To our customers,

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Renesas Electronics Corporation

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RENESAS

APPLICATION NOTE

RELIABILITY IN NEC'S MICROWAVE POWER TRANSISTORS

1. INTRODUCTION.

In NEC microwave power transistor's market requirements are anticipated by a careful survey of the market and are feedback with the device design. The factors determining the reliability of power devices and the fault mode of such factors are accurately grasped by performing a thorough reliability analysis of conventional power devices. The device designs incorporates the positive steps and corrective actions prevent the occurence of failure.

Furthermore, adequate process control is exercised over all manufacturing process covering from production to delivery of the product and, in addition, appropriate process conditioning and characteristic stabilization is achieved through conformance to a quality assurance program which has been amply proved in actual practice by, satellite borne, high reliability microwave transistors. This assures that high quality, high reliability NEC power transistors are always offered to customers.

2. DESIGN FAILURE AND CORRECTIVE ACTION.

Table 1. Problems of conventional Power Devices and Corrective Action taken against the same.

Problem	Cause of failure	Corrective action
Increase of I_{CBO} and I_{EBO} Decrease of BV_{CBO} and BV_{EBO}	Degradation of junction.	o Adoption of Ti-Pt-Au multi-layer electrode. o Adoption of Dopos.
Variation of h_{FE} Increase of I_{CBO} and I_{EBO}	Degradation of surface.	o Adoption of hermetically sealed package. o CVD SiO_2 passivation. o Si_3N_4 passivation.
Increase of V_{FE} Variation of P.G.	Electro-migration.	o Adoption of Ti-Pt-Au multi-layer electrode. o CVD SiO_2 passivation of appearance and control of thickness of Au. o Perfect execution of check.
Breakdown due to load variation.	Poor surge resisting characteristic.	o Adoption of emitter ballast resistor. o Adoption of double epitaxial.

In addition, in order to improve the reliability of the device when used in the field, attention was paid to the following points in the design of the device.

o Reduction of operating voltage (Reduction from conventional, 28V to 20V). And, in order to reduce the junction temperature as much as possible when operating, the employment of appropriate design for the chip and the package and the adoption of IMN for the input and output. (According to MIL-HDBK-217B, compared to when IMN is not applied, the failure rate is reduced to 1/4 when IMN is applied to the input and output.)

In order to completely meet the market requirements and to make the device easier for the customer to use the following design features are incorporated in the devices.

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- A stepped electrode is structure used so that high power, gain, and efficiency may be realized at low voltage (20V).
- With the aim of obtaining high stability, porous SiO_2 is employed under the bonding pad in order to reduce feedback capacity (MOS capacitance).
- Adoption of IMN for the input and output, which also enhances wide band use.

NEC microwave power transistors, designed as described above, display performance which is extremely useful for all applications including communication, telemetry, and radar, and in addition are of extremely high quality and reliability.

To take the NEM4203B-20 type as an example:
at, $f = 4.2GHz$ and $Vcc = 20V$
typically, $Po = 3W$, $P_G = 5$ dB, $\eta_C = 30\%$, and B.W. = 400MHz
is obtained.

Under the above conditions the device will withstand any variations of the load and is very easy to use.

Further under the above operating conditions the junction temperature of the device is a low 120°C, which enables the device to be operated at ample margin from the rating, $Tj = 200°C$.

3. QUALITY ASSURANCE SYSTEM AND PROCESSING.

NEC has established a quality assurance program for high reliability microwave transistors which are intended for use in satellites etc. Numerous products manufactured and delivered under this program have won an excellent reputation in many fields.

NEC microwave power transistors are subject to appropriate process conditioning and characteristic stabilization under a program based on the above quality assurance program and, thus, high quality and reliability products are offered to customers.

This program is composed as shown in Table 3-1, according to the 4 grades of reliability prescribed in Table 2.

Table 2. NEC's Microwave Power Transistors Reliability Grade

Reliability Grade	Expected Field Failure Rates with 60% Confidence Level	Application
A Super High Reliability	~15 (FIT)	Space electronics, submerged cable repeater, high speed PCM and other super high-rel applications.
B High Reliability	~70 (FIT)	Space electronics, phased array radar, microwave carrier relay link, carrier transmission and other industrial and communication systems requiring high reliability.
C Military Grade (JAN TX and JAN TXV equivalent)	~300 (FIT)	General industrial and military applications such as mobile radios, avionics, ECM, EW applications.
D Industrial Grade	~1200 (FIT)	General industrial and consumer applications such as TV tuners, test equipment, radio sets, tape recorders, mobile radios, CATV, MATV, and transceivers.

The expected values of failure rate shown in Table 2 are based on actual market performance of NEC microwave semiconductor devices, such as bipolar signal transistors, conventional microwave power transistors, etc. and are considered to be values on which full reliance can be placed.

As a method for forecasting the failure rate of semiconductor devices in the field, there is MIL-HDBK-217B. However, regarding NEC microwave power transistors there is a great difference between the values forecasted by this method and the expected values of NEC.

