

UCRL-85894
PREPRINT

MASTER

OPPORTUNISTIC REPLACEMENT OF
FUSION POWER SYSTEM PARTS

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This paper was prepared for submittal to
Reliability and Maintainability Symposium
Los Angeles, California
Jan. 22-24, 1982

October 26, 1981



Lawrence
Livermore
Laboratory

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Opportunistic Replacement of Fusion Power System Parts*

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Key Words: Conditional maintenance, Replacement, Opportunistic, Optimal, Fusion power system, Availability

Abstract

This paper describes a maintenance problem in a fusion power plant. The problem is to specify which life limited parts should be replaced when there is an opportunity. The objective is to minimize the cost rate of replacement parts and of maintenance actions while satisfying a power plant availability constraint. The maintenance policy is to look ahead and replace all parts that will reach their life limits within a time called a screen. Longer screens yield greater system availabilities because more parts are replaced prior to their life limits.

Introduction to Fusion Power Plant Maintenance

Nuclear fusion is the joining of atomic nuclei--usually the hydrogen isotopes deuterium and tritium. This process produces energy in our sun and other stars. Fusion releases energy in the form of energetic neutrons and charged particles. The neutron's energy can be captured as heat which then boils water to run a conventional steam-electric generator. The charged particles can be collected and their energy converted at high efficiencies into direct electric current.

As a potential source of energy, fusion is attractive for two reasons: the process produces a few containment wastes and the fuel is found in virtually limitless supply in water.

But the fusion process is very difficult to initiate. In order to fuse, the nuclei of fuel atoms must approach each other forcefully enough to overcome their mutual repulsion. In magnetic fusion approaches, the positively-charged nuclei and the negatively charged electrons are separated from each other, forming a "plasma." Since the plasma particles are electrically charged, they may be contained by a magnetic field.

Two magnetic field shapes are being studied in America. The Tokamak (Figure 1), a Russian invention shaped like a doughnut, is being studied at the Princeton Plasma Physics Laboratory, General Atomic Co., and Oak Ridge National Laboratory. The Tokamak is a pulsed, closed system. Fuel is injected and held for relatively long times in the center of the doughnut-shaped plasma. After "burning" for as long as several seconds, the system must be evacuated to remove energy robbing impurities and the cycle begun anew. In contrast, the magnetic mirror being studied at Lawrence Livermore National Laboratory (Figure 2) is a steady state system. The strength of a magnetic mirror field increases from the center to the sides. The shape of the field resembles a twisted bow tie. Magnets which produce this field are built in the shape of a baseball seam or as a pair of interlocking C-coils (called a "Yin-Yang" configuration). Nuclei are reflected toward the center by the high field regions at the ends of the magnetic mirror. Some particles, however, are also lost out the ends. Lost or consumed fuel is replaced by steady state neutral beam injectors.

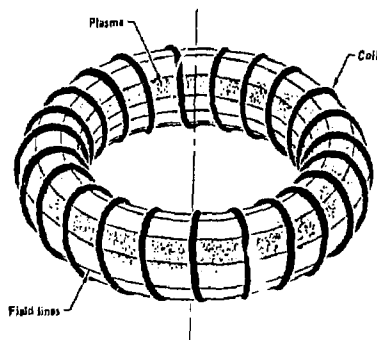


Figure 1. Closed system--simple to us.

Neutral beams provide a means of heating and fueling magnetic fusion devices. Because they lack electrical charge, neutral atoms of fuel pass unaffected through magnetic fields, whereas charged particles are deflected away.

Figure 3 shows a typical neutral beam injector. Neutral beams are made by creating and accelerating a beam of positive ions then neutralizing the ions "on the run" in a gas cell. The neutral ions then pass through the magnetic field, are re-ionized by the fusion plasma and trapped by the same magnetic field. Neutral atoms thus "add fuel to the fire" and maintain the density and temperature of the fusion plasma.

Figure 4 shows how the Mirror Fusion Test Facility (MFTF) plasma machine will look. Please note both the size (see scale men models) and the location and number (up to 45) of neutral beam injectors. They are the rectangular protrusions.

Neutral beam injectors have become a key part in the successful operation of magnetic fusion systems. The injectors being manufactured today have two repairable parts with service life cycle times considerably shorter than most other parts of the Mirror Fusion Test Facility (MFTF). The MFTF operations goal availability has been established at 70% successful shots. (A shot is an attempt to sustain fusion for approximately 30 seconds.) Each shot requires most of the neutral beam injectors to operate for success.

