Lifetime Evaluation Method for Electronic Equipment of Wayside Signalling Systems

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It is often difficult to determine the intervals at which trackside electronic equipment for railway signalling system needs to be replaced. In a previous study, Fujita et al. proposed a lifetime evaluation method for electronic interlocking equipment installed in an indoor environment. In this paper, the authors focus on the electronic equipment used in wayside signalling systems, which is exposed to more severe outside conditions. We evaluated the lifetimes not only of electronic components but also of substrates. The results of a case study using the developed evaluation method are also reported. Lifetimes depend on operating environment stress factors, especially temperature changes. Therefore, we recommend that replacement intervals should be adjusted according to the operating environment.

**Keywords:** lifetime, electronic equipment, wayside signalling system, wear-out failure period, acceleration test, stress factor

1. Introduction

Railway signalling systems have been widely installed along railway lines to ensure safe and stable train operation. In recent years, electronic devices have been introduced in railway signalling systems, to replace relays, in order to reduce the size and improve the performance of these systems. However, it is often difficult to grasp how these devices deteriorate, and in turn difficult to determine the correct intervals to replace them.

In a previous study, Fujita et al. proposed a lifetime evaluation method for electronic interlocking equipment installed in an indoor environment [1]. In this paper, the authors focus on the electronic equipment of wayside signalling systems, exposed to more severe conditions in an outside environment. It is assumed that there are more stress factors outdoors, than indoors. Consequently, the previous method needs to be expanded to achieve more accurate lifetime evaluations for electronic equipment used in wayside signalling systems.

This paper summarizes the stress factors influencing the environment in which electronic devices are installed along railway lines and explain the developed lifetime evaluation method. We also report the results of a case study carried out using this new method.

2. Concept of lifetime evaluations for electronic equipment of wayside signalling systems

2.1 Failure distribution of electronic devices

In general, the failure distribution of industrial products can be broadly divided into three periods with the different causes of failure: early failure period, random failure period, and wear-out failure period. Figure 1 shows the relationship between field use time and the instantaneous failure rate (Bathtub curve).

Failures occur due to design defects and quality variations soon after product manufacturing (early failure period). After that, the failure rate becomes constant and they operate stably (random failure period), then the failure rate increases due to the lifetime of components or units (wear-out failure period). Finally, all products fail. There are many electronic devices installed along tracks. Hence, if the replacement period is incorrectly set after the wear-out failure period, a lot of electronic devices fail at the same time and many human resources will be needed for the maintenance. It is important to determine the lifetime of a device so that it can be replaced before the wear-out failure period begins. Therefore, we focused on the wear-out failure period as the target period for the lifetime evaluation method.

2.2 Actual conditions survey of used electronic devices failures

In order to obtain a realistic understanding of the actual situation surrounding wayside equipment failure, we
analyzed the data of faulty products returned from railway operators to manufacturers. After excluding causes related to disasters and human error, we extracted data about failures due to deterioration. This search showed that breakdowns were frequently caused by the failure of one specific type of electronic component.

This component was further analyzed using a cumulative hazard method considering shipping volume. The results of the analysis suggested that the electronic components had already reached their wear-out period. Although a similar analysis was conducted when we developed the lifetime evaluation method for electronic interlocking devices, the analysis results indicated a tendency for failure to be in the random failure period. The difference between analyses was therefore thought to be due to the fact that the installation environment of electronic devices along the railway line is severer than the environment of electronic interlocking devices, increasing the effect of stress and accelerating deterioration.

3. Operational environment of the target device

Possible stress factors for wayside signalling systems were identified, and field tests were conducted for each one. The main types of wayside equipment examined, were level crossing related devices, ATS (Automatic Train Stop system) control units and other devices installed in trackside cabinets, as shown in Fig. 2.

There are various types of trackside cabinet, differing in size, color, with / without shielding plates, presence / absence of ventilation holes, etc. Trackside cabinets are normally closed, and opened only for maintenance and inspection.

