HEWLETT hp PACKARD

COMPONENTS

APPLICATION NOTE 1002

Consideration of CTR Variations in Optically Coupled Isolator Circuit Designs

INTRODUCTION – Optocouplers Aging Problem

A persistent, and sometimes crucial, concern of designers using optocouplers is that of the current transfer ratio, CTR, changing with time. The CTR is defined as the ratio of the output current, I_O, of the optocoupler divided by the input current, I_F, to the light emitting diode expressed as a percentage value at a specified input current. The resulting optocoupler's gain change, ΔCTR^{+}, with time is referred to as CTR degradation. This change, or degradation, must be accounted for if long, functional lifetime of a system is to be guaranteed.

A number of different sources for this degradation will be explained in the next section, but numerous studies have demonstrated that the predominant factor for degradation is reduction of the total photon flux being emitted from the LED, which, in turn, reduces the device's CTR. This degradation occurs to some extent in all optocouplers.

$$^{+}\Delta CTR = CTR_{final} - CTR_{initial} \tag{1}$$

Causes

The main cause for CTR degradation is the reduction in efficiency of the light emitting diode within the optocoupler. Its quantum efficiency, η, defined as the total photons per electron of input current, decreases with time at a constant current. The LED current is comprised primarily of two components, a diffusion current component, and a space-charge recombination current:

$$I_F(V_F) = \underbrace{A\,e^{qV_F/kT}}_{\text{Diffusion}} + \underbrace{B\,e^{qV_F/2kT}}_{\text{Space-Charge Recombination}} \tag{2}$$

where A and B are independent of V_F, q is electron charge, k is Boltzmann's constant, T is temperature in degrees Kelvin, and V_F is the forward voltage across the light emitting diode.

The diffusion current component is the important radiative current and the non-radiative current is the space-charge recombination current. Over time, at fixed V_F, the total current increases through an increase in the value of B. From another point of view, with fixed total current, if the space-charge recombination current increases, due to an increase in the value of B, then the diffusion current, the radiative component, will decrease. The specific reasons for this increase in the space-charge recombination current component with time are not fully understood.

The reduction in light output through an increase in the proportion of recombination current at a specific I_F is due to both the junction current density, J, and junction temperature, T_J. In any particular optocoupler, the emitter current density will be a function of not only the required current necessary to produce the desired output, but also of the junction geometry and of the resistivity of both the P and N regions of the diode. For this reason, it is important not to operate a coupler at a current in excess of the manufacturer's maximum ratings. The junction temperature is a function of the coupler packaging, power dissipation and ambient temperature. As with current density, high T_J will promote a more rapid increase in the proportion of recombination current.

The junction and IC detector temperature of Hewlett-Packard optocouplers can be calculated from the following expressions:

$$T_J = T_A + \theta_{JA}(V_F I_F) + \theta_{D\text{-}E}(V_o I_o + V_{cc} I_{cc})$$

$$T_D = T_A + \theta_{E\text{-}D}(V_F I_F) + \theta_{DA}(V_o I_o + V_{cc} I_{cc}) \tag{3}$$

where the T_J is the junction temperature of the LED emitter, T_D is the junction temperature of the detector IC, T_A is ambient temperature, and the thermal resistances are the emitter junction to ambient, $\theta_{JA} = 370°C/W = \theta_{DA}$ detector to ambient, and the detector to emitter thermal resistance is $\theta_{D\text{-}E} = 170°C/W = \theta_{E\text{-}D}$. V_F, I_F are the forward LED voltage and current; V_o, I_o are the output stage voltage, and current and V_{cc}, I_{cc} are the power supply voltage and current to the device. In general, it is desirable to maintain $T_J \leqslant 125°C$.

A useful model can be constructed to describe the basic optocoupler's parameters which are capable of influencing the current transfer ratio. The 6N135 optocoupler, Figure 1 is the simplest device and one which is easily accessible for needed parameter measurements. However, any optocoupler can be modeled in this fashion within its linear region. Figure 1 shows the system block diagram which yields the relationship of input current, I_F, to output current, I_o. The resulting expression for CTR is:

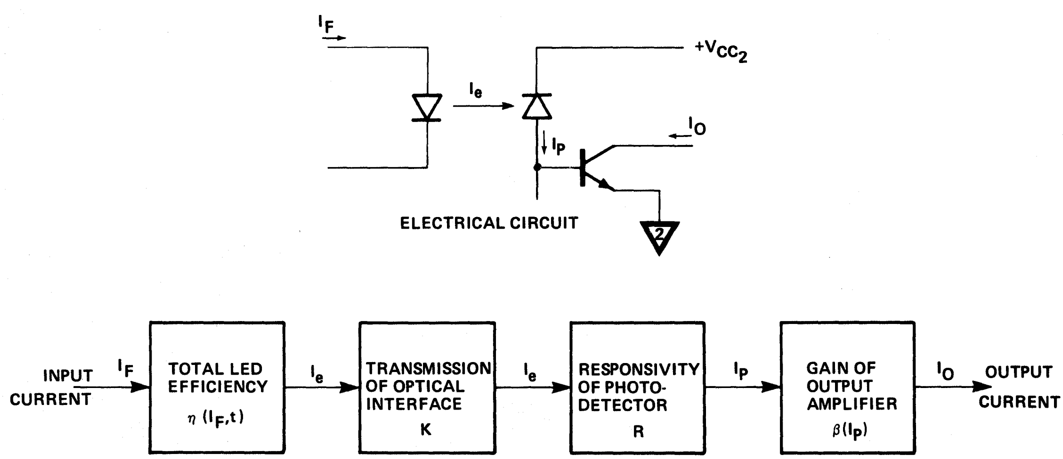
$$\text{CTR} = \frac{I_o}{I_F}(100\%) = K\,R\,\eta(I_F,t)\,\beta(I_P,t) \qquad (4)$$

where K represents the total transmission factor of the optical path, generally considered a constant as is R, the responsivity of the photodetector, defined in terms of electrons of photocurrent per photon. η is the quantum efficiency of the emitter defined as the photons emitted per electron of input current and depends upon the level of input current, I_F, and upon time. Finally, β is the gain of the output amplifier and is dependent upon I_P, the photocurrent, and time. Temperature variations would, of course, cause changes in η, β as well.

From Equation (4), a normalized change in CTR, at constant I_F, can be expressed as:

$$\frac{\Delta \text{CTR}}{\text{CTR}} = \left(\frac{\Delta\eta}{\eta}\right)_{I_F} + \left(\frac{\Delta\eta}{\eta}\right)_{I_F}\left(\frac{\partial \ln\beta}{\partial \ln I_P}\right)_t + \left(\frac{\Delta\beta}{\beta}\right)_{I_P} \qquad (5)$$

The first term, $\Delta\eta/\eta$, represents the major contribution to ΔCTR due to the relative emitter efficiency change; generally, over time, $\Delta\eta$ is negative. This change is strongly related to the input current level, I_F, as discussed earlier and more elaboration will be given later. The second term, $(\Delta\eta/\eta)_{I_F}\ (\partial\ln\beta/\partial\ln I_P)_t$, represents a second order effect of a shift, positive or negative, in the operating point of the output amplifier as the emitter efficiency changes. The third term, $(\Delta\beta/\beta)_{I_P}$, is a generally negligible effect which represents a positive or negative change in the output transistor gain over time. The parameters K and R are considered constants in this model.



$$\therefore I_O = I_F\,\eta\,(I_F,t)\,K\,R\,\beta\,(I_P)$$

Figure 1. System Model for an Optocoupler

Degradation Model

In this section, an extensive test program conducted at Hewlett-Packard to characterize the CTR degradation of optocouplers is discussed. The development which will follow is mainly of interest to those concerned with reliability and quality assurance. From the basic data, the CTR degradation equations will be developed in order to predict the percentage change in CTR with time. Complete data and analysis of CTR degradation will be found in an internal Hewlett-Packard report.

