CONF-940602--22

Economics of ALMR Deployment*

J. G. Delene
L. C. Fuller
C. R. Hudson

Engineering Economics Evaluations Group
Engineering Technology Division
Oak Ridge National Laboratory

Presented at

American Nuclear Society
1994 ANS Annual Meeting
June 19-23, 1994
New Orleans, Louisiana

* Work done at Oak Ridge National Laboratory, managed by Martin Marietta Energy Systems, Inc. for U.S. Department of Energy under Contract No. DE-AC05-84-OR21400.

DISCLAIMER

1. INTRODUCTION

The Advanced Liquid Metal Reactor (ALMR) has the potential to extend the economic life of the nuclear option and of reducing the number of high level waste repositories which will eventually be needed in an expanding nuclear economy. This paper reports on an analysis which models and evaluates the economics of the use of ALMRs as a component of this country's future electricity generation mix.[1] The ALMR concept has the ability to utilize as fuel the fissile material contained in previously irradiated nuclear fuel (i.e., spent fuel) or from surplus weapons grade material. While not a requirement for the successful deployment of ALMR power plant technology, the reprocessing of spent fuel from light water reactors (LWR) is necessary for any rapid introduction of ALMR power plants. In addition, the reprocessing of LWR spent fuel may reduce the number of high level waste repositories needed in the future by burning the long-lived actinides produced in the fission process. With this study, the relative economics of a number of potential scenarios related to these issues are evaluated. While not encompassing the full range of all possibilities, the cases reported here provide an indication of the potential costs, timings, and relative economic attractiveness of ALMR deployment.

2. DEPLOYMENT ECONOMICS MODEL

The model used to evaluate the ALMR deployment economics was developed by the Engineering Economic Evaluations Group at Oak Ridge National Laboratory for the Department of Energy (DOE). The model calculates year-by-year costs, net present value costs, and levelized generation costs during an analysis period of 2010-2070. Developed in Lotus spreadsheet format, the analysis reflects the deployments of ALMR and LWR power plants, ALMR fuel recycle facilities, LWR reprocessing facilities, and high-level waste repositories. Technical and cost data used in the model were supplied by the DOE ALMR program participants.

A pictorial description of the model is shown in Fig. 1. The ALMR is introduced into a nuclear power generation economy consisting of light water reactors (LWR). The maximum rate of ALMR deployment depends on the availability of fissile material which in turn depends on the reprocessing capacity and the quantity of spent LWR fuel available. The annual electrical power produced by nuclear (both ALMRs and LWRs) was based on the National Energy Strategy[2] projections through the year 2030 with a linear extrapolation thereafter. Power not produced by ALMRs is assumed to come from LWRs. LWR spent fuel may either be disposed of directly or it can be reprocessed to obtain start-up fuel for ALMRs. An ALMR economy cannot exist without a source of start-up fuel. Actinides recovered from LWR spent fuel is a prime source for this material. Other potential sources of fissile material include surplus defense plutonium (Pu) or highly enriched uranium. A deployment model for the LWR reprocessing facility is included in the overall model. Reprocessing capacity is brought on-line as needed to sustain the growth of ALMRs. The growth rate of LWR spent fuel reprocessing capacity is restricted by the availability of spent fuel as well as by the demand for ALMR fuel. The deployment of these plants is also constrained by the economic need to have full capacity operation over the life of the facility.

The recovered actinides are sent to an ALMR fuel recycle facility for fabrication into ALMR fuel assemblies. The reprocessing wastes are sent to the high level waste repository for permanent disposal and uranium recovered from the LWR spent fuel is sent to storage. There is no provision in the current model for the re-enrichment of this uranium for use in LWRs.

ALMR fuel recycle facilities are deployed when adequate ALMR spent fuel inventories are available. Deployment is based on the availability of spent ALMR fuel, the need for fresh ALMR assemblies, and the economic desirability for nearly full capacity operation. The model includes a provision for the use of defense Pu up to a maximum amount assumed available. Waste from the

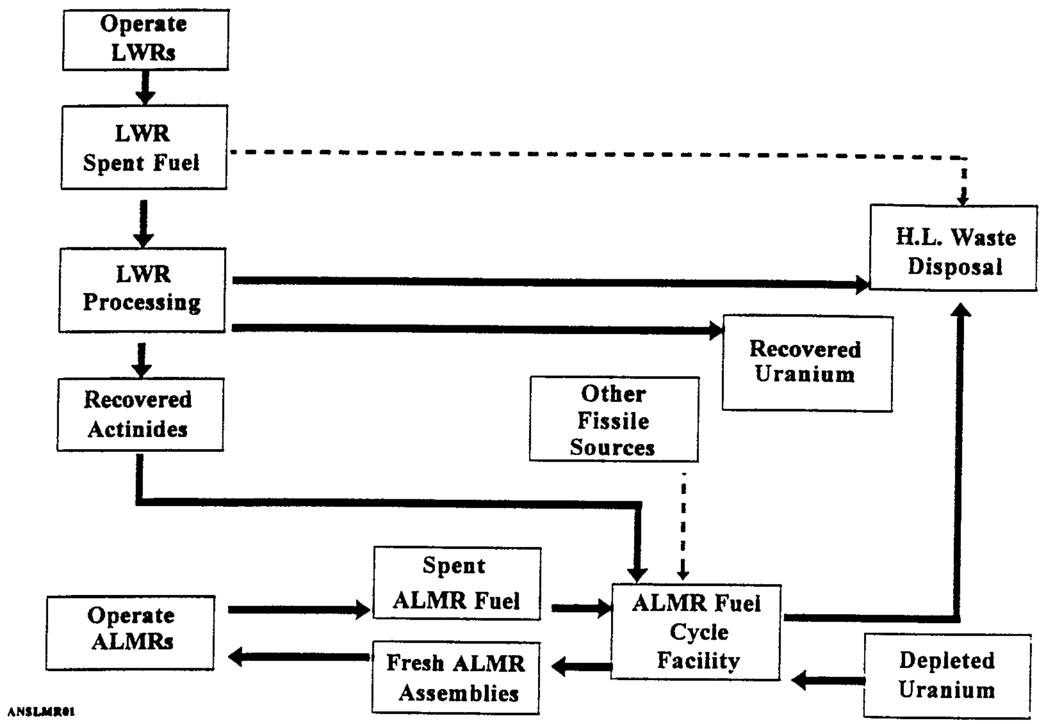


Fig. 1. ALMR deployment economics model

ALMR fuel recycle facility is sent to the high level waste repository. In the current model, depleted uranium is used as the source of any makeup uranium needed for the fuel assemblies. Although not currently reflected in the model, recovered uranium from the LWR reprocessing plant could be used as an alternative uranium source.

A pictorial view of the ALMR economics model is shown in Fig. 2. A utility revenue requirements approach is used to calculate the year-by-year costs for the ALMR plants. Each plant coming on-line produces a future stream of cost associated with capital investment, operation and maintenance (O&M), final decommissioning of the plant, and for fuel. The basic revenue requirements method is discussed in the Nuclear Energy Cost Data Base[3] (NECDB). ALMR fuel cycle costs are based on the cost of the fuel assemblies purchased by the operating utilities. This assembly cost is capitalized and depreciated for tax purposes over the 5-year tax life currently allowed for nuclear fuel. The initial core fuel is depreciated for book purposes over a 30 year period whereas reload fuel is depreciated for book purposes over a fuel life of 5-years.

