Memoirs of the Faculty of Engineering, Nagoya University
Vol. 34. No. 1 (1982)

EXPERIMENT OF ARTIFICIAL LIGHTNING TRIGGERED WITH ROCKET

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(Received May 1, 1982)

Abstract

The experiment of artificial lightning triggered with a rocket pulling up the grounded wire has been carried out since 1977 in cooperation with the following members; I. Miyachi, K. Horii, Y. Kito, H. Akiyama, H. Yamashita, Y. Higashiyama (Nagoya Univ.), S. Muto, K. Nakamura (Nagoya Inst. of Tech.), G. Ikeda, S. Sumi (Chubu Inst. of Tech.), S. Aiba (Kanazawa Inst. of Tech.), R. Ishibashi (Kanazawa Univ.), H. Sakurano (Ishikawa Tech. College) and N. Kitagawa (Saitama Univ.).

The purposes of this experiment are to investigate the mechanism of the lightning discharge including predischarge phenomena, and to develop the technique protecting from the hazards by lightning discharge. Though the lightning has not been triggered in summers, 32 lightnings were triggered in winters at Hokuriku, the north coast of Japan. The peak value and the duration of discharge current, the electric field intensity at ground, the altitude of rocket, and others were measured, and the relations among them were discussed. The mechanism of lightning discharge was made clear from the optical observation and the measurement of current. The long gap discharges between the bobbin hanging in air and the ground were successfully performed three times, and the hairpin effect of mannequin and the safety in a motorcar for the lightning discharge were confirmed. The surge voltages induced on the test line of power distribution were measured and the shielding effect of the overhead grounded wire to the test line was confirmed. At last, the subjects to be investigated are described with the conclusion of this paper.

CONTENTS

1. Introduction

After the first success to trigger a lighting with rocket pulling up a grounded wire by Newman in 1960,[1] a big project of the experiment has been performed actively by Hubert, Fieux, Gary and others in France since 1973.[2],[3]

After the preliminary research in 1976, the experiment of artificially triggered lightning in Japan has been carried out since the summer of 1977 by the support of the grant in aid for scientific research from the Ministry of Education, in cooperation with the following members and many students.[4],[5]

I. Miyachi, K. Horii, Y. Kito, H. Akiyama, H. Yamashita, Y. Higashiyama, (Nagoya University), S. Muto, K. Nakamura, (Nagoya Institute of Technology), G. Ikeda, S. Sumi, (Chubu Institute of Technology), S. Aiba (Kanazawa Institute of Technology), R. Ishibashi (Kanazawa University), H. Sakurano (Ishikawa Technical College), and N. Kitagawa (Saitama University).

The purposes of this research are as follows;

a) Investigation of the mechanism of lightning discharge by the observation of discharge including predischarge and the measurement of discharge characteristics.

b) Investigation of the damages to the human body, the architectural structure, and the electrical apparatus caused by lightning strokes, and the development of the technique protecting those from lightning discharge.

The significance and characteristics of the experiment to trigger the lightning with rocket are as follows;

a) A triggered lightning is induced to the fixed point at a predicted time, so that it is possible to observe the whole process of discharge in detail, in comparison with a natural lightning. For example, though the observation of lightning striking the tower on the top of the mountain,[6] the tower of television antenna,[7] or the weather observation tower[8] offered many usefull data, it was difficult to measure the predischarge process or to take the high speed photograph of the natural discharge because of the difficulty to operate the measuring devices just before the flash. The experiment of artificilly triggered lightning changed the experiment of the lightning from passive to active investigation.

b) The relations among the parameters, such as the electric field at ground, the altitude of an ascending rocket and the electric characteristics of lightning discharges, are investigated from a lot of data. The mechanism of lightning discharges, including the condition of discharge to strike a tall construction, is discussed from the above results.

c) It is possible to carry out a damage test with a actual lightning by triggering a discharge to a test object on the ground. In a laboratory test, the voltage, the current and the energy of the discharge are limited by the capacity of impulse generator. The full scale test by triggered lightning is necessary to investigate the large scale phenomena, such as the back flashover at the power transmission tower struck by lightning and the induction of surge voltage on the power transmission line located near the discharge point.

d) The techniques controlling the lightning motivates the new protection methods against the lightning. One of the methods is to arrest the striking to a important place by guiding the lightning to a safe place through the wire trailed by a rocket, and the other method is to neutralize the bipolar charges in the cloud itself by triggering a cloud discharge.

The experiments have been carried out since 1977 both in summer and winter. The summer experiments have been performed mainly at the mountain area in Central Japan, and winter experiment at north coast in Hokuriku area in Central Japan. The thundercloud in summer is caused by mixing a cold air blowing from the north at the high altitude with a damp warm air blowing upward from the ground heated by the sunlight. This thundercloud appears in the central mountain area of Honshu Island, and usually comes down to the south field. The thundercloud in winter is generated over the Sea of Japan by mixing the cold wind blowing across the Sea of Japan from Siberia with the damp air warmed by the warm sea current flowing along the coast of the Sea of Japan. The thundercloud comes to the coast with north-west wind.

For four years from 1977, the rockets made for anti-hail were imported from France. The new types of rockets have been made in Japan since 1980. The 97 pieces of rockets, including the test shots of 26, were shot. The 55 of 97 succeeded to ascend without early cutting off of the wires and 7 of 55 were shot in summers. Although it was unsuccessful to trigger the lightning in summers, 32 lightning flashes were triggered in winters.

The experimental results in winters are as follows;

a) The techniques to trigger the lightning were established, and the rate of success was 64 % for the case pulling up the wire to the altitude higher than 300 m. The timing of the shooting of rocket was determined by the electric field intensity at ground with the aid of alarming device which detects a point corona, after the information about the thundercloud was obtained from the rader system in Komatsu airport.

b) The electric characteristics, such as the electric field intensity at ground, the predischarge and main discharge currents and the charge transferred from the cloud, were measured and discussed statistically.

c) The mechanism of lightning discharge was made clear by the optical observations using high speed cameras.

d) The actual tests striking the mannequin, the motorcar, and the power transformer with the triggered lightning were performed with the test of induced voltage on the power distribution line installed near the discharge point.

Finally the future subjects and the remaining problems on the experiment to trigger the lightning are proposed. The main subject is the development of the safe technique to pull up a wire by means of an electric motor instead of the explosive powder as an example. Another technique is to vaporize the wire by means of flowing artificially a pulse current before falling on the ground in the unsuccessful case to trigger the lightning.

2. Outline of Experiments

2. 1. Terms and Places of Experiments

The terms and the places are shown in Table 1, and the places are also shown in the IKL map of Fig. 1.

Table 1. The terms and the experimental places in summers and winters.

(a) summers

years	places	Terms	Features of Experiment
1977	Iruka Lakeside, Inuyama, Aichi Prefecture.	July 16 ～ Aug. 31	Development of technique to trigger lightning with rocket.
1978	The tower of resting power transmission line, Noguchi, Komaki, Aichi Prefecture.	July 2 ～ Sept. 10	Back flashover from tower to power transmission line.
1979	Iruka Lakeside, Inuyama, Aichi Prefecture.	July 19 ～ Aug. 28	Only observation of natural lightning owing to delay of import of rocket from France.
1980	Iruka Lakeside, Inuyama, Aichi Prefecture. Watarase Reservoir, Fujioka, Tochigi Prefecture.	July 20 ～ Sept. 7 July 15 ～ Aug. 30	Separate experiments at two places.
1981	Mt. Gongen, Yaotsu, Gifu Prefecture.	July 20 ～ Aug. 27	Experiment by rocket of new type at high land.

(b) winters

years	places	Terms	Features of Experiment
1977	Kahokugata reclaimed land Tsubata, Ishikawa Prefecture.	Nov. 30 ~ Dec. 28	Development of technique to trigger lightning with rocket.
1978	〃	Nov. 27 ~ Dec. 31	Experiment of mannequin struck by triggered lightning through long gap.
1979	〃	Nov. 25 ~ Dec. 29	First measurement of induced surge voltage on transmission line.
1980	〃	Dec. 1 ~ Dec. 27	Experiment of motorcar struck by triggered lightning with rocket made in Japan.
1981	〃	Nov. 24 ~ Dec. 29	Experiment using plastic flame for long gap discharge.

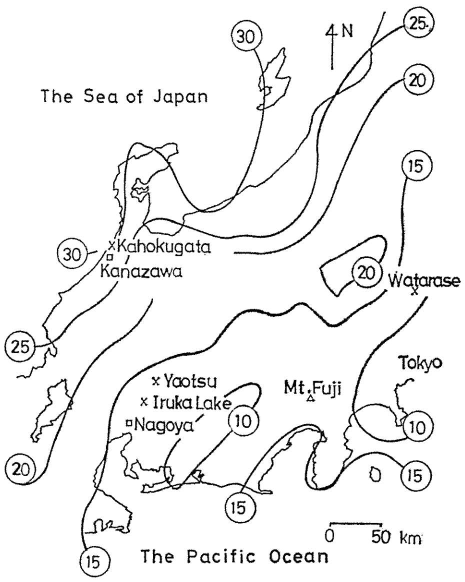


Fig. 1. Isokeraunic Level in Central Japan. The numerals and × show the number of thundercloudy days a year and the experimental places respectively.

1. 2. 2. Thunderclouds over the Locations of Experiments

Figure 2 shows the schematic diagram of the thunderclouds in summer and winter, and Fig. 3 shows the radar echo. The temperature in summer of Japan rises over 30 ℃. The damp warm air coming from the south sea of Japan is heated by the hot ground and mixed with the cold air at high altitude in the central mountain area of Honshu Island, where the thunderclouds are generated. The clouds come down to the south field along big rivers. The many strong thunderclouds sometimes appear along a warm front and move with the front. The IKL

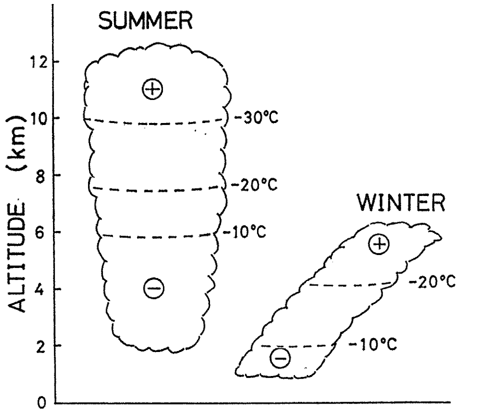


Fig. 2. Schematic diagram of the thunder-clouds and distributions of charges in summer and winter.

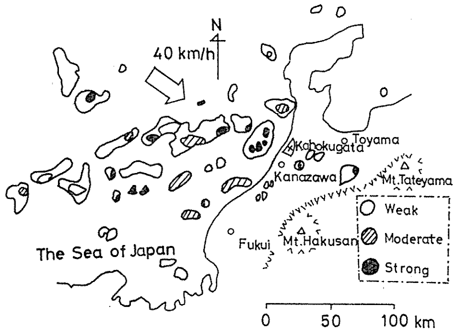


Fig. 3. Radar echo near Kahokugata, north coast of Japan, in winter.

number attains to 35 in the central mountain area in Japan. Although the thunder days are 5 $\sim$ 10 days in a month in summer, the appropriate days to shooting the rocket are about one fourth of them. There are a few or no chances to shoot the rocket in some summers. The altitude at the botom of thundercloud is higher than a few km. At the most active time of a thundercloud, the several flashes occur every minute. The polarity of the charge in the low altitude of thundercloud is almost negative.

The unusual thundercloud in winter appears at the coast of the Sea of Japan.[9] The warm sea current from the Pacific Ocean flows along the north coast of Honshu Island. The cold wind from Siberia blows into the damp air warmed by the warm current. The thunderclouds are generated in the unstable mixing area. The altitude of the thundercloud is lower than 1 km at the botom and 3 — 5 km at the top. Many clouds come to the coast with the north-west or west wind in a period of about one hour. Lightning discharges occur within the narrow coastal region of about 50 km in width and the clouds disappear at the mountains with the falling snow.

