Liquid-metal fast reactors: Technical and economic status

Significant strides in LMFR technology have been made in recent years

by Simcha Golan, Jean Leduc, and Hiroshi Nakagawa

Building on 40 years of liquid-metal fast reactor (LMFR) development and technical demonstration, Japan, Western Europe, the Soviet Union, and the United States are all proceeding with the next phase of LMFR projects. This article briefly reviews the technical state-of-the-art, the current expectations for economic feasibility, and some views on deployment of LMFR plants from various perspectives.

Technical state-of-the-art

The experience from about 200 reactor-years of experimental and mid-size LMFR power units has demonstrated that sodium-cooled fast reactors are reliable, as easy to operate as current light-water reactors (LWRs), require straightforward maintenance with relatively low personnel dose exposures, and result in minimal routine radioactive waste generation and handling. The experience from prototype reactors such as the 250-MWe Phénix (15 years) in France, the 250-MWe PFR (16 years) in the United Kingdom, the BN-350 (16 years) in the USSR, and the 400-MWth FFTF (10 years) in the USA has been particularly valuable. All four of these prototypes have recently been operating at high reliability. In addition, the BN-600 in the USSR has been operating solely for commercial electricity production for nearly 9 years and the world's largest LMFR, the 1250-MWe Superphénix in France, reached full power in December 1986. As a result of a leaking external fuel storage tank, it was shut down in May 1987 and, after successful repair and operating procedure alterations, was restarted in January 1989.

Fuel burnup in excess of 100 000 MWd/t has been demonstrated in several countries and experiments indicate there is a potential for burnups in excess of 200 000 MWd/t for both oxide and metal fuels. Burnups reached in Phénix and PFR are about 130 000 MWd/t under conditions similar to those of commercial LMFRs. The LMFR fuel cycle closure has been demonstrated in France, the UK, and the US on a significant scale. Fuel fabrication for Phénix and Superphénix has provided a large base of mixed oxide fuel production experience in France. Also in Europe, over the past 15 years, about 25 tons of spent oxide fuel has been successfully reprocessed, and the fission product waste from reprocessing has been vitrified in preparation for long-term storage. Substantial progress in the development of ternary metallic (U-Pu-Zr) fuel and associated reprocessing technology is being achieved in the USA by Argonne National Laboratory (ANL). Burnups in excess of 185 000 MWd/t have been achieved in EBR-2 test fuel assemblies. Significant progress has been made on metal fuel pyroprocessing, which provides for the recovery of the valuable fuel constituents, uranium and plutonium, and for removal of fission products. A notable feature of this process is that the majority of the actinide elements accompany plutonium through the process and are thereby removed from the waste stream. Facility modifications at the EBR-2 site are under way to demonstrate this fuel cycle by the mid-1990s on a larger scale, including reprocessing, fuel fabrication, and waste management.

It is important to realize that experience to date has been mostly from reactors completed prior to the mid-1970s and technology developed in the 1960s or earlier. Great strides have been made in LMFR technology in the more recent past and these new developments will only manifest themselves in the next generation of plants. The new technical directions for the next-generation designs reflect significant research and development gains as well as the more recent experience from operating plants. The key has been to take advantage of the intrinsic favourable properties of the LMFR to enhance safety and minimize cost. Perhaps the three most important properties are related to the essentially atmospheric operating pressure of the reactor coolant system, the large margin to reactor coolant boiling at its operating temperatures, and to the reactor's strong negative reactivity feedback with increased temperature. These properties coupled with sodium's high-temperature capability, compatibility with a wide range of materials, and high thermal and electrical conductivity, continue to challenge designers to produce a preferred LMFR product.