Each neutral beam injector consists of many short life components assembled into two parts, the arc chamber and the accelerator. Failure of either part constitutes injector failure with consequent system shutdown--a process both time consuming and expensive. Deterioration of these parts from shot to shot suggests preventive replacement (like lightbulbs) before failure. Consequently, life limits are set on both parts, and the injector life limit is the smaller of the two part life

* This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract no. W-7405-ENG-48.

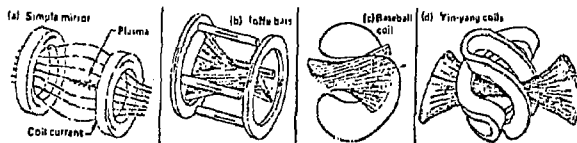


Figure 2.

(a) Simple magnetic-mirror cell with axisymmetric field concentrated at the ends (the mirrors) to reflect ions back toward the center. (b) Current in Ioffe bars imposes transverse multipole field on the simple-mirror field resulting in magnetic pocket (minimum-B) at the center. (c) The single baseball coil produces the same minimum-B field configuration more efficiently than the Ioffe-bar system. (d) The two nested yin-yang coils produce the same minimum-B field but provide greater flexibility by permitting different currents in the two coils, thus different strengths of magnetic mirrors.

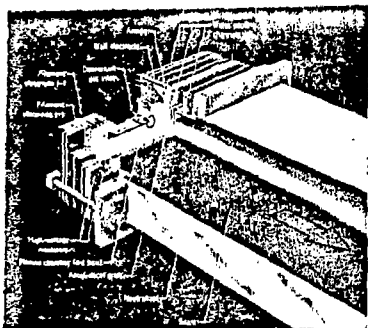


Figure 3.

Cutaway of neutral beam injector. This injector produces a 50-A-equivalent current of neutral deuterium atoms at an average energy of 18 keV. The current drawn between the filaments and the anode ionizes the deuterium gas to about 1% , roughly 10^{12} ions/cm³. Positive ions and neutrals stream through defining accel-decel grids. Subsequent charge-exchange collisions between the positive ions and the deuterium gas result in a beam of neutral deuterium atoms having almost the full energy of the extracted positive deuterium ions. The plasma chamber is virtually free of magnetic fields, and the source plasma in the chamber is free of instabilities and turbulence. The uniformity of this source plasma is one of the factors contributing to achieving the small angular divergence of the emitted beam.

limits. Tables 1 and 2 give proposed life limits. They are chosen so that the probabilities of failures prior to the life limits are small.

Shut down of MFTF for repair or service is complicated both by the physical difficulty due to its size and shape and by its neutronics history. If the time to replace for each failure becomes long or the number of spares required becomes too large, inefficiency results. Any unscheduled shutdown is costly, perhaps \$15,000 per shift. Shutdown to replace an injector or several injectors takes one shift. An injector can be disassembled to replace one of its two parts, reassembled, and reinstalled in one shift. Or another injector may be installed. Periodic shutdowns to do other

work are scheduled every 13 weeks. At that time many injectors can be replaced. Repair of an injector takes approximately 4 man weeks and costs about \$5,000.

Table 1. Proposed Life Limits of Neutral Beam Injectors*

Injector Type	Number Required	Shot Duration (sec)	Life Limit (shots)	System Success Note
20Kv start up	20	0.010	10000	1
80Kv sustaining	7	30	2000	2
80Kv sustaining	16	0.5	10000	3

*The actual design may be different.

System Success Notes:

1. If no more than one startup injector at each end fails.
2. If no sustaining (30 sec) injectors fail or if only the middle injector fails, and
3. If no more than two sustaining (.5 sec) injectors fail, the shot is a success, unless the two failed sustaining injectors are adjacent.

Table 2. Proposed Injector Part Life Limits

Part Name	Number Required	Injector Type	Life Limit (shots)
Accelerator	1	30 sec sustaining	4000
Filament	1	30 sec sustaining	2000
Accelerator	1	Other	20000
Filament	1	Other	10000

There are two opportunistic replacement problems in the fusion power plant. Both have the objective of minimizing the cost rate (cost per unit time) of parts and downtime. One is replacement of injector parts, and the other is replacement of one or more injectors. If one injector part has reached its life limit, shall we replace the other part too? If the MFTF system is shut down to replace an injector, shall we replace some other injectors? We will deal with these two problems separately although this is suboptimal.