Now, when the failure rate in the field of a NEM4203B-20 device used in a communication application is forecasted according to MIL-HDBK-217B, the result is as follows:

$\lambda_P = \lambda_B \cdot \pi_Q \cdot \pi_A \cdot \pi_F \cdot \pi_T \cdot \pi_M \cdot \pi_E$
where,

λ_P: Parts failure rate.
λ_B: 0.1 failures/10^6 hours
π_Q: Quality factor
Grade C (JAN TX or equivalent) → 2
π_A: Application factor
Continuous wave → 4
π_F: Factor for frequency and peak operating power.
$f = 4.2\text{GHz}$ $P_{out} = 3\text{W} \rightarrow 10.0$
π_T: Temperature factor
$V_{CC}/BV_{CES} = 20/45 = 0.44$ $T_j = 120°\text{C} \rightarrow 0.2$
π_M: Matching network factor
with input and output IMN → 1
π_E: Enviromental factor
Ground fixed → 2

therefore,

$\lambda_P = 0.1 \times 2 \times 4 \times 10 \times 0.2 \times 1 \times 2 = 3.2$ failures/10^6 hours
= 3200FIT

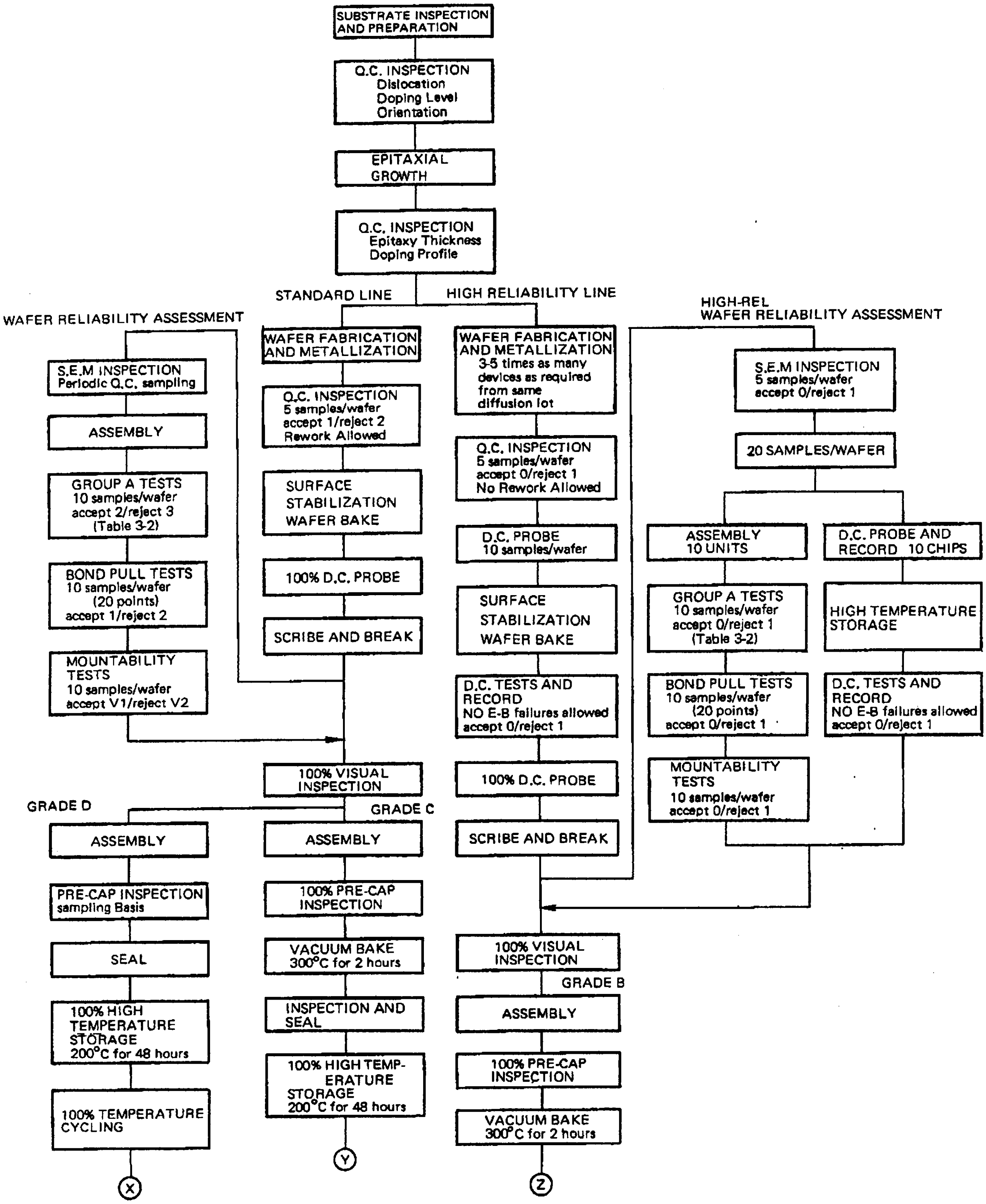
(When there is no input and output IMN, λ_P = 12800FIT)