The fuel cycle facility (ALMR fuel recycle) plant is assumed to be industrially owned. The initial investment in this plant and its annual costs are modeled explicitly and a levelized cost of product (ALMR fuel assemblies) is calculated using an assumed 30-year plant life. The cost information for this plant was obtained from ALMR program information.[4] The cost structure for an LWR spent fuel reprocessing plant was not modeled explicitly. Instead, an input reprocessing cost in terms of \$/kg of heavy metal (\$/kgHM) was used. Surplus defense plutonium was assumed to be provided at a zero net cost to the ALMR. The cost of fuel assembly hardware was added to the cost of recovery to obtain the overall fuel assembly costs. Costs were estimated for the ALMR economy as a whole, and the cost of any specific reactor was not

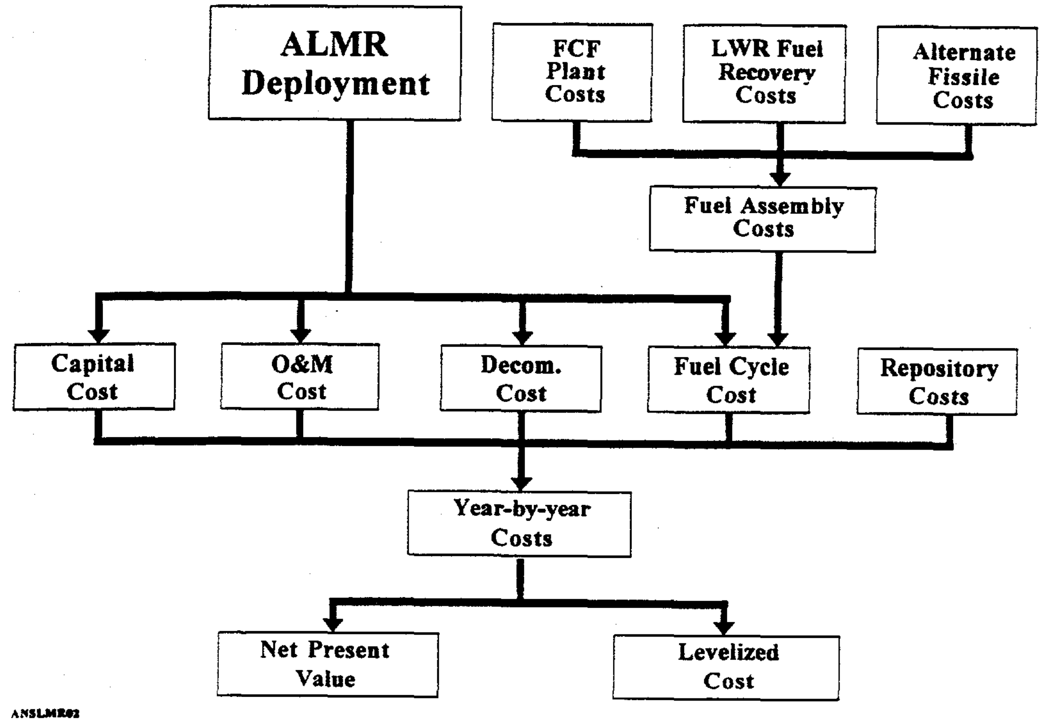


Fig. 2. ALMR economics model

broken out separately in the model.

The LWR fuel cycle cost was estimated based on a revenue requirements calculation and 30-year mass flow requirements for an advanced LWR. The 30-year levelized unit fuel cost (mills/kWh) as a function of each fuel commodity price (i.e., uranium, conversion, enrichment and fabrication) was calculated. This sensitivity of levelized cost to commodity price was then used together with the annual power generation and the unit price of the commodity each year to obtain year-by-year fuel costs for the LWR. The capital, O&M, and decommissioning costs for the LWR plants operating in the same time frame as the ALMR plants were not modeled explicitly. Instead it was assumed that these costs will be the same for the two types of reactors.

The first repository and Monitored Retrievable Storage (MRS) system is assumed to be installed prior to the start-up of the first ALMR. The implementation and cost of subsequent repositories, and repository operating costs are estimated based on the quantity and type of high level waste disposal. These annual costs are considered to be part of the overall fuel cycle and are added to the annual costs from the ALMR and LWR fuel cycles. The 1-mill/kWh waste disposal fee is excluded from the fuel cycle cost. The model calculates the total fuel/waste cost explicitly and independently of the assumed waste disposal fee.

Year-by-year costs are generated over a 60 year period extending from 2010 to 2070. The year-by-year costs are combined into a Net Present Value (NPV). Comparisons of these NPVs between any two scenarios gives the net savings or cost of implementing a specific strategy.

3. INPUT DATA

Basic input information used in the analyses is shown in Tables 1–6. In addition to thes data, the year-by-year ALMR power plant deployment, recycle facility deployment and LWR reprocessing plant deployment are input. The various deployment schedules are inter-related and are dependent on the fuel cycle mass flow characteristics for each case.

Table 1. General financial information

Reference year	1992
Facilities book life, years	30
Inflation rate, %	5.0
Decommissioning sinking fund rate, %	7.0
Utility effective cost of money, %	9.57
Fuel facility average Cost of money, %	13.74
Property tax rate, %/yr	2.0
Effective tax rate, %	36.64
Discount rate,%	9.57

The basic financial and cost parameters in Table 1 were obtained from DOE's Nuclear Energy Cost Data Base (NECDB) Report.[3] A January 1992 date was taken as the reference date for cost information. The year-by-year total nuclear power generation assumed is shown in Fig. 3. This was obtained from the National Energy Strategy (NES) at 5-year increments from 2010 to 2030 with linear interpolation for the intervening years.[2] The rate of increase in nuclear power generation during the 2025-2030 period (39,400 GWh/year) was maintained after 2030.

Table 2 contains information on ALMR plant capital and O&M costs. The capital and operating costs were obtained from General Electric[4] for a first commercial plant and an Nth-of-a-kind (NOAK) plant. Mod A and Mod B are two different reactor designs being considered for the ALMR. Table 2 gives the reactor power and costs for these two systems. Mod A consists of 9 reactor modules in groups of 3 modules per power block, each reactor module having a power of about 165 MWe. Mod B has larger sized reactor modules, with 6 reactor modules per plant with each module having a power of 303 MWe.

