# Flexible High-Voltage Cable for HEV/EV

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The advancement of hybrid electric vehicle/electric vehicle technology has led to an increase in the size of high-voltage cables used as power cables, and accordingly their flexibility is strongly required for easy handling. Our flexibility simulation revealed that the elastic modulus of an insulator contributes to the cable flexibility more than the structure of a conductor. We found that polyolefin polymers are ideal insulation base-resins because the softness of polyolefin can be controlled by the ratio of the crystal region and amorphous region, which changes with the amount of co-monomers. Using an anti-oxidant agent, flame retardant, and polymer cross-linking, we have developed a new flexible insulation material that meets JASO/ISO standard. Going forward, we will strengthen our product lineup of flexible cables.

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## 1. Introduction

In hybrid electric vehicles (HEVs) and electric vehicles (EVs), which have recently been becoming increasingly popular, the low-voltage power from the battery is amplified to 500 V or higher by an inverter and output to the drive motor via a large-diameter, high-voltage power cable with sufficient current capacity. At automobile manufacturing factories, automotive cables are manually assembled into wiring harnesses. and installed in vehicles; this preparation entails processing each cable end, fitting a connector to each cable, and laying each cable. Therefore, wiring harness installation efficiency, workload, and accuracy depend largely on the flexibility of harness cables. More specifically, high-voltage HEV/EV cables with large diameters and low flexibility are difficult to handle.

Automakers try to downsize engine room to expand the interior space of vehicles without increasing external dimensions. The process of bending wiring harnesses to small radii in such restricted spaces is critical in achieving this aim. Accordingly, demands for high-voltage and high-current drive systems have increased with advancing performance of HEVs/EVs. These demands consequently require an increase in the size of power cables used for drive systems (Fig. 1). Thus, there has been growing demand for the development of a high-flexibility, high-voltage cable. To meet such a demand, the authors undertook research on improving the flexibility of high-voltage power cables for HEV/EV applications.

## 2. Development Goal

The bending repulsive force of a cable reduces as its flexibility increases. The test method specified in IEC60794-1-2, Method 17C, was used to evaluate the bending repulsive forces of cables. Although this test method was established for evaluating the characteristics of optical fibers, we employed this test method because it proved to be an appropriate measure for quantitatively evaluating cable flexibility. In this test, the cable to be tested is bent to 180° and set between two vertically parallel plates. After fixing both ends of the test cable to the plates, the upper plate fitted with a load cell is pressed downward until the distance between the upper and lower portions of the cable is reduced to a predetermined value (Fig. 2). The bending repulsive force of the cable is determined from the maximum load exerted on the cable. The test is carried out at room temperature. Subsequent to estimating the minimum bending radius of cables installed in a vehicle, we specified 60 mm as the distance between both
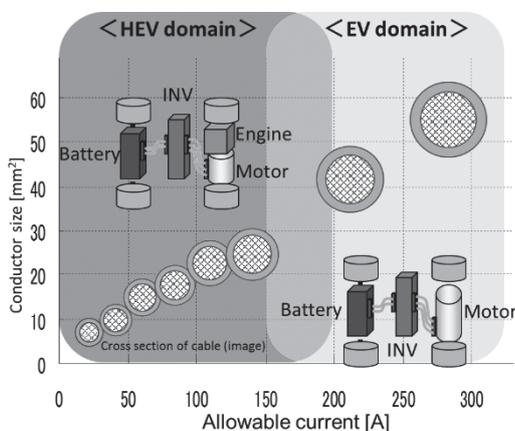


Fig. 1. Sizes of HEV/EV cables
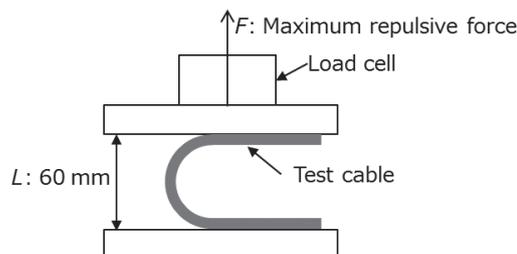


Fig. 2. Cable flexibility test method

end portions of the test cable, and defined the maximum bending repulsive force of the test cable as the flexibility index of the cable.

