

The LMFBR will provide more energy because it follows throughout the world with a greater per-  
 is consumed per person. A similar pattern will be  
 the population of the U.S. increases and more power  
 which shows the growth in energy requirements as  
 from nuclear resources. The fact that such addi-  
 tional energy is required is indicated by Table 8,  
 which shows the increase in available energy it provides  
 the most important long-term advantage of the  
 Available Nuclear Energy

case with enriched uranium reactors.  
 material or an active separation process, as is the  
 a continuing supply of either large amounts of raw  
 the country with respect to another country by retaining  
 advantage with respect to another country by retaining  
 ly and self-generated. The LMFBR does not place  
 by LMFBR ability to provide essentially limitless  
 Worldwide interest and investment is motivated  
 construction schedules.

England, and France but are behind them in plant  
 technology in the sodium-reactor field with Russia,  
 water reactor technology, we now have competitive  
 in contrast to the lead which the U.S. had in  
 U.S.

competitive, viable, and economic industry in the  
 government-utility-industry program is to develop a  
 and plant. The ultimate objective of the cooperative  
 project definition phase permits some work on a re-  
 construction and funding. AEC authority under the  
 after the first demonstration plant is committed for  
 will probably be larger, with authorization arranged  
 at reactor has not yet been specified but the unit  
 Power output for the second demonstration breed-  
 wealth Edison.

Financial benefits to society from the LMFBR  
 might best be summarized by an AEC cost-benefit  
 analysis which indicates benefits to the nation over a  
 10-year period of \$21.5 billion, discounted at 7 per-  
 cent to mid-1971. Other specific LMFBR benefits to  
 society will be described in the sections that follow.

The Plans for LMFBR Plants

World status and plans for LMFBR power plants  
 are given in Table 2, which lists LMFBR projects  
 that are operable (7), under construction (6),  
 planned (9), and decommissioned (4), with country  
 location, megawatts thermal and electric, and initial  
 operation date. Table 2 also shows whether a loop  
 or pool configuration is used.

Present plans for the U.S. LMFBR program in  
 the 1970s consist of completion of the 400-MW Fast  
 Flux Test Facility (FFTF) on the ARZ at Hanford  
 reactor in the state of Washington. It will not  
 produce electric power but will test heat to an air  
 heat exchanger. Its development will provide base  
 technology applicable to LMFBRs and associated in-  
 dustry experience needed in order to supply the com-  
 ponents and systems for such a plant. The reactor  
 will contain closed loops for advanced fuel tests,  
 which will be isolated from process sodium in the  
 main reactor coolant loop so that fuel failures will  
 not harm the reactor.

In addition to FFTF, the highest priority U.S.  
 LMFBR program for the 1970s is construction of the  
 two demonstration plants mentioned by President

The request for proposal for the first demonstra-  
 tion plant specified a power level between 300 and  
 500 MW (approximately 350 MWe). Approximately  
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can utilize approximately 75 percent of the energy  
 available from uranium ore compared with less than  
 2 percent utilization capability for enriched-uranium  
 light-water reactors.

At present, therefore, over 95 percent of the poten-  
 tial energy available from uranium ore is not utilized  
 but is rejected as uranium 238 in burned-out fuel or  
 as waste tailings of depleted uranium at the diffusion  
 plants. By 1980 tailings produced during the pro-  
 cess of supplying enriched fuel for the light-water re-  
 actors will reach over 250,000 tons of depleted urani-  
 um. Since a 1000-MW electric plant of the LMFBR  
 type burns up less than a ton of uranium per year,  
 250,000 tons would supply today's total U. S. power

requirements of about 300,000 MWe for centuries.  
 The LMFBR obtains more energy from uranium  
 by converting uranium 238 to plutonium and then  
 fissioning it. A gram of plutonium fissioned in a fast  
 breeder reactor provides approximately 50 percent  
 more Btu's than would the same gram of plutonium  
 if fissioned in a thermal neutron reactor. This oc-  
 curs because of the greater efficiency of fission in the  
 fast reactor, which does not permit as much parasitic  
 absorption of neutrons in plutonium as occurs in the  
 thermal reactors. Also, about twice as much urani-  
 um 238 is fissioned directly by fast neutrons in the  
 fast reactor as in the thermal neutron reactors.  
 The thermodynamic efficiency for conversion of

