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* To be published as the proceedings of the "International Conference on Radiation Effects and Tritium Technology for Fusion Reactors," held in Gatlinburg, Tenn., October 1-3, 1975.

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ABSTRACT

The effect of first wall lifetime of 0.5 to 8 years on the cost of generating electricity in the UWMAK-I and UWMAK-II reactors is investigated. It was assumed that there was little incentive to develop walls with lifetimes (determined by radiation damage) greater than 10 years because of failures due to conventional mechanisms. Based on this assumption the cost of electricity from these two reactors increased over the 10 year lifetime value by 8 to 10% for a wall life of 4 years, 17 to 28% for 2 years, 35 to 65% for 1 year, and 85 to 150% for 0.5 year lifetimes. It appears that wall lifetimes of <2 years are economically unattractive for these reactors and that there is a great incentive to find materials which will have in-service lifetimes between at least 4 and 10 years.

INTRODUCTION

It has now become quite apparent that the first walls (sometimes referred to as vacuum walls) of fusion power reactors will not last the lifetime of the plant.[1-3] There are many reasons why materials scientists have come to this conclusion, but by far the most prominent one relates to a loss of mechanical integrity under the high stresses and strains associated with typical fusion reactor operations. Void swelling, transmutation effects, neutron and charged particle sputtering would also limit the wall lifetime even if the mechanical property degradation could be eliminated. Current estimates of wall lifetime vary from 2 to 5 years[1-3] under typical 1-5 MW/m^2 neutron wall loadings.

Given the necessity to replace the first walls periodically (and even part of the blanket structure), it is legitimate to ask, "How much does such a replacement effect the cost of generating electricity in a fusion power plant?" It is difficult to give a definite answer to that question at this early stage of reactor design because the absolute cost

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of electricity from fusion is not known to probably within a factor of two. Nevertheless, we can gain a qualitative picture of how much of a relative cost penalty is paid by analyzing two rather specific designs in the open literature. We have chosen the UWMAK-I[4] and UWMAK-II[5] reactor designs for this study. It must be noted that the results of this work only apply to these reactors at the 5000 MW_{th} power level and one cannot simply apply these results to other systems at different power levels.

General Effects of Radiation Damage on Fusion Power Economics

The unit cost of electricity from any power source depends on 4 factors;

- Operation and Maintenance Costs
- Fuel Costs
- Return on Capital
- kWh of Energy Generated Per Unit of Time

The necessity to replace the first wall obviously will increase the O & M charges by the cost of replacement material and the labor cost associated with the replacement time. It is fairly easy to calculate the costs associated with the materials but at present one can only make rough estimates of the labor time involved. This latter point is especially true with irradiated components which must be handled remotely. However, we shall see that such costs are not a major factor compared to the material cost.

There is no obvious direct relationship between first wall lifetime and the fuel costs and we shall assume that it is unaffected by radiation damage. There is an indirect relationship in that the need for outage time to replace the walls decreases fuel use. However, the fuel costs for a fusion reactor are so small that the changes will have an insignificant effect in our analysis.

The increase in capital costs of a fusion reactor required by the replacement of the first wall on a regularly scheduled basis is mainly due to:

(A) Inventory costs associated with the spare modules which must be on hand for quick insertion into the reactor.

(B) Larger or more hot cell facilities to handle the repair and/or replacement of the entire reactor component which is removed from the reactor.

(C) Increased long term storage space for the damage components. Before we address the problem of finite wall lifetime, it is worthwhile to note that fusion reactors will have to be designed for quick and frequent wall repair even _if_ the predicted first wall life is greater than the plant lifetime. This is true because failures will occur which are unrelated to radiation damage. Typical causes might be hot spots, corrosion, inhomogeneties due to fabrication procedures, or abnormal operating conditions. It is reasonable to assume that the entire blanket structure can not function for 30 years at high temperatures and with varying loads without a single failure. Once the concept of replacement is accepted, then all of the procedures, equipment, hot cells, shielding and radioactive component storage areas must be designed, tested and installed. It is also reasonable to assume that at any given time something like 10-15% of the blanket structure may have to be removed per year for external repair or replacement.* This means that the concept of a finite first wall lifetime is only significant if the wall life is less than 10 years or so. We will make estimates for the increased capital costs in UWMAK-I and II based on our knowledge of the system but the reader ought to recognize the qualitative nature of such estimates and not concentrate on the exact numbers.

The last important quantity that is affected by a wall life of $\leq$ 10 years is the time the reactor is unavailable for generation of electricity. This results in lost revenue which can be as high as $700,000 to $800,000 per day. Again, it is certainly recognized that "normal" failures will occur in any power facility and we expect the same will hold true for fusion power plants. In this study, 4 weeks of down time per year is assumed for routine and emergency maintenance unrelated to first wall replacement. Here, we will be concentrating on the additional downtime required for a systematic replacement of the first wall.

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*A simple pinhole leak could require replacement of a very large component.

Method of Calculation

We will use as a starting point for this study the economic studies published in the UWMAK-I and II reports.(4,5) A summary of the capital and electrical costs for both reactors is shown in Tables 1 and 2. These costs are based on a two year wall life.

Once a decision on the first wall lifetime has been made, the next major task is to determine the optimum time for replacement of the modules. Intuitively, this would appear to be the stated wall life. However, this would require excessively high inventory costs of the blanket modules which must be ready outside the reactor when the shutdown is made. Therefore, one usually tries to remove only a part of the defected parts at a time and replace them with new components. The repair of the damaged components is conducted while the reactor is running. These repaired components then can be reinserted into the reactor at the next outage and the process started all over again. While this means that early in the reactor lifetime some components are changed before their anticipated lifetime, it requires a smaller inventory of components and results in a lower electricity cost.

