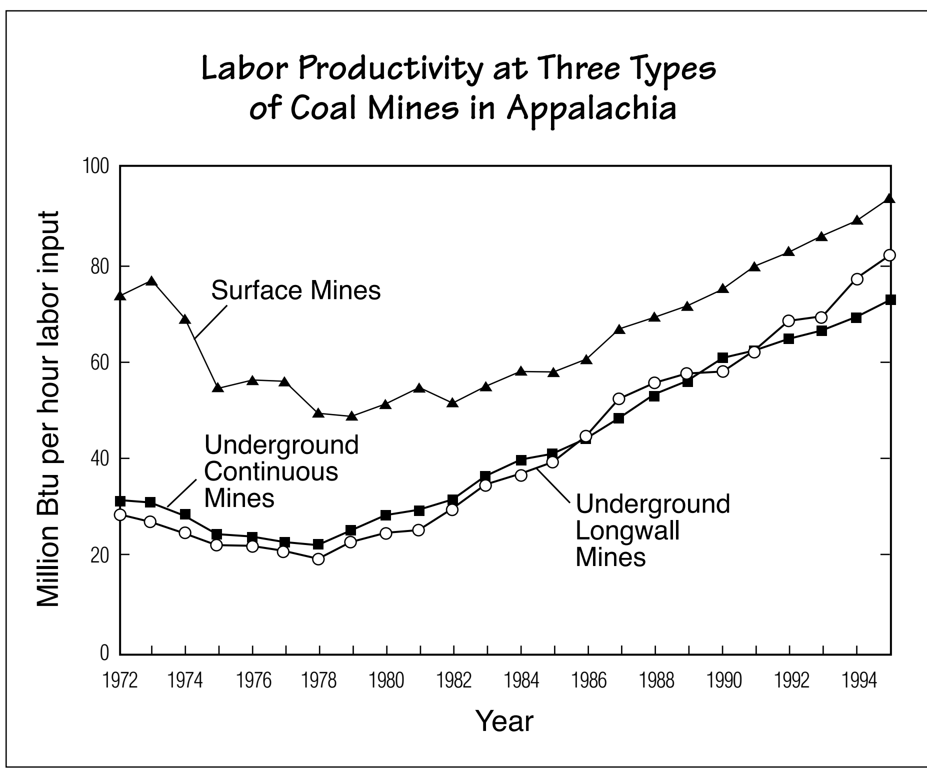
Energy Laboratory research and related activities at the Massachusetts Institute of Technology

July–September 1998

Coal-Mining Productivity: National Aggregates Conceal Large Differences

National statistics on coal-mining productivity show that—except during the 1970s—coal mines have become steadily more efficient. More coal is removed per hour of work, causing a drop in both mining costs and coal prices. However, a new Energy Laboratory study suggests that those national statistics do not tell the whole story. When the researchers analyzed productivity data for more than nineteen thousand mines from 1972 through 1995, they found that some regions and some technologies lagged far behind others. Thus, while western longwall mines were five times more productive in 1995 than in 1972, other types of mines improved by less than half as much—a discrepancy lost in the nationally aggregated data. Detailed analyses of why productivity changed brought some unexpected results. For example, even after accounting for geology and technology, bigger mines were more productive than smaller ones. And prices affect the national aggregates. When coal prices increase relative to labor prices, companies open smaller mines with less favorable geology and overall productivity drops. Indeed, according to the analysis, price increases were more important than new regulations in causing overall productivity to plummet in the 1970s. The study shows that aggregated national productivity data do not provide an accurate picture of the efficiency with which an industry uses its resources or of the causes of changes in overall productivity.

Coal plays an important role in our national well-being: it provides more than a fifth of the energy and half of the electricity consumed in the United States. Much attention therefore focuses on coal-mining productivity: how much coal can be mined for each hour of labor spent? The higher the coal output per



These curves show labor productivity (measured in million Btu produced per hour of labor) from 1972 to 1995 at three groups of Appalachian mines: underground mines using longwall technology, underground mines using continuous technology, and surface mines. After a decline in the 1970s, productivity improved in all three groups. Surface mines are consistently more productive than both types of underground mines. However, over the time period covered, the productivity of the underground mines more than doubled—a much greater increase than experienced by the surface mines.

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hour, the more efficient our use of human and other resources, the lower the cost of mining, and the lower the price of coal.

