Reprinted from

Journal of
ELECTROSTATICS

Fundamentals, Applications and Hazards

Journal of Electrostatics 51–52 (2001) 319–325

The Franklin lightning conductor: conditions necessary for the initiation of a connecting leader

Mose Akyuz, Vernon Cooray*

Division on Electricity and Lightning Research, The Ångström Laboratory, University of Uppsala, Box 539, 751 21 Uppsala, Sweden

ELSEVIER

ELSEVIER

Journal of Electrostatics 51–52 (2001) 319–325

Journal of
ELECTROSTATICS

www.elsevier.com/locate/elstat

The Franklin lightning conductor: conditions necessary for the initiation of a connecting leader

Mose Akyuz, Vernon Cooray*

Division on Electricity and Lightning Research, The Ångström Laboratory, University of Uppsala, Box 539, 751 21 Uppsala, Sweden

Abstract

The attachment of a lightning flash to a Franklin conductor takes place through a connecting leader that rises from the Franklin rod towards the down coming stepped leader of the lightning flash. The successful launching of a connecting leader requires the inception of a streamer discharge from the rod and its transformation into a leader (i.e. streamer to leader transition). Here, the occurrence of these physical processes at the tip of the Franklin rod is investigated. The results shows that for Franklin conductors of radii less than about 0.35 m artificial initiation of streamers at the conductor tip would not result in any increase in the attractive distance. For rod of radii larger than 0.35 m it may be possible to launch a connecting leader by artificially triggering of streamer discharges at the conductor tip but the gain in attractive distance would not be larger than about 30%.

Keywords: Lightning; Franklin rod; Lightning protection; Step leader; Streamer

1. Introduction

In negative cloud to ground flashes, the first return stroke is initiated by a discharge that travels from cloud to ground, called a stepped leader. As the stepped leader approaches the ground, the electric field at the extremities of the grounded objects increases to such a level that they launch connecting leaders towards the down coming stepped leader. The first return stroke is initiated at the instant of connection between the down coming stepped leader and one of the connecting leaders. The strike point of the lightning flash is the point from which the connecting leader that made the successful connection to the stepped leader was initiated. With the knowledge, derived mainly from laboratory experiments, available at present one can specify the

* Corresponding author. Tel.: +46-18-471-58-09; fax: +46-18-471-58-10.
E-mail address: vernon.cooray@hvi.uu.se (V. Cooray).

0304-3886/01/$ - see front matter
PII: S0304-3886(01)00113-9

conditions necessary, which of course may not be sufficient, to launch a successful connecting leader from an grounded object such as a Franklin conductor. These conditions are the following: (1) The inception of a streamer discharge at the tip of the Franklin rod (*Condition* 1). (2) The presence of the correct spatial distribution of the background electric field needed for streamer to leader transition (*Condition* 2). (3) The availability of the critical background electric field necessary for the continuous propagation of the connecting leader (*Condition* 3). (4) The successful attachment of the connecting leader and the stepped leader which may depend on the geometry and the propagation speeds of leaders (*Condition* 4). One important point to remember is that as the stepped leader approaches the ground, these conditions may not be satisfied in the same order as given above. For example, it is possible that Condition 2 is satisfied before Condition 1. In this case as soon as the streamer is incepted it will be converted to a leader. In the alternative scenario, the electric field at the tip of the Franklin rod may be high enough for the creation of streamers but the electric field distribution ahead of the rod may not be the optimum for the streamer to leader transition. In this case, streamers will be incepted again and again until the conditions are ripe for the inception of a leader. The purpose of this paper is to investigate the order in which the first two conditions given above are satisfied as a stepped leader approaches a Franklin conductor.

2. The model

The model used in the investigation is shown in Fig. 1. The cloud is simulated by an infinitely large flat plate at a given potential located at a height of 5 km above the ground surface. This arrangement provides a uniform field between the cloud and the ground. Most of the calculations were performed by assuming this potential to be 100 MV. The stepped leader channel is simulated by a perfect conductor, at cloud potential, that extends in steps towards the ground. The base of the Franklin rod is