Different reactor/fuel cycles were considered as given in Table 3. The Mod A burner case was the base case for the analysis. The breakeven and breeder cases were included to assess the sensitivity of the results to increased breeding gain. The fuel cycle time, driver fuel assembly equivalent charge and discharge fissile material content, assembly heavy metal loading and the number of core and blanket assemblies for the initial core and each reload were provided by GE.[4] Where applicable, the equivalent fissile Pu discharge value includes Pu discharged in the blanket assemblies prorated to the driver

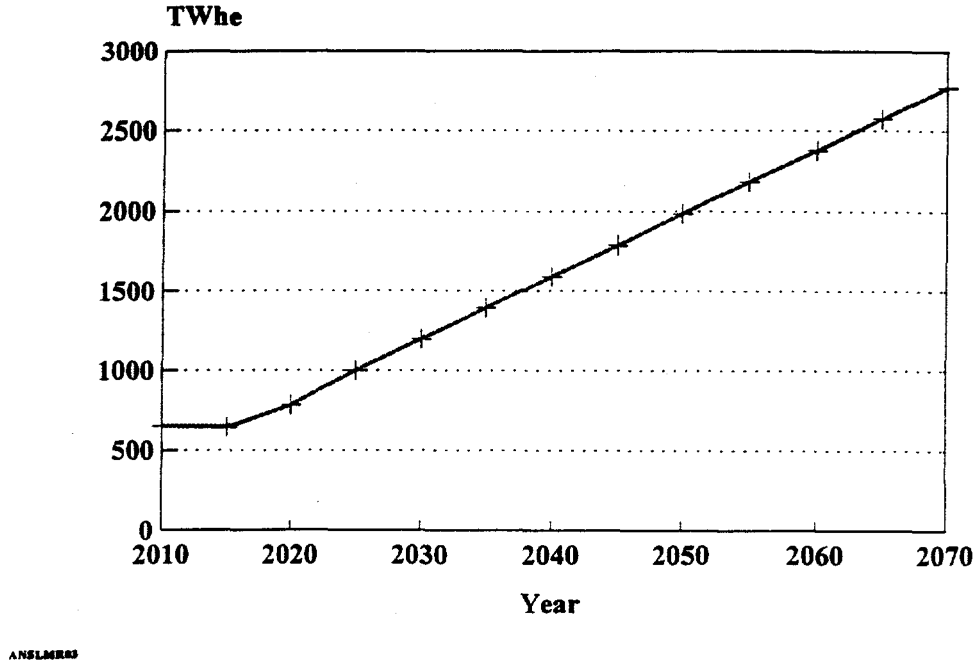


Fig. 3. Annual nuclear energy generation

Table 2. ALMR plant cost factors

Plant type	(million 1992 dollars) Mod A	Mod B
Reactor power, MWe	1488	1818
Decommissioning cost	508	524
First commercial plant		
initial investment	2825	2992
annual O&M cost	113.3	119.8
NOAK plant		
initial investment	2413	2556
annual O&M	89.6	94.9

assemblies. In the base case, there was assumed to be no alternative fissile material (e.g., weapons Pu) available. The fissile Pu in LWR spent fuel varies depending on fuel characteristics, spent fuel burnup, and time since discharge. The value shown is typical and will vary approximately in the range of 6 to 7 kg/MTHM.

Fuel processing and recycle facility cost data used in the analyses are given in Table 4. The LWR actinide recovery (reprocessing) plant was sized to meet the fuel cycle needs while continuing to operate at full capacity. The $350/kgHM LWR spent fuel reprocessing cost is a program assumption based on

Table 3. ALMR fuel cycle parameters

Reactor model	Mod A	Mod A	Mod B
Fuel cycle type	Burner	Breakeven	Breeder
Conversion/breeding ratio	0.69	1.05	1.24
Fuel cycle time, months	15	24	23
Equiv. fissile Pu/driver, kg			
charged	6.53	21.9	14.52
discharged	6.12	22.1	17.30
Assembly heavy metal, kg			
driver	69.4	88.0	120.03
blanket	NA	151.0	166.13
Full plant driver assemblies			
initial core	1242	594	756
reloads	414	198	252
Plant blanket assemblies			
initial core	0	648	648
reloads	0	162	180

preliminary estimates by Argonne National Laboratory (ANL).[5] Initial core fuel loadings were depreciated for book purposes over the same period as the reactor plant (30 years). A 5-year book depreciation was assumed for the reload fuel. In all cases the fuel was depreciated for tax purposes over the 5-year tax depreciation schedule allowed for nuclear fuel. Any weapons Pu used in the analyses was assumed to be Provided at zero net cost.

The ALMR fuel recycle facility cost data is based on programmatic information.[4] A facility life of 30 years is assumed. The base size for the recycle facility is 200 MTHM/year although various sizes were used in the analysis in order to maintain adequate flows of material. The costs shown are for a First-of-a-kind (FOAK) plant. Unit learning curves were used to move from the FOAK to NOAK plant costs. Capital costs for a fourth-of-a-kind plant were estimated at 83% of the FOAK plant costs. Plant costs were fixed at this level for all subsequent plants. The second and third plant were assumed to have a cost equal to 91% of the FOAK cost. The manpower and consumables cost learning was based on the cumulative driver assemblies recycled. The base amount for learning was the total number of assemblies required for 30-years of operation for a reference single full size plant. The hardware cost is based on the cumulative driver assemblies fabricated. The learning factor applied over the number of cumulative quantity doublings shown gives the NOAK cost.

Table 5 shows the high level waste repository assumptions. There are many aspects of the repository and its costs which are uncertain and extrapolations had to be made from existing information in several instances. Basic technical and year-by-year cost information for several scenarios can be found in a DOE report.[6] This report, however, does not include any information on disposal of reprocessing waste or the scenarios considered herein. The current repository capacity planned is 70,000 MTHM with

Table 4. Fuel processing/recycle facilities data

LWR spent fuel reprocessing		$350/kgIHM
ALMR recycle facility FOAK costs: (200 MTHM/year)		
- Initial capital		$1.26 billion
- 5-year capital replacement		$85 million
- 10-year capital replacement		$170 million
- Annual O&M cost		$111 million
- Annual fuel assembly hardware		$160-380 million
Cost reduction factors:	Doublings	Factor per doubling
-fuel facility capital	2	0.91
-Manpower	3	0.90
-Consumables	3	0.94
-Hardware	4	0.90

7,000 devoted to defense wastes, hence the assumed capacity of 63,000 MTHM. The model provides for either the disposal of intact LWR fuel assemblies or the reprocessing wastes therefrom. The current assumed spent fuel disposal rate[6] is 3,000 MTHM/year. The analysis assumes this rate for the first repository, however, this rate will not be adequate to dispose of all spent fuel in an expanding nuclear economy, so it was assumed that provisions will be made to increase this maximum rate (doubled) for subsequent repositories. Spent fuel was assumed available for disposal or reprocessing 2-years after discharge from the reactor. At this point it entered an inventory available for disposal. Actual disposal follows availability by several years depending on the inventory magnitude.

The first repository is assumed to be in place by the initial year of this analysis (2010) and is the same for all scenarios considered in this study. With respect to this study, it is a sunk cost with an assumed zero incremental cost. The cost for subsequent repositories was derived from cost information for a second repository in Ref. 6, escalated to 1992 dollars. It is the total cost of all site characterization, licensing, construction, etc. paid toward putting a second repository in place.

Operating costs can be divided into fixed costs which are independent of the waste throughput and a variable component which is proportional to the waste disposal rate. The numbers shown are approximate values for the disposal of intact spent fuel and are based on this study's analysis of the reported cost estimates. The fixed cost is a per repository cost and is applied even if a repository is full.

Since more reprocessing wastes than assembly wastes (based on the heavy metal in the initial fuel) can be placed in a single can,[7,8] a cost reduction per unit of initial fuel can be expected. The magnitude of this savings is not well defined but could be significant. Estimates range from a 20-30% savings to as high as 75%. The latter is based on the amount of material that can be put in a single package and does

Table 5. Repository data

Commercial nuclear capacity	63,000 MTIHM
Rate of disposal	
- First repository	3,000 MTIHM/year
- Subsequent repositories	6,000 MTIhm/year
Repository Capital	$7.2 billion
Annual fixed cost	$20 million
Variable cost	$145/kgIHM

not include consideration of concomitant costs such as increased costs of handling, additional expenditures for additional ventilation shafts, ventilation equipment, and power to run the equipment.[8] A cost factor (multiplier to variable cost of disposing of fuel assemblies) range of 0.5 to 0.75 was considered in this study with a reference value of 0.75. In other words, the disposal of reprocessing wastes from a given amount of spent fuel is assumed to cost 75% of the cost of disposing of the same amount of intact spent fuel.

