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TITLE: Human Error Considerations and Annunciator Effects in Determining Optimal Test Intervals for Periodically Inspected Standby Systems

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Human Error Considerations and Annunciator Effects in Determining

Optimal Test Intervals for Periodically

Inspected Standby Systems

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Abstract

This paper incorporates the effects of four types of human error in a model for determining the optimal time between periodic inspections which maximizes the steady state availability for standby safety systems. Such safety systems are characteristic of nuclear power plant operations. The system is assumed to possess the following characteristics:

(1) System failures occur according to a specified lifetime distribution, while on standby, which may have a time-dependent failure rate. The system may include a detection/annunciator device which will announce a failure with a known constant probability.

(2) The system is periodically inspected for failures which may not have been detected by the annunciator.

(3) Four types of human errors may occur in the inspection/repair process: the system may not be correctly replaced on-line after inspection/repair (type A error); a failed system may be judged good during a periodic inspection (type B error); a failed system may be improperly repaired (type C error); or the failure causing an annunciator-activated inspection may not be located (type D error).

(4) Inspection times are assumed fixed and known.

(5) Repair times are assumed to have a lognormal distribution.

The system described above is modeled by means of an infinite state-space Markov chain. The purpose of the paper is to demonstrate techniques for computing steady-state availability A and the optimal periodic inspection interval τ^* for the system described above. The model can be used to investigate the effects of human error probabilities on optimal availability, study the benefits of annunciating the standby-system, and to determine optimal inspection intervals. Several examples which are representative of nuclear power plant applications are presented.

1. Introduction

This paper considers the availability of a safety system designed for standby operation under emergency conditions. The system is assumed to be subject to the possibility of failure while on standby, and must be periodically inspected to insure proper operation when required. Examples of such a system might include an emergency power generator at a hospital, or an emergency core cooling system in a nuclear power plant.

We develop an infinite state Markov chain model which characterizes the behavior of a standby system during a sequence of on-line, testing, and maintenance periods. The model is then used to determine the effect on the optimal test interval and corresponding availability taking into consideration:

(1) various types of human error which may take place during the testing/maintenance process. The possibility of such errors is obviously present, and recent events in the nuclear power industry, such as TMI, have generated increased interest in the study of such errors;

(2) the incorporation into the system of an annunciator device designed to detect failures, at the time of occurrence, with a specified probability.

Several recent studies have taken human error into account in the development of inspection plans and procedures. Susceptibility of components subject to test and maintenance procedures to human error caused failures have previously been recognized (Ref. 1). Apostolakis and Bansal (Ref. 2) consider the effect of a single type of human error on a k-out-of-n:G system, while

Swain and Guttmann (Ref. 3) discuss human error rate estimation in the specific case of the nuclear power industry. Swain and Guttmann (Ref. 4) have also prepared a handbook for use in evaluating the effects of human error on the availability of engineered safety systems in nuclear power plants. A variety of types and causes of errors and methods for their reduction is discussed by Street (Ref. 5).

The problem of determining optimum test intervals has been addressed by various authors, including Chay and Mazumdar (Ref. 6) (maximizing availability for k-out-of-n:G configured standby systems), Sherwin (Ref. 7) (optimum cost inspection schedules of condition-maintained items), and others (Refs. 8-10).

None of the papers referenced above integrate the concepts of human errors and optimum test intervals. This paper considers the determination of an optimum test interval which maximizes steady state availability for a standby system which includes the possibility of four types of human errors.

In a previous paper, McWilliams and Martz (Ref. 11) considered a less refined model which considered the effects of only two types of human errors and repair times which were assumed to be fixed. The model developed in this paper significantly extends the results of the previous research by allowing four possible human errors, random repair times, and the possibility of incorporating an annunciator into the system. Section 2 gives the assumptions which underlie the model and defines the notation used throughout the paper. The Markov model is developed in Section 3, along with the mathematics involved in the calculation of steady state availability. Section 4 describes the computer program used to determine optimum test intervals and its specific application to a Weibull failure-time and lognormal repair time distribution. Examples relating to nuclear power plant applications are presented in Section 5, and some conclusions are given in Section 6.

2. Assumptions and Notation

The following assumptions are made in the development of the availability model of Section 3.

(1) A single system is periodically inspected, and is repaired if found to be in a bad or failed state (no consideration is given to the component configuration of the system).

(2) There are three ways of classifying the system:

A. Up (available for use when called upon),
Down (unavailable)

B. Good
Bad

C. Under inspection/repair
Not under inspection/repair

The three classifications can be related as follows:

	Bad	Good
Under inspection/repair	Down	Down
Not under inspection/repair	Down	Up

(3) The system can fail while up according to a known, possibly non-constant failure (hazard) rate function. A failure may be detected immediately by an annunciator having a known probability of detection, or it may be detected during a periodic inspection.

(4) Inspection consists of the following three actions:

A. Remove/Test. Take the system off-line to see if it is good or bad. The test procedure always judges a good system correctly. However, it sometimes judges a bad system as good. If this error occurs during a normal, periodic inspection it is called a Type B human error. If it occurs during an annunciator-investigated inspection it is called a Type D human error. The time to remove and test the system is assumed to be a known fixed constant; however, it may have two different values depending upon whether the inspection is annunciator induced or is a periodic maintenance inspection.

B. Repair. If the system is judged to be bad, it is repaired. If repaired properly, it is returned to a good-as-new state (i.e., time is turned back to zero). If repaired improperly, it is left in a bad state. Failure to repair properly is called a Type C human error. Repair times are assumed to be random.

C. Return. Return system to on-line status. During this action a human error can occur in which a good system is left in a bad state, e.g., a maintenance engineer fails to return a manually operated valve to its normal condition after the system is replaced on-line. This error is called a Type A human error.

(5) Type A, B, C, and D error probabilities are assumed known and constant.