Two Part Opportunistic Replacement

This section shows how to find the optimal stationary opportunistic look ahead replacement policy for a two part system. A replacement policy says when to replace parts whether worn out or not. A look ahead replacement policy says replace a part if it reaches its life limit within a time called a screen. An opportunistic policy considers all parts for replacement at

Figure 4. The MFTF-B Vacuum Chamber showing magnets in the cut away area and neutral beam injectors as rectangular protrusions. (See man standing by lower right hand support?)

every opportunity such as replacement of another part. A stationary policy doesn't change the screen as the system ages. An optimal policy minimizes the cost rate of parts and maintenance.

An opportunistic look ahead replacement policy saves money when the cost of replacing both parts simultaneously is less than the cost of replacing them separately. This is due to reduced downtime or labor cost. We recommend an opportunistic replacement policy for the two parts of neutral beam injectors.

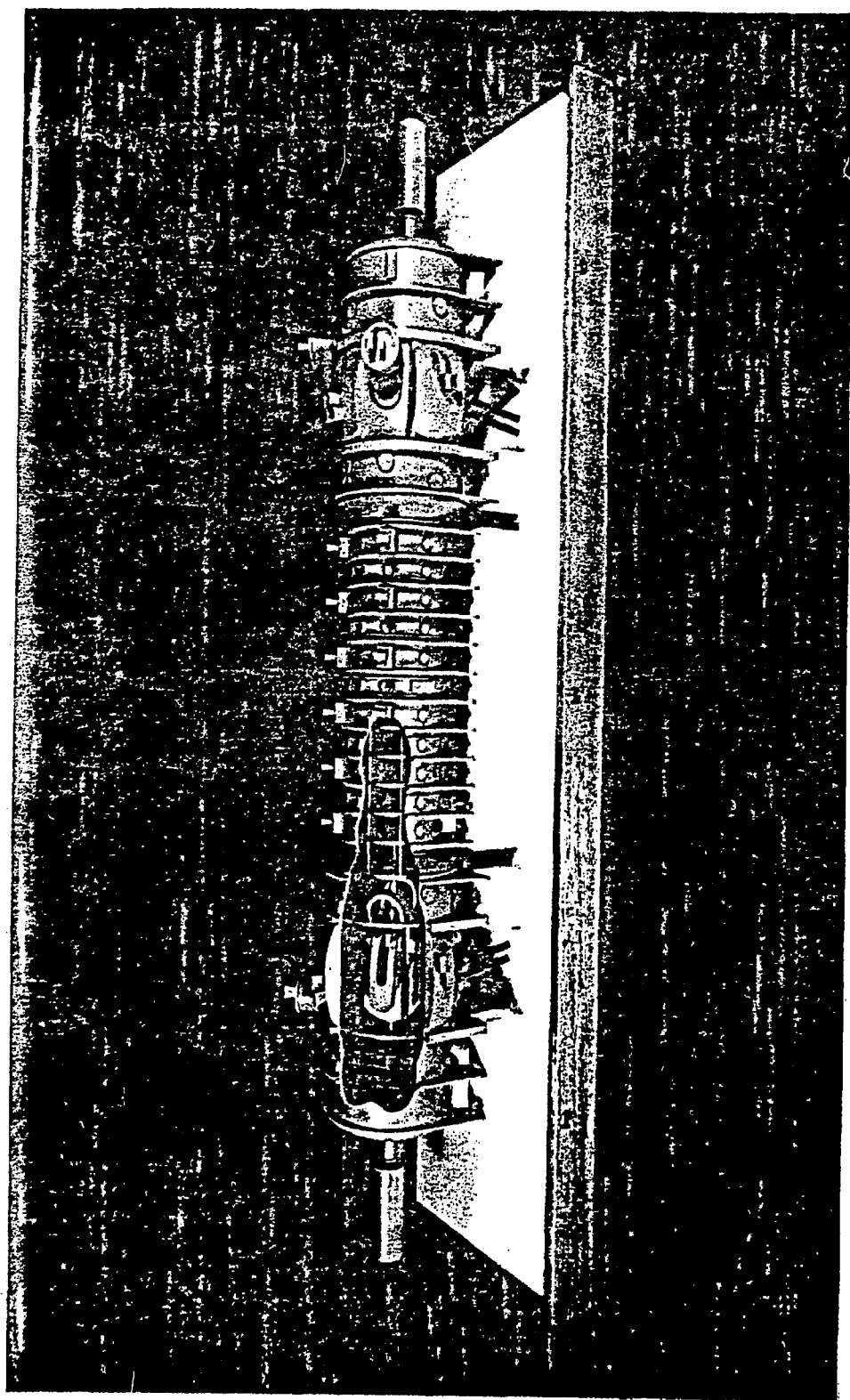
The two parts have life limits that force the system to be shut down for replacement whenever a life limit is reached. The life limits are chosen so that premature failure is unlikely.