For the past two years, Dr. A. Denny Ellerman and Professors Thomas M. Stoker and Ernst R. Berndt have been working to understand what determines the labor productivity of coal mining. Historical trends in coal-mining productivity are intriguing. For many decades, productivity steadily increased and prices gradually declined. Then during the 1970s productivity dropped significantly while coal prices rose sharply. By the 1980s prices were again declining and productivity was rising, now at a more rapid pace. Throughout those decades, the total amount of coal mined nationwide rose steadily. What factors were responsible for those trends in productivity?

Studies of productivity in a given industry are generally based on nationwide statistics. Data are aggregated such that a single number represents productivity at all plants, mines, or factories in a given year. But if the individual plants, mines, or factories differ much, they may not be well represented by that aggregate. And coal mines do differ, dramatically. At some mines, the geology is favorable and the coal is easy to remove. At others, the coal is less accessible. Some mines occur at the surface, others underground. And different mines use different types of equipment. Given such variation in individual mines, aggregate productivity data for coal mining—based on total coal produced for total hours spent at all mines—is hard to interpret. For example, if aggregate productivity goes up, are all mines in the group really improving? Or might less productive mines be shutting down and more productive mines be opening up?

In their study, the MIT researchers were able to unravel the characteristics and behavior of the individual mines represented by the aggregate productivity data. The key was an unusually detailed data set. Since 1972, the Mine Safety and Health Administration has collected mine-by-mine data on coal output and labor input as well as location, operator identity, and mining technique.

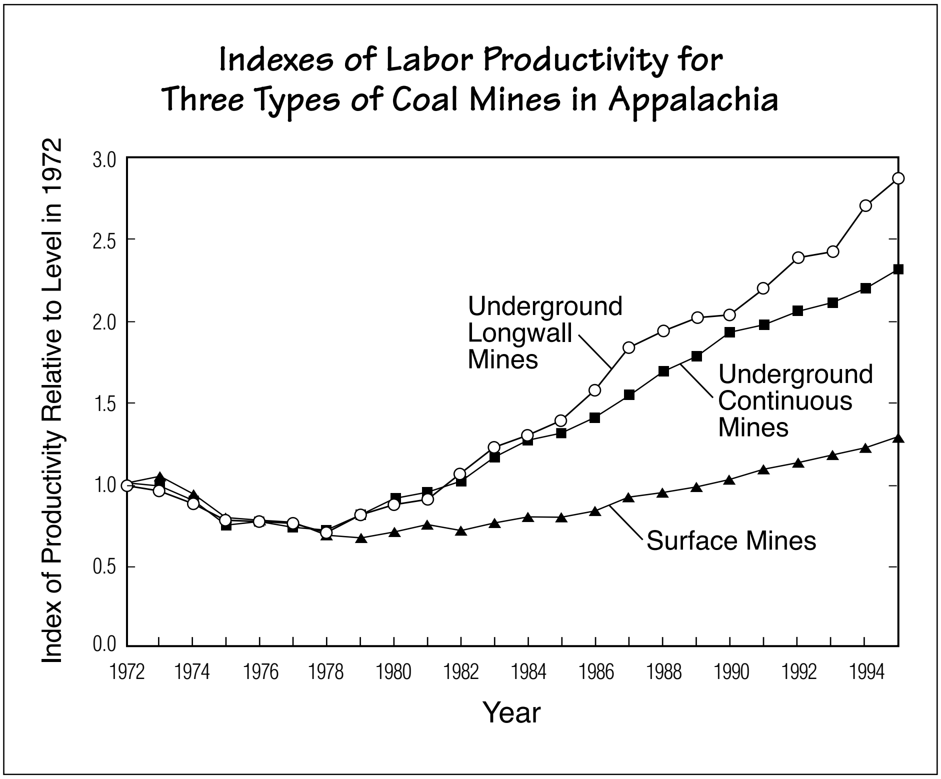
Based on quarterly data, the researchers assembled annual data on coal output and labor input for 19,098 mines from 1972 through 1995. They converted all the output data from tons of coal to Btu—a more meaningful productivity measure, as the heat content of various coals differs considerably. They then sorted mines with similar geography, geology, and technology into eleven groups. One group, for example, includes underground Appalachian mines that use continuous mining technology. Another group includes interior surface mines. Finally, the researchers calculated productivity data for each group based on the total Btu produced and the total hours spent at all mines in that group. Those "subaggregates" should be more meaningful than the conventional national aggregrate because they describe relatively homogeneous groups of mines.

