Reliability

Summary of SEC450 GaAs:Si IRED Chip Long-Term Operating Life Study

IRED CHIP DEGRADATION STUDIES

Honeywell is engaged in an ongoing study of degradation of radiant output over time as a function of temperature for the SEC450 GaAs IRED (gallium arsenide infrared emitting diode) chip. This IRED chip is used in Honeywell's High Reliability IRED as well as in a variety of commercial components and assemblies. The results of the study through July 1986 are presented below.

INTRODUCTION

Honeywell is committed to the manufacture of reliable, high quality optoelectronic products. An ISO 9001 quality system is maintained, providing the necessary controls to assure that all product meets or exceeds the specified requirements. To assure contin-uing performance under conditions of environmental and mechanical stress, periodic reliability testing is performed on samples from production. All new products are thoroughly tested and characterized before introduction, with particular attention given to those parameters which relate to operational life and reliability.

Optoelectronic components, being semiconductors, share with all other semiconductor devices a susceptibility to certain mechanical failure modes. To be acceptable, semiconductors must withstand stress of temperature, humidity, mechanical shock and vibration. The industry employs established test methods and reliability projection techniques to ensure acceptability.

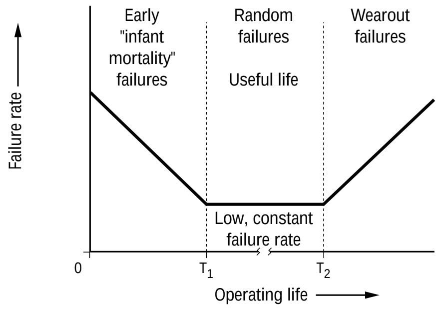
Degradation of radiant output is a reliability factor that is unique in infrared emitting diodes (IREDs). Honeywell has pioneered the development of a characterization model which projects the effect of this phenomenon on component reliability. Validation of this model continues as Honeywell products and those of other manufacturers are tested. In addition, the resulting knowledge of factors affecting reliability aids in the improvement of products and processes.

The SEC450 chip is a gallium arsenide (GaAs) silicon doped (GaAs:Si) infrared emitting diode (IRED) chip which is widely used on component packages and higher level assemblies. This report details the results of an ongoing study to characterize the fundamental long-term degradation mechanisms in the SEC450 which will allow projection of expected behavior under various conditions in all Honeywell packages.

MECHANICAL RELIABILITY

Mechanical integrity of optoelectronic components, and the range of stress conditions over which reliable operation results, are of critical importance to the system designer. Optoelectronic components exhibit failure rates and mechanical wear-out characteristics which fit the well known "bath tub curve" (Figure 1) common to semiconductor devices. IRED power output degradation is a wear-out mechanism.

Figure 1 Semiconductor Failure Rate as a Function of Time



Components utilizing the SEC450 IRED chip are in two basic package types: hermetic glass-lens-to-metal-header devices and plastic molded-lead-frame devices. Figure 2 summarizes these packages and their properties.

Figure 2 Honeywell Products Utilizing the SEC450 Chip

Product	Package Type	Thermal Resistance (No Heat Sink)	Maximum Operating Temperature
SE1450 SE1455	Hermetic Pigtail	785°C/W	125°C
SE2460	Hermetic Pillpack	-	125°C
SE3450 SE5450	Hermetic TO-46	370°C/W	125°C
SEP8505	Plastic T1	670°C/W	85°C
SEP8506	Plastic Sidelooker	750°C/W	85°C
SEP8507	Plastic Endlooker	-	85°C

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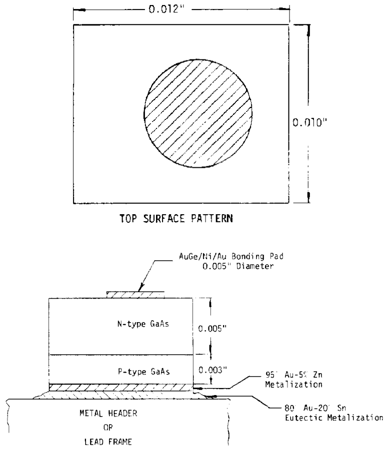
SEC450 CHIP STRUCTURE

The Gallium arsenide, silicon doped construction is shown in Figure 3. The GaAs PN junction is formed by liquid-phase-epitaxy (LPE) grown of GaAs layers onto GaAs substrates. Wafer processing produces the final chip pattern with N/P metal contacts. Radiance emission occurs over the full 10 x 12 mil area of the chip junction with side and top surface emission, with obstruction on the top surface by the metal bond pad.