A simple schematic of how we estimated the major effect of changing the first wall on reactor costs is shown in Figure 1. We first determined the annual outage time as a function of time between replacement. This requires that we know the number of modules replaced per outage. Once this is known, the annual outage time is calculated by

$$\left(\frac{\text{outage days}}{\text{year}}\right) = \left[\left(\frac{\text{X days replacement}}{\text{module}}\right)\left(\frac{\text{No. of modules replaced}}{\text{outage}}\right) + \left(\frac{\text{Y Days Cool Down and Startup}}{\text{outage}}\right)\right] \times \left(\frac{\text{No. of outages}}{\text{year}}\right)$$

One peculiar fact about present reactor designs is that they are usually made up of a finite number of modules which can be conveniently replaced. For example, UWMAK-I had 12 such modules, UWMAK-II had 24, and a more recent design UWMAK-III has 18.(6) Therefore, if one finds that the wall life is 2 years, then he can replace 12 modules every 2 years, or

Table I

UWMAK-I Cost Data

(Prices are 1974 Dollars and Based on a 40 Hour Work Week)

Account Number	Account Title	Total
	DIRECT COSTS:	
Nondepreciating Assets:		
20	Land and Land Rights	$1,200,000
Depreciating Assets:		
	Special Materials	28,290,000
	Physical Plant	
21	Structures and Site Facilities	139,807,000
22	Reactor Plant Equipment	573,636,000
23	Turbine Plant Equipment	170,580,000
24	Electric Plant Equipment	142,859,000
25	Miscellaneous Plant Equipment	9,410,000
	SUB-TOTAL Physical Plant	1,036,292,000
	INDIRECT COSTS (All Depreciating Assets):	
91	Construction Facilities, Equipment	24,300,000
92	Engineering Services	48,500,000
93	Other Costs	76,600,000
94	Interest During Construction	218,618,000
	SUB-TOTAL	367,018,000
	SUB-TOTAL (Total Depreciating Assets)	1,431,600,000
	TOTAL PLANT CAPITAL INVESTMENT:	1,432,800,000
	COST PER KILOWATT GENERATED	$971/kWe

Table 2

UWMAK-II Cost Data

(Prices are 1974 Dollars and Based on a 40 Hour Work Week)

Account Number	Account Title	Total
	DIRECT COSTS:	
Nondepreciating Assets:		
20	Land and Land Rights	$1,200,000
Depreciating Assets:		
26	Special Materials	5,820,000
Physical Plant		
21	Structural and Site Facilities	161,590,000
22	Reactor Plant Equipment	775,179,000
23	Turbine Plant Equipment	160,150,000
24	Electric Plant Equipment	84,218,000
25	Miscellaneous Plant Equipment	19,110,000
	SUB-TOTAL Physical Plant	1,200,100,000
	INDIRECT COSTS (All Depreciating Assets):	
91	Construction Facilities, Equipment and Services	24,300,000
92	Engineering Services	48,500,000
93	Other Costs	90,800,000
94	Interest During Construction	250,923,000
	SUB-TOTAL	414,523,000
	Sub Total (Total Depreciating Assets)	1,613,420,000
	TOTAL PLANT CAPITAL INVESTMENT	$1,614,620,000
	COST PER KILOWATT GENERATED	$944/kWe