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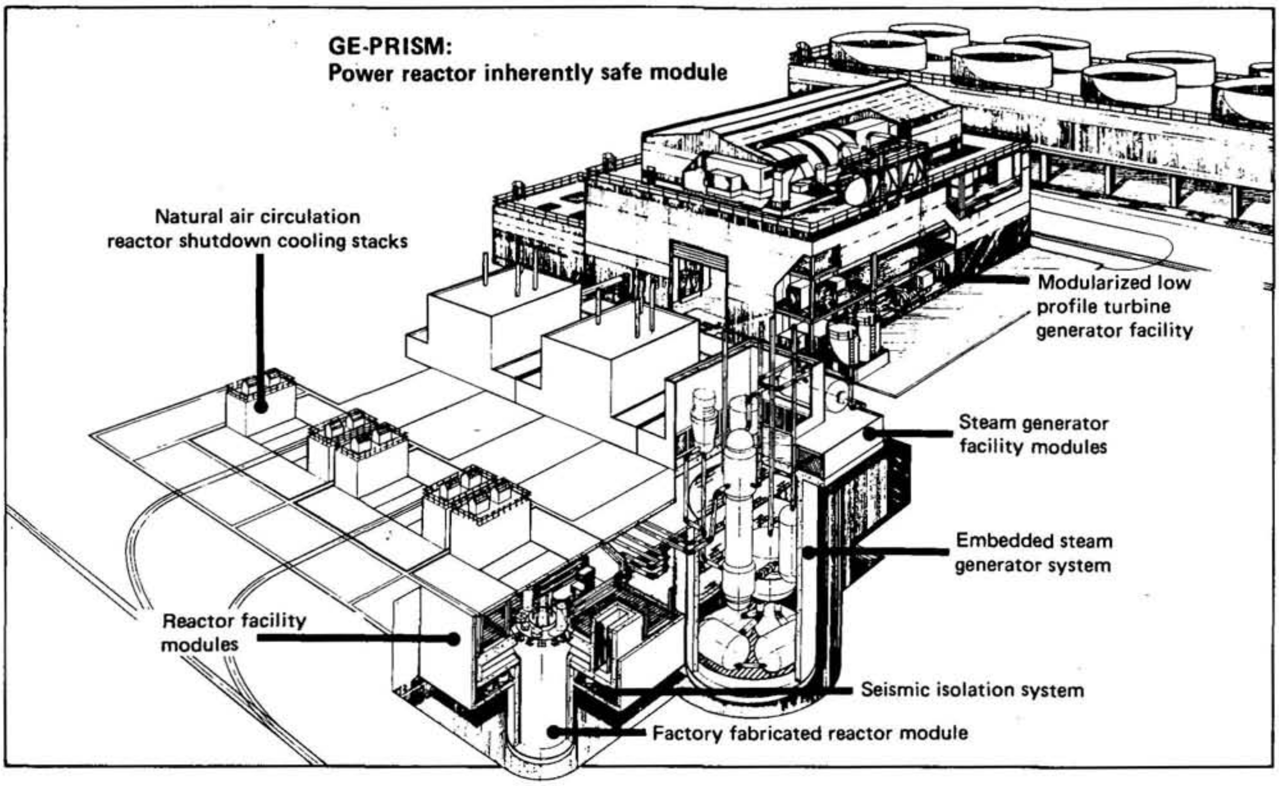
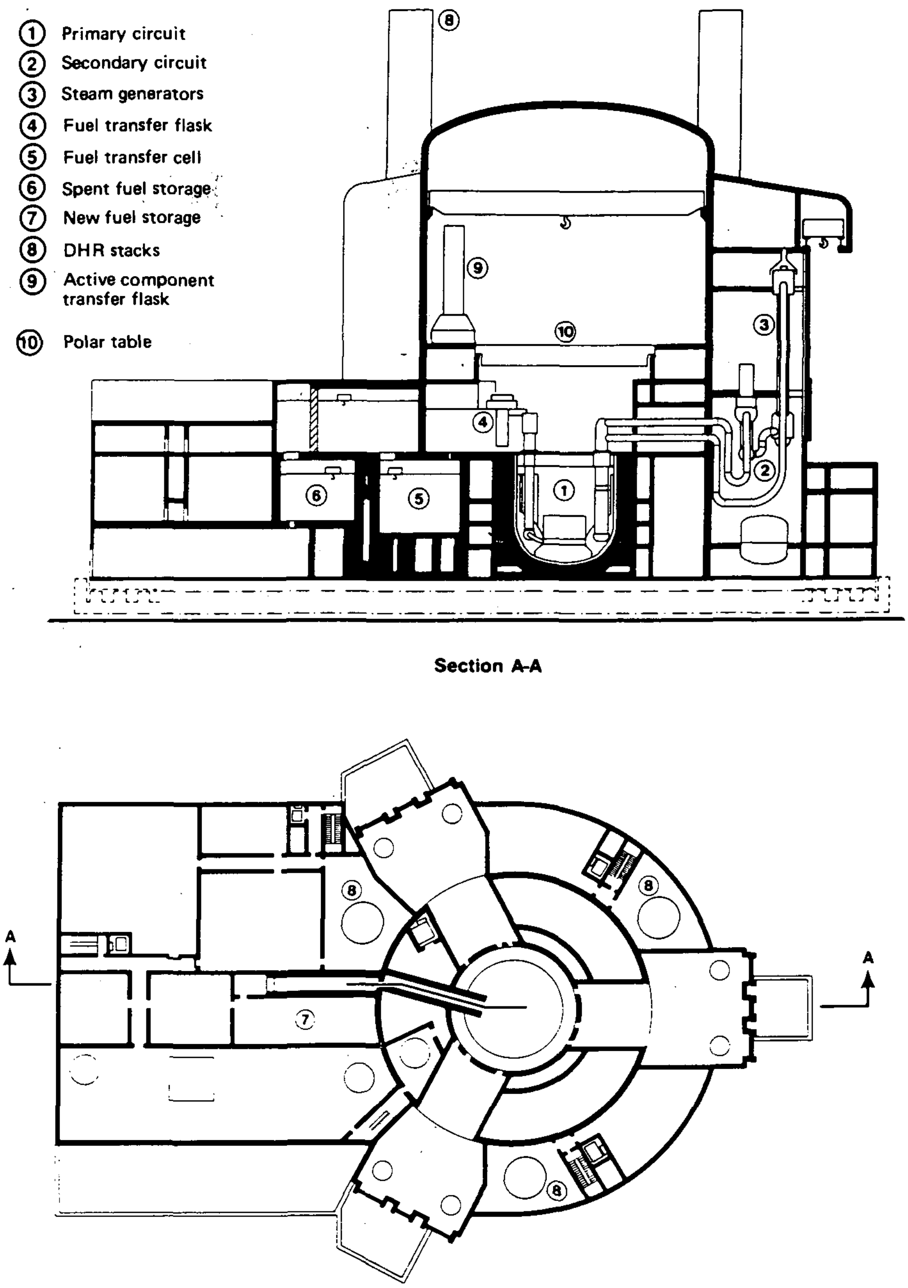