Figure 4 shows the frequency of the thunder clouds in winter, and Fig. 5 (a) and (b) show the typical variations of the electric field intensity in summer and winter respectively. The electric field at ground is intensified with the approach of the thundercloud. The electric field at ground decreases or sometimes changes the polarity suddenly by a lightning flash. In summer, the flashes are repeated with a high frequency because of the rapid recreating of the charge in cloud.

In winter, the polarity of the electric field intensity changes gradually, according to the movement of a bipolar cloud, as shown in Fig. 5 (b). The bipolar cloud is produced by strong wind in the high altitude, which makes a horizontal distribution of the bipolar charge. The many thunderclouds pass the coastal region without lightning. However, the tall construction, such as a chimney, the antenna at a radio station and power transmission towers, are frequently struck by the lightning. The reason is that the thunderclouds generated at the low altitude on a flat sea come to the coast without discharge and the charge inside the cloud makes a

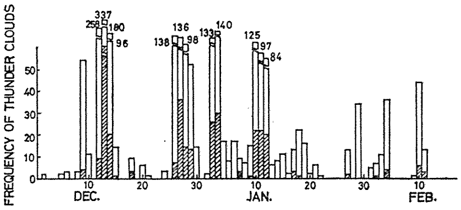


Fig. 4. Frequency of thunderclouds at Kahokugata from Dec. 1981 to Feb. 1982. Frequency is the number counted whenever the intensity of electric field at ground is over 6 kV/m, and shaded region is the number over 8 kV/m.

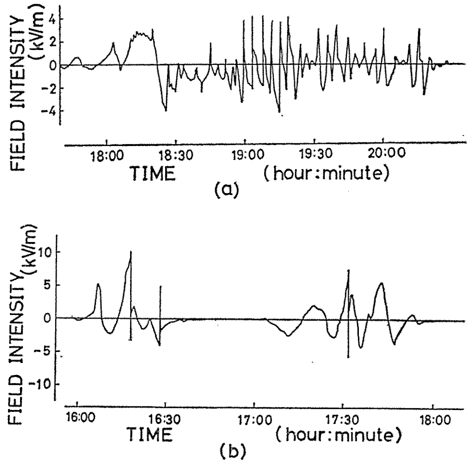


Fig. 5. (a) and (b) show the typical variations of electric field at ground at Iruka Lakeside in summer and at Kahokugata in winter respectively.

intense electric field at the tip of tall construction. In some cases, one flash discharges all the charge inside a cloud, and the charge is over 100 C.

The lightning flash on 25 December 1977 was such a giant one, which struck the lightning rod at the tower of a fire house near our experimental station. In spite of the low grounding resistance of the lightning rod, the electrostatic potential of the building increased because of the enormous discharge current, and almost all of the electric power system and the communication equipments inside the buildings of both the fire house and a neighbor town hall were destroyed by the back flashovers.

2. 3. Methods of Experiments

When the appearance of the thunderclouds is informed from the radar station, we asked the control center of the airport for the permission to shoot the rockets. The approach of the thundercloud is alarmed by the point corona detector. The rocket is shot at a moment, when the thundercloud comes just over the head, that is, the electric field intensity at ground is increased. The countdown to shoot the rocket is announced to other stations by a wireless system, and the measuring equipments are synchronized to the time of shooting.

The launchers of rockets were set up at the site where neither the house nor the electric power line is within a range of 200 ~ 300 m. As those places, a lakeside, the top of a mountain or a reclaimed land was selected except the back flashover experiment at the tower of the resting power transmission line on a hill in summer of 1978 as shown in Fig. 6.

The small rockets of the anti-hail, type 614, were imported from the Establishment of Ruggieri in France from 1977 to 1980. As the import of the rockets became difficult owing to the provision for the safety, the rockets remodeled from the linethrowing appliance have been made by Koa Kako Company in Japan since winter of 1980. The details of rockets are shown in Table 2. There is the

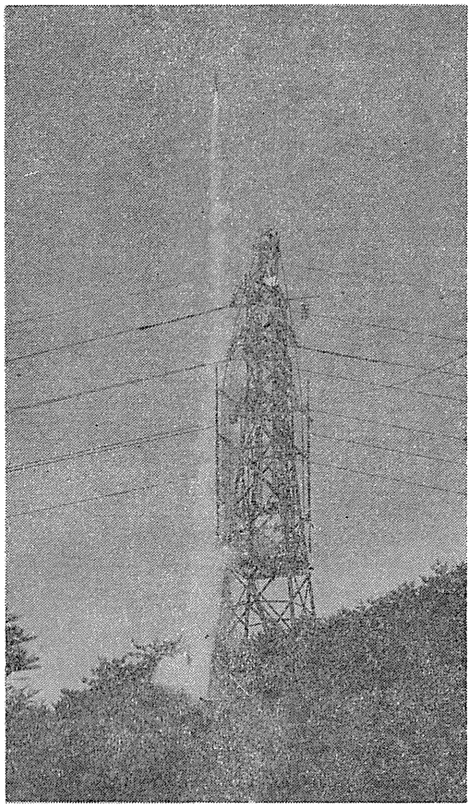


Fig. 6. Rocket shot from the tower of resting power transmission line in summer of 1978.

Table 2. Details of rockets

Rocket of anti-hail, type 614 (made by Establishment of Ruggieri, France)	Material of body; plastics Total length: 849 mm Total weight: 2360 g Black powder propellant: 930 g Explosive compound: 400 g
Rocket remodeled from the line throwing appliance (made by Koa Kako Co., LTD, Japan)	Material of body; steel Total length: 430mm (body: 133mm, leg: 297mm) Total weight: 550 g Composite propellant: 150 g
Rocket of new type (made by Koa Kako Co., LTD, Japan)	Material of body; steel Total length: 1155mm (body: 405mm, leg: 750mm) Total weight: 3385g Composite propellant: 735g

explosive of 400 g at the head of the anti-hail roket, and the plastic body of rocket is cracked to pieces at the altitude of about 500 m by the explosion. The bodies of Koa Kako Company-made rockets are made of steel, and fall down on the ground. The parachute was blown off from the falling body in the experiment of winter in 1980. The safety has deen assured without the parachute by the control of the ballistic trajectory since 1981. It was one of the motivations for developing a new rocket in Japan that some rockets of the anti-hail exploded abnormally early owing to the crack in the solid propellant generated during the transportation by ship.

The launchers are constructed by angled steel frames and wood rods. The picture of the launcher is shown in Fig. 7. The guide rail of rocket is about 4 m

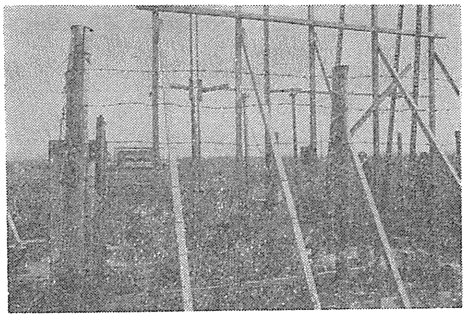


Fig. 7. Photograph of launcher.

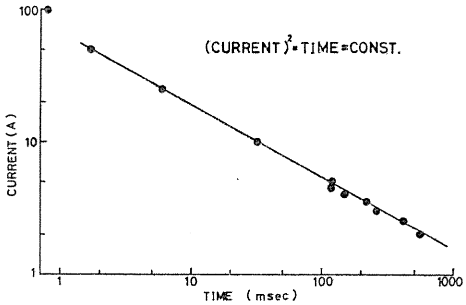


Fig. 8. Characteristics of wire vaporization.

in length. The compressed black powder or composite propellant for the propulsion was fired with a detonater by switching the three dry cells with the series connection. The switch attached to the launcher was operated by an air piston pressurized through plastic pipe of about 100 m in length from the control room to the launcher in summer of 1977. Since winter of 1977, the switch has been turned on by pulling a plastic string of 80 m in length because of the rapid and reliable switching. In summer of 1981, the launcher was set at the top of a mountain, and the rockets were fired by the radio controller of 154 MHz, using the pulse logical circuit. One mistaken firing was caused by the interference of radio noise.

The steel wire of 0.2 mm in diameter is covered with Formal, and spooled on a bobbin. The steel wire has the resistivity of 13.3 Ω per meter at the room temperature, and is burned off by the continuous current of 1.05 A or the pulsed current as shown in Fig. 8. The wire exploded with the pulse current becomes the molten fine pieces including the metal vapor, and is blown out through the cracks of formal cover.

The steel wire is spooled off the bobbin with the ascending speed of rocket without twist. Although the tensile strength is 5.6 kg, the wire is easily broken by kink. The load to spool the wire off the bobbin is $5\times10^{-2}v^2$ (kg), where v (meter/second) is the velocity of rocket. The wire of 0.8 mm in diameter, the rubber string, and the steel wire are connected with the rocket wings in order. The wire and the rubber string are covered with the silicone glass fiber tube to protect those from the flame of rocket. The rubber string is the absorber of the shock at the shooting of rocket.

The ring made of a copper tube of 12 mm in diameter collects the discharge current flowing through the steel wire, and then the current flows to the earth conductor, The current is measured at the earth conductor. The wire system is

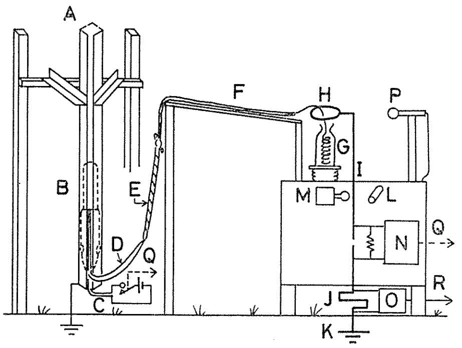


Fig. 9. Arrangement of launcher and measuring equipments.
A : launcher, B : rocket, C : detonator,
D : wire of 0.8mm in diameter,
E : rubber string, F : plastic string,
G : bobbin, H : collector ring,
I : copper pipe, J : shunt resister,
K : earth conductor,
L : magnetic link,
M : steepness indicator,
N : predischarge current detector,
O : main discharge current detector,
P : microphone,
Q: string for switching,
R : optical fiber.

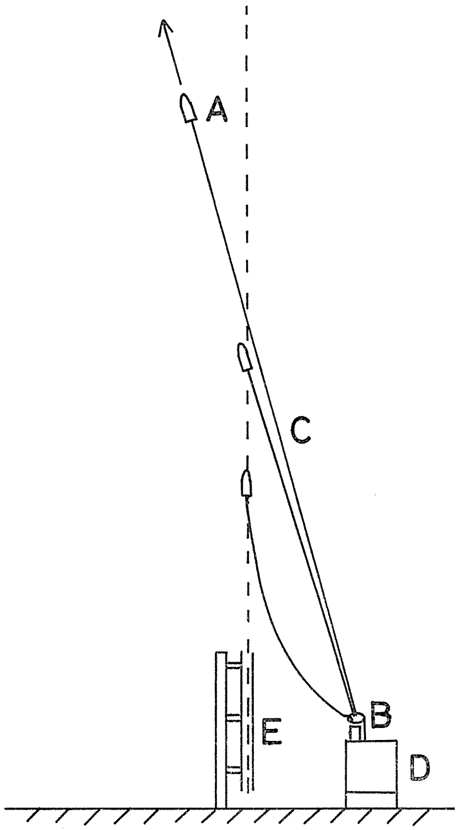


Fig. 10. Deflection of the trajectory of rocket.
A : rocket, B : bobbin, C : wire,
D : box of measuring device,
E : launcher

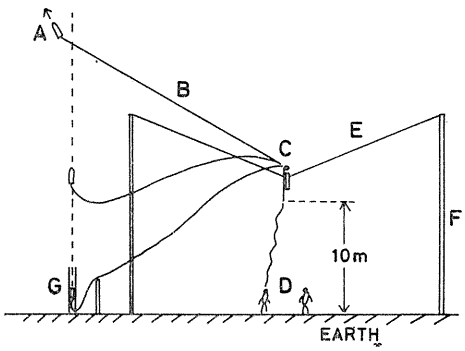


Fig. 11. Experimental apparatus for the long gap discharge.
A : rocket, B : wire, C : collector ring,
D : mannequin, E : plastic rope,
F :wooden pole, G : launcher

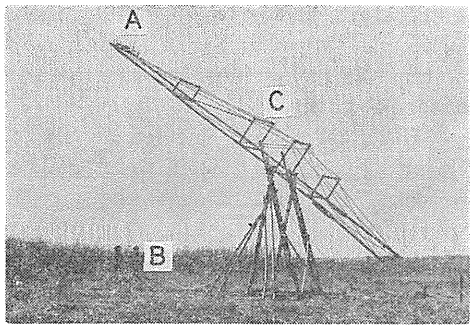


Fig. 12. Plastic frame for the long gap discharge.
A : bobbin, B : model of human body,
C : plastic frame

constructed as shown in Fig. 9.