As expected, productivity levels for the eleven groups differ both in value and in how they behave over time. For example, the curves on page 1 show results for the three groups of Appalachian mines: underground mines using continuous technology, underground mines using longwall technology, and surface mines. The surface mines are consistently more productive than the underground mines are—a comparison that holds nationally through almost all of the period covered. One group of surface mines—those in the Powder River Basin (PRB) of Montana and Wyoming—is in a class by itself due to its remarkable geology. In 1995, the PRB group produced about 505 million Btu per labor hour—three times more than the next highest group.

While such comparisons are interesting, the researchers' main focus has been on how productivity changes over time and why. Analysis of their new productivity data shows that the rates at which productivity increased or decreased differ substantially among the eleven groups. The figure on page 3 shows data for the three Appalachian groups. The plotted points represent indexes of productivity change, specifically, productivity in a given year divided by its level in 1972. According to the curves, productivity gradually declined in all three groups of Appalachian mines during most of the 1970s. In the late 1970s, it began to improve. However, it improved far more in underground mines than in surface mines; and underground mines using longwall technology improved more than those using continuous technology. (Keep in mind that, while the underground mines improved more, the surface mines still had higher absolute levels of productivity.)

Data for the rest of the nation show a similar discrepancy between surface and underground mines. Again, longwall underground mines show the greatest improvement, with western longwall mines doing best. Productivity for the western longwall group was fully five times greater in 1995 than in 1972—almost twice the growth in productivity of any other group. Region-to-region differences are also apparent. In general, western mines improved more than Appalachian mines and Appalachian mines more than interior mines. Such insights cannot be gleaned from national data on productivity.

To explore the causes of past changes in productivity, the researchers used special econometric techniques to analyze data for the individual mines within each group. They identified and quantified four factors that influence the level of productivity and together explain why it changes over time.



These curves present changes in labor productivity between 1972 and 1995 in the three groups of Appalachian mines. Individual data points indicate the change from that group's productivity level in 1972. For example, underground mines using continuous technology were about twice as productive in 1991 as they were in 1972. During the 1970s productivity declined in all three groups of mines. Subsequently, productivity improved, especially in the two groups of underground mines. Such differences are not evident in conventional national productivity statistics, which are based on aggregated data for all mines nationwide.

Scale effects: Productivity depends strongly on a mine's level of annual output. Bigger mines tend to be more productive than smaller ones are, regardless of mining technique or geology. Economies of scale are ubiquitous and substantial—a finding not discernible in the researchers' previous work at the industry-wide level.

Fixed effects: Certain fixed characteristics of a mine strongly influence how productive the mine is. Most important are the geology—the width, length, and slope of the coal seam and its accessibility—and the type of equipment installed. (As described above, scale is treated separately.) The impact of such characteristics on a single mine's productivity does not change over time. A mine with favorable geology will always be more productive than a mine with less favorable geology (assuming all else is equal). Because mines open and close over time, the impact of fixed effects on the subaggregate for a given group will change from year to year. When new mines with better coal seams or more advanced equipment begin operating, the fixed-effects factor pushes productivity up for that year. But the impact is not always upward. For example, sometimes less-favorable mines push out more-favorable ones because the former are close to less-expensive transportation.

Price effects: The third important factor influencing productivity is the relationship between the price of labor (the wage rate) and the price of coal. That relationship changes over time and influences which mines operate in a given year. An increase in the price of coal relative to the price of labor leads to the opening of additional mines—typically less-productive, less-economic ones. As a result, overall productivity goes down. A decrease in coal prices tends to push out the least productive mines, and overall productivity goes up.