The United States has very recently decided, after a competitive process, to focus on small (471 MWth/155 MWe equivalent) modular reactors fuelled with the ternary metal alloy. Modular reactors allow more extensive shop preassembly, greater serial production economies, simpler and passive safety features, and more gradual generating capacity additions. The metallic alloy also allows core designs with benign response to accidents and the use of compact pyrometallurgical processes for fuel recycle which could facilitate economic fuel cycle closure during the early period of LMFR introduction. In contrast, Japan, the USSR, India, and European countries are currently following a more traditional path aimed at large (800 to 1500 MWe), monolithic reactors fuelled with a mixture of uranium and plutonium oxides, believing that large reactors yield substantial economies of scale in both construction and operation. Experience gained from the construction and early operation of Superphénix indicates a potential for large cost reduction with future large monolithic plants. Mixed oxide fuel technology is better established and capitalizes on the experience of reprocessing and fabricating LWR fuel. Thus, there are currently alternative approaches toward a commercial LMFR industry. Although the specific designs are different, the fundamentals are similar and provide the basis for international collaboration.

United States. The main thrust in the USA, under the leadership of General Electric, is to develop a mid-size power block (PRISM) that can be built up, in modular fashion, to larger plant ratings. Each power block is comprised of three 471-MWth reactor modules connected to a single 465-MWe turbine-generator. *(See accompanying figure.)* Notable examples of the plant's innovative characteristics are: compact factory-fabricated reactor modules capable of overland shipment; the use of ternary metal fuel with pyrometallurgical reprocessing; inherent reactor shutdown and stabilization by thermal and reactivity response characteristics of the reactor, even under extremely unlikely accidents; passive decay heat removal systems; reactor seismic isolation for high seismic margins and greater flexibility for standard plant siting; containment consisting of a guard vessel around the reactor vessel and a reactor closure with seal-welded penetrations; use of electromagnetic rather than mechanical primary pumps; elimination of power-dependent auxiliary cooling systems and safety-class emergency diesel generators; modular construction with extensive factory preassembly; separated construction of safety-related and conventional portions of the plant; and regulatory certification of a standard design based on extensive prior testing of a full-scale prototype module for a wide range of normal and off-normal events.

Europe. The main thrust in Europe, under the leadership of the European Fast Reactor Utilities Group (EUFRUG), is to develop a 1500-MWe power unit (EFR) that meets the safety and economic requirements in the United Kingdom, France, and Federal Republic of Germany. The EFR design, building on previous European national designs, e.g., CDFR, SNR-2 and Superphénix-2, and conducted by EFR Associates (Ansaldo, Belgonucléaire, Interatom, NCC, and Novatome), indicates that significant cost reductions can be

EFR first consistent design



achieved leading to economic competitiveness with contemporary LWR plants in Europe. *(See accompanying figures.)* Notable examples of the EFR's characteristics which contribute to its economic potential are: high burnup (over 150 000 MWd/t) mixed oxide fuel; a single 3600 MWth pool-type reactor with large capacity components for heat transport (three primary pumps, six intermediate heat exchangers, and three or six secondary loops); a compact primary containment comprised of the reactor vessel and closure with a reinforced concrete cylindrical reactor building providing secondary containment; a simple direct reactor decay heat removal system; six once-through, straight-tube, ferritic steel steam generators; and a thermally efficient steam cycle (490°C/185 bar turbine inlet). A major effort is under way to enhance the EFR safety by greater reliance on passive safety features.

Soviet Union. Based on the experience gathered from four operating LMFRs (BR-10, BOR-60, BN-350 and BN-600), the USSR has recently completed the design of the larger BN-800 version and construction of plants has started at two sites, Beloyarsk and South-Ural. The BN-800 incorporates several overall plant improvements but also makes maximum use of equipment developed for the BN-600. For example, the reactor vessel is the same size as in the BN-600 even though the core size is increased. This was accomplished by reducing the in-vessel shielding as a result of BN-600 operational experience. To improve steam generator performance, the temperature of the secondary sodium has been slightly reduced compared to the BN-600 (505°C vs. 520°C) and the steam temperature is also somewhat lower (490°C vs. 505°C). The BN-800 also uses a single turbine generator. The next step in the design evolution in the USSR is the BN-1600, considered to be the prototype for future commercial reactors. In 1988, the design was reviewed and the decision made to continue development with the objective of improving safety characteristics and achieving better economics.