For reference, the maximum bending repulsive force of conventional 30 sq high-voltage HEV/EV cables (19/19/0.32) was measured to be 79 N in this test.

We set a development goal of reducing the bending repulsive force of cables to one-half that of the conventional cables to enable practical realization of enhanced flexibility of the new cable.

Automotive cables must meet the requirements of the applicable JASO and ISO standards. A high-voltage HEV/EV cable generates heat from the conductor when it carries an electric current. An HEV cable is exposed to additional heat from the engine exhaust; therefore, the ability to maintain sufficient heat resistance for an extended period of time is a critical feature of this cable. We set the target heat resistance temperature of the cable to be 150°C, i.e., the general temperature required for high-voltage HEV/EV cables. According to the corresponding JASO standard, a cable with a heat resistance temperature of 150°C shall maintain the absolute elongation of its conductor within 100% under the condition of exposure to a temperature of less than 150°C for a minimum of 10,000 h. Alternatively, the relevant ISO standard requires that a cable with a heat resistance temperature of 150°C shall not dielectrically break down when it is aged for 3,000 h at 150°C, wound at a diameter 1.5 times that of the cable, and then subjected to a 1 kV withstand voltage test for one minute. Automakers in Japan require automotive cables to adhere to the JASO standard, while automakers in North America and Europe require these cables to meet the ISO standard. In our research study, we aimed to develop a cable that can satisfy the requirements of both the JASO and ISO standards to permit global use. The principal target characteristics of the cable are shown in Table 1.

Table 1. List of major target characteristics selected from JASO and ISO standards

| Standard | Item | Condition | Unit | Requirement |
|---|---|---|---|---|
| JASO | Tensile properties of insulator | Tensile strength | MPa | ≥ 10.3 |
| | | Elongation | % | ≥ 150 |
| | Heat resistance 1B | Winding and withstand voltage test after exposure to 150°C for 240 h | - | No fracture |
| | Heat resistance 1C | Winding after exposure to 200°C 30 min | - | No fracture |
| | Low-temperature resistance | Winding and withstand voltage test after exposure to -40°C for 4 h | - | No fracture |
| | Oil resistance | Winding after immertion for 20 h in gasoline maintained at 23°C | - | No exposure of comductor |
| | Abrasion resistance | Tape abrasion 1.9 kgf | Minimum abrasion resistance | ≥ 550 |
| | Flame resistance | Horizontal flame resistance | s | Flame extinction within 30 s |
| | Long-term heat resistance (insulator) | Heat resistance temperature following 100% elongation for 10000 h | °C | ≥ 150 |
| ISO | Long-term heat resistance (cable) | Winding and withstand voltage test after exposure to 150°C for 3000 h | - | No fracture |

## 3. Cable Flexibility Simulation

The primary components of a cable are the conductor and insulator and, therefore, enhancing the flexibility of

these components is critical in improving the flexibility of the entire cable. However, considerable time and costs are required for the experiments and evaluation of the flexibility of a large diameter conductor used in a high-voltage HEV/EV cable. To quantitatively estimate the effects of each component on cable flexibility and validate the need for development of a new high flexibility cable, we decided to establish our development strategy subsequent to carrying out a numerical simulation of cable flexibility.

The maximum repulsive force of a cable when it is bent as described in Chapter 2 can be calculated from Eq. (1).[1] Given that flexural rigidity of a substance can be determined by multiplying its moment of inertia of area by its elastic modulus, the flexural rigidity of a cable is determined as the sum of the flexural rigidities of both cable components.

$$F = K_B / (0.348\ (L - D)^2) \quad\cdots\cdots\cdots\cdots\cdots\cdots\quad (1)$$

$$K_B = K_{cnd} + K_{ins} = E_{cnd}\ I_{cnd} * N + E_{ins} * I_{ins} \quad\cdots\cdots\cdots\quad (2)$$

where $F$ = maximum repulsive force, $K_B$ = flexural rigidity, $L$ = distance between the bent ends, $D$ = cable outside diameter, $K_{cnd}$ = flexural rigidity of conductor, $K_{ins}$ = flexural rigidity of the insulator, $E_{cnd}$ = elastic modulus of the conductor wire, $E_{ins}$ = elastic modulus of the insulator, $I_{cnd}$ = moment of inertia of area of the conductor wire, $N$ = number of conductor wires, and $I_{ins}$: moment of inertia of area of the insulator.

