BWR CONTROL BLADE REPLACEMENT STRATEGIES

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Abstract

The reactivity control elements in a BWR, the control blades, perform three significant functions: provide shutdown margin during normal and accident operating conditions; provide overall core reactivity control; and provide axial power shaping control. As such, the blades are exposed to the core's neutron flux, resulting in irradiation of blade structural and absorber materials. Since the absorber depletes with time (if B_4C is used, it also swells) and the structural components undergo various degradation mechanisms (e.g., embrittlement, corrosion), the blades have limits on their operational lifetimes. Consequently, BWR utilities have implemented strategies that aim to maximize blade lifetimes while balancing operational costs, such as extending a refuelling outage to shuffle high exposure blades. This paper examines the blade replacement strategies used by BWR utilities operating in U.S., Europe and Asia by assembling information related to: the utility's specific blade replacement strategy; the impact the newer blade designs and changes in core operating mode were having on those strategies; the mechanical and nuclear limits that determined those strategies; the methods employed to ensure that lifetime limits were not exceeded during operation; and blade designs used (current and replacement blades).

1. VENDOR DESIGNS AND LIFETIME LIMITS

1.1. Overview

Definition of Terms

Several terms common to the discussion of control blade exposure and limits are defined below.

1) **Nuclear end of life** – the exposure corresponding to a 10% reduction in initial cold reactivity worth, $\Delta k/k$, averaged over any quarter axial segment of the blade.

2) **Quarter axial segment** – the significant control blade segment relative to the core cold axial power distribution.

3) **snvt** – smeared thermal neutron fluence based on the exposure of the four fuel assemblies adjacent to the control blade of interest, units of 10^{21} n/cm^2.

4) **Tip adder** – exposure increment applied to a blade fully withdrawn from the core (i.e., absorber tip located below the active fuel region) to account for B_4C swelling and absorber tube sensitization in the tip region as a consequence of thermal neutron leakage and fast neutron thermalization below the core region.

Background

The original equipment blade designs offered by the various vendors consisted of all B_4C absorber contained within commercial purity stainless steel materials although the designs varied slightly, with GE and Siemens encapsulating the boron carbide in sealed tubes while ABB-Atom loads the absorber into gun-drilled holes in the blade wings. The mechanical limits of these early designs were based on loads expected during normal operation and accident conditions and included criteria on wear, fatigue, seismic loadings, and internal pressure. The nuclear end of life for the GE original equipment blades was calculated to be 42% ^{10}B depletion.

With irradiation, it was quite apparent that mechanical limits could not be met by the early original equipment designs. In 1978, for example, GE observed absorber tube cracking and boron carbide washout in high exposure blades. The vendor determined that cracking and washout occurred at 50% local ^{10}B depletion (Siemens observed similar degradation at 1.6 snvt or ~40% local depletion). The mechanism was determined to be irradiation assisted stress corrosion cracking (IASSC) of the absorber tubes, and ligaments between the holes in the ABB-Atom design, with tubing stresses generated by B_4C swelling. Figure 1 provides the worth vs. depletion curves for GE original equipment blades for the cases where 1) the nuclear lifetime is limiting (42% ^{10}B depletion) and, 2) the mechanical lifetime is limiting due to washout of boron carbide (34% ^{10}B depletion).

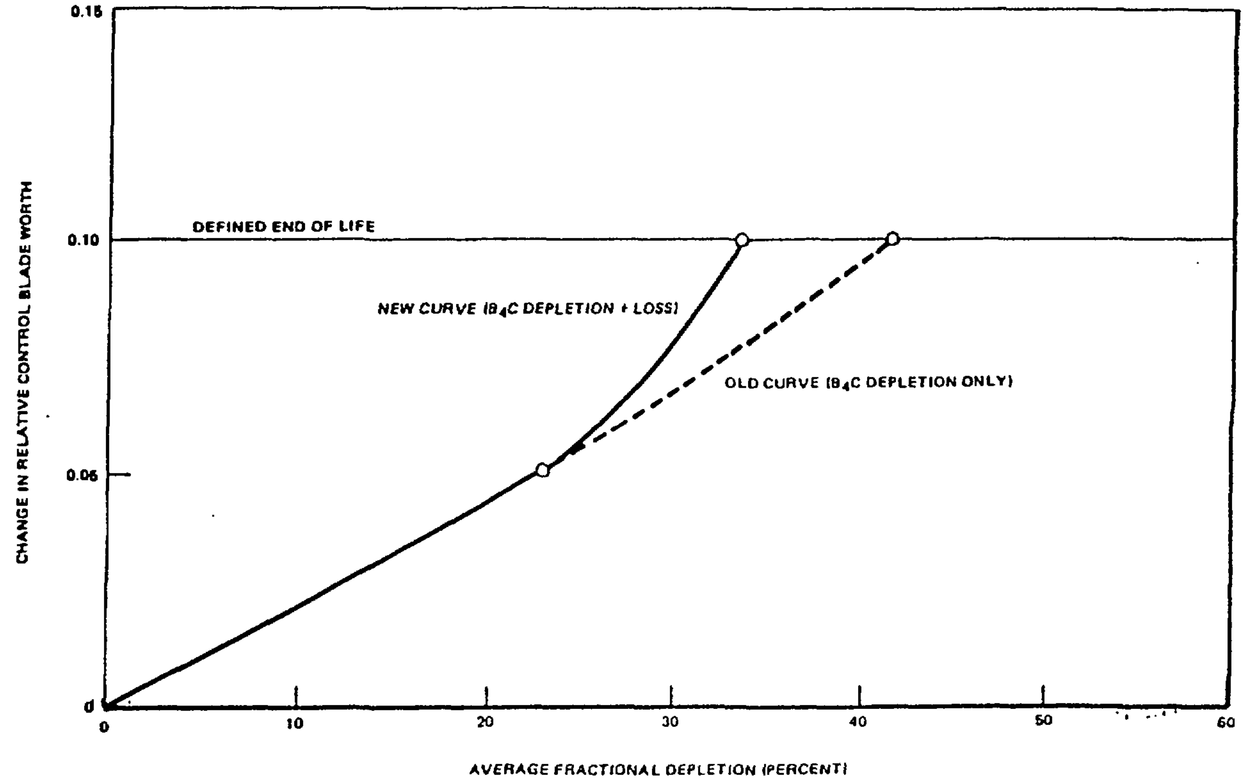


FIG. 1. Changes in relative blade worth as a function of fractional depletion (Reference: GE)

Subsequent to the observation of cracking and absorber washout in the early blade designs, the vendors have offered more and more advanced designs to first address blade integrity issues and secondly, to provide designs that could achieve higher exposures. Remedies included three major changes:

- use of high purity stainless steels for absorber tubes and wings, thereby improving material ductility and cracking thresholds;
- use of hafnium in the high duty blade areas (wing tip and outer edge) to reduce absorber swelling effects; and
- increased boron carbide loading effectively reducing the ^{10}B depletion rate and the attendant swelling rate.

