THE ALMR SYSTEM'S MISSIONS FOR TRANSMUTING WASTE INTO ENERGY

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ABSTRACT

The Advanced Liquid Metal Reactor (ALMR) Actinide Recycle System is being developed in the United States for application early in the 21st century. The ALMR is a major part of this system and has missions beginning with near-term (10 years), medium term (15-20 years), and long-term (beyond 20 years) horizons. These missions use the same reactor design with modifications only to the reactor core details and constituents. The expected near-term mission is disposal of plutonium from dismantled weapons. The medium-term mission is the utilization of LWR spent fuel actinides (transuranics) as startup fissile material for significant commercialization and the long-term mission is the extension of economic uranium resources through the 21st century. This paper summarizes the basic reactor design, including its passive safety features, discusses its missions and the important elements supporting its missions, including the metal fuel cycle, the conversion of weapons material to ALMR fuel and the LWR spent fuel processing. It also reports the status of the prelicensing activities and the economic projections for this reactor design.

INTRODUCTION

The U.S. National Energy Strategy includes four key goals for nuclear policy: maintain safety and design standards, reduce economic risk, reduce regulatory risk, and establish an effective high-level nuclear waste program. The denaturing/consumption of plutonium (Pu) from dismantled weapons has also become an important goal. The top-priority long term nuclear program in the U.S. Department of Energy (DOE) is the Advanced Liquid Metal Reactor (ALMR) Actinide Recycle System which offers the promise of fulfilling all five of these goals. This very flexible ALMR Actinide Recycle System with passive safety features and an innovative pyrometallurgical fuel cycle has the ability to fulfill multiple missions including: (1) the conversion of excess Pu to produce power while destroying or denaturing the Pu (2) utilizing the tremendous energy potential associated with spent LWR fuel, (3) providing long term energy security, and (4) achieving a significant reduction in the heat load and time constant associated with processed waste.

The ALMR is a DOE sponsored fast reactor design based on the Power Reactor, Innovative Small Module (PRISM) concept originated by GE. The ALMR plant design and development program, led by GE, is a national program involving wide participation by US industry (Westinghouse, Bechtel, Bums & Roe, Raytheon Engineers and Constructors, Foster-Wheeler, and Babcock & Wilcox) as well as national laboratories, universities, and international organizations. The ALMR combines a high degree of passive safety characteristics with a high level of modularity and factory fabrication to achieve attractive economics. It utilizes the metal fuel cycle being developed by Argonne National Laboratory (ANL) which inherently recycles actinides to the reactor in the reference breakeven/breeder and burner designs. Key features of the metal fuel cycle concept are the metallic fuel form (actinide-zirconium alloy) and the compact, economic techniques being developed and demonstrated for fuel processing (pyrometallurgical process) and fabrication (injection casting) and associated waste processing. The metal fuel cycle has a number of attractive features in connection with the management of man-made actinides. First, the main processing step (electrorefining) accomplishes separation of transuranic (TRU) species from most of the uranium and fission products; minor actinides accompany plutonium and are thus automatically recycled. Secondly, the high radioactivity and low purity of the TRU product stream enhances the resistance of the fuel cycle to diversion and proliferation threats. Waste produced from recycle is less toxic and contains less long-lived high level waste than thermal neutron reactor designs utilizing once-through fuel cycles.

Key objectives of the program are to develop an ALMR power plant design with improved safety margins, licensability, constructability, operations, maintenance, and cost such that it is a viable option for commercialization. The design confidently meets these objectives and is nearing completion of its Preapplication Safety Evaluation Report (PSER) review by the U.S. Nuclear Regulatory Commission (NRC).