TABLE 2 Liquid-Metal-Cooled Fast-Reactor Projects

| Name                  | Country                 | Power             |         | Pool or Loop  | Initial Operation |
|-----------------------|-------------------------|-------------------|---------|---------------|-------------------|
|                       |                         | MWt               | MWe     |               |                   |
| <b>Operable</b>       |                         |                   |         |               |                   |
| BR-5                  | U.S.S.R.                | 5 <sup>a</sup>    | —       | Loop          | 1959              |
| DFR                   | U. K.                   | 72                | 14      | Loop          | 1959              |
| EBR-II                | U. S.                   | 62.5              | 16      | Pool          | 1963              |
| FERMI                 | U. S.                   | 200               | 60.9    | Loop          | 1963              |
| RAPSODIE              | France                  | 40                | —       | Loop          | 1967              |
| SEFOR                 | U. S.                   | 20                | —       | Loop          | 1969              |
| BR-60 (BOR)           | U.S.S.R.                | 60                | 12      | Loop          | 1970              |
| <b>Under Constr.</b>  |                         |                   |         |               |                   |
| BN-350                | U.S.S.R.                | 1000 <sup>b</sup> | 150     | Loop          | 1972              |
| PFR                   | U. K.                   | 600               | 250     | Pool          | 1972              |
| PHENIX                | France                  | 600               | 250     | Pool          | 1973              |
| FFTF                  | U. S.                   | 400               | —       | Loop          | 1974              |
| JOYO                  | Japan                   | 100 <sup>c</sup>  | —       | Loop          | 1974              |
| BN-600                | U.S.S.R.                | 1500              | 600     | Pool          | 1976              |
| KNK-11                | W. Germany              | 58                | 20      | Loop          | 1973              |
| PEC                   | Italy                   | 140               | —       | Modified pool | 1976              |
| SNR                   | W. Germany <sup>d</sup> | 730               | 300     | Loop          | 1977              |
| DEMO NO. 1            | U. S.                   | 750-1250          | 300-500 | Loop          | 1977              |
| MONJU                 | Japan                   | 750               | 300     | Loop          | 1978              |
| DEMO NO. 2            | U. S.                   | 750-1250          | 300-500 | Not decided   | 1979              |
| CFR                   | U. K.                   | 3125              | 1320    | Not decided   | 1979              |
| PHENIX 1000           | France <sup>e</sup>     | 2500              | 1000    | Pool          | 1979              |
| SNR 2000              | Germany <sup>e</sup>    | 5000              | 2000    | Loop          | 1983              |
| <b>Decommissioned</b> |                         |                   |         |               |                   |
| CLEMENTINE            | U. S.                   | 0.025             | —       | Loop          | 1946              |
| EBR-I                 | U. S.                   | 1                 | 0.2     | Loop          | 1951              |
| BR-2                  | U.S.S.R.                | 0.1               | —       | Loop          | 1956              |
| LAMPRE                | U. S.                   | 1                 | —       | Loop          | 1961              |

<sup>a</sup>To be increased to 10 MWt in 1972.  
<sup>b</sup>Dual purpose; 150 MWe for electric power and 200 MWe equivalent for desalination.  
<sup>c</sup>To be operated at 50 MWt initially.  
<sup>d</sup>In cooperation with Belgium and The Netherlands.  
<sup>e</sup>Tripartite effort: France, German and Italian electric utilities.