Also included were low cobalt materials to reduce activation. The latest generation blades using these features have effectively tripled control blade lifetimes relative to the original equipment designs. Figure 2 graphically shows the exposure advantage of simply increasing B_4C loading in a given blade design.

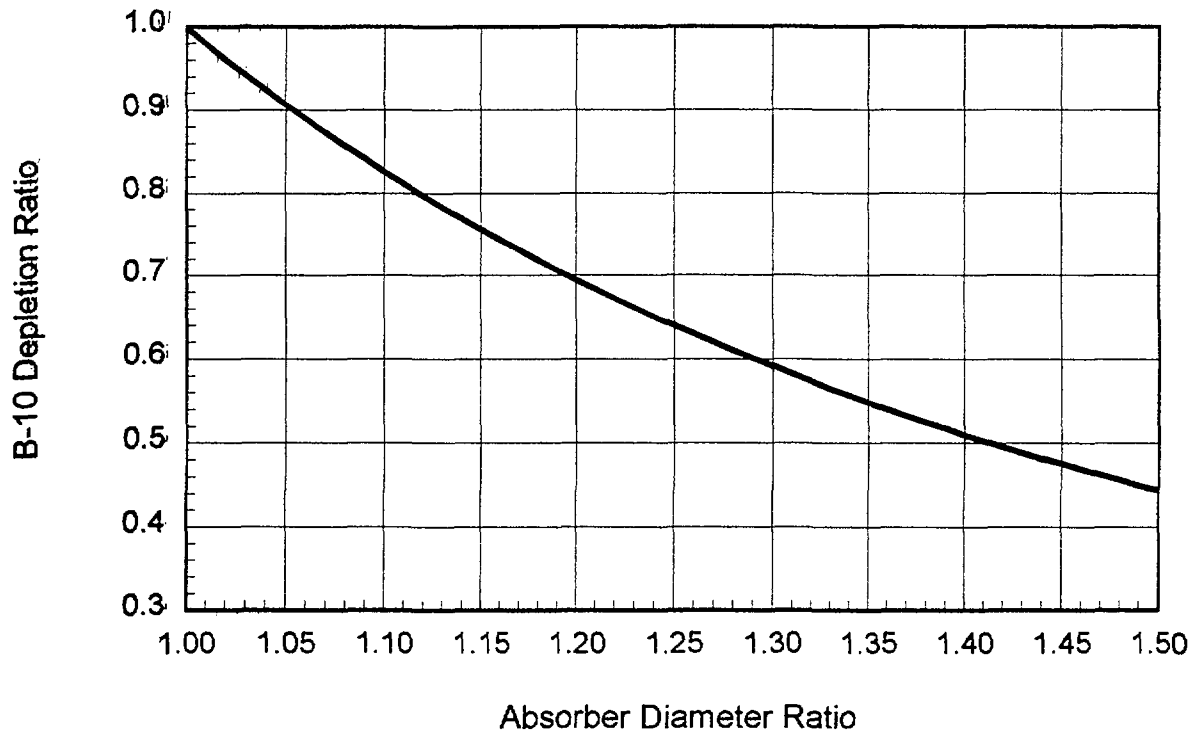


FIG. 2. Impact on depletion ratio of increasing absorber loading

Hafnium has been introduced into the designs in either plate or rod geometries, and in both cases, unclad. This is also true of the all hafnium Hitachi and Toshiba designs which are available with the absorber configured as either as full length plates or rods contained within a sheath similar to the GE Duralife series, for example. The exception is ABB-Atom, which maintains the solid stainless steel wing feature even in the hybrid configurations. In this case, solid hafnium rodlets and plugs are loaded into selected horizontal holes in each blade wing to provide the hafnium tip and edge regions, respectively.

Table I summarizes the blade designs offered by vendors. Note that Siemens does not actively market replacement control blades. Siemens will, however, provide blades if economical to do so.

1.2. ABB-Atom

The original equipment blade (CR-70) is an all-B_4C design wherein the boron carbide is loaded into holes bored horizontally into the 304 stainless steel wings. Like other vendors' designs, the CR-70 was susceptible to IASCC of the ligaments between the holes.

ABB-Atom introduced the CR-82 (hybrid with hafnium tip) in 1982 and the CR-85 (hybrid with hafnium tip and edge) in 1985. Although lifetimes were improved with the use of hafnium in the highest exposure regions of the designs, they are still prone to cracking as they use 304 SS as the blade wing material. In 1992, ABB-Atom introduced the CR-82M and CR-85M designs. These are similar to the CR-82 and CR-85 designs except that 316L is used for the wings and the absorber hole geometry has been modified. PIE examinations have confirmed improved in-reactor performance of 316L vs. 304. Note that all blades manufactured post-1992 use 316L for the wings.

ABB-Atom currently offers two additional designs, the CR-82M-1 and CR-85M-1. These are similar to the CR-82M and CR-85M designs, respectively, except for the absorber hole geometry which is consistent with that of the original CR-82 and CR-85 designs.

TABLE I. SUMMARY OF CONTROL BLADE FEATURES

Vendor	Blade Series	Absorber Type and Placem.			Comments
		TABLE I	Hf Tip	Hf Edge	
ABB	CR-70	X			Original equipment design
	CR-82	X	X		~Original equipment blade + Hf
	CR-82M	X	X		M series uses 316L, revised hole geometry
	CR-85	X	X	X	~Original equipment blade + Hf
	CR-85M	X	X	X	M series uses 316L, revised hole geometry
	CR-85M-1	X	X	X	CR-85 with 316L; used in Japan
GE	OE	X			Original equipment design
	D120	X			~Original equipment blade + HP304; susceptible to crevice corrosion
	D140	X	X		~Original equipment blade + HP304; susceptible to crevice corrosion
	D160	X		X	HP304 + Hf
	D190	X	X	X	HP304 + Hf
	D215	X	X	X	HP304 + Hf
	D230	X	X	X	HP304 + Hf
	Marathon	X	X	X	Rad Resist + Hf + new design abs. tubes
Siemens	OE	X			Original equipment design
	Hybrid-1	X		X	HP SS + Hf
	Hybrid-4	X	X	X	HP SS + Hf
Toshiba	OE	X			Original equipment design
	All-Hf		X	X	HP SS + All-Hf

The vendor has developed inspection-based guidelines addressing blade reuse and replacement that are a culmination of examinations performed to date. For U.S. utilities, the guidelines are relatively conservative. For example, for blades with 304SS wings which have reached an exposure of 3.0 snvt:

- visually inspect blade wings for cracks;
- discharge blade if cracked;
- if the blade is uncracked, reuse for one cycle and re-inspect applying the above criteria.

