Operational Availability Model of Equipment in Storage Based on Periodic Inspection Modelling

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***Abstract*—With regard to the problem of equipment operational readiness, the important parameter of operational availability is studied. The periodic inspection of equipment in storage is divided into perfect periodic inspection and imperfect periodic inspection from the point of view of whether the failure detection rate and the false alarm rate are considered. Considering factors such as test equipment, personnel and additional stress, models of operational availability in perfect and imperfect cases are discussed. Finally, according to the established model, the influences of fault detection rate and false alarm rate on the operational availability of storage equipment are analyzed theoretically and the behavior of the operational availability according to the time between checkouts is analyzed by setting the model parameter values. This model combines operational availability and reliability, maintainability, testability, etc. together, and provides a reference value for the subsequent improvement of equipment operational readiness.**

Keywords-operational readiness; operational availability; fault detection rate; false alarm rate; inspection period

I. INTRODUCTION

Operational readiness is defined as the capability of a given weapon system to be available to perform its task at any time under peace or wartime conditions [1], and is one of the important indicators measuring equipment's combat effectiveness. Operational availability is an important characterization parameter for operational readiness and is an availability parameter associated with up- and down-time.

During long-term storage, the reliability of equipment will be reduced due the latter's exposure to a variety of external environmental conditions [2-4]. To ensure a high degree of operational readiness, periodic testing of the components that are prone to failure must be undertaken. However, the equipment is also stressed due to the periodic testing process and usage by operators and this may also lead to system failures. Furthermore, the fault detection rate, false alarm rate and thus unnecessary repairing of the weapon system will affect the on-demand availability of the equipment [5].

There are many researches on the periodic detection and operational availability of storage equipment up to now. Duan presents the operational availability for k-out-of-n system under the (n, r, r) maintenance policy [6]. Reference [7] gives a mathematical model of operational availability for repairable k-out-of-N equipment system given (m, NG) maintenance policy and limited spares. When the distribution of system life, delayed repair and imperfect repair time are all exponential, Markov renewal process for reducing the availability is presented [8]. Cui gives a model of operational availability and an evaluation method based on availability [9]. Reference [10] presents an evaluation method combined with surface-to-air missile mission requirements and maintenance data. These researches mainly study from the parameter distribution, availability calculation method, maintenance strategy, equipment characteristics and other aspects. Reference [11-12] established a periodic detection model to study the best detection strategy and the availability of equipment. Bayesian model is used to develop the optimal detection strategy [13]. Yang establishes a nonlinear tradeoff optimization model to guide the test periodicity optimization design [14]. But these documents do not take into account the actual test process of testing and additional stress on the impact of equipment testing.

This paper presents an operational availability model for equipment in long-term storage, which combines operational availability and reliability, maintainability, testing, etc. to study the impact of testability (fault detection rate, false alarm rate) and additional stress on the availability of equipment during periodic testing. Through numerical simulations, the effect of storage time on operational availability is investigated, and the failure detection and false alarm rates' influence on the availability of equipment are analyzed. The methodology presented can provide insights for improving equipment's operational readiness.

II. OPERATIONAL AVAILABILITY PARAMETER

Operational availability (A_o) refers to the ability of equipment to be available reliably and without significant additional effort at any random time [1]. Operational availability of equipment considers up-time, maintenance time, support resources and management delay time, which can fully reflect equipment's availability characteristics.

A system is considered 'down' when failure has occurred or it is undergoing periodic checkout or repair. The system is assumed to 'up' during standby periods preceding a failure. A_o may also be defined as the proportion of time that a system is 'up'. Thus:

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$$A_o = \text{total uptime / total time in use.} \quad (1)$$

A_o is also often interpreted as system integrity, that is, the expected percentage of normal operation time in a given environment and time period. Let an inspection interval be divided into n intervals of time, and u_k and t_k represent uptime and the total duration of the k th interval, respectively. Then

$$\begin{aligned} A_o &= \lim_{n\to\infty} \sum_{k=1}^{k=n} u_k \Big/ \sum_{k=1}^{k=n} t_k \\ &= \lim_{n\to\infty} (1/n)\sum_{k=1}^{k=n} u_k \Big/ (1/n)\sum_{k=1}^{k=n} t_k = Eu / Et \end{aligned} \quad (2)$$

where Et and Eu are the averages of the interval length and uptime.

III. Notation

The following notation will be used:

T = duration of storage.

T_c = duration of a checkout period.