However, the expected value of the failure rate of NEM4203B-20 devices delivered through the program shown in Table 3-1 corresponds to grade C. As shown in Table 2 this is 300FIT and is only 1/10 of the value forecasted by MIL-HDBK-217B. This is the value on which ample expectations can be placed, when inferred from the actual market performance of 7FIT for high reliability NEC microwave bipolar transistors (grade B products) and 40FIT for conventional microwave power transistors (grade B products), such transistors having been delivered and put to practical use in great numbers in the past.

That is, NEC microwave power transistors, which have been designed carefully as described before (see paragraph 2) and have been delivered through the Microwave Power Transistor Quality Assurance Program shown in Table 3-1, are of grade C level and have an expected failure rate which is less than 1/10 of that forecasted by MIL-HDBK-217B.

In other words, in regards to NEC microwave power transistors the failure rated forecast by MIL-HDBK-217B is not worth using even as a reference.

Table 3-1 Microwave Power Transistors Quality Assurance Program



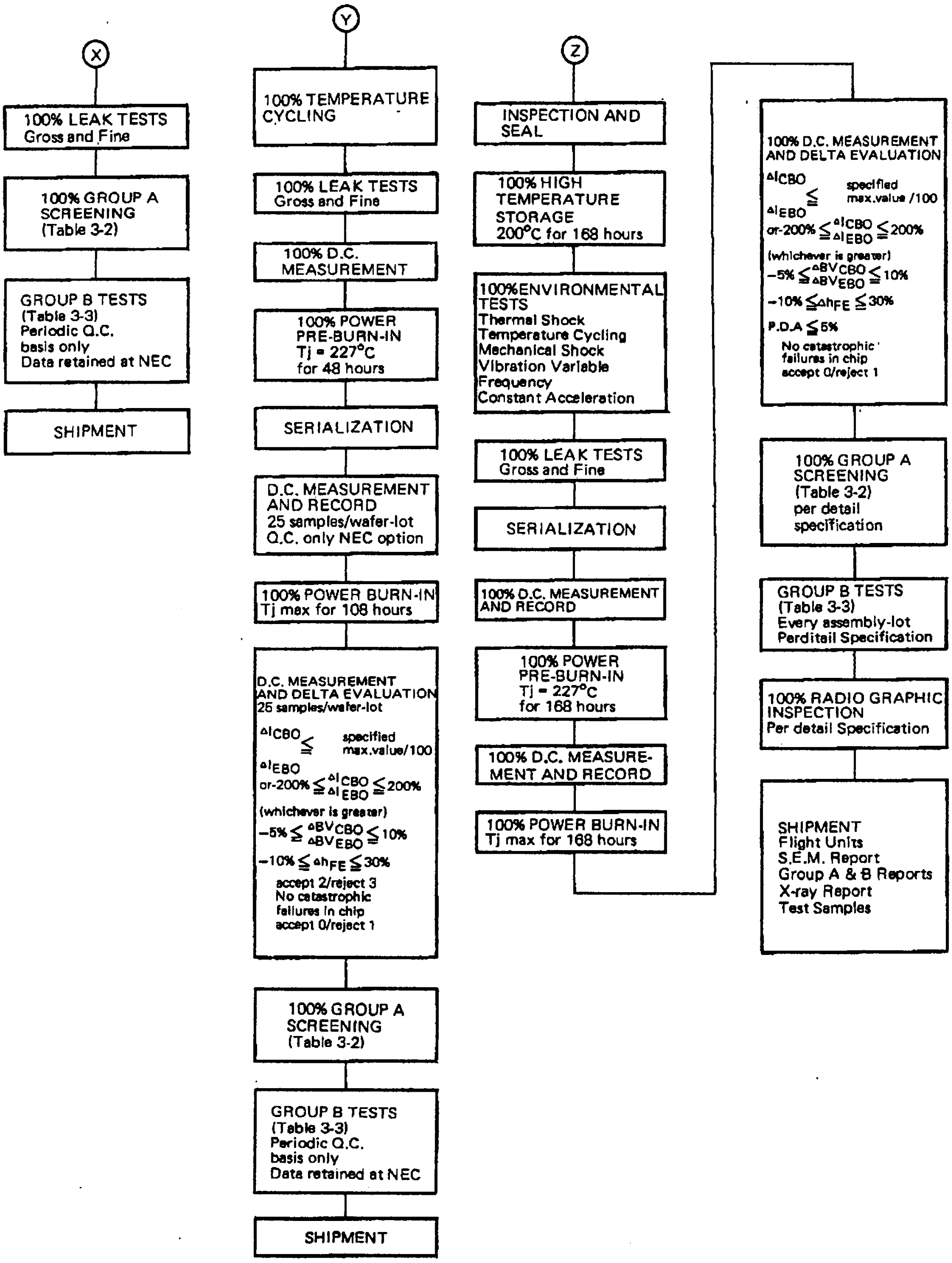

X
100% LEAK TESTS Gross and Fine
100% GROUP A SCREENING (Table 3-2)
GROUP B TESTS (Table 3-3) Periodic Q.C. basis only Data retained at NEC
SHIPMENT
Y
100% TEMPERATURE CYCLING
100% LEAK TESTS Gross and Fine
100% D.C. MEASUREMENT
100% POWER PRE-BURN-IN $T_j = 227°C$ for 48 hours
SERIALIZATION
D.C. MEASUREMENT AND RECORD 25 samples/wafer-lot Q.C. only NEC option
100% POWER BURN-IN Tj max for 108 hours
D.C. MEASUREMENT AND DELTA EVALUATION 25 samples/wafer-lot
$\frac{\Delta I_{CBO}}{\Delta I_{EBO}} \leqq$ specified max.value/100
or $-200\% \leqq \frac{\Delta I_{CBO}}{\Delta I_{EBO}} \leqq 200\%$
(whichever is greater)
$-5\% \leqq \frac{\Delta BV_{CBO}}{\Delta BV_{EBO}} \leqq 10\%$