This study is based on a total of 640 optocouplers of the 6N135 type (Figure 1) with 700 nm $GaAs_{.7}P_{.3}$ LEDs from twenty different epitaxial growth lots representing a range of n-type doping and radiance. The 6N135 allows access to measurement of the emitter degradation via the relative percentage change in photodiode current, $\Delta I_P/I_P$, as well as output amplifier β change. Stress currents of I_{FS} = .6, 7.5, 25 and 40 mA were applied to different groups of optocouplers, and at each measurement time of t = 0, 24, 168, 1000, 2000, 4000 and 10,000 hours, measurement currents of I_{FM} = .5, 1.6, 7.5, 25 and 40 mA were used to determine the CTR.

The important results to be noted are the following. First, a factor of major significance in the study of CTR degradation is the ΔCTR varies as a function of the ratio of $I_{FS}/I_{FM} \equiv R$. Large values of R will result in greater CTR degradation than at lower R values with the same magnitude of I_{FS}. However, knowledge of the ratio of I_{FS}/I_{FM} alone does not give a complete picture of degradation because ΔCTR is also dependent upon the absolute magnitude of the stress current, $|I_{FS}|$. The following data will allow the derivation of the necessary equations with which to predict ΔCTR as a function of I_{FS}, I_{FM} and time.

Figure 2 displays the mean and mean plus 2σ values of emitter degradation versus R for 1K, 4K, and 10K hours at 25°C. Accelerated degradation can be seen at larger R values.

The data of Figure 2 can be replotted to illustrate the percentage degradation versus time as a function of R. Figure 3 illustrates the mean and mean plus 2σ distribution with R = 1 and 50.

From this curve, a useful expression which relates the average degradation in emitter efficiency to time is obtained for the mean or mean plus 2σ distributions. [The symbol "D" will refer to CTR degradation due solely to emitter degradation, $\Delta\eta/\eta$, whereas ΔCTR/CTR will refer to total CTR degradation as expressed in Equation (5)].

$$D_{\bar{x}} \text{ or } D_{\bar{x}+2\sigma} \equiv \frac{-\Delta I_P}{I_P} = A_o R^{\alpha} t^{n(R)} \quad \text{for } I_{FS} = \bar{I}_{FS} \text{ in \%} \tag{6}$$

where t is in 10^3 hours and A_o and α differ for mean or mean plus 2σ. Equation (6) represents an average degradation corresponding to a specific R, t, and an average stress current $\bar{I}_{FS}$. A knowledge of $\bar{I}_{FS}$ and the actual device operating stress I_{FS} can be utilized to correct D to reflect the absolute magnitude of I_{FS}. This will be shown in the development of Equations (11) and (13). The data shows that $\bar{I}_{FS}$ increases with R and can be represented as follows:

$$\bar{I}_{FS}(R) = 14.13 + 9.06 \log_{10} R \quad , \; T_A = 25°C \tag{7}$$

$$\bar{I}_{FS}(R) = 10.5 + 5.76 \log_{10} R \quad , \; T_A = 85°C \tag{8}$$

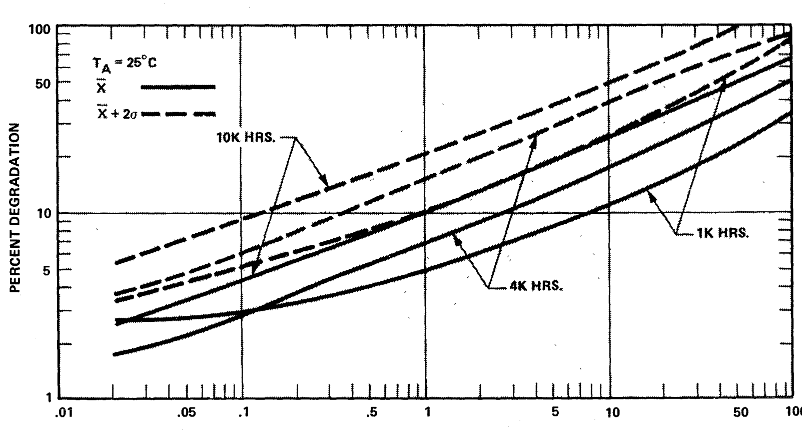


Figure 2. Emitter Degradation vs. R (Ratio of Stress Current to Measurement Current) for 1k, 4k, and 10k Hours, Mean, Mean +2σ Distribution, T_A = 25°C.

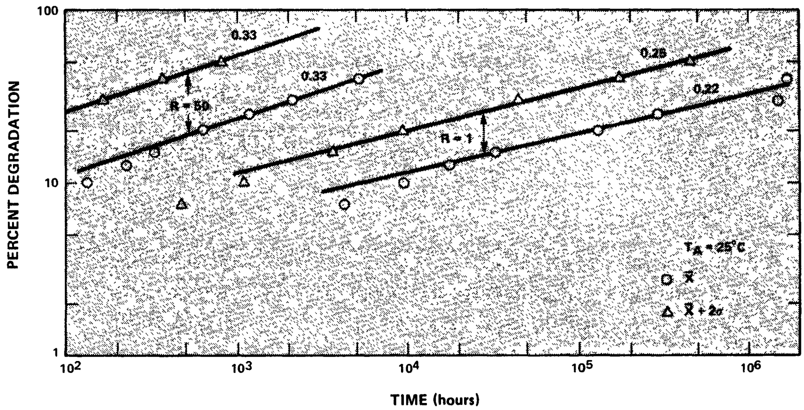


Figure 3. Degradation vs. Time at R = 1 and R = 50 for Mean, Mean + 2σ Distributions, T_A = 25°C.

These equations are obtained from averaged degradation data versus I_{FS} at different measurement times.

The expression for n(R) was found to obey the relationship

$$n(R) = .0475 \log_{10} R + .25 \qquad (9)$$

A_o and α were determined from degradation data versus R and are found in Figure 7, "Matrix of Coefficients."

Equation (6) gives a direct relationship between the average degradation, $\bar{D}$, and time. As mentioned earlier, the magnitude of the stress current also determines the amount of degradation. In order to allow for the effect of $|I_{FS}|$, empirical observations were made on D at different I_{FS} and at different times for several values of R. The dependence of degradation on stress current is linear up to I_{FS} = 40 mA, for all values of R. From these observations, the average rate of change, or slope, S(R,t), of degradation D with I_{FS} over time was found to behave in the following fashion for any R:

$$S \equiv \frac{\partial D}{\partial I_{FS}} = \alpha(R) \log_{10} t + \beta(R) \quad \%/\text{mA} \qquad (10)$$

where t is in 10^3 hours, the coefficients $\alpha(R)$ and $\beta(R)$ can be found on Figure 7.

Along with Equation (10), the mean distribution degradation, $D_{\bar{x}}$, can be estimated for any specific stress current, I_{FS}, ratio R, and time t via the subsequent expression:

$$D_{\bar{x}} = \bar{D}_{\bar{x}} + S\,[I_{FS} - \bar{I}_{FS}] \quad \% \qquad (11)$$

or substituting Equation (6),

$$D_{\bar{x}} = A_o R^{\alpha} t^{n(R)} + S\,[I_{FS} - \bar{I}_{FS}] \quad \% \qquad (12)$$

where, again, $D_{\bar{x}}$ is the average degradation at time t, in units of 10^3 hours, corresponding to a stress current, $\bar{I}_{FS}$, given by Equations (7) and (8); I_{FS} is the actual stress current and $R = I_{FS}/I_{FM}$; S is the expression (10) for the change of slope of D versus I_{FS} with time; n(R) is a power of t, given by Equation (9), and A_o,α are found in Figure 7.

Equation (12) gives the mean distribution degradation by using a degradation value, $\bar{D}$ (first term), corresponding to the ratio of I_{FS}/I_{FM}, or a stress current, $\bar{I}_{FS}$, and then applying a correction quantity (second term) to $\bar{D}$ due to the magnitude of the actual stress current, I_{FS}, yielding the actual degradation D.