3.1 Extraction of assumed stress factors

Electronic devices are normally composed of multiple substrates, and electronic components such as ICs and capacitors are soldered on a printed circuit board. Therefore, failures that disrupt the operation of an entire electronic device can be broadly divided into electronic component failures, printed circuit board failures and solder joint failures. In electronic component failures, the main stress factors are assumed to be steady-state temperature and temperature changes, humidity, and voltage and current loads during use. It is considered that printed circuit board and solder joint failures are greatly affected by thermal factors such as temperature changes and mechanical factors such as vibration and shaking from passing trains. From the results of past examinations of products collected from wayside signalling systems, there was no rust and no cracks were found on the printed circuit boards, but cracks were found in the solder joints. Therefore, the influence of the stress factors on the solder joints was considered to be relatively greater than on the printed circuit boards. Therefore, we excluded printed circuit board failures from the target for the lifetime evaluation.

Table 1 summarizes the stress factors assumed to affect the lifetime of electronic devices in wayside equipment, for both in indoor and outdoor conditions. Indoor conditions assume an environment with air-conditioned stable tem-

| No. | Broad classification | Factor classification1 | Factor classification2 | Inside environment (assumed) | WAYSIDE environment (assumed) |
|-----|---------------------|------------------------|-----------------------|-----------------------------|-------------------------------|
| 1   | Thermal factors    | Steady-state temperature | Y | Signal house (25℃) | Y | Depending on the installation environment |
| 2   | Thermal factors    | Temperature change | N | None | Y | Depending on the installation environment |
| 3   | Electrical factors | Electromagnetic wave / Surge | EF | External stress factor | EF | External stress factor |
| 4   | Environmental Stress | Surrounding environmental factors | Atmosphere | N | Good (little activated gas) | Y | Depending on the installation environment |
| 5   | Environmental Stress | Moisture / Humidity | N | Good (about 30-50%) | Y | Depending on the installation environment |
| 6   | Mechanical factors | Vibration, Shock, Acceleration | N | None | Y | Depending on the installation environment |
| 7   | Mechanical factors | Bending, Fatigue, Sliding | N | None | N | None |
| 8   | Operational Stress | Electrical factors | Voltage | Y | Depending on the component | Y | Depending on the component |
| 9   | Operational Stress | Electrical factors | Current load | Y | Depending on the component | Y | Depending on the component |
peratures, the expected stress factors are therefore steady-state temperature (No. 1), voltage (No. 8), and current load (No. 9). For the electronic devices in wayside signalling systems installed in outdoor trackside cabinets, however, the stress factors are expected to be temperature change (No. 2), atmosphere (No. 4), moisture / humidity (No. 5), vibration (No. 6) in addition to stress factors considered for indoor conditions. In both environments, electromagnetic waves / surges (No. 3) are external stress factors caused by lightning: these were excluded because lightning induced failure does not correspond to the wear-out failure period.

3.2 Quantification of extracted stress factors

The degree of influence on the deterioration of the electronic devices was quantified by measuring the stress factors, extracted in the previous section, in the real environment where wayside equipment was installed. Three locations were selected in Japan (cold region: Hokkaido, intermediate region: Tokyo, temperate region: Ehime). Temperature and humidity inside and outside the trackside cabinet were measured for one year. For atmospheric stress (No. 4), the concentration of corrosive gas was measured using a corrosive gas measuring kit at the same three locations and in cabinets near paper mills where corrosive gas is likely to be generated. For vibration-related stress (No. 6), we measured the vibration acceleration of the trackside cabinet and electronic equipment when trains passed through, considering the track beds (ballast / slab) and train types (express train / local train / freight train) and including elevated sections. For the voltage (No. 8) and current load (No. 9), the operating voltage and current were confirmed with the manufacturer.

(1) Temperature and humidity stress

Figure 3 shows the measured temperature and humidity in Tokyo. We measured the environments of two types of trackside cabinet (with ventilation holes) with and without shielding plates of the same size without electronic devices inside. The results showed that there is a difference in the maximum temperature and daily temperature variation because of solar radiation in fine weather depending on the presence or not of a shielding plate. In addition, comparing the measurement results at three locations, we confirmed that the temperature inside the trackside cabinet rose due to self-generated heat from the electronic equipment inside the cabinet, depending on whether or not with it power on. Figure 3 also shows that relative humidity reached 100% in rainy weather due to the ventilation hole. With the exception of specific environments, such as inside tunnels, we think that dew condensation is rare [2], but it is necessary to consider the effect of humidity on deterioration.