For example, the two parts of the neutral beam injectors are easy to separate, so replacement of both when one requires replacement costs no more maintenance time than replacement of one. Figure 5 shows a two-part replacement problem with part life limits 8 and 11, part costs \$1 and \$2, and maintenance cost of \$1. The optimal stationary screen is 2 which ends the life cycle at time 22. The maintenance cost excludes parts costs, so the cost rate is $(2 + 3 + 2 + 4)/22 = \$0.50$ per unit of time.

The first model of opportunistic replacement is summarized by Jorgenson, McCall, and Radner (Ref. 1).

Figure 5. A complete cycle for a two-part replacement problem with no early replacement. If the screen is 2, the cycle ends at time 22.

Their model describes several randomly failing components one of which may be replaced early at inspection or at exponentially distributed failure times of the other components. The problem is to choose inspection times and the replacement policy. The cost of replacing the special part at the inspection time or at replace-



ment of another part is less than the cost of replacement of the part alone.

Their solution method was extended to non-exponential life distributions by Gertsbakh (Ref. 2), chapter 2, section 3. Vergin and Scriabin (Ref. 3) used dynamic programming to solve the problem. Sethi (Ref. 4) studied the problem under the assumption of increasing failure rate for the special part and formulated the problem as a Markov decision process. He also determined the optimal replacement policy for a series system of two parts with an opportunity to replace either part at reduced cost when the other fails. He assumed both parts had increasing failure rates.

The differences between the previous papers and our problem are that opportunistic replacement can take place at the time either part reaches its life limit and that premature failure does not occur because life limits are set so that the probability of failure is low. Some notation is necessary to describe our problem.

Let

- $C(J)$ = cost of part J , $J=1,2$;
- $T(J)$ = life limit of part J , $T(J) \in \{1,2,\dots\}$;
- C_M = cost of maintenance;
- I = the look ahead screen interval, $I \in \{0,1,\dots, \min T(J) - 1\}$;
- T = $T(I)$ = cycle time, the time until both parts are replaced simultaneously, $\min T(J) \leq T \leq T(1)T(2)$;
- $N(J)$ = $N(J,I)$ = number of replacements of part J in a cycle; and
- M_J = $M_J(I)$ = number of maintenance actions in a cycle.

The stationary opportunistic replacement policy is, at the time of any replacement, look ahead amount I . If the other part is due for replacement at or before I , replace it. The objective function is

$$\min_I \left[\sum_{J=1}^2 C(J) N(J) + C_M (M_J) \right] / T. \quad (1)$$

The formulas for T , $N(J)$ and M_J as functions of I are in George and Lo (Ref. 5). The number of values of I for which the objective function differs is small. An efficient enumeration program finds the optimal I . The flowchart of the program is in Figure 6. A FORTRAN listing can be obtained from George. (Write to me at the address in the biography.)

A single screen stationary opportunistic look ahead replacement policy may not be optimal. There may be a double screen which looks ahead different amounts of time for each part and gives a lower cost rate. However, we have never found an example. Therefore we conjecture that a single screen stationary policy always exists that yields the same minimal cost rate as the optimal double screen policy.

The conjecture has been proved by enumeration for all integer costs $C(I)$ and C_M in $0, 1, \dots, 10$ and for integer life limits $T(1) \leq T(2) = 3, 4, \dots, 7$, $T(1) = 7$, $T(2) = 11$, and $T(1) = 8$, $T(2) = 11$.

We believe a single screen policy is optimal for all integer life limits and costs. This is because of the following observations made during enumerations:

1. A reversal is the second occurrence of a specified time between scheduled replacements. Reversals occur symmetrically during the time $T(1)T(2)$. (See Figure 5. Reversals occur at times 44, 48, 55, 64, 66, 72, and 77.)
2. All screens which change the cycle time T and cost rate terminate the cycle before the midpoint of $T(1)T(2)$.