The expression for the mean + 2σ distribution degradation, $D_{\bar{x}+2\sigma}$, (worst case) is almost of the same form as Equation (12). The dissimilarity arises from the fact that the standard deviation, σ, is dependent upon the stress current, I_{FS}, the ratio R, and upon time. This complex dependency was analytically deduced from the data to be the following expression:

$$D_{\bar{x}+2\sigma} = \bar{D}_{\bar{x}+2\sigma} + [S + 2P]\,[I_{FS} - \bar{I}_{FS}] \quad \% \qquad (13)$$

or substituting Equation (6)

$$D_{\bar{x}+2\sigma} = A_o R^{\alpha} t^{n(R)} + [S + 2P]\,[I_{FS} - \bar{I}_{FS}] \qquad (14)$$

where $D_{\bar{x}+2\sigma}$ is the degradation for $\bar{x}$ + 2σ distribution corresponding to the stress current $\bar{I}_{FS}$, Equations (7) and (8). A_0 and α are found in Figure 7 under the $\overline{X}+2\sigma$ category. S [Equation (10)] represents the slope to correct for actual I_{FS} versus $\overline{I}_{FS}$ current levels, and P [Equation (15)] is the new term which is a slope to correct for the α variation with I_{FS}, R and t. The coefficients $\gamma(R)$, $\delta(R)$ in P are found in Figure 7.

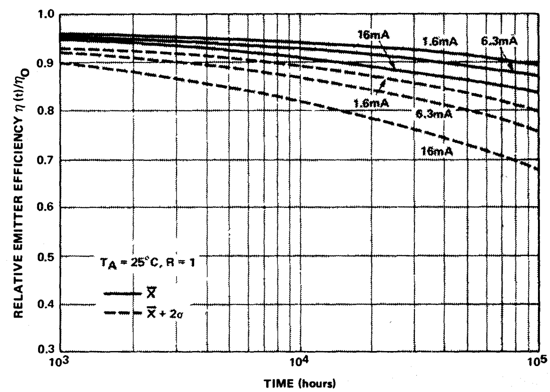
$$P = \gamma(R)\log_{10}t + \delta(R) \quad \%/mA \tag{15}$$

where t is in 10^3 hours.

The degradation Equations (11) and (13) are considered accurate for the ranges of $I_{FS} \leqslant 40$ mA and $R \leqslant 20$; outside this range, the model does not predict degradation as well. Hence, check to see if I_{FS} and R satisfy the above conditions. If I_{FS} or R exceed these limits, predition of D will be, in general, greater than the actual degradation due to large values for S and P which do not reflect actual S and P. If $\overline{I}_{FS}$ is approximately equal to the actual I_{FS}, then the second term in the degradation equations need not be determined. Otherwise, the second term needs to be determined to obtain true emitter degradation, D. If $\overline{I}_{FS} < \overline{I}_{FS}$, then the degradation, D, will be less than the degradation, $\overline{D}$, corresponding to $\overline{I}_{FS}$, and vice versa when $\overline{I}_{FS} > \overline{I}_{FS}$. A quick and coarse estimate for degradation $\overline{D}$ can be obtained by using $\overline{D} = A_0 R^{\alpha} t^{n(R)}$ for a specific R with approximate values for $\alpha \approx 0.4$ and $n \approx 0.3$. Figure 4 represents plots of Equations (11) and (13) for R = 1 and I_{FS} = 1.6, 6.3, and 16mA at both T_A = 25°C and T_A = 85°C. These plots are very useful in making a quick approximation of D for the specific conditions for which the plots have been made. These conditions represent the recommended operating conditions for the three HP optocoupler families.

This discussion of reliability data and its interpretation with model equations is qualified to specific optocouplers, 6N135 and 6N138, where continuous LED operation was maintained, and extrapolation of data for times beyond 10,000 hours is assumed to be valid. Different types of LEDs or preparation processes may produce different results than those presented in this section. These expressions only incorporate the first order effect, emitter degradation $\Delta\eta/\eta$, whereas comments about higher order effects upon total CTR degradation will be given in the following section. With these expressions for degradation, accelerated testing may be accomplished by employing large values of R. Such testing can provide a means by which to determine acceptable emitter lots for optocoupler fabrication, acceptable degradation performed for lot selection, or predict functional lifetime expectance for optocouplers under specific operational conditions.

An important point to note is that the total operational life of an optocoupler is greater than the worst case mean plus 2σ distribution implies. Specifically, the worst case degradation given in Figures 4a (25°C) and 4b (85°C) are for the continuous operation of the 6N135 optocoupler. The actual lifetime for an optocoupler is greater than Figures 4a and 4b would indicate since the majority of units will be centered around the mean distribution lifetime. Secondly, the optocoupler which is operated at some signal duty factor less than 100%, for example 50%, would increase the optocoupler's life by a factor of two. Third, the fact that an optocoupler is used within equipment which may have a typical 2000 hours per year (8 hours/day – 5 days/week – 50 weeks/year) instrument or system operating time, could expect to increase the optocoupler's life by another factor of 4.4 in terms of years of useful life.



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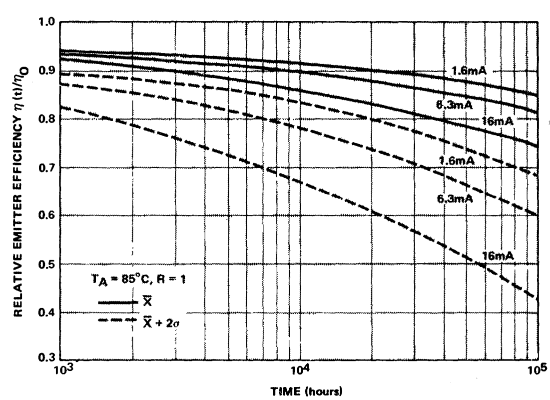


b

Figure 4. Calculated Curves of Relative Emitter Efficiency vs. Time for P = 1: $I_{FS} = I_{FM}$ = 1.6, 6.3, and 16mA which are Recommended I_F for 6N138, 6N137, and 6N135 Optocouplers Respectively. Mean, Mean + 2σ Distributions. a) T_A = 25°C, b) T_A = 85°C.

The appropriate operating time considerations will vary depending upon the designer's knowledge of the system in which the optocoupler will be used. The operating lifetime of an optocoupler can be expressed, for a maximum allowable degradation at a particular I_{FS}, by using Figures 4a and 4b for $t_{\text{continuous lifetime}}$ and the following expression:

$$t_{\substack{\text{continuous}\\ \text{lifetime}}} = \left[\begin{matrix} t_{\text{system}} \\ \text{lifetime} \end{matrix}\right] \left[\begin{matrix} \text{Data Duty} \\ \text{Factor} \end{matrix}\right] \left[\begin{matrix} \text{System Use} \\ \text{Data Factor} \end{matrix}\right] \qquad (16)$$

Another equally important point to observe is that of the worst case conditions under which the optocoupler is used. As will be illustrated in the design examples, the worst possible combination of variations in V_{cc1}, V_{cc2}, R_{in}, CTR, R_L, I_{IL}, and temperature still result in the optocoupler functioning over an extended length of time (10^5 hours) for a particular maximum allowable degradation. However, the likelihood of seven parameters all deviating in their worst directions at the same time is extremely remote. A thorough statistical error accumulation analysis would illustrate that this worst-worst case is not a representative situation from which to design.

Higher Order Effects

The first order effect of emitter degradation, $\Delta\eta/\eta$, has a pronounced influence upon the ΔCTR as explained in the previous sections; however, consideration of higher order effects is important as well.

Consider the second term in Equation (5) $(\Delta\eta/\eta)I_F$ $(\partial \ln\beta/\partial \ln I_P)_t$, the emitter degradation part has been explained; however, $(\partial \ln\beta/\partial \ln I_P)_t$ represents a shift in the operating point of the output amplifier of an optocoupler. The term $(\partial \ln\beta/\partial \ln I_P)$ can be rewritten as $(1/2.3\beta)(\partial\beta/\partial \log_{10} I_P)$ which is more convenient to use with the accompanying typical curves of β versus $\log_{10} I_P$ for the two optocouplers 6N135 and 6N138, given in Figure 5a.

If the operating photocurrent, I_P, is to the right of the maximum β point of either curve, then with reduced emitter efficiency over time, I_P will decrease, but the increasing β will tend to compensate for this degradation. However, if the operating I_P is to the left of the maximum β and then I_P decreases, the β change will accentuate the emitter's degradation, yielding a larger CTR loss. The magnitude of the contributions of $\partial \ln\beta/\partial \ln I_P$ to overall CTR degradation can be illustrated by the following examples.