The careful handling is needed to prevent the wire from being spooled off and being entangled by strong wind, and to prevent the connection part between the wire and the rubber string from being broken by the shock at the shooting of rocket.

The trajectory of rocket is deflected by the force drawing the wire just after the firing of rocket, as shown in Fig. 10. The deflection is remarkable in the experiment of the long gap discharge, where the bobbin is hung with a plastic rope as shown in Fig. 11, or with a plastic frame as shown in Fig. 12. The spark discharge occurs between the bobbin and the ground, and test objects, such as a mannequin and a motorcar, are struck by the spark discharge.

2. 4. Measuring System

Figure 13 shows the arrangement of the measuring sites in winter of 1980 as a typical example.

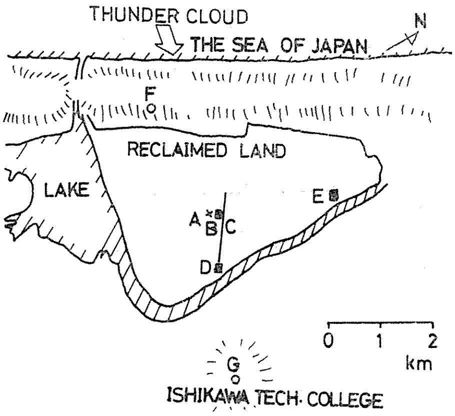


Fig. 13. Arrangement of the measuring sites at Kahokugata in winter of 1980.
A : discharge point,
B : control station,
C : test line of power distribution,
D and E : observation stations,
F and G : sites measuring the point corona current.

The control and the two observation stations were situated at the distances of 80 m and 1 ~ 2 km from the launcher respectively, and were built provisionally. The arrangement was changed every year. One of the still photographs was taken at the observation station, which was a motorcar in some winters, and in the last winter a camera set in the building was controlled with a wireless system. As the electric power line was not installed at the control station, the electric power was supplied by engine generators.

The measurements at the control station were as follows ;

a) Electric field intensity at ground

Two field mills were set at the distance of about 20 m from the control room. The detector of the field mill had the electronic guard system for the leakage current caused by rain, so that the detector was faced upward against rain. The response time was about 10 ms. The field mills were connected to the measuring devices in the control room through the coaxial cable, and the signals were recorded with the FM and pen-writing recorders.

b) Point corona current

The electric field intensity at ground was able to be measured with the corona current flowing into the air from the point of grounded needle. A point of 0. 15 mm in the radius of curvature was set on the tip of the bamboo rod of about 5 m in height, and the corona current was recorded in the control room. The relation between the electric field intensity and the corona current is shown in Fig. 14. Although the corona current is affected by the weather conditions, such as the rain or the wind, the corona current starts to flow at a critical electric field, which is changed by both the height of the point from the ground and the radius of curvature of the point as shown in Fig. 15.[10]

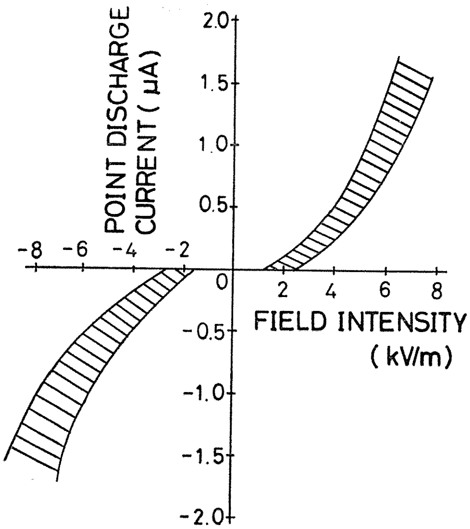


Fig. 14. Relation between the intensity of electric field at ground and the corona current.

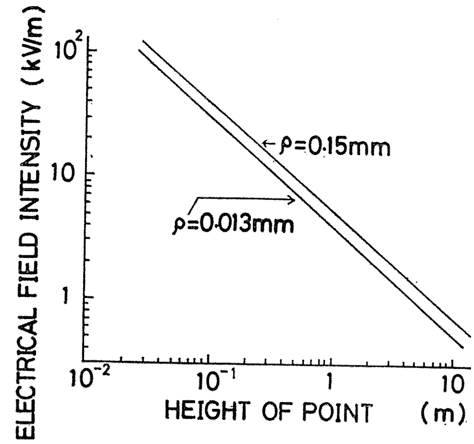


Fig. 15. Relation between the intensity of electric field at ground to start the point corona discharge and the height of point.
ρ: radius of curvature of point.

The characteristics of the corona discharge was used to alarm the approach of the thunderclouds.[11] In winter, as the thunderclouds moved with the north-west wind, the alarming devices with a wireless system were set on the windward to alarm before the thundercloud came above the head. The flash-counter is useless to alarm the approach of the thunder clouds, because there are few lightning flashes during passing above the sea. Moreover, the response of the corona current to the electric field change is so quick that it is possible to detect the fast change of the electric field caused by the predischarge just before the flash. The corona current detector also has the advantages of simple and power-sourceless device, in comparison with the field mill or the flash-counter.

c) Predischarge current

The predischarge current flows from the tip of rocket or wire to the ground through the wire on the way of the ascent of rocket. In the initial stage of predischarge, the current increases from the order of μA to mA, and the current of the leader stroke attains to 100 A immediately before a flash. The current was detected at the earth conductor connected with the collector ring, and recorded on the magnetic tape recorders using the amplitude modulator or the frequency modulator for the carrier frequency of 5 kHz. Although the measuring device does not respond to the pulse with the duration less than 1 ms, the peak of the recorded pulse corresponds to the integration of the pulse, that is the charge.

d) Main discharge current

The main discharge current was detected through the shunt resistor of 0. 00575 Ω, and converted to a light signal with a light emission diode. The signal was conducted to the control room through an optical fiber, and measured with an oscilloscope, a digital memory and a data recorder after the inversion to an electric signal.

e) Magnetic link

The peak current of the main discharge was measured with the residual magnetization of the steel sticks, which were set at the distance of 5 and 10 cm respectively from the earth conductor.

f) Steepness of main discharge current

The steepness was indicated from the breakdown of diode, which was caused by the induction voltage in a coil linked with the magnetic flux around the earth conductor.

g) Change of electric field intensity at the moment of main discharge

The voltage difference between an aluminum plate with 50cm square and the ground plate was measured with a digital memory through an optical fiber system, or simply with a Klydonograph on a photographic film. The gap length between two plates was 20 cm.

h) Step voltage on the surface of ground

The step voltage between two earth conductors near the discharge point was induced by the main discharge current, and measured with a Klydonograph, the breakdown of diodes or the photograph of a light emission diode.

i) Light emission from lightning stroke

The intensity of the emission was measured by a photodiode, a photo-multiplier, and a discharge tube sensitive to the ultra-violet light.

j) Acoustic emission from the lightning stroke

The shock wave was generated around the discharge stroke. This wave was measured with a microphone near the discharge point.

k) High speed framing photograph

A high speed movie camera of 1000 $\sim$ 1500 frames a second was directed to the discharge stroke or to the leader stroke propagating from the tip of rocket with the elevation angle of 52°.

l) Streak photograph

The streak camera with an image intensifier in front of the camera was directed to the predischarge propagating from the tip of rocket with the elevation angle of 47°, and the film was driven with the velocity of 1 $\sim$ 2 m/s.

The measurements at the observation stations were as follows;

a) High speed framing photograph

A whole of the discharge strokes propagating from the tip of rocket to the thundercloud was taken with the high speed movie camera of about 1000 frames a second.

b) Streak photograph

The same camera as that at the control station was used to catch the discharge strokes between the thundercloud and the ground.

c) Point corona current

The point corona current was measured to detect the change of the charge in the cloud, which was discharged by the triggered lightning.

d) Reconstruction of discharge channel by acoustic signals

Three microphones were set on the ground at the vertices of the equilateral triangle with the base line distance of 3.5 m. The discharge channel was determined from the time differences among the acoustic signals measured by the microphones, and between the acoustic and the electric signals of the discharge.

e) Induced surge voltage on a power distribution line

The test line was at the distance of about 77 m from the discharge point and 1.5 km in length. The induced surge voltage was measured with an oscillograph, a digital wave memory and a magnetic tape recorder. The shielding effect of overhead ground wire was examined by means of earthing the upper parallel line.

3. Experimental Results

3. 1. Summary

Table 3. Experimental results in summers.
E: Intensity of electric field at ground just before the shot.
L: Altitude of the tip of wire pulled up by rocket.
S. U. T.: Success ○, Unsuccess ×, Test shot —.

Experimental No.	Date/ Month	Hour : Minute	S. U. T	E (kV/m)	L (m)	Notes
1977—1	16/7	9:22	—		446	
2	17/7	10:15	—		551	
3	27/7	19:26	×		500	
4	28/7	18:56	×		320	
5	〃	19:01	×		49	Wire was cut off.
6	〃	19:03	×		559	
7	20/8	17:09	—		519	
8	31/10	13:00	—			Combustion test at Nihon Yushi Co. LTD.
1978—1	8/7	18:04	×	−7.0	5	Early explosion of rocket.
2	25/7	18:42	×	−6.6	0	Wire was cut off.
3	〃	19:10	×	−7.0	508	
4	〃	19:19	×	−11.0	80	Wire was cut off.
5	15/8	16:11	×	−6.8	261	
6	17/8	14:03	×	−8.0	335	
1979						Only observation.
1980—1	15/8	14:25	×	−3.0	87	Wire was cut off.
2	16/8	17:11	×	+2.0	140	Wire was cut off.
3	23/8	15:40	×	+2.0	51	Wire was cut off.
1981—1	20/7	16:20	—			
2	25/7	7:55	—			Mistaken firing.
3	28/7	15:30	—			
4	11/8	16:14	—			

Table 4. Experimental results in winters.
I : Peak value of lightning current.
Q : Electric charge of dischage.
*: Lightning not to follow the path of vaporized wire.