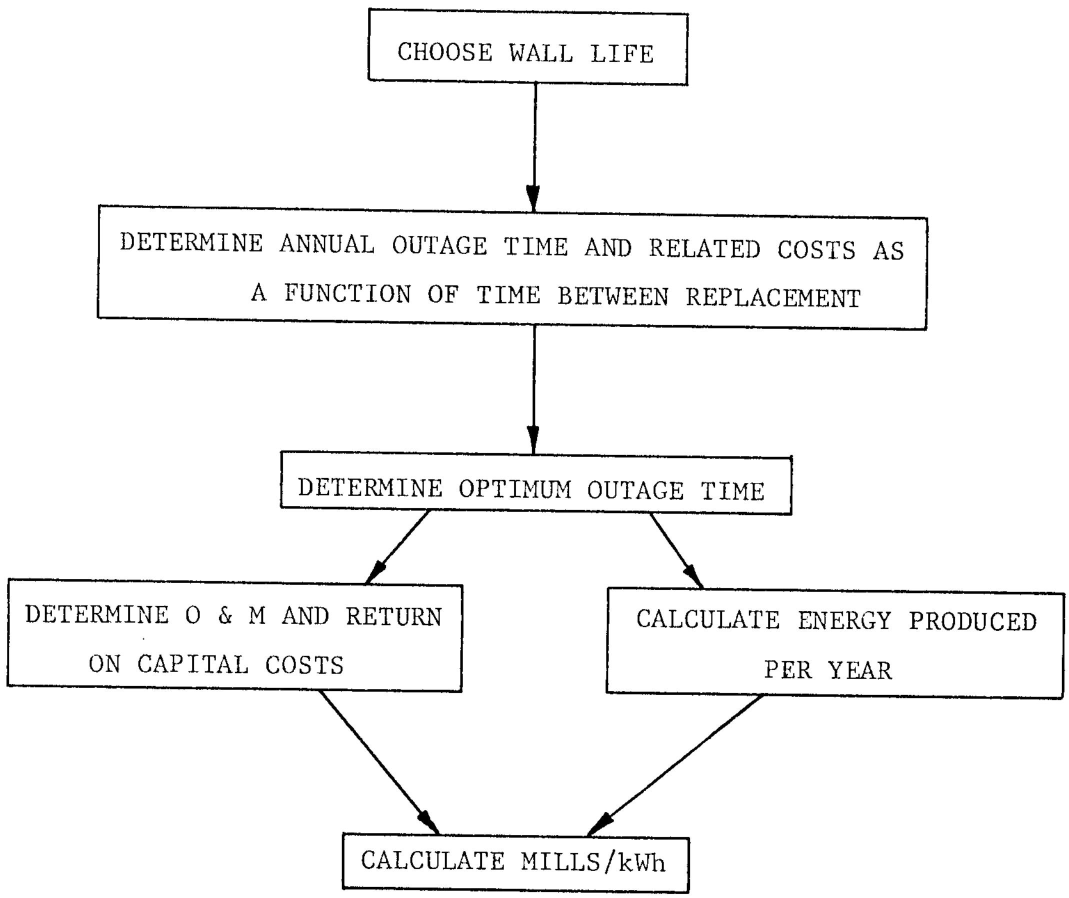


Figure 1

Method of Calculation of the Effect of First Wall Life on the Cost of Electricity From Fusion Power Plants

6 modules every year, 3 every 6 months, 2 every 4 months, or 1 every 2 months. The same analyogy can be applied to other systems.

The values of X and Y are somewhat arbitrary at this time because of reactor characteristics but consideration of the mode of construction and afterheat in these reactors led to use of X=3 days for UWMAK-I, X=1.5 days for UWMAK-II, and Y=5 days for both reactors.

We then used this information to calculate the optimum outage time. This depends on three major costs -

(A) Inventory costs for spare modules

$$\left(\frac{\$}{\text{module}}\right) \times \left(\frac{\text{\# of modules replaced}}{\text{outage}}\right) \times (\text{return on capital})$$

(B) Labor costs to replace modules

$$\left(\frac{\text{\# of days}}{\text{outage}}\right) \times \left(\frac{\text{Labor costs}}{\text{day}}\right)$$

(C) Revenue lost during time required to change modules

$$\left(\frac{\text{mills}}{\text{kW}_e\text{h}}\right) \times (\text{power level of reactor in kW}_e) \times (\text{annual outage time})$$

Once the optimum outage time is determined, we can calculate increased O & M costs and costs associated with increased capital requirements as well as the reduced kWh generated. This then allows a determination of mills/kWh to be made.

A new wall life is then assumed and the entire process is repeated.

Results for UWMAK-I and UWMAK-II

A comparison of the annual outage time as a function of number of modules replaced per outage and assumed wall life is given in Table 3. There are two points worth noting here, the wall replacement for <u>these</u> two reactors probably will be done on the basis of integral fractions of 12 or 24, and the outage time is the same for I and II except twice as many modules must be changed in II as in I.

The optimum outage time was calculated assuming the following values.[4-5]

Table 3

Annual Outage Time UWMAK-I and II

First Wall Life - Years	Intervals Between Replacement Outages	No. of Modules Replaced per Outage		Annual Outa Time - Days I and II
		I	II	
0.5	6 months	12	24	82
	3 months	6	12	92
	1.5 months	3	6	112
	1 month	2	4	132
	0.5 months	1	2	192
1 year	1 year	12	24	41
	6 months	6	12	46
	3 months	3	6	56
	2 months	2	4	66
	1 month	1	2	96
2 years	2 years	12	24	21
	1 year	6	12	23
	6 months	3	6	28
	4 months	2	4	33
	2 months	1	2	48
4 years	4 years	12	24	10
	2 years	6	12	12
	1 year	3	6	14
	8 months	2	4	17
	4 months	1	2	24
8 years	8 years	12	24	5
	4 years	6	12	6
	2 years	3	6	7
	16 months	2	4	9
	8 months	1	2	12

	UWMAK-I	UWMAK-II
Cost/Module - $	20,300,000	6,250,000
Increased Facility Costs - $ per module	13,000,000[a]	3,300,000[b]
Return on Capital	0.15	0.15
Labor Costs $/Day	28,500	28,500
Loss of Income $/Day (at 20 mills/kWh)	710,000	840,000

(a) for number of modules per outage exceeding 2

(b) for number of modules per outage exceeding 4

The cost per module includes those costs attributable to insurance (~10%) and interest during construction since these modules will probably be long lead time items. The increased facility costs were calculated on the basis of the fraction of the containment facilities attributable to remote handling of components and assuming that the increase in those facilities is 10% per module over the minimum number of modules required for normal outage. For example, we assumed that facilities to handle two damaged modules in UWMAK-I and 4 modules in UWMAK-II would be required regardless of the first wall life. If an extra module had to be changed or held in readiness due to first wall life, then the increased cost is 10% of that required for the basic number in UWMAK-I and 5% for UWMAK-II. These numbers also include the insurance and interest factors.

The cost of labor was calculated on the basis of 96 men working per shift, 3 shifts per day, and these men cost approximately 50% more than the normal maintenance crew (i.e. 20,000 $/man year including fringe benefits).[11] This amounts to labor costs of ~28,500/day of outage.

The loss of revenue has been calculated as if fusion power plants were operating in an economy where electricity is being produced ~20 mills/kWh. Hence, when the plant is shut down it will lose that revenue. For UWMAK-I operating at 1473 MW_e (continuous power) this amounts to ~710,000 $/day. For UWMAK-II at 1716 MW_e, this is 840,000 $/day.