(6) A cycle is the period of time between the end of one inspection/repair phase and the end of the next inspection/repair phase. The flow diagram of Fig. 1 illustrates the behavior of the system during a cycle.

(7) All random events in the model (system failure time, repair time, annunciation, and human errors) are mutually s-independent.

<u>Notation</u>

θ_k	k=1,2,...; state representing a system which 1) has survived (k-1) previous cycles and 2) is good at the beginning of inspection k.
δ_k	k=1,2,...; state representing a system which 1) has survived (k-1) previous cycles, and 2) is bad at the beginning of inspection k.
γ	state representing a system which is bad at the beginning of any cycle.
q_k	$Pr\{(k-1)\tau \leq T \leq k\tau \mid T \geq (k-1)\tau\}$, k=1,2,... . Conditional probability that the system fails during cycle k, given that it has survived (k-1) previous cycles.
τ	time between normal periodic inspections (test interval).
τ^*	optimal value of τ.
τ_1	remove/test (inspection) time for normal inspections.
τ_2	repair time (random).
τ_3	remove/test (inspection) time for an annunciator induced inspection.
T	system failure-time, a random variable.
$F(t)$	Cdf of T.
[illegible]	Weibull scale and shape parameters.
[illegible]	Lognormal parameters.
P_A	Pr {Type A human error }.
P_B	Pr {Type B human error }.
P_C	Pr {Type C human error }.
P_D	Pr {Type D human error }.

P_I — probability of immediate detection of a failure by the annunciator (annunciator reliability).

$A(\tau)$ — steady-state availability.

A^* — $\max\{A(\tau)\}$, the maximum steady-state availability.

P_o — $(1-r_A)(1-p_B)(1-p_C)$, the probability that a system which is bad just prior to a normal, periodic inspection is correctly judged, repaired, and returned.

P_1 — $p_I(1-p_A)(1-p_C)(1-p_D)+(1-p_I)p_o$, the probability that a system which fails while on-line is up at the beginning of the next cycle.

P_{ab} — Markov transition probability from state [illegible] to state [illegible].

π — vector of steady-state probabilities for Markov chain states [illegible], $[illegible]_1$, $[illegible]_1$, $[illegible]_2$, $[illegible]_2$, $[illegible]_3$, $[illegible]_3$, ...

3. Steady State Availability

System behavior from cycle to cycle can be described by a Markov process having infinite state space $\{\gamma;\ (\alpha_k, \beta_k),\ k = 1, 2, \ldots\}$. The transition matrix determining movement from state to state is given by

$$
P = \begin{array}{c|ccccccc}
 & \gamma & \alpha_1 & \beta_1 & \alpha_2 & \beta_2 & \alpha_3 & \beta_3 \\
\hline
\gamma & 1-p_0 & p_0q_1 & p_0(1-q_1) & 0 & 0 & 0 & 0 \ldots \\
\alpha_1 & 1-p_1 & p_1q_1 & p_1(1-q_1) & 0 & 0 & 0 & 0 \ldots \\
\beta_1 & p_A & 0 & 0 & (1-p_A)q_2 & (1-p_A)(1-q_2) & 0 & 0 \ldots \\
\alpha_2 & 1-p_1 & p_1q_1 & p_1(1-q_1) & 0 & 0 & 0 & 0 \ldots \\
\beta_2 & p_A & 0 & 0 & 0 & 0 & (1-p_A)q_3 & (1-p_A)(1-q_3) \ldots \\
\alpha_3 & 1-p_1 & p_1q_1 & p_1(1-q_1) & 0 & 0 & 0 & 0 \ldots \\
\cdot & & & & & & & \\
\cdot & & & & & & & \\
\cdot & & & & & & &
\end{array} \qquad (1)
$$

The steady-state probability vector π for the process is found by solving the equation $\pi = \pi P$, which generates the system of equations

$$\pi_1 = (1-p_0)\pi_1+(1-p_1)(\pi_2+\pi_4+\pi_6+\ldots)+p_A(\pi_3+\pi_5+\pi_7+\ldots)$$

$$\pi_2 = p_0q_1\pi_1 + p_1q_1(\pi_2+\pi_4+\pi_6+\ldots)$$

$$\pi_3 = p_0(1-q_1)\pi_1+p_1(1-q_1)(\pi_2+\pi_4+\pi_6+\ldots)$$

$$\pi_4 = (1-p_A)q_2\pi_3$$

$$\pi_5 = (1-p_A)(1-q_2)\pi_3 \qquad (2)$$

$$\pi_6 = (1-p_A)q_3\pi_5$$

$$\pi_7 = (1-p_A)(1-q_3)\pi_5$$

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Substituting step-by-step, we obtain the equations

$$\pi_4 = (1-p_A)q_2\pi_3$$

$$\pi_{2k} = (1-p_A)^{k-1}\, q_k \left(\prod_{i=2}^{k-1} (1-q_i)\right)\pi_3,\ k \geq 3 \qquad (3)$$

$$\pi_{2k+1} = (1-p_A)^{k-1} \left(\prod_{i=2}^{k} (1-q_i)\right)\pi_3,\ k \geq 2$$

so π_4, π_5, ... can all be expressed in terms of π_3. Substituting equations (3) into the first three equations of (2) and adding the constraint $\sum_{i=1}^{\infty} \pi_i = 1$, we have

$$
\begin{aligned}
\pi_1 &= (1-p_0)\pi_1+(1-p_1)(\pi_2+\mu_1\pi_3)+p_A(\pi_3+\mu_2\pi_3) \\
\pi_2 &= p_0q_1\pi_1+p_1q_1(\pi_2+\mu_1\pi_3) \\
\pi_3 &= p_0(1-q_1)\pi_1+p_1(1-q_1)(\pi_2+\mu_1\pi_3) \qquad (4) \\
1 &= \pi_1 + \pi_2 + (1+\mu_0)\pi_3
\end{aligned}
$$

where

$$
\begin{aligned}
\mu_0 &= (1-p_A) + \sum_{k=3}^{\infty}\left[(1-p_A)^{k-1}\prod_{i=2}^{k-1}(1-q_i)\right] \\
\mu_1 &= (1-p_A)q_2 + \sum_{k=3}^{\infty}\left[(1-p_A)^{k-1}q_k\prod_{i=2}^{k-1}(1-q_i)\right] \qquad (5) \\
\mu_2 &= \sum_{k=2}^{\infty}\left[(1-p_A)^{k-1}\prod_{i=2}^{k}(1-q_i)\right].
\end{aligned}
$$