The moment of inertia of areas of the conductor wire and insulator are determined from the following equations, respectively, based on the assumption that the former is a solid cylinder while the latter is a hollow cylinder (Fig. 3).

$$I_{cnd} = \pi R^4 / 4 \quad\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\quad (3)$$

$$I_{ins} = \pi\ (D^4 - d^4) / 64 \quad\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\quad (4)$$

where $R$ = radius of the conductor wire, $D$ = outside diameter of the insulator, and $d$ = inside diameter of the insulator.
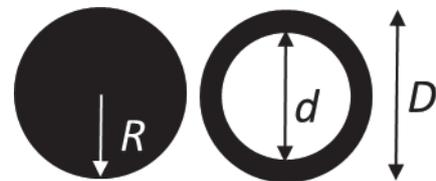


Fig. 3. Assumed cross sections of conductor wire and insulator used in calculations of respective moment of inertia of areas

To confirm the validity of the above calculations, we calculated the bending repulsive forces of conventional cables with differing sizes, and subsequently compared the calculated values with measured values. The results are demonstrated in Table 2 and Fig. 4. The estimated values were nearly equivalent to the measured values, thus

confirming that the numerical simulation is effective in establishing our development goal.

Table 2. Comparison between estimated and measured bending repulsive forces of conventional cables

| Conductor size | | sq | 8 | 30 | 50 |
|---|---|---|---|---|---|
| Conductor | Number of strands/dia. of strand | Pcs/Pcs/mm | 1/50/0.45 | 19/19/0.32 | 16/32/0.32 |
| | Outside diameter | mm | 3.7 | 7.8 | 10.1 |
| Insulator | Thickness | mm | 0.8 | 1.4 | 1.6 |
| | Outside diameter | mm | 5.3 | 10.6 | 13.3 |
| Elastic modulus of conductor | | GPa | 100 | 100 | 100 |
| Elastic modulus of insulator | | MPa | 96 | 96 | 96 |
| Estimated repulsive force | | N | 11.0 | 71.4 | 171 |
| Measured repulsive force | | N | 6.68 | 78.8 | 183 |

Table 3. Repulsive force estimation results for cables with varying con-ductor and insulator properties

| Conductor size | | sq | 15 | 20 | 30 | 40 | 50 |
|---|---|---|---|---|---|---|---|
| Conductor | Number of strands/dia. of strand | Pcs/Pcs/mm | 19/9/0.32 | 19/13/0.32 | 19/19/0.32 | 19/26/0.32 | 19/32/0.32 |
| | Outside diameter | mm | 5.3 | 6.5 | 7.8 | 9.1 | 10.1 |
| Insulator | Thickness | mm | 1.1 | 1.1 | 1.4 | 1.4 | 1.6 |
| | Outside diameter | mm | 7.5 | 8.7 | 10.6 | 11.9 | 13.3 |
| Elastic modulus of conductor | | GPa | 100 | 100 | 100 | 100 | 100 |
| Elastic modulus of insulator | | MPa | 96 | 96 | 96 | 96 | 96 |
| Estimated repulsive force | Conductor without insulator | N | 8.45 | 12.8 | 19.6 | 28.2 | 36.1 |
| | Conductor and insulator | N | 20.8 | 34.2 | 71.4 | 109 | 171 |

