Development of an Application Program to Calculate Short-Circuit Temperature Rise in OPGW

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ABSTRACT Composite cables with optical-fiber ground wire (OPGW) support both power transmission and data communication, making more effective use of real estate and line facilities. The inclusion of optical fibers within the cable structure, however, means that the temperature rise limit differs from that of conventional overhead ground wires. Specifically, in power line ground faults, virtually all of the short-circuit current flows in the ground wire, resulting in large instantaneous rises in temperature that are a major factor in power line design. Further the OPGW structure incorporates elements not previously used in power lines, such as pipes, spacers, etc., and this increases the error in calculating ordinary short-circuit temperature rise. A study was therefore carried out to calculate short-circuit temperature rise, taking into account the structural features specific to OPGWs, and personal computer software was developed. Comparisons with results from short-circuit tests at a representative conductor size confirmed that calculations were accurate to within 5%.

1. INTRODUCTION

An overhead ground wire is installed to protect phase conductors from lightning and to reduce electromagnetic interference against telecommunication lines during the grounding of power lines. The construction of overhead ground wires having the above purposes, is generally composed of relatively small-sized, mechanically excellent wires such as Aluminum Clad wires, Steel stranded wires, or AACSR. Recently, an optical fiber composite ground wire (OPGW) has been widely used for effective utilization of land and equipment. An optical fiber can transmit a large amount of information in high speeds and suffers no electromagnetic interference because of its non-metallic characteristics. This advantageous feature makes it possible to construct long distance telecommunication lines with high reliability. The OPGW must have the same mechanical strengths and electrical characteristics of the conventional overhead ground wire, and there are many construction ways to built-in optical fiber. The basic construction of OPGW is: an optical fiber unit is placed at the center of stranded ground wires, this unit itself is accommodated in a preventive aluminum pipe housing, Aluminum Clad wires and aluminum alloy wires are arranged peripherally to obtain intended characteristics. An example of typical construction and characteristics of the OPGW is illustrated in Table 1.

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2. TEMPERATURE-CURRENT CHARACTERISTICS OF OPGW

2.1 Current through Overhead Ground Wire

A steady current that is electromagnetically induced by the phase conductors always runs through the overhead ground wire. A shunt current from the phase conductors is to be superimposed to the induced current in case of grounding. The induced current and this shunt current are calculated from factors such as: distance from the phase conductor, grounding resistance, soil resistance and wire conductivity. The relationship between these currents and the temperature rise in the ground wire is obtained by calculating such factors: (1) the heat generated by induced steady current, (2) the heat absorption from the sun, (3) the heat radiation from the wire, (4) the equilibrium state of heat (initial temperature) through the above absorption and radiation, (5) the heat generated by the superimposed current when grounded, and (6) calculation of the transient state including (1) through (5).

The relationship between the induced current and wire temperature in a steady state has been investigated in the past and summarized as the calculation of current carrying capacity in the overhead transmission wires[1)~2)].

The transient temperature rise due to short-circuit current is calculated by adding the temperature rise in the short-circuit to the steady state temperature rise. The following equation shows the relationship between the temperature change dθ and lapse of time dt. The ratio of both parameters is calculated by dividing the difference (which is obtained by the addition of heat generated by current flowing and heat absorbed from the sun and subtracting radiating heat from the wire) with the heat capacity of the wire *C*.

$$\frac{d\theta}{dt} = \frac{I^2 \beta R_{dc} \times 10^{-5} + W_s d\eta - \pi d K_m \theta}{C}$$

Where,
I : Current (A)
β : The ratio of AC to DC resistance
R_{dc}: Conductor DC resistance (Ω/km)
W_s: Solar radiation (W/cm^2)
d : Conductor outer diameter (cm)
η : Absorptivity = Emissivity
K_m: A coefficient according to the Stephan-Boltzman law
θ : Temperature rise (°C)
C : Heat capacity (J/cm·°C)

Solving the above differential equation, the transient temperature rise is obtained as follows.

$$\theta = \theta_m (1 - e^{-t/\tau}) + \theta_0 e^{-t/\tau}$$

$$\theta_m = \frac{I^2 \beta R_{dc(20)} \times 10^{-5} \{1 + \alpha (T + 20)\} + \eta W_s d}{\pi d K_m - \alpha I^2 \beta R_{dc(20)} \times 10^{-5}}$$