3. The only reason to have a double screen is to terminate a cycle at a reversal.
4. No-early-replacement is cheaper than or as cheap as early-replacement at a reversal.

Since the optimal single screen policy may be cheaper than no-early-replacement and since no-early-replacement is cheaper than early-replacement at a reversal, we recommend a single screen policy for a two part neutral beam injector.

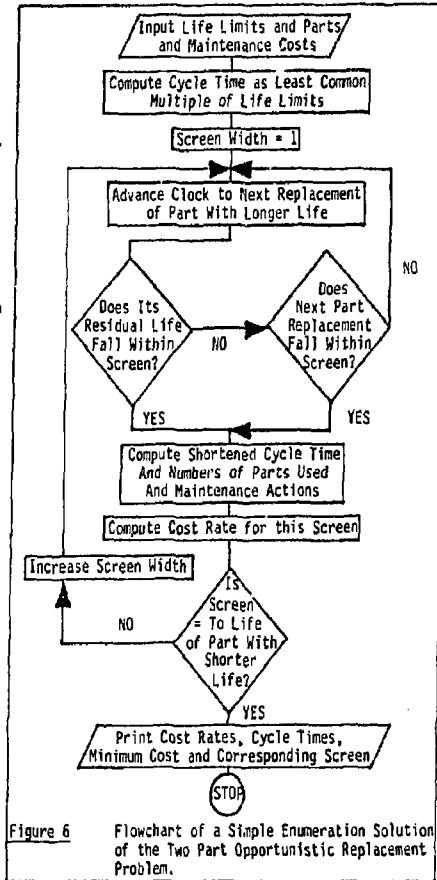


Figure 6 Flowchart of a Simple Enumeration Solution of the Two Part Opportunistic Replacement Problem.

Single Screen, Multiple Part Opportunistic Replacement of Injectors

The multiple-part opportunistic replacement problem is to find a stationary screen to minimize the cost rate of parts and maintenance. Let N be the number of parts. The cost rate is

$$\left[\sum_{J=1}^N C(J) N(J) + C_M M_J \right] / T. \quad (2)$$

The numbers of parts required $N(J)$, $J = 1, 2, \dots, N$, and maintenance actions M_J and T are functions of the screen. The maintenance cost is assumed to be the same, C_M , regardless of the number of parts replaced simultaneously. No early replacement is done unless all parts are due for replacement within a screen. There-

fore, early replacement terminates a cycle by renewing all parts.

The two part replacement problem is imbedded in the multiple part replacement problem. The solution of the multiple part problem uses all optimal two part screens as trial screens. The computer program that solves the problem is in Figure 7. The reason for trying optimal two part screens is that enumeration of all possible screens may take too long.

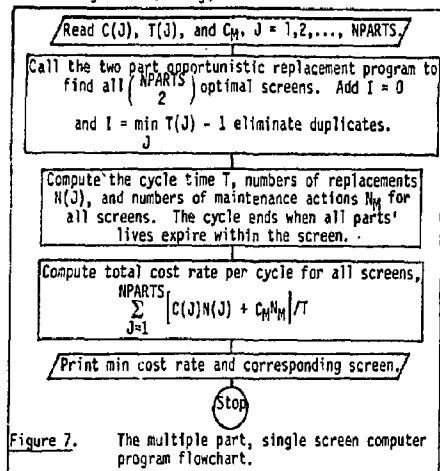


Figure 7. The multiple part, single screen computer program flowchart.

We conjecture that the optimal single screen stationary policy for the multiple part problem is in the set of

all two part optimal screens or is $I=0$ or $\min T(J)-1$. We have not found an exception yet. We have observed the following results in comparison of complete enumeration with the enumeration of only optimal two part screens, 0 and $\min T(J)-1$. (See Figure 7.)

1. We have never had an optimal multi-part screen that was not an optimal two part screen, zero or $\min T(J)-1$.
2. Complete enumeration is wasteful because there are only a few screens for which the cost rates differ.
3. When the set of two part screens plus 0 and $\min T(J)-1$ misses a unique cost rate, that missing cost rate is not minimal.

Therefore, we recommend the program in Figure 7 if enumeration is impractical. If $\min T(J)$ is small, then enumeration is practical.

Tables 3 and 4 show several four part problems. The input values are in Table 3, and the results are in Table 4. The vector entries are $(T(1), \dots, T(4))$ and $(C(1), \dots, C(4))$. Problems 1 and 4 had the optimal screen of zero. Problems 2, 3, 5, and 6 had optimal screens which were two part optimal screens.