Experimental No.	Date/month	Hour : minute	S.U.T	E (kV/m)	L (m)	I (kA)	Q (C)	Duration (mS)	Pulses	Notes
1977— 1	20/12	16:40	×		0					Rubber string was cut off.
2	22/12	02:01	○	+9.0	78	+2.2				
3	27/12	02:47	○	−7.5	153	−1.8				
4	〃	07:50	—		503					
1978— 1	20/12	00:07	○	+5.7	100	+5				
2	〃	01:06	×	+5.5	35					Mannequin test, wire was cut off.
3	23/12	21:56	○	+4.8	300	<+1		24	1	
4	29/12	08:14	○	+8.5	190	+15		177	2	Mannequin test.
5	〃	08:25	×	−5.4	284					
6	〃	09:23	○	+5.5	167	+16		185	1	
7	30/12	05:44	○	−6.2	240	(10A)				Mannequin test, discharge along rope
8	〃	05:58	○	−9.0	83	<−1		58	1	
9	31/12	09:10 ~ 10:10	—							
10	〃		—							
11	〃		—							
12	〃		—							
1979— 1	30/11		—							
2	1/12	23:31	○	+9.3	96	+3.6		30	1	
3	5/12	23:24	×	−5.6	595					
4	〃	23:34	○	−7.1	143	<−1.2		113	1	
5	10/12	14:15	○	−9.4	108	<−1.2		26		
6	15/12	07:49	○	−10.6	37	−24		330	1	
7	25/12	00:20	×	+7.1	63					Early explosion of rocket.
8	〃	11:45	×	+12.3	116					
*9	〃	11:49	○	−9.4	114	−16		707	4	
10	〃	12:05	×	+2.7	271					
11	27/12	06:21	×	−5.9	0					Wire was cut off.
12	〃	06:35	○	−7.2	132	−1.4		760	2	

13	〃	06:58	×	+5.6	102					Early explosion.
14	〃	16:26	○	−7.4	231	−12		320	23	
1980— 1	5/12	16:38	—		100					
2	6/12	13:30	—		372					
3	〃	17:19	×	+5.5	357					
4	〃	18:42	×	−11.5	284					
5	8/12	00:07	○	+7.5	148	+12	+90	307	1	
6	〃	02:15	×	−7.9	351					
7	9/12	09:09	×	+4.7	126					Motorcar test, early explosion.
8	〃	17:15	×	+10.0	97					Motorcar test, early explosion.
9	〃	17:22	×	+6.0	0					Wire was cut off.
10	〃	18:09	○	−9.0	159	−2	−1.5	250		
11	〃	19:01	○	+7.0	261	+5		140		Motorcar test.
12	12/12	23:02	×	+9.0	30					Wire was cut off.
13	13/12	01:54	×	−11.0	20					Early explosion.
14	18/12	14:34	×	−8.3	400					
15	〃	23:54	○	−7.0	243	−11	−80	427	1	
16	20/12	14:39	×	−10.0	0					Early explosion.
17	〃	14:50	○	+11.5	106	+24		357		Motorcar test.
18	〃	15:13	○	+11.0	77	<+0.5	+3.5	47		
19	23/12	17:00	○	+9.0	212	<+0.5	+20	284		
20	24/12	06:18	×	−8.0	10					Motorcar test, wire was cut off.
21	〃	06:31	○	−8.8	89	−13	−90	649	multi.	
22	〃	06:45	○	−6.2	195	−26		390	multi.	Transformer test.
23	26/12	06:54	×	−5.0	418					Motorcar test.
24	〃	08:39	○	−6.5	126	<+0.5		19	1	
1981— 1	27/11	17:10	—		537					
2	〃	17:20	—		543					
3	28/11	06:58	—		520					Mannequin test.
4	〃	07:00	—		513					
5	〃	07:04	—		438					
6	2/12	00:36	○	−9.0	66	−2.8		260	1	
*7	〃	01:27	○	−7.1	133	−9.0		350	5	Transformer test.
8	9/12	18:10	×	−4.8	511					

9	11/12	23:37	○	+7.2	173	+22.3		220	1	Mannequin test, abnormal discharge.
10	12/12	00:38	○	+6.0	166	+21.1	{+46, <−1}	260	4	
11	〃	00:46	○	−7.2	123	−6.6	{−50, +20, −8, −26}	618	4	Transformer test.
12	〃	02:57	×	+7.0	120					Mannequin test, wire was cut off.
13	19/12	18:01	○	−4.0	326	<−0.1		29	1	
14	〃	18:21	×	+6.0	405					Mannequin test.
15	〃	23:35	×	+6.0	206					Mannequin test.
16	24/12	01:25	○	+6.0	141	+23.8	+110	335	1	
17	〃	01:52	×	−3.0	0					Transformer test, wire was cut off.

Among the 71 rockets launched during summers and winters of 1977–1981, the rocket and the wires worked 55 times correctly.

Though 7 rockets of them were launched during summers, the lightning flashes were not triggered. It is considered that the causes of unsuccess during summers are due to only a few chances of shooting of rockets, the condition of the insufficient intensity of electric field at ground, and the shortage of the rocket altitude in comparison with the altitude of thundercloud.

During winters, 48 rockets were launched, and 32 flashes were triggered. The rate of success during winters was 66.7%.

The results during summers and winters are summarized in Tables 3 and 4 respectively, and the results during winters are described in the following sections.

3. 2. Distributions of Parameters in Table 4

Figure 16 shows the intensity of electric field at ground just before the shooting of rocket for both cases of the success and the unsuccess to trigger the lightning flash. The experimental values are arranged in order of the intensity of electric field at ground. The minimum, the maximum and the median values in the success cases are 4.0 kV/m, 11.5 kV/m and 7.4 kV/m respectively. There is not a large difference for the rate of success between the positive and the negative lightning flashes.

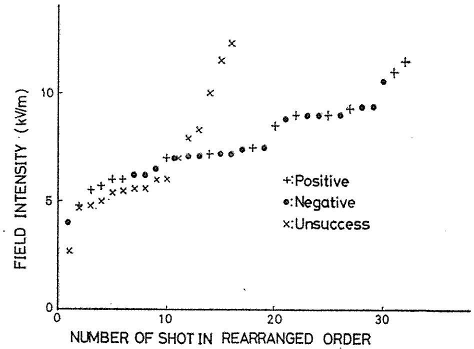


Fig. 16. Distribution of electric field intensity at ground just before rocket shot.
+ : cloud with the positive charge,
● : negative charge,
× : unsuccess case to trigger the lightning.

Figure 17 shows the dependence of the rate of success on the intensity of electric field at ground, where the rate is the ratio of the number of the success to the number of the launched rockets, and the width of rectangle represents the number of the launched rockets.

Figures 18, 19 and 20 show the distributions of the altitudes of triggering,

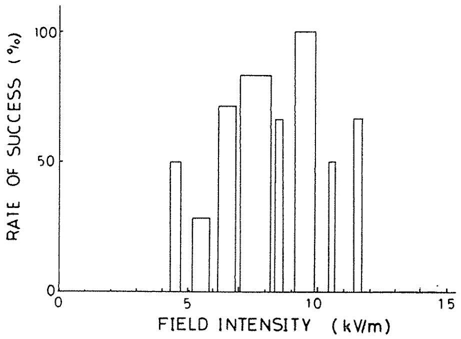


Fig. 17. Dependence of rate of success on the intensity of electric field at ground.

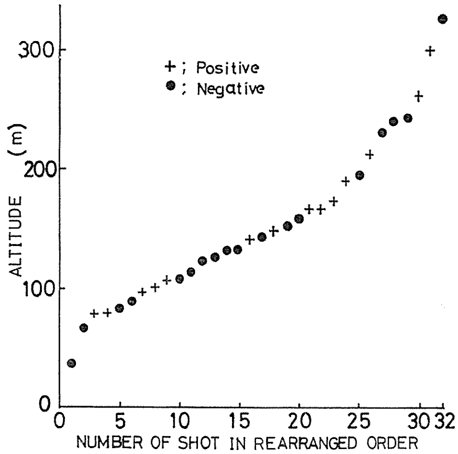


Fig. 18. Distribution of altitudes of rockets where the lightnings are triggered.

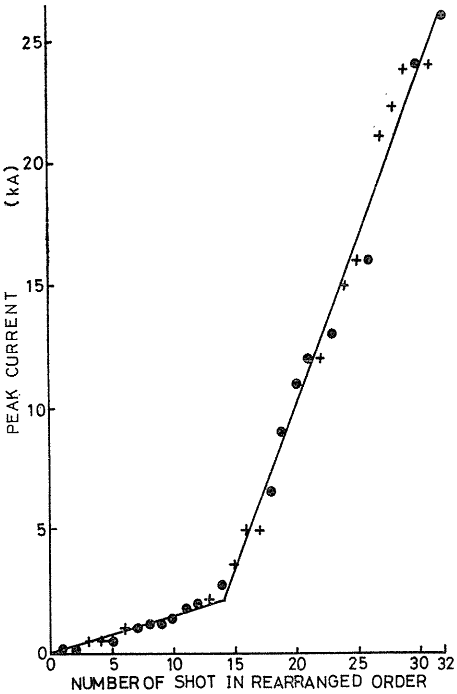


Fig. 19. Distribution of peak values of discharge currents.

Fig. 20. Distribution of durations of flashes.

the peak values of the discharge currents and the durations of flashes respectively. The minimum and the median altitudes of triggering are 37 m and 142 m respectively. The distributions of altitude and current are distinguished into two groups bounded by about 180 m and 2.2 kA respectively. The group with the large current has the median value of 15 kA, which is near the median value of the natural lightning. The group with the small current, which is the character of the triggered lightning, is due to the forced triggering of the flashes for the thundercloud with a little charge.

3. 3. Relations between Parameters

Figure 21 shows the relation between the altitude of rocket and the intensity of electric field at ground just before the shooting of rocket, including the

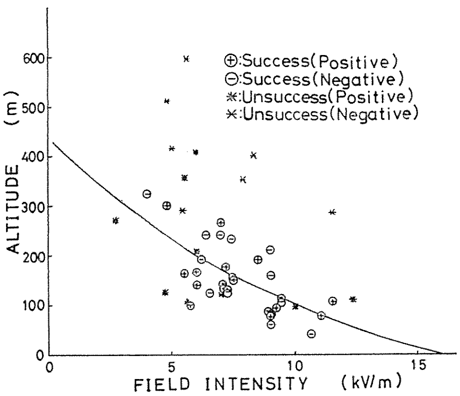


Fig. 21. Relation between the altitude of rocket and the intensity of electric field at ground just before rocket shot. The solid line is calculated from eq. (4).

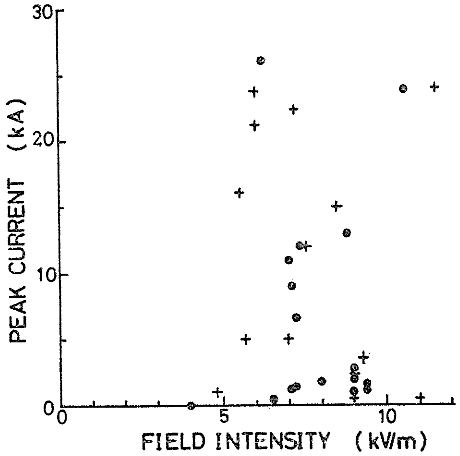


Fig. 22. Relation between the peak current of triggered lightning and the intensity of electric field at ground.

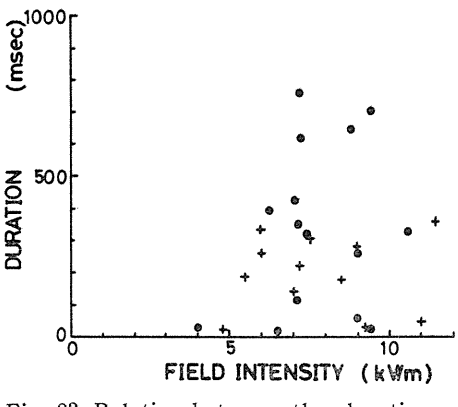


Fig. 23. Relation between the duration of flash and the intensity of electric field at ground.

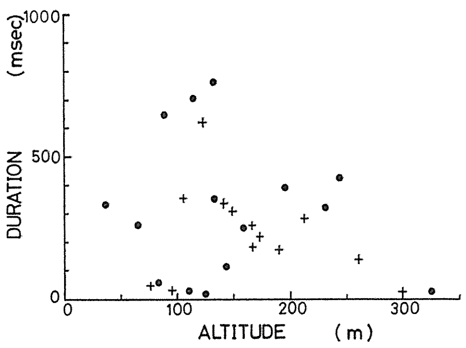


Fig. 24. Relation between the duration of flash and the altitude of rocket.