If the inspection at 3 snvt shows a blade to be uncracked, it can be shuffled to a shutdown bank. No further examinations are required. However, tip adders are recommended for evaluating CR-70 exposures.

For post-1992 blades using 316L, ABB-Atom recommends visual inspection of only the lead blades of each design. Currently, the CR-82M lead blades are in Unit R2. Inspections have identified limited cracking in two of the highest exposure blades which resided in high duty control cells for three cycles. Although the root cause analysis is not complete, the location of the cracks leads ABB-Atom to believe that the failure cause is manufacturing related.

Although guidelines for European utilities are similarly based on observations of cracking, there is a much larger experience base of operation with limited cracking. In some cases, utilities reload blades observed to have *minor* cracking for an additional cycle of operation.

Current replacements are primarily the CR-82M and CR-82M-1 designs.

1.3. General Electric

Table I provides a summary of the of the various blade designs offered by GE beginning with the original equipment blade offered in ~1960 to the most advanced, Marathon. One observes a progression in features based on the mechanical limitations identified in the original equipment, Duralife 120 and Duralife 140 designs. These advancements include high purity 304SS, redesigned handle-to-sheath and sheath-to-structure joints, and the use of hafnium absorber. The Duralife 200 series used higher B_4C loadings and the Marathon, a welded absorber design, to extend lifetimes even more.

Figure 3 provides the ^{10}B depletion rate curves, as a function of exposure in snvt, for two blades operated in a late generation BWR/5 plant. The original equipment blades have a 34% depletion limit based on cracking while the advanced design blades are limited to 58% ^{10}B depletion. Depletion rates differ because of the higher boron carbide loading in the advanced design blade. The 'real' lifetime advantage of the hybrid blade is the ratio of the EOL exposures in snvts, i.e. $4.39 \div 1.96 = 2.24$.

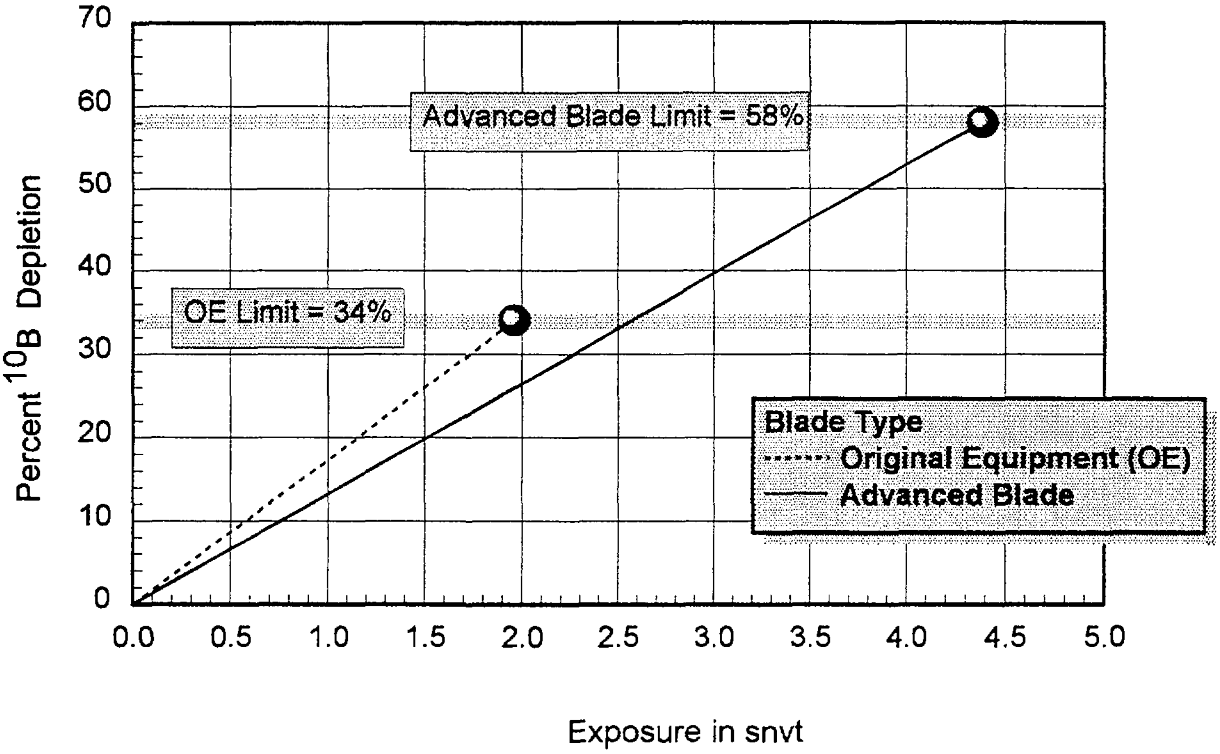


FIG. 3. Depletion rate and lifetime comparison, original equipment vs. advanced blade design

The original equipment, Duralife 120, and Duralife 140 designs (see Table I) have mechanical limits based on the observation of cracking. The Marathon design is limited mechanically by internal pressure at high exposures. The remaining designs have nuclear limits.

GE provides guidelines related to shuffling original equipment blades in Service Information Letter (SIL) 157 (similar guidelines are provided in SIL 579 for Duralife 120 and 140 designs):

- the exposure limit in terms of ^{10}B depletion is 34% peak quarter segment corresponding to ~2 snvt in a BWR/5 plant;
- if the exposure is less than 20% ^{10}B depletion, the blade can be moved to a new core position and remain there until its exposure reaches 34% at which time it must be discharged; and
- if the exposure is ≥20% and less than 34%, the blade may be shuffled but its residence time is limited, being the greater of:

- one cycle, or
- the equivalent number of cycles the blade would have remained in its prior position without exceeding the 34% limit.

This methodology introduced a 'phantom' exposure increment. That is, the exposure increment received in the new position was based on the exposure increment consistent with the prior core position. There are apparently no restrictions on shuffling advanced blade designs as long as nuclear and mechanical limits are met.

GE recommends tip adders for non-hafnium tip designs when placed in shutdown positions. Utilities have been reluctant to use them since 1) there were no requirements for their use, and 2) there was not a rigorous basis for the correlations.