Plutonium for startup of commercial plants is expected to come from processing LWR spent fuel. The minor actinides in the LWR spent fuel will be included with the Pu to produce the initial core and first two reloads for each new ALMR. Subsequent reloads will be produced at the ALMR fuel recycle facility from processed ALMR spent fuel and blanket assemblies. In the ALMR's hard neutron spectrum, the actinides from both the LWR spent fuel and the ALMR fuel largely fission creating thermal energy while being reduced to shorter lived fission products. Ultimately, the fission products are removed from the fuel cycle as waste products whose radioactive level, from a toxicity standpoint, will be less than their source, natural uranium in a few hundred years. Thus, by using recycled LWR spent fuel the ALMR has the potential to extend the nuclear fuel supply to many centuries while at the same time reducing the long-term radiological toxicity associated with waste disposal.

Reactor Design and Passive Safety Features

The ALMR is designed as a safe, reliable, and economically competitive liquid metal fast reactor power plant. The ALMR is designed with the following key features:

1. The compact reactor modules are sized to enable factory fabrication, economical shipment to both inland and water-side sites, and permit affordable, full-scale prototype testing to confirm predicted safety and performance characteristics.
2. Passive reactivity control to a safe, stable state during undercooking and overpower transients with failure to scram, with abundant time for ultimate shutdown to cold conditions by operator initiated action.
3. Passive shutdown heat removal for loss-of-cooling accidents, designed to be invulnerable to operator error and equipment failures.
4. Protection against severe accidents by a combination of simple and passive preventive and mitigative design features such that radioactive releases are limited with sufficient margins to make the exercise of formal public evacuation plans unnecessary.
5. Self-sustaining fissile supply with the capability for breeding more fuel than is consumed.
6. The capability to utilize long-life radioactive actinide wastes from LWR spent fuel as fissile material for startup and/or makeup to reduce repository loading.
7. The capability to utilize excess weapons grade plutonium as fissile material for startup and/or makeup and to reduce proliferation concerns.

The reference commercial ALMR plant (see Figures 1 and 2) utilizes six reactor modules arranged in three identical 606 MWe power blocks for an overall plant net electrical rating of 1818 MWe. This same configuration is used for the Pu burner plant. Each power block features two identical reactor modules which supply superheated steam to a single turbine generator. Table I lists general design data. Smaller plant sizes of 606 and 1212 MWe

