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 potential 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 process of supplying enriched fuel for the light-water reactors will reach over 250,000 tons of depleted uranium. Since a 1000-MW electric plant of the LMFBR type burns up less than a ton of uranium per year, 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 occurs 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 uranium 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		
Operable					
BR-5	U.S.S.R.	5[a]	—	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
Under Constr.					
BN-350	U.S.S.R.	1000[b]	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[c]	—	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[d]	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[e]	2500	1000	Pool	1979
SNR 2000	Germany[e]	5000	2000	Loop	1983
Decommissioned					
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

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

TABLE 3 U. S. Electric-Utility Power Statistics

	Actual			Projections for		
	1950	1960	1970	1980	1990	2000
Population (millions)	152	181	205	234[a]	270[a]	305[a]
Total power capacity (millions of kw)	69	168	340	665[b]	1260[b]	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[b]	5.9[b]	10[b]
Nuclear power capacity (millions of kw)	0	0.3	7.5	150	475[b]	1100
Nuclear power, percentage of total	0	0.2%	2%	23%	38%	50%

[a] Bureau of the Census Report Series P-25, No. 470, 11/71

[b] 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 4 Fuel-Cycle Cost (mills/kWh)

[illegible]

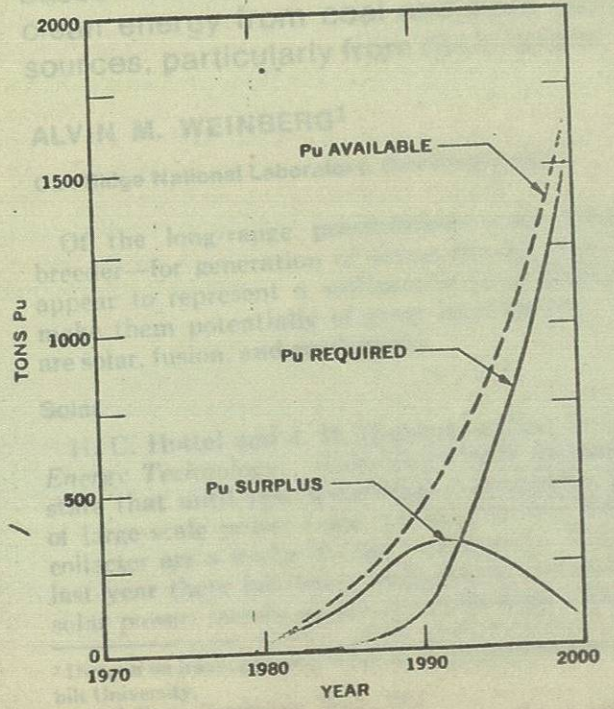
Capital Investment

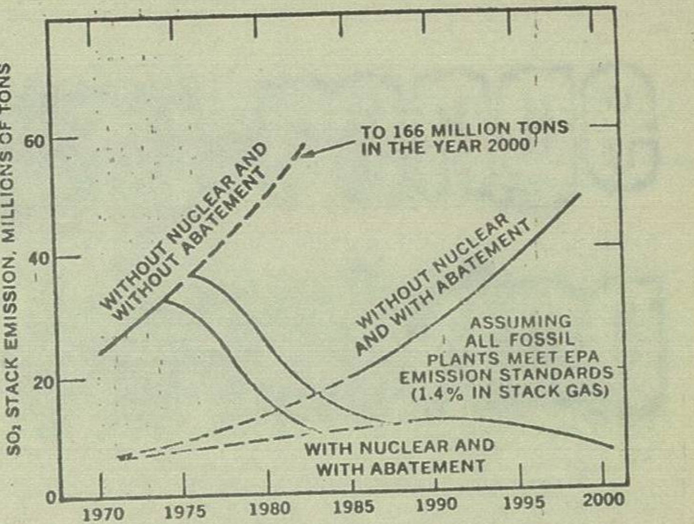
As breeder plants are put on line in the 1980s and 1990s and the effects of plutonium production are felt, the demand for enriched uranium and hence for uranium ore to feed the diffusion plants will increase less rapidly. This occurs not only because the fast breeder does not require enrichment from 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.





(Source: Milton Shaw, statement to Joint Committee on Atomic Energy, Feb. 22, 1972.)

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.