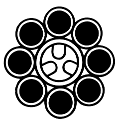
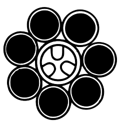
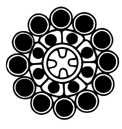
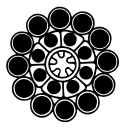
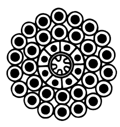
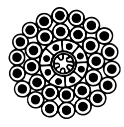
$$T = \frac{C}{\pi d K_m - \alpha I^2 \beta R_{dc(20)} \times 10^{-5}}$$

Where,
$R_{dc(20)}$: DC resistance at 20°C (Ω/km)
α : Resistance temperature coefficient
t :Time (sec)
θ_0: Initial temperature of wire (°C)
K_m: hrη+hw (wind)
K_m: hrη+hc (no wind)

Table 2 Maximum operating temperature of bare wire conductor

Type	Maximum operating temperature (T+θ)˚C		
	Continuous	Short time	Instantaneous
Aluminum clad steel wire (AC)	200	230	400
Galvanized steel wire	200	230	400
I -aluminum alloy steel reinforced (IACSR)	90	100	150
Aluminum conductor steel reinforced (ACSR)	90	120	180
Thermo-resistant aluminum alloy conductor steel reinforced (TACSR)	150	180	260

Table 1 Construction and characteristics of OPGW

Items		Product code	OPGW60mm^2	OPGW80mm^2	OPGW170mm^2	OPGW290mm^2	30AC OPGW500mm^2	40AC OPGW500mm^2
Stranded wire construction No. / Dia.(mm)		Construction						
		Outer layer	23AC 8/3.2	23AC 7/3.9	27AC 12/3.5	40AC 12/4.5	30AC 30/4.2	40AC 30/4.2
		Inner layer	—	—	40AC 8/SB(2.89)	40AC 8/SB(4.0)	40AC 8/SB(3.62)	40AC 8/SB(3.62)
		OP unit	OP1/5.0	OP1/5.0	OP1/6.0	OP1/6.5	OP1/6.5	OP1/6.5
* Minimum tensile load kN{kgf}			73.5{7,490}	95.6{9,750}	144.6{14,750}	179.9{18,340}	381.0{38,850}	307.4{31,350}
Reference	Cross sectional area (mm$^{2)}$	Aluminum clad steel wire	64.34	83.65	168.0	291.4	497.8	497.8
		OP unit	13.55	13.55	20.36	23.39	23.39	23.39
		Total	77.89	97.2	188.4	314.69	521.1	521.1
	Mass (kg/km)	Aluminum clad steel wire	411.4	535.0	940.0	1,372	2,770	2,358
		OP unit	42.57	42.57	62.97	72.88	72.88	72.88
		Total	454.0	577.6	1,003	1,445	2,843	2,431
	Outer diameter (mm)		11.4	12.8	17.5	22.5	29.4	29.4
	*Modulus of elasticity GPa{kgf/mm^2}		149.1{15,200}	149.1{15,200}	130.4{13,300}	108.9{11,100}	128.5{13,100}	108.9{11,100}
	*Linear expansion coefficient (1/km)		12.9×14^{-6}	12.9×14^{-6}	14.0×14^{-6}	15.5×14^{-6}	14.0×14^{-6}	15.5×14^{-6}
	*Electrical resistance (Ω/km)		1.19	0.914	0.336	0.150	0.112	0.0884

* optical fiber not included

This equation is a general formula, therefore, the temperature is calculated by substituting t =∞ at steady state, t=0 at transient current flowing. For the flowing current in a short-circuited state, the time lapsing is regarded extremely short. Heat generated by Joule's Law in the short-circuit only affects the temperature rise of the wire. Therefore the instant heat absorption and radiation of the wire itself can be negligible factors.

At present, the calculation method for steady state current temperature rise has been reexamined internationally by IEEE and CIGRE. In Japan, a technical committee in JIEE has been held to collect the recent results of the investigation[5]. The calculation formula by CIGRE is relatively in good agreement with the measured results, therefore, this equation will be widely used from now on.