$-10\% \leqq \Delta h_{FE} \leqq 30\%$
accept 2/reject 3
No catastrophic failures in chip accept 0/reject 1
100% GROUP A SCREENING (Table 3-2)
GROUP B TESTS (Table 3-3) Periodic Q.C. basis only Data retained at NEC
SHIPMENT
Z
INSPECTION AND SEAL
100% HIGH TEMPERATURE STORAGE 200°C for 168 hours
100%ENVIRONMENTAL TESTS Thermal Shock Temperature Cycling Mechanical Shock Vibration Variable Frequency Constant Acceleration
100% LEAK TESTS Gross and Fine
SERIALIZATION
100% D.C. MEASUREMENT AND RECORD
100% POWER PRE-BURN-IN $T_j = 227°C$ for 168 hours
100% D.C. MEASUREMENT AND RECORD
100% POWER BURN-IN Tj max for 168 hours
100% D.C. MEASUREMENT AND DELTA EVALUATION
$\frac{\Delta I_{CBO}}{\Delta I_{EBO}} \leqq$ specified max.value /100
or $-200\% \leqq \frac{\Delta I_{CBO}}{\Delta I_{EBO}} \leqq 200\%$
(whichever is greater)
$-5\% \leqq \frac{\Delta BV_{CBO}}{\Delta BV_{EBO}} \leqq 10\%$
$-10\% \leqq \Delta h_{FE} \leqq 30\%$
$P.D.A \leqq 5\%$
No catastrophic failures in chip accept 0/reject 1
100% GROUP A SCREENING (Table 3-2) per detail specification
GROUP B TESTS (Table 3-3) Every assembly-lot Perditail Specification
100% RADIO GRAPHIC INSPECTION Per detail Specification
SHIPMENT Flight Units S.E.M. Report Group A & B Reports X-ray Report Test Samples

Table 3-2 Group A Tests for Microwave Power Transistors

EXAMINATION OR TEST	SYMBOL	MIL-STD-750 METHOD	LTPD (MAX ACCEPTABLE NUMBER OF ACCEPTANCE)
			Grades B, C, D
1 Visual and Mechanical Examination		2071	15 (3)
2 Leakage Current Breakdown Voltage	I_{CBO}, I_{EBO} BV_{CBO}, BV_{EBO} etc.	3001D 3026D 3011D 3026D	5 (4)
3 DC Dynamic Characteristics	h_{FE}, $V_{CE(S)}$ etc.	3076	7 (3)
4 RF Dynamic Characteristics	Cob, P, G etc.	3261 3236	10 (3)
5 RF Dynamic Characteristics	Pout B. W. etc.		10 (3)
6 Temperature Characteristics	I_{CBO}, BV_{CBO} h_{FE} etc.	3936	15 (3)