T_p = duration of replacement / repair period.

q = probability of failure due to additional stress during a checkout period.

p_c = probability of failure due to additional stress before actual test, if failure occurs during a checkout period.

E = fault detection rate.

α = false alarm rate.

IV. Operational Availability Model Based on Periodic Inspection

Let's assume that a specific equipment is in storage for a long time, with sufficient spare parts. The component failure time obeys the index distribution of [15-16]. To ensure a high degree of operational readiness, equipment must be taken for testing and maintenance after storage for a period of time. If a failure is suspected during inspection period, the system undergoes repair immediately. Once repaired, the equipment is assumed to be functional until the next failure. There are two types of time intervals; Type 1, in which a failure occurs during the first standby period, and Type 2 in which no such failure occurs, as shown in Figure 1.

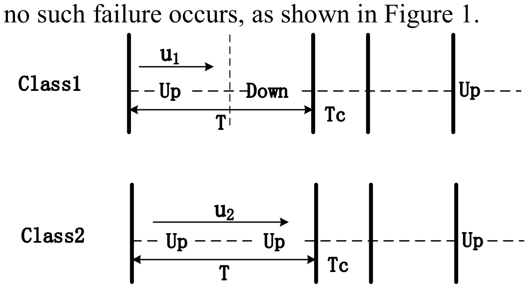

Figure 1. Two basic classes of intervals.

Let Eu_i and Et_i be the average lengths of time corresponding to Type $i(i=1,2)$, and let p_i be the probability that the next interval will be of Type $i(i=1,2)$.

Then

$$\begin{aligned} p_1 &= 1 - e^{-\lambda T}, \\ p_2 &= e^{-\lambda T}, \\ Eu_1 &= \int_0^T u\lambda e^{-\lambda u} / (1-e^{-\lambda T}) du \\ &= (1 - e^{-\lambda T} - \lambda T e^{-\lambda T}) / (\lambda - \lambda e^{-\lambda T}), \\ Eu_2 &= T, \\ Eu &= p_1 Eu_1 + p_2 Eu_2 = (1-e^{-\lambda T})/\lambda \end{aligned}$$

Thus, the operational availability is given by

$$A_o = Eu / Et = (1-e^{-\lambda T})/\lambda Et \quad (3)$$

To calculate A_o of the weapon system, we need to calculate Et for each type having periodic detection. The detection period includes storage time, detection time and maintenance time.

The checkout period is composed of preparation before the test, actual testing and post-testing activities. Throughout the checkout period, the equipment to be tested may suffer additional stress resulting in failure, so failure may occur before or after the equipment is tested. In addition, in each test process there is test equipment and testing personnel participating, and the fault detection capability of testing equipment is affected by human factors and test equipment performance. The following model considers both perfect and imperfect detection to calculate operational availability.

A. Perfect Periodic Inspection

Assume that $\alpha = 0, E = 1$, that is, the detection process will characterize a failed system accurately, and never cause a false alarm. However, the system may suffer from additional stress caused by the testing equipment and the inspectors during each detection process, and the failure may occur before the start of the test or after its conclusion.

Thus, Type 1 intervals will always compose of the sequence of periods $I_1 = (T, T_c, T_p)$. Type 2 intervals are depend on whether a failure occurs before the detection period, or after detection period, or whether no failure at all is found during the detection process. Then it can be composed of one of the following sequences of periods $I_2 = (T, T_c, T_p)$; $I_3 = (T, T_c, T, T_c, T_p)$; or $I_4 = (T, T_c)$, as shown in Figure 2.

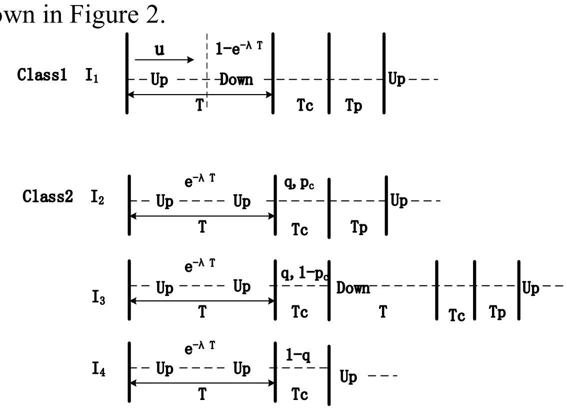

Figure 2. Perfect period inspection.