The mechanical adhesion of the chip to metal header or lead frame employs a gold-tin die attach. Gold ball bonding contacts the top surface N-side of the junction.

Figure 3 SEC450 IRED Structure



POWER OUTPUT DEGRADATION THEORY

Optical power output degradation during operation has been established as a wear-out mechanism for the SEC450 chip. Although all devices degrade in this manner with time, they do so with widely varying rates, resulting in a non-constant failure rate. This process varies also with temperature and operating current. Circuit and system designers must have knowledge of the magnitude of typical and worst case IRED degradation to assure adequate optical power output throughout the intended design life of the system being created. The Honeywell approach to this requirement is summarized in this section.

QUANTUM EFFICIENCY

Optical power output of an IRED is directly proportional to the applied forward current:

Equation 1

$$P_o = \eta \bullet E \bullet I_F$$

Where

- P_o = Optical power output in watts
- η = IRED external quantum efficiency
- E = Energy per photon emitted in eV
- I_F = Applied forward current in amps

Optical power output degradation of an IRED at a fixed operating current (I_F), which is the normal mode for industrial applications, will occur as a result of a decrease in the IRED external quantum efficiency (η).

I-V CHARACTERISTICS

The forward current-voltage characteristic of a semiconductor PN junction diode has two current components, diffusion current and space charge recombination current:

Equation 2

$$I_F = A \bullet [\exp(qV_F/kT)] + B \bullet [\exp(qV_F/2kT)]$$

Where

- q = Electronic charge (1.6×10^{-19} C)
- I_F = Forward current
- V_F = Forward voltage
- k = Boltzmann's constant
- T = Junction temperature (K)
- A = Diffusion current coefficient
- B = Space-charge recombination current coefficient

For an IRED, only the diffusion current component contributes to radiative (light emission) current. The space-charge recombination current contributes to non-radiative current. The ratio of radiative to non-radiative current at a fixed forward current, which is the normal mode for industrial applications, directly affects the IRED external quantum efficiency. Quantum efficiency directly relates to IRED emitted power as was previously shown by equation (1).

As the SEC450 IRED chip ages, the radiative ("kT") current component decreases for a fixed forward current due to a decrease in the diffusion current coefficient A. The radiative current decrease causes decreased IRED optical power output. The mechanism for degradation appears to be a bulk diffusion. This may be related to the silicon dopant, since the diffusion component changes only for silicon doped GaAs structures. Visual inspection of degraded devices shows only a general "dimming" of the radiant output, with no "dark-line-defects" common to zinc diffused GaAs and double heterostructure GaAlAs devices.

TIME DEPENDENCE

Time dependence of IRED degradation has been measured by Honeywell and others. Logarithmic degradation rate versus square root of time for a wide range of degradation rates has been observed. The degradation rate can be described by:

Equation 3

$$P_o(t) = P_o(t{=}0) \bullet [\exp(-(t/\tau)^{0.5})]$$

Where

- $P_o(t)$ = Optical power output at time t
- P_o (t=0) = Initial optical power output
- t = Total operating time
- τ = Degradation characteristic time constant

TEMPERATURE/CURRENT DEPENDENCE

The temperature and current dependence of the degradation process is described by Arrhenius's Law:

Equation 4

$$\tau = \tau_o \bullet [\exp(E_A/kT)]$$

Where τ_o is current dependent and assumed to have power-law relationship.

Equation 5

$$\tau = A_1(I_F)^n \bullet [\exp(E_A/kT)]$$

Where

- A_1 = Constant of proportionality
- I_F = Applied forward current in amps
- n = Exponent of current dependence
- E_A = Thermal activation energy in eV
- k = Boltzmann's constant
- T = Operating junction temperature

The equations describe the acceleration of IRED optical power output degradation due to increasing junction temperature and/or operating current. Because heat sinking and thermal resistance have a direct effect on actual junction operating temperature, these parameters also affect the IRED degradation rate.