The solution to (4), determined algebraically, is

$$\pi_3 = \left[1 + \mu_0 + \frac{q_1}{1-q_1} + \frac{1}{p_0}\left(\frac{q_1(1-p_1)}{1-q_1} + 1 - p_1\mu_1\right)\right]^{-1}$$

$$\pi_2 = \frac{q_1}{1-q_1}\pi_3 \qquad \pi_1 = \frac{(1-p_1)}{p_0}\pi_2 \quad \frac{(1-p_1\mu_1)}{p_0}\pi_3. \tag{6}$$

Once π_1, π_2 and π_3 have been determined, the remaining values of the stationary distribution are computed using equations (3).

Steady state availability calculations require, in addition to the Markov chain steady state distribution, knowledge of the length of time each state or cycle length requires. Letting E_1, E_2, ..., be the expected cycle lengths in states {[illegible], ...}, respectively, the steady state probabilities for the various states at a given time point are

$$r_i = \frac{\pi_i E_i}{\sum_{k=1}^{\infty} \pi_k E_k} \tag{7}$$

After the $\{r_i\}$ sequence is determined, steady state availability is determined by

$$A(\infty) = \sum_{i=1}^{\infty} r_i \cdot P\{\text{system up} \mid \text{state } i\}. \tag{8}$$

The expected cycle length sequence is computed according to

$$E_1 = E(\gamma) = \tau + \tau_1 + (1-p_B)\, E(\tau_2)$$

$$E_{2k} = E(\delta_k) = p_I[E(T_k)+\tau_3+(1-p_D)E(\tau_2)] \qquad (9)$$

$$+ (1-p_I)[\tau + \tau_1 + (1-p_B)\, E(\tau_2)],\ k \geq 1$$

$$E_{2k+1} = E(\eta_k) = \tau + \tau_1$$

where T_k represents the portion of the δ_k cycle or state during which the system is up. Since for a δ_k cycle the system begins at age $(k-1)\tau$ and fails during the cycle, the expected value of T_k is given by

$$E(T_k) = E(T \mid (k-1)\tau < T \leq k\tau) - (k-1)\tau \qquad (10)$$

where T represents system failure-time. Finally, the conditional availability sequence required for equation (5) is computed according to

$$P\{\text{system up} \mid \gamma\} = 0$$

$$P\{\text{system up} \mid \eta_k\} = \tau/(\tau + \tau_1) \qquad (11)$$

$$P\{\text{system up}|\delta_k\} = p_I(1-p_D)E\,\frac{T_k}{T_k+\tau_2+\tau_3}$$

$$+\ p_I p_D E\left(\frac{T_k}{T_k+\tau_3}\right) + (1-p_I)(1-p_B)E\left(\frac{T_k}{\tau+\tau_1+\tau_2}\right) + (1-p_I)p_B\,\frac{E(T_k)}{\tau+\tau_1}$$

Steady state availability is computed by finding the $\{E_i\}$ sequence according to equations (9), the $\{r_i\}$ and conditional availability sequences according to equations (7) and (11), respectively, and finally substituting into equation (8). Note that (11) requires three calculations of the expected ratio of independent random variables. Each of these expectations is approximated by means of Taylor series expansions in the examples presented in Section 5.

4. Optimum Test Interval

A FORTRAN program has been developed to compute $A(\tau)$ and find the test interval τ^* which maximizes $A(\tau)$ for a given set of input parameters. The program computes finite approximations of all infinite series and sequences required, and the number of terms used in the computations can be varied to insure convergence and to control the degree of accuracy required. The expected ratios required in equations (11) are approximated through Taylor series expansions. The ratios are expanded about the means of the appropriate random variables, and the expansion is carried out to third-order terms. The approximation requires as input the mean, second and third central moments of the repair and lifetime distributions. The program currently uses a lognormal repair-time distribution for T_2 and a Weibull failure-time distribution for T. Although we feel that these distributions allow a reasonable amount of flexibility, other distributions can be used by altering appropriate subroutines. A simple and direct search technique is used to determine the value τ^* that maximizes steady state availability.

The Weibull failure-time distribution used in the program is parameterized in the form

$$f(t;\alpha,\beta) = \frac{\beta}{\alpha}\left(\frac{t}{\alpha}\right)^{\beta-1} e^{-(t/\alpha)^{\beta}} \qquad (12)$$

Using the corresponding distribution function $F(t) = 1 - e^{-(t/\alpha)^{\beta}}$, the conditional failure probability sequence q_k is found to be

$$q_k = \frac{\exp\{-[(k-1)\tau/\alpha]^{\beta}\} - \exp\{-[k\tau/\alpha]^{\beta}\}}{\exp\{-[(k-1)\tau/\alpha]^{\beta}\}} . \qquad (13)$$

In addition, the conditional expectation required in equation (10) is given by

$$E\{T \mid (k-1)\tau \leq T \leq k\tau\} = \frac{\alpha\{I[1+\frac{1}{\beta}, (k\tau/\alpha)^{\beta}] - I[1+\frac{1}{\beta}, ((k-1)\tau/\alpha)^{\beta}]\}}{\exp\{-[(k-1)\tau/\alpha]^{\beta}\} - \exp\{-[k\tau/\alpha]^{\beta}\}} \tag{14}$$

where I(a,x) is the incomplete gamma function defined by

$$I[a,x] = \int_0^x y^{a-1} e^{-y} dy. \tag{15}$$

The lognormal repair time distribution used in the program is parameterized as

$$f(t) = \frac{1}{t\sqrt{2\pi}\sigma} e^{-\frac{(\log t - \mu)^2}{2\sigma^2}} \tag{16}$$

5. Examples

Nuclear power plants contains a variety of safety systems which reasonably satisfy the assumptions of the model. The cycle length for redundant systems in nuclear power plants is typically one month, while the inspection duration is but a few hours. Based on the results of Refs. 1 and 4, the probability of human errors of the type considered here will be nominally assumed to be equal to 10^{-2}. Thus, $p_A = p_B = p_C = p_D = 10^{-2}$.