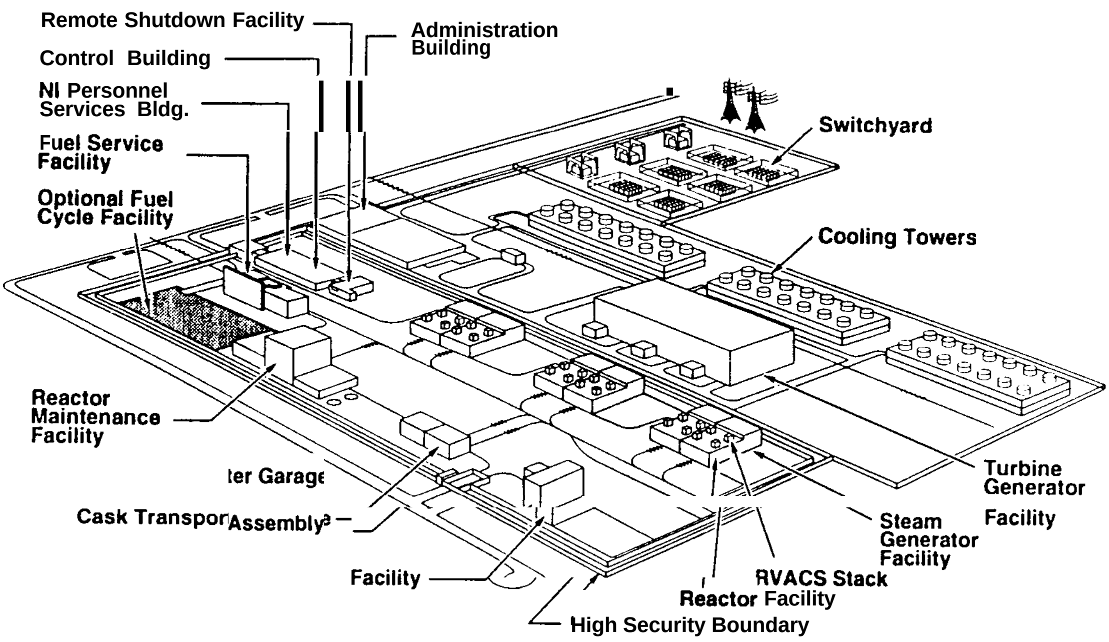

Figure 1. ALMR POWER PLANT (3 Power Blocks) -1818 MWe

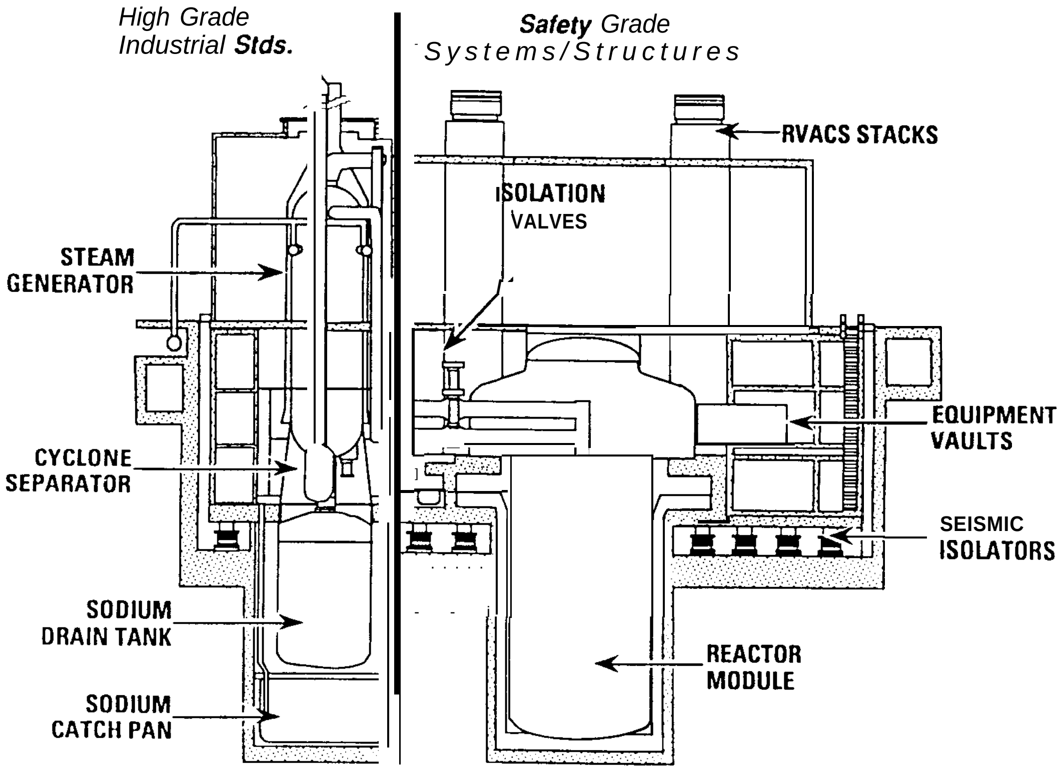

Figure 2. ALMR STEAM SUPPLY SYSTEM

would use one and two, respectively, of the standard power blocks, thus providing size flexibility to the utility in meeting its projected load growth. Nuclear safety-related systems and buildings are enclosed within a double-fenced and barricaded high security area. The steam generator system is physically separated from the nuclear safety-related portion of the plant and is designed to seismic category II criteria and tornado hardening. This system and the intermediate heat transport system