The LMFBR obtains more energy from uranium by converting uranium 238 to plutonium and then fissioning it. A gram of plutonium fissioned in a fast breeder reactor provides approximately 50 percent more heat than would the same gram of plutonium fissioned in a thermal neutron reactor. The reason for this is because of the greater efficiency of fission in the fast reactor, which does not permit as much parasitic absorption of neutrons in plutonium as occurs in the thermal reactor. Also, about twice as much uranium 238 is fissioned directly by fast neutrons in the fast reactor as in the thermal neutron reactor.

TABLE 2 Liquid-Metal-Cooled Fast Reactor Projects

| Year | Initial Operation | Type       | Power   |          | Country    | Name        |
|------|-------------------|------------|---------|----------|------------|-------------|
|      |                   |            | MWt     | MWe      |            |             |
| 1981 | Loop              | U.S.       | 1       | 0.1      | U.S.       | LAMPRE      |
| 1981 | Loop              | U.S.       | 1       | 0.1      | U.S.       | EBR-1       |
| 1981 | Loop              | U.S.       | 0.5     | 0.5      | U.S.       | CLEMENTINE  |
| 1986 | Loop              | U.S.       | 0.05    | 0.05     | U.S.       | CLEMENTINE  |
| 1988 | Loop              | Germany    | 2000    | 2000     | Germany    | SNR 2000    |
| 1988 | Loop              | France     | 1000    | 1000     | France     | PHENIX 1000 |
| 1979 | Pool              | U.K.       | 1350    | 3125     | U.K.       | CFR         |
| 1979 | Not decided       | U.S.       | 300-800 | 150-1500 | U.S.       | DEMO NO. 2  |
| 1979 | Not decided       | Japan      | 300     | 750      | Japan      | MONJU       |
| 1978 | Loop              | U.S.       | 300-800 | 150-1500 | U.S.       | DEMO NO. 1  |
| 1977 | Loop              | W. Germany | 300     | 750      | W. Germany | SNR         |
| 1977 | Loop              | Italy      | 140     | 140      | Italy      | FEC         |
| 1978 | Loop              | W. Germany | 58      | 58       | W. Germany | KWK-11      |
| 1978 | Loop              | U.S.       | 600     | 1800     | U.S.       | BN-800      |
| 1978 | Pool              | Japan      | 100     | 100      | Japan      | JOYO        |
| 1974 | Loop              | U.S.       | 400     | 400      | U.S.       | FTT         |
| 1974 | Loop              | France     | 280     | 600      | France     | PHENIX      |
| 1973 | Pool              | U.K.       | 600     | 600      | U.K.       | PF3         |
| 1973 | Pool              | U.S.       | 250     | 600      | U.S.       | BN-350      |
| 1973 | Loop              | U.S.       | 150     | 1000     | U.S.       | U.S.S.R.    |
| 1970 | Loop              | U.S.       | 15      | 60       | U.S.S.R.   | BR-60 (BOR) |
| 1969 | Loop              | U.S.       | 50      | 50       | U.S.       | SEFOR       |
| 1969 | Loop              | France     | 40      | 40       | France     | RAPSODIE    |
| 1967 | Loop              | U.S.       | —       | 40       | U.S.       | —           |
| 1967 | Loop              | U.S.       | 60.9    | 200      | U.S.       | FERM        |
| 1963 | Loop              | U.S.       | 18      | 82.5     | U.S.       | EBR-II      |
| 1959 | Loop              | U.K.       | 14      | 75       | U.K.       | DFR         |
| 1959 | Loop              | U.S.S.R.   | —       | 5*       | U.S.S.R.   | BR-5        |

\*To be increased to 10 MWt in 1972.  
 \*Dual purpose, 150 MWt for electric power and 200 MWt equivalent for desalination.  
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can utilize approximately 75 percent of the energy available from uranium ore compared with less than 5 percent utilization capability for enriched-uranium light-water reactors. At present, therefore, over 96 percent of the potential energy available from uranium ore is not utilized but is rejected as waste heat in burned-out fuel or as waste fission products. By 1980, however, the production of enriched fuel for the light-water reactor will reach over 200,000 tons of depleted uranium. Since a 1000-MW electric plant of the LMFBR type burns up less than a ton of uranium per year, 200,000 tons would supply today's total U.S. power requirements of about 300,000 MWe for centuries.