(2) Atmospheric stress

A corrosive gas measuring kit was used to measure the concentrations of corrosive gases: sulfurous acid gas (SO₂), hydrogen sulfide gas (H₂S), and chlorine-based gas (Cl₂, HCl) at the three locations in Japan, in cabinets with and without ventilation holes, and in cabinets located near paper mills, where corrosive gases are likely to be generated, without ventilation holes. Results were compared with the 3C1L classification of IEC60721-3-3 “Classification of environmental conditions Part 3 : Classification of groups of environmental parameters and their severities Section 3 : Stationary use at weather protected locations” and the silver corrosion rate of ANSI / ISA-71.04-2013 “Environmental Conditions for Process Measurement and Control Systems: Airborne Contaminants.” This confirmed that the concentrations of corrosive gases inside trackside cabinets were below the reference values. Therefore, it is considered that the direct effect of vibration stress on the deterioration of electronic devices is small excluding specific environments such as where resonance is likely to occur.

Based on these measurement results, the stress factors assumed to cause deterioration of electronic devices and thus impact the lifetime of trackside signalling systems, were considered to be: steady-state temperature (No. 1), temperature change (No. 2), and moisture / humidity (No. 5). Vibration (No. 6) stress would have to be considered in environments where the vibration acceleration exceeded the JIS reference value.

3.3 Vibration-related stress

Measured vibration acceleration generated by passing trains was compared with JIS E 3014 “Parts for Railway Signal-Vibration test methods.” This confirmed that the vibration acceleration of the trackside cabinet and electronic devices were below the reference values. Therefore, it is considered that the direct effect of vibration stress on the deterioration of electronic devices is small excluding specific environments such as where resonance is likely to occur.

4. Lifetime evaluation method

As summarized in Table 1, the assumed stress factors for electronic interlocking devices, in indoor conditions controlled through air conditioning, are steady-state temperature and electrical factors. This means that the lifetime of the entire device is evaluated assuming only electronic component failures. Trackside equipment however requires more stress factors to be taken into account, such as tem-
perature changes, moisture / humidity. Therefore, to evaluate the lifetime of wayside equipment, a dual approach is necessary, to consider electronic component failures and solder joint failures. In the lifetime evaluation method of the electronic devices of wayside signalling systems, as shown in Fig. 4, electronic component evaluation and solder joint evaluation are carried out independently, considering the stress and conditions in the operational environment. Finally, the results of two evaluations are merged to determine the shortest lifetime failure point, which is the lifetime of the entire device.

4.1 Evaluating the lifetime of electronic components

The lifetime evaluation method of the electronic interlocking device [1] was expanded to deal with stress factors affecting wayside environments. Figure 4 shows the flow of the evaluation method. In the electronic component evaluation, the components that affect the main function of the electronic device are extracted and the reliability test results of the extracted components are obtained from the manufacturer. From the survey results of stress factors in the operational environment, the failure mechanism is identified. Next, by applying the reliability test results to the operational environment conditions using the acceleration model formula according to the failure mechanism, the cumulative failure probability is estimated. Finally, by calculating the number of years needed to reach a specific cumulative failure probability, the lifetime of each electronic component can be evaluated for that operational environment.

4.1.1 Extraction of electronic components affecting overall function

We analyzed the degree of influence on overall function of an electronic device when a specific electronic component failed. The degree of influence was defined according to a five-point scale: level 0: no effect, level 1: unstable operation, level 2: partial function stop, level 3: unit stop, level 4: device function stop. We selected, among the extracted components on level 2 or above, the parts that are generally considered to have a limited lifetime, such as aluminum electrolytic capacitors or parts that generate a large amount of heat when switched on.

4.1.2 Understanding electronic component specifications and stress factors

We acquired the manufacturers’ reliability test data (number of samples, accelerated environmental conditions, test time, number of failures, etc.) for the extracted electronic components. From the operational environment survey of electronic devices of wayside signalling systems, steady-state temperature, temperature change, humidity, voltage, and current load were assumed to be the main stress factors that affect individual electronic components.

