

## Technical Paper

# Study of Thermal Stress Durability Evaluation for Thermoelectric Module Using Quality Engineering

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*A thermoelectric module, or TEC (thermoelectric cooler), is a solid-state device that converts electric energy to endothermic energy using the Peltier effect. The requirements for TEC include the durability against the thermal stress generated inside TEC as well as the endothermic efficiency with respect to input power. For increased thermal stress durability of TEC, we examined functionality evaluation methods and conducted a parameter design based on quality engineering without using the conventional approach of durability testing. In this functionality evaluation, we measured the voltage response of TEC under the noise factor of applying the desired thermal stress to the TEC, and made an evaluation based on the standardized signal-to-noise (S/N) ratio. The time it took for functionality evaluation was 5 hours per one TEC, which is considered to be a short time as compared with the 500 hours needed for durability testing. The results of the parameter designing indicated a certain additivity, which could provide at least 1.78<sup>2</sup> times improvement in functionality in terms of gain as compared with the current condition. We also examined the errors included in the results, which provided us with insight into the factors to be considered for further improvement in additivity and functionality. We are planning to examine the effect of the gain achieved in this study on TEC's life in durability tests.*

**Key Words:** *Thermoelectric module, TEC, Thermal stress, Quality engineering, Functionality evaluation, Parameter design, Gain, Additivity, Durability test*

## 1. Introduction

KELK Ltd. is a manufacturer and supplier of thermoelectric modules. Thermoelectric module is also called TEC (thermoelectric cooler). A TEC is a solid-state device that converts electric energy to endothermic energy using the Peltier effect, and provides accurate and responsive temperature control. The TECs manufactured by KELK, which take advantage of this feature, are used for temperature control of optical parts such as laser diodes for optical communications as well as for temperature control in semiconductor manufacturing processes. As shown in **Fig. 1**, a typical TEC consists of P- and N-type thermoelectric elements that are connected in series in the form of the Greek letter  $\Pi$  (pi) via electrodes on ceramic substrates. When the TEC is operated, a temperature difference is generated

between the substrates. This requires the durability against the thermal stress that is generated inside the TEC by the temperature difference as well as the high endothermic efficiency with respect to the supplied electric energy. One of the conventional methods of evaluating thermal stress durability is the ON/OFF electrification test. However, this test takes a long time, 500 hours per one TEC<sup>1)</sup>. Therefore, this method is to be used for the final quality check of particular types of TECs, and is not considered to be a high-throughput evaluation method for validating the numerous design parameters of TECs, which is required in the research and development stage. In this study, we employed a quality engineering approach to examine methods that allow the thermal stress durability of TECs to be evaluated in a short period of time in the research and development phase. We

also conducted a parameter design using an L<sub>18</sub> orthogonal array to find effective design parameters for improving the thermal stress durability. This report was first published at the 22nd Quality Engineering Society Annual Conference (QES2014), and revised for this issue of Komatsu Technical Report<sup>2)</sup>.

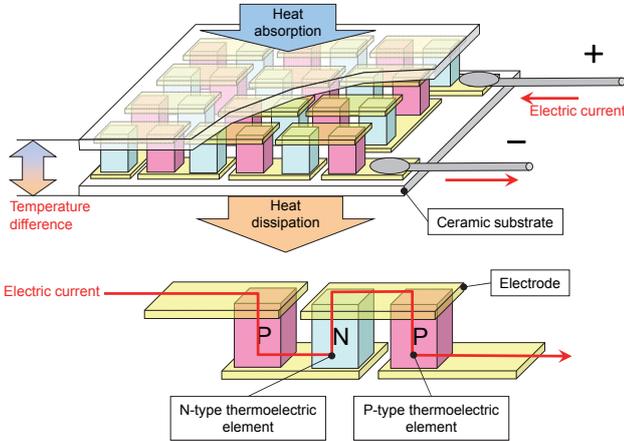


Fig. 1 Structure of TEC

## 2. Operating Principle of TEC

In short, the role of a TEC is to convert supplied electric energy to endothermic energy. Its energy balance is shown in Fig. 2 in terms of the relationship between the endothermic amount  $Q_c$ , the amount of heat dissipation  $Q_h$ , and the supplied electric power  $P$ . When current  $I$  is applied to the TEC, this relationship is expressed by equations (1) to (3)<sup>3)</sup>. Where  $T_c$ ,  $T_h$ , and  $\Delta T$  are the endothermic temperature, the heat dissipation temperature, and the temperature difference ( $= T_h - T_c$ ), respectively.  $A$ ,  $R$ , and  $K$  are the Seebeck coefficient [V/K], the internal resistance [ $\Omega$ ], and the thermal conductance [W/K] of the TEC, respectively, which are determined by the material properties, shape and the number of the thermoelectric elements.