| Conductor size | | sq | 15 | | 20 | | 30 | | 40 | | 50 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Conductor | Number of strands/dia. of strand | Pcs/Pcs/mm | 19/30/0.18 | | 19/42/0.18 | | 19/63/0.18 | | 19/80/0.18 | | 37/54/0.18 | |
| | Outside diameter | mm | 5.5 | | 6.5 | | 7.9 | | 8.9 | | 10.2 | |
| Insulator | Thickness | mm | 1.1 | | 1.1 | | 1.4 | | 1.4 | | 1.6 | |
| | Outside diameter | mm | 7.7 | | 8.7 | | 10.7 | | 11.7 | | 13.4 | |
| Elastic modulus of conductor | | GPa | 100 | | 100 | | 100 | | 100 | | 100 | |
| Elastic modulus of insulator | | MPa | 96 | 48 | 96 | 48 | 96 | 48 | 96 | 48 | 96 | 48 |
| Estimated repulsive force | Conductor without insulator | N | 2.84 | | 4.13 | | 6.53 | | 8.62 | | 11.9 | |
| | Conductor and insulator | N | 16.0 | 9.52 | 24.8 | 14.6 | 58.6 | 32.9 | 82.0 | 45.8 | 147 | 80.4 |



Fig. 4. Estimated and measured repulsive forces of conventional cables
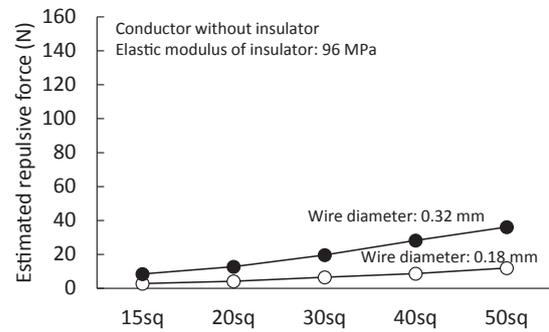


Fig. 5. Effects of wire diameter on repulsive force
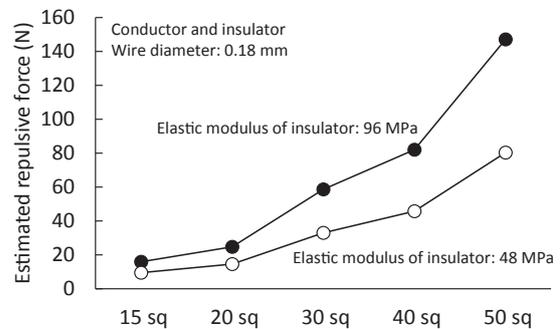


Fig. 6. Effects of the elastic modulus of the insulator on repulsive force
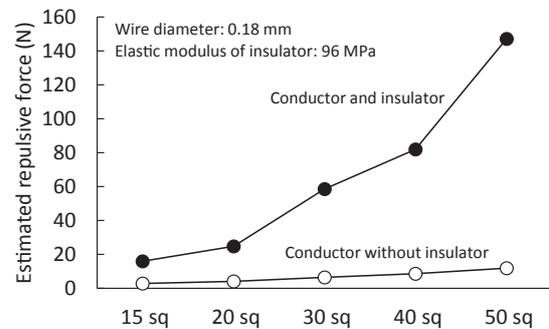


Fig. 7. Effects of conductor and insulator on repulsive force

Using this numerical method, we estimated the repulsive forces of cables fabricated using various conductors and insulators. In this process, we determined the repulsive force of each conductor and insulator to determine the respective effects on the flexibility of the cable. Cables with sizes from 15 to 50 sq were applied in the numerical models based on the supposition that the conductors comprised 0.32-mm and 0.18-mm diameter wires, and that the insulators had elastic moduli of 96 MPa and 48 MPa—these elastic moduli are equal to and one-half that of the conventional cables, respectively. The repulsive force calculation results for each conductor as an independent unit and for each cable (comprising a conductor and insulator) are shown in Table 3. The difference in the dependence of repulsive force on the conductor wire diameter is shown in Fig. 5, and the difference in the dependence of repulsive force of each size of the cable on the elastic modulus of the conductor is shown in Fig. 6. In addition, Fig. 7 demonstrates a comparison between repulsive forces of conductors consisting solely of 0.18-mm diameter wires and those of cables comprising 0.18-mm diameter wire conductors and insulators with an elastic modulus of 96 MPa.

We first evaluated the difference in effects on repulsive force between 0.18-mm and 0.32-mm diameter wires. As a result, it was found that the smaller diameter wire reduced the repulsive force to approximately one-third that of the larger diameter wire, thus verifying that reducing the conductor wire diameter is effective in enhancing cable flexibility. The reason is that a smaller diameter wire undergoes less strain than a larger diameter wire when bent to an identical radius.