The approximate annual increase in costs due to each of the above items is reported in Table 4 for UWMAK-I and in Table 5 for UWMAK-II. They are also plotted in Figures 2 and 3. The optimum time between outages is

Table 4

Annual Increase in Costs - UWMAK-I as a Function of Wall Life and Time Between Outages

Time Between Outages	Return on Capital	Labor Costs	Lost Revenue	Total
	Million of Dollars			
	0.5 Year Wall Life			
6 months	56.0	2.3	58.2	117
3 months	26.1	2.6	65.3	94
1.5 months	11.1	3.2	79.5	94*
1 month	6.1	3.8	93.7	104
0.5 months	3.1	5.5	136.3	145
	1 Year Wall Life			
1 year	56.0	1.2	29.1	86
6 months	26.1	1.3	33.7	61
3 months	11.1	1.6	39.8	53*
2 months	6.1	1.9	46.9	55
1 month	3.1	2.7	68.2	74.
	2 Year Wall Life			
2 years	56.0	0.6	14.9	72
1 year	26.1	0.7	16.3	43
6 months	11.1	0.8	19.9	32
4 months	6.1	0.9	23.4	30*
2 months	3.1	1.4	34.1	39
	4 Year Wall Life			
4 years	56.0	0.3	7.1	63
2 years	26.1	0.3	8.5	35
1 year	11.1	0.4	9.9	21
8 months	6.1	0.5	12.1	19*
4 months	3.1	0.7	17.0	21
	8 Year Wall Life			
8 years	56.0	0.1	3.6	60
4 years	26.1	0.2	4.3	31
2 years	11.1	0.2	5.0	16
16 months	6.1	0.3	6.4	13
8 months	3.1	0.3	8.5	12*

* Optimum

Table 5

Annual Increase in Costs - UWMAK-II as a Function of Wall Life and Time Between Outages

Time Between Outages	Return on Capital	Million of Dollars Labor Costs	Lost Revenue	Total
		0.5 Year Wall Life		
6 months	32.4	2.3	68.9	104
3 months	15.3	2.6	77.3	95*
1.5 months	6.7	3.2	94.1	104
1 month	3.8	3.8	111	119
0.5 months	1.9	5.5	161	168
		1 Year Wall Life		
1 year	32.4	1.2	34.4	68
6 months	15.3	1.3	37.6	55
3 months	6.7	1.6	47.0	55*
2 months	3.8	1.9	55.4	61
1 month	1.9	2.7	80.6	85
		2 Year Wall Life		
2 years	32.4	0.6	17.6	51
1 year	15.3	0.7	19.3	35
6 months	6.7	0.8	23.5	31*
4 months	3.8	0.9	27.7	32
2 months	1.9	1.4	40.3	44
		4 Year Wall Life		
4 years	32.4	0.3	8.4	41
2 years	15.3	0.3	10.1	26
1 year	6.7	0.4	11.8	19
8 months	3.8	0.5	14.3	19*
4 months	1.9	0.7	20.2	23
		8 Year Wall Life		
8 years	32.4	0.1	4.2	37
4 years	15.3	0.2	5.0	21
2 years	6.7	0.3	5.9	13
16 months	3.8	0.3	7.6	12*
8 months	1.9	0.3	10.1	12

* Optimum

Figure - 2

Determination of Optimum Time Between Outages For UWMAK-I As A Function of First Wall Life