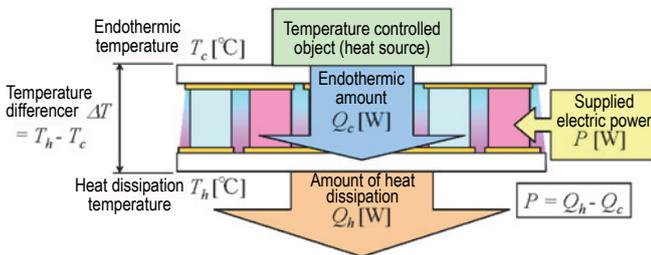


Fig. 2 Energy balance of TEC

$$Q_c = AT_c I - \frac{1}{2} I^2 R - K \Delta T \quad (1)$$

$$Q_h = AT_h I + \frac{1}{2} I^2 R - K \Delta T \quad (2)$$

$$P = Q_h - Q_c \quad (3)$$

In both equations (1) and (2), the first, second and third terms on the right side are the thermal contributions by the Peltier effect, Joule heating, and solid heat conduction, respectively. As shown in equation (3), the difference between the endothermic amount and the amount of heat dissipation corresponds to the electric power. Substituting equations (1) and (2) into equation (3),  $P$  is expressed by equation (4). The electric power is generally the product of current and voltage, so the voltage  $V$  of the TEC is given by formula (5). Thus, the voltage of the TEC corresponds to the sum of the voltage drop ( $IR$ ) based on the Ohm's law and the thermoelectromotive force ( $A\Delta T$ ) that is generated in proportion to the temperature difference.

$$P = I(IR + A\Delta T) \quad (4)$$

$$V = IR + A\Delta T \quad (5)$$

## 3. Evaluation of TECs

### 3.1 General evaluation method

The general quality characteristics for indicating the performance of a TEC include  $\Delta T$  and  $Q_c$  based on equation (1). For the TECs marketed by KELK, information on these quality characteristics is provided for each product model<sup>4)</sup>.  $\Delta T$  and  $Q_c$  can be evaluated through actual measurement, where a heat source and temperature sensors are attached to a sample TEC, and  $\Delta T$  and  $V$  with respect to  $I$  under the heat load  $Q_c$  from the heat source are measured<sup>5)</sup>. While this measurement is direct and effective if the specification of TEC's quality characteristics is to be determined, it tends to incur a dispersion of results depending on how the sensors are attached, thus requiring standardization of the measurement procedure and repeated measurements. In fact,  $\Delta T$  and  $Q_c$  are rarely measured in durability tests of TECs. Instead, the internal resistance  $R$  is usually measured as a representative characteristic. However, this is not directly evaluating the function of the TECs, as it is based on the assumption that any deterioration of TECs appears as the increase in  $R$ .

### 3.2 Evaluation method in this study

In quality engineering, which we employed in this study, the stability of product functions against external disturbances (functionality) is evaluated. The term functionality used in quality engineering does not simply mean quality characteristics. It refers to the input-output relationship (dynamic characteristics) of basic functions that support the quality characteristics. For example, when looking at the internal resistance of an electronic device, measuring the resistance will suffice to determine the quality characteristic

values only. In quality engineering, however, current-voltage characteristics based on the Ohm's law are treated as a function, which is subject to functionality evaluation. This is based on the assumption that if current-voltage characteristics are stable against external disturbances, the resistance, which is one of the quality characteristics, should also naturally be stable, and that, therefore, study should be focused on the improvement of functionality instead of quality characteristics in the research and development stage. For functionality evaluation in this study, the authors looked at the voltage response  $V(t)$  with respect to the step input of constant current  $I_0$  into a TEC. Although  $Q_c = 0$  when there is no heat source on the heat absorbing surface in the steady state of TEC operation, the transient state until  $\Delta T$  reaches the steady state can be expressed by equation (6), where  $C$  is the heat capacity of the TEC and  $t$  is time.