1.4. Siemens

Siemens has long had a co-operative research and development program with GE. It is not surprising that the two vendors' designs are similar and share similar failure mechanisms (IASCC and crevice corrosion cracking). Based on absorber tube cracking observed in the original equipment blades in early cycles in several German BWR plants Siemens characterized the cracking phenomenon as a function of exposure (see Table II) and developed the following strategy for shuffling and replacement:

- original equipment blades can occupy high duty control cell positions to an exposure of ≤ 1.8 snvt projected EOL with subsequent discharge or movement to a core edge position;
- if the exposure is ≥1.4 snvt at beginning of cycle (BOC), the blade can be placed in any shutdown position; and
- if the exposure is ≥1.6 snvt at BOC, the blade can only be placed in a low duty shutdown position (not near core center).

TABLE II. SIEMENS ORIGINAL EQUIPMENT BLADE LIMITS

Characteristic	Local B-10 Depletion, %	% Nuclear Lifetime	Exposure, snvt
Begin cracking	30	37	~1.0
Begin TABLE I loss	40	49	~1.3
10% S/D margin reduction, B_4C + washout	54	66	~1.8
10% S/D margin reduction, B_4C without washout	82	100	~2.7

Original equipment blades are still used quite extensively in German reactors. The current advanced design offered is the Hybrid-4 blade (since ~1988) using high purity stainless steel, redesigned welds to minimize crevice corrosion, and hafnium at high duty blade tip and edge locations. The current limits are given in Table III (~BWR/6 plant design):

TABLE III. CURRENT BLADE LIMITS

Blade Design	Nuclear, snvt (%)	Mechanical, snvt (%)
Original equipment	3.2 (45)	~2.1 (~30)
Hybrid-4	5.3 (62)	≥4.0 (≥47)

The %^{10}B depletion values are peak segment average values. Operating experience supports blade exposures of more than 3.7 snvt as cracks have not been observed at these exposure levels.

2. UTILITY BLADE REPLACEMENT STRATEGIES

Data has been analyzed from a total of 23 utilities, operating 45 BWRs in the U.S., Europe, and the Far East, concerning their blade replacement strategies and operational limits. The responses are believed to be representative of the industry. The geographical breakdown of the utility companies consists of:

- 9 U.S. utilities (13 plants);
- 10 European utilities (19 plants); and
- 4 Far Eastern utilities (12 plants).

As summarized in Table IV, these represent BWR/2 to BWR/6 plant designs and GE, Siemens, and ABB-Atom NSSSs operated in control cell, conventional, and mono-sequence control cell modes. The table shows that the utilities have implemented a full range of blade designs, from all-B_4C to hybrid B_4C/hafnium to all-hafnium absorber materials.

2.1. Control Blade Shuffling Strategies

Frequency of Blade Shuffling

Table V summarizes blade shuffling activities performed by the responding utilities. More than one-half (58%) shuffle blades. Most obviously, this is to extend blade in-core residence times. Blades are generally moved from high duty positions (i.e., control cells in CCC cores) to shutdown positions where they remain withdrawn during operation. In such positions, the incremental exposure is negligible. Additionally, as noted by one utility, shuffling allows the high exposure but low cobalt blades to replace original equipment designs incorporating high cobalt materials.

Slightly less than one-half of the utilities do *not* shuffle blades, choosing instead to leave the blades in the same position from one cycle to the next. These utilities note that the life extension benefit is marginal, especially in light of the increased costs to shuffle blades which can only be done during a refuelling outage. One domestic utility estimates the cost to be as much as $10,000 per outage hour with it taking 4 to 8 hours to shuffle a pair of blades. With utilities moving to shorter and shorter outages, there is more pressure not to shuffle blades. Over the last 18 months in the U.S. there has been a 117% *increase* in the number of plants with outages of 40 days or less and a 93% *increase* in the number of plants with 50 day outages or less.

Shuffling Strategies

Vendors have a minor influence on the strategies implemented by utilities especially as the original equipment blades with their short mechanical lifetimes are replaced by hybrid blades incorporating advanced materials and absorbers. Siemens, for example, developed guidelines on where a blade could be placed based on its exposure level (see Table II) while GE proceduralized their guidelines in SIL 157 and SIL 579 for the original equipment and Duralife 120/140 series blades, respectively.

The strategies with the various designs are, of course, to move high burnup blades to low exposure regions and vice versa. The actual strategy depends primarily on design features C GE original equipment blades, for example, are still prone to B_4C swelling at blade tip positions even when fully withdrawn from the active core region in shutdown banks. This necessitates the use of 'phantom' exposures in subsequent cycles.

Figure 4 shows an example of the strategy used by Utility D for the end of cycle (EOC) 12 refueling outage at Unit D1. Four different types of moves were planned, the specific move depending on blade type and exposure:

Table IV. SUMMARY OF BWR PLANT FEATURES

Utility		Plant	NSSS Vendor	Plant Type	# Fuel Ass'ys	# Control Blades	Blade Types Currently Used	Operating Mode
USA	A	A1	GE	BWR/4	764	185	OE, D140, D215	CCC
	B	B1	GE	BWR/6	800	193	OE	CONV
		B2	GE	BWR/6	624	145	OE, CR82M	CONV
	C	C1	GE	BWR/2	560	137	OE, D160, D190, D230, M	CCC
	D	D1	GE	BWR/4	560	137	OE, D190, D230, M, CR82M	CCC
	E	E1	GE	BWR/2	532	129	OE, D190, D230	CONV
		E2	GE	BWR/5	764	185	OE, D190, D215, M	~CCC
	F	F1	GE	BWR/3	580	145	D140, CR82, CR82M, M	CCC
	G	G1	GE	BWR/4	560	137	OE, D190, D230	CONV
		G2	GE	BWR/4	560	137	OE, D190, D230, CR82	CONV
	H	H1	GE	BWR/4	764	185	OE, D160	CCC
		H2	GE	BWR/4	764	185	OE	CCC
	I	I1	GE	BWR/5	764	185	OE, D215	CCC
Europe	J	J1	KWU	N/A	592	145	OE, CR70, CR82, CR85	MSCC
	K	K1	GE	BWR/4	240	57	D230 + others	CCC
	L	L1	GE	BWR/6	648	149	OE, D230, CR85	CCC
	M	M1	KWU	N/A	532	129	OE, CR82, CR82M, CR85, M	MSCC
		M2	KWU	N/A	840	205	OE, CR82, CR82M, CR85, M	MSCC
	N	N1	GE	BWR/6	624	145	OE	CCC
	O	O1, O2	KWU	N/A	784	193	OE, Duralife series, M	CONV
	P	P1	KWU	N/A	592	145	OE, CR82, M	CCC
	Q	Q1, Q2	ABB	N/A	444	109	CR70, CR82, CR85	MSCC
		Q3, Q4, Q5	ABB	N/A	444-700	109-169	CR70, CR82, CR82M, M	MSCC
	R	R1, R2	ABB	N/A	500	121	CR70, CR82, CR82M, SR88	MSCC
	S	S1, S2, S3	ABB	N/A	676-700	161-169	CR70, CR82, CR82M, M	MSCC
Far East	T	T1, T2, T3, T4	GE	BWR/4, BWR/5	N/A	N/A	OE, all-Hf	CCC
	U	U1, U2	~GE	BWR/2, BWR/5	N/A	N/A	OE, CR85, CR85M1	CCC
	V	V1, V2	GE	BWR/4	408	97	OE, D215	CONV
		V3, V4	GE	BWR/6	624	145	OE, D230	CONV
	W	W1, W2	~GE	BWR/4	N/A	N/A	OE, all-Hf	CCC