Suppose also that we are interested in determining the optimal test interval for a standby system having a linearly increasing standby failure rate with MTTF = 10^5h (α = 112837.5, β = 2). Also let us assume that repair time is lognormally distributed with σ^2 = 0.04 and μ = 2.2826 (MTTR = 10h, VTTR = $4h^2$). Further suppose that p_I = 0.0, t_1 = 3h, and t_3 = 2h. In this case the standby system is not annunciated. The search program was used to find the optimal test interval which was found to be τ^* = 810h for which A^* = 0.983. On the other hand, if $p_A = p_B = p_C = p_D$ = 0.0, while all other parameter values are unchanged, then τ^* = 740h and the corresponding optimal unavailability is 100-99.2 = 0.8 percent. This is less than half the former value. If the standby system is annunciated with p_I = 0.99 and all remaining parameters are unchanged, the optimal test interval increases to τ^* = 3330h for which A^* = 0.988. Thus, by incorporating an annunciator which is 99% reliable into the standby system, the net effect is to increase the optimal time between inspections from 34 days to 139 days (a factor of 4), while simultaneously increasing the optimal availability by 0.5%.

Now consider the case of a constant standby failure rate (β=1) equal to 10^{-5}f/h (MTTF = 10^{-5}h). If p_I = 0.0, $p_A = p_B = p_C = p_D$ = 10^{-2}, and all other parameters remain the same as above, the optimal test interval is τ^* = 780h for which A^* = 0.982. If the standby system is annunciated with p_I = 0.99, then τ^* = 3480h and A^* = 0.988. Thus, for a constant failure rate system, the optimal procedure is to inspect more (less) often when p_I = 0.0 (p_I = 0.99) compared to a system with a linearly increasing standby failure rate function.

Let us now examine the sensitivity of the optimal solution to changes in certain parameter values used in the example. For convenience, only a single parameter will be varied at a time, while all remaining parameters will be fixed at the respective values given by $p_A = p_B = p_C = p_D = 10^{-2}$, p_I = 0.0 or p_I = 0.99, α = 112837.5, β = 2, σ^2 = 0.04, δ = 2.2826, t_1 = 3h, and t_3 = 2h. These values are nominally consistent with nuclear power plant safety systems.

(1) Consider the sensitivity to changes in p_A. Fig. 2 gives the optimal value τ^* which maximizes the steady-state availability, as well as A^* itself, as p_A varies between 0 and 0.1. Curves for p_I = 0.0 and p_I = 0.99 are both shown. It is observed that τ^* increases as p_A increases when p_I = 0.0 which says that the larger the probability of returning the system in a bad state after inspection, the longer τ should be. This result supports decreased inspection whenever type A human errors are present compared to the case when there is no recognition that such errors may be present (p_A=0). The optimal availability also significantly decreases as p_A increases. When p_I = 0.99, the optimal availability is slightly higher than when p_I = 0. The optimal test interval τ^* is approximately 2-4 times longer than when p_I = 0 and tends to either decrease or remain constant as p_A increases.

(2) Consider the model's sensitivity to p_B. Increasing the value of p_B has only a slight decreasing effect on τ^* as observed in Fig. 3. The optimal availability is nearly constant. Again, if p_I = 0.99 as opposed to 0.0, the optimal test interval is approximately 4 times longer, while the optimal unavailability is decreased by approximately 30%.

(3) Figs. 4 and 5 show the sensitivity of τ^* and A^* to p_C and p_D, respectively. When p_I = 0.99, τ^* decreases as p_C increases, although the optimal availability is nearly constant over the indicated range of p_C.

(4) The sensitivity of the optimal value of τ to the annunciator reliability, p_I, is shown in Fig. 6. It is observed that τ^* increases as p_I increases, with the largest gradient occurring as p_I approaches 1.

6. Conclusions

A model has been developed for determining the optimal time between periodic inspections which maximizes the steady state availability for standby systems, such as those used in nuclear power plant operations.

A limited sensitivity analysis with parameter values not unlike those found in nuclear power plant safety systems was conducted. The optimal inspection interval was observed to most significantly depend upon p_A, the probability of returning the system in a bad state, when the standby system is not annunciated. The optimal system availability is significantly reduced as p_A increases. When the standby system is alarmed with a 99% reliable annunciator, the optimal availability is also significantly reduced as p_A increases.

For all three remaining error types, the optimal availability was not observed to be significantly reduced as the probability of each error increased (with the remaining error probabilities held fixed), provided that the optimal inspection interval is used.

The benefits of annunciating such a system were also examined in view of the four types of human errors. By incorporating an annunciator which has a 99% reliability of detecting system failure while on standby into the system, the optimal time between periodic inspections increased from approximately 1 month to 4.5 months. At the same time, the optimal system unavailability decreased by approximately 30%.