Japan. Building on the successful operation of Joyo (11 years), and fabrication and construction experience of the 280-MWe Monju prototype with expected criticality by 1992, Japan's utilities are about to select the key specifications for the next LMFR demonstration project aimed to start construction by the late 1990s. After about 6 years of cost-reduction studies and supporting development, the next plant is likely to be in the 800 to 1000 MWe range; will use oxide fuel; and will utilize a once-through, helical coil type, ferritic steel steam generator. Key decisions which are yet to be made relate to the choice between a pool-type and top-entry loop-type configuration for the heat transport system, and the type of aseismic features which would be needed to meet Japan's severe earthquake design conditions.

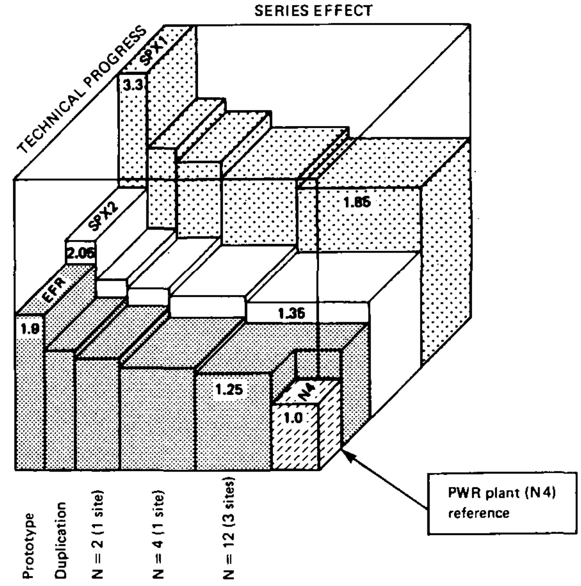
India. In India, the fast breeder test reactor (FBTR) went critical in October 1985. Operational experience with this reactor will carry over to the design of the 500-MWe pool-type prototype fast breeder reactor (PFBR) on which conceptual design has been completed.

Economic feasibility

Current operating LMFR plants, including the 1250-MWe Superphénix, were primarily based on LWR safety criteria with exceedingly conservative design margins. New data, new calculation tools, and utilization of new innovative core designs have allowed the development of LMFR-unique safety criteria, compaction of the reactor power block, and simplification of auxiliary systems and structures. Relying on natural convection for decay heat removal, localizing safety-related systems in close proximity to the reactor, minimizing safety-related power requirements, and otherwise capitalizing on the favourable physical characteristics of sodium, have all contributed to simpler and lower capital-cost designs. For example, the improved understanding of the thermohydraulics of sodium as a result of temperature measurements in Superphénix has allowed a more compact arrangement for the EFR with a potential 62% steel weight per MWe reduction for the primary system.

A key issue is the anticipated capital cost for a n^{th}-in-a-series LMFR plant relative to an equivalent LWR plant. *(See accompanying figure, which illustrates the current expectations on the basis of experience from Superphénix and more recent European design studies.)* The left hand column of this graph shows the improvements expected from technical progress. Very substantial reductions in component steel weights and concrete volumes per megawatt-electric are expected in the EFR compared to Superphénix with consequent major reductions in capital cost. With series deployment of the EFR, further cost reductions are expected as demonstrated by the French LWR multiple unit deployment programme. For the specific case of French conditions, it is estimated that the EFR n^{th}-in-a-series cost would be reduced to a level about 25% greater than that of a comparable advanced LWR plant. On the other hand, with high burnup fuel, the EFR fuel cycle cost is expected to be significantly below the fuel costs for a LWR even when fuelled with modestly priced uranium, with the net result that the total generation cost should be close to the LWR when the LMFR is in series production.