$$Q_c = C \frac{d\Delta T}{dt} \tag{6}$$

Substituting equation (1) into equation (6) gives a linear differential equation, and the solution  $\Delta T(t)$  for  $\Delta T(0) = 0$ ,  $\Delta T(\infty)$  in the steady state, and the time constant  $\tau$  can be expressed as follows:

$$\Delta T(t) = \Delta T(\infty) (1 - e^{-t/\tau}) \tag{7}$$

$$\Delta T(\infty) = \frac{AT_h I_0 - \frac{1}{2} I_0^2 R}{K + AI_0} \tag{8}$$

$$\tau = \frac{C}{K + AI_0} \tag{9}$$

Also, from equations (5) and (7),  $V(t)$  is given by equation (10). Its build-up rate is given by equation (11). These relationships are illustrated in Fig. 3.

$$V(t) = I_0 R + A \Delta T(t) \tag{10}$$

$$\frac{dV(0)}{dt} = A \frac{\Delta T(\infty)}{\tau} \tag{11}$$

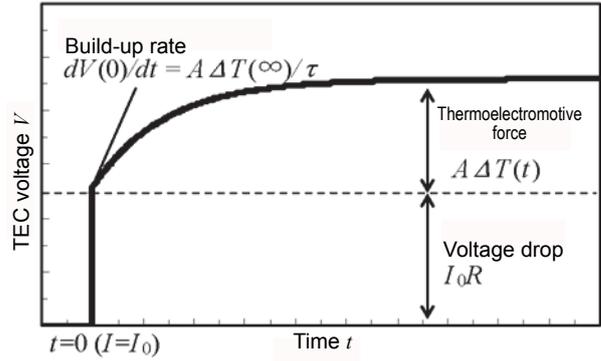


Fig. 3 Voltage response during step input of constant current to TEC

Thus,  $V(t)$  is considered to include information on  $Q_c$  and  $\Delta T$  that indicate the performance of the TEC. In addition, the measurement of  $V(t)$  produces less dispersion and takes less time as compared with temperature measurement. For this reason, we regarded  $V(t)$  in the step input of constant current  $I_0$  as a TEC function, and assumed that TECs with stable  $V(t)$  are those having high functionality, i.e., high durability against thermal stress.

#### 4. Parameter Design

##### 4.1 Noise factors

In quality engineering, the noise factor means the user conditions, which include all conditions that are affected during the period when a product is used, such as the dispersion of materials and parts, the dispersion of manufacturing and assembly, the dispersion of use conditions and environments, and deterioration over time. The functional stability (functionality) with respect to the noise factors is evaluated using the S/N ratio. Searching for design parameters that contribute to the improvement of functionality using the S/N ratio and orthogonal array is called parameter design. Although noise factors cannot be controlled in the market, parameter design for evaluating functionality is conducted under the influence of noise factors that are intentionally controlled. In quality engineering, how the correct noise factors are set for specific purposes is important, in addition to how the functions are defined and measured, both of which are largely dependent on specific technologies. In this study, we focused on the thermal stress durability of TECs and evaluated the functionality with respect to the thermal stress generated by the temperature difference  $\Delta T$  during TEC operation. As a substitute for the thermal stress load in the market, we intentionally applied thermal stress to TECs by a certain method and used it as noise factors. In

conventional ON/OFF durability tests, thermal stress cycles by  $\Delta T$  were applied for 500 hours. In order to reduce the testing time in this study, we devised a method for quickly and efficiently applying a thermal stress in a repeatable manner. Considering the risk that the TEC's functionality would not be accurately observed if the noise factors were too large, we formulated a method for applying the appropriate thermal stress based on preliminary experiments, and set the levels of noise factors as  $N_0$ : thermal stress not applied (standard condition),  $N_1$ : application of medium thermal stress, and  $N_2$ : application of high thermal stress.