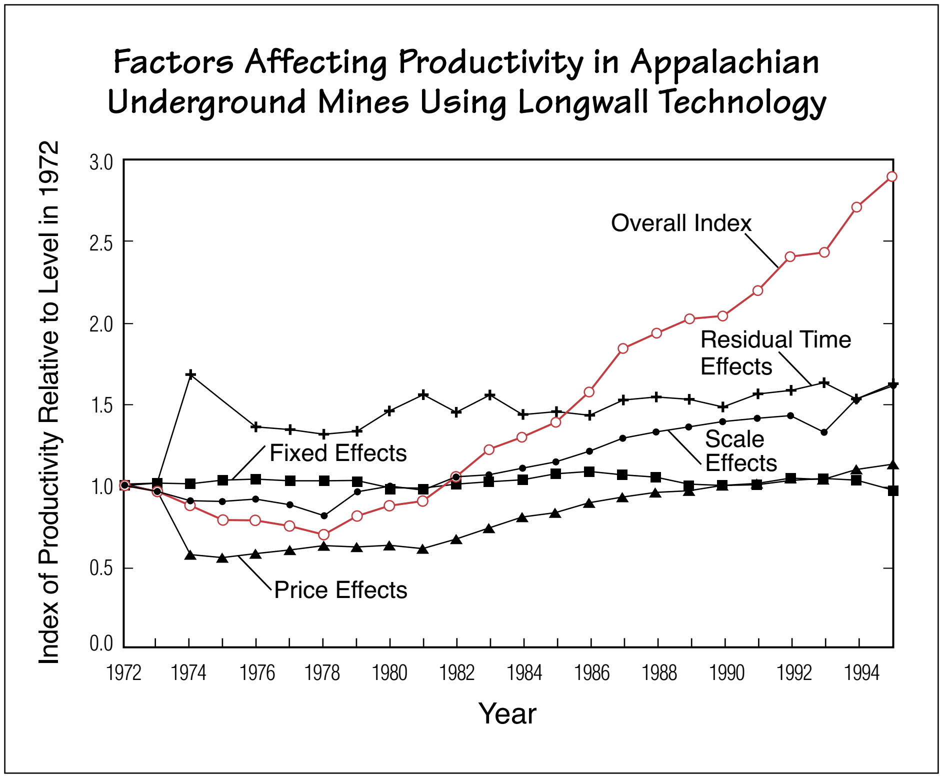
Residual time effects: According to the econometric analysis, the three factors cited above are responsible for most of the observed change in productivity. The rest of the change is caused by several hard-to-quantify factors that change over time and affect all mines. One is resource depletion. As a mine gets older, less-accessible seams have to be exploited and productivity declines. At the same time, techniques and equipment constantly improve, causing productivity to go up. Productivity can also decline due to the imposition of new regulations, for example, requiring land reclamation or additional environmental or health controls.

Based on their mine-by-mine findings, the researchers calculated how much each of those four factors contributed to the observed changes in productivity for the eleven groups of mines. Sample results for one group—Appalachian underground mines using longwall technology—are shown in the figure to the right. The black curves show the impact on productivity of each of the four factors: scale, fixed, price, and residual time effects. Taken together, those effects yield the red productivity curve for that group (the same curve that appears in the figure on page 3).

Combining similar analyses for all eleven groups provides new insight into the causes of the decline in productivity of the 1970s. The conventional explanation is that productivity dropped because of new health, safety, and environmental regulations that were implemented during that period. However, according to the analysis of the eleven groups, prices had an even greater negative impact on productivity. The price of coal relative to the price of labor increased sharply during the 1970s for all regions. As a result, lower-quality geological formations began to be mined and smaller mines opened, pushing productivity down. Equipment continued to improve, but not enough to offset the downward influence of the other effects. Regulations appear to have had a greater effect on surface mines than on underground mines in the years after 1972.

The upturn and subsequent rapid increase in productivity in the 1980s are largely explained by the declining price of coal relative to the price of labor, the closing of less-productive mines, and the opening of larger mines, as well as continuing technological improvement. The process of implementing the new regulations came to an end, and the resulting negative effects on productivity gradually lessened.

The coal-mining study demonstrates the potential difficulties involved in interpreting conventional aggregated productivity data for any industry. If firms, factories, or other units that make up the industry differ substantially in character and behavior, aggregated data can be misleading. And if those units do not compete with one another, the picture is even muddier. During the 1970s, high-productivity western mines increased output at a greater rate than did lower-productivity eastern mines. That shift was not the result of competition—of more-efficient mines capturing market share from less-efficient ones. Instead, it occurred simply because people were moving to the regions served by these mines, the west and the southwest. Thus, aggregate productivity increased because demand changed—not a meaningful gain in the efficiency with which we use our national resources. Clearly, productivity data at all levels must be handled with care.



This figure shows the extent to which four key factors were responsible for productivity changes in underground Appalachian mines using longwall technology. Included in those factors are the level of output (scale effects); the geology and type of equipment used (fixed effects); the impact of new regulations, resource depletion, and "learning" (residual time effects); and the relationship between the price of coal and the price of labor (price effects). The overall index, the red curve, combines the other four curves.