LMFR/LWR projected relative capital costs per kilowatt-electric (under conditions in France)



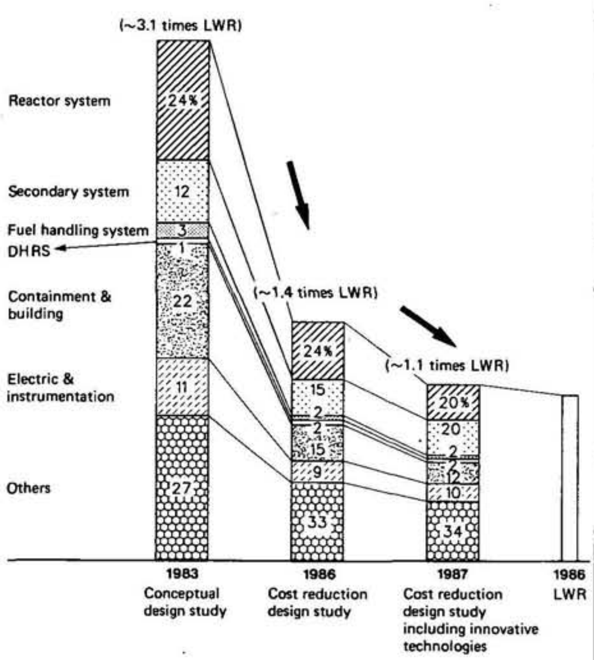
Independent recent studies in the USA and Japan have produced similar, if not somewhat more encouraging results. The Japanese utilities have utilized an extensive computer-based cost estimation methodology, developed with the co-operation of experienced US suppliers, for consistent intercomparison of recent advanced LMFR designs with cost calibration against LWR experience. *(See figure on page 34, which summarizes the capital cost trends from recent Japanese studies.)* These studies indicate a potential for LMFR/LWR capital cost ratios around 1.1, fuel cost ratios of significantly less than 1.0 for metal fuel, and around 1.0 for oxide fuel even at current uranium prices. The US cost projections for standardized 1400-MWe (three PRISM power blocks) LMFR plants indicates capital cost and total generation cost ratios of near unity.

Control room of the Superphénix fast breeder reactor in France. (Credit: CEA)

At the current level of cost definition it is not possible to distinguish any significant cost difference between an LMFR and an LWR under US conditions. *(See accompanying figure.)* However, any future increases in uranium costs will benefit the LMFR. Thus both Japanese and US studies expect future LMFR plants to be economically competitive with LWR plants when replicated as commercial standardized plants.

It is important to note that these LMFR vs. LWR relative economic comparisons reflect the experiences and anticipated conditions in the respective countries and do not take into account the large differences in LWR absolute capital cost between these countries. The competitiveness of the LMFR in France is probably more of a challenge than in other countries because of their low LWR costs. Thus the 25% excess LMFR capital costs in France do not necessarily mean a higher capital cost plant in absolute terms as compared to projected costs in the USA or Japan.