**4.2 Control factors and mapping to orthogonal array**

While noise factors correspond to unintentional external disturbances to product functions in the market, control factors to be mapped to an orthogonal array correspond to product design parameters that can be selected by the designers as desired. Orthogonal array are used in the experimental design method for minimizing the number of experiments to obtain information, which otherwise would require numerous experiments by combining the various levels of many factors. Dr. Genichi Taguchi, the founder of quality engineering, was an expert of the experimental design method and is also known as a winner of the Deming Prize for Individuals for the invention of the linear graph. The expert of experimental design developed applications of orthogonal array into the form of quality engineering. While the second or third level orthogonal array are mostly used in the conventional experimental design method, mixed type orthogonal array are often used for parameter design in quality engineering<sup>9)</sup>. In second and third level orthogonal array, there are columns where interactions appear (this situation is indicated in a linear graph), and factors cannot be mapped in these columns. This is a shortcoming because a smaller number of factors relative to the number of experiments can be mapped. In mixed type orthogonal array, on the other hand, interactions do not appear in specific columns, which is an advantage over the conventional method because the effects of a greater number of factors can be examined with a smaller number of experiments. In quality engineering that uses mixed type orthogonal array that do not directly show interactions, we cannot know the number and places of interactions. But there is a way to find the existence of interactions. This is done by checking for repeatability (additivity) in the confirmation run described later. Although details are not disclosed here, we used design parameters related to the mechanical structure of TECs as control factors, which are mapped in an  $L_{18}$  orthogonal array as shown in

**Table 1.** The column in the table shows the factor types (A to H), while the row shows the test numbers (1 to 18). The numbers in the table represent the level (1 to 3) of each factor. For example, the factors in experiment number 1 are all level 1. Factor A is level 2 and factors B to H are level 3 with the total number of combinations is  $2 \times 3 = 4,374$ , but these combinations are represented by only 18 combinations. As for factors A and B in our parameter design, however, those that affect each other were selected, so six combinations in the table were selected for mapping from the feasible combinations among those of factor A in level 2 and factor B in level 4. Since only level 2 can be set to factor E, E1 in level 1 in column E was mapped to level 2 in column E as a dummy (E1'). Control factors were not mapped to columns G and H, which were treated as error columns. This resulted in 18 combinations to be selected for experiment from the total of 324 ( $6 \times 3 \times 3 \times 2 \times 3 \times 1 \times 1$ ) combinations. In our parameter design, 18 TECs were actually assembled for use as test pieces according to **Table 1**.

**Table 1** Mapping to  $L_{18}$  orthogonal array

Test No.	Control factor code						
	A×B	C	D	E	F	G e	H e
1	1×1	1	1	1	1	1	1
2	1×1	2	2	1'	2	2	2
3	1×1	3	3	3	3	3	3
4	1×2	1	1	1'	2	3	3
5	1×2	2	2	3	3	1	1
6	1×2	3	3	1	1	2	2
7	1×3	1	2	1	3	2	3
8	1×3	2	3	1'	1	3	1
9	1×3	3	1	3	2	1	2
10	2×1	1	3	3	2	2	1
11	2×1	2	1	1	3	3	2
12	2×1	3	2	1'	1	1	3
13	2×4	1	2	3	1	3	2
14	2×4	2	3	1	2	1	3
15	2×4	3	1	1'	3	2	1
16	2×3	1	3	1'	3	1	2
17	2×3	2	1	3	1	2	3
18	2×3	3	2	1	2	3	1