2.2 Permissible Temperature of Conductors

The permissible temperature of conductors is normally determined by the following factors: mechanical deterioration affected by the heat hysteresis of a conductor, equipment conditions, and heat characteristics of accessory parts. Among these, a predominant factor is the annealing property of the wire. The existing level of the acceptable deterioration range in tensile strength is less than 10% of normal value considering the material's properties, vibration fatigue and corrosion.

When strength deterioration occurs, the relation between temperature and the lapse of time becomes to differ by materials. On the other hand, the instantaneous permissible temperature is defined as a temperature which does not cause the wire's annealing by instantaneous current upon failure. As a concrete example, it is the temperature when the tensile strength of the conductor does not decrease in a flowing current under 1/4 tensile strength of the conductor for two seconds. The data is shown in Table 2. An OPGW has optical fibers inside its construction, therefore, the permissible temperature of OPGW must be determined by taking into consideration not only the deterioration of the mechanical properties but also the thermal deterioration of the optical fiber. The permissible temperature of an optical fiber is determined by the heat resistant property of a buffer material which plays a role in protecting the optical fiber. The allowable temperature of a silicon buffer type wire is defined as 300°C, and 180°C in UV acrylic type wires. In other words, in designing the OPGW, it is required that the maximum temperature absorbed in an aluminum pipe (spacer) should be less than the above temperature, i.e. 300°C or 180°C, respectively. In actual lines, the OPGW is used, assuming that the short-circuit current in failure will flow scarcely in full amount estimated in the designing stage.

2.3 Temperature Rise in Short -Circuit Current

The instantaneous temperature rise of a ground wire is obtained, as mentioned above, by solving the differential equation which expresses a transient state, i.e., occurrence of instantaneous heat by ohmic loss in the ground wire based on Joule's Law and the temperature rise of the wire(which has a certain thermal capacity) with the duration of time. The running time of a short-circuit is regarded so short that heat radiation or absorption from and into the wire will not occur. The next equation gives the instantaneous temperature rise.

$$I=\sqrt{\frac{C\,\log_e\left(\frac{\alpha\theta+1}{\alpha\theta_0+1}\right)}{t\alpha R_{dc(20)}\times 10^{-5}}}$$

I : Short circuit current (A)
t : Time (sec)

In the case that the conductors are made of a single material, current distribution is relatively uniform. The temperature difference between the conductors is small, and the measured value and the calculated value are in agreement with each other. An OPGW does include optical fibers in itself, however, its construction is composed of several materials and is rather complicated in general. Thus, the composite conductor like OPGW has materials whose conductivities are also different from each other. The instantaneous current which flows through the composite conductor is distributed to each wire in proportion to the wire's own conductivity due to the contact resistance between wires. Each wire has its own specific heat and heat capacity, thus each wire has a different temperature rise. The temperature of each conductor is different under the initial condition during the short-circuit current flowing , and gradually falls into an equilibrium state through thermal heat transfer. As mentioned above, the temperature difference by the conductors creates a new problem in OPGW designing. It is necessary to calculate the maximum temperature rise of the unit which accommodates optical fibers because the rise is extremely important. An actual conductor is spiral-shaped with stranded pitches and has impedance against an alternative current. It must

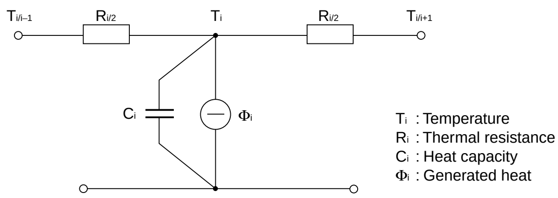


Figure 1 Equivalent circuit for heat conduction in OPGW

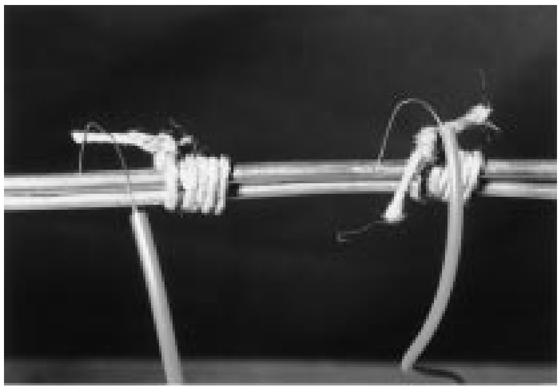


Figure 2 Experiment on heat transfer

be considered that each wire has a mutual inductance. When the wire is an aluminum clad which contains ferromagnetic steel, the iron losses due to the hysteresis property and eddy-current affect the temperature rise of the wire. Because OPGW is so complicated, there were several cases that the data measured had shown more than a 30% deviation from the experimental value by using the method of the conventional short-circuit temperature rise calculation.