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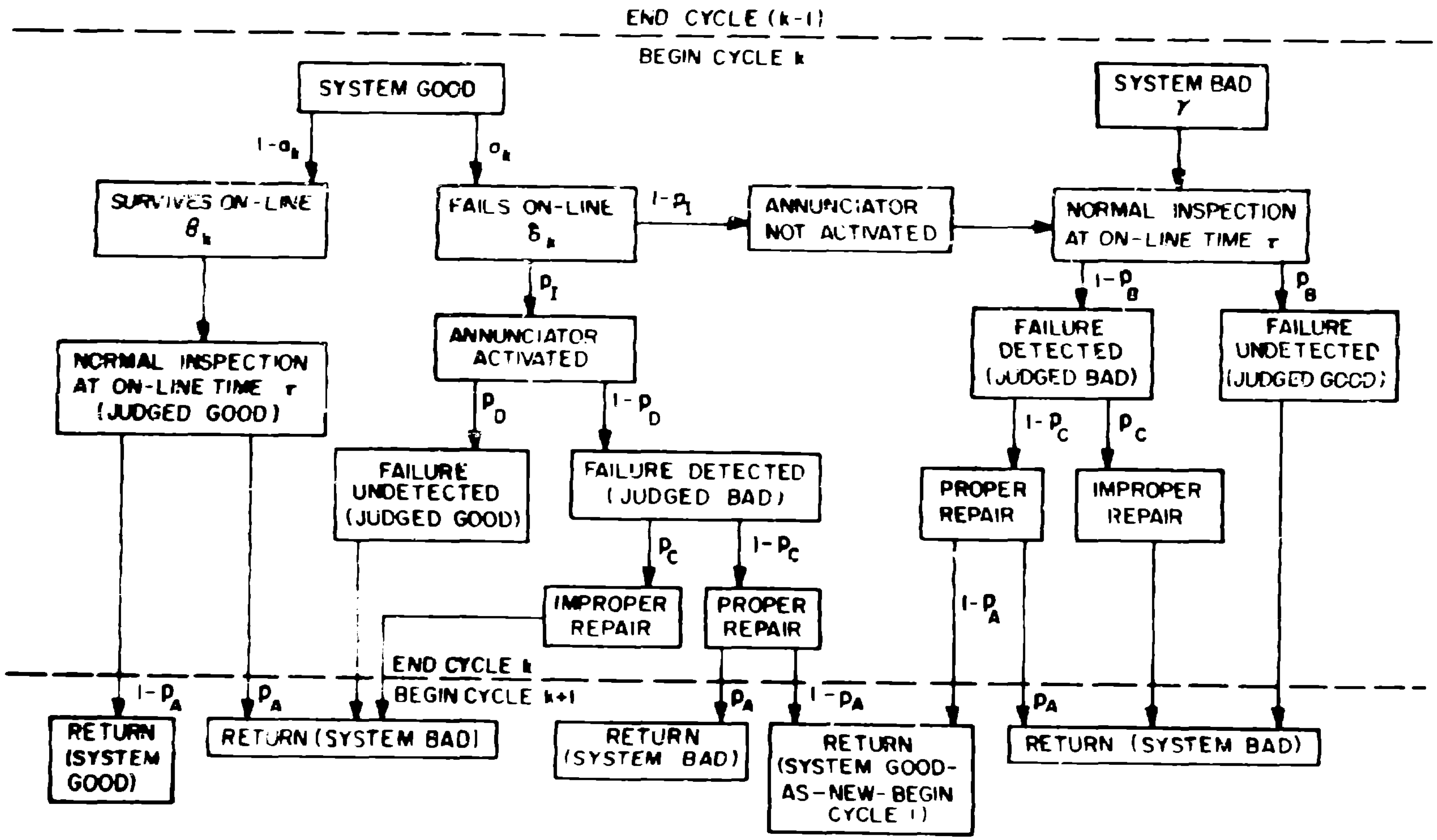

Figure 1. Flow Diagram of System Behavior During a Cycle.