Table 3-3 Group B Tests for Microwave Power Transistors

EXAMINATION OR TEST	MIL-STD-750 METHOD	CONDITION	LTPD (MAX ACCEPTABLE NUMBER OF ACCEPTANCE)		
			B	C	D
Subgroup 1					
Physical Dimensions	2066	Per Product Data Sheet	20 (0)	20 (0)	20 (0)
Subgroup 2			10 (0)	20 (0)	20 (0)
Solderability	2026.2				
Temperature Cycling	1051	Condition C			
Thermal Shock (Strain)	1056	Condition A			
Moisture Resistance	1021.1	Omit Para. 2a (Initial conditioning)			
Hermetic Seal. Fine Leak	1071	Condition G (max leak rate 5 x 10^{-8} atm cc/s)			
Hermetic Seal. Gross Leak	1071	Condition C, Step 1			
End Points:					
Forward Current Gain	3076.1	Per Data Sheet Limits			
Reverse Leakage Current	3036.1D	Per Data Sheet Limits			
Subgroup 3			10 (0)	20 (0)	20 (0)
Shock, Nonoperating	2016	1500G, t=0.5ms, 5610ws. X_1, Y_1, Y_2			
Vibration, Variable Frequency	2056	(Nonoperating)			
Vibration, Fatigue	2046	(Nonoperating)			
Constant Acceleration	2006	20,000G. Y_1 only			
End Points:					
Same as Subgroup 2					
Subgroup 4					
Terminal Strength	2036	Condition E	20 (0)	20 (0)	20 (0)
Subgroup 5			20 (1)	30 (1)	30 (1)
Steady State Operating Life	1026.3	1000 hours @ Tj max			
End Points:					
Same as Subgroup 2					
Drift Criteria:					
Δh_{FE}, ΔI_{CBO1} (or ΔI_{CBO2})		$-30\% \leqq \Delta h_{FE} \leqq 50\%$ of initial value $\Delta I_{CBO} \leqq$ specified max. value/10 or $-500\% \leqq I_{CBO} \leqq 500\%$ of initial value whichever is greater			

Note: Subgroups listed are standard for all parts. Other subgroups are optional. The number of samples specified will be changed according to the customer's specification, or the NEC can reserve the right to specify the number of samples to be tested according to field data.

4. RESULTS OF RELIABILITY EVALUATION.

Various aspects of reliability evaluation were performed on NEC microwave power transistors, which had been carefully designed as described in paragraph 2.

The substance and results of these evaluations are shown in Tables 4-1 and 4-2, and Fig. 1 and 2.

Table 4-1 LIFE TESTS

EXAMINATION	CONDITION	SAMPLES	QUANTITY	RESULTS	DRIFT CRITERIA
High Temperature Life (Nonoperating)	Ta = 200°C	NEM2003B-20* NE 3001B-20* NEM4201B-20*	20 each	See, Fig. 1, Fig. 2	$-20\% \leqq \Delta BV_{CBO} \leqq 20\%$ $-20\% \leqq \Delta BV_{EBO} \leqq 20\%$ $I_{CBO} \leqq$ Specified Value $I_{EBO} \leqq$ Specified Value $-50\% \leqq \Delta h_{FE} \leqq 50\%$ $-20\% \leqq \Delta h_{FE} \leqq 20\%$ $-20\% \leqq \Delta \theta_{J\text{-}F} \leqq 20\%$
	Ta = 259°C		20 each		
	Ta = 295°C		20 each		
	Ta = 337°C		15 each		
	Ta = 365°C		10 each		
Steady State Operating Life	Tj = 200°C		20 each		
	Tj = 259°C		20 each		
	Tj = 295°C		20 each		
High Temperature Reverse Bias Test	Ta = 150°C V_{CES} = 30V 5000H	NEM2003B-20 NE 3001B-20 NEM4201B-20	20 each	Failure 0	
Moisture Resistance	85°C, 85% 5000H		20 each	Failure 0	
High Temperature Life (Nonoperating)	Ta = 227°C 5000H		20 each	Failure 0	
Steady State Operating Life	Tj = 227°C 5000H		20 each	Failure 0	
Operating Life (RF)	Tj = 140°C 5000H	NEM2000 Series	12 each	Failure 0	$\Delta PG \leqq 1$ dB

* A package which is resistive upto 365°C is used for the sample.

Table 4-2 ENVIRONMENTAL TESTS

EXAMINATION	CONDITION	SAMPLES	QUANTITY	RESULTS	DRIFT CRITERIA
Thermal Test	Resistance to Soldering Heat 260°C, 10 seconds	NEM2003B-20 NE3001B-20 NEM4201B-20	40 each	Failure 0	$-30\% \leq \Delta h_{FE} \leq 50\%$ $\Delta I_{CBO} \leq$ Spec. Value/10 or $-500\% \leq \Delta I_{CBO} \leq 500\%$ (Whichever is greater) Hermetic seal Fine Leak 10^{-8} atm cc/sec. Gross Leak
	Thermal Shock 0°C ~ 100°C, 100∿				
	Temperature Cycling −65°C ~ 200°C, 100∿				
Mechanical Test	Mechanical Shock 1500G, 0.5ms, 20 times in each of three directions		40 each	Failure 0	
	Variable Frequency 100 ~ 2000Hz, 20G, 4 minutes, 20 times in each of three directions				
	Constant Acceleration 20000G, 1 minutes, 5 times in each of three directions				
Solderability	230°C, 5 seconds	NE3001B-20 NEM4203B-20	60 each	Failure 0	Good Soldering
Terminal Strength	Pull Test 0.5 kg in 30 seconds for collector lead 1 kg in 30 seconds for emitter lead		60 each	Failure 0	No damage Hermetic Seal Fine Leak 10^{-8} atm cc/sec. Gross Leak
	Bend Test 3 times, 227 g for collector lead 3 times, 450 g for emitter lead				

In order to speed the analysis of data, life tests were conducted under accelerated stress conditions. And extrapolation was employed when estimating, from these test results, the life of devices under operating conditions (Tj = 120°C). Also, the environmental tests were performed with the number of stresses increased further than that of the conditions of Group B shown in paragraph 3.