Consider a 6N138 optocoupler of Figure 5c operating at its recommended I_F = 1.6 mA which corresponds to an $I_P \approx 1.6\mu A$. (An I_F to I_P relationship for Hewlett-Packard optocouplers is 1 mA input current yields approximately $1\mu A$ of photodiode current.) At $I_P = 1.6\mu A$, the slope of the V_{CE} = 5V curve is equal to -15,000 and the gain is β = 26,000; hence, $\partial \ln\beta/\partial \ln I_P \approx -0.25$. If, for instance, the emitter degradation $\Delta\eta/\eta$ is -10%, then the second order term would improve the overall CTR degradation, i.e.,

$$\frac{\Delta \text{CTR}}{\text{CTR}} = \left(\frac{\Delta\eta}{\eta}\right) + \left(\frac{\Delta\eta}{\eta}\right)\left(\frac{\partial \ln\beta}{\partial \ln I_P}\right) + \ldots = -10\% + 2.5\% = -7.5\% \qquad (17)$$

This improvement is what was expected while operating on the right side of the β maximum. In fact, with an I_F = 4 mA or $I_P \approx 4\mu A$, the term $\partial \ln\beta/\partial \ln I_P$ = -0.8, and again, if $\Delta\eta/\eta$ = -10%, the resulting ΔCTR/CTR = -2%, nearly cancelling the emitter's degradation.

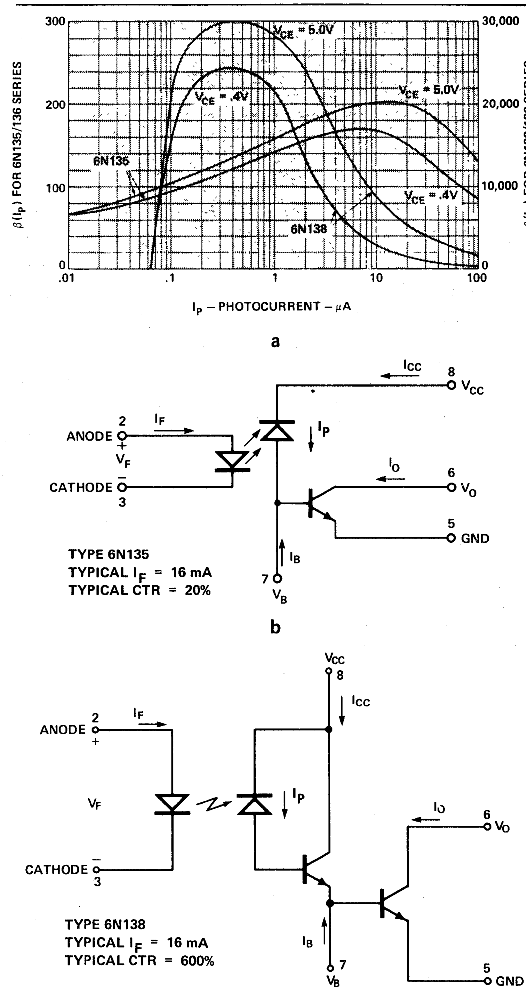
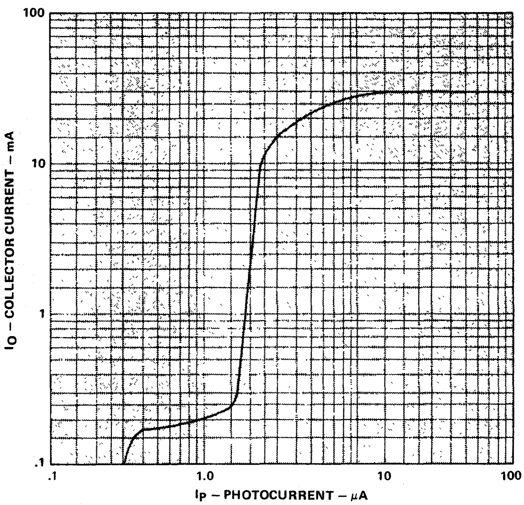


Figure 5. a) DC Current Gain, β, vs. Photocurrent, Ip, for 6N135 and 6N138 Optocouplers. Current Diagrams and Typical Values of I_F and CTR for Hewlett-Packard Optocouplers, b) 6N135, c) 6N138.

With the 6N135 optocoupler, Figure 5b operating at $I_F = 10$ mA, or $I_P \approx 10\mu A$, which corresponds to the maximum β point on the $V_{CE} = .4V$ curve, the slope is zero and the total CTR degradation is basically the emitter's degradation.

Another subtle effect is seen from the third term in Equation (5), $(\Delta\beta/\beta)I_P$, over time. At constant I_P, β can increase or decrease by a few percent over 10,000 hours. This change is so small that the third term is generally neglected.



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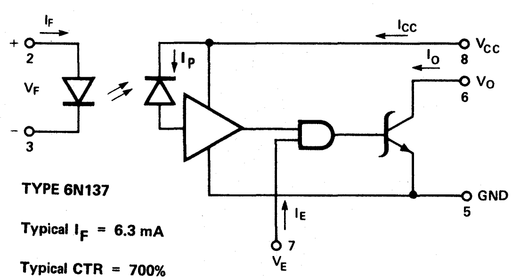

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Figure 6. a) Output Current, I_O, vs. Photocurrent, I_P, for 6N137 Optocoupler.
b) Circuit Diagram and Typical Values of I_F and CTR for 6N137 Optocoupler.

For the optocouplers containing an output amplifier, such as the 6N137, which switches abruptly about a particular threshold input current, the actual emitter degradation can be determined from Equations (11) and (13). An appropriate $I_{F_{initial}}$ can be determined to provide for adequate guard band current which will allow the optocoupler emitter to degrade while maintaining sufficient I_P to switch the amplifier. An actual design procedure to determine the needed $I_{F_{initial}}$ for proper operation of Hewlett-Packard optocouplers is given in the design examples section.

MATRIX OF COEFFICIENTS

	25°C		85°C			
	$\bar{X}$	$\bar{X} + 2\sigma$	$\bar{X}$		$\bar{X} + 2\sigma$	
			R<6	6≤R	R<8	8≤R
A_o	4.95	9.7	6.8	5.0	15.0	11.0
α	.388	.428	.302	.467	.284	.430
	25°C		85°C			
	R≤1	R≥1	R≤1		R≥1	
$\alpha(R)$	$.19\ R^{.052}$	$.19\ R^{.32}$	$.32\ R^{.08}$		$.32\ R^{.30}$	
$\beta(R)$	.055	$.055\ R^{.68}$	$.11\ R^{.25}$		$.11\ R^{.65}$	
	25°C		85°C			
$\gamma(R)$	$.063\ R^{.30}$		$.154\ R^{.26}$			
$\delta(R)$	$.081\ R^{.38}$		$.196\ R^{.39}$			

Figure 7. Matrix of Coefficients.

Procedure for Calculation of CTR Degradation

1. Specify I_{FS}, I_{FM}

2. Determine $\left.\begin{array}{l} R = I_{FS}/I_{FM} \leqslant 20 \\ I_{FS} \leqslant 40 \text{ mA} \end{array}\right\}$ Degradation Model Equations (11) and (13) Valid

3. First Approximation of Degradation

$$D_{\bar{x}} \text{ or } D_{\bar{x}+2\sigma} = A_o R^{\alpha} t^{n} \quad (\%)$$

with $\alpha \approx .4$, A_o (Figure 7)
$n \approx .3$, t in 10^3 hours
(D corresponds to I_{FS})

4. Calculate $\bar{I}_{FS} = \begin{cases} 14.13 + 9.06 \log_{10} R \text{ @ } 25^\circ\text{C} & \text{Equation (7)} \\ 10.5 + 5.76 \log_{10} R \text{ @ } 85^\circ\text{C} & \text{Equation (8)} \end{cases}$

If $I_{FS} \approx I_{FS}$, Step 6 and the second terms in Equations (11) and (13) do not need to be calculated.