A. Denny Ellerman is a senior lecturer in the Sloan School of Management and executive director of the Center for Energy and Environmental Policy Research. Thomas M. Stoker is the Gordon Y Billard Professor of Applied Economics. Ernst R. Berndt is the Louis E. Seley Professor of Applied Economics. *This research was supported by the Center for Energy and Environmental Policy Research. Further information can be found in reference 1 (on-line at <http://web.mit.edu/ceepr/www/wpabstracts.html#WP-98-004>).*

Reducing Downtime in Nuclear Power Plants

Today, the typical US nuclear power plant spends almost two out of every 18 months shut down for refueling. As owners of such plants face new competition for customers, they are looking for ways to reduce costs; and refueling less often is one option. Working closely with power plant operators, Energy Laboratory researchers have designed reactor cores and operating procedures that would enable power plants to run for up to about four years before needing to refuel. Because of the extra cost of the necessary enriched fuel, adopting a four-year "extended operating cycle" under today's economic conditions would be cost-effective at plants that now experience relatively long downtimes for refueling and forced shutdowns but not at plants that operate more efficiently. A three-year operating cycle requiring less highly enriched fuel would bring savings at many more plants. And if laser-based technology now being developed reduces the cost of enriched uranium, the economics of the extended cycles would improve significantly. Perhaps most important, the MIT team identified strategies that plant operators can use to reduce forced shutdowns and to perform more maintenance procedures while their plants are on-line. The researchers emphasize that any reduction in downtime will not only reduce costs but also prevent possible long-term damage to plants caused by repeated stopping and starting.

To improve their position in the now-competitive electricity market, owners of nuclear power plants would like to reduce the amount of time their plants are not producing power. One reason for such idleness is the need to refuel. Every 18 to 24 months, plants are typically shut down while their operators put in new fuel and perform a variety of maintenance and testing tasks. Such "refueling outages" can mean a month or two of downtime and a serious loss of revenues. The nuclear power company has no electricity to sell. Moreover, to satisfy its customers, it must buy "replacement power" from other electricity generators. If plants could shut down for refueling less often or for a shorter time, the savings could be significant.

For the past three years, an Energy Laboratory team led by Professor Neil E. Todreas has been looking at the technical feasibility and the economic effects of refueling less often. Faculty participants in the study included Professors Michael J. Driscoll, Michael W. Golay, and John E. Meyer. Eleven graduate students contributed to the integrated analysis, as did personnel from Boston Edison Company, the Idaho National Engineering and Environmental Laboratory, PECO Energy, North Atlantic Energy Services Corporation, Studsvik of America, and Yankee Atomic Electric Company (now Duke Engineering & Services). Faculty and students alike went to nuclear power plants to work on-site with utility managers and plant operators.

The potential economic benefit from refueling less often is clear. Suppose a plant shuts down once a year for 40 days of refueling activities. If instead it spends 40 days refueling only once every two years, the average annual downtime for refueling drops to 20 days. Average annual income would increase, everything else being equal.

But everything else is not equal. Perhaps most important, to operate longer without refueling, a plant must be equipped with fuel (uranium) that is more highly enriched than is conventional fuel. Enriching uranium involves increasing the amount of the fissile uranium-235 isotope that naturally occurs. The more highly enriched the fuel, the more costly it is. The economic viability of the extended operating cycle thus depends on whether the savings from postponing refueling offset the added cost of the highly enriched fuel plus the cost of any other technical changes required.

The MIT team's first concern was whether refueling less often would be technically feasible and, if so, what changes would be required. As an example, they considered extending the typical 18-month operating cycle for pressurized water reactors (PWRs) and the increasingly popular 24-month cycle for boiling water reactors (BWRs) to 48 months. They addressed three key questions. Is it possible to design a core that can run that long without replenishing the fuel? Can the testing and maintenance activities now performed during refueling be delayed or performed while the plant is on-line? And can a plant operate that much longer without more and more shutdowns as stressed equipment begins to fail?

The first challenge was to design a reactor core that could generate the required level of electricity for four calendar years and could handle the more highly enriched fuel safely. (The term "calendar years" rather than "operating years" assumes that the plant will sometimes be shut down or operated at less than full power.) Using state-of-the-art computer codes, Professor Todreas and his team designed new cores suited for use in the typical PWR and BWR. Analyses of neutronic behavior and thermal and mechanical fuel performance confirmed that both designs could operate for close to four calendar years without renewing the fuel.

For successful operation, the new cores require fuel that contains more than 7% uranium-235 (U-235) by weight—two to three times more than is contained in the fuel used now. The current regulatory limit for commercial uranium is 5% U-235 enriched. Military and research reactors use uranium that is far more highly enriched, so making the fuel is technically feasible. Commercial use of 7% U-235 fuel would raise regulatory issues and would require changes in procedures and facilities for fuel fabrication, transportation, storage, and disposal. However, the technology to make those changes is proved and available.