In this case, the duration of Type 1 and Type 2 is given by:

$$Et_1 = T + T_c + T_p, \qquad (for\ I_1)$$

$$Et_2 = (T + T_c)q(1-p_c) + T_p q. \ (for\ I_2, I_3, I_4)$$

Hence the total testing period interval length is,

$$\begin{aligned} Et &= p_1 Et_1 + p_2 Et_2 \\ &= (T+T_c)[1+q(1-p_c)e^{-\lambda T}] \\ &\quad + T_p[1-(1-q)e^{-\lambda T}] \end{aligned} \tag{4}$$

Thus, the operational availability is given by:

$$A_o = \frac{1-e^{-\lambda T}}{\lambda(T+T_c)[1+q(1-p_c)e^{-\lambda T}] + \lambda T_p[1-(1-q)e^{-\lambda T}]} \tag{5}$$

It is assumed that $p_c = 1, T_c = 0$, that is, a failure occurs during the detection procedure due to extra stress and it occurs before the testing equipment begins to test. In addition, the detection period is relatively short compared with the system storage time and maintenance replacement time, and can be ignored. Thus, the operational availability can be simplified as:

$$A_o = \frac{(1-e^{-\lambda T})}{\lambda T + \lambda T_p[1-(1-q)e^{-\lambda T}]} \tag{6}$$

B. Imperfect Periodic Inspection

During a general detection procedure, we need to take into consideration the characteristics of the test equipment, that is, there are false alarm and fault detection rates where $0 \le \alpha \le 1$ and $0 \le E \le 1$. The case where $E = 0$ can be ignored, for if the system failure cannot be detected, the system cannot be repaired, so that the equipment eventually fails. Taking into account the two types of periodic detection, the false alarm rate and the fault detection rate, are shown in Fig. 3.

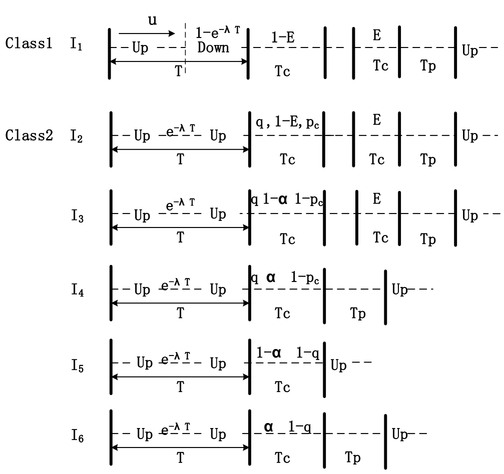

Figure 3. Imperfect periodic inspection

Regarding the fault detection rate, some faults may not be detected in any limited number of continuous tests. Thus, intervals of Type 1 can consist of the sequence

$$\begin{aligned} I_1 &= (TT_c, TT_c, \cdots, TT_c T_p) \\ &= [TT_c \times (n-1)TT_c T_p] \end{aligned}$$

where a failure that occurs during the first storage period T is not detected for $(n-1)$ continuous detection intervals, where $n = 1, 2, \cdots$.

Type 2 intervals can vary and consist of the sequences:

If a failure that occurs during the first T_c period can be detected, but is not for $(n-1)$ consecutive tests, then

$$\begin{aligned} I_2 &= (TT_c, TT_c, \cdots, TT_c T_p) \\ &= [TT_c \times (n-1)TT_c T_p] \end{aligned}$$

If the fault occurred during the first T_c period occurred after the test equipment has been detected and cannot be detected and there is no false alarm rate before it occurs, and is not detected for the next $(n-1)$ continuous detection, thus

$$I_3 = (TT_c \times nTT_c T_p)$$

If a false alarm occurs before the occurrence of undetectable failure during T_c, then

$$I_4 = (T, T_c, T_p)$$

If no false alarm and no failure occurs, then

$$I_5 = (T, T_c)$$

If a false alarm takes place during the testing period, but no failure occurs, then

$$I_6 = (T, T_c, T_p)$$

Referring to Fig. 3, the average time interval for Type 1 is given by:

$$\begin{aligned} Et_1 &= \sum_{n=1}^{\infty} n(T+T_c)(1-E)^{n-1}E + T_p \\ &= (T+T_c)E^{-1} + T_p \end{aligned} \tag{7}$$