Subsequent to completing the above procedure, we evaluated the effects of the elastic modulus of the insulator on the repulsive force of the cable. The evaluation result demonstrated that reducing the elastic modulus of the insulator to half the original value subsequently reduces the repulsive force of the cable to nearly half. This analysis confirmed that reducing the elastic modulus of the insulator is also effective in enhancing cable flexibility. Figure 7 illustrates that the insulators reduced the repulsive force more effectively than the conductors. More specifically, the absolute value of repulsive force suppression effects by the insulator increased as the cable size increased. Therefore, reducing the elastic modulus of insulators is expected to offer manufacturing employees the advantage of utilizing high-flexibility power cables.

As previously explained, experimental study results demonstrated that reducing the elastic modulus of the insulator is the most efficient way of minimizing the repulsive force of the cable. Although reducing the conductor wire diameter improves the flexibility of the cable, the effect is less than that obtained by reducing the elastic modulus of the insulator. Additionally, reducing the conductor wire diameter introduces the problem of increased cable production cost. Upon considering the allowable limit of automotive cable production cost, we decided not to use the 0.18-mm diameter wire unless a particularly high-flexibility cable is required.

We calculated the elastic modulus of the cable insulator that would ensure the development goal of reducing the repulsive force of the cable to half that of the corresponding conventional cable. Results yielded a maximum target elastic modulus of 43 MPa. We then determined the material necessary to attain the target elastic modulus.

## 4. Selection of Insulator

To improve the flexibility of an insulator, it is essential to select a flexible, high heat-resistant polymer as the base material. A polyolefin-based material, silicone rubber, acrylic rubber, fluorine rubber, and EP rubber were selected as promising base materials. Their features are summarized in Table 4.

- Polyolefin-based material
  This material is flexible, heat-resistant, and low in material cost.
- Silicone rubber
  This rubber lacks the mechanical properties (tensile and tearing strength) and oil resistance essential to automotive cables; it is expensive.

Table 4. Summary of polymer features

|  | Polyolefin-based material | Silicone rubber | Acrylic rubber | Fluoro rubber | EP rubber |
|---|---|---|---|---|---|
| Flexibility | Good | Excellent | Excellent | Excellent | Excellent |
| Long-term heat resistance | Good | Excellent | Good | Excellent | Poor |
| Mechanical strength | Good | Poor | Good | Good | Good |
| Oil resistance | Good | Poor | Good | Excellent | Good |
| Electrical characteristics | Good | Good | Average | Good | Good |
| Material cost | Good | Poor | Average | Poor | Good |

- Acrylic rubber
  This rubber excels in flexibility, but lacks volume-intrinsic resistance and is expensive.
- Fluoro rubber
  This rubber excels in heat and oil resistance, but is expensive. Its heat resistance temperature of 200°C exceeds the target value (150°C). However, this rubber can be used in future high voltage/current power cables with heat resistances greater than 150°C.
- EP rubber
  Although this rubber is sufficiently flexible and reasonable in cost, it lacks long-term heat resistance.

Based on the above evaluation results, we selected polyolefin-based material as the insulator material of the new cable.

## 5. Improving the Flexibility of Polyolefin-based Material

The flexibility of polyolefin depends largely on the percentage of its crystalline components. The molecular structure of polyolefin is schematically shown in Fig. 8. Polyolefin is a crystalline polymer consisting of crystalline and amorphous regions. In the crystalline regions, a portion of polyolefin molecules line up systematically, thus increasing the density and rigidity of the regions. In contrast, the amorphous regions contain polyolefin molecules that line up randomly. This reduces the molecular density of the regions and allows the molecules to move easily within the regions, making these regions flexible. This implies that the flexibility of a polyolefin polymer can be modulated by controlling the ratio between the crystalline and amorphous regions. Deterioration of the characteristics of the polymer due to an increase in the ratio of the amorphous regions can be minimized by cross-linking the polymer.
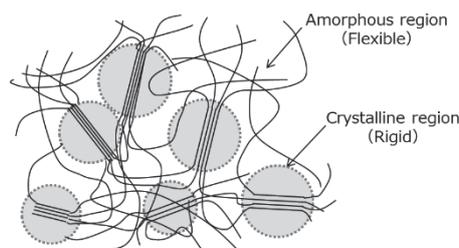