5. Calculate $n(R) = .0475 \log_{10} R + .25$

6. Calculate
$S = \alpha(R) \log_{10} t + \beta(R)$ — $\alpha(R), \beta(R)$ — Figure 7
$P = \gamma(R) \log_{10} t + \delta(R)$ — $\gamma(R), \delta(R)$ — t in 10^3 hours

7. Calculate Mean, Mean + 2σ Degradation

$$D_{\bar{x}} = A_o R^{\alpha} t^{n(R)} + S\,[I_{FS} - I_{FS}] \qquad \% \qquad \text{Equation (11)}$$

$$D_{\bar{x}+2\sigma} = A_o R^{\alpha} t^{n(R)} + [S + 2P]\,[I_{FS} - I_{FS}] \qquad \% \qquad \text{Equation (13)}$$

(A_o, α via Figure 7, t in 10^3 hours)

8 For Second Order Effect, Determine Slope

$$\frac{\partial \ln\beta}{\partial \ln I_P} = \frac{1}{2.3\beta}\,\frac{\partial\beta}{\partial \log_{10} I_P}$$

Figure 5a — typical curves with an approximation for HP optocouplers of $I_F = 1$ mA yields $I_P \approx 1\mu$A

9a. Total CTR Degradation for Mean Distribution

$$\frac{\Delta CTR}{CTR} = D_{\bar{x}} + D_{\bar{x}}\,\frac{\partial \ln\beta}{\partial \ln I_P}$$

9b. Total CTR Degradation for Mean + 2σ Distribution

$$\frac{\Delta CTR}{CTR} = D_{\bar{x}+2\sigma} + D_{\bar{x}+2\sigma}\,\frac{\partial \ln\beta}{\partial \ln I_P}$$

APPLICATION NOTES

Practical Application

A very common application of an optocoupler is to function as the interfacing element between digital logic. In this section, the designer will be shown an approach which will insure the initial and long term performance of such an interface, and take into account the practical aspects of the system that surrounds it. These system elements include the data rate, the logic families being interfaced, the variations of the power supply, the tolerances of the components used, the operational temperature range, and lastly the expected lifetime of the system.

The system data speed can be considered as the primary selection criteria for selecting a specific optocoupler family. Figure 9 lists the ranges of data rates for four Hewlett-Packard optocoupler families when driven at specified LED input current, I_F. With this table, and the knowledge of the system data rate requirements, it is possible to select an optimum coupler.

An example of an optocoupler interconnecting two logic gates is shown in Figure 8. A logic low level is insured when the saturated output sinking current, I_O, is greater than the combined sourcing currents of the pull-up resistor, and the logic low input current, I_{IL}, of the interconnecting gate. Using the coupler specifications selected from Figure 9 and the corresponding CTR (MIN) from Figure 10,

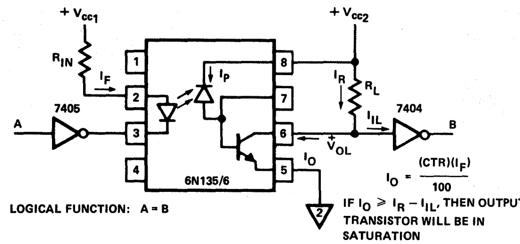


Figure 8. Typical Digital Interface Using an Optocoupler.

$$I_{F\,(MIN)} = \frac{V_{cc1\,(MIN)} - V_{F\,(MAX)} - V_{OL}}{R_{in\,(MAX)}} \tag{18}$$

$$I_{F\,(MAX)} = \frac{V_{cc1\,(MAX)} - V_{F\,(MIN)} - V_{OL}}{R_{in\,(MIN)}} \tag{19}$$

$$I_F = \frac{I_o \times 100}{CTR(MIN)} \tag{20}$$

$$R_{in} = \frac{V_{cc1} - V_F - V_{OL}}{I_F} \tag{21}$$

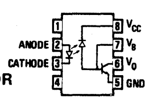
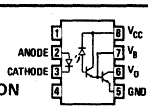
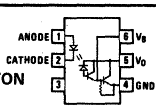
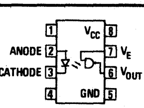
FAMILY	NRZ DATA RATE BITS/S	INPUT CURRENT – I_F						
		.5mA	1.0mA	1.6mA	7.5mA	10mA	12mA	16mA
6N135/6 SINGLE TRANSISTOR 	MIN							333k
	TYP							2M
6N138/9 SPLIT DARLINGTON 	MIN	12k		22k			125k	
	TYP	100k		200k			840k	
4N45/6 DARLINGTON 	MIN					1.8k		
	TYP		640			6.5k		
6N137 OPTICALLY COUPLED GATE 	MIN				6.7M			
	TYP				10M			

Figure 9. Figure 13.5-2. Optocoupler Data Rates Specifications.

FAMILY		% CTR @ I_F = (mA) .5	1.0	1.6	5	10	16	TEMP °C	V_{OL}
SINGLE TRANSISTOR	6N135						7	25	0.4
	6N136						19		
SPLIT DARLINGTON	6N138		300					0–70	0.4
	6N139	400	500					0–70	0.4
DARLINGTON	4N45		250			200		0–70	1.0
	4N46	350	500			200		0–70	1.0
OPTICALLY COUPLED GATE	6N137				400			0–70	0.6

Figure 10. Optocoupler CTR (MIN).

it is possible to determine from Equation (20) the minimum initial value of I_F for the coupler. The design criteria is that $I_O \geqslant I_{IL} + I_R$ for the V_{IL} specified in Figure 11.

Using Equation (21), the typical value of R_{in} can be calculated for the selected I_F and the logic low output voltage, V_{OL}, of the driving gate. The V_{OL} of the logic family is given in Figure 11. The next step is to determine the worst case value of the LED input current, I_F, resulting from the tolerance variations of the LED current limiting resistor, R_{in}, and the power supply voltage, V_{cc1}. The conditions of $I_{F(MIN)}$ and the initial CTR (MIN) are then used to determine the initial worst case value of $I_{O(MIN)}$. Conversely, the worst case CTR degradation will occur when the LED is stressed at $I_{F(MAX)}$ conditions; thus, $I_{F(MAX)}$ will be used to determine the worst case degradation of the optocoupler performance. Using the maximum V_{cc1} and the minimum R_{in} will accomplish this worst case calculation, as shown in Equation (19).

TTL FAMILY	I_{IL}	V_{IL}	I_{IH}	V_{IH}	I_{OL}	V_{OL}	I_{OH}	V_{OH}
74S	–2 mA	.8V	50 μA	2V	20 mA	.5V	–1000 μA	2.7V
74H	–2 mA	.8V	50 μA	2V	20 mA	.4V	– 500 μA	2.4V
74	–1.6 mA	.8V	40 μA	2V	16 mA	.4V	– 400 μA	2.4V
74LS	–.36 mA	.8V	20 μA	2V	8 mA	.5V	– 400 μA	2.7V
74L	–.18 mA	.7V	10 μA	2V	3.6 mA	.4V	– 200 μA	2.4V

Figure 11. Logic Interface Parameters.

The change in CTR from the initial value at time t = 0 to a final value at some later time can be compensated by choosing a value of R_L which is consistent with $I_{O(MIN)} - mI_{IL}$ at the end of system life. Equation (22) describes this worst case calculation.

(22)

$$R_{L\,(MIN)} \geqslant \frac{V_{cc2\,(MAX)} - V_{OL}}{\left[\dfrac{I_{F(MIN)} \cdot CTR(MIN) \cdot \left(1 - \dfrac{D_{\bar{x}} + 2\sigma}{100}\right)}{100} - mI_{IL}\right]}$$

$D_x + 2\sigma$ = worst case CTR degradation

The selection of the maximum value of R_L is also of important in that its value insures that the collector is pulled up to the logic one voltage conditions, V_{IH}, under the conditions of maximum I_{OH} of the coupler, and the I_{IH} of the interconnecting gate.

(23)

$$R_{L\,(MAX)} \leqslant \frac{V_{cc2\,(MIN)} - V_{IH}}{I_{OH\,(MAX)} + m\,I_{IH}}$$

The selection of the value of R_L between the boundaries of $R_{L\,(MIN)}$, and $R_{L\,(MAX)}$ has certain trade offs. As in any open collector logic system, T_{PLH} increases with increasing R_L. Conversely, as R_L is increased above R_{LMIN}, a larger guardband between I_{OMIN} and $I_{IL} + I_R$ is achieved. Engineering judgement should be employed here to achieve the optimum trade off for desired performance.