4.1.3 Evaluation of the lifetime based on acceleration model

The possible failure mechanisms according to the assumed stress factors are listed and the corresponding acceleration model equations are identified. Using examples of aluminum electrolytic capacitors and ICs, Table 2 shows the failure mechanisms and acceleration model formulas, which can be considered from the stress factors (steady-state temperature, temperature change, humidity, voltage and current load) assumed in the operational environment. For the acceleration model formula corresponding to each failure mechanism, we refer to the application guide of the accelerated life test for semiconductor devices [3] issued by the Japan Electronics and Information Technology

Table 2  Failure mechanism and acceleration model formula for individual electronic components [3]

| Electronic component         | Failure mechanism          | Acceleration model formula                                                                 |
|------------------------------|----------------------------|--------------------------------------------------------------------------------------------|
| Aluminum electrolytic capacitor | Evaporation of electrolyte | $AF = \left( \frac{T_a - T_i}{10} \right)^n$                                               |
| IC                           | Electromigration           | $AF_{EM} = \left( \frac{1}{T_1} \right)^n \exp \left[ \frac{E_a}{k} \left( \frac{1}{T_1} - \frac{1}{T_f} \right) \right]$ |
|                               | Time Dependent             | $AF_{TDDB-\text{Dielectric Breakdown}} = \exp \left[ \frac{E_a}{k} \frac{T_1 - T_0}{T_1 - T_f} - \gamma (E_{\text{ext}} - E_{\text{ox}}) \right]$ |
|                               | Sealing resin moisture      | $AF_{VF} = \left( \frac{E_a}{k} \frac{T_1 - T_0}{T_1 - T_f} \right)^n$                   |
|                               | Sealing resin crack        | $AF_{ST} = \left( \frac{\Delta T_1}{\Delta T_f} \right)^n$                                |

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industries association (jeita). in the acceleration model formula, subscript 1 indicates operating environment conditions, 2 indicates test environment condition, $AF$ is the acceleration coefficient, $k$ is the boltzmann constant, $E_a$ is the activation energy, $T$ is the absolute temperature, and $J$ is the operating current density. $E_o$ is the electric field in the oxide film, $V_p$ is the absolute water vapor pressure, $RH$ is relative humidity, $\Delta T$ is the temperature difference, and $n, \gamma$ are the electric fields, current densities, and other factors’ acceleration parameters.

in evaluating the lifetime of electronic components, the acceleration coefficient $AF$ according to the operational environment is obtained based on the acceleration model formula of the failure mechanism and the test environment conditions of the reliability test, as in the lifetime evaluation method of the electronic interlocking device [1]. from the reliability test data and the acceleration coefficient, we determine a guaranteed range based on the required reliability level. By assuming the worst failure distribution of failure mechanisms of the extracted electronic component, we evaluate a lifetime for any cumulative failure probability.

4.2 Evaluating the lifetime of solder joints

the flow chart for solder joint evaluation in fig. 4, identifies stress factors in the operational environment, and then an accelerated test reproducing the failure mechanism corresponding to the stress factors can be carried out. By applying the acceleration test results and operational environment conditions to the acceleration model formula for the failure mechanism, the lifetime of solder joint is evaluated. Since the arrangement of the electronic components and the device mounting method on the board differs by type of electronic device in the wayside signalling system, it is necessary to carry out an accelerated test for each piece of equipment.

4.2.1 Understanding stress factors on solder joints

solder cracks are assumed to be the main failure mechanism of solder joints that affect equipment function, based on the results of the failure survey and the survey of removed products from the operational environment. Possible causes of solder cracks are thermal stress such as temperature change and mechanical stress such as vibration. Vibration measurements from the operational environment, confirmed that vibration acceleration applied to electronic devices on a general wayside environment is below the jis e 3014 reference value. Therefore, it can be said that thermal stress has a greater effect.

4.2.2 Accelerated tests on solder joints

from the examination in the previous section, it is considered that solder cracks can be reproduced by conducting a temperature cycle test as an accelerated test. The lifetime can be calculated by taking the number of cycles required for solder cracks to occur in the accelerated test, and converting this to an actual failure time under operational environment conditions.