Fig. 8. Schematic illustration of crystalline and amorphous regions in polyolefin

A method for increasing the ratio of the amorphous region to the crystalline region is copolymerization of the co-monomers*[1] that inhibit the crystallization of polyolefin molecules. Increasing the ratio of co-monomers introduces difficulty in the systematic lining up of the polyolefin chains, thereby reducing the ratio of the crystalline regions. We measured the relationship between co-monomer ratio and elastic modulus. The results are provided in Fig. 9. As was estimated in advance, this figure illustrates that the quantity of crystals decreases as the co-monomer ratio increases, which then results in a tendency of the elastic modulus to decrease. It was determined from this figure that, to acquire the target elastic modulus, the minimum co-monomer ratio must be 20%.

Adverse effects of improving the flexibility of a polyolefin polymer via reduction of the ratio with respect to the crystalline region are the respective deteriorations of the abrasion and oil resistance of the polymer. The cause of abrasion resistance deterioration resulting from flexibility improvement is made evident by the following fact: flexible amorphous regions are easily deformed or damaged. Additionally, the reason oil resistance deteriorates is that oil penetrates into the amorphous regions, thereby reducing the mechanical strength of the polyolefin polymer.
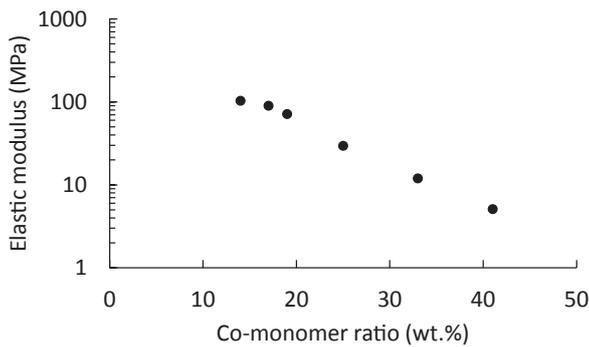


Fig. 9. Relationship between co-monomer ratio and elastic modulus

Both the applicable JASO and ISO standards require that automotive cables to satisfy the specified abrasion and oil resistance requirements. To meet the requirements for abrasion and oil resistance while also improving the flexibility of the cable, we devised a plan to cross-link the polymer. Cross-linking is a technique for bonding molecular chains to each other via a chemical reaction. As a result, the molecules form a three-dimensional network distribution, thus enhancing the strength and heat resistance of the polymer. There are three cross-linking techniques: thermal cross-linking, cross-linking by electron beam irradiation, and silane cross-linking. All of these techniques have nearly identical effects on the improvement of polymer mechanical strength and wear resistance. However, the disadvantage of thermal and silane cross-linking is that the large amount of an antioxidant, which is added to enhance the long-term heat resistance of the polymer, interferes with the cross-linking. Conversely, cross-linking by electron beam irradiation rarely obstructs

polymer cross-linking and can be applied to various types of polymers. We decided to perform cross-linking via electron beam irradiation since this technique is most suited for our study objective.

Based on the above results, we worked to optimize the co-monomer ratio to ensure that we achieved our development goal. We created several compounds by mixing the components in a manner that would enable the compounds to exhibit sufficient heat and flame resistance. Using these compounds, we prepared several polymers, each with different co-monomer ratios, and evaluated their characteristics. The evaluation results are presented in Table 5. Based on the evaluation results, we selected polymer B as the material that will meet the requirements of the relevant standards. Then, we prototyped an 8 sq cable with an insulator composed of polymer B and subsequently confirmed that this cable meets the requirements of JASO and ISO standards. The key characteristics of this cable are shown in Table 6. The elastic modulus of the new cable, which was measured to be 37 MPa, cleared our target value.