STATISTICAL VARIATION OF IRED DEGRADATION

Analysis of IRED degradation is a statistical process which deals with varying degradation rates within a given sample of units. Using statistically significant samples, a log-normal distribution of degradation rate for the SEC450 IRED chip has been observed. Gen-erally, the end of IRED operating life is defined as the point in time when the power output drops to one-half its initial value (50% or 3 dB drop). If end-of-life data for an IRED group tested to failure is plotted on log-normal scale of % population versus logarithm of operating lifetime, the result should be a straight line with the point of 50% of the population representing the median half-life of the group. The median half-life of an IRED product is a useful figure of merit for comparing products and projecting system lifetimes (see Figure 15).

DESIGN AND ANALYSIS OF BURN-IN

In this study, an SEC450 IRED chip lot was assembled in hermetic TO-46 packages and placed on heatsinked burn-in at several temperatures and forward current conditions. Initial and periodic measurements of I-V-P data (forward current, forward voltage, and optical power output) were recorded using a Teradyne A360 test system. Thermal resistance measurements along with power dissipation calculations determined the typical chip junction temperature for each burn-in condition.

Figure 4 summarizes the results of the burn-in study. The data of Figure 4 is plotted in Figures 5, 6 and 7. The expected straight line fit of Figure 5 for temperature dependence of half-life yields a measured activation energy of E_A = 0.50 eV. The current dependence of half-life is plotted in Figure 6 with temperature effects uncorrected, and in Figure 7 with temperature effects of the 0.50 eV activation energy removed. The graphs show essentially no current dependence when junction heating due to current variations is removed. These results are in general agreement with similar studies done here at Honeywell on GaAlAs fiber optic IRED structures.

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Figure 4 SEC450 Burn-In Test Summary
Chip Type: GaAs:Si 0.010" x 0.012"

Temp °C	I_F (mA)	# Units	Burn-In Hours	# Units Fail	Median Half-Life Hours
T_C = 80	100	35	14,600	1	-
T_C = 100	100	35	18,000	8	32,000
T_C = 125	100	35	18,000	12	32,000
*T_C = 125	100	35	10,400	9	25,000
T_C = 125	50	25	14,000	3	60,000
*T_C = 125	100	35	18,000	12	32,000
T_C = 125	150	25	14,000	7	40,000
T_C = 125	200	25	14,000	6	28,000

Figure 5 Arrhenius Plot of SEC450 Burn-In Data

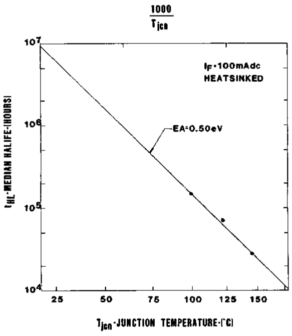


Figure 6 Current Dependence of SEC450 Burn-In Data

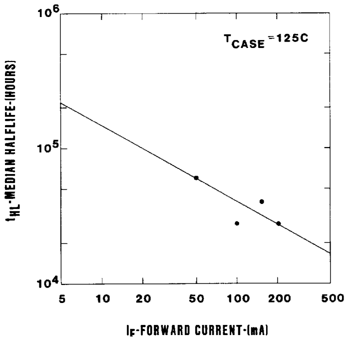
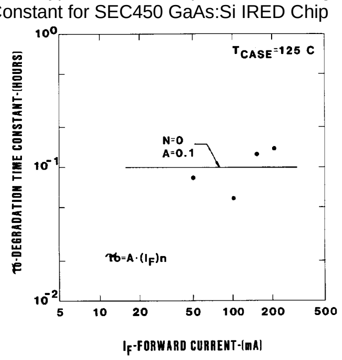


Figure 7 Typical Current Dependence of Degradation Time Constant for SEC450 GaAs:Si IRED Chip



From these results, values for the E_A, A_1, and n of equations (3) and (5) are determined, allowing a general equation for optical power output degradation of the SEC450 chip.