The average time interval for the five Type 2 cases is given by:

$$\begin{aligned} Et_2 &= \sum_{n=1}^{\infty} n(T+T_c)qp_c(1-E)^{n-1}E + T_p q p_c \\ &\quad + \sum_{n=2}^{\infty} n(T+T_c)q(1-p_c)(1-\alpha)(1-E)^{n-2}E \\ &\quad + T_p q(1-p_c)(1-\alpha) \\ &\quad + (T+T_c+T_p)q(1-p_c)\alpha \\ &\quad + (T+T_c)(1-q)\alpha + (T+T_c+T_p)(1-q)\alpha \\ &= (T+T_c)[1+qp_c(1-E)E^{-1} \\ &\quad + q(1-p_c)(1-\alpha)E^{-1}] + T_p[\alpha + q(1-\alpha)] \end{aligned} \tag{8}$$

Thus:

$$\begin{aligned} Et &= p_1 Et_1 + p_2 Et_2 \\ &= [(T+T_c)/E]\{1+e^{-\lambda T}[q(1-\alpha+\alpha p_c - p_c E) \\ &\quad -(1-E)]\} + T_p[1-(1-q)(1-\alpha)e^{-\lambda T}] \end{aligned} \tag{9}$$

Therefore, in this case the operational availability is given by:

$$A_{\mathrm{o}} = \frac{1-e^{-\lambda T}}{\lambda (T+T_{\mathrm{c}})E^{-1}\{1+e^{-\lambda T}[q(1-\alpha+\alpha p_{\mathrm{c}}-p_{\mathrm{c}}E) -(1-E)]\}+\lambda T_{\mathrm{p}}[1-(1-q)(1-\alpha)e^{-\lambda T}]} \quad (10)$$

V. Example Analysis

In order to study the relationship between operational availability with time between checkouts and the effect of false alarm rate and fault detection rate on the availability of equipment, A_{o} was plotted as a function of time between checkouts, T, for representative values. Assume that the following model parameter values were fixed throughout the simulations:

$$p_{\mathrm{c}}=0.5, T_{\mathrm{c}}=4h, \lambda=0.01/day, T_{\mathrm{p}}=1\,\text{day}, q=0.25$$

In Fig. 4 the fault detection rate E is fixed at the value 0.9, while the false alarm α is allowed to vary to show its effect on the operational availability. Fig. 5 shows the effect of the fault detection rate E on the operational availability for a value of $\alpha=0.1$. Both two figures show the trend of operational availability plotted as a function of time between checkouts.

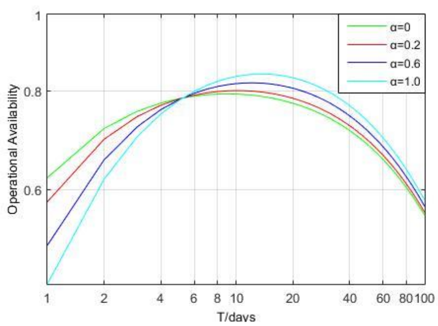

Figure 4. Effect of false alarm rate on operational availability.

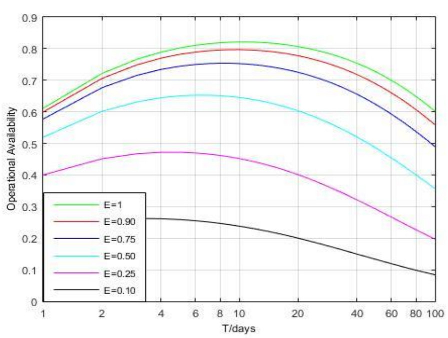

Figure 5. Effect of fault detection rate on operational availability.

From Figs. 4 and 5 we see that,

(1) Operational availability first increases and then decreases with increasing time between checkouts;

(2) The fault detection rate seems to have more influence on operational availability than the false alarm rate;

(3) It can be seen from Figure 4 that when the detection interval is relatively small, the difference between the operational availability values is more obvious, and the smaller the false alarm rate, the greater the value of operational availability. When the detection interval is relatively large, the impact of false alarms is not obvious, and when the time between checkouts exceeds a certain value, the greater the false alarm rate, the greater the operational availability of system;

(4) As can be seen from Figure 5, the greater the fault detection rate, the greater the operational availability value. When the detection interval is relatively small, the difference of operational availability values becomes smaller. With the time between checkouts increases, the fault detection rate has a more apparent effect on operational availability.

The results shown in the above figures can be accounted for as follows:

When the time between checkouts is small, equipment will be taken frequently for testing and maintenance, making the operational availability value smaller. With the increase of the time between checkouts, availability will increase will achieve the maximum value at certain period of time. Due to the decline in equipment reliability, the longer the time between checkouts, the lower the reliability, making the operational availability value reduce. Therefore, the shape of the curve is parabolic.