Table 5. Characteristics evaluation results for selecting the optimal poly-mer

| resin | Co-monomer ratio (wt.%) | Elastic modulus of compound (MPa) | Heat resistance specified by JASO | Oil resistance and abrasion resistance specified by JASO |
|---|---|---|---|---|
| A | Low | 96 | Good | Good |
| B | Middle | 37 | Good | Good |
| C | High | 13 | Poor | Poor |

Table 6. Cable characteristics evaluation result

| Standard | Item | Condition | Unit | Requirement | result |
|---|---|---|---|---|---|
| JASO | Tensile properties of insulator | Tensile strength | MPa | ≥ 10.3 | 14.5 |
| | | Elongation | % | ≥ 150 | 561 |
| | Heat resistance 1B | Winding and withstand voltage test after exposure to 150°C for 240 h | - | No fracture | No fracture |
| | Heat resistance 1C | Winding after exposure to 200°C 30 min | - | No fracture | No fracture |
| | Low-temperature resistance | Winding and withstand voltage test after exposure to -40°C for 4 h | - | No fracture | No fracture |
| | Oil resistance | Winding after immersion for 20 h in gasoline maintained at 23°C | - | No exposure of comductor | No exposure |
| | Abrasion resistance | Tape abrasion 1.9 kgf | Minimum abrasion resistance | ≥ 550 | 788 |
| | Flame resistance | Horizontal flame resistance | s | Flame extinction within 30s | 0 |
| | Long-term heat resistance (insulator) | Heat resistance temperature following 100°C elongation for 10000 h | °C | ≥ 150 | 152 |
| ISO | Long-term heat resistance (cable) | Winding and withstand voltage test after exposure to 150°C for 3000 h | - | No fracture | No fracture |
| Elastic modulus of insulator | | | MPa | ≤ 43 | 37 |

To satisfy the requirements corresponding to long-term heat resistance as specified in the JASO standard, we estimated the ambient temperature that would degrade the cable until its elongation reached 100% after 10,000 h. For the estimation, we used an Arrhenius plot that was obtained from heat deterioration data acquired under a temperature condition of higher than 150°C. The results indicated that the absolute elongation of the cable following exposure to 150°C for 10,000 h would exceed 100%.
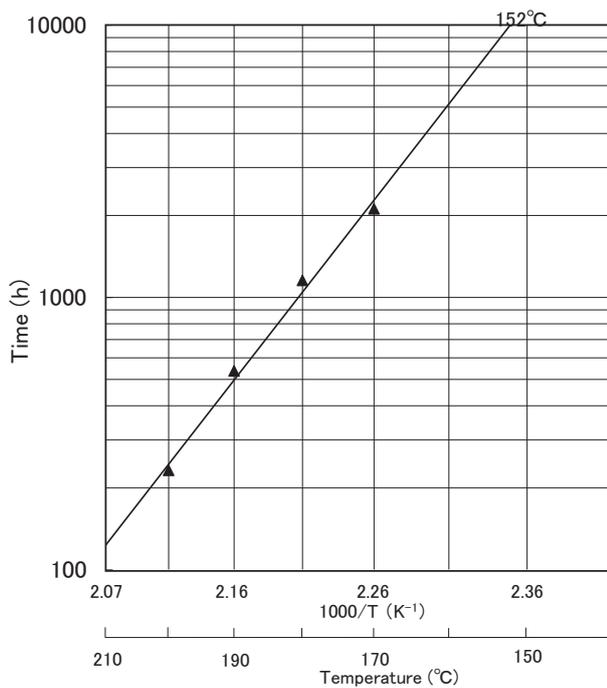
Fig. 10. Arrhenius plot

## 6. Conclusion

The high flexibility cable we have developed in this study is currently mass-produced and employed by auto-makers. In the belief that the same technical approach employed for the development of the 150°C heat-resistant cable will continue to be applicable, we have already begun to develop a higher heat-resistant, high-flexibility cable that can be used at temperatures ranging up to 200°C.

### Technical Term

∗1  Co-monomer: A monomer that bonds to surrounding polymer molecules when pol-ymerized along with a base monomer (ethylene in the case of polyeth-ylene).

### Reference

(1)    M. Tachikura, H. Takemoto and N. Tomita, OECC'97, p.526

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