In addition to the unit cost impact, as a result of reprocessing there is also a potential to load more material into the repository in terms of the initial heavy metal in a fuel assembly. For this study, a reprocessed waste equivalence factor has been used as a measure of the repository's ultimate capacity. The base waste density factor of 4 assumes that four times as much material in terms of initial heavy metal can be stored in a waste repository if the spent fuel has been reprocessed. This increase in loading density is due to reduced long-term thermal loading brought about by removal of the actinides. This factor is consistent with Refs. 7 and 8.

Consistent with the analysis in Ref. 6, an MRS is assumed to be in place prior to the time frame in this analysis. Examination of the repository program cost information indicates an incremental cost for added MRS storage of less than $20/kgHM. This value was used as a one time charge if the inventory of spent fuel increased over its previous maximum value. The amount of spent fuel available and the amount of uranium used in the future will depend on various factors. Consistent with current estimates[9], spent fuel will total 60,000 MTHM in 2010 and there will be 400,000 tons of U_3O_8 consumption between 1992 and 2010.

Table 6 contains LWR fuel cycle parameters. For its baseline analysis, this study assumed an LWR spent fuel burnup of 40 MWd/kg. The projected burnup from U.S. reactors in the post 2010 period is generally in the 40–50 MWd/kg range.[9] The 0.25% enrichment tails value has been projected for the post 2010 period.[9]

The fuel cycle commodity prices shown are the estimated price in 1992 dollars in the year 2010. The prices assume a nuclear resurgence with new production coming on line. The enrichment price is the price for a U.S. enrichment enterprise "Utility Service Contract" at the time of this study. Conversion and fuel fabrication prices are estimated prices from new facilities. The projected price of uranium as a function of cumulative U.S. uranium consumption is shown in Fig. 4. The uranium base price of $25/lb U_3O_8 is an estimate of the price to which uranium will have to rise before such new production will be

Table 6. LWR fuel cycle information

Average LWR fuel burnup, MWd/kg	40.0
Fuel enrichment, %	3.66
Tails enrichment, %	0.25
Fuel commodity costs[a]	
Uranium price, \$/lb U_3O_8	(b)
Enrichment price, \$/SWU	125
Conversion, \$/kgU	9
Fabrication, \$/kgU	250

[a] Unit prices for year 2010 in 1992 dollars.
[b] price varies with cumulative uranium consumption (see Fig. 4).

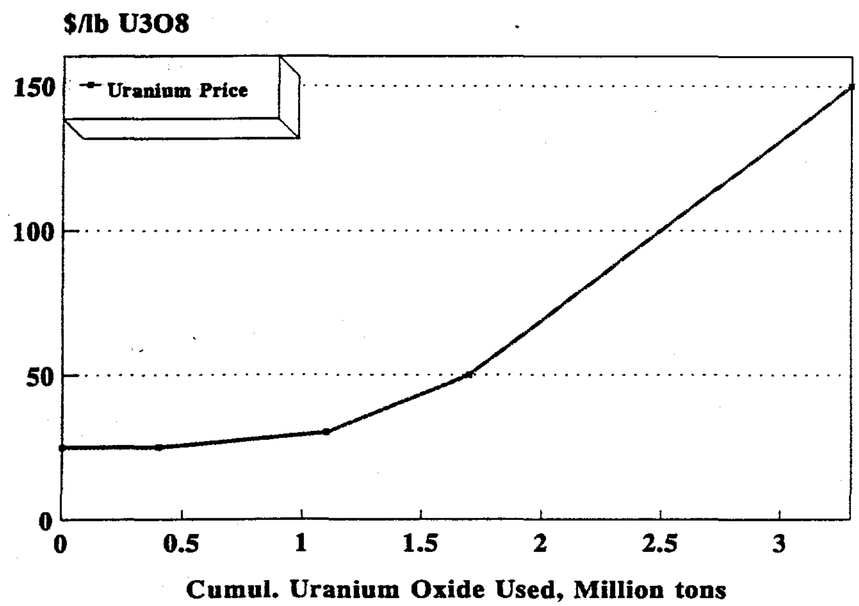


Fig. 4. Uranium price projection

economic in the United States. As the resource is used up, the price of uranium should increase. There is a great deal of uncertainty as to what the future cost of uranium will be and on the quantity of uranium which will ultimately be available. The uranium price vs. cumulative consumption is based on the reported[10] reasonably assured reserves available at various forward costs of uranium. Information was given at \$30, \$50 and \$100/lb. U_3O_8. The \$150 point was obtained by making a linear extrapolation from the \$50 and \$100 points. The \$150/lb value is about the minimum cost where uranium might be extracted from sea water so the price was projected to remain constant after 3.3 million tons U.S. uranium oxide consumption.

In addition to the input discussed above, sensitivity of the results to variations in the input data was examined. Other parameters varied in the sensitivity analysis are given in Table 7. Variations in cost parameters were made around the ALMR burner base case.

Table 7. Additional parameters varied

Item	Base Parameters	Parameter Variations[a]
Deploy ALMRs	Yes	No (null case)
Nominal capacity factor	0.86	0.80, 0.75
ALMR power in 2030, Gwe	27	Max achievable
Conversion/breeding ratio	0.69	1.04, 1.25
Pu available from weapons, MT	0	100
LWR fuel recovery cost, $/kgHM	350	200, 1000
Cost to implement repository, $B	7.2	15
LWR processing waste		
repository load factor	0.25	0.5
repository cost factor	0.75	0.5
LWR fuel processing costs charged to repository	No	Yes

[a]Parameters varied one at a time from base parameter set.

4. RESULTS

As described in Sect. 3, several different scenarios have been modeled. The selection of cases is by no means exhaustive. The results of these cases do show, however, the degree of economic sensitivity to changes in various input assumptions. The figure of merit used is the difference between the Net Present Value (NPV) of the costs between the years 2010 and 2070 of a particular scenario compared to that for the case in which no ALMRs are deployed.