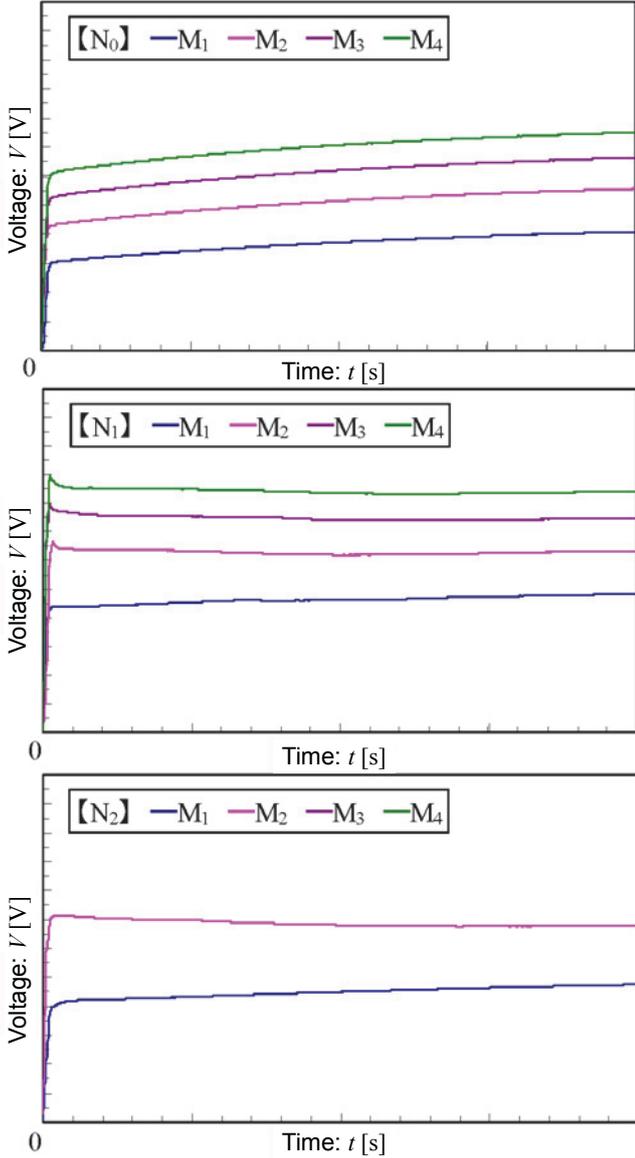
**4.3 Experiment procedure**

As described above, the  $V(t)$  with respect to the constant current  $I_0$  is the item to be measured. We determined  $I_0$  to be applied so that the supplied electric power at  $t = 0$  was equal among the test pieces. The level of the supplied power was defined as signal factor  $M_j$ , and 4 levels ( $j=1, 2, 3, 4$ ) were set in the order from the lowest power. Since the voltage response  $V_{ij}(t)$  for  $M_j$  is to be measured for each noise factor  $N_i$  ( $i=0, 1,$

2), voltage response was measured 12 (4 × 3) times for each test piece. First, the  $V(t)$  of  $N_0$  was measured from  $M_1$  to  $M_4$  in this order, next,  $M_1$  to  $M_4$  in this order after applying  $N_1$ , then  $M_1$  to  $M_4$  in this order after applying  $N_2$ . These experiments with test numbers 1 to 18 were conducted on all of the 18 test pieces.

**4.4 Test results and standardized S/N ratio**

Taking test number 12 as an example, the measurement results of  $V(t)$  are shown in Fig. 4.



**Fig. 4** Measurement results of voltage response  $V(t)$  (Test No. 12)

For  $N_0$ ,  $V(t)$  is similar to that in Fig. 3, which is considered that the TEC function is maintained. However, for  $N_1$  and onward, the voltage build-up was lost in the initial time of electrification. Furthermore, in  $M_3$  and onward for  $N_2$ ,

the internal resistance  $R$  became  $\infty$  to cause an electrification failure, and the measurement became unable to perform. These are conditions (functional limit) where TECs' functions are lost due to deterioration destruction caused by thermal stresses. With the application of the noise factors, more than half of the TECs reached their functional limit through the entire test numbers. In general experiments where quality characteristics are measured, care is taken not to destruct test pieces. In quality engineering, on the other hand, analysis can be made even if more than half of the test pieces are destructed. In addition, the time it took for our experiment was 5 hours per TEC, which is considered to be a great reduction in time as compared with evaluation processes based on conventional durability tests. To present the experiment results in terms of S/N ratio, we used the standardized S/N ratio of  $N_1$  and  $N_2$  based on the measurement data for  $N_0$ . Expressing the voltage as  $V_{ij}(t_n)$  for noise factor  $N_i$ , signal factor  $M_j$  at  $t_n$  seconds,  $V_{ij}(t_n)$  became  $\infty$  in the test pieces that caused an electrification failure due to functional limit, making it impossible to calculate the standardized S/N ratio. So we used the reciprocal  $y_{ij}(t_n)$  of  $V_{ij}(t_n)$ , or  $y_{ij}(t_n) \rightarrow 0$  in this case, to determine the standardized S/N ratio. Expressing the signal  $W_j$  as  $y_{0j}(t_n)$ , the output as  $y_{ij}(t_n)$  ( $i=1,2$ ), and the time sections as  $t_0$  to  $t_k$ , the effective divisor  $r_{0j}$  and the liner expression  $L_{ij}$  were calculated using formulas (12) and (13). The virtual data  $y_{i'j}(t_n)$  for  $N_{i'}(i'=1,2)$  used for calculation was expressed by equation (14), and the liner expression  $L_{i'j}$  was calculated using equation (15).