OE = Original equipment **D140** = Duralife 140 **D160** = Duralife 160 **D190** = Duralife 190 **D215** = Duralife 215
D230 = Duralife 230 **M** = Marathon **CR70** = CR-70 **CR82** = CR-82 **CR82M** = CR-82M
CR85 = CR-85 **CR85M1** = CR-85M-1 **CCC** = control cell core **CONV** = conventional mode **MSCC** = mono-sequence control cell

Table V. CONTROL BLADE SHUFFLING - UTILITY RESPONSES

Utility		Shuffle Blades?	Comments
USA	A	Y	Shuffle to extend blade lifetimes
	B	N	Increases outage costs
	C	Y	Shuffle to extend blade lifetimes; high duty blades moved to shutdown positions
	D	Y	Shuffle to extend lifetimes & to replace high cobalt original equipment blades
	E	Y	Limited shuffling performed; extends lifetimes; blades moved from high duty positions to peripheral & core edge positions
	F	N	Increases outage costs
	G	N	Limited shuffling in past; used as a last resort
	H	N	Increases outage costs
	I	Y	Shuffle to extend blade lifetimes; high exposure blades moved to peripheral positions, peripheral blades moved to high duty positions
Europe	J	Y	Shuffle to extend blade lifetimes; high exposure blades moved to peripheral shutdown positions, shutdown blade moved to high duty positions
	K	Y	Shuffle to extend blade lifetimes; high exposure blades moved to peripheral shutdown positions, shutdown blades discharged
	L	N	Life extension is minimal; increases outage costs
	M	Y	Shuffle to extend blade lifetimes; high exposure blades moved to low duty shutdown positions
	N	Y	Shuffle to extend blade lifetimes
	O	N	Increases outage costs
	P	N	Increases outage costs
	Q	Y	Limited shuffling for life extension
	R	Y	Shuffle to extend blade lifetimes
	S	Y	Shuffle to extend blade lifetimes; typically move blades from control cells to shutdown positions
Far East	T	N	Life extension is minimal; replace with all-Hf designs
	U	N	Life extension is minimal
	V	Y	Shuffle to extend blade lifetimes
	W	N	Life extension is minimal; replace with all-Hf designs

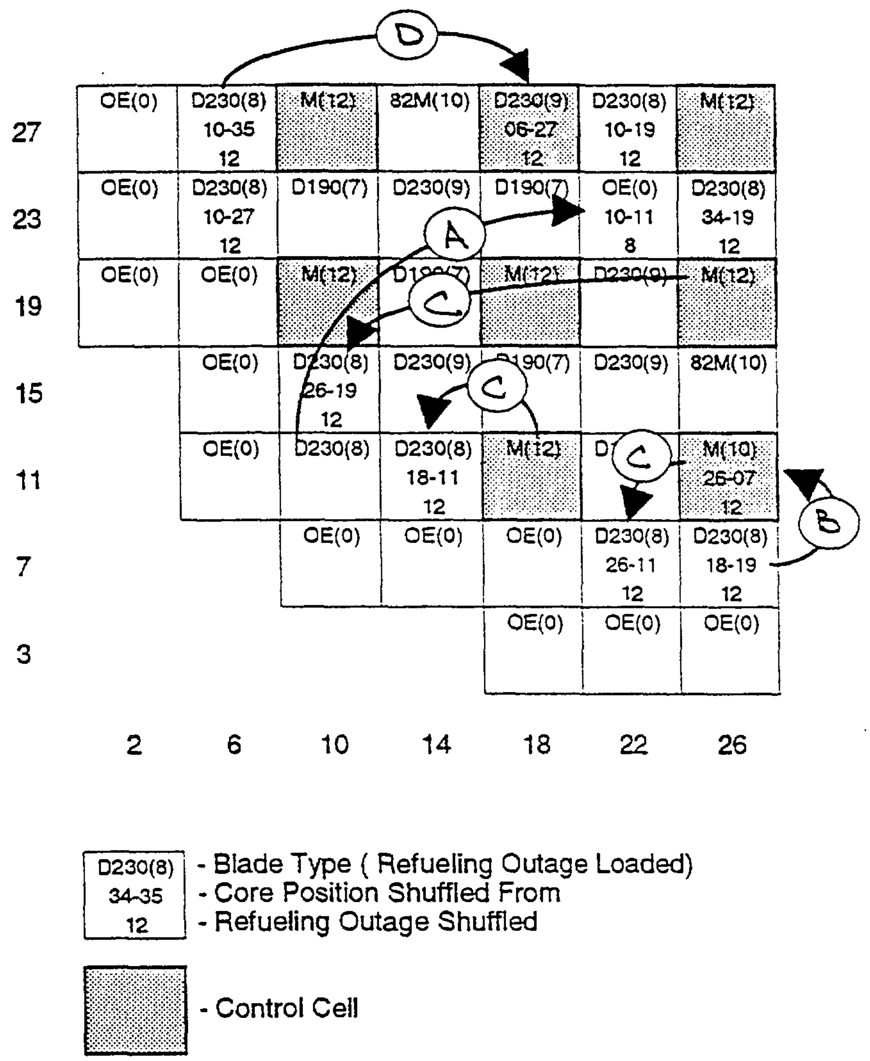
- **Move A** – selected original equipment blades were moved to interior shutdown positions after having occupied shutdown positions near the core periphery for eight cycles;

- **Move B** – selected Marathons inserted at EOC 10 resided in shutdown positions for two cycles and were then moved into control cells;

- **Move C** – selected Duralife 230s inserted EOC 8 resided in control cell positions for four cycles and were then moved to shutdown positions; and

- **Move D** – selected Duralife 230s inserted EOC 9 resided in shutdown positions near the core periphery for three cycles and were then moved to control cell positions.

Examples typical of these moves are shown in Figure 4.