4.1 NO ALMR CASE (NULL CASE)

The case in which there is no ALMR deployment serves as a relative benchmark for all ALMR deployment cases. Economic results for cases involving ALMR deployment are expressed as relative Net Present Values compared to this no ALMR deployment case. In this null case, it is assumed that all nuclear generation is provided by LWR plants and that unreprocessed spent fuel is buried in the

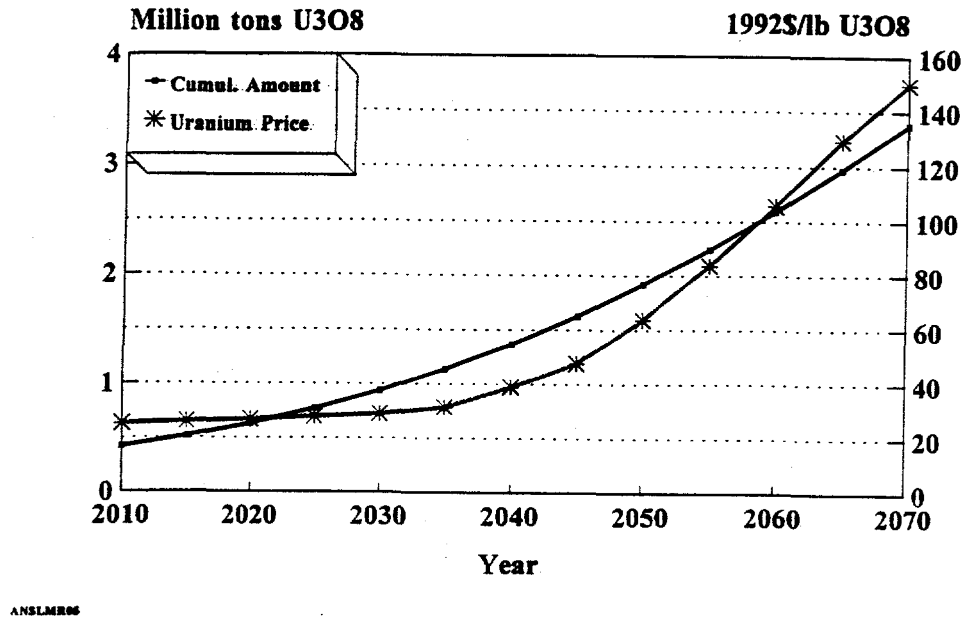


Fig. 5. Uranium use and price without ALMR deployment

repositories. The LWR fuel cycle costs were developed on the basis of the data provided in Table 6. Due to the growing amount of nuclear generation, demand for uranium ore increases as shown in Fig. 5. This results in an increased price for ore, also shown in Fig. 5.

One of the most significant impacts of this case is the amount of spent fuel (heavy metal) that will have to be placed in repositories. The limit of the first repository is reached in 2029, with new repositories needed approximately every 10 years. During the 60 year analysis period, five repositories would be needed at the current repository capacity limit.

4.2 ALMR BASE CASE

For purposes of relative comparison, the ALMR burner was selected as the base case. The annual energy generation estimated for this case for both the ALMR and the LWR nuclear are shown in Fig. 6. By the year 2070, the LWR and ALMR are nearly in equilibrium with the ALMR producing about 40% of the total nuclear power. The ALMR depends on LWR spent fuel for new plant startups and to maintain existing plants. The cumulative uranium ore use with ALMR deployment is presented in Fig. 7. Uranium price projections with and without ALMR deployment is shown in Fig. 8. Ore use and price for both the ALMR burner and breeder are included in Figs. 7 and 8. As a result of the deployment of ALMRs, the demand for uranium is less than in the no ALMR case and the uranium cost for LWRs is reduced.

One of the most striking features of this case, and for all ALMR cases, is the reduction in the rate at which waste repositories are filled. Owing to the removal of spent fuel actinides via reprocessing, and the resulting decrease in long-term thermal heat loading, more spent fuel material (i.e., fission products) can be volumetrically accommodated in a given repository. This leads to a thermal heavy metal equivalence which, in effect, fills the repositories at a much slower rate. With the base case waste density factor, four times as much initial heavy metal in the form of reprocessing wastes can be accommodated in a repository as compared to intact spent fuel assemblies. Therefore, one metric ton of ***equivalent*** heavy

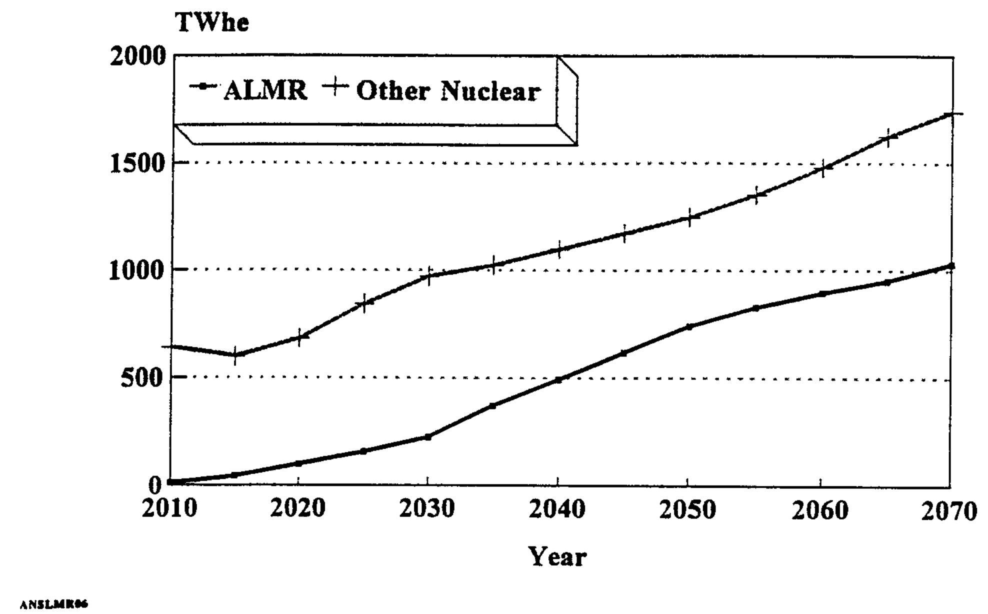


Fig. 6. Annual nuclear energy generation for ALMR base burner case.

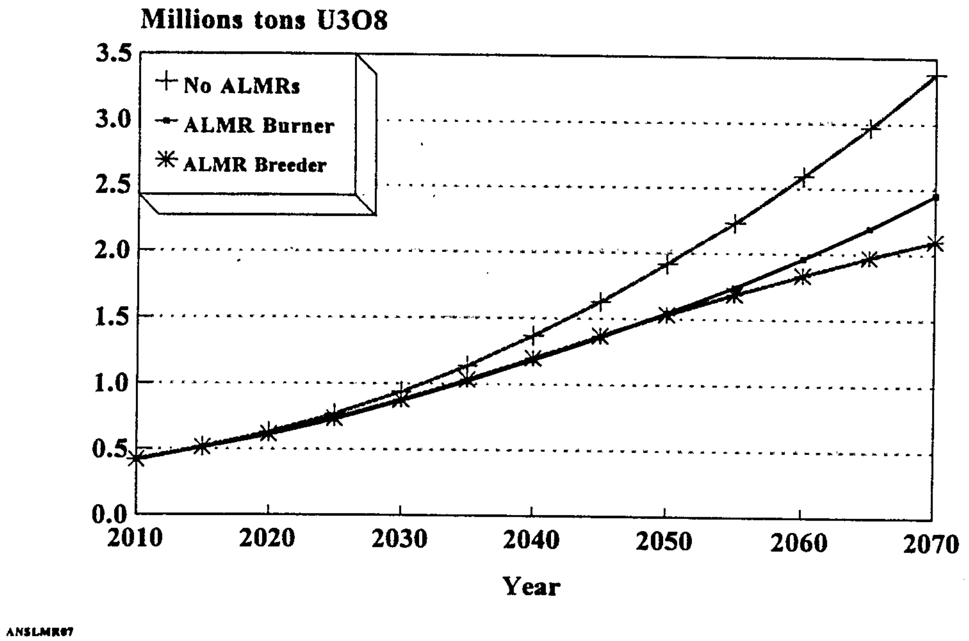


Fig. 7. Cumulative uranium use.

metal corresponds to four MTHM in an unprocessed (intact) state. For the ALMR base case, the equivalent heavy metal disposed in the repositories is such as to not require a second repository (at the current loading limit of 63,000 MTHM) until 2061, 51 years after the start of the first repository.