4.2.3 Evaluation of the lifetime based on accelerated test results

since eutectic solder is used in signalling electronic devices, the modified coffin-manson model [4] shown in (1) is applied as an acceleration model equation for solder cracks caused by thermal deterioration. In (1), subscript 1 indicates the operating environment condition, 2 indicates the test environment condition, $f$ indicates the number of temperature cycles per day, $\Delta T$ indicates the temperature difference during the temperature cycle, and $T_{max}$ indicates the maximum temperature, activation energy $E_o$ is 0.123 eV, Boltzmann coefficient $k$ is 8.62 × 10^{-5} eV/K, frequency parameter $m$ is 1/3, material stress parameter $n$ is 1.9. As shown in (1), the number of temperature cycles in the accelerated test can be converted to actual time in the operational environment by inputting the thermal environmental conditions such as the maximum temperature and the temperature difference.

$$AF = \left( \frac{f_1}{f_2} \right)^m \left( \frac{\Delta T_1}{\Delta T_2} \right)^n \exp \left( \frac{E_o}{k} \left( \frac{T_{max}}{T_{max}} - 1 \right) \right)$$

5. Examination by case study

This section reports on a case study which applied the evaluation method for electronic devices in wayside signalling systems, shown in the previous chapter. A train detector for a level crossing product widely used in Japan, was selected as the test-piece. The electronic component evaluation and solder joint evaluation were carried out separately, and the lifetime of the entire electronic device was
calculated by merging the results. In this case study, the results of measuring the temperature and humidity inside the trackside cabinet in Tokyo were used as the operational environment conditions. Table 3 shows the temperature / humidity environment profile with the seasons which are the necessary conditions extracted from the operational environment survey.

5.1 Evaluated lifetime of electronic components

Among the electronic components constituting the test electronic device, ICs, 3-terminal regulators, aluminum electrolytic capacitors, etc. were extracted as the components that would most affect overall function if they failed. Those components were also considered to have a limited lifetime or generate a large amount of heat when switched on. For the extracted components, we identified the possible failure mechanisms that could occur due to the assumed stress factors in the operational environment. The relationship between the cumulative failure probability and lifetime was calculated based on the acceleration model formula and the obtained reliability test data of each electronic component. For each extracted component, the lifetime when the cumulative failure probability reached 1% (B1 Lifetime) was calculated and is shown in Table 4. As a result, the electronic component with the shortest B1 Lifetime in the operational environment in Tokyo was the IC for the CPU. The evaluated lifetime (B1 Lifetime) was 29.5 years with the shielding plate and 27.5 years without the shielding plate. The effect of solar radiation differs depending on with or without the shielding plate. The difference in the evaluated lifetime was attributed to the gap between maximum and daily temperatures. The evaluated lifetime of aluminum electrolytic capacitors shown in Table 4 was the B1 Lifetime for the failure mechanism linked to evaporation of electrolytes. However, since the manufacturer’s warranty for the failure mechanism of the sealing rubber is generally about 15 years, this component should also be carefully considered when considering replacement of components.

5.2 Evaluated lifetime of solder joints

In order to reproduce the solder cracks caused by thermal deterioration, a new specimen was installed in a thermostatic chamber and a temperature cycle test was conducted with the electronic device power on. The temperature cycle setting conditions for the thermostatic chamber were set in the range of -25 - 62°C in 3 cycles per day so that the substrate temperature would follow within the manufacturer’s guaranteed range (-20 - 60°C). Figure 5 shows the actual image of the experiment, and Fig. 6 shows the temperature cycle setting conditions of the thermostatic chamber.

An accelerated test was conducted until a total number of 600 cycles were applied to the electronic equipment. Every 100 cycles, the appearance of the solder joint was observed with a microscope, and the manufacturer conducted a functional test equivalent to the pre-shipment inspection. In addition, solder cross-section observations were conducted for product after 500 and 600 cycles, respectively. We extracted electronic components which were susceptible to solder cracks to determine the appearance and cross-section observation points. The selected parts were those with a large difference in thermal expansion coefficient between

| Electronic component          | Failure mechanism                  | B1 Lifetime [years] | With | Without |
|------------------------------|-----------------------------------|--------------------|------|---------|
| 1C (for CPU)                 | Electromigration                  | 29.5               | 27.5 |         |
|                              | Time Dependent Dielectric Breakdown | 29.5               | 27.5 |         |
|                              | Sealing resin moisture resistance (shortest) | 35.1 | 32.7 | |
|                              | Joint / sealing resin crack        | 1015.5             | 178.2|         |
| 3-terminal regulators        | Electromigration                  | 45.9               | 42.9 |         |
|                              | Time Dependent Dielectric Breakdown | 45.9               | 42.9 |         |
|                              | Sealing resin moisture resistance (shortest) | 84.3 | 80.3 | |
|                              | Joint / sealing resin crack        | 1309.7             | 229.8|         |
| Aluminum electrolytic capacitors | Evaporation of electrolyte        | 72.7               | 68.9 |         |
the substrate and the components, the parts with a large amount of heat generation and the parts which are easily stressed on the substrate.