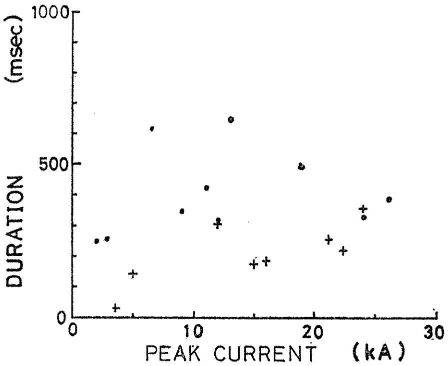


Fig. 25. Relation between the duration of flash and the peak current of lightning.

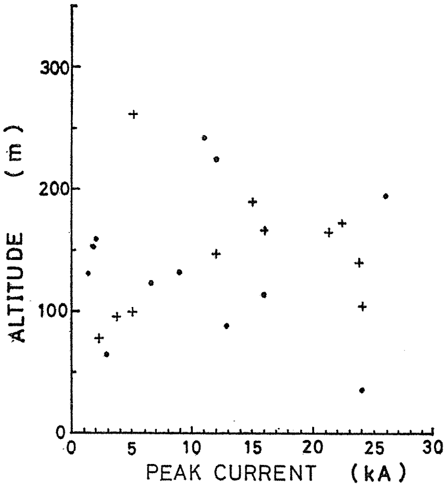


Fig. 26. Relation between the altitude of rocket and the peak current of lightning.

unsuccess case where the altitude shows the length of the wire trailed by rocket in both cases of the early explosion of rocket and the cutting off of wire on the way of the ascent of rocket. The altitude of triggering decreases with the increases of the intensity of electric field at ground. The experimental values fit the solid line calculated from the theory described in chapter 4. 1. The intensity of the electric field extrapolated to zero altitude is 16 kV/m, which corresponds to the condition for the natural lightning on the flat ground. Figures 22~26 show the other relations among the intensity of electric field at ground, the altitude of triggering, the discharge current and the duration of the flash. There is no correlation among them.

3. 4. Predischarge Current at the Tip of Rocket and Electric Field Variation at Ground during Ascent of Rocket

The predischarge current flows toward cloud from the tip of rocket or wire during the ascent of rocket. Figure 27(a) shows the typical case of the predischarge current, which flows through the conductor between the earth and the collector ring. The current of a few μA flows from just after the launching and the current increases with the ascent of rocket. When the altitude of the rocket reaches about 100 m at about one second after the launching small current pulses are superposed on the base current of several mA. The current of the main discharge flows, after the wire is vaporized by a large pulse current near 100 A.

Figure 28 shows the four typical waveforms of the predischarge current. These waveforms are classified as follows;

a) The large pulse current vaporizes the wire after two small current pulses, and then the main discharge current flows.

b) The large pulse current vaporizes the wire after many small current pulses, and the large pulse current decreases abruptly, and then the main discharge current

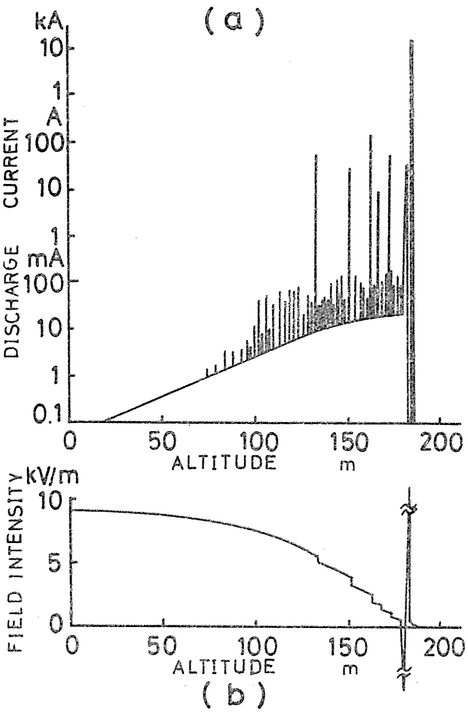


Fig. 27. (a) and (b) show the typical variations of discharge current and of electric field respectively during the ascent of rocket.

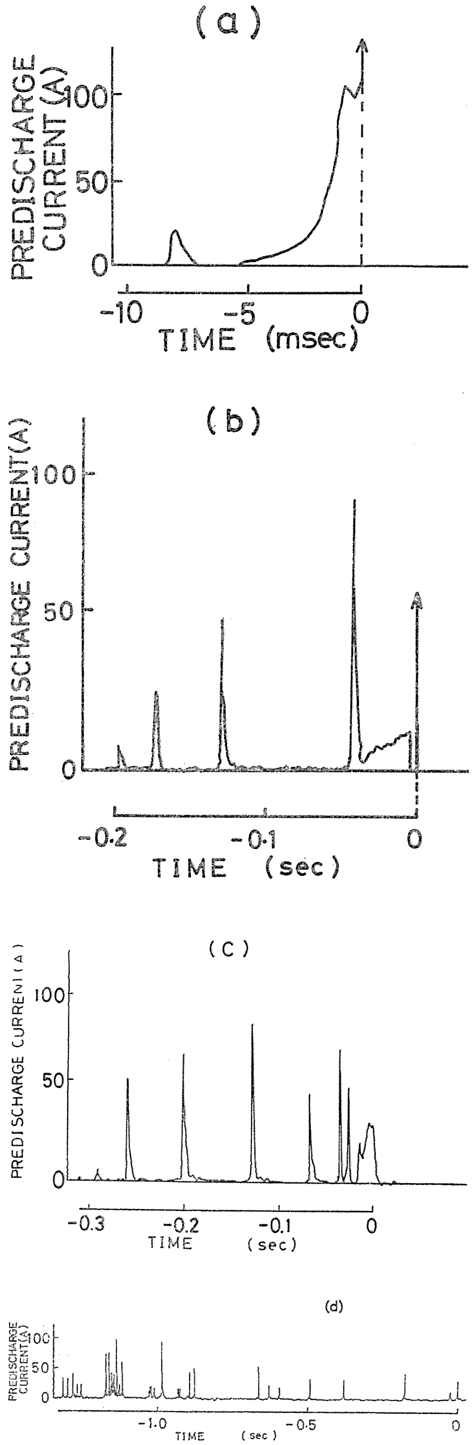


Fig. 28. Four typical waveforms of predischarge currents. The zero of the horizontal axis in (a) and (b) is the time when the main discharge current begins to flow, and zero in (c) and (d) is the time when the predischarge current stops to flow. [Experimental No.; (a): 1979-6, (b): 1980-21, (c): 1980-24, (d): 1980-4]

flows at several ms after the vaporization of wire.

c) The large pulse current stops abruptly after the vaporizaton of the wire, and the main discharge does not occur.

d) Though the many small current pulses flow, the large pulse current vaporizing the wire does not flow.

As the response time of the measuring device is about 1 ms, the peak value of the current pulse is not accurate. However, it is infered that the charge of the current pulse is between 1 and 10 mC. As the rise time of the large pulse current vaporizing the wire is longer than the response time of the recorder, the peak current of 10～100 A is accurate. The decrease of the current just after the vaporization of the wire in the cases of (b) is due to the low conductivity of the wire vaporized. The total electric charge before the vaporization is a value of 0.1～0.5 C, which is a reasonable value corresponding to the results of wire vaporization in Fig. 8.

Figure 27 (b) shows the typical example of the electric field variation at ground during the ascent of rocket at a distance of about 50 m from the wire bobbin. The decrease of the electric field during the ascent of rocket is not due to the shielding effect by the grounded wire but the space charge produced by the predischarge current. The electric field decreases with a step, when a current pulse flows.

Figure 29 shows the some examples for the decrease of the electric field at ground during the ascent of rocket. The decrease of the electric field is small for the case of unsuccess to trigger the lightning (B in Fig. 29).

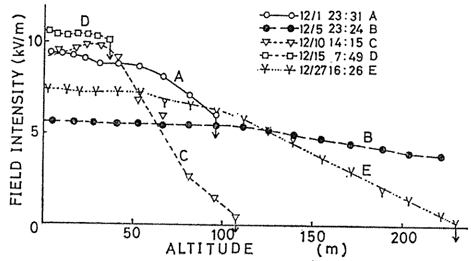


Fig. 29. Some examples of the variation of electric field at ground during ascent of rocket. The values of field intensity are absolute values. (1979)

3.5. *Current and Charge of Main Discharge*[12)]

The main discharge current generally includes some current pulses. As the oscilloscope is triggered with the current pulses, it is difficult to measure only a waveform with a maximum current. Figures 30, 31, and 32 show the waveforms of the discharge currents, which were measured by the oscilloscope of upper frequency range of 100 MHz, and the electromagnetic oscillograph or the magnetic tape recorder, whose response time is about 0.3 ms. The electric charge calculated from the area of current pulses is shown in Table 4. The maximum values of the duration and the electric charge of the main discharge are about 0.7 s and over 100 C respectively. The steepness of the current pulses is less than 46 kA/μs from the results measured with the steepness indicator of loop coil.

3.6. *High Speed Framing Photographs*[13)]

Figure 33 shows the traces of photographs taken with the movie camera and the still camera placed at a distance of 2.2 km from the launcher. The upward discharge propagates with the speed of about 10^5 m/s from the tip of the rocket,

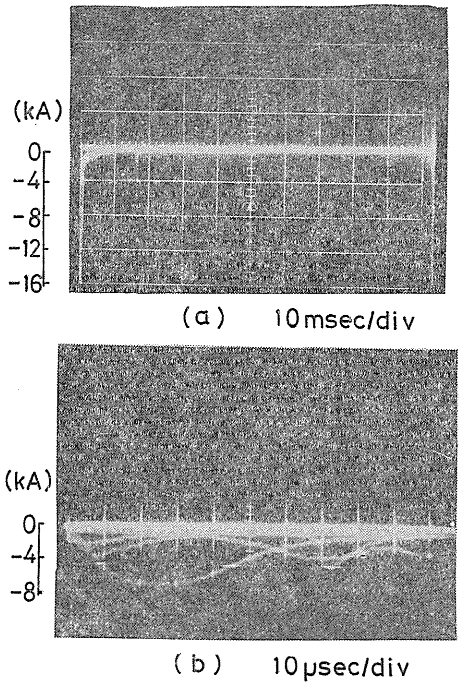


Fig. 30. Waveform of the main discharge current measured by the oscilloscope. (Experimental No. 1979-6)

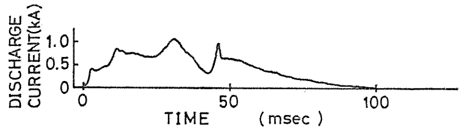


Fig. 31. Waveform of the main discharge current measured by the data recorder. (Experimental No. 1980-19)

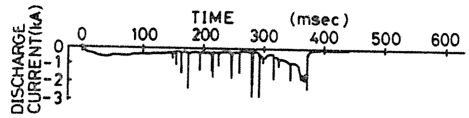


Fig. 32. Waveform of the main discharge current measured by data recorder. (Experimental No. 1980-21)

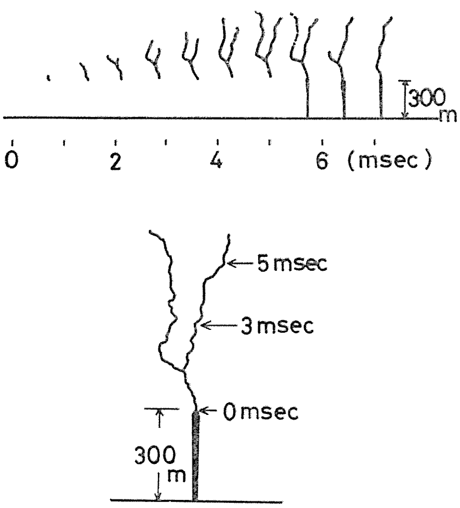


Fig. 33. Traces of photographs taken with the movie and the still cameras placed at a distance of 2.2 km from the launcher. (Experimental No. 1978-15)

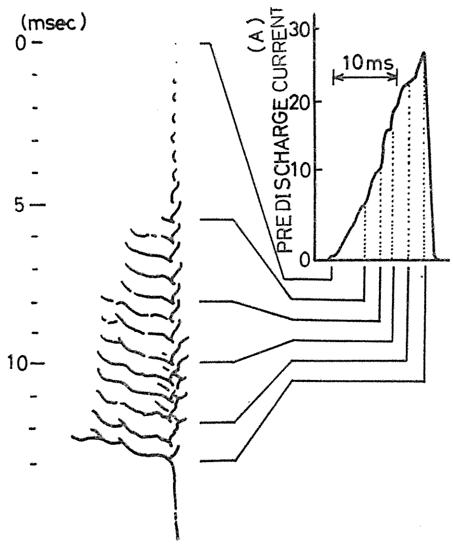


Fig. 34. Predischarge current waveform and photograph of the upward direction taken with the movie camera from the control room. (Experimental No. 1979-9)

and the light emission continues for 37 ms after the vaporization of the wire. As the stroke at the altitude higher than 800 m is inside the thundercloud, it cannot be observed on the photograph.