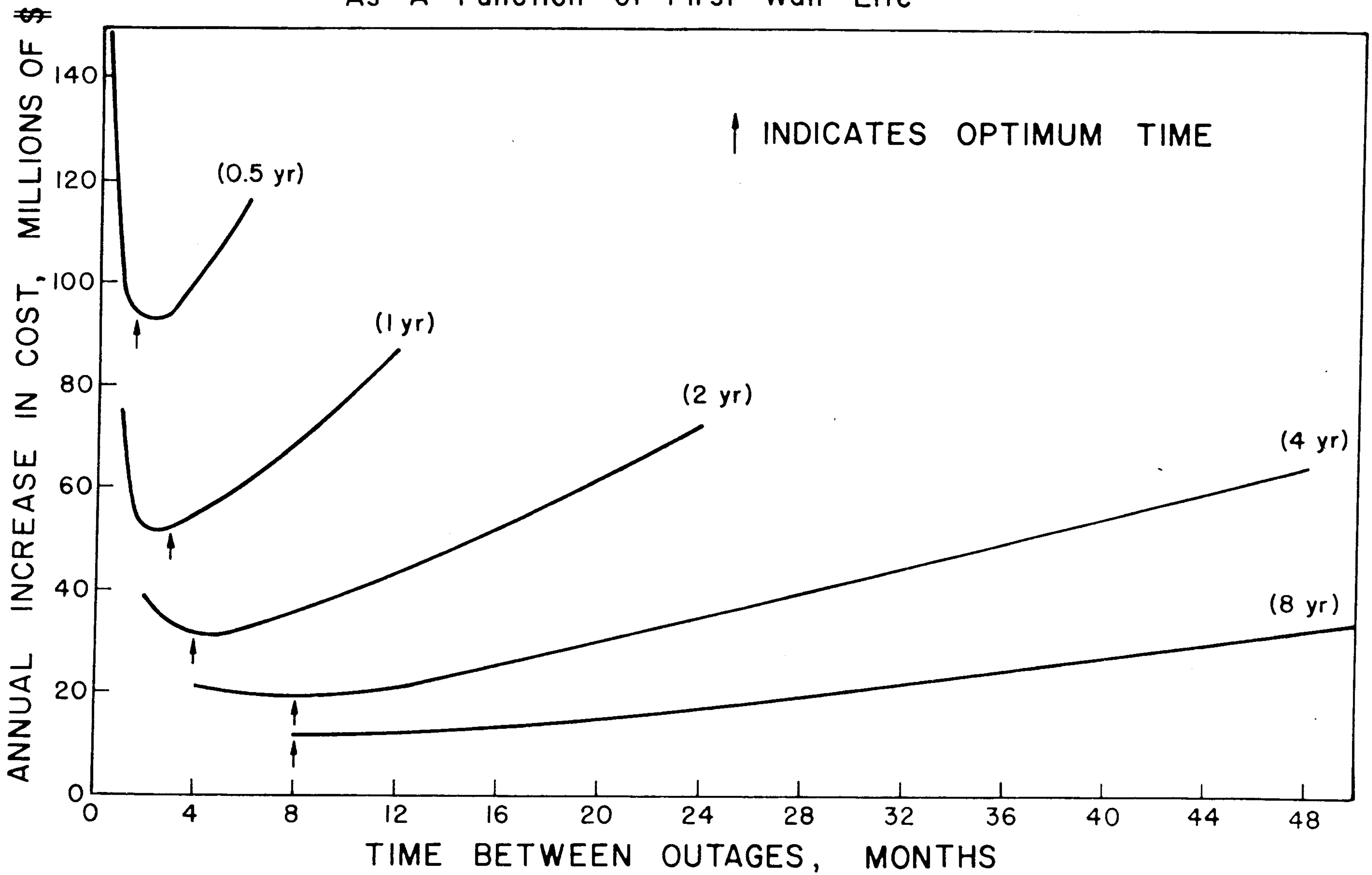
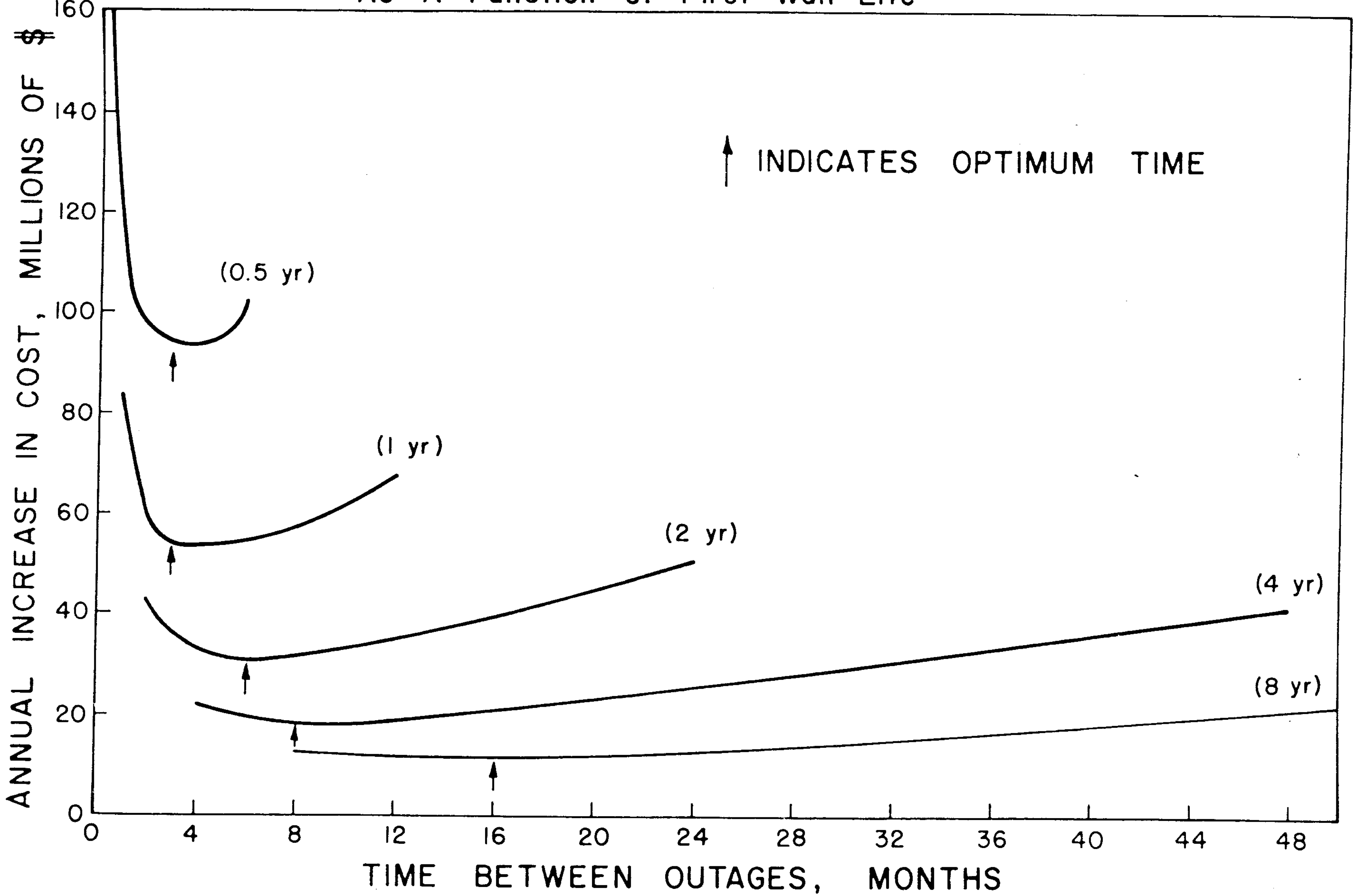


Figure – 3
Determination of Optimum Time Between Outages For UWMAK – II
As A Function of First Wall Life



a balance between the high costs associated with inventory of spare modules (and the increased hot cells to handle them) and the loss of revenue associated with down time.