2.4 Short Circuit Temperature Rise Calculation Program

As mentioned above, in order to calculate the temperature rise of OPGW precisely, the following must be considered:

- Each wire has its own impedance to the AC current, and therefore the current distribution in the conductor is not uniform,
- The heat in each wire is produced by the resistivity and current based on Joule's Law and also produced by the iron losses due to its magnetic characteristics. This heat moves from a wire to another wire with time by the temperature difference.

In order to design OPGW reasonably, a personal computer program has been developed which makes it possible to calculate the precise short-circuit temperature rise by taking into consideration the above effects. The impedance of each wire is estimated by calculating magnetic fields produced by the distributed currents which are affected by the geometric construction of conductors and the conductivity of each wire. This estimated impedance is used to again calculate current distribution. This algorithm is iterated and the ultimate current distribution in the conductor is obtained by converging these outputs in steps. The temperature rise in the conductor is derived from the conductor's thermal capacity and the heat which is generated by the current and wire's resistance based on Joule's Law and by the iron losses due to magnetic field. Then the heat generated by each wire begins to move by temperature difference. The heat transfer between each wire is impeded by each contact condition and surface condition. Figure 1 shows a heat flow of the OPGW in a form of electrical equivalent circuit. The temperature change in the conductor can be calculated from a transient state in the equivalent circuit. Heat transfer constant differs by contact conditions (wire shape, stranded wire structure etc.), therefore, theoretical calculation is difficult. The constant is obtained by an actual short-circuit test in which the temperature rise is measured using actual wires. Figure 2 shows a heat transfer test.