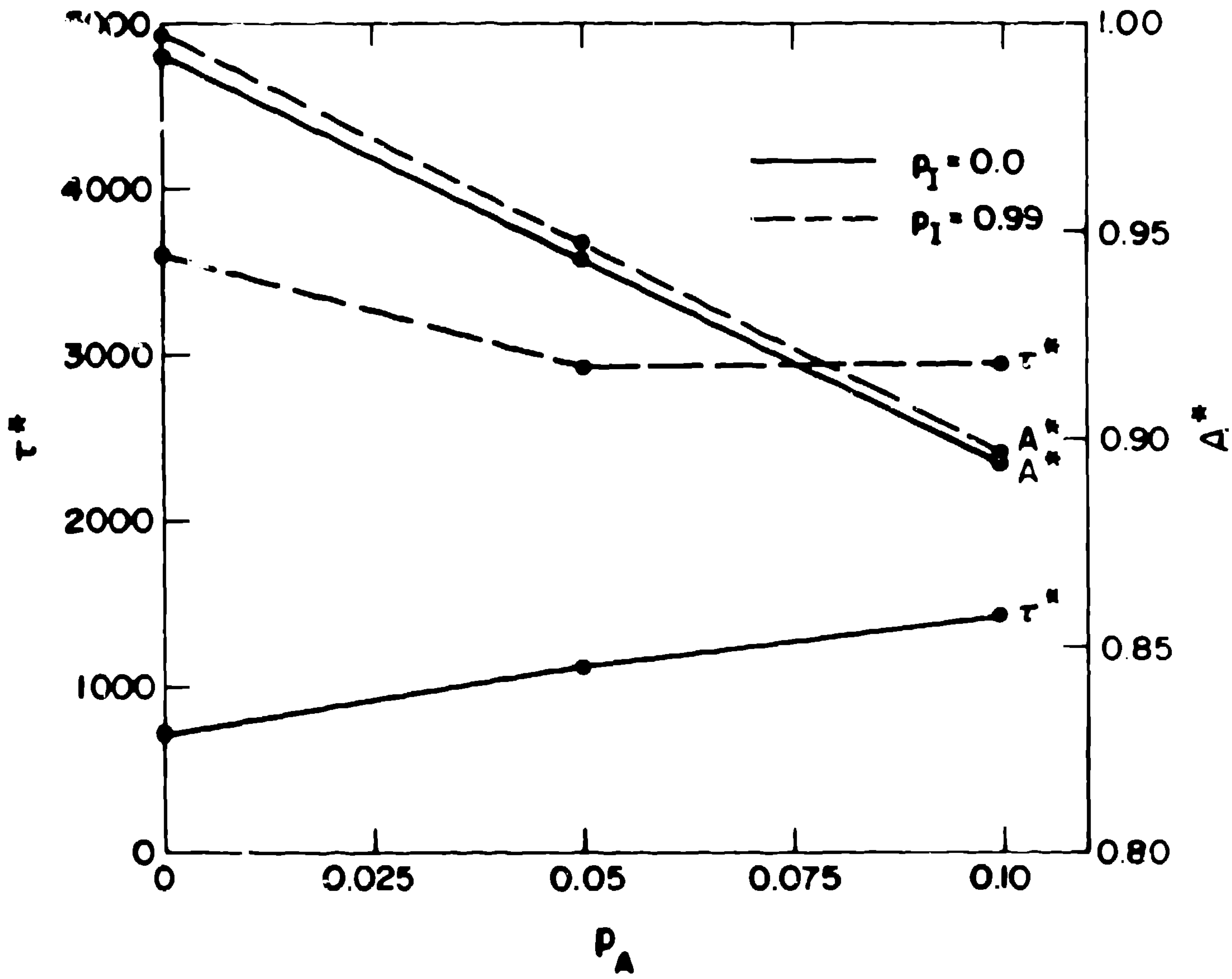

Figure 2. Optimal Test Interval and Associated Availability as a Function of p_A.

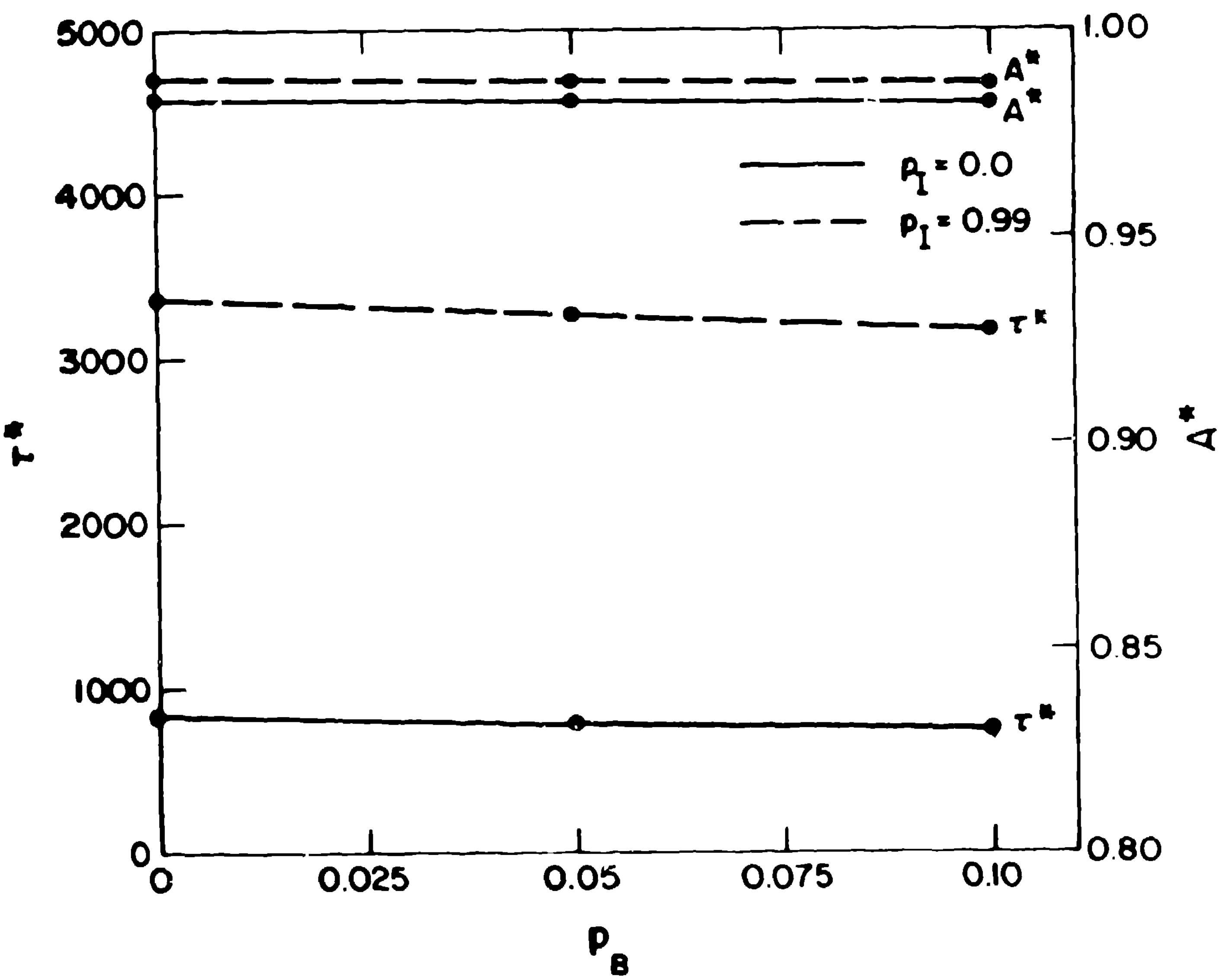

Figure 3. Optimal Test Interval and Associated Availability as a Function of p_B.