Equation 6

$$P_O(t) = P_O(t=0) \bullet \exp[-t / \{A_1 \bullet (I_F)^n \bullet \exp(E_A / kT)\}]^0$$

and

Equation 7

$$P_O(t) = P_O(t = 0) \bullet \exp[-t / \{0.1 \bullet \exp(0.50 / kT\}]^{0.5}$$

yielding for median half-life t_{HL}:

Equation 8

$$t_{HL} = 0.048 \bullet \exp[5800 / T] \text{ (T in °K)}$$

This equation (8) is plotted in Figure 8, giving a general Arrhenius plot for the SEC450 IRED chip. This plot can be used to predict half-life performance of the SEC450 IRED chip in various packages when the junction temperature is calculated using appropriate thermal resistance and power dissipation values.

Figures 9 through 12 show the SEC450 I_F - V_F changes for small and large optical power output changes. The radiative current component change with significant IRED degradation is clearly shown in Figure 9.

Figures 13 and 14 show the reasonably good straight line fit of logarithmic optical power output versus square root of time.

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Figures 15 and 16 show the log-normal statistical variation of the IRED degradation. The dashed line shows the actual burn-in hours. The solid circle represents units with measured half-life, and the open circles represent extrapolated half-life using the expected logarithmic power output versus square root of time behavior.

Figure 8 Arrhenius Plot for SEC450 GaAs:Si IRED Chip

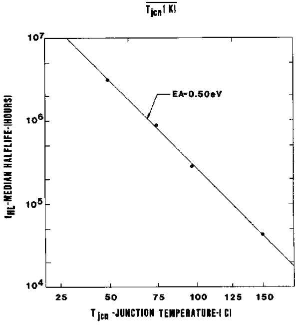

Figure 9 Typical P_O - V_F Change During Power Output Degradation for SEC450 IRED Chip

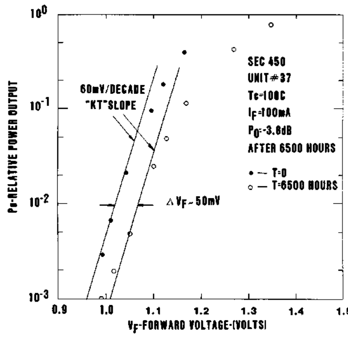

Figure 10 Typical P_O - V_F Change During Power Output Degradation for SEC450 IRED Chip

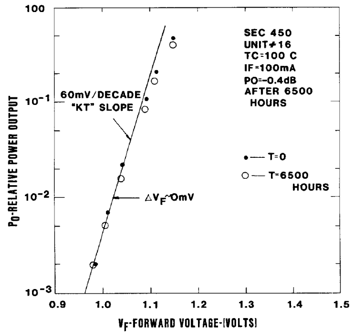

Figure 11 Typical I_F - V_F Change During Power Output Degradation for SEC450 IRED Chip

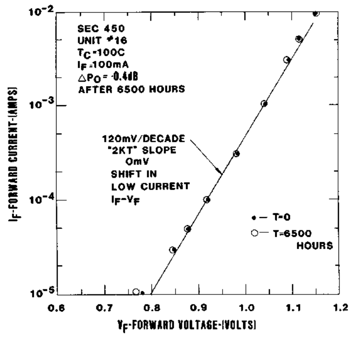

Figure 12 Typical I_F - V_F Change During Power Output Degradation for SEC450 IRED Chip

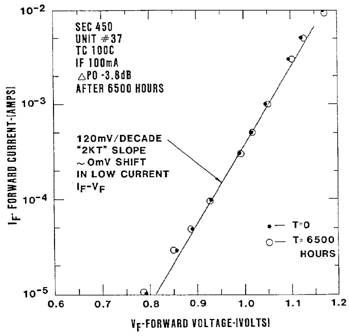

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Figure 13 SEC450 GaAs:Si 10 x 12
T_C = 125°C, I_F = 100 mA