Figure 34 shows the predischarge current waveform and the photograph of upward direction taken from the control room near the launcher. The current pulses are correspondent to the propagation of the leader stroke from the tip of rocket. At about 50 ms after the wire is vaporized by the peak current of 28 A, the main discharge current flows along a distant path of 78 m from the vaporized wire, as shown in Fig. 35.

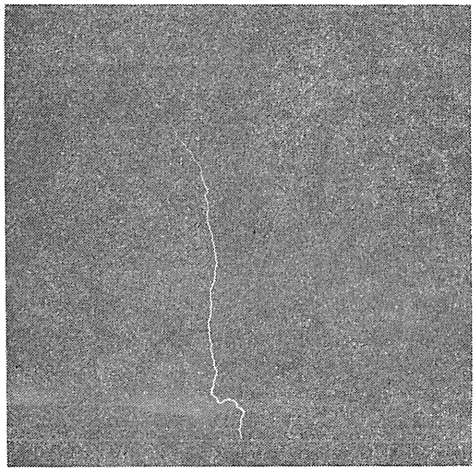


Fig. 35. Abnormally triggered lightning along a distant path of 78 m from the vaporized wire. (Experimental No. 1979-9)

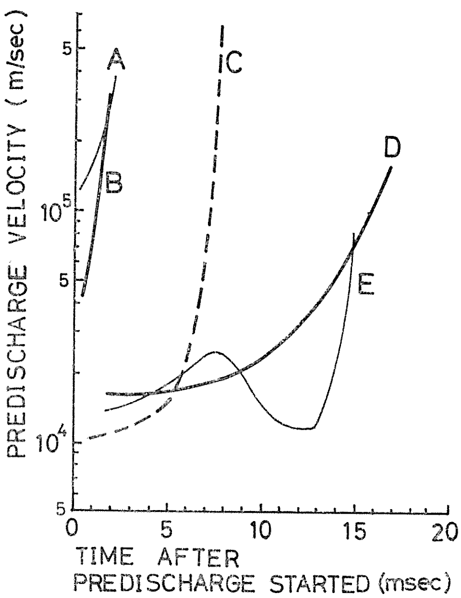


Fig. 36. The velocity of the upward leader obtained from the framing photographs. Experimental No.; A : 1980-19, B : 1980-5, C : 1979-6, D : 1979-12, E : 1980-15.

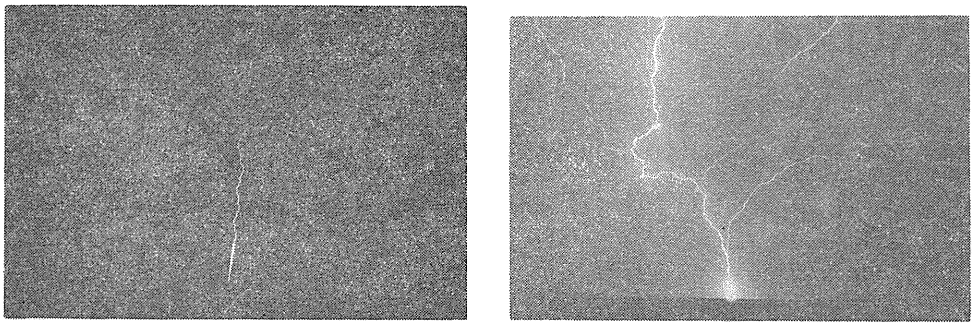


Fig. 37. (a) and (b) show the typical still photographs for the cases of the thunderclouds with positive charge and negative charge respectively. (a) : No 1980-19, (b) : No. 1980-10.

Figure 36 shows the velocity of the upward leaders obtained by the framing photographs, where the velocity is corrected by stereoscopical analysis of the still photographs taken from two observation stations. Figures 37 (a) and (b) show the still photographs for the cases of the thundercloud with the positive and the negative charges respectively. The velocity of the upward leader and the number of the branches for the positive thundercloud are faster and less than those for the negative thundercloud respectively.

3. 7. Observation of Discharge by Streak Camera[12]

Figure 38 shows the photograph taken by the streak camera (the speed of 2 m/sec) with an image intensifier at the observation station of 2 km from the launcher. The upward leader stroke starts from the tip of rocket, and propagates, as shown by the straight line with the positive gradient. When the tip of rocket reaches the altitude of about 243 m, the wire is vaporized, and the whole region of the leader stroke flashes intensively. The weak flashes appear at the tip of rocket, corresponding to the current pulses before the beginning of the upward leader.

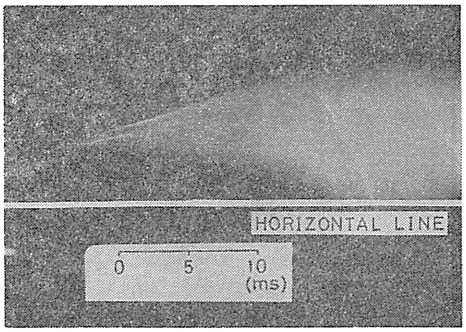


Fig. 38. Photograph taken by the streak camera with an image intensifier at the observation station. (No. 1980-15)

The weak emission from the tip of rocket was observed before the beginning of the upward leader by another streak camera with an image intensifier from the control room. The emission is inferred to be, what is called, a pilot streamer.

3. 8. Estimation of Lightning Channel by Acoustic Measurement

Three microphones were set on the ground at the vertices of the equilateral triangle with the base line of 3. 5 m to reconstruct the lightning channel from the thunder, which was produced by the discharge. Figure 39 shows the waveforms of the thunder measured by the three microphones. The distance from the microphone to the acoustic source is calculated from the time difference between the signal of electric field variation and the acoustic signal. The direction of the acoustic source is determined from the time difference, which is calculated from the cross-correlation functions, among the acoustic signals measured by the three microphones. When the acoustic signals from different sound sources have almost the same amplitude at the same time at the microphone array, the directions are not determined from the cross-correlation functions. In such a case, if the sound signals from the different sound sources have the different frequencies, the directions are determined from the cross-power spectra which are the Fourier transformation of the cross-correlation functions. The time window to calculate the cross-correlation function and the cross-power spectrum was 125 ms or 250 ms. The dependences of the wind velocity and the temperature on altitude were considered to calculate the location of the sound source.

Figure 40 shows the altitude versus north-south range projection for the lightning channels reconstructed from both the acoustic signals and the two still photographs.

The solid and the broken lines show the results from the photographs and the acoustic signals respectively. This lightning has both the vertical and the horizontal channels with the negative and the positive currents respectively, as shown in the next section.

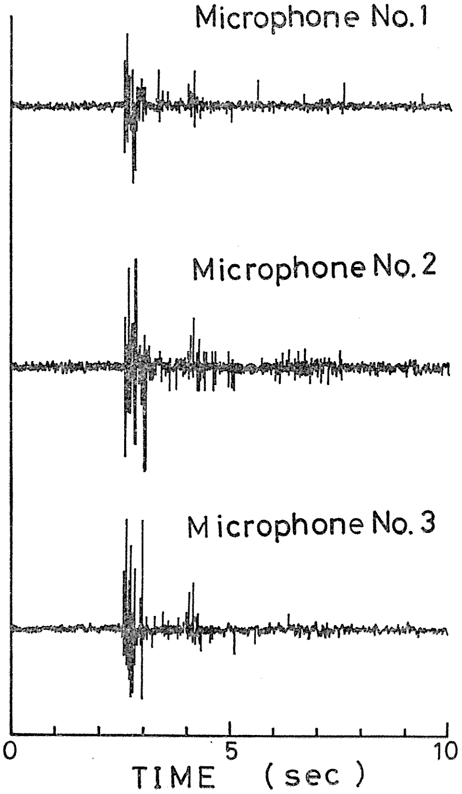


Fig. 39. Waveforms of the thunder measured by three microphones. (No. 1981-11)

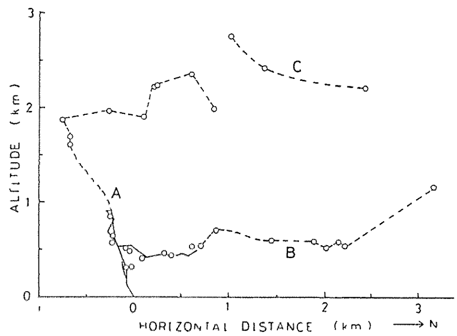


Fig. 40. Altitude versus north-south range projection for the lightning channels reconstructed from both the acoustic signals and the two still photographs. (No. 1981-11)

3. 9. Bipolar Lightning Flash

The flash with both positive and negative polarities was observed by French team.[2] In our experiment, four flashes with both positive and negative strokes were observed.

Figure 41 shows the electric field intensity at ground on 12 December 1981. Separate flashes were triggered at 00:38 and 00:46 by each of two rockets shot at the electric field of +6 kV/m and −7.2 kV/m respectively.

Figure 42 shows the waveform of the discharge current. After the first stroke with the negative current pulse, the positive current pulse and the two small negative current pulses flowed at 34, 275 and 318 ms. The first and the second strokes correspond to A and B respectively in Fig. 40, which are the vertical discharge into the negative thundercloud and the horizontal discharge with the length of 3 km respectively. The discharge in the cloud is recognized to occur between the first and the second strokes from the streak photograph as C in Fig. 40.