Fig. 1 The Results of Life Tests

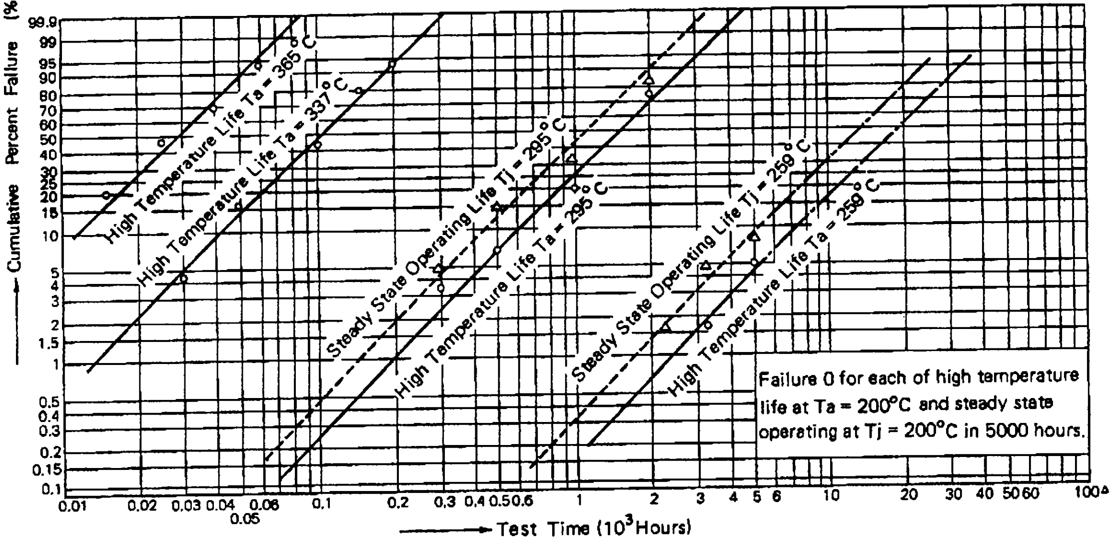


Fig. 2 Life vs. Junction Temperature

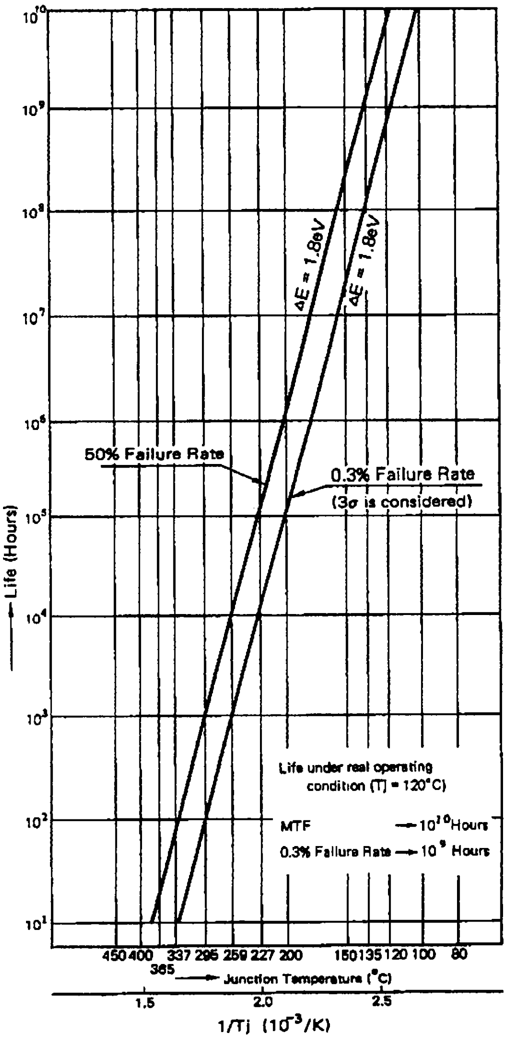


Fig. 1 shows the results of the life tests plotted on weibull probability graph paper. Fig. 2 shows the relationship between life and junction temperature deducted from the results of the life tests.

Failure modes observed in the accelerated life tests were degradation of the junction and variation of h_{FE} of which degradation of the junction dominated.

Degradation of the junction was caused by Au of the multilayer electrode diffusing, through the Pt and Ti layers, into the Si bulk.

From the life tests, an activation energy of E = 1.8eV was obtained as the life versus junction temperature. This value matches approximately the activation energy of the Au diffusion phenomenon mentioned above.