The temperature rise of the wire in short-circuit tests

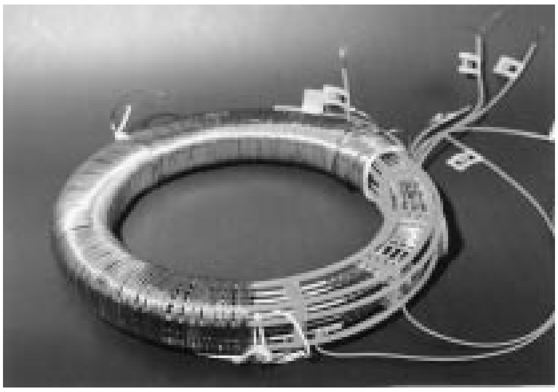


Figure 3 Experiment on magnetic characteristics of AC wire

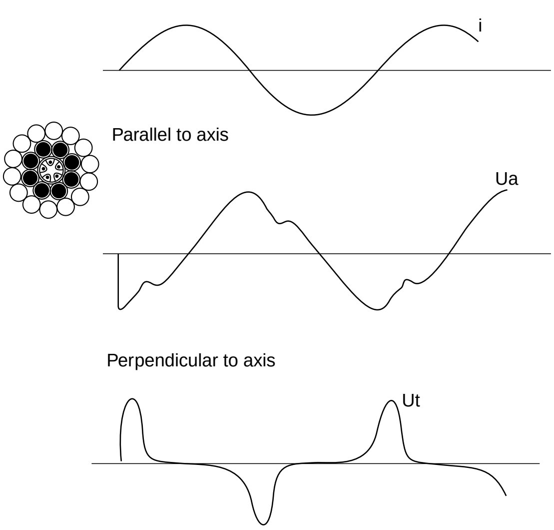


Figure 4 Waveform of induced voltage on OPGW

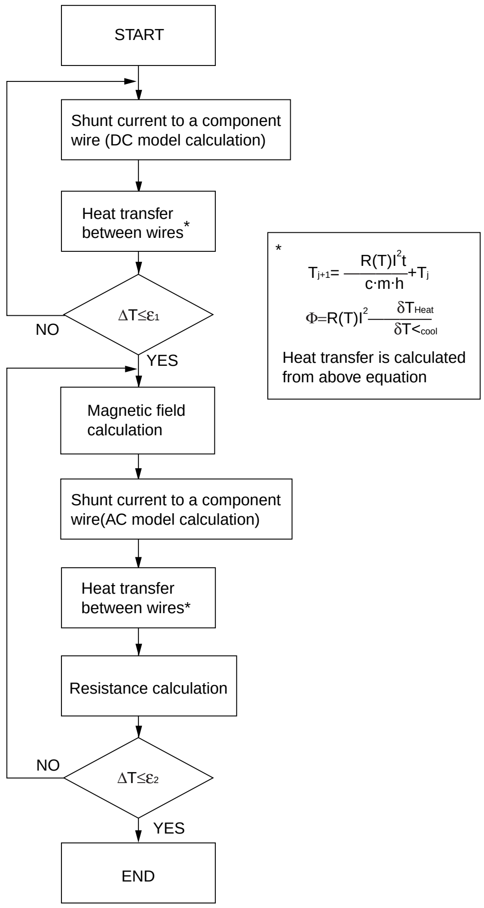


Figure 5 Program flow chart for calculation of OPGW temperature in short-circuit conditions

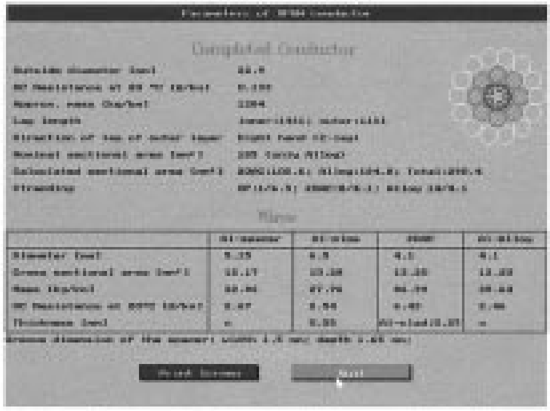


Figure 6 Data output of OPGW calculation

increases each wire resistance with time (the temperature coefficient of resistance is assumed constant), and both the current distribution and the magnetic fields are calculated in the next step. Thus, iteration of these procedures brings out the actual nearest temperature rise in short-circuit failure. As mentioned above, an aluminum clad wire used in the OPGW produces iron losses and the values must be included in the calculation as additional amounts of heat.

The magnetic field produced by the current which flows through the stranded wire has magnetic flux of the both axial and line directions, and the total magnetic field acting on the wire is gained by composing both directional forces. The magnetic characteristics of aluminum clad wires placed in this magnetic field are difficult to theoretically calculate. Therefore, the B-H curve is obtained experimentally using an actual wire. In this experiment, both magnetic saturation characteristics of a coiled aluminum clad wire and magnetic field originated by the current which flows through the stranded wire are measured by a sensor coil. Figure 3 shows the experiment for the magnetic characteristics of an aluminum clad wire, and Figure 4 shows the wave form samples of the induced voltage in the stranded wire.

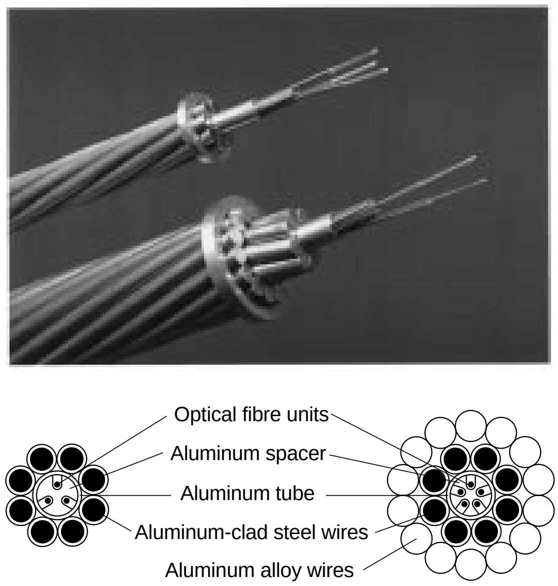
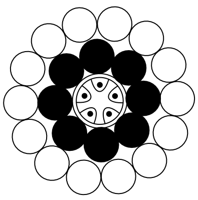
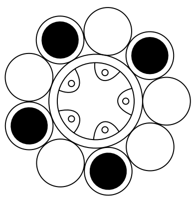


Figure 7 Construction of OPGW

The short circuit temperature rise calculation has been programmed using Turbo-Pascal, and is available for a personal computer(Windows version). By inputting such data: initial temperature, short-circuit current, short-circuit time, duration etc., a tabulating and graphing output of the relationship between rise in temperature and the elapse of time is obtained. Figure 5 and 6 show a flow chart and output of the calculation.