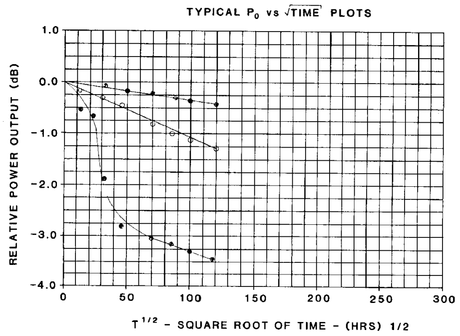


Figure 14 SEC450 GaAs:Si 10 x 12
T_C = 125°C, I_F = 200 mA

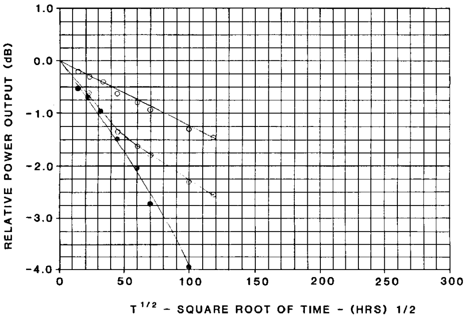


Figure 15 SEC450 Log-Normal Distribution
(T_C = 125°C, I_F = 50 mA, Burn-In Time = 14,000 Hours,
Projected Median Half-life = 60,000 Hours)

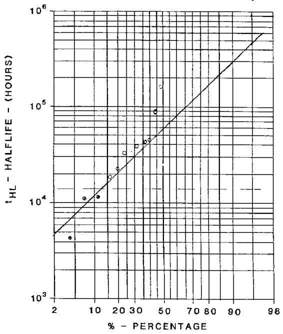


Figure 16 SEC450 Log-Normal Distribution
T_C = 125°C, I_F = 200 mA, Burn-In Time = 14,000 Hours,
Projected Median Half-life = 28,000 Hours

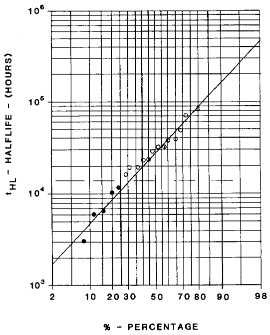
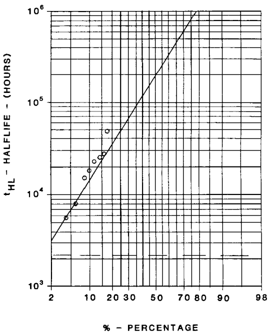


Figure 17 SEP8506 GaAs Sidelooker IRED Log-Normal Distribution
T_C = 100°C, I_F = 20 mA, Burn-In Time = 2,100 Hours,
Projected Median Half-life = 200,000 Hours



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OPERATIONAL RELIABILITY PREDICTION

IRED optical power output (P_O) increases with forward current (I_F). However, increasing the forward current also increases power dissipation (P_d) and chip junction temperature (T_j). This results in decreased optical power output and device operating lifetime.

Data sheets for IRED products allow the systems designer to determine optical power output (or switch CTR) as a function of IRED forward current. The systems designer will need also to factor in the effect of IRED forward current on operating lifetime to select an optimum operating point.

The relationship of chip junction temperature to operating condition is:

Equation 9

$$T_j = T_A + \theta_{th} \bullet P_d$$

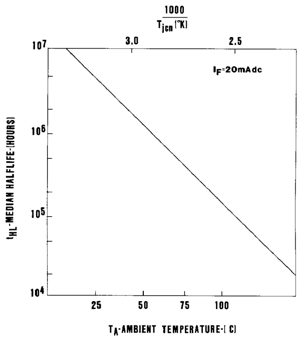
$$T_j = T_A + \theta_{th} \bullet V_F \bullet I_F$$

where

- T_j = Chip junction temperature (°C)
- T_A = Ambient operating temperature (°C)
- θ_{th} = Package thermal resistance-junction to ambient (°C/W)
- P_d = Power dissipation (watts)
- V_F = Applied forward voltage (volts)
- I_F = Applied forward current (amps)

The Arrhenius plot for the SEC450 half-life (Figure 8) along with the application's calculated junction temperature can be used to predict the median half-life of a particular SEC450 package and operating condition. An example for the Honeywell SEP8506 sidelooker package is given.