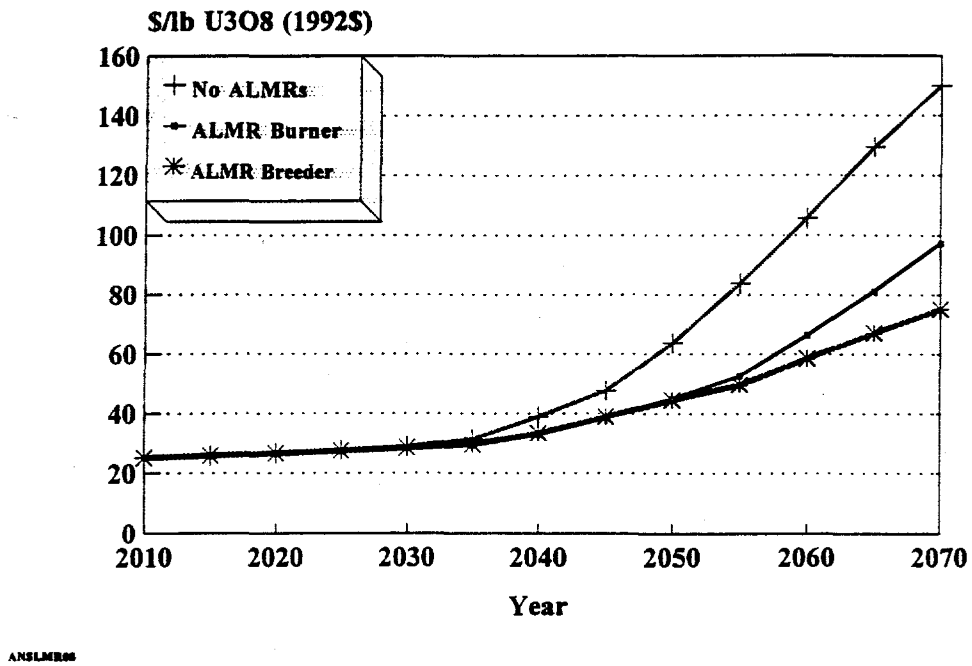


Fig. 8. Uranium price projections.

The differential NPV cost for this case relative to the no ALMR case leads to a $16.6 billion (1992$) net present value advantage for the ALMR over the 2010–2070 period.

4.3. SENSITIVITY TO PARAMETER VARIATIONS

The sensitivity of the results to variations in various parameters was examined. A list of the parameters varied is shown in Table 7. The NPV results are shown in Table 8. Discussions of results of several of the sensitivity variations follows.

<u>4.3.1. Sensitivity to LWR processing cost</u>: The results of the analysis are most sensitive to the LWR spent fuel reprocessing cost. The range of reprocessing costs from $200/kgHM to $1000/kgHM correspond to very optimistic cost assessments on the low end to a cost more consistent with European bids on the higher end. The relative Net Present Value results are shown in Fig. 9 for both the ALMR burner and for the ALMR breeder cases. This figure shows that the ALMR burner will have a net benefit compared with LWR once-through at an LWR spent fuel reprocessing costs of about $550/kgHM or less, whereas the ALMR breeder will show a net benefit up to an LWR spent fuel reprocessing cost of about $950/kgHM.

<u>4.3.2. Sensitivity to future repository costs</u>: The sensitivity of the results to the cost of future repositories is given in Fig. 10. The power plant, fuel cycle facilities and repository deployment were unchanged. The change in the repository cost effects both the ALMR base case and the case with no ALMR deployment. The increased repository cost results in increased costs for both ALMR and the null case.

The results show that approximately doubling the follow on repository costs from $7.2 to $15 billion increases the ALMR NPV cost advantage to $23.5 billion. This is approximately $6.9 billion more than the differential for the ALMR base case.

Table 8. Relative Cost Summary

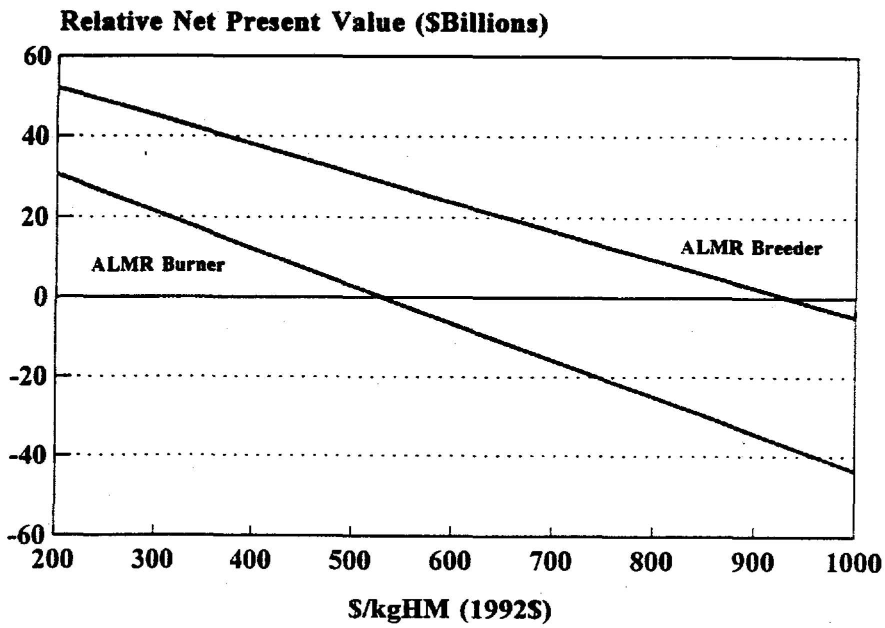
Case	Relative Net Present Value[a] 2010-2070 (Billions 1992$)
Burner with $1000/kg LWR reprocessing	- 43.74
No utilization of initial LWR spent fuel stocks	12.52
Maximum rate of deployment of base case burner	14.09
Burner with 2.0 waste density factor	14.98
Burner at 75% capacity factor	14.99
Burner at 80% capacity factor	16.30
Base case ALMR burner (conversion ratio = 0.69)	16.63
Burner with 0.5 repository disposal cost factor	19.41
ALMR Mod A breakeven (breeding ratio = 1.04)	19.54
Maximum rate of deployment of breakeven plant	20.74
LWR reprocessing cost included with waste system	21.92
Burner with 100 MT defense Pu	23.12
$15 billion follow-on repository cost	23.53
Burner with $200/kg LWR reprocessing	30.57
ALMR breeder (breeding ratio = 1.24)	41.41
Maximum rate of deployment of breeder plant	46.82
Breeder plant with defense Pu	48.10

[a] Benefits compared to the no-ALMR case (null case).

4.3.3. Sensitivity to waste density factor: The waste density factor affects the frequency at which new repositories will have to be brought on line. The disposal of reprocessing plant wastes compared to LWR assembly disposal has been estimated to increase the effective capacity of a given repository by substantially reducing long term heat load. Fig. 11 generically demonstrates the effect of increasing the amount of material which can be loaded into a single repository (density factor) on the frequency at which new repositories will have to be brought on line. For instance, if LWR spent fuel assembly disposal (density factor = 1) requires a new repository every 20 years, then reprocessing waste disposal with a density factor of 4 will require a new repository only every 80 years.