When the time between checkouts is relatively small, the false alarm rate has a greater impact on the availability of equipment; a greater the false alarm rate means that the system will experience more unnecessary maintenance, replacement parts, etc., thus reducing operational availability. When the time between checkouts is relatively large, the equipment performance degrades and the failure rate increases; a greater the false alarm rate leads to equipment being removed for fault detection, maintenance or replacement activities, thus increasing its availability. Due to the existence of real failures, the false alarm rate has little effect on operational availability; on the contrary, the ability to detect faults (the failure detection rate) has a much greater impact.

VI. Conclusion

Testing equipment, testing personnel and other factors may make a system withstand additional stress resulting in failure. The fault detection and false alarm rates are greatly affected by human factors and testing equipment performance, resulting in equipment undergoing unnecessary maintenance, which has a significant effect on the operational availability.

In this paper, periodic detection is divided into perfect periodic detection and imperfect periodic detection, and the operational availability model of equipment in storage is deduced. The influence of fault detection rate and false alarm rate on the operational availability of equipment and the behavior of operational availability with respect to the testing period is analyzed.

During the actual equipment's storage, maintenance and regular testing process, the troops can combine the long-term accumulation of data to determine the time between checkouts, maintenance time and test parameters to analyze the parameters of operational availability theoretically, which will then allow them to reasonably determine the optimal testing period and improve the operational readiness of equipment.

REFERENCES

[1] GJB 451A-2005. Reliability, Maintainability and Supportability Terms[S], 2005.

[2] Yan W A. Research on the method of Storage Reliability for Torpedo [D]. Xi'an: Northwestern Polytechnical University, 2014: 15-24.

[3] LU M Z, LI Y F, YANG Z G, ZHAO H J. Reliability Assessment of Storage Long-term Equipment Based on Testing Data [J]. Failure Analysis and Prevention, 2014, 9(1): 58-60..

[4] WANG L, LU W M, TENG K N. Real-time health condition assessment of long-term storage equipment based on testing data [J]. Systems Engineering and Electronics, 2013, 35(06):1212-1217.

[5] Li Z, Song B W. Testing period optimal of storage material[J]. Systems Engineering and Electronics, 2004, 10: 1432-1434+1499.

[6] DUAN H L, LIU R Y. Operational availability for the k-out-n system under (n,r,r) maintenance policy [J]. Journal of Gansu Lianhe University (Natural Sciences), 2008, 22(5): 15-17..

[7] ZHANG T, WU X Y, GUO B, TAN Y J. Operational availability model for repairable system under (m, NG) maintenance policy [J]. Journal of Systems Engineering, 2007, 22(6): 627-634.

[8] CHEN X, ZHANG G F. Availability of a repairable system with delayed repair and imperfect repair [J]. Journal of Zhejiang University (Science Edition), 2008, 35(1): 19-22.

[9] Cui X T, Wang L B, Zhang Y. Research of Evaluation Model of Missile Equipment Operational Availability Based on the Availability Theory[J]. Fire Control & Command Control, 2014, 39(10): 99-103.

[10] Zhang X H, Wang C H. Operational Availability of Surface to Air Missile [J]. Modern Defense Technology, 2015, 43(1): 129-134.

[11] Ito K, Nakagawa T. Optimal inspection policies for a storage system with degradation at periodic test [J]. Mathematical and Computer Modeling, 2000, 31(10-12): 191-195.

[12] Nakagawa T, Mizutani S, Chen M. A summary of periodic and random inspection polices [J]. Reliability Engineering and System Safety, 2010, 95(8): 906-911.

[13] Kallen M J, Van Noortwijk J M. Optimal maintenance decisions under imperfect inspection [J]. Reliability Engineering and System Safety, 2004, 90(2): 177-185.

[14] YANG S M, QIU J, LIU G J, YANG P. Test periodicity optimization of equipment health management information under availability constraints [J]. Acta Armamentarii, 2012, 33(7): 892-896.

[15] Elsayed A. Elsayed. Reliability Engineering (Second Edition)[M]. YANG Z, translated. Beijing: Publishing House of Electronics Industry, 2013:10-11.

[16] Chen Zehua, Zheng Shurong. Lifetime distribution based degradation analysis [J]. IEEE Transactions on Reliability, 2005, 54(1):3-10.