$$r_{0j} = \sum_{n=0}^k \{v_{0j}(t_n)^2\} \tag{12}$$

$$L_{ij} = \sum_{n=0}^k \{v_{0j}(t_n) \cdot y_{ij}(t_n)\} \tag{13}$$

$$y_{i'j}(t_n) = 2y_{0j}(t_n) - y_{ij}(t_n) \tag{14}$$

$$L_{i'j} = \sum_{n=0}^k \{y_{0j}(t_n) \cdot y_{i'j}(t_n)\} \tag{15}$$

Using the above effective divisor and liner expression, and applying the least squares method, the total sum of squares  $S_T$  was decomposed as equation (16) (decomposition of sum of squares). Each term was calculated using equations (17) to (20), and the standardized S/N ratio  $\eta$  was calculated using equations (21) and (22).

$$S_T = S_\beta + S_{N \times \beta} + S_{W \times \beta} + S_e \tag{16}$$

$$S_T = \sum_{i=1}^2 \sum_{j=1}^4 \sum_{n=0}^k \{v_{ij}(t_n)^2 + y_{i'j}(t_n)^2\} \tag{17}$$

$$S_{\beta} = \left( \sum_{i=1}^2 \sum_{j=1}^4 (L_{ij} + L_{i'j}) \right)^2 / \left( 4 \sum_{j=1}^4 r_{0j} \right) \quad (18)$$

$$S_{N \times \beta} = \sum_{i=1}^2 \left[ \left\{ \left( \sum_{j=1}^4 L_{ij} \right)^2 + \left( \sum_{j=1}^4 L_{i'j} \right)^2 \right\} / \sum_{j=1}^4 r_{0j} \right] - S_{\beta} \quad (19)$$

$$S_{W \times \beta} = \sum_{j=1}^4 \left[ \left\{ \sum_{i=1}^2 (L_{ij} + L_{i'j}) \right\}^2 / 4r_{0j} \right] - S_{\beta} \quad (20)$$

$$S_N = S_e + S_{N \times \beta} + S_{W \times \beta} \quad (21)$$

$$\eta = 10 \log \left( \frac{S_{\beta} - V_e}{V_N} \right) \quad (22)$$

$S_{\beta}$  is the sum of squares of signal components ( $\beta \doteq 1$  for the standardized S/N ratio), which is almost the same as four times the effective divisor.  $S_{N \times \beta}$  is the effect of noise, which corresponds to the influence of noise factors  $N_1$  and  $N_2$ .  $S_{W \times \beta}$  is the effect of the difference in supplied power, which corresponds to the amount of influence due to the difference among  $W_1$  to  $W_4$ .  $S_e$  is the sum of squares of errors excluding signal components, the effect of noise, and the effect due to the difference in supplied power, and including the interaction between errors and supplied power, the nonlinearity of  $N_1$  and  $N_2$  as compared with  $N_0$ , and casual errors. The variance  $V_e$  of noise is obtained by dividing  $S_e$  by the degree of freedom  $f$ . Since  $V_e$  is the correction term for the estimated value  $\beta^2$ , it is used to the numerator of the S/N ratio  $\eta$ .  $S_N$  is the remainder obtained by subtracting the signal components from the total sum of squares  $S_T$ , that is, the sum of squares of the noise components.  $S_N$  divided by the degree of freedom  $f$  is the variance  $V_N$  of the noise components, which is the denominator of the S/N ratio  $\eta$ . The S/N ratio was expressed in db (decibel) by multiplying its common logarithm by 10 in order to make the value easier to handle, as in the field of acoustics and the signal theory. Using the reciprocal  $y_{ij}(t_n)$  of the actual measurement of  $V_{ij}(t_n)$  as an example of the above,  $y_{ij}(t_n)(i=1,2)$  with respect to  $y_{0j}(t_n)$  is graphed in Fig. 5, and the results of decomposing the sum of squares are shown in Table 2. A list of the calculation results of the S/N ratio  $\eta$  and the graph of factorial effects are shown in Table 3 and Fig. 6, respectively. The graph of factorial effects was created by averaging the S/N ratios of test numbers in the  $L_{18}$  orthogonal array for each level of control factors, and then representing the effect of each level of control factors by a graph. This diagram very clearly shows the effective control factors and the degree of the effect in each level. Marks in the graph indicate the current design parameters (current conditions) and the combinations (optimum conditions) that maximize the

S/N ratio.