Professor Todreas and his colleagues next considered the feasibility of postponing the testing and maintenance procedures that are now typically performed every 18 or 24 months during refueling outages. Working closely with power plant engineers, they analyzed the "surveillance" programs of two typical nuclear plants, one a PWR and the other a BWR. They reviewed the roughly 4,000 surveillance activities that are now performed, from checking valve and containment leak rates and instrument calibrations to testing standby safety equipment to make sure it will operate if necessary.

Analysis of those tasks confirmed that many of them could be delayed until the 48-month refueling. Today's more frequent schedule has arisen simply because the plant is shut down for refueling anyway. Other tasks could be performed on-line—a practice that is already growing in the industry and is preferable for the many standby safety systems that should be available during outages. Only about 1% of all the surveillance activities for the PWR and 4% for the BWR could not be delayed or performed on-line. The MIT team and plant personnel outlined possible engineering solutions for most of those activities, for example, by duplicating certain critical systems so that one could run while the other shuts down for maintenance.

The final technical task was to consider how adopting the extended cycle might affect the forced outage rate (the percentage of time a plant is down due to equipment failure and other problems). Most US nuclear plants experience forced outages. "Record runs" up to 20 months have occurred—but rarely. Certain equipment has been designed for a limited lifetime, so running a plant nonstop for 48 months could well cause the rate of forced outages to increase. Steps must be taken to prevent that outcome.

To identify the common causes of forced outages in today's plants, the researchers examined the US Nuclear Regulatory Commission's database of PWR and BWR plant operation between 1989 and 1995 as well as records from two specific BWR plants run by PECO Energy. As expected, the results showed that most problems were caused by failures not in the nuclear reactor and safety-related systems but in other systems, such as the turbine and its control system and the feedwater system. The research team described strategies that would enable plant operators and designers to reduce such failures.

Very few data exist on failures that occur after about 20 months. Therefore, the researchers recommend that plant operators undertake "age exploration," a procedure now under way at nuclear installations run by the US Navy. After upgrading all the components and systems that have known problems, operators run their plant—with appropriate monitoring and safety shutdown systems in place—until something fails. They then repair and upgrade the failed equipment and resume operation. In time, the weak links in the plant will be gone. The up-front cost of this procedure will be appreciable, but the long-term payoff will be a significant decrease in the forced outage rate.

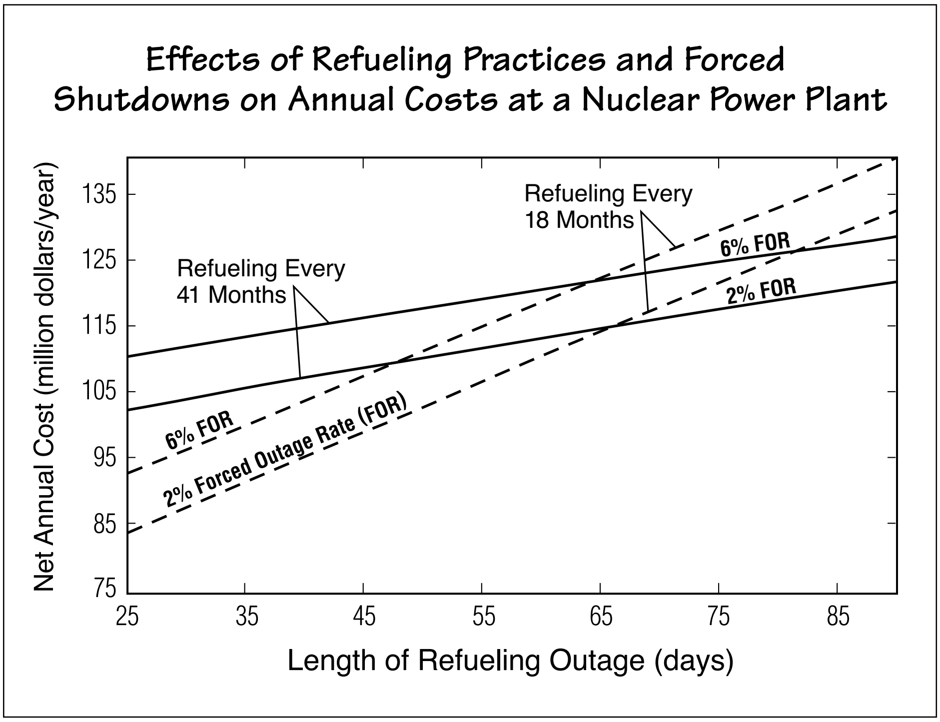
The researchers' conclusions suggest that a four-year operating cycle is technically possible. However, the economic benefits proved less straightforward than expected. The technical analysis suggests that the switch to the longer operating cycle would be accompanied by changes other than just the added fuel cost. In particular, for the longer cycle to be effective, forced outages must not become more frequent. Plant operators would have to ensure that their plants were extremely well run and well maintained—a task with an unexpected impact. In such a smoothly running plant, refueling could no doubt be accomplished more quickly. With the refueling time shorter, buying more costly uranium to refuel less often might not provide a net economic gain.