The optimum time between outages is summarized below from Tables 4 and 5.

Wall Life - Years	Optimum Outage Time - Months UWMAK-I	UWMAK-II
0.5	1.5	3
1	3	3
2	4	6
4	8	8
8	8	16

It is interesting to note that the optimum outage time does not increase in proportion to the first wall life time, e.g. a factor of 16 increase in wall life only results in less than a factor of 5 increase in the optimum outage time for UWMAK-I and II.

Having determined the optimum outage time, and hence the number of outage days per year due to the first wall replacement (remember that 4 weeks of additional time is set aside for routine maintenance or repairs required by "normal" component failures) we can now estimate the cost of electricity as a function of wall life.

The first area to investigate is that contribution due to O & M costs. The costs are listed for both reactor systems in Table 6 and the explanation for their derivation is given elsewhere.[4] The outside support services are primarily the labor costs determined in Tables 4 and 5. The materials costs of replacing the first wall were determined by using the weights and cost figures from the UWMAK reports.[4-5] For UWMAK-I, this amounts to 17.6 \$/kg for the first 20 cm of blanket and 8.8 \$/kg for the remainder of the blanket. The stainless steel reflector is assumed to have a lifetime five times that of the first wall due to the neutron attenuation. The total weight of the first 20 cm is 491,000 kg and that of the rest of the blanket is 7,323,000 kg. The amount of 316 SS replaced per year is given in Table 7 as a function of the first wall lifetime.

Table 6

Summary of Operations and Maintenance Costs Associated with UWMAK-I and II

Cost Item	Annual Cost - $ UWMAK-I	UWMAK-II
Salaries (incl. Fringe Benefits)	1,350,000	1,350,000
Misc. Supplies & Equipment	1,000,000	1,000,000
Outside Support Services	350,000+[(a)]	350,000+[(a)]
Miscellaneous Costs	200,000	200,000
Subtotal	(b)	(b)
General and Administrative (15% of Subtotal)	(b)	(b)
Replacement of Inner Wall (annual rate)	(a)	(a)
Coolant Make Up	38,000	43,000
Total Annual Cost	(b)	(b)

(a) Depends on Wall Life

(b) To be determined as a function of wall life

Table 7

Cost of Changing First Wall and Associated Blanket Structure Due to First Wall Lifetimes - UWMAK-I

Wall Life-yr	Wt-First 20 cm MT/yr[a,b]	Wt-Rest of Blanket MT/yr[a,c]	Total MT/yr[a]	Annual Cost-M$
8	61	-	61	1.1
4	123	366	489	5.4
2	246	732	978	10.8
1	491	1465	1956	21.5
0.5	982	2929	3911	43.1

(a) average numbers, MT = metric tonne
(b) 17.60 $/kg
(c) 8.80 $/kg

Table 8

Cost of Materials for First Wall and Blanket Replacement in UWMAK-II

Wall Life-yr	Wt-316 SS First Wall & Tube MT/yr[a]	Wt-316 SS Manifold MT/yr[a]	Wt. of $LiAlO_2$ MT/yr[a]	Wt. of Be MT/yr[a]	Wt. of Graphite MT/yr[a]	Cost $-M/yea
8	112	-	59	54	-	12.4
4	224	170	119	108	65	26.6
2	449	340	238	217	131	53.4
1	897	680	475	433	261	107
0.5	1794	1360	950	866	523	213

(a) average number, MT = metric tonne.

A similar analysis for replacement materials has been conducted for UWMAK-II (Table 8). There is a difference in this reactor because materials other than 316 SS must be replaced due to the high cost of refabricating radioactive material and/or the damage incurred in other materials ($LiAlO_2$, Be or graphite) during their residency in the reactor. Pertinent costs and weights are given below for UWMAK-II.

Component	Metric-Tonnes	Repl. Time (First Wall=1)	\$/kg [(a)]
316 SS-First Wall and Tubes	897	1	17.6
316 - Blanket Manifold	3402	0.2	8.8
$LiAlO_2$ [(b)]	475	1	40
Be [(b)]	433	1	150 [(c)]
Graphite	1307	0.2	3

(a)fabricated cost
(b)make up neglected
(c)reprocessed Be

There is now enough information to calculate the O & M costs as a function of wall life. The results are given in Table 9 for both UWMAK-I and II. The O & M costs increase dramatically by a factor of 10 to 14 when the wall life decreases from 8 to 0.5 years with the replacement costs of the materials dominating in both of the reactors.

The data for the effect of increased capital costs on the annual costs has already been reported in Tables 4 and 5. In order to get this into a more standard format, we recalculated the total capital costs and the required return on capital. This is shown in Table 10.

The capital costs change less than 5% for a wall life which varies by a factor of 16. This insensitivity is largely due to the fact that we expect the plant will have to be designed for remote changing of first wall components regardless of whether the wall has a lifetime determined by radiation damage.