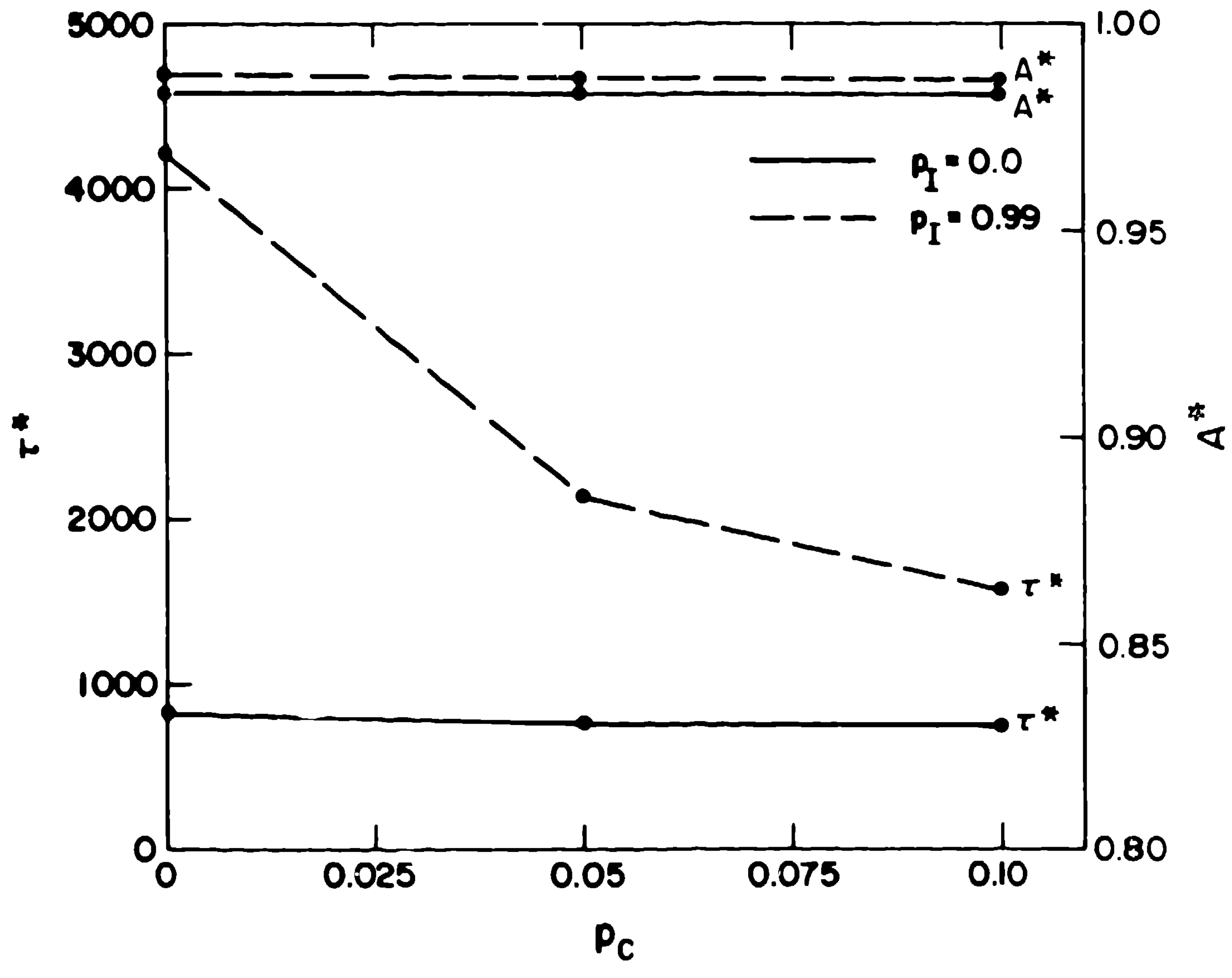

Figure 4. Optimal Test Interval and Associated Availability as a Function of p_C.