Observations confirmed discoloration of the flux and roughness of the solder surface, but revealed no solder cracks reaching the surface. It was also confirmed that there were no problems in functional inspection up to 600 cycles. In the cross-sectional observation, solder cracks were confirmed at several selected points. In all cases, roughening of the solder particles was confirmed, and deterioration due to thermal stress was observed. Figure 7 shows the actual image of solder cracks at the same observation point for 500 and 600 cycles. It is considered that once a crack occurs, it progresses rapidly, therefore, in this paper, the lifetime was set to when the crack reached about half the solder thickness, in other words, 500 cycles was considered to be the lifetime.

The 500 cycles of the accelerated test were converted into actual time in the environment profile shown in Table 3 using (1). Since the number of cycles in the operational environment is once a day, the 500 cycles of the accelerated test are equivalent to 41 years in the trackside cabinet with the shielding plate and 17 years without the shielding plate.

It is considered that once a crack occurs, even if the vibration acceleration is below the JIS reference values, the vibration easily affects the electronic devices. Therefore, it should be noted that the combined stress of thermal and mechanical factors in the operational environment can accelerate deterioration and shorten the lifetime.

5.3 Evaluated lifetime of entire electronic devices in wayside signalling systems

We summarize the results of the electronic component evaluation and the solder joint evaluation in Table 5. By merging the two evaluations, it is assumed that the shortest number of years is the lifetime for the entire electronic device.

Therefore, it is considered that the evaluated lifetime in the case study with the environment profile shown in Table 3 was 29.5 years (the lifetime of the IC for the CPU) with the shielding plate, and 17 years (the lifetime of the solder joint) without the shielding plate. This confirmed that the evaluated lifetime differs depending on the operational environment conditions such as with/without shielding plate based on the result of the case study. Figure 8 shows the evaluated lifetime transition when the average temperature is changed based on the environment profile in Tokyo shown in Table 3. It was found that the evaluated lifetime of the electronic component evaluation (B1 Lifetime) was affected by the average temperature and the evaluated lifetime of the solder joint evaluation (equivalent to 500 cycles of the accelerated test) is affected by the temperature difference depending on the presence or absence of a shielding plate.

From the above, the evaluated lifetime of electronic devices in wayside signalling systems depends on operational environment conditions (temperature conditions in the installation location and presence/absence of a shielding plate, etc.). Therefore, replacement intervals should be determined considering the installation environment.

6. Conclusion

We have developed a lifetime evaluation method focusing on the wear-out failure period for electronic devices in wayside signalling systems installed outside.

It was assumed that trackside electronic devices were exposed to more severe environmental conditions than electronic interlocking devices installed indoors. Therefore, we investigated real operational conditions, to determine a set of assumed stress factors. This confirmed that thermal factors such as temperature changes were the main source of stress affecting the lifetime of the electronic devices. It was also confirmed that the thermal environment of trackside electronic devices differed depending on real conditions such as the installation place and the type of trackside cabinet.

We proposed an evaluation method that comprehensively evaluates the lifetime of electronic devices by evaluating solder joints, in addition to the evaluation of individual electronic components based on a previously developed lifetime evaluation method for electronic interlocking devices.

Table 5 Results of the evaluated lifetime in the case study

| Trackside cabinet condition | Electronic component evaluation | Solder joint evaluation | Comprehensive evaluation |
|----------------------------|---------------------------------|-------------------------|--------------------------|
| With shielding plate       | 29.5 years                      | 41 years                | 29.5 years               |
| Without shielding plate    | 27.5 years                      | 17 years                | 17 years                 |

Fig. 7 The state of the solder cracks

Fig. 8 Relationship between average temperature and evaluated lifetime
devices. The developed method can evaluate the lifetime in the light of operational environments, and can therefore be used to inform the definition of replacement intervals, taking into account real installation conditions.

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