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TABLE 3 U. S. Electric-Utility Power Statistics

|  | Actual |      |      | Projections for |       |       |
|--|--------|------|------|-----------------|-------|-------|
|  | 1950   | 1960 | 1970 | 1980            | 1990  | 2000  |
| Population (millions)                    | 152    | 181  | 205  | 234*            | 270*  | 305*  |
| Total power capacity (millions of kw)    | 69     | 168  | 340  | 665*            | 1260* | 2100  |
| kw capacity/person                       | 0.45   | 0.93 | 1.6  | 2.8             | 4.7   | 6.9   |
| Power consumed per person per year (kwh) | 2200   | 4200 | 7300 | 13000           | 22000 | 33000 |
| Total consumption (trillion kwh)         | 0.33   | 0.75 | 1.5  | 3.1*            | 5.9*  | 10*   |
| Nuclear power capacity (millions of kw)  | 0      | 0.3  | 7.5  | 150             | 475*  | 1100  |
| Nuclear power, percentage of total       | 0      | 0.2% | 2%   | 23%             | 38%   | 50%   |

\*Bureau of the Census Report Series P-25, No. 470, 11/71  
 \*FPC.

heat to electric power in an LMFBR is 40 percent, as compared with the 33 percent typical for a light-water reactor; hence more electric power is produced per kilogram of uranium fissioned.

Economic Power

The key to the breeder's potential for low overall power-generation costs is its fuel cycle and high thermal efficiency. Whereas light-water-reactor energy is supplied mainly by fission of the rare isotope uranium 235, the breeder reactor is more economically fueled with plutonium and actually produces more than it consumes. With a breeding ratio of 1.3, the breeder produces 1.3 atoms of fissile plutonium from the abundant isotope uranium 238 for every atom of fissile plutonium it consumes, and thus doubles its

inventory of plutonium approximately every 12 years.

Fuel-cycle costs are given in Table 4. As can be seen from the table, the fuel-cycle costs for the LMFBR are capital-intensive: the cost of plutonium inventory is the major component of the fuel-cycle cost. Because of this capital-intensive nature of the fuel cycle, the cost of incremental kilowatt-hours is very low; hence the LMFBR nuclear power plant will be dispatched on any power system as a base-load plant.

The statement is commonly made that the capital cost for the LMFBR power plant will be greater than that for a water reactor, and this is indicated by considerations of an additional intermediate loop of sodium as well as by learning- or experience-curve considerations. Market predictions are such that total megawatts of electric experience for the LMFBR might not be comparable with that of water reactors until the year 2000; hence the LMFBR will not have progressed as far down its learning curve as the water reactors until 2000. Despite these considerations, however, the unit costs of LMFBR heat-generating systems do not have to be as low as water reactors, since the LMFBR, because of its greater thermal efficiency, does not handle as much heat energy as a water reactor to produce the same electric power. Since the water reactor must produce approximately 30 percent more heat power than the LMFBR to produce the same amount of electrical power, the LMFBR capital cost per unit megawatt thermal could be 30 percent higher for heat-handling components of the LMFBR and still produce electric power with the same associated capital for total electric power plant. For these reasons, economic competitiveness of the LMFBR is considered just a question of time, development, and experience.