To assess the economics of switching to the longer operating cycle, the researchers developed an economic model incorporating all the key factors. They made realistic assumptions for the costs of enriched uranium, replacement power, material and personnel during outages, and so on. They then examined how the net annual cost would vary with the frequency of refueling, the time required to refuel, and the forced outage rate.

Sample results for the PWR are shown in the figure to the right. The horizontal axis shows the number of days spent refueling; the vertical axis shows net annual cost. The two dashed lines present results assuming an 18-month operating cycle at forced outage rates of 6% and 2%. The two solid lines present results for an extended cycle of 41 months (a cycle the researchers found technically feasible for PWRs) and the same two outage rates. The results show that, regardless of the forced outage rate, it costs more to refuel every 41 months rather than every 18 months if the time required for refueling is shorter than about 65 days.

Based on such data, the economics of the extended cycle for today's average plant look disappointing. As a reference case representing today's conditions, the researchers assumed an 18-month operating cycle, a refueling time of 49 days, and a forced outage rate of 6%. They then considered a switch to the extended cycle along with a reduction of the refueling time to 42 days and of the forced outage rate to 3%—improved operating conditions that the US fleet of plants is likely to achieve. Such a change would decrease costs at the average PWR only slightly and would actually increase costs at the average BWR.

The researchers also examined a more modest 36-month operating cycle for the PWR, and projected savings proved greater. Such a cycle would require less fuel enrichment. Analyses showed that the 36-month cycle with the improved operating conditions defined above would be $11 million per year less



This figure shows the impact on annual cost of shutting down a typical pressurized water reactor for refueling every 41 months rather than every 18 months, which is usual today. Results are shown for two forced outage rates (the percentage of time the plant is shut down due to equipment failure and other problems). The cost effectiveness of switching to the longer refueling interval varies with the number of days required for refueling. If the refueling outage is relatively short, staying with the 18-month cycle is less expensive than shifting to the 41-month cycle, which requires more expensive fuel and technical changes. If the refueling outage is long, the 41-month cycle looks good. In all cases, reducing the forced outage rate decreases cost substantially. The lowest cost comes at the standard refueling interval, the shortest refueling time, and the minimum forced outage rate.

expensive than the 18-month reference cycle without the improved operating conditions (estimated at $110 million per year). If, however, the 18-month cycle is accompanied by the improved operating conditions, it breaks even with the 36-month cycle. Overall, the researchers conclude that—under present economic conditions—the best means of lowering costs is to stick with the standard operating cycle and minimize both the time needed to refuel and the forced outage rate.

Several external changes could alter the results of the MIT analyses. For example, new technologies such as laser isotope enrichment could reduce the cost of highly enriched uranium. The extended cycle would then become more cost-effective—perhaps even preferable. On the other hand, competition in the new regulatory environment could cause the cost of replacement power to drop, lowering the cost of frequent refuelings.

The study has provided a variety of useful results. It has produced analytical tools that can help plant operators assess what operating cycle is best for their specific situation. It has identified ways for today's operators to reduce the frequency of forced outages and to accomplish many of their surveillance activities on-line. And it has focused new attention on the noneconomic impacts of shutting down nuclear plants. Avoiding forced and refueling outages is still not a top priority for many US plants. Operators assume that forced outages will occur periodically, and they use them as a chance to inspect their plants from top to bottom. Yet outages themselves are known to create technical problems. Operating records show that forced outage rates are typically high for several months after plants have shut down and restarted. Perhaps more important, the process of cooling down and heating up a plant, draining and refilling certain systems, and so on can adversely affect both materials and chemicals inside the plant. Temperature changes are made slowly, and other steps are taken to minimize damage. But no one knows the engineering consequences of such practices over the long term.

Professor Todreas believes that clarifying those long-term consequences should be a top priority for the nuclear power industry. If the long-term impacts of shutdowns are better understood and if technical improvements make forced outages less common, the nuclear industry may begin to place a higher value on less frequent refuelings and on uninterrupted operation in general—an attitude that Professor Todreas believes would improve both the near-term economics and the long-term engineering performance of today's nuclear power plants.