Table 1. ALMR DESIGN DATA

Overall Plant	
- No. of Reactors(Power Block Two	
- No. of power Blocks	One/Two/Three
– Net Electric Output	606/1212/1818
– Net Station Efficiency	36.1%
- Turbine Throttle Conditions	2200 psig/805 "F
Reactor Module	
– Thermal Power	840 MWt
- Primary Sodium Inlet/ Outlet Temperature	680°F/930°F
- Secondary Sodium Inlet/ Outlet Temperature	620°F/890°F
Reactor Core	
- Fuel	Metal
- Refueling Interval	23 months
- Breeding Ratio	1.05 Ref, 1.23-0.6 Capability (0.02 possible with a Pu-Zr fueled burner)

(IHTS) connecting it to the reactor will be designed and built to appropriate industrial standards. The plant "footprint" for this 1818 MWe plant is comparable in size to that of a current LWR plant of similar capacity.

The reactor module is about nine meters (30 feet) in diameter and about 18 meters (60 feet) high. Full containment is provided by the containment vessel, which surrounds the reactor vessel, and the containment dome, which encloses the head access area above the reactor closure. The reactor module, the IHTS, and the major portion of the steam generator system are underground (see Fig. 2).

Reactor and containment vessels have no penetrations below the top head. Primary sodium is circulated in the reactor by four submerged, self-cooled electromagnetic pumps during normal operation. The relatively tall and slender reactor geometry enhances uniformity and stability of internal flow distribution and natural circulation for shutdown heat removal. The reactor and its safety-related systems are seismically isolated in the horizontal direction. The relatively small reactor vessel diameter results in a structure that is stiff in the vertical direction eliminating the need for vertical isolation. The safe shutdown earthquake licensing basis is 0.3g, with structural margins to accommodate more severe, very low probability earthquakes that may approach 1.Og acceleration.

MISSIONS

Core flexibility is a major attribute of the ALMR. As shown in Figure 3, the modular ALMR design can accommodate fissile material from a variety of sources within the same configuration.

This core design flexibility and the unique ALMR design and fuel recycle approach make it attractive for application to several missions. These missions, readily adaptable to the ALMR include, (1) weapons plutonium disposition, (2) utilization of LWR spent fuel actinides (transuranics) as startup fissile material and, (3) extension of economic uranium resources via breeding fuel in the ALMR.

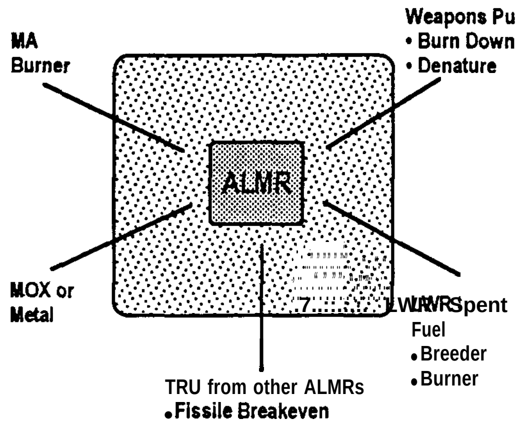

Fig. ALMR CORE FLEXIBILITY

METAL FUEL CYCLE

The reference fuel for the ALMR is a metallic uranium-plutonium-zirconium alloy where the plutonium could readily be excess Pu from the defense program. The ferritic stainless steel alloy, HT9, is used for cladding and assembly ducts to minimize swelling associated with long burnups. A heterogeneous arrangement of blankets and driver fuel is used in the reference design, with six control rods(see Figure 4). Figure 4 also shows the homogeneous core layout used in the actinide burning configuration. Reference core refueling occurs after each 24 months of operation, with one-third of the core being changed each reload outage; this results in a 6-year fuel life (150 MWd/kg [16 a/o] peak burnup). Metal fuel provides excellent negative reactivity feedback for loss of cooling and transient overpower events, as well as competitive fuel costs.