Using the coefficient Figure 7 and Equations (11) and (13), the following examples are developed to demonstrate the methods of optocoupler system design in the presence of the mean and mean plus two sigma CTR degradation.

Example 1.

System Specifications

Data Rate	20 k bit NRZ
Logic Family	Standard TTL
Power Supply 1 & 2	5V ± 5
Component Tolerances	± 5%
Temperature Range	0 – 70°C
Expected System Lifetime	350 k hr (40 yr) at 50% system use time and 50% Data Duty Factor

Interface Specifications

Coupler 6N139

$CTR_{(MIN)} = 500\% @ I_F = 1.6$ mA
$V_{OL(MAX)} = .4V @ I_F = 1.6$ mA
$I_{OH(MAX)} = 250\mu A @ V_{cc2} = 7V$
$V_{F(MAX)} = 1.7V @ I_F = 1.6$ mA
$V_{F(MIN)} = 1.4V @ I_F = 1.6$ mA
$V_{F(TYP)} = 1.6V @ I_F = 1.6$ mA

Logic Standard TTL

I_{IL} = 1.6 mA		I_{IH} = 40μA	
V_{IL} = .8V		V_{IH} = 2V	
I_{OL} = 16 mA		I_{OH} = 400μA	
V_{OL} = .4V		V_{OH} = 2.4V	

Step 1. $R_{in\,(TYP)}$

$$R_{in} = \frac{V_{cc1} - V_{F\,(TYP)} - V_{OL}}{I_{F\,(TYP)}} \quad (24)$$

$$R_{in} = \frac{5.0 - 1.6 - .4}{1.6 \times 10^{-3}} = 1.87k\Omega, \text{ select } 1.8k\Omega \pm 5\%$$

$R_{(MIN)} = 1710\Omega$
$R_{(MAX)} = 1890\Omega$

Step 2. $I_{F\,(MAX)}$

$$I_{F\,(MIN)} = \frac{V_{cc1\,(MIN)} - V_{F\,(MAX)} - V_{OL}}{R_{in\,(MAX)}} \quad (25)$$

$$I_{F\,(MIN)} = \frac{4.75 - 1.7 - .4}{1890\Omega} = 1.4 \text{ mA}$$

Step 3. $I_{F\,(MAX)}$

$$I_{F\,(MAX)} = \frac{V_{cc1\,(MAX)} - V_{F\,(MIN)} - V_{OL}}{R_{in\,(MIN)}} \quad (26)$$

$$I_{F\,(MAX)} = \frac{5.25 - 1.4 - .4}{1710\Omega} = 2.02 \text{ mA}$$

Step 4. **Determine continuous operation time for LED emitter.**

$$t_{\text{continuous lifetime}} = \left[t_{\text{system lifetime}}\right]\left[\text{Data Duty Factor}\right]\left[\text{System Use Duty Factor}\right]$$

$$= (40 \text{ yr} \times 8.76 \text{ k hr/yr})(50\%)(50\%)$$

$$t_{\text{continuous lifetime}} = 87.60\text{K hr}$$

Step 5. **Obtain the mean and mean + 2σ CTR degradation at $I_{F\,(MAX)}$ and $t_{\text{continuous lifetime}}$ either as an approximation from Figure 4 or by calculations as shown below.**

Step 5a. **Determine $D_{\bar{x}}$**

$$D_{\bar{x}} = A_o t^{.25} + S\,[I_{FS} - \bar{I}_{FS}] \quad (27)$$

$$D_{\bar{x}} = 4.95 t_{(k\,hr)}^{.25} + [.186 \log t_{(k\,hr)} + .055]$$

$$[I_{F\,(MAX)} - 14.13 \text{ mA}]$$

$$D_{\bar{x}} = 4.95\,(87.6)^{.25} + (.186 \log 87.6 + .055)$$

$$(2.02 \text{ mA} - 14.13 \text{ mA})$$

$D_{\bar{x}}$ = 10.10% for 40 yr system operation

Step 5b. **Determine $\bar{D}_x + 2\sigma$**

$$D_{\bar{x}} + 2\sigma = A_o t^{.25} + [S + 2P]\,[I_{FS} + \bar{I}_{FS}] \quad (28)$$

$$D_{\bar{x}} + 2\sigma = 9.7 t_{(k\,hr)}^{.25} + [2\,(.063 \log t_{(k\,hr)} + .081)$$

$$+ (.186 \log t_{(k\,hr)} + .055)]$$

$$\times [I_{F\,(MAX)} - 14.13\text{ mA}]$$

$$D_{\bar{x}+2\sigma} = 9.7\,(87.6)^{.25} + [2\,(.063 \log 87.6 + .081)$$

$$+ (.186 \log 87.6 + .055)]$$

$$\times [2.02\text{ mA} - 14.13\text{ mA}]$$

$$D_{\bar{x}+2\sigma} = 19.71\%$$

Step 6. Guardband the worst case value of CTR degradation.

It is often desirable to add some additional operating margin over and above conditions dictated by simple worst case analysis. The use of engineering judgement to increase the worst possible CTR degradation by an additional 5% margin would insure that the entire distribution would fall within the analysis. Thus,

$$D_{\bar{x}+2\sigma} + 5\% = 24.71\%$$

Step 7. Selecting $R_{L\,(MIN)}$ for guardbanded worst case

$D_{\bar{x}+2\sigma} + 5\%$, $m = 1$

$$R_{L(MIN)} \geqslant \frac{V_{cc2\,(MAX)} - V_{OL}}{\dfrac{I_{F(MIN)} \cdot CTR_{(MIN)} \cdot 1 - \left(\dfrac{D_{\bar{x}+2\sigma} + 5\%}{100}\right)}{100} - mI_{IL}} \quad (22)$$

$$R_{L(MIN)} \geqslant \frac{5.25 - .4}{\dfrac{1.4 \times 10^{-3} \cdot 500\% \cdot 1 - \left(\dfrac{24.71\%}{100}\right)}{100} - 1\ 1.6\text{ mA}}$$

$$R_{L\,(MIN)} = 1.32\text{k}\Omega$$

Step 8. Select $R_{L\,(MAX)}$

$$R_{L\,(MAX)} \leqslant \frac{V_{cc2\,(MAX)} - V_{OL}}{I_{OH\,(MAX)} + mI_{IH}} \quad (29)$$

$$R_{L\,(MAX)} \leqslant \frac{4.75 - 2.4}{250\mu A + 40\mu A} = 8.1\text{k}$$

The range of R_L is from 1.32kΩ to 8.1kΩ. It is desirable to select a pull-up resistor which optimizes both speed performance and additional I_O guardband. This criteria leads to a tradeoff between a value close to $R_{L\,(MIN)}$ for speed performance and one bordering near $R_{L(MAX)}$ for I_O guardbanding. In this design example, the system's lifetime has a higher priority than does the moderate speed performance demanded from the optocoupler. An R_L of 3.3kΩ ± 5% is selected under this condition.

An additional guardband of 5% was added to the worst case $D_{\bar{x}+2\sigma}$ CTR degradation guardband to insure that even a greater percentage of the distribution would be accounted for. The actual percentage difference between $I_{OL\,(MAX)}$ and $I_{O\,(MIN)}$ at the end of system life is shown below:

$$I_{O\,(MIN)} = \frac{CTR_{(MIN)} \cdot I_{F\,(MIN)} \cdot 1 - \left(\dfrac{D_{\bar{x}+2\sigma}}{100}\right)}{100} \quad (30)$$

$$I_{OL\,(MAX)} = \frac{V_{cc2\,(MAX)} - V_{OL}}{R_{L\,(TYP-5\%)}} + m|I_{IL}| \quad (31)$$

$$\%\text{ Guardband} = \left[1 - \frac{I_{OL\,(MAX)}}{I_{O\,(MIN)}}\right] \times 100 \quad (32)$$

For the example shown, the additional end of system life I_O guardband results from the selection of an R_L greater than the $R_{L\,(MIN)}$ as shown in Steps 9, 10, and 11.