From the data of Fig. 2, the following value can be expected as the life of the device under actual operating conditions (Tj = 120°C).

The life (MTF) when 50% of the parent body is faulty.

10^{10} hours.

The life when 0.3% of the parent body is faulty.

10^9 hours.

(The 3σ variation of life taken into consideration)

From the above results, it is clear that there is absolutely no problem existing concerning the life, in regards to thermal stress, of NEC microwave power transistors.

Also, absolutely no problems exist in regards to the environmental tests.

In contrast to small signal transistors, power devices which are operated at high temperatures and current densities, have electro-migration of the electrodes as a prominent factor determining the device reliability.

Measures taken in design to minimize the above electro-migration in NEC microwave power transistors and the reliability evaluation in this regard is explained below.

When designing NEC microwave power transistors, the design target is placed so that a life against electro-migration of over 10^6 hours (114 years) could be obtained under actual operating conditions (Tj ≅ 120°C, rated RF operating conditions). (For details of design refer to paragraph 2.)

Electro-migration is a phenomenon where colliding occurs between thermally activated conduction electrons and metal ions, inside metal films operating at high temperature and current density, and the metal ions are moved in the direction of the electron flow, thus, creating a void at the negative potential end and, conversely, a hillock at the positive potential end which will finally cause a open or short circuit. The electro-migration phenomenon is greatly dependent upon the temperature and current density of the metal film.

J. R. Black has experimentally shown that the life of a metal film due to electro-migration is as follows:

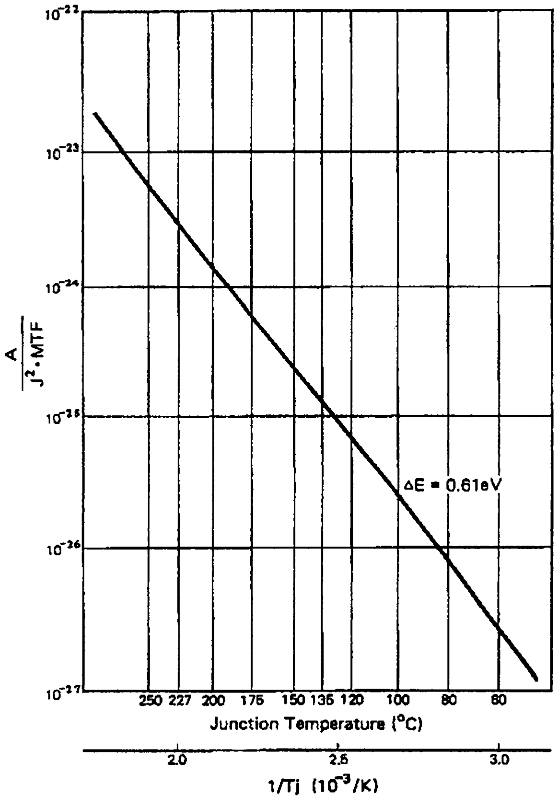
$$\mathrm{MTF} = C\frac{A.\exp\,(\Delta E/KT)}{J^2} \quad \text{(Hours)}$$

where,

C: Constant dependent on characteristics of the metal film.
A: Cross section of the metal film (cm^2).
E: Activation energy (eV).
K: Boltzmann's constant.
T: Temperature of metal film (K).
J: Current density of metal film ($\mathrm{A/cm}^2$).

The above equation shows that the life of metal film due to electromigration is inversely proportional to the square of the current density and the temperature of the metal film. From experiments conducted in NEC microwave power transistors, the results shown in Fig. 3 were experimentally obtained. From the data shown in Fig. 3, in regards to NEC microwave power transistors, the above equation becomes as follows.

Fig. 3 MTF for gold Film in NEC'S microwave Power Devices as a Function of current density, Junction Temperature and cross sectional dimensions



$$MTF = 2.36 \times 10^{17} \times \frac{A.\exp(0.61/KT)}{J^2} \quad \text{(Hours)}$$

When, based in the above equation, the MTF of NEC microwave power transistors is shown as a function of the square of the operating current and the junction temperature, the results are as shown in Figs. 4 to 6.

When employing the data of Figs. 4 to 6 as reference, the MTF under rated RF operating conditions (actual operating conditions) of type NEM2010B-20, NE3003B-20, and NEM4203B-20 NEC microwave power transistors are determined, the results are as shown below.