The metal fuel cycle concept is being developed by ANL with the objective of providing a safe, economical, and environmentally attractive fuel cycle for resource extension and/or excess plutonium disposition. Key features of the metal fuel cycle concept are the metallic fuel form (actinide-zirconium alloy) and the compact, economic techniques being developed and demonstrated for fuel processing (pyrometallurgical process) and fabrication (injection casting) and associated waste processing. The metal fuel cycle has a number of attractive features in connection with the management of man-made actinides. First, the main processing step (electrorefining) accomplishes separation of transuranic (TRU) species from most of the uranium and fission products; minor actinides accompany plutonium and are thus automatically recycled. Secondly, the high radioactivity and low purity of the TRU product stream enhances the resistance of the fuel cycle to diversion and proliferation threats. The metal fuel processing and fuel fabrication techniques are being demonstrated at the EBR-II plant and its adjoining Fuel Cycle Facility. Work is currently underway on the development of approved waste forms, and future work calls for the development and execution of waste qualification.

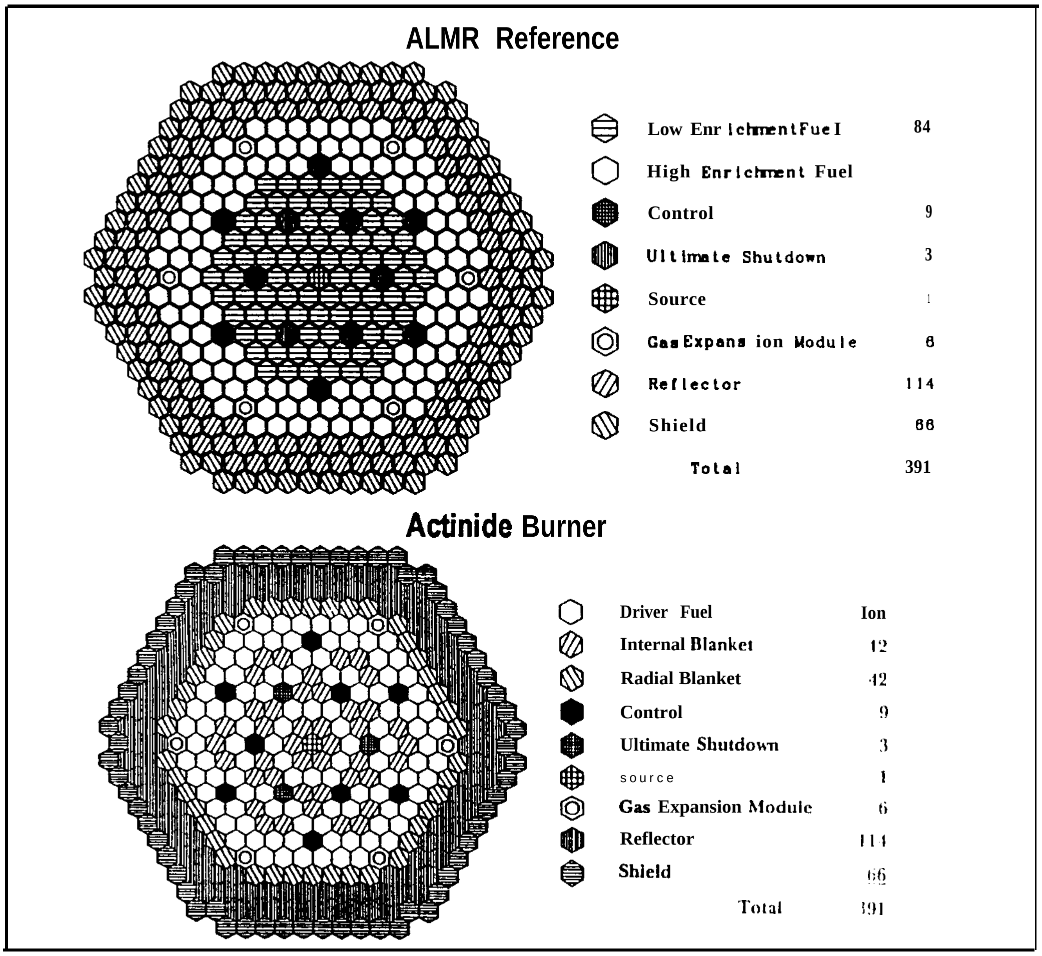

Figure 4.