Blade Type	Description
OE	Original Equipment
D190	Duralife 190
D230	Duralife 230
M	Marathon
82M	CR 82M

FIG. 4. Planned blade shuffling for unit D1 at EOC 12

2.2. Control blade replacement strategies

Replacement Designs

Table VI provides a summary of the replacement blade designs used by the responding utilities and the calculational methods used to evaluate exposure. Quite apparent is the full range of replacement designs, from original equipment blades in three utilities to all-hafnium designs in several Far Eastern plants. The majority of utilities (87%) replace discharge blades with advanced designs incorporating improved structural steels and at least hafnium tips.

In the U.S., the majority of the utilities are using Duralife 190 and 200 series blades with hafnium tips and edges. Less common are Marathon designs and ABB-Atom's CR-82 and CR-82M designs. In Europe, most replacement blades are ABB-Atom's CR-82, CR-82M, and CR-85 designs with GE providing a relatively small number of Duralife and Marathon blades. In the Far East, replacement designs incorporate either hafnium tips and edges (Duralife 200 series, CR-85, CR-85M-1) or are all-hafnium designs.

TABLE VI. CONTROL BLADE REPLACEMENT - UTILITY RESPONSES

Utility		Exposure Calculations	Tip Adders Used?	Replacement Designs
USA	A	-----	-----	D140, D215
	B	PowerPlex, 3D MONICORE	Y	OE, CR82M
	C	RODEX	Y	D160, D190, D230, M
	D	3D MONICORE	N	D190, D230, M, CR82M
	E	3D MONICORE	N	OE, D190, D215, D230, M
	F	-----	Y	D140, M, CR82, CR82M
	G	3D MONICORE	N	D160, D190, D230, CR82
	H	3D MONICORE	Y	OE, D160
	I	PowerPlex	N	D215
Europe	J	-----	-----	CR82, CR85
	K	-----	-----	D230
	L	Core Master/Presto	Y	D230, CR85
	M	-----	N	CR82, CR82M, CR85, M
	N	-----	-----	OE
	O	-----	-----	Duralife, M
	P	-----	-----	CR82, M
	Q	-----	-----	CR82, CR82M, CR85, M
	R	POLCA4	Y	CR82, CR82M
	S	-----	-----	CR82, CR82M, M
Far East	T	-----	-----	All-Hf
	U	3D MONICORE	N	CR85, CR85M1
	V	PowerPlex, 3D MONICORE	-----	D215, D230
	W	-----	N	All-Hf

As noted above, three utilities replace discharge blades with original equipment blades – Utilities E, H, and N. In these cases, the utilities have purchased (or received) the blades from canceled plants and use them as inventory for replacements. High cobalt pins and rollers are replaced in all cases to reduce primary system activation.

As these blades incorporate all-B_4C absorber, commercial purity steels, relatively high cobalt components, and geometries that promote coolant stagnation, they are prone to absorber tube cracking. Consequently, lifetimes are restricted by mechanical limits (exposures $\leq 34\%$ B^{10} depletion) requiring that more blades be replaced over the life of the plant. This requires more handling of blades and the use of SIL 157 restrictions in shuffling. Additionally, the higher cobalt content relative to modern replacement designs increases primary system radiation fields.

In spite of these disadvantages, economic analyses tend to favor the use of the original equipment blades simply due to their extremely low price. In order to characterize the economic advantage of original equipment vs. advanced blades, we performed an analysis based on the following assumptions:

- the cost of the original equipment blades is $5,000 (replacement of high cobalt pins and rollers);

- the purchase price of a new advanced design blade is $75,000;
- nuclear lifetimes are 34% ^{10}B depletion (peak segment) for the original equipment blades, 54% for the advanced blades;
- disposal costs are $25,000 per blade;
- outage costs are $10,000 per hour;
- control cell core operation with typical blade exposure increments per cycle;
- no allowance for enhanced primary system radiation fields due to higher cobalt blade materials;
- no blade shuffling; and
- no escalation, future worth, etc. corrections.

Results are provided in Figures 5 and 6 through fifteen cycles of operation under these conditions.

Figure 5 shows the resulting blade replacement schedule. As one would expect, more original equipment blades are needed due simply to their shorter lifetimes. A total of 144 original blades are needed vs. 103 advanced design blades – an increase of 30%. Figure 6 provides the cumulative cost of using each blade type through EOC 15. Even with the larger number of blades needed and higher costs due to having to purchase and dispose of more blades, the economic advantage of the original equipment blades is substantial, with the cumulative EOC 15 cost being approximately 70% of that of the advanced blades. When averaged over the fifteen cycles, the cost advantage is about $300,000 per cycle.

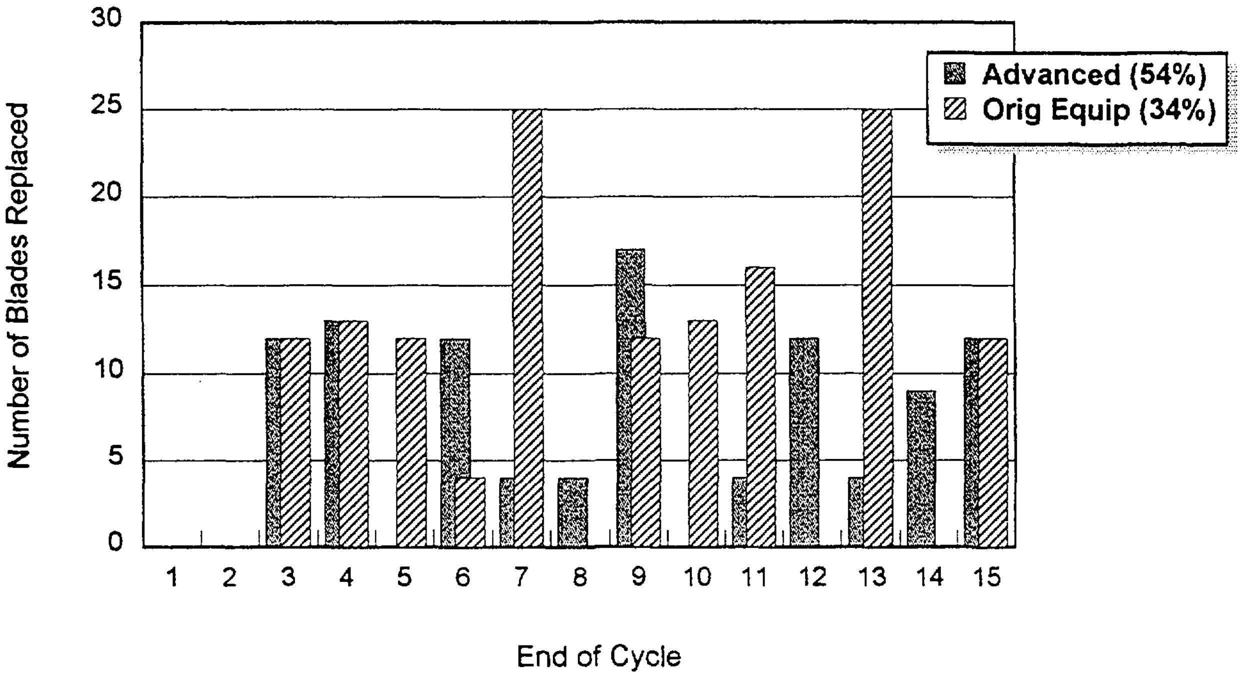


FIG. 5. Impact of blade type on replacement schedule

Replacement Criteria – Utilities Using ABB-Atom Blades

The early blade designs incorporating 304SS for structural materials have lifetimes limited by IASCC. These are the CR-70, CR-82, and CR-85 series. The exposures to date of the advanced designs are not sufficient to determine if they are also limited by absorber integrity concerns.