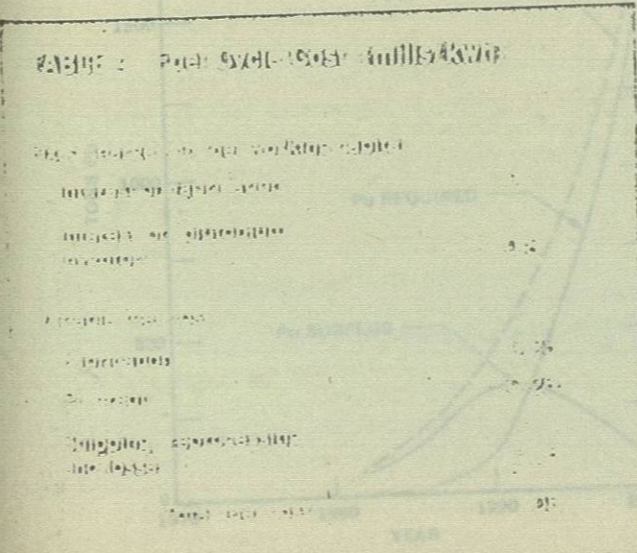


TABLE 3 U.S. Electric-Utility Power Statistics

| Percentage of total nuclear power | Actual |      | Projections for |       |       |       |
|-----------------------------------|--------|------|-----------------|-------|-------|-------|
|                                   | 1970   | 1975 | 1980            | 1985  | 1990  | 2000  |
| 0.5%                              | 0.5%   | 2%   | 23%             | 38%   | 50%   | 50%   |
| 0                                 | 0      | 0.3  | 0.5             | 1.0   | 1.5   | 2.0   |
| 0.33                              | 0.33   | 0.78 | 1.2             | 1.7   | 2.2   | 2.7   |
| 2300                              | 4300   | 7300 | 13000           | 22000 | 33000 | 33000 |
| 0.45                              | 0.93   | 1.6  | 2.8             | 4.7   | 6.9   | 6.9   |
| 69                                | 169    | 340  | 682             | 1260  | 2100  | 2100  |
| 181                               | 305    | 505  | 734             | 1070  | 1500  | 1500  |
| 152                               | 181    | 205  | 234             | 270   | 305   | 305   |

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Capital Investment

As breeder plants are put on line in the 1980s and 1990s and the effects of plutonium production are felt, the demand for enriched uranium and hence for uranium ore to feed the diffusion plants will increase less rapidly. This occurs not only because the fast breeder does not require enrichment from the diffusion plant but because the breeder also provides plutonium that can be utilized in the thermal reactors to provide enrichment instead of uranium 235 from the diffusion plants.

Plutonium available and required in the U. S. is given in Fig. 1. As can be seen, there is a surplus of plutonium with respect to inventory requirements for LMFBR reactors. In fact, LMFBR inventory requirements do not exceed the plutonium available from water reactors until the early 1990s, at which time excess plutonium from LMFBRs will provide inventory for new plants. This means that breeding ratios and doubling times for LMFBRs in the early years can be based on economic considerations rather than doubling time of the utility industry.

Since, as was mentioned before, approximately 250,000 tons of uranium will exist as tailings at the diffusion plants by 1980, this would supply all the uranium requirements of the fast breeder reactor for hundreds of years. The uranium hexafluoride tailings contained in cylinders at the diffusion plants are an energy source in proper chemical form waiting to be used for fuel processing and fabrication. As the uranium 238 becomes useful, it reduces requirements for prospecting for new uranium-ore reserves and the capital associated with putting in the mines and the chemical-upgrading plants associated with them.

Fig. 1 Plutonium availability.