Table 3. Input Data for Multiple Part Problems

Problem Number	Number of Parts	Part lives T(J) times	Part costs C(J) \$	Maintenance cost C_M \$
1	4	(4,7,11,15)	(7,7,7,7)	1
2	4	"	(4,4,4,4)	1
3	4	"	(2,2,2,2)	1
4	4	(7,11,15,19)	(1,1,1,1)	1
5	4	"	"	4
6	4	"	"	7

Table 4. Multiple Part Optimal Screen Solutions

Problem Number	Screen I time	Cycle T time	Numbers of Parts/cycle N(J)	Number of Maintenances N_M	Cost Rate \$/time
1	0	4620	{1156,661,420,308}	2100	4.308 (opt)
	1*	539	{135,77,49,36}	243	4.308+
	2	75	{19,11,7,6}	35	4.387
	3	42	{11,6,4,3}	20	4.476
2	0	Same			2.656
	1*				2.655 (opt)
	2				2.707
	3				2.762
3	0	Same			1.555
	1*				1.553 (opt)
	2				1.587
	3*				1.619
4	0	21945	{3135,1995,1463,1155}	6825	.664 (opt)
	1*	209	{30,19,14,11}	66	.670
	2,3*,4*	75	{11,7,5,4}	24	.680
	5*,6	55	{8,5,4,3}	17	.673
5	0	Same			1.597 (opt)
	1*				1.617
	2,3,4*				1.690
	5*,6				1.600
6	0	Same			2.530
	1*				2.565
	2,3,4*				2.600
	5*,6				2.527 (opt)

*These screens are in the set of optimal two part screens.

A General Multiple Part Opportunistic Replacement

The policy in the previous section never replaces any part early unless all unexpired part lives end within the screen. This policy ignores the possibility that early replacement of a subset of parts may be worthwhile. It is necessary to specify maintenance costs for replacement of subsets of parts before we can determine whether early replacement of a subset is worthwhile. Then perhaps a different screen for each subset yields a lower cost rate. Replacement costs for subsets of neutral beam injectors are necessary to plan opportunistic replacement in the MFTF system. We know replacement of all injectors simultaneously is too costly.

There is some doubt whether complete renewal of a system will ever occur if we replace subsets of parts. Complete renewal is desirable occasionally. On the other hand, spare parts supply limitations may prohibit simultaneous replacement of all parts. The three part problem with $T(J) = 3, 4, 5$ never terminates if $j = 1$. There is no time when all three parts are replaced simultaneously.

Opportunistic Replacement and System Availability

A design constraint on the MFTF experiment states that neutral beam injector system availability must be at least 70%. This means that the conditions in Table 1 for successful operation must all be satisfied for at least 70% of the shots.

This section shows how to compute system availability and how system availability varies with the opportunistic replacement policy. Any opportunistic replacement increases availability because parts are fresher than if no opportunistic replacement is done. However, the lack of increase is surprising. Figure 8 shows the availability computation.

Neutral beam injectors have bathtub shaped failure rates. Assuming a neutral beam injector survives burn in, its life is characterized by a long interval of nearly constant failure rate and then an increasing failure rate function. MFTF operator intervention can stretch the life of an injector substantially once an injector shows signs of impending failure. Consequently, sample injector lives can't be used to estimate failure rate functions of future injectors. This section illustrates availability when parts have quadratically increasing failure rate functions.

The probability a part survives to time t is

$$P[\text{Part life} > t] = \exp\left(-\int_0^t r(u) du\right) \quad (3)$$

where $r(u)$ is the failure rate function. If part J is replaced $N(J)$ times in a cycle, then the probability it doesn't fail in a cycle is

$$P[\text{Part } J \text{ does not fail in } (0, T)] = \left[\exp\left(-\int_0^{T(J)} r(u) du\right) \right]^{N(J)} \\ = \exp\left\{-N(J) \int_0^{T(J)} r(u) du\right\} \quad (4)$$

This is a lower bound if part J is replaced early at the end of a cycle.