The last item to be calculated is the number of kWh of energy generated per year of normal operation. The 93.3% duty factor for UWMAK-I and the 94.2% duty factor for UWMAK-II is already taken into account when

Table 9

Calculation of O & M Costs as a Function of Wall Life

Millions of Dollars

Wall Life years	Salaries	Supplies	Fixed O.S. Support	Variable O.S. Support	Misc.	G & A	Material Replacement	Coolant Make Up	Total
UWMAK-I									
8	1.35	1.0	0.35	0.3	0.2	0.48	1.1	0.038	4.8
4	↓	↓	↓	0.5	↓	0.51	5.4	↓	9.4
2	↓	↓	↓	0.9	↓	0.56	10.8	↓	14.9
1	↓	↓	↓	1.6	↓	0.68	21.5	↓	26.7
0.5	↓	↓	↓	3.2	↓	0.84	43.1	↓	49.9
UWMAK-II									
8	1.35	1.0	0.35	0.3	0.2	0.48	12.4	0.043	16.1
4	↓	↓	↓	0.5	↓	0.50	26.6	↓	30.5
2	↓	↓	↓	0.8	↓	0.56	53.4	↓	57.7
1	↓	↓	↓	1.6	↓	0.63	107	↓	112
0.5	↓	↓	↓	2.6	↓	0.84	213	↓	219

Table 10

Effect of Finite First Wall Life on the Capital Costs of UWMAK Type Reactors

Wall Life Years	No. of Modules Changed per Outage	Capital Costs $ Millions	Return on Capital - $ Millions
	UWMAK-I		
8	1	1379.2	206.9
4	2	1399.5	209.9
2	2	1399.5	209.9
1	3	1432.8	214.9
0.5	3	1432.8	214.9
	UWMAK-II		
8	4	1595.5	239.3
4	4	1595.5	239.3
2	6	1614.6	242.2
1	6	1614.6	242.2
0.5	12	1634.4	245.2

quoting continuous power outputs of 1473 MWe for UWMAK-I and 1716 for UWMAK-II. The calculations also include the four weeks of "normal" downtime in addition to that required to change the first wall. The resulting numbers are summarized in Table 11. The energy produced per year drops from 35 to 45% as the wall life changes from 8 to 0.5 years. We shall see that this has a major effect on the final costs.

The final numbers for the calculation of the cost of electricity are given in Table 12 and plotted in Figure 4.* A few interesting observations can be made about the cost calculations. First of all, the two reactors systems respond remarkably the same considering that they have drastically different designs and coolants. Second, the relative increase in electricity costs (over that for a wall life of >10 years) is low until the wall life drops below approximately two years. The rate of increase in the electricity cost over a projected 10 year life is given below.

% Increase in Electricity Costs Over Those Projected for a 10 Year Life

Wall Life	UWMAK-I	UWMAK-II
10	0	0
8	2	2
4	10	8
2	28	17
1	65	35
0.5	150	85

Thus it can be seen that radiation damage to the first wall can cause an increase of 85 to 150% in the base cost of electricity generated if the wall life is 0.5 years.

The third point to make is that while the relative cost of electricity increases rapidly only below a 2-4 wall life, the absolute costs to the consumer is truly enormous. For example, assuming that fusion is economically competitive in the year 2020 where it may capture some 25 to 33% of the market, we might expect to have some 10^6MWe of installed capacity.[7] If fusion plants were to have an 80% plant factor, then approximately

*These numbers differ slightly from those in Tables 1 & 2[4,5] because we have changed the optimum time between outages in I and because of a slightly different treatment of hot cell costs.

Table 11

Calculation of the Number of kW_eh Generated Per Year as a Function of First Wall Life in UWMAK-I & UWMAK-II

Wall Life Year	Normal Maintenance-hr	First Wall Changes-hr	Production Hours(a)	kW_eh(b)
		UWMAK-I		
8	672	288	7800	1.15×10^{10}
4	↓	408	7680	1.13×10^{10}
2	↓	792	7296	1.07×10^{10}
1	↓	1344	6744	0.993×10^{10}
0.5	↓	2688	5400	0.795×10^{10}
		UWMAK-II		
8	672	216	7872	1.35×10^{10}
4	↓	408	7680	1.32×10^{10}
2	↓	672	7416	1.27×10^{10}
1	↓	1344	6744	1.16×10^{10}
0.5	↓	2208	5880	1.01×10^{10}