LMFR/LWR relative capital cost projections in Japan

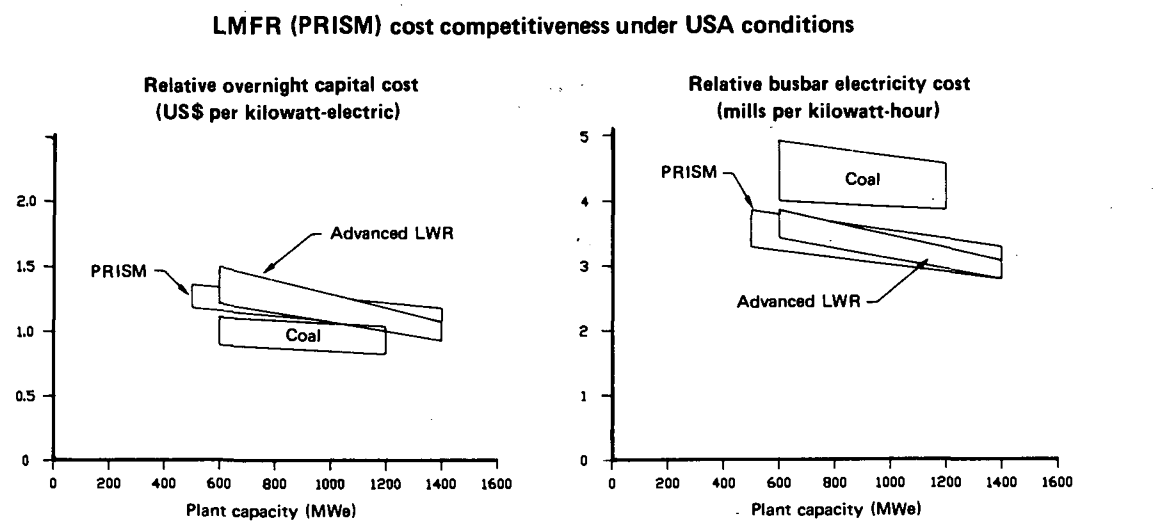


Commercial deployment

Japan's current view is that it may take one or two additional successive plant demonstration steps before they begin multiple-unit LMFR commercialization — perhaps as late as 2030. In Europe, it is now considered that LMFR plants would begin to replace the decommissioned LWR plants after 2010, in competition with the then-available advanced LWR. This presumes that an economical demonstration plant, such as EFR, will have been constructed during the next decade or so. In the USA, as in Europe and Japan, the decision process relevant to the timing of LMFR commercial deployment involves many variables, such as: demand for electricity, available modest-cost nuclear and fossil fuel resources, nuclear alternatives, and environmental constraints brought about by fossil fuel burning. It is therefore very difficult, if not impossible, to predict a specific time by which the LMFR will be absolutely needed. This important issue can be viewed from several different perspectives.

One perspective recognizes the major worldwide investment (over $30 billion in 1988 US dollars) already made in the development and demonstration of this unique technology and the potential value of having this technology as an affordable energy option at the turn of the century as an insurance policy against any number of plausible future energy supply upheavals. Since the remaining cost to make this technology commercially available is relatively modest, this perspective suggests that the completion of development makes economic sense.

A second perspective considers the global energy view as driven by the expected population explosion in



the developing world (an increase of over 1.5 billion by the end of the first quarter of the next century), the continually rising economic expectations of people everywhere, and the growing environmental concerns such as acid rain and the "greenhouse effect". To facilitate economic growth in the developing world without unduly impairing the global environment, the industrial countries should slow down the consumption rate of fossil fuels and low-cost uranium resources and save these for use in affordable and easy-to-operate fossil and nuclear power plants in the developing countries. This suggests that the industrial countries should consider earlier deployment of LMFR plants, even at somewhat higher cost during the early introduction period, in order to conserve the low-cost uranium resources for the developing world.

A third perspective relates to a symbiotic relationship between the LWR and the LMFR. For the most part, startup cores for new LMFR plants will be fuelled by plutonium extracted from LWR spent fuel. An LWR during its lifetime produces enough plutonium to start up a half-size LMFR plant. Therefore, based on the anticipated LWR capacity worldwide by 2010, there should be enough plutonium to fuel over 200 gigawatt-electric of LMFR capacity. There is no better way for "storing" and utilizing plutonium than in an LMFR plant. The recycling of plutonium into LMFRs would also allow "burning" of the associated extremely long-life transuranic waste, particularly neptunium-237 and other minor actinides, thus reducing the required isolation time for high-level wastes from tens of thousands of years to hundreds of years for fission products only. This additional important mission for the LMFR is gaining worldwide interest as a result of the growing concerns about the safe disposition of the very long-life nuclear power plant wastes.

All these perspectives strongly suggest that we should maintain the momentum for LMFR development and demonstration until at least commercially viable LMFR standard designs are fully licensed and demonstrated. Actual deployment of such proven designs should be left to the marketplace after the turn of the century. The LMFR is the only proven technology capable of providing virtually unlimited new fissile material from the world's ample supply of depleted uranium, low-grade natural uranium, and thorium resources to fuel the increased need for nuclear power in the next century and beyond.