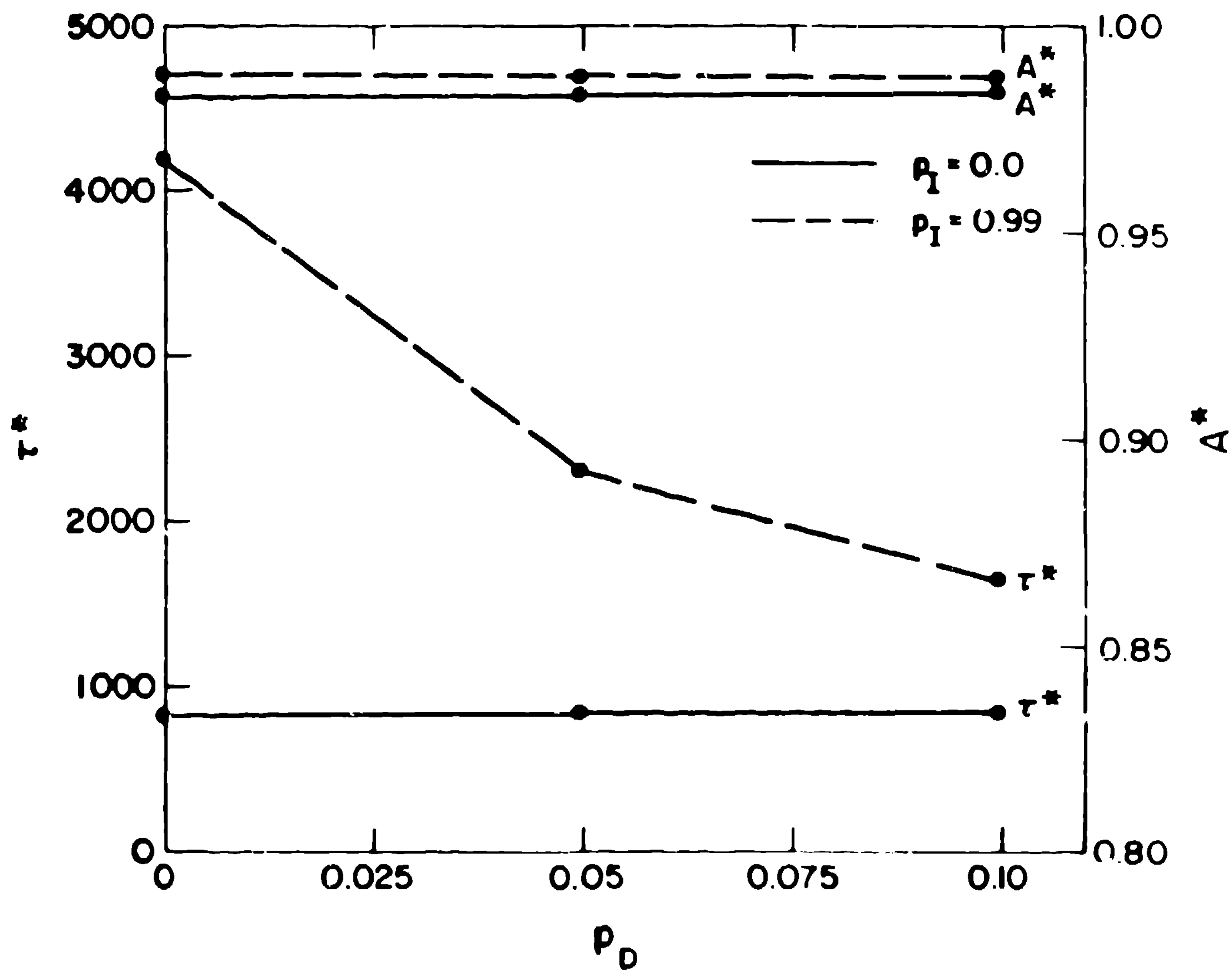

Figure 5. Optimal Test Interval and Associated Availability as a Function of p_D.

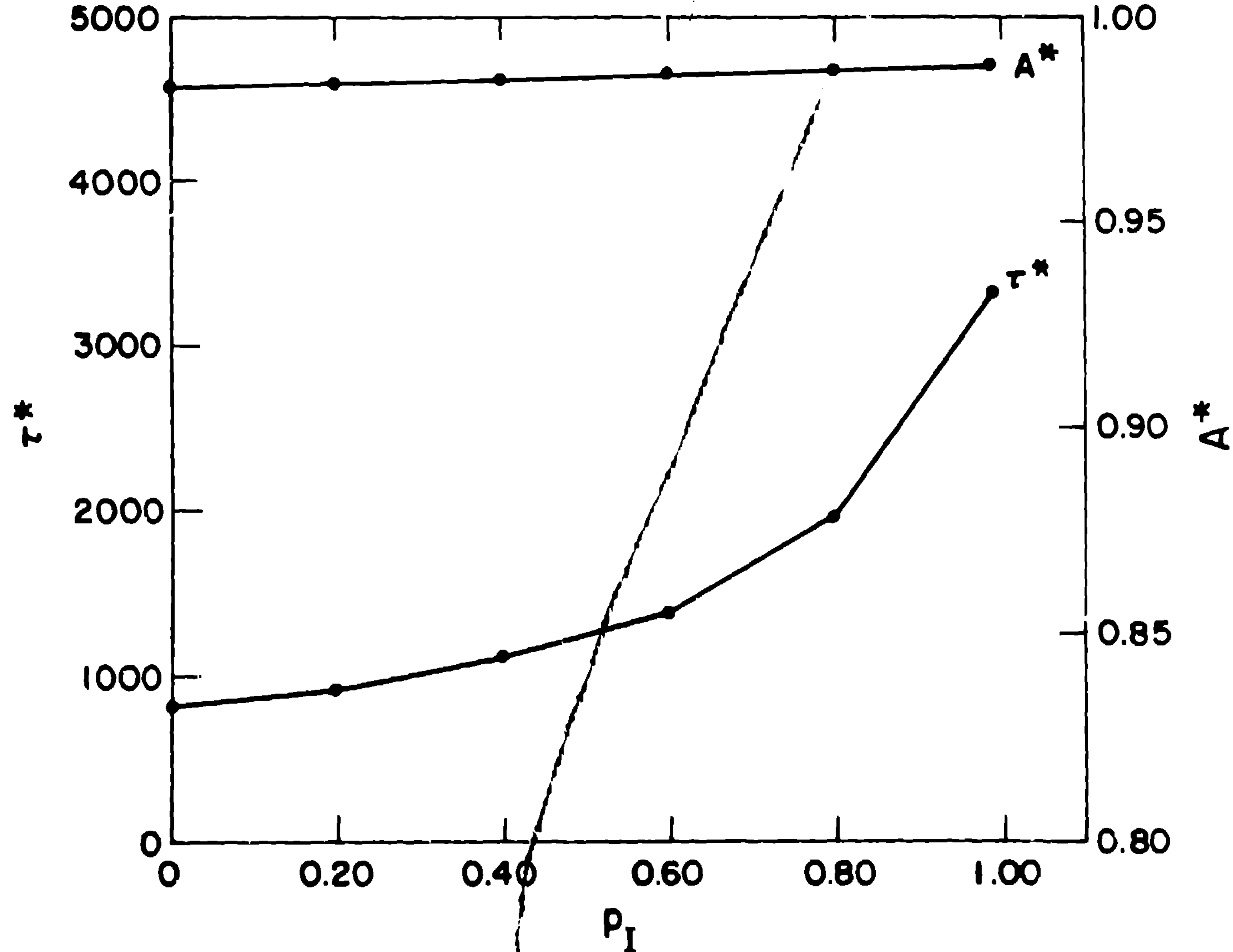

Figure 6. Optimal Test Interval and Associated Availability as a Function of p_I.