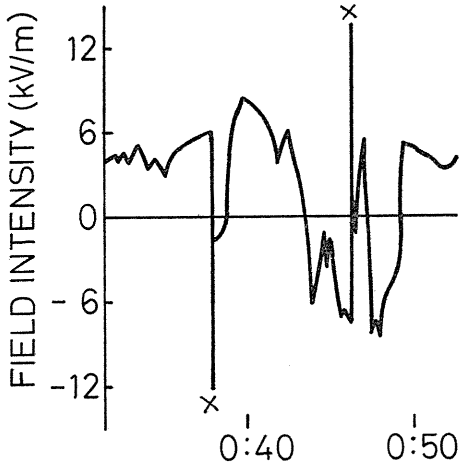


Fig. 41. Variation of the intensity of electric field at ground on 12 December 1981.
× : triggered lightning

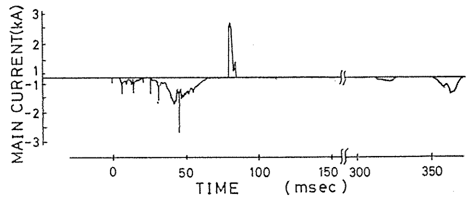


Fig. 42. Waveform of the main discharge current which shows the bipolar lightning flash. (No. 1981-11)

3. 10. Experiments of Mannequin and Motorcar Struck by Triggered Lightning through a Long Gap[4,5]

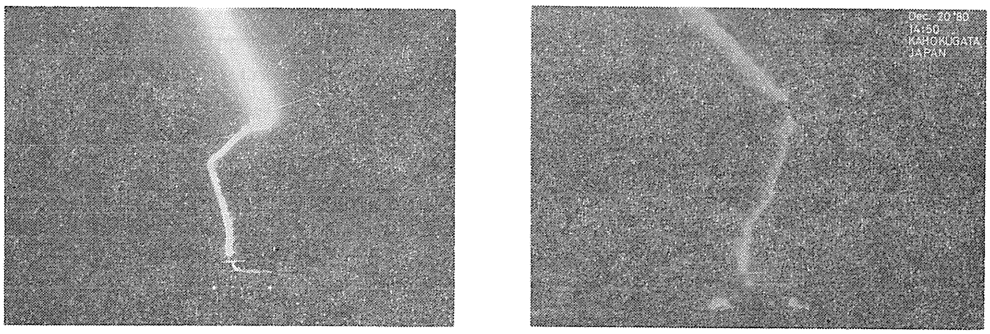
The flashes not to follow the path of the vaporized wire were observed in two cases up to date. In spite of metal structures of the measuring apparatus and the launching rod, the lightning shown in Fig. 35 struck the ground and made a crack with the length of about 70 cm and the depth of 100 cm reaching the water level of the underground.

The experiments striking the mannequin and the motorcar on the ground were carried out by making the discharge not to follow the wire artificially.

Figure 43 shows the photograph of the mannequin with a hairpin on the top of the head, struck by the lightning triggered at 8:14 on 29 December 1978. The bobbin and the collector ring were hung by the plastic rope at the height of 10 m above the ground. The surface resistance between the head and the foot of mannequin was about 300 Ω, which was about the same value with the resistance of human body. The height of the head of mannequin was 2.7 m from the ground, and the foot was connected to the earth conductor. This flash was composed of two strikes with the peak current of 15 kA. After the flashover occurred on the surface of mannequin through the hairpin, the current flowed through the support bar inside the mannequin, and the mannequin was divided into two parts. There was no trace of the discharge on the other mannequin without a hairpin. The position of the arc spot on the mannequin struck by the lightning did not move, though the arc channel of the second stroke moved about 1 m by the wind with the velocity of 4 m/s.

Figures 44 (a) and (b) show photographs of the motorcar struck by the lightning triggered at 19:01 on 9 December and 14:50 on 20 December 1980 respectively. The engine of the motorcar with fuel was resting during the experiment, and a radio antenna was projected by the height of about 26cm from the body, which was not connected to the earth conductor. The tip of the antenna was

Fig. 43. Photograph of the mannequin with a hairpin on the top of the head, struck by the triggered lightning. (No. 1978-4)



(a) (b)

Fig. 44. Photographs of the motorcar struck by the triggered lightning. (a) : No. 1980-11, (b) : No. 1980-17.

molten by the first discharge with the peak current of 5 kA. The second discharge with the peak current of 24 kA made the hole of about 10 mm in diameter on the body at the root of the antenna, which burned away by 30 cm from the tip and the arcing spots were found at the rims of tires. The voltage difference between the ceiling and the floor inside the car was not detected from the Lichtenberg's figure of Klydonogroph. The troubles of the motorcar including the radio set were not recognized, and the rabbit in the motorcar was healthy.

3. 11. *Experiment of Power Distribution Transformer Struck by Triggered Lightning*

The high-tension side of the power distribution transformer was struck by triggered lightning. Figures 45 (a) and (b) show the connections of high-tension windings for the cases of the foating and grounding respectively. In the case of (a), though the flashover through the surface of the insulator bushing occured, there was no damage inside the transformer. This flashover is due to the v-t characteristics of discharge for the slow increase of the wire potential during the ascent of the rocket. In the case of (b), the high-tension winding was burned out at the terminal inside the transformer by the impulse current of the main discharge.

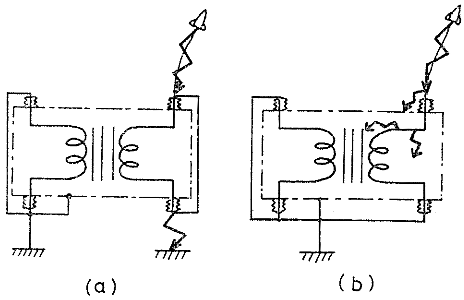


Fig. 45. Schematic diagram of power distribution transformer struck by triggered lightning.

3. 12. *Measurement of Surge Voltage Induced on the Test Line of Power Distribution*

Figure 46 shows the waveform of the surge voltage induced on the test line of power distribution, which is located at a minimum distance of 77m from the dis-

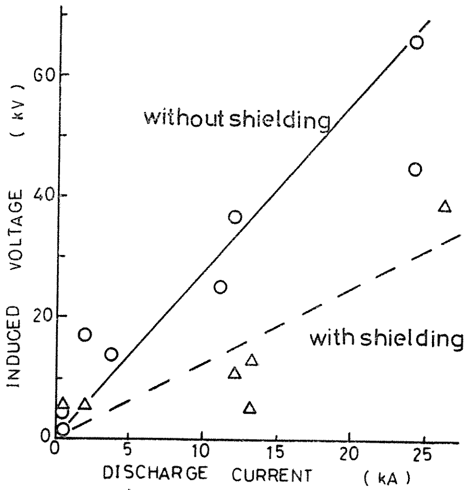


Fig. 47. Relation between the induced surge voltage and the main discharge current. Triangles and circles show the experimental values with and without the overhead ground wire.

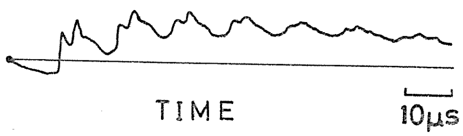


Fig. 46. Waveform of the surge voltage induced on the test line of power distribution. (No. 1980-15)

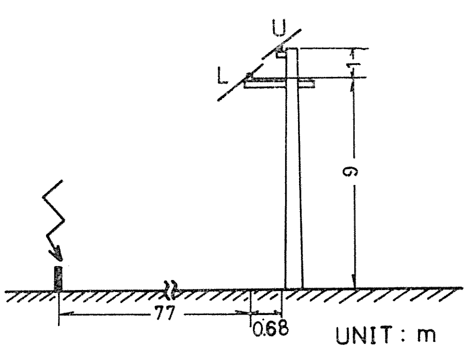


Fig. 48. Schematic diagram of the test line of power distribution.
U : overhead ground wire.
L : overhead wire.

charge point and terminated by the voltage divider of 5 or 10 kΩ resistor.

Figure 47 shows the relation between the peak value of the induced surge voltage and the peak current of main discharge where the surge voltage is affected by the reflection at the terminal. The surge voltage is directly proportional to the current. When the test line of power distribution was shielded by the overhead ground wire, as shown in Fig. 48, the induced surge voltage was reduced to about 40 % of that in the test line without the ground wire.

3. 13. Measurement of Electric Field Variation near Discharge Point

Figures 49 (a) and (b) show the fast variations of the electric field intensity at ground at distances of 20 m and 50 m from the discharge point respectively. This difference between waveforms in (a) and (b) is due to the connection between the downward and the upward streamers near the ground. The analysis of the waveforms is progressing now and it may make clear the mechanism of the main discharge triggered by rocket.

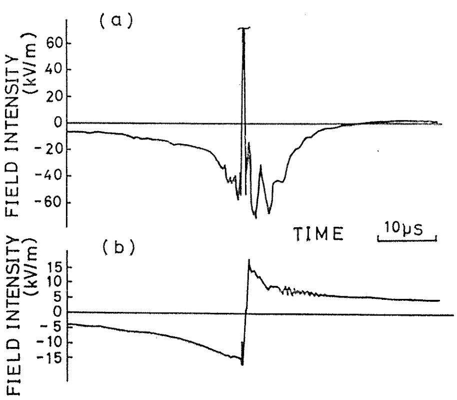


Fig. 49. (a) and (b) show the fast changes of the electric field at ground at distances of 20 m and 50 m from the discharge point respectively. (No. 1981-10)

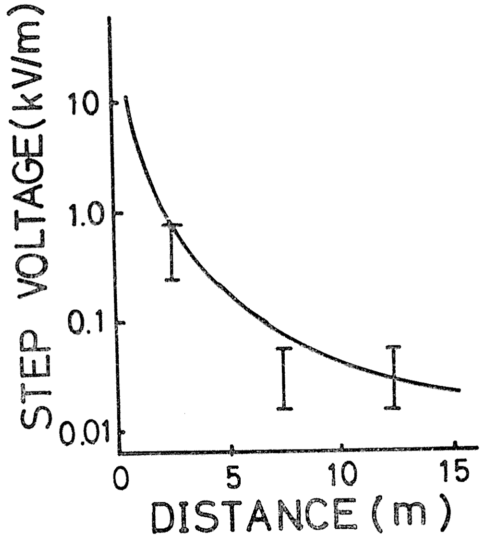


Fig. 50. Dependence of step voltage on the distance from the discharge point. (No. 1978-4)

Figure 50 shows the dependence of the electric field of horizontal direction at ground (step voltage) on the distance D from the discharge point[14]. The electric field is obtained from the voltage difference between two earth conductors The elecric field is over 10 kV/m at the discharge point, and decreases rapidly with the increase of D. If it is assumed that the discharge current flows hemispherically into the ground, the electric field of horizontal direction is expressed as $E=\rho I/2\pi D(D+s)$, where ρ, I and s are the resistivity ($\Omega\cdot$m) of the soil, the peak current (kA) and the distance (m) between the earth bars respectively. The solid line in Fig. 50, which is calculated from the above equation, almost coincides with the experimental results.

4. Discussion

4. 1. Condition to Trigger a Lightning

The rough estimation of the relation between the electric field intensity E(kV/m) at ground and the altitude L(m) of the rocket to trigger a lightning is given here[12]. The electric field caused by the point charge Q(C) at the altitude H(m) in the thundercloud is expressed as

$$E=1.8\times 10^7 \frac{Q}{H^2}. \tag{1}$$

If it is assumed that the lightning channel between the rocket and the center of the thundercloud is discharged, the charge Q is given by

$$Q=\frac{1}{2}CK(H-L)^2, \tag{2}$$

where C and K are the capacitance and the potential gradient along the discharge channel respectively. The equations (1) and (2) can be combined to yield

$$E=16\left(1-\frac{L}{H}\right)^2, \tag{3}$$

for C of 6×10^{-12} F/m and K of 3×10^5 V/m. After the leader propagates to the altitude of four times of L, the main discharge usually occurs, as known from the photograph taken by the streak camera. If $4L$ is used for L in eq. (3), it becomes

$$E=16\left(1-\frac{4L}{H}\right)^2. \tag{4}$$

The solid line in Fig. 21 was calculated from eq. (4). As the altitude H of the thundercloud in winter is lower than that in summer, L in winter is shorter than that in summer for the same value of E from eq. (4), and E in winter is larger than that in summer for the same value of Q from eq. (1). Therefore, there are more chances to trigger the lightning in winter than in summer.

The condition, at which a tall structure is struck by lightning, may be obtained by substituting the height of the structure for L in eq. (2). However, it is one of the important subjects to investigate the difference between the lightning triggered by the rocket ascending with a high speed and the natural lightning striking a still structure.

4. 2. Mechanism of Discharge

Figure 51 shows the schematic diagram of the mechanism of discharge considered from the photographs taken by the movie and the streak cameras. The corona or the pilot streamer with the current less than 1 mA and the total charge of several mC propagates for several tens of meters from the tip of rocket, and then the pulse streamers with several mC for one pulse propagate. The charges of these streamers are not sufficient to shield the electric field at ground.