(a) basis - 8760 hrs. in a year

(b) Power level averaged over burn - UWMAK-I = 1473 MWe, UWMAK-II = 1716 MWe

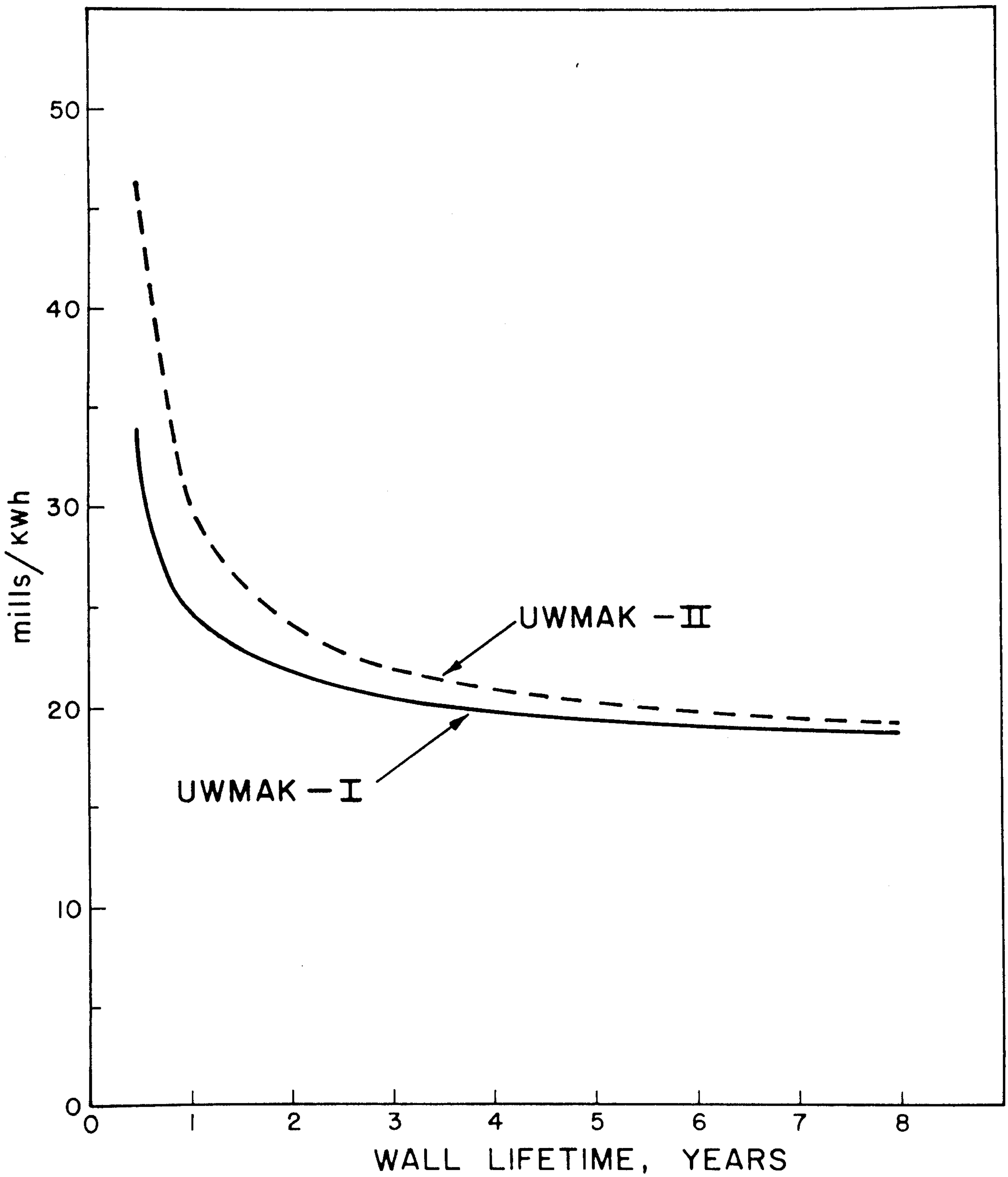
Table 12

Effect of First Wall Life on Cost of Electricity in UWMAK-I and II

Wall Life Year	$M O & M	$M Fuel	$M Return on Capital	kWh x 10^{10}	Mills/kWh
			UWMAK-I		
8	4.8	0.136	206.9	1.15	18.4
4	9.4	0.134	209.9	1.13	19.4
2	14.9	0.127	209.9	1.07	21.0
1	26.7	0.118	214.9	0.993	24.3
0.5	49.9	0.094	214.9	0.795	33.3
			UWMAK-II		
8	16.1	0.131	239.3	1.35	18.9
4	30.5	0.128	239.3	1.32	20.4
2	57.7	0.123	242.2	1.27	23.6
1	112	0.112	242.2	1.16	30.5
0.5	219	0.098	245.2	1.01	46.0

Figure 4

Effect of Wall Lifetime on Electricity Costs in UWMAK – I



7×10^{12} kWh would be generated per year by D-T reactions.

Each mill/kWh that fusion is over the competitive price represents some 7 billion dollars. Hence, there is considerable incentive to find first walls which will last at least as long as 2-4 years. It appears, that for the UWMAK reactors, wall lifes of less than 2 years are economically unattractive.

Future studies in this area such as the use of neutron spectral shifters(8-10) may alleviate these problems and can indeed be quite attractive if unprotected walls have lifetimes below 2 years. It is hoped that this admittedly broad brush and somewhat approximate determination of the cost of low first wall life will stimulate designers to alleviate the problem.

Discussion of Results

Periodic replacement of the inner walls of a fusion power reactor can have a significant effect on the unit cost of the electricity production. An average wall lifetime of two years could result in an increase of as much as one-quarter in the unit cost of electricity in comparison to an average wall life of ten years. A wall lifetime of only six months could cause as much as a 150 percent increase in the electricity unit cost.

The actual increase in the electricity cost because of inner wall replacements appears to be dependent primarily on the average wall lifetime, the capital cost of the reactor components kept in inventory to minimize wall replacement outage time, and the average outage time required to replace one wall module. The labor costs for the wall replacement appear to be of much smaller importance.

Study of the three primary determinants of the costs due to replacement of the inner walls reveals several important guidlines for fusion reactor research and design. First, considerable research is justified for determining the characteristics of inner wall materials and methods for increasing the average lifetime. In general, the costs due to replacement are inversely proportional to the average lifetime. A major effort appears justified for identifying materials which will accumulate radiation damage at a much lower rate and wall designs resulting in less damaging operating conditions.

And, finally, there is a large incentive for developing reactor designs requiring a minimum of outage time for replacing an inner wall segment. The lost revenue while the inner walls are being replaced appears to be over half of the total wall replacement cost for average wall lifetimes of eight years or less. Emphasis should be placed on developing reactor designs which permit rapid removal and replacement of entire reactor segments or inner wall segments. If either reactor or wall segments are replaced, quick disconnect methods are needed for all cooling and instrumentation systems. And, if possible, the connections between reactor segments and foundations or other segments should be simple (or non-existent) requiring no complicated activities such as welding or precision gasketing.

In summary, the costs for fusion reactor inner wall replacement could have a significant effect on the cost of electricity production. Large efforts appear justified for increasing the average wall lifetime, decreasing the inventory costs for spare wall or reactor segments, and reducing the reactor outage time for wall replacement.

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