Neil E. Todreas is KEPCO Professor of Nuclear Engineering; Michael J. Driscoll is professor of nuclear engineering, emeritus; and Michael W. Golay and John E. Meyer are professors of nuclear engineering. *This research was funded by the Idaho National Engineering and Environmental Laboratory University Research Consortium.* *Further information can be found in references 2–10.*

News Items

On June 9–11, the Energy Laboratory hosted a summer short course entitled "**ISO Operations Planning and Design**," taught by Dr. Marija Ilić, senior research scientist in the Department of Electrical Engineering and Computer Science, and Mr. Stephen Connors, director of the Energy Laboratory's Electric Utility Program. The course focused on Independent System Operators (ISOs), competitive goals, and overall electric market structure and covered many of the topics in Dr. Ilic's coedited Kluwer text, *Power Systems Restructuring: Engineering and Economics* (see *e-lab*, April–June 1998). Several of the book's contributors gave guest lectures. Companies and organizations sending representatives to the short course included the Edison Electric Institute, Electricité de France, ISO New England, Ontario Hydro, Ottertail Power, the US Department of Energy, Williams, Virginia Polytechnic Institute and State University, and Princeton University.

In early June, the American Institute of Aeronautics and Astronautics (AIAA) named **János M. Beér**, professor of chemical and fuel engineering and a longtime leader of Energy Laboratory combustion research, as the 1998 recipient of the **AIAA Energy Systems Award**. The award is presented for a significant contribution in the broad field of energy systems, specifically as related to the application of engineering sciences and systems engineering to the production, storage, distribution, and conservation of energy. Professor Beér was cited for his "distinguished contributions as an educator, researcher, and consultant in techniques, development, and applications in the field of combustion."

PUBLICATIONS AND REFERENCES

The following publications of Energy Laboratory and related research were released during the past period or are cited as references in this issue. The **Center for Energy and Environmental Policy Research** (http://web.mit.edu/ceepr/www/) and the **MIT Joint Program on the Science and Policy of Global Change** (http://web.mit.edu/globalchange/www/) provide most of their documents on-line. Instructions for ordering paper copies can be found at those World Wide Web sites or by telephoning 617-253-3551 for Center publications and 617-253-7492 for Joint Program publications. **MIT theses** may be ordered from Library Document Services, MIT, Room 14-0551, Cambridge, MA 02139-4307. Other publications may be ordered from Energy Laboratory Publications, MIT, Room E40-473, Cambridge, MA 02139-4307, *only* if a price is assigned and *only* if prepaid by check payable to "MIT Energy Laboratory." Prices are postpaid surface mail. For air delivery, add 15% to US, Canada, and Mexico, and 30% elsewhere. A list of publications is available on request.

Reports and Working Papers

Adelman, M. *Crude Oil Supply Curves*. June 1998. Center for Energy and Environmental Policy Research Working Paper No. MIT-CEEPR 98-008WP. 7 pages.

Connors, S. *Issues in Energy and Sustainable Development.* September 1998. Energy Laboratory Report No. MIT-EL 98-004. 14 pages. $10.00

Connors, S. *Societal Issues in Transitioning Toward Sustainable Systems*. September 1998. Energy Laboratory Working Paper No. MIT-EL 98-001WP. 14 pages. $10.00 (Also Rapporteur's paper, 17th World Energy Congress, Houston, Texas, September 13–18, 1998. Issues Paper Session 4.2.)

Ellerman, A. *Electric Utility Response to Allowances: From Autarkic to Market-Based Compliance*. July 1998. Center for Energy and Environmental Policy Research Working Paper No. MIT-CEEPR 98-009WP. 14 pages.

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Montero, J., and A. Ellerman. *Explaining Low Sulfur Dioxide Allowance Prices: The Effect of Expectation Errors and Irreversibility*. September 1998. Center for Energy and Environmental Policy Research Working Paper No. MIT-CEEPR 98-011WP. 23 pages.

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Other Publications

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Energy Choices for a Greenhouse Gas Constrained World	Kawasaki Heavy Industries Ltd.; Mobil Oil Corp.	L. Glicksman *(Architecture and Mechanical Engineering)*
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Energy Prices, Investment, and Environmental Policy	CEEPR	R. Pindyck *(Sloan School of Management)*
New Markets in the Electricity Sector	CEEPR	P. Joskow *(Economics)*

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Massachusetts Institute of Technology
Energy Laboratory
Room E40-479
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