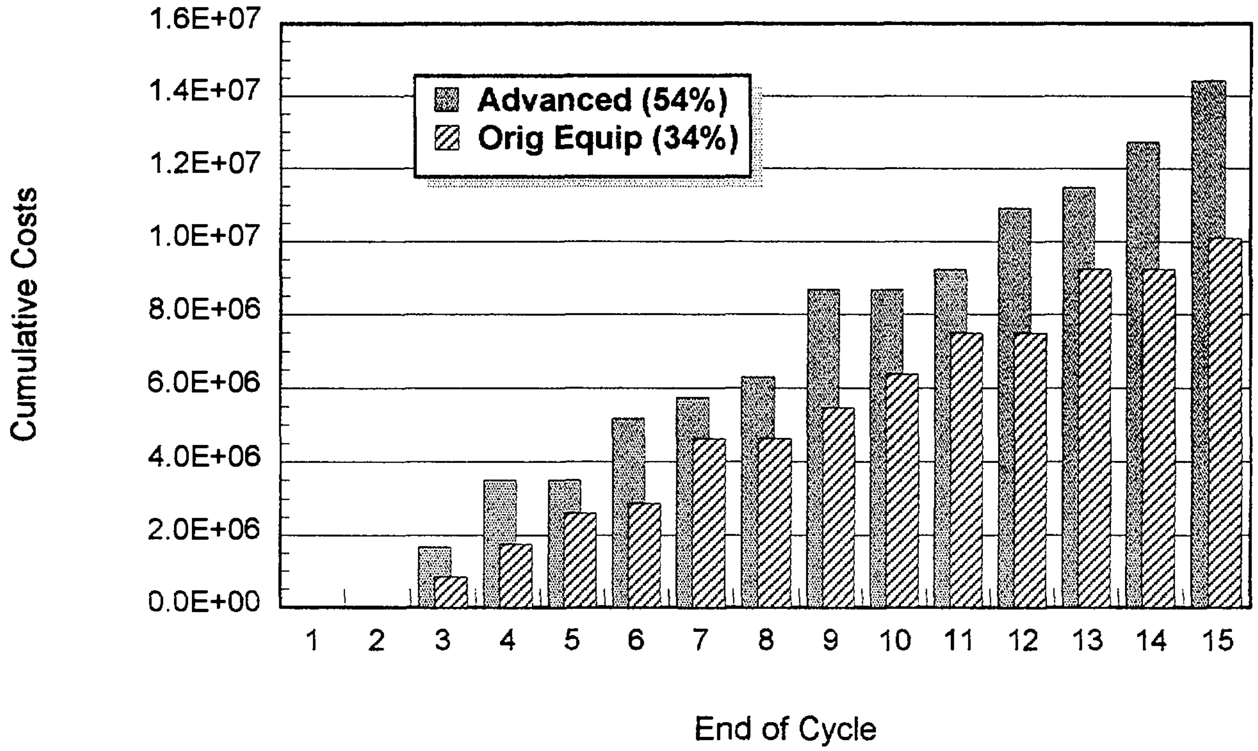


FIG. 6. Cumulative costs as a function of cycle completed

U.S. utilities have adopted ABB-Atom's guidelines and criteria related to blade replacement. As such, lead blades are inspected and discharged if cracks are observed.

European utilities, on the other hand, have adopted criteria that are, at times, more restrictive than those suggested by ABB-Atom. For example, Utility J has implemented limits of 1.9 snvt for CR-70s and a modest 3.0 snvt for the hybrid CR-82s and CR-85s. These are based on their own experiences of cracking in Unit J1.

The majority of other European utilities visually inspect blades on a frequent basis to assess cracking. A typical example is Utility S which operates several units in Sweden. The utility has developed exposure-related criteria for their units based on their experience with cracking in the CR-70 control blades. These criteria, noted below, apply specifically to the CR-70 blades and are recommended for the CR-82, CR-82M, and Marathon designs:

- blades with tip exposures exceeding 57% ^{10}B depletion shall be inspected before continued irradiation;
- blades with maximum quarter segment exposures above 18% ^{10}B depletion shall be inspected before continued service; and
- blades scheduled for control positions with quarter segment exposures in excess of 45% ^{10}B depletion shall be inspected before insertion in those positions (these particular blades are also inspected at EOC *after* their use in the control positions).

An additional criteria is applied to blades exposed in Units S1 and S2. Blades that are free of cracks with 1) tip exposures between 57% and 60% ^{10}B depletion, and 2) having a maximum quarter segment exposure below 18% ^{10}B depletion are allowed to continue operation for a maximum of two years in a shutdown position. These blades are, however, considered to be cracked during their second year of exposure with penalties applied in the shutdown margin evaluations.

Although most European utilities discharge blades when cracked, Utility S allows a cracked blade to be reinserted for an additional cycle only if it is moved to a shutdown position.

Replacement Criteria – Utilities Using GE Blades

With very few exceptions, vendor criteria and guidelines are implemented by U.S., European, and Far Eastern utilities. Inspections are not performed due to the presence of the sheath covering the absorber tubes. Blades are discharged when exposure limits are approached.

Two utilities have discharged blades well before their lifetimes. At EOC 2, Utility A discharged 165 original equipment blades and replaced them with Duralife 140s to reduce cobalt activation and, consequently, primary system radiation fields. Utility L, at EOC 3 in Unit L1, replaced 16 original equipment blades with Duralife 230s and CR-85s in order to quickly gain experience with hybrid designs.

Replacement Criteria – Utilities Using Siemens Blades

U.S. utilities responding to the survey have no experience with Siemens blades. Limits on original equipment blades used by European utilities vary from 1.6 snvt at Unit P1 to 2.7 snvt at Units M1 and M2. Referring to Table II, these limits approximate the 10% reduction in blade worth due to B_4C depletion plus washout (~1.8 snvt, BWR/2-5) and the 10% reduction in blade worth due only to B_4C depletion (~2.7 snvt, BWR/2-5).