If failure of any part causes system failure, the probability the system survives a cycle is the probability of no failures:

$$P(T) = \prod_{J \in Q} \left[\exp\left(-N(J) \int_0^{T(J)} r(u) du\right) \right] \\ \prod_{J \in Q'} \left[\exp\left(-N(J)-1 \int_0^{T(J)} r(u) du\right) \exp\left(-\int_0^{T \bmod T(J)} r(u) du\right) \right] \quad (5)$$

assuming parts are independent. The parts are divided into 2 sets; Q contains all parts whose lives end at the end of the cycle and Q' contains the parts that are replaced early at the end of the cycle. The last exponential is the probability of survival through the last partial lifetime of length $T \bmod T(J)$. ($T \bmod T(J)$ denotes the modulo operator; e.g., $8 \bmod 5 = 3$, $17 \bmod 2 = 1$, etc.)

The formula for $P(T)$ is approximately

$$P(T) \approx 1 - \prod_{J \in Q} \left[N(J) \int_0^{T(J)} r(u) du \right] - \prod_{J \in Q'} \left[(N(J)-1) \int_0^{T(J)} r(u) du + \int_0^{T \bmod T(J)} r(u) du \right] \quad (6)$$

when the sum of negative terms is small. This approximation is flowcharted in Figure 8. The approximation failed for long cycles in the example problems.

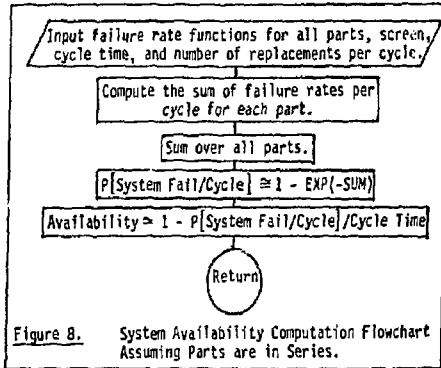


Figure 8. System Availability Computation Flowchart Assuming Parts are in Series.

The probability of at least one failure during a cycle is $1-P(T)$. The long run average availability per shot is approximately $1.0 - (1-P(T))/T$ if $1-P(T)$ is small. Since we assume part lives are chosen so that the probability of premature failure is negligible, the approximation is adequate for short cycles. Table 5 gives the availabilities for all problems assuming the failure rate function is $r(u) = (1.0E-6)(u^2 + u + 1/6)$. The availability could be combined with the objective function and minimized as in Sule and Harmon (Ref. 6).

Table 5. Availability as a Function of Screen

Problem Number	Screen I_s (time)	Cycle (time)	Availability $(1-P(T))/T$
1-3	2	75	.99855
	3	42	.99860
4-6	2-4	75	.99753
	5,6	55	.99756

Ultimately, spares availability should also be incorporated into the objective function and constraints. This is because there may not be a spare available to replace a part even though the opportunistic replacement policy says replace it. Or there might be two unequal spare parts with different residual lives. The choice of which of several unequal spares to use is called the build problem. We've hardly started to study the build problem. (See George, et al., Ref. 7, George Ref. 8, and Friesen and Deuennmeyer Ref. 9.)

References

1. Jorgenson, D. J., J. McCall, and R. Radnor, Optimal replacement policy, North-Holland, Amsterdam, 1967.
2. Gertsbakh, I. B., Models of preventive maintenance, North-Holland, Amsterdam, 1977.
3. Vergin, R. C. and M. Scriabin, "Maintenance scheduling for multicomponent equipment", *AIIE Transactions*, vol 9, no 3, 1977, pp 297-305.
4. Sethi, O. P. S., "Opportunistic replacement policies for maintained systems", *Operations Research Center Report 76-26*, University of California, Berkeley, CA 94720, 1976.
5. George, L. L. and Y. H. Lo, "An opportunistic look-ahead replacement policy", *The Annals of the Society of Logistics Engineers*, Vol. 14, No. 4, pp 51-55, 1980.
6. Sule, D. R. and B. Harmon, "Determination of coordinated maintenance scheduling frequencies for a group of machines", *AIIE Transactions*, vol 11, no 1 pp-43-53, 1979.
7. George, L. L., H. Mahlooji, and P. W. Hu, "Optimal replacement and build policies", *Proceedings Annual Rel. and Maint. Sym.*, January 1979.
8. George, L. L., "Optimal build policies" *Proceedings Annual Soc. of Log. Eng. Meeting*, Pasadena, CA 1980.
9. Friesen, D. K. and B. L. Deuermeyer, "Analysis of greedy solutions for a replacement part sequencing problem", *Math. of Ops. Res.*, Vol. 6, No. 1, pp 7-86, 1981.

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