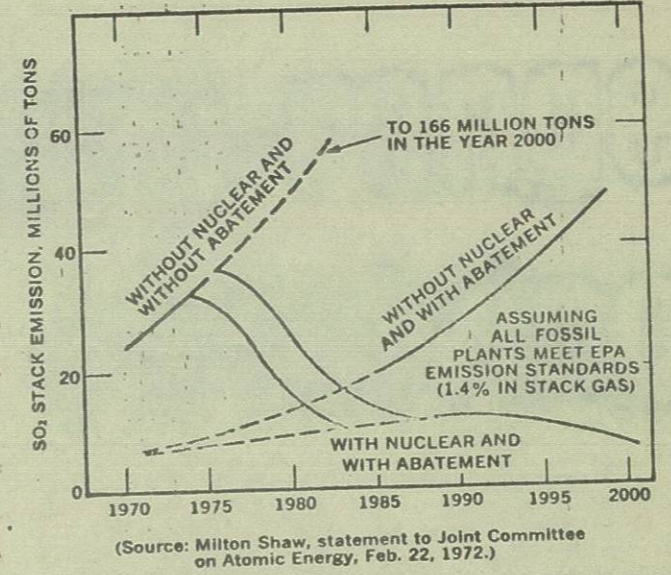
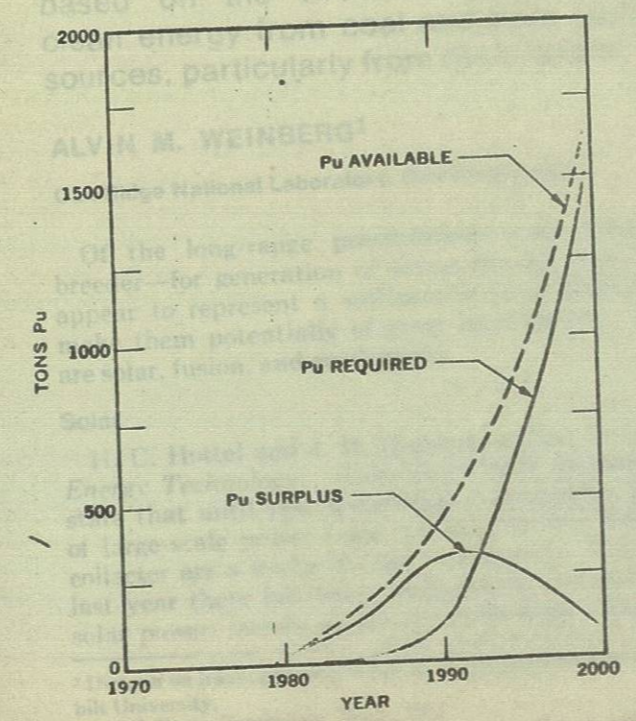


Fig. 2 Projected sulfur dioxide annual stack emissions from U. S. electric power plants.

In addition, the need for additional isotope separation plants also decreases. Since the three diffusion plants built in the U. S. cost approximately \$1 billion each, this is a major capital consideration. Put in other terms, about \$15 capital is required in diffusion-plant capacity for each kilowatt electric of installed enriched-uranium reactors. This requirement will be eliminated eventually for the LMFBR. However, the LMFBR will not come on stream fast enough to influence separative work requirements until the late 1980s. If all water reactors were retired after 30 years and replaced by LMFBRs and all new capacity were supplied by LMFBRs, the diffusion-plant load would go essentially to zero in the year 2020. New isotope separation plants will be needed in the early 1980s and will not be influenced by the LMFBR.

Environmental Effects

Figure 2 shows the projected annual sulfur dioxide stack emission from U. S. fossil-fuel electric power plants and how it is reduced dramatically by nuclear power. The chemical-emission benefits claimed for nuclear occur whether the plant is an LMFBR or a water-type reactor, and the benefit is dramatic and can be useful to society.

Summary

LMFBR provides benefits to the world in terms of greatly increased energy resources. The additional energy supplements the fossil-fuel energy reserves and greatly increases the potential for production of useful power from the nuclear-energy reserves already available. A cost-benefit analysis by the AEC indicates benefits to the U. S. over a 34-year period of \$21.5 billion, discounted at 7 percent to mid-1971. The higher temperatures involved provide greater thermal efficiency, which reduces the effect of heat rejection to the environment.