Step 9. $I_{O\,(MIN)}$ at end of system life

$$I_{O\,(MIN)} = \frac{500\% \cdot 1.4\text{ mA} \cdot \left(1 - \dfrac{19.17\%}{100}\right)}{100} = 5.65\text{ mA}$$

Step 10. $I_{OL\,(MAX)}$ for worst case of $I_{R\,(MAX)} + I_{IL}$

$$I_{OL\,(MAX)} = \frac{5.25 - .4}{3.13\text{k}\Omega} + 1.6\text{ mA} = 3.14\text{ mA} \quad (33)$$

Step 11. % Guardband

$$\% = 1 - \frac{3.14\text{ mA}}{5.65\text{ mA}}\ 100 = 44.4\% \quad (34)$$

APPLICATION NOTES

Thus, this circuit interface design offers an additional 44.4% I_O guardband beyond the 19.71% required to compensate for the CTR change caused by 86.7k hr of continuous operation at an $I_{F\,(MAX)}$ of 2 mA. This extra guardband results from having chosen an $R_L = 3.3k$ rather than the lowest allowable value of R_L plus the engineering guardband chosen in Step 6.

Example 2.

System Specifications

Data Rate	250K bit NRZ
Logic Family	TTL to LSTTL
Power Supply 1 and 2	5V ± 5%
Component Tolerance	± 5%
Temperature Range	25°C
Expected System Lifetime	175 k hr (20 yr) at 50% System Use Time and 50% Data Duty Factor

Interface Conditions

Coupler 6N136

$CTR_{(MIN)}$ = 19% @ I_F = 16 mA
V_{OL} = .4V
I_{OH} = 500 nA @ V_{cc2} = 5.0V
$V_{F(TYP)}$ = 1.6V @ I_F = 16 mA
$V_{F(MIN)}$ = 1.5V @ I_F = 16 mA
$V_{F(MAX)}$ = 1.7V @ I_F = 16 mA

Logic LSTTL

I_{IL} = .36 mA	I_{OL} = 8 mA
V_{IL} = .8V	V_{OL} = .5V
I_{IH} = 40μA	I_{OH} = 400μA
V_{IH} = 2V	V_{OH} = 2.7V

Again using Figure 7, the data rate dictates the use of a 6N136 at an $I_{F\,(TYP)}$ of 16 mA. Using the same 12 step worst case analysis, it is possible to determine the values of R_{in}, R_L and the degree of guardbanding of I_O at end of system lifetime.

Step 1. R_{in} = 187Ω, select 180Ω ± 5%
$R_{L\,(MIN)}$ = 179Ω
$R_{L\,(MAX)}$ = 189Ω

Step 2. $I_{F\,(MIN)}$ = 14.02 mA

Step 3. $I_{F\,(MAX)}$ = 19 mA

Step 4. **System Lifetime**

t = 43.8k hr

Step 5. **$D_{\bar{x}}$ and $D_{\bar{x}+2\sigma}$ for $I_{F\,(MAX)}$ of 19 mA by calculation or from Figure 4**

$D_{\bar{x}}$ = 14.5%
$D_{\bar{x}+2\sigma}$ = 28.5%
43.8k hr continuous lifetime

Step 6. **Engineering Guardband of 5%,**

$D_{\bar{x}+2\sigma}$ + 5% = 33.5%

Step 7. **R_L selection with guardbanding of $D_{x+2\sigma}$ + 5%**

$R_{L\,(MIN)}$ = 3.44kΩ

Step 8. $R_{L\,(MAX)}$ = 50kΩ

Step 9. $R_{L\,(TYP)}$ = 5.1kΩ ± 5%, $R_{L\,(TYP-5\%)}$ = 4.84kΩ, $R_{L\,(MAX+5\%)}$ = 5.35kΩ

Step 10. **End of System Life $I_{O\,(MIN)}$**

$I_{O\,(MIN)}$ = 1.5 mA

Step 11. $I_{OL\,(MAX)}$ = 1.36 mA

Step 12. **Engineering % Guardband of $I_{O\,(MIN)}$ = 9.3%**

Example 3.

If a particular design requirements specifies a maximum tolerable degradation over a system lifetime, the optimum value of $I_{F(TYP)}$ can be obtained from Figure 12. For example, if a maximum acceptable degradation, $D_{\bar{x}+2\sigma}$, is 40%, and a continuous operation of 400k hr is desired, this curve specifies that $I_{F\,(TYP)}$ should be less than or equal to 10 mA. A 400k hr continuous operation with 100% system duty factor as might be encountered in telephone switching equipment is equivalent to 45 years of system lifetime.

If a 6N139 split Darlington were used to interface an LSTTL logic gate with the system specifications stated, a collector pull-up resistor of as low as 160Ω could be used. If an R_L of 1k were selected, this optocoupler would offer an additional end of life guardband of 81.8%. This worst case analysis points out that with the knowledge of selecting proper values of R_L, the CTR performance of the

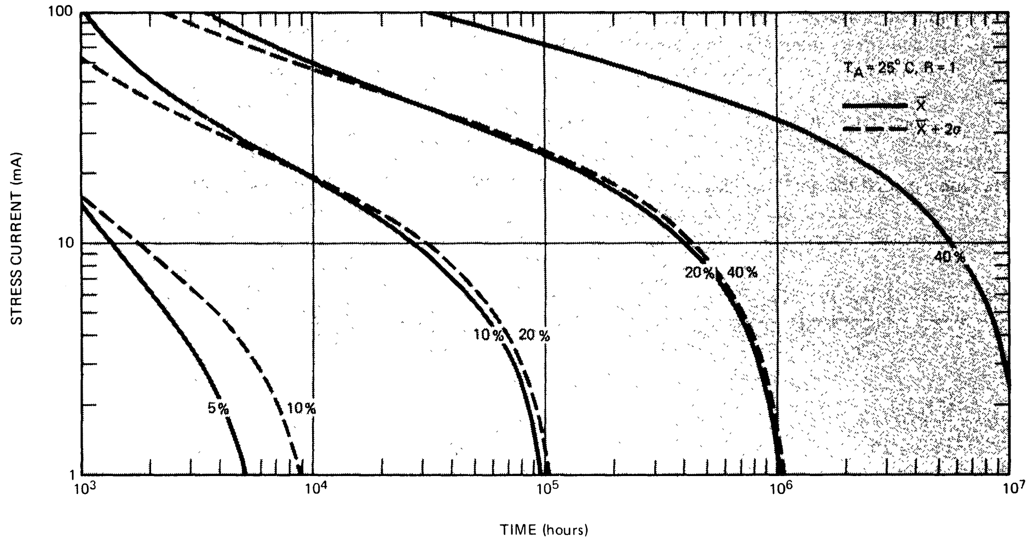


Figure 12. Stress Current (I_{FS}) vs. Time vs. % Degradation.

coupler far exceeds the normal MTBF requirements for most commercial electronic systems.

Consideration of the Optically Coupled Gate

System data speed requirements in the multi-megabit range can also be communicated through an optocoupler. The first three coupler families listed in Figure 9 are not applicable in these very high speed data interface applications; however, the optically coupled gate, 6N137, will function to speeds of up to 10 MHz. This type of coupler differs in operation from the single transistor and Darlington style units in that it exhibits a non-linear transfer relationship of I_F to I_O. This is shown in Figure 13. The relationship is described as a minimum threshold of LED input current, I_{Fth} which is required to cause the output transistor to sink the current supplied by the pull-up resistor and interconnected gate. As the LED degrades, the effect is that a larger value of $I_{F\ th}$ is required to create the same detector photodiode current necessary to switch the output gate.

In the previous interface examples, the worst case analysis and guardbanding is based on the output collector current, I_O. With the optically coupled gate, worst case guardbanding is concerned with the selection of the initial value of the I_F, which at end of system lifetime will generate the necessary threshold photocurrent demanded by the gate's amplifier to change state.