Table 3 Comparison of measured and calculated results for OPGW under short-circuit conditions

OPGW		Short circuit current I [kA]	Time t [sec]	Initial temperature Ti [˚C]	Ambient temperature Ta [˚C]	Spacer temperature Tsp [˚C]	Aluminum clad wire temperature Tac [˚C]	Aluminum wire temperature Taa [˚C]
	Measured	33.5	0.38	50	20	145	75	140
	Measured	33.3	0.56	50	20	185	88	180
	Measured	33.5	0.70	50	20	248	117	235
	Measured	33.2	0.96	50	20	305	135	292
	Calculated	32.41	0.38	50	20	145	75	140
	Calculated	32.02	0.56	50	20	185	91	180
	Calculated	34.24	0.70	50	20	248	116	242
	Calculated	33.01	0.96	50	20	305	147	298
	Measured	14.3	0.30	19	20	135	66	132
	Measured	14.3	0.30	24	20	140	70	138
	Measured	14.4	0.16	25	20	90	50	86
	Measured	14.4	0.46	25	20	220	107	215
	Measured	10.8	0.30	25	20	90	—	86
	Measured	11.0	0.40	47	20	139	—	136
	Measured	11.1	0.50	41	20	154	—	152
	Measured	1.0	0.80	41	20	235	—	230
	Calculated	14.60	0.30	19	20	135	63	132
	Calculated	14.48	0.30	24	20	140	67	136
	Calculated	15.32	0.16	25	20	90	48	88
	Calculated	14.59	0.46	25	20	220	102	215
	Calculated	1.15	0.30	25	20	90	48	88
	Calculated	10.99	0.40	47	20	139	79	135
	Calculated	10.86	0.50	41	20	154	82	150
	Calculated	10.91	0.80	41	20	235	117	230

2.5 OPGW Short-Circuit Test

To verify the calculation data, a short-circuit test for a typical OPGW was carried out. The OPGW was produced by Philips-Fitel Inc., Canada, and the construction is shown in Figure 7. The test was conducted at VEIKI Kft in Hungary. The length of OPGW is approximately 10 m, and the tension applied is about 10% UTS.

2.6 Evaluation

The calculated data, given by the developed software, and measured results are compared and they are in close agreement with each other within 5% as shown in Table 3. This is considered satisfactory in consideration of the test precision. In the temperature measurement, it was found that the rising was extremely fast, so the time-lag of the transient response must be considered in the measurement system. The thermocouple used in the test was small enough in thermal capacity, but should inevitably include a small margin of error. Also, the wave form deformation of the current might exist. Taking all factors of errors into consideration, this calculation data is accurate and satisfactory.

From the test results, the temperature of the optical unit seems to be high regardless of the surface temperature being low. This trend must be taken into account beforehand in transmission line designing.

3. IN SUMMARY

It is found that the short circuit temperature rise calculation program for a conductor makes it possible to estimate the momentum temperature of an OPGW with sufficient accuracy. A reasonable design for the OPGW is expected to be carried out for overhead transmission line by various customers, using the program to obtain necessary mechanical characteristics and a satisfactory tolerable temperature of the optical fiber cable in the unit. Recently, a larger capacity of transmission is required and the number of optical fibers involved is now increasing. The spacer type OPGW in the conventional design, therefore, suffers unfitting in OPGW designing. The development of a new construction of OPGW is urgently required. This program is intended to be used for examination of the operating current capacity of the new construction design.

This study has been carried out by VEIKI in Hungary who subcontracts Phillips-Fitels Inc. in Canada. The analysis of test data was done in cooperation with FETI in Hungary. The outline of this study is reported to CIGRE SC22 WG12, and will be soon reported to ELECTRA.

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