Replacement Criteria – Utilities Using All-Hafnium Blades

All-hafnium blades are used in several Far Eastern plants. The utilities implement the vendor criteria and guidelines. Utility T limits original equipment (i.e., all B_4C designs) to $\leq$1.74 snvt due to cracking. All-hafnium blades are limited to $\leq$9.0 snvt at the top axial segment.

Use of Tip Adders

Nearly one-half of the responding utilities use tip adders to account for B_4C swelling and absorber tube sensitization occurring in the tip region of a blade when located in a shutdown position (i.e., fully withdrawn during operation). ABB-Atom and GE recommend that tip adders be used for all-B_4C blade designs. Tip adders are not needed for designs incorporating hafnium tips as hafnium experiences little swelling and growth during irradiation. With the exception of one utility, all responders still have original equipment blades under irradiation. Tip adders are typically on the order of 1 to 3% ^{10}B depletion per cycle. One U.S. utility uses 2% tip depletion per 10,000 MWd/st.

Reasons given for *not* using tip adders include:

- blades located on the core periphery receive effectively zero exposure;
- with operation in a conventional (i.e., sequence exchange) mode, all non-peripheral blades receive some exposure during the cycle and that exposure can be estimated and tracked;
- vendors do not *require* the use of tip adders;
- correlations for tip exposure are poorly benchmarked; and
- no trend has been observed in measured shutdown margin to indicate absorber loss.

Handle Embrittlement Issues

Although ABB-Atom and GE indicate that handle embrittlement is not a threat to blade integrity, several utilities have directly addressed this issue. Utility Q, in Units Q1 and Q2, discharges blades when they have reached a fluence of ~10^{22} n/cm^2 based on calculational methods. This corresponds to about 20 years residence time. Hot cell examinations have been performed on blades from Units Q3, Q4, and/or Q5 and from these some correlations were developed based on fast fluence. The utility replaces blades after 10 to 25 cycles of operation.

Blade Exposure Calculational Methods

Utilities use vendor correlations in calculating blade exposures. The methods consist of evaluating the exposures of the fuel assemblies adjacent to the blade of interest and converting the smeared thermal fluence (in snvt) to B^{10} depletion. Most utilities with GE NSSSs use 3D MONICORE from GE, or PowerPlex from Siemens, to estimate and trend blade exposures. Utilities with ABB NSSSs perform the exposure calculations using similar methods (i.e., COREMASER/PRESTO). In some instances, ABB-Atom performs the exposure evaluations for the utility.

The correlation between fluence in snvt and percent ^{10}B depletion is dependent on blade design (see, for example, Figure 3) and on the following factors:

- average void in the adjacent assemblies;
- design of the adjacent assemblies; and
- relationship between thermal fluence and core power.

The most sophisticated methods to date use correlations for the aforementioned factors, evaluating exposures in the four axial blade segments and blade tip (typically 6 in., 152 mm axial region).

3. CONCLUSIONS

On Shuffling

1) A total of 58% of the utilities shuffle blades at least on a limited basis, most often to extend lifetimes. Blades are generally moved from high duty positions (control cells, for example) to lower duty shutdown positions. One utility shuffles preferentially to positions occupied by *original equipment* blades to accelerate the removal of those blades containing high cobalt materials;

2) Slightly less than one-half of the utilities do *not* shuffle blades. Although blade lifetimes can be increased by moving them to low duty positions, shuffling increases outage costs through additional manpower and time requirements.

On Replacement Blade Designs

1) Utilities replace discharged blades with ones having a wide range of design features, from original equipment blades (similar to those they are discharging) at three utilities to all-hafnium designs used at two Far Eastern utilities. However, the majority of the utilities insert designs that employ at least crack-resistant structural materials and hafnium tips;

2) There tends to be a strong correlation between NSSS vendor and replacement blade supplier. Utilities with GE NSSSs (or NSSSs based on GE's designs) tend to load Duralife and/or Marathon designs while utilities with KWU and ABB NSSSs most often replace with ABB's designs (Siemens designs are essentially no longer available). However, it is quite apparent that both vendors are actively pursuing the replacement blade market and have been successful in loading their designs into the other vendor's NSSSs;

3) Three utilities have a large inventory of original equipment blades available from canceled plants that are used as replacements.

On Blade Replacement Strategies

1) Utilities Using ABB-Atom Blade Designs

- ABB-Atom recommends that utilities using 304SS blade designs (CR-70, CR-82, CR-85) begin inspecting blades at a peak segment exposure of 3 snvt;

- No specific mechanical limits have been established for blades using 316L wings i.e., CR-82M, CR-82-M-1, CR-85M, CR-85M-1. The strategy followed worldwide is that the lead blades are visually inspected each year. In this way, the observation of cracking will establish if the mechanical lifetimes are more limiting than the nuclear lifetimes.

2) Utilities Using GE Blades

- With few exceptions, vendor limits are implemented by utilities. Original equipment, Duralife 120, and Duralife 140 blades have a mechanical lifetime equivalent to 34% ^{10}B depletion due to absorber tube cracking and crevice corrosion. The Duralife 160 through 230 series, incorporating better materials, hafnium, and higher boron carbide loadings (Duralife 215 and 230), have resulted in an incremental improvement in lifetimes to a maximum of about three times that of the original equipment blade;

- Marathon designs are limited mechanically as a consequence of internal pressurization at high exposures due to helium generation from the (neutron, alpha) reaction with ^{10}B. The corresponding exposure limit is about 5.0 snvt;

3) Utilities Using Siemens Blades

- Designs offered by Siemens are similar to GE, so are susceptible to the same degradation phenomena. Although the nuclear limit for original equipment blades in BWR/2-5 series plants is 2.7 snvt (10% rod worth reduction due to B_4C depletion only), cracking begins at 1.0 snvt while B_4C loss is initiated at 1.3 snvt;

- Exposure limits employed by utilities using original equipment blades range from 1.6 snvt to 2.7 snvt;

- The Hybrid-4 design, incorporating hafnium, improved materials and design modifications, has a mechanical lifetime limit of ≥ 4.0 snvt. Lead blades have reached exposures of 3.7 snvt without indications of cracking.

On Tip Adders

- Nearly one-half of the responding utilities use tip adders to explicitly account for the exposure in the tip region of shutdown blades. Tip adders, used only for original equipment designs, range from 1 to 3% ^{10}B depletion per cycle;

- Reasons for *not* using tip adders are varied, but most common are 1) the vendor does not *require* them to be used, and 2) no trend is observed from BOC shutdown margin measurements to suggest absorber loss.