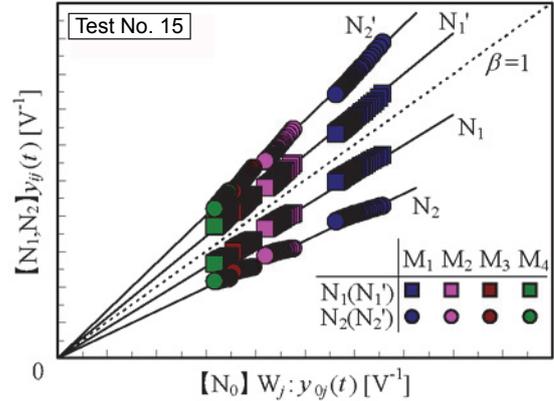


Fig. 5  $y_{ij}(t_n)(i=1,2)$  with respect to  $y_{0j}(t_n)$  (Test No. 15)

Table 2 Results of decomposing the sum of squares (Test No. 15)

Source	S	f	V
$\beta$	66683.336	1	66683.336
$N \times \beta$	4542.317	3	1514.106
$W \times \beta$	0.000	3	0.000
e	41.218	79209	0.001
(N)	4583.535	79215	0.058
T	71266.872	79216	0.900

Table 3 Calculation results of the S/N ratio  $\eta$

Test No.	$\eta$ [db]	Test No.	$\eta$ [db]	Test No.	$\eta$ [db]
1	87.11	7	64.19	13	72.05
2	74.93	8	80.13	14	68.24
3	70.74	9	79.17	15	60.62
4	81.22	10	65.34	16	67.12
5	60.16	11	48.99	17	54.39
6	78.21	12	56.51	18	81.14

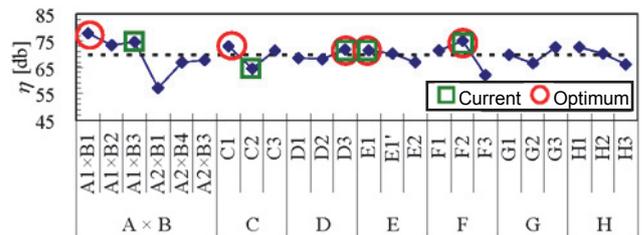


Fig. 6 Graph of factorial effects of the standardized S/N ratio

### 4.5 Confirmation run

In quality engineering, confirmation runs are conducted by making another set of TECs using a combination of levels

in the current conditions and optimum conditions as indicated in the graph of factorial effects. In confirmation runs, estimated and experiment values of the S/N ratio are compared and its repeatability (additivity) is evaluated. The estimation of the S/N ratio just consists of the addition of the effect of any combination of control factors in each level. Although this calculation does not guarantee the correct estimation, it can be assumed that accurate estimation is possible if additivity exists because of a smaller degree of interactivity. It can even be assumed that additivity existed when an accurate estimation has been made. According to the theory of quality engineering, technologies having additivity provide a high degree of repeatability in the market, which is considered to be superior technologies. The purpose of the experiment using orthogonal array is to prevent unexpected failures in the market by checking if additivity exists in the technology to be examined. As shown in **Fig. 6**, the optimum condition where the S/N ratio was maximized was the combination of A1×B1-C1-D3-E1-F2 whose estimated value was 89.93 [db]. Similarly, the current condition was A1×B3-C2-D3-E1-F2 whose estimated value was 78.47 [db]. We assembled TECs with combinations of the optimum and current conditions, and determined the experiment values of the S/N ratio, which were 86.28 [db] and 73.19 [db], respectively. These results of the confirmation run are shown in **Table 4**.