CORE LAYOUT COMPARISON

LWR SPENT FUEL PROCESSING

In assessing the LWR spent fuel disposal challenge in the United States it is important to note that there is approximately 100 GWe of operating LWR capacity at present (approximately 20% of the US total electricity generation). These nuclear plants generate about 600 billion kWe-hours of electricity each year, and 2000 metric tons (800 M^3) of heavy metal in spent fuel (before secondary containment - about 4700 M^3 after). The current US plan calls for at-reactor storage of this spent fuel with transfer to a Monitored Retrievable Storage (MRS), and subsequent disposal in a deep geologic repository. The utilities pay 1 mill per KWhr of electricity generated to the Government for the disposal costs. As stated previously, the US National Energy Strategy predicts a significant increase in nuclear generated electricity after the turn of the century. At the expected rate of LWR TRU production, the first repository will reach its capacity (615 MTHM TRU equivalent) by 2015, making it necessary to commit a second repository at a relatively early date. The impact on repository demand by a series of new ALMR plants fueled by processing spent LWR fuel is to cap the need for TRU storage. However, the waste from the processed LWR fuel will require disposal, but the long-term thermal effects will be significantly reduced.

Although additional work needs to be performed to better define the risks and the benefits of recycling spent LWR fuel, there is an incentive to maintain this option and thoroughly examine it before this LWR spent fuel is placed in an unretrievable location for several very significant reasons. First, the spent LWR fuel represents a very large indigenous energy resource. It is estimated that LWR spent fuel scheduled for disposal in the first geologic repository would be sufficient to startup 32 GWe of ALMRs. The LWR spent fuel in excess of the first geologic repository capacity is sufficient to provide the startup material for an additional 27 GWe of ALMRs by about 2030. Due to the self sustaining nature of the ALMR, this fissile material could provide hundreds of years of electrical power production using only the previously mined and stored depleted uranium for makeup and with less residual waste generated. Second, depending on the processing and packaging efficiency, the geologic repository could be extended by a factor of at least 4 in terms of equivalent years of LWR spent fuel storage while reducing the toxicity risk to the public from this material from millions to hundreds of years.

WEAPONS UTILIZATION

The ALMR, in a plutonium "burner" configuration, consumes plutonium by converting it into fission products thus totally eliminating the plutonium. In addition, the plutonium not destroyed in a given cycle is denatured by build-in of other plutonium isotopes and TRU which are recycled and consumed in subsequent cycles. The annual TRU consumption rate (actual TRU/Pu destruction) for a "moderate" burner with a 0.60 conversion ratio is 500-750 kg/year/ 1818 MWe plant. The annual consumption rate for this plant with a Pu only fuel core (0.02 conversion ratio) is about 1500 Kg/year. At these consumption rates, the total TRU/Pu consumed over 40 years is 20-30 metric tons and 60 metric tons, respectively. In the breakeven/breeding option, as well as the other options, the original weapons grade Pu is converted to reactor grade Pu and is therefore "denatured" during plant operations. In addition, disposed waste consists primarily of relatively short half-life fission products with essentially no TRU/Pu.

PRELICENSING

Both the ALMR Design Team and the NRC recognize the desirability of reviews by NRC during the early stages of the design process to ease regulatory approval of the final product. Such reviews have been an integral part of the ALMR program plan in the form of regulatory review cycles, starting at the conceptual design stage. A Preliminary Safety Information Document (PSID) was submitted to the NRC for review in November, 1986. This document is similar to a Preliminary Safety Analysis Report (PSAR), but with less detail because of the conceptual nature of the design. The results of this first review were a Draft Preapplication Safety Evaluation Report (PSER) prepared by the NRC Staff, and a review letter by the Advisory Committee on Reactor Safety (ACRS) reporting the findings. Overall, they found the design responsive to the NRC's Advanced Reactor Policy, and that the design provides several passive and other desirable features enhancing the safety of the power plant. The passive reactivity feedback and decay heat removal features are recognized and credited by the reviewers, as are the long response time and low risk of core damage under many severe challenges to the plant, and the reduced dependence on and vulnerability to human actions and errors.