The leader with the current of several tens of amperes propagates for the length longer than 100 m. The charge of the leader is 0.1–0.5 C, which corresponds to the charge of conductive sphere of several hundred meters in diameter and 300 m in altitude, under the electric field of 10 kV/m. Therefore, it is assumed that branched leader is surrounded extensively by the corona or pilot streamers.

The current of the main discharge, which is initiated between the tip of leader and the thundercloud, flows through the wire vaporized by the leader current. The direction and velocity of the propagation of the main stroke have not been measured. It is important for the understanding of the main discharge to observe it by using the image converter camera with a resolution of μs.

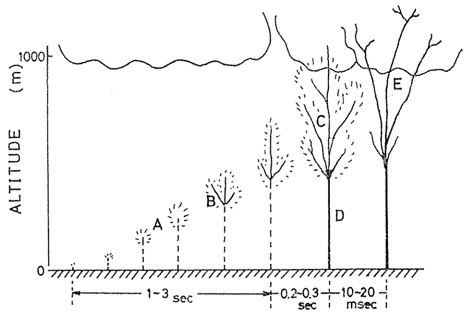


Fig. 51. Schematic diagram of discharge mechanism.
A: corona (point streamer),
B: pulse streamer, C: leader,
D: vaporized wire,
E: main discharge.

The multiple strokes in a flash occur by the discharge of the separate charge centers at the different time. When the continuous current of hundred amperes is superposed on the pulse currents of the multiple strokes, the total charge sometimes becomes the large value over 100 C.

The electric field variation at ground by the triggered discharge with the peak current of 1.8 kA on 27 December 1977 were measured with five field mills around the discharge point by members of Research Institute of Atmospherics, Nagoya University. It was estimated from these measurements that the charge center of about 20 C existed at the altitude of 4 km and the distance of 5 km from the discharge point, and the continuous current had the duration of 100 ms.

This continuous current gives a damage to the objects by heating, and also causes the failures to interrupt the arc current with a switch gear and to reclose the power transmission line with high speed. The movement of the discharge channel of the continuous current by wind causes the transition of the arc spot to the other transmission line in parallel.

As the multiple bipolar strokes exist in a flash, as described in 3.9, it will be needed to reconsider the impulse withstand voltage test, which usually applies the repetitive voltages of the negative polarity to a test object.

4.3. Long Gap Discharge and Hairpin Effect

It is possible to discharge the long gap with the length of about 10 m by the technique of rocket-triggered lightning, as described in 3.10. Figure 52 shows the mechanism of the long gap discharge. The voltage difference between the overhead bobbin and the ground increses with the ascent of rocket by the electrostatic induction to the wire. After the flashover of long gap occurs at the moment of the upward propagation of leader, the wire is vaporized by the current of 10~100 A, and then main discharge occurs. The rise time of the voltage of 1~10 ms, which is determined by the upward propagation of leader, is longer than the rise time of the standard lightning impulse voltage (1/50 μs). The hairpin of the mannequin was not necessarily the arc spot at the experiment using the impulse voltage of 1/40 μs.[15] It may be the cause of the difference between their and our results that the hairpin becomes or not the arc spot for the discharge occurring by the voltage with long rise time. The experiment to strike the cylindrical body surrounded by the cloth of the same conductivity with the human body failed on 1980 and 1981. It is one of subjects to verify more clearly the hairpin effect for the lightning.

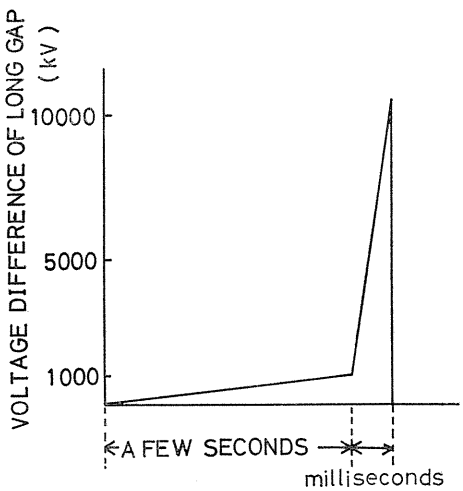


Fig. 52. Voltage difference between the overhead bobbin and the ground during the ascent of rocket.

4. 4. Induced Surge Voltage on Transmission Line[16, 17]

When the distance Y(m) from the test transmission line to the discharge point is less than the value multiplying the velocity of light by the rise time T (1~2 μs) of the main discharge current, the surge voltage is mainly induced by the electrostatic effect of the charge neutralized by the main discharge current.

The peak value V(kV) of surge voltage on transmission line is expressed as

$$V=30\frac{Ih}{Y},$$

where I(kA) and h(m) are the peak value of the discharge current and the height of transmission line respectively. The solid line in Fig. 47 is lower than the theoretical result by about 20 %, if the reflection of the surge is considered at terminals. As the above theory is derived under the assumption of the rise time of zero for the main discharge current, the difference between the theoretical and the experimental results is within a reasonable range.

4. 5. Comparison between Natural and Triggered Lightnings

The main discharges of the natural and triggered lightnings generally occur after the downward and upward leaders respectively. The upward leader frequently occurs from the tip of the tall construction in the case of the natural lightning in winter. Though this upward leader looks like the one of the triggered lighthning, it is the difference between two lightnings to supply a lot of charge from the still structure to the space in the case of the natural lightning.

The discharge along the wire is the arc discharge with the vaporized metal, and is different from the discharge of the natural lightning. The long gap discharge between the ground and the collecter ring is similar to the natural lightning.

5. Conclusion and Future Subjects

The experimental results obtained from artificially triggered lightning are as follows;

a) Though the flash was not triggered with rocket in summers, 32 flashes were obtained with the rate of success of 66.7% in winters. The causes of unsuccess in summers are due to the insufficient altitude of rockets and few thundercloudy days, and the causes of success in winters are due to the low altitude of thundercloud and a lot of thundercloudy days.

b) The relations among the peak values of the discharge current, the altitude of rocket, the intensity of electric field at ground, and the other usefull parameters were obtained. The median values of the electric field intensity at ground just before the shooting of rocket, the altitude of rocket at the triggering of discharge, the peak value of the discharge current and the duration of the discharge are 7.4 kV/m, 142m, 15 kA and 420 ms respectively. The relation between the intensity of electric field just before the shooting of rocket and the altitude of rocket is expressed by $E=16(1-4L/H)^2$, which is derived from a consideration of the discharge mechanism. There are no correlations among the other parameters.

c) The mechanism of the predischarge was made clear from the optical observation and the measurement of predischarge current. The current of the predischarge initiated by the corona discharge with the current of μA increases to the order of mA, and the weak radiation of the pilot streamer appears ahead of the rocket. Then, after the current pulses with the charge of mC flow, the upward leader with the charge of 0.1~0.5 C propagates toward a thundercloud at the speed of $10^4 \sim 10^5$ m/s. The main discharge current flows, after the vaporization of the wire is caused by the leader current of 10~100 A.

d) The several strokes were frequently superposed on the continuous current, and the multiple strokes with both polalities were observed too. As the maximum duration of discharge current is 0.76 sec, the thermal damage is caused by the current. It is considered that the long duration is one of the causes of the polyphase fault of the power transmission line and the failure of the interruption of arc.

e) The long gap discharges were successfully performed three times, and the hairpin effect of mannequin and the safety in the motorcar were confirmed. These experiments were carried out under the conditions of longer rise time of voltage and of much larger charge and energy of the discharge in comparison with the laboratory experiment using 1/50 μs impulse generator.

f) The variation of electric field intensity at ground was over 50 kV/m at 20 m distance from the discharge point, and the horizontal electric field was over 10 kV/m. The surge voltage was observed on the power distribution line near the discharge point, and is expressed by $V=30\,Ih/Y$. The shielding effect of the overhead ground wire reduced the surge voltage to about 40%.

g) The corona current from the point increased with the increase of the electric field at ground. By using this current, the thunder alarm device combined with the wireless information system was developed, and was used to determine the best time to shoot the rocket.

The subjects remaining to be investigated are as follows;

a) The new techniques without a explosive powder should be developed for safety, although the technique to trigger the lightning with rocket has been accomplished. As an example, a model helicopter will be used to drop or hold a wire in winter of 1982. Another interesting plan is to throw a ball with wire by an electric motor.

b) A plastic wire coated with a conductive paint should be used instead of the steel wire, and it is required to burn off the wire by a pulse current before falling down on the ground to prevent the trouble on the power line or the structures, in the case of the unsuccess of triggering.

c) Although the experiment striking a mannequin, a motorcar, and a transformer were carried out successfully, the experiments striking objects, such as a power transmission line, the power apparatus like an arrestor and a switch gear, the antenna of radio station, a house and an oil tank, are remaining. The back flashover test for a power transmission line by the direct stroke to the transmission tower was unsuccessful in 1978, and the experiment striking a house is planned in winter of 1982 to investigate the damage of indoor electric equipments. The hairpin effect of a human body needs to be reconfirmed by the experiment striking the model of human body.

d) It remains to make clear the mechanism of the final discharge changing from the leader to the main discharge. Both the high speed photographs and the measurement of the intensity of electric field with the resolution less than 1 μs are necessary to investigate the mechanism.

e) It is reported that the electric field intensity at ground is fairly disturbed by the space charge distributed between the ground and the thundercloud.[18] The measurement of the space charge using a model helicopter is intended in winter of 1982.

f) Further future subjects are the development of the new techniques, such as the protection from lightning by means of a giant lightning rod of the wire lifted up with a rocket, and the neutralization of the bipolar charges in a thunder cloud by means of shooting a rocket pulling up a floating wire to trigger a discharge in the thundercloud itself.

Acknowledgements

The author would like to express his thanks to Chubu Electric Power Company, Inc., Hokuriku Electric Power Company, Inc., and many others for their cooperations. This work was supported by the Grant in Aid for Scientific Research from the Ministry of Education of Japan.

References

1) M. M. Newman, et al; J. Geophys. Res. **72**, 18, 4761 (1967).
2) C. Gary, et al; Rev. Gen. Elect., **84**, 1, 44 (1975).
3) R. Fieux, et al; IEEE Trans. Power Apparatus Syst., PAS-**97**, 3, 725 (1978).
4) I. Miyachi, et al; 3rd Int. Sympo. on High Volt. Eng., 51·10 (1979).
5) I. Miyachi, K. Horii; 7th Int Conf. on Gas Discharges and their Applications (1982).
6) K. Berger; J. Franklin Inst. **283**, 6, 478 (1967).
7) B. N. Gorin, et al; 4th Int Conf. on Gas Discharge, 271 (1976).
8) T. Tada, H. Fujinami; Research Report of Cent. Res. Inst. Elect. Power Ind. No. 180071 (1981).
9) T. Takeuchi, et al; J. of Geophys. Res., **83**, C5, 2385 (1978).
10) Y. Higashiyama, et al; Trans. IEE of Japan, **99**-A, 9, 411 (1979).
11) K. Nakamura, et al, Trans. IEE of Japan, **101**-B, 2, 93 (1981).

12) S. Sumi, et al; Trans. IEE of Japan, **102**-B, 5, 289 (1982).
13) Y. Higashiyama, et al; Trans. IEE of Japan, **101**-B, 2, 93 (1981).
14) K. Ishikura, et al; Research on Atmospheric Electricity (Japan), **22**, 47 (1979).
15) N. Kitagawa; Proc. Inst. Electrostatics Japan, **6**, 1, 23 (1982).
16) G. Ohwa; Reserach Report of Cent. Res. Inst. Elect. Power Ind. No. 63027 (1964).
17) S. Yokoyama; IEE Proc., **127**, C, 1, 33 (1980).
18) S. Chauzy, P. Raizonville; J. Geophys. Res. 87, C4, 3143 (1982).