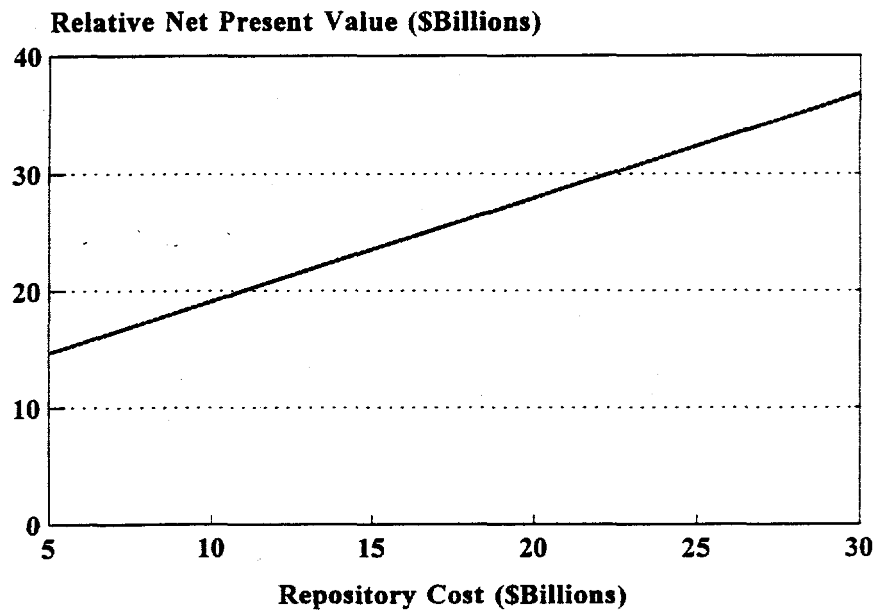
The sensitivity of the relative NPV to the density factor for the base case burner compared to the no ALMR case is shown in Fig. 12. All factors are the same as for the ALMR base case except that the waste density factor for reprocessing waste disposal was varied. The sensitivity of the NPV to repository density factor is small. The NPV benefit for ALMR deployment is reduced to $15.0 billion or $1.7 billion less than for the ALMR base case if the density factor is reduced by half to 2.

4.3.4. Sensitivity to availability of defense Pu: The availability of surplus weapons plutonium for startup fuel for ALMRs will delay LWR spent fuel reprocessing and will increase the NPV benefit of ALMR deployment. The relative NPV benefit of deploying the ALMR as a function of the weapons plutonium availability is shown in Fig. 13. This case uses the same data as the ALMR Base Case burner except that defense-related plutonium is assumed to be made available to the ALMR system at no cost for the fissile material. The energy generation, uranium



ANSLMR09

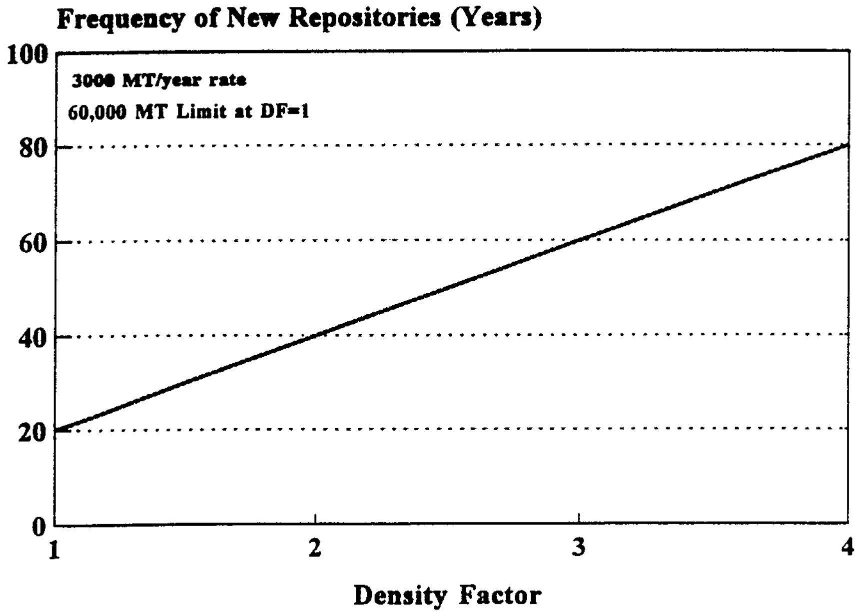
Fig. 9. Sensitivity to LWR spent fuel reprocessing costs



ANSLMR10

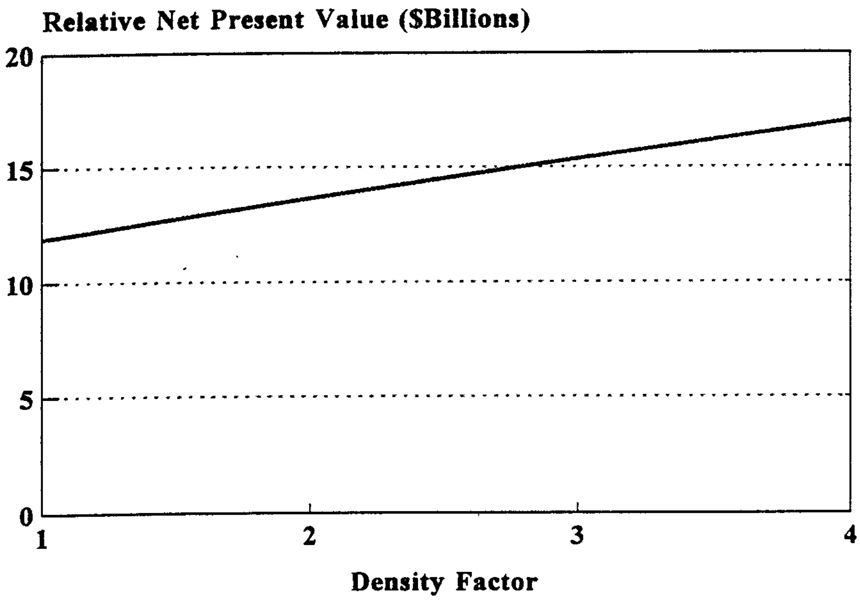
Fig. 10. Sensitivity to future repository cost.

demands, and repository requirements are nearly identical to the base case. The differential NPV for 100 MT of weapons Pu availability is $23.1 billion or $6.4 billion greater than the base case in which no weapons Pu was available.



ANSLMR11

Fig. 11. Repository frequency sensitivity to waste density factor.



ANSLMR12

Fig. 12. Sensitivity to waste density factor.