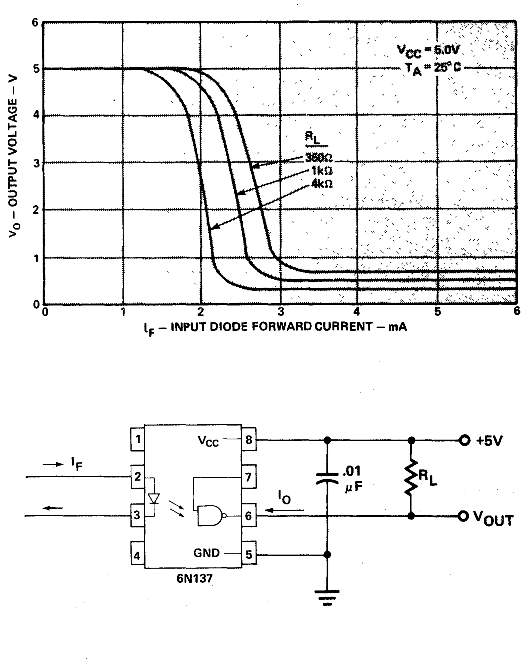


Figure 13. 6N137 Input – Output Characteristics.

The calculation of the required I_F to allow for worst case LED degradation is approached by guardbanding the guaranteed minimum isolator input current, I_{FH}, for a specified I_{OL} and V_{OL} interface. Equation (35) shows the relationship of the I_P to I_F for this coupler.

$$I_P \alpha (I_F)^n \quad \text{, where } 1.1 \leqslant n \leqslant 1.3 \qquad (35)$$

Using the concept that the guardbanding of the initial value of I_F will result in a similarly guardbanded I_P, the relationship presented in Equation (36) results:

$$\left[1 - \frac{D_{\bar{x}} + 2\sigma}{100}\right] = \left[\frac{I_{PH}}{I_P}\right] = \left[\frac{I_{FH}}{I_F}\right]^n \qquad (36)$$

$$I_F = \frac{I_{FH}}{\left[1 - \frac{D_{\bar{x}} + 2\sigma}{100}\right]^n} \qquad (37)$$

The previous interface example showed that the first term of the $D_x + 2\sigma$ equation dominated the magnitude of the worst case degradation. This term, $A_o R^{\alpha} t^{n(R)}$, i.e., $(9.7 \ t_{(k\ hr)}^{.25})$, does not contain an I_F current dependent term; thus, an approximation of the worst case LED degradation can be made that relates to the system's lifetime. This initial value of $D_x + 2\sigma$ can be used in Equation (37) to calculate the initial value of the I_F. With this initial I_F, a more accurate degradation value can be calculated using Equation (28). This procedure results in an iterative process to zero in on a value of I_F that will insure reliable operation.

The following example will illustrate this approach.

Example 4.

System Specifications

Data Rate	6 MHz NRZ
Logic Family	LSTTL to TTL
Power Supply 1 and 2	5V ± 5%
Component Tolerance	± 5%
Temperature Range	0 – 70°C
Expected System Lifetime	203k hr (23 yr) at 50% System Use Time and 50% Data Duty Factor

Step 1. Determine the continuous operation time for LED emitter

$$t_{\text{continuous lifetime}} = \left[t_{\text{system lifetime}}\right]\left[\text{Data Duty Factor}\right]\left[\text{System Use Factor}\right]$$

$$= \left[23\ \text{yr} \quad 8.76\text{k hr/yr}\right]\left[50\%\right]\left[50\%\right]$$

$$= 50.3\text{k hr}$$

Step 2. Calculate the worst case LED degradation

$$D_x + 2\sigma \approx 9.7\ t_{(k\ hr)}^{.25}$$

$$D_x + 2\sigma \approx 9.7\ (50.3)^{.25}$$

$$D_x + 2\sigma \approx 26\%$$

Step 3. Calculate the first approximation of guardbanded I_F, n = 1.2

$$I_F = \frac{I_{FH}}{\left[1 - \frac{(\approx D_{\bar{x}} + 2\sigma)}{100}\right]^{1/n}} = \frac{5\ \text{mA}}{.78} = 6.41\ \text{mA}$$

Step 4. Calculate input resistor R_{in}

$$R_{in} \leqslant \frac{V_{cc1\ (MIN)} - V_{F\ (MAX)} - V_{OL}}{I_F}$$

$$R_{in} \leqslant \frac{4.75 - 1.7 - .4}{.00641}$$

$R_{in} \leqslant 413\Omega$ select $R_{in} = 390\Omega \pm 5\%$

Rin (MAX)

$$R_{in\ (MAX)} = 409\Omega$$

$$R_{in\ (MIN)} = 370\Omega$$

Step 5. Calculate the $I_{F\ (MAX)}$

$$I_{F\ (MAX)} = \frac{V_{cc1\ (MAX)} - V_{F\ (MIN)} - V_{OL}}{R_{in\ (MIN)}}$$

$$I_F = \frac{5.25 - 1.4 - .4}{370}$$

$$I_F = 9.32\ \text{mA}$$

Step 6. Calculate the worst case $D_{\bar{x}} + 2\sigma$ for $I_{F\ (MAX)}$

$$D_{\bar{x}} + 2\sigma = 25.8\% + .747\ (9.32\ \text{mA} - 14.13\ \text{mA})$$

$$D_{\bar{x}} + 2\sigma = 22.2\%$$

Step 7. Calculate the new minimum required I_F at end of life based on degradation found in Step 6.

$$I_{F(EOL)} = \frac{I_{FH}}{\left[1 - \frac{22.2}{100}\right]^{1/1.2}} = \frac{5}{.81} = 6.16\,\text{mA}$$

Step 8. Calculate $I_{F\,(MIN)}$

$$I_{F\,(MIN)} = \frac{V_{cc1\,(MIN)} - V_{F\,(MAX)} - V_{OL}}{R_{in\,(MAX)}}$$

$$I_{F\,(MIN)} = \frac{4.75 - 1.7 - .4}{409}$$

$$I_{F\,(MIN)} = 6.47\text{ mA}$$

Step 9. $R_{L\,(MIN)}$, $m = 1$

$$R_{L\,(MIN)} = \frac{V_{cc2\,(MAX)} - V_{OL}}{I_{OL\,(MIN)} - mI_{IL}}$$

$$= \frac{5.25 - .6}{.016 - .0016}$$

$$R_{L\,(MIN)} = 332\Omega$$

Step 10. $R_{L\,(MAX)}$, $m = 1$

$$R_{L\,(MAX)} = \frac{V_{cc2\,(MAX)} - V_{OH}}{I_{OH\,(MAX)} + mI_{IH}}$$

$$R_{L\,(MAX)} = \frac{4.75 - 2.4}{250\mu A + 40\mu A}$$

$$R_{L\,(MAX)} = 8.1\text{k}\Omega$$

Step 11. Minimum % Emitter Degradation Guardband

$$\%_{(MIN)} = \left[1 - \frac{I_{F\,(EOL)}}{I_{F\,(MIN)}}\,100\right] \qquad (38)$$

$$4.8\% = \left[1 - \frac{6.16\text{ mA}}{6.47\text{ mA}}\,100\right]$$

where $I_{F\,(EOL)}$ represents the switching threshold at the end of life.

Step 12. Maximum % Emitter Degradation Guardband

$$\%_{(MAX)} = \left[1 - \frac{I_{F\,(EOL)}}{I_{F\,(MAX)}}\right]100 \qquad (39)$$

$$34\% = \left[1 - \frac{6.16\text{ mA}}{9.32\text{ mA}}\,100\right]$$

The conclusions that are to be drawn from this analysis are that as long as the $I_{F\,(MAX)}$ is less than $I_{\overline{FS}} = 14.13$ mA, the worst-worst case CTR degradation may be calculated using only the first term, $A_oR^{\alpha}t^{n(R)}$, of the $D_{\overline{x}} + 2\sigma$ case. In the example presented, 26% degradation was determined from the first term, and when the more accurate calculation using Equation (28) was used, a 22% degradation resulted. The end of life I_F guardband may be calculated using Equations (38) and (39). Using Equation (38), the minimum guardband is 5.7%, and with Equation (39), the maximum guardband is 35%.

APPLICATION NOTES