Figure 18 Arrhenius Plot for SEP8506 Sidelooker IRED Product



SEP8506 GaAs SIDELOOKER IRED EXAMPLE

A common application of the SEC450 IRED chip is the plastic sidelooker package for opto switch assemblies. Typically, the part is operated at I_F = 20 mA at up to 100°C ambient temperature. The maximum operating temperature is 85°C and operation above this temperature is not recommended. We will calculate the expected half-life at T_A = 100°C and I_F = 20 mA DC, and compare the results to actual burn-in data at that condition.

$T_j = T_A + \theta_{th} \bullet V_F \bullet I_F$

T_j = 100°C + 750°C/W • 1.25 V • 0.020 A

T_j = 118.75°C

1,000 / T_j (°K) = 2.55

From Figure 8 we determine that for 1,000 / T_j = 2.55 that t_{HL} = 125,000 hours. For comparison, figure 17 shows actual SEP8506 burn-in data which projects t_{HL} = 200,000 hours at T_C = 100°C indicating reasonably good agreement. Figure 18 shows the predicted variation of half-life versus ambient temperature for I_F = 20 mA. At 25°C, 20 mA, approximately 500 years half-life is projected.

Figure 19 shows a plot of median half-life versus temperature for three different current levels for the SE1450/1455 IREDs.

The statistical distribution of the IRED degradation process must be considered by the system designer. Figure 17 shows that even though the ***median*** half-life of the product will be 200,000 hours (23 years) for T_C = 100°C, approximately 6% of the distribution will fail in 8,800 hours (1 year).

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A final consideration is the system tolerance to IRED degradation. All data and calculations in this report are for half-life where 50% (3 dB) drop in optical power output constitutes a failure. Specific system applications may fail at very different degradation points which will significantly shift the time of failure.

SEC450 IRED PRODUCT'S OPERATING LIFETIME

In Figures 19 - 24, the previous discussion and development of theoretical and measured long-term behavior of the SEC450 IRED chip is summarized into projections of typical operating lifetimes of IRED products which utilize the SEC450 chip. Three DC current conditions are projected.

Figure 19 SE1450/1455 Typical Operating Lifetime

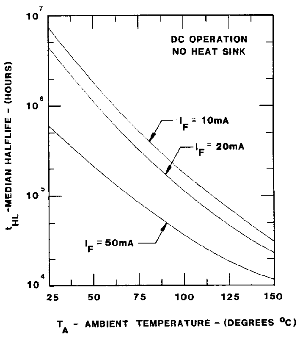

Figure 20 SE2460 GaAs Pillpack IRED Typical Operating Lifetime

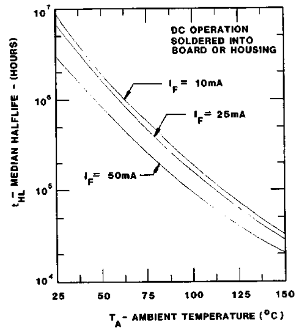

Figure 21 SE3450/5450 GaAs Hermetic TO-46 IRED Typical Operating Lifetime

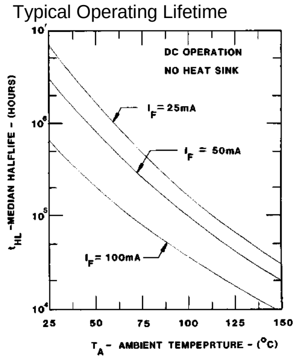

Figure 22 SEP8505 GaAs Plastic Endlooker IRED Typical Operating Lifetime

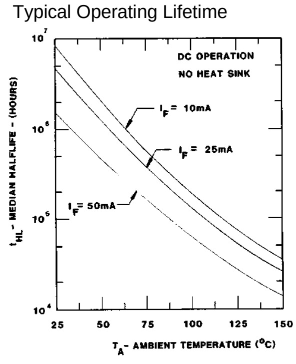

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Figure 23 SEP8506 GaAs Sidelooker IRED Typical Operating Lifetime

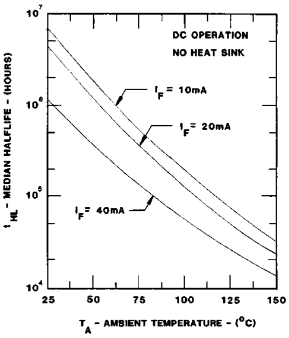

Figure 24 SEP8507 GaAs Plastic Endlooker IRED Typical Operating Lifetime