4.3.5. Sensitivity to conversion ratio: The ALMR NPV benefit increases as the plant conversion (breeding) ratio is increased. The ALMR relative NPV benefit as a function of breeding ratio is shown in Fig. 14. In order to maintain a consistent comparison, Mod B ALMR plant designs were used here for the burner and breakeven fuel cycles as well as for the breeder. The Mod

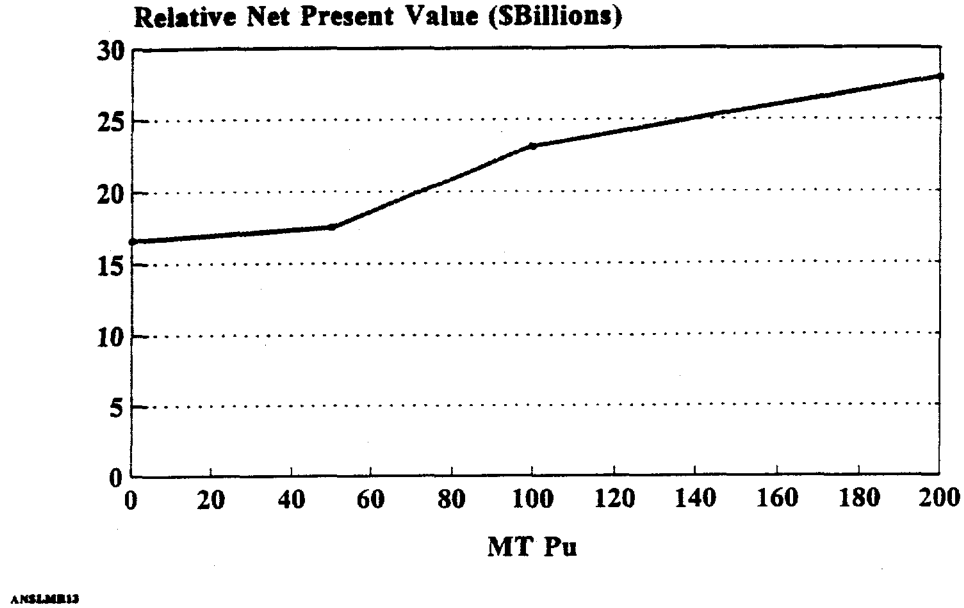


Fig. 13. Sensitivity of ALMR net benefit to weapons plutonium availability.

B plant design gives a higher relative NPV benefit than found with the Mod A designs, increasing the NPV benefit for the burner case by approximately $12 billion compared to the Mod A burner. Generally, increasing the plant conversion ratio will increase the penetration of ALMRs into a nuclear economy. The replacement of LWRs by ALMRs will reduce the uranium requirements (see Fig. 7) bringing about a concomitant lower price of uranium for existing LWRs (see Fig. 8).

4.3.6. Initial LWR spent fuel not utilized: All the previous ALMR cases have assumed that all LWR spent fuel is processed to recover the useful fissile materials as fuel for ALMR power plants. This case addresses the scenario in which the total amount of LWR spent fuel accumulated as of the inception of ALMR commercial deployment (i.e., 60,000 MTHM in the year 2010) is not processed to recover the actinides but rather is disposed intact in the first repository, starting in 2010. Only LWR spent fuel generated in 2010 and beyond is assumed to be processed for actinide recovery. In the case of the ALMR burner, without utilization of the initial spent fuel inventory a second repository will be required by 2035 with a third repository needed by 2070 compared to a third repository requirement by 2040 for the null case with no ALMR deployment. The outcome of this scenario is influenced by the initial lack of fissile material for ALMR startups. Not utilizing the accumulated LWR spent fuel limits the number of ALMR plants that can be deployed. As a result, more nuclear energy is obtained from uranium burning plants, thereby increasing the demand and therefore cost of the uranium-burner fuel cycle. In addition, the assumed intact disposal of spent fuel assemblies requires an earlier second repository and is more costly than the disposal of process waste assumed in the ALMR base burner case. The resulting ALMR NPV benefit relative to the null (no-ALMR) case is $12.5 billion, which is $4.1 billion less than the ALMR burner case utilizing all available LWR spent fuel.

Additional sensitivity cases and complete output for all cases run are included in Ref. 1.

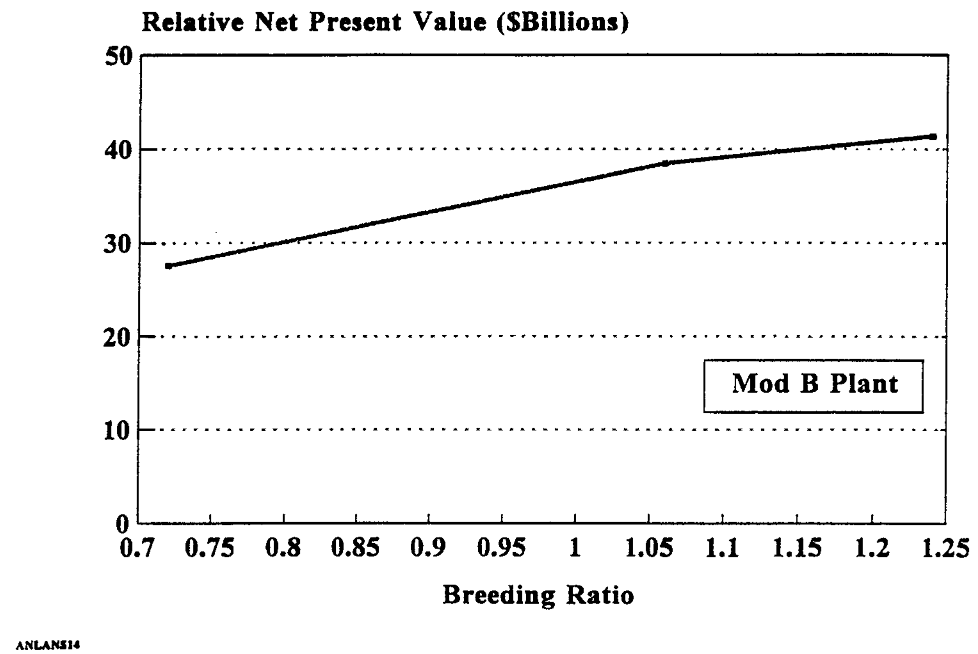


Fig. 14. ALMR benefit sensitivity to breeding ratio.

5. CONCLUSIONS

Based on the assumptions made in this study, there appears to be an economic incentive for the development and eventual deployment of ALMRs. This economic incentive is enhanced by potential benefits of actinide burning on the need for future high-level waste repositories.

REFERENCES

1. J. G. Delene, L. C. Fuller and C. R. Hudson, *ALMR Deployment Economic Analysis*, Oak Ridge National Laboratory Report ORNL/TM-12344 (June 1993).

2. National Energy Strategy, Technical Annex 2, *Integrated Analysis Supporting the National Energy Strategy: Methodology, Assumptions and Results*, DOE/S-0086P, 1991/1992.

3. *Nuclear Energy Cost Data Base: A Reference Data Base for Nuclear and Coal-fired Powerplant Power Generation Cost Analysis*, DOE/NE-0095 (September 1988).

4. B. H. Hutchins, GE, personal communications with J. G. Delene, ORNL.

5. Personal communications from Y. I. Chang, ANL.

6. *Analysis of the Total System Life-Cycle Cost for the Civilian Radioactive Waste Management Program*, DOE/RW-0236 (May 1989).

7. Allen G. Croff, *A Concept for Increasing the Effective Capacity of a Unit Area of a Geological Repository,* Oak Ridge National Laboratory Draft Report (December 8, 1992).

8. C. C. McPheeters and R. O. Pierce, *Nuclear Waste from Phyrochemical Processing of LWR Spent Fuel for Actinide Recycle,* ANL-IFR-165 (March 1992 draft).

9. *World Nuclear Fuel Cycle Requirements 1991,* DOE/EIA-0436 (91) (October 1991).

10. *Uranium Industry Annual 1990,* Energy Information Administration, DOE/EIA-0748 (90) (September 1991).