Several design changes, most notably the addition of a low leakage, pressure retaining containment dome above the vessel closure head, and additional safety analyses performed in response to the first-round regulatory review were submitted to the NRC in May, 1990. Meetings with the NRC staff and the ACRS are continuing as part of the review of the revised design. The initial indications are that the design changes submitted are generally well received and found to be responsive to the issues raised in the first-round review. It is expected that the NRC Staff will request a new ACRS review letter to support the PSER. The NRC is scheduled to issue the PSER in late 1993.

More formal regulatory review will begin with the preliminary design phase in 1994 leading to preliminary design approval (PDA), and will continue into the detailed design phase. This phase will be followed by construction of a full-size prototype reactor to demonstrate the passive, natural safety features of the concept during actual performance. The prototype will support the technical basis for NRC's Final Design Approval (FDA) and standard design certification. Current planning projects this certification about the year 2008.

ECONOMIC PROJECTIONS AND COMMERCIALIZATION

The ALMR is specifically designed to maximize factory fabrication of components, rather than field fabrication. Higher fabrication throughput rates for modular units in factories result in stronger learning and improved economics when compared to fewer field fabricated units. Cost reduction also occurs due to simplifying features.

Figure 5 shows a comparison of projected power costs (busbar) for the ALMR, advanced LWR, and advanced coal plants in the northeastern U.S. These results indicate that the ALMR, complete with the metal fuel cycle, should be competitive with advanced LWRS by 2010, and beyond, and achieve considerable savings over coal plants in areas of high coal prices. The ALMR fuel cycle cost projections for future plants are on the order of about 7 mills per kilowatt hour, or less than twenty percent of total ALMR busbar costs. Commercialization is expected to follow NRC's design certification depending on electrical demand and realization of economic competitiveness.

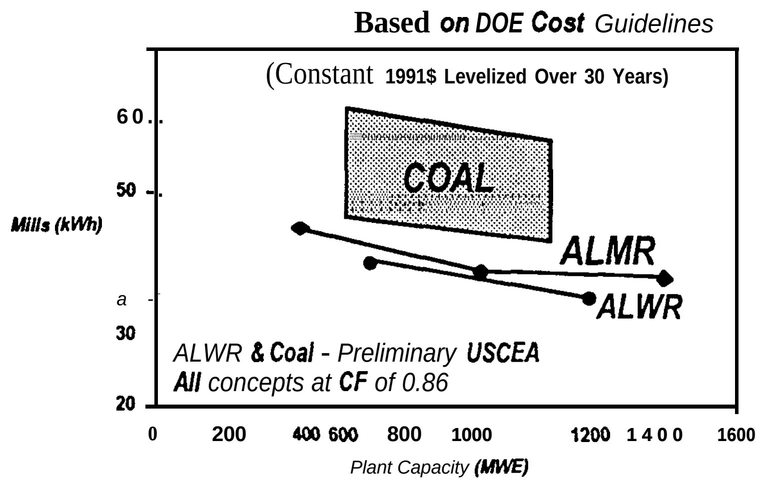

Figure 5. **ALMR BUSBAR COSTS**

CONCLUSION

The ALMR is a very flexible reactor system with passive safety features. The ALMR has the ability to fulfill multiple missions including: (1) converting excess Pu to power, (2) utilizing the tremendous energy potential associated with spent LWR fuel and the expected reduction in the heat load and time constant associated with the processed waste, and (3) providing long-term energy security. These attributes make it a unique and timely machine which warrants focused near-term development efforts so that its many applications and benefits can be verified and utilized as needed.

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