**Table 4** Results of confirmation run

Unit: [db]			
Condition	Combination	Estimated value	Experiment value
Optimum	A1×B1-C1-D3-E1-F2	89.93	86.28
Current	A1×B3-C2-D3-E1-F2	78.47	73.19
	Gain	11.46	13.09

Here, the gain is the difference in the S/N ratio between the optimum and current conditions, which indicates the degree of improvement in functionality achieved through the parameter design. These results show that the estimated value is greater than the experiment value in terms of the absolute value of the S/N ratio. If we look at the gain, however, the estimated and experiment values are 11.46 [db] and 13.09 [db], respectively, indicating a relatively good repeatability.

## 5. Considerations

The difference between the estimated and experiment values shown in the confirmation run results is smaller than the value expected, due to the fact that the error columns G

and H in the graph of factorial effects in **Fig. 6** has a width of approximately 6 [db], which should be flat if there is good additivity. As for the gain, both the estimated and experiment values were greater than 11 [db]. However, the actual gains might have been 5 [db] considering the errors. The 5 [db] is expressed as the antilogarithm of  $1.78^2$ , which means that the functionality of this parameter design against thermal stress has improved at least  $1.78^2$  times. Although the results include errors, the tendency of the gain was consistent between the estimated and experiment values. This indicates that the parameter design using the orthogonal array provides a certain level of additivity. Thus, it can be said that the methods of setting noise factors and evaluating functionality were appropriate. On the other hand, the authors set level A2 of control factors as the improvement level. However, level A2 generally gave a smaller S/N ratio as compared with level A1 as shown in the graph of factorial effects in **Fig. 6**, which was a result against our expectations. In this parameter design, we used factors related to the mechanical design conditions of TECs as control factors. However, we had to change some conditions during the process of assembling TECs to which level A2 was applied. This change was not sufficiently taken into account, which we consider led to the result against our expectations. That is, uncontrolled factors in the process may have been included in the test pieces as errors, which is considered to have contributed to the effect in the error column described above. The result can be considered a failure in the sense that the S/N ratio was not improved with level A2 as we expected. However, this result allowed us to notice that, when conducting a parameter design next time, factors in the assembling process that are related to the application of level A2 should be taken into full account as control or noise factors. Furthermore, since we have found that the gains achieved through the functionality evaluation in this study have a certain degree of repeatability, we plan to examine how much effect the gains will have on TEC's lifetime in durability tests.

## 6. Conclusion

In this study, which focused on the improvement of thermal stress durability of TECs, we conducted a parameter design by devising a functionality evaluation method based on quality engineering. In the functionality evaluation, we measured the voltage response of TECs under the noise factor of applying a certain thermal stress to the TECs, and made an evaluation based on the standardized S/N ratio. The time it took for functionality evaluation was 5 hours per TEC, which is a short time as compared with the 500 hours needed for

conventional durability testing. The results of the parameter design indicated a certain additivity, which may provide at least  $1.78^2$  times improvement in functionality in terms of gain as compared with the conditions currently used. We also examined the noise factors, which provided us with insight into the factors to be considered for further improvement in additivity and functionality. We plan to examine the effect of the gains achieved in this study on TEC's lifetime in durability tests.

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### References

- 1) GR-468-CORE Issue 2: Generic Reliability Assurance Requirements for Optoelectronic Devices Used in Telecommunications Equipment, Telcordia Technologies, Inc., (2004).
- 2) Tetsushi Tanaka, et al., "Journals of the 22nd Quality Engineering Society Annual Conference (QES2014)", pp.70-73 (2014)
- 3) Toru Sakata, "Thermoelectric Conversion: Basics and Applications" Shokabo, pp.207-211 (2005)
- 4) <http://www.kelk.co.jp/english/thermo/pdf/KSML007.pdf>
- 5) Takenobu Kajikawa, et al., "Handbook of Thermoelectric Conversion", N.T.S. Co., Ltd., pp.447-452 (2008)
- 6) Genichi Taguchi, "Quality Engineering Handbook", Nikkan Kogyo Shimbun, pp.780 (2007)

### Introduction of the writers



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**[A few words from writers]**

In considering what engineers should do proactively in the upstream technology development stage to reduce the dispersion of product quality in the market, we thought that quality engineering was an excellent approach that offers a good opportunity. Although we are still in the learning stage with quality engineering itself, we will continue our effort to provide higher quality thermoelectric modules through a TQM activity that combines our work in the upstream and the conventional QC activities in the downstream.