Fig. 4 MTF Factor vs. Junction Temperature for 2 GHz power transistors Failure due to electromigration

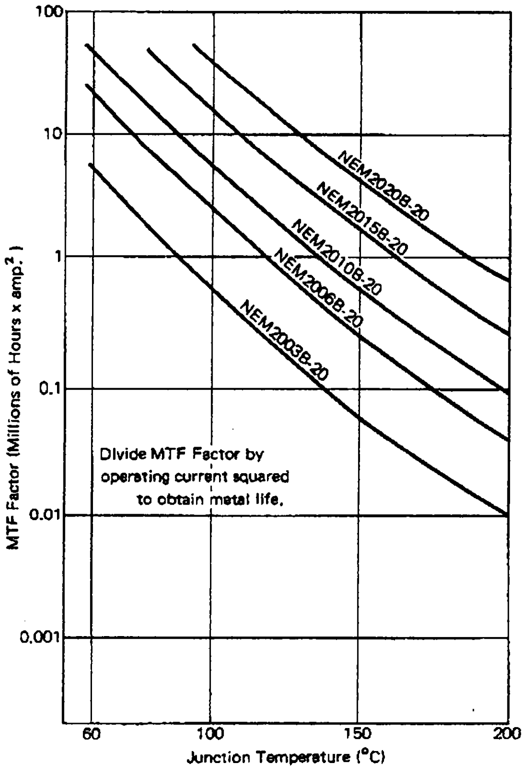


Fig. 5 MTF Factor vs. Junction Temperature for 3 GHz power transistor Failure due to electromigration

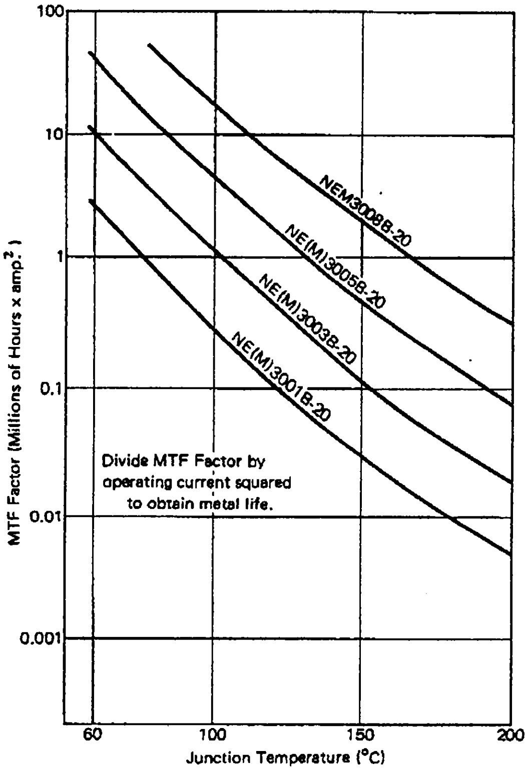
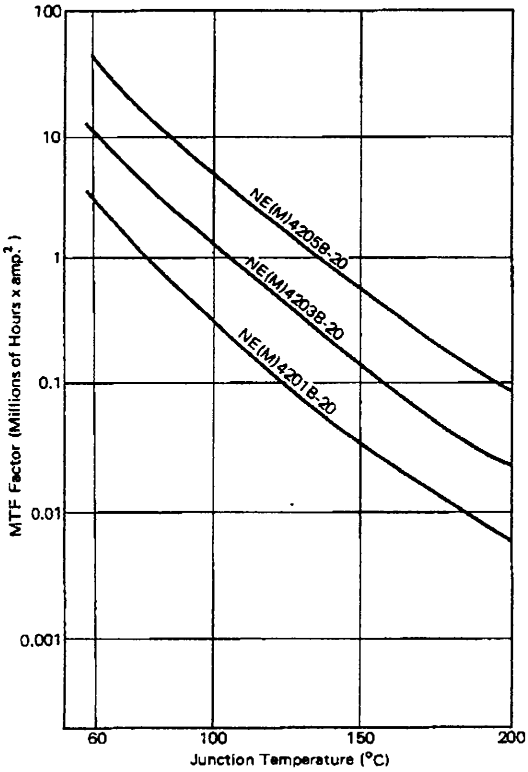


Fig. 6 MTF Factor vs. Junction Temperature for 4 GHz power transistor Failure due to electromigration.
Divide MTF Factor by operating current squared to obtain metal life.



	freq. (GHz)	Vcc (V)	Pi (W)	Po (W)	η_C (%)	$\theta_{J\text{-}F}$ (°C/W)	Tflange (°C)	I_C (A)	Pdiss. (W)	Tjunc. (°C)	MTF factor at Tjunc. (10^6 hours x A^2)	MTF (10^6 hours)
NEM2010B-20	1.9	20	2	10	48	4.8	60	1.04	12.8	121	1.85	1.71
NE3003B-20	3	20	0.5	3	30	8	60	0.5	7.5	120	0.42	1.68
NE4203B-20	4.2	20	1	3	30	7.5	60	0.5	8	120	0.5	2.0

$$I_C = \frac{Po}{\eta_C \times V_{CC}}$$

$$P_{diss.} = Pi + (V_{CC} \times Ic - Po)$$

$$T_{junc.} = T_{flange} + \theta_{J\text{-}F} \times P_{diss.}$$

As can be seen from the above calculations, under actual operating conditions NEC microwave power transistors have a MTF of over 10^6 hours, as desinged.

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