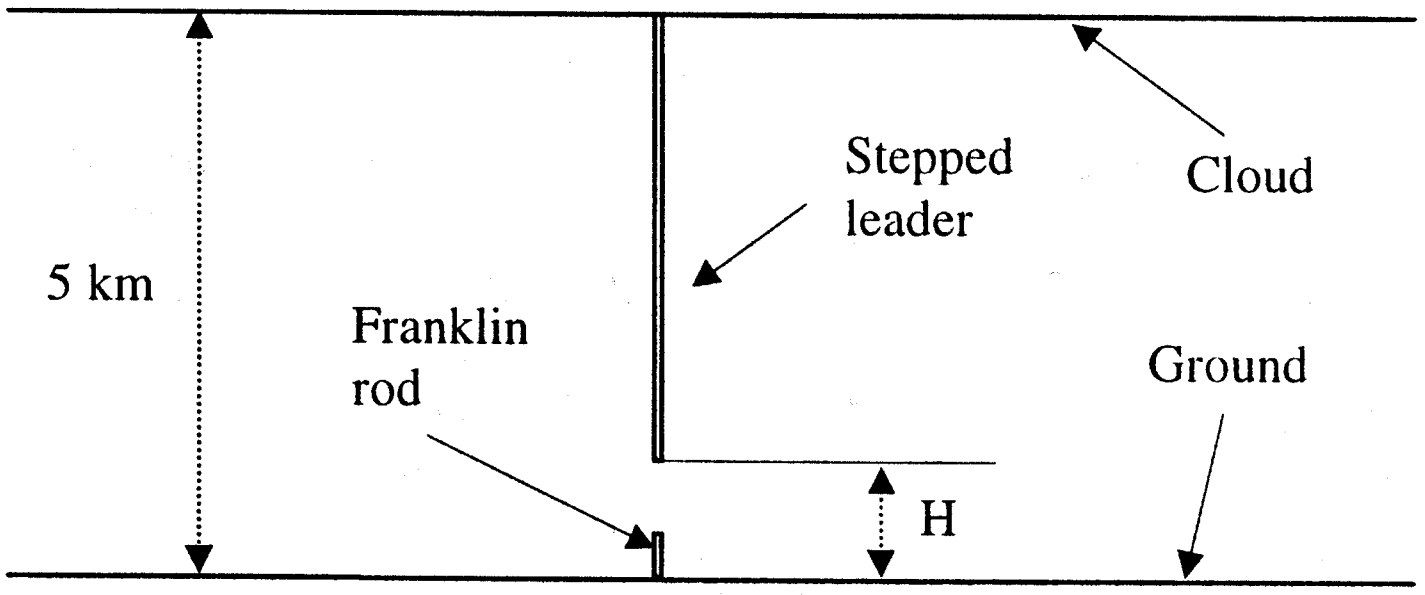

Fig. 1. The cloud is simulated by an infinitely large flat plate at a given potential located at a height of 5 km above the ground surface. This arrangement provides a uniform field between the cloud and the ground. The stepped leader channel (radius 20 mm) is simulated by a perfect conductor, at cloud potential, that extends in steps towards the ground. The Franklin rod is assumed to be located directly under the down coming stepped leader.

located at ground level and it is situated directly under the down-coming stepped leader. The Franklin rod is modelled as a cylindrical conductor which ends in a half-sphere having a radius equal to that of the cylindrical section. In the calculations the stepped leader is extended towards the ground in discrete steps. In each step the electric field in the volume of interest is calculated using a finite element field calculating routine [1] and an investigation is made to check whether the conditions necessary for the streamer inception from the Franklin rod or streamer to leader transition are reached. The criterion for the streamer inception is identical to that used by Gallimberti [2], in which an electron avalanche is assumed to transform into a streamer when the positive charge number density at the avalanche head increases beyond a critical limit. The condition necessary for the streamer to leader transition is the following. The laboratory experiments with long sparks with rod plane configuration show that the critical length of the streamer initiated from the rod at the time of leader inception is equal to about 3 m [3,4]. This is the minimum streamer intensity to originate a direct transition from streamer to leader. In the present investigation, once the streamers are initiated the electric field configuration in front of the Franklin rod is evaluated to estimate how far the streamers can propagate in front of the Franklin rod tip. In this exercise it is assumed that positive streamers require a background field of minimum 500 kV/m to propagate [3,4]. If the extension of the streamers is larger than or equal to 3 m then it is assumed that the streamer stem will be transformed to a leader discharge. The physical process that takes place from the inception of a connecting leader to its successful connection to the down coming stepped leader is a dynamic process. First, the background field should be larger than a critical value for the connecting leader to propagate. The experimental data indicate that this field is about 200 kV/m. Second, when and where the two leaders will meet depend on the relative speed and the orientation of the two leaders. In this paper we consider the physical development only up to the inception of a connecting leader, since this event decides the magnitude of the so called 'attractive distance' [5].

3. Results and discussion

The results in Fig. 2 show the height of the stepped leader tip from ground level at which a connecting leader is incepted (i.e. both Conditions 1 and 2 are satisfied) at the tip of the Franklin rod as a function of the cloud potential. The Franklin rod is 10 m long with a 0.03 m radius. Note that, as the cloud potential increases, the height of the stepped leader tip when a connecting leader from the Franklin rod is initiated increases. Moreover, note that this height increases almost linearly with the cloud potential. Fig. 3 shows the height of the stepped leader tip from ground level, as a function of the height of the Franklin rod for two rod radii, when a connecting leader is launched from the Franklin rod. Note that the ability to launch a connecting leader increases with increasing rod length. Observe also that as the stepped leader approaches the ground the Franklin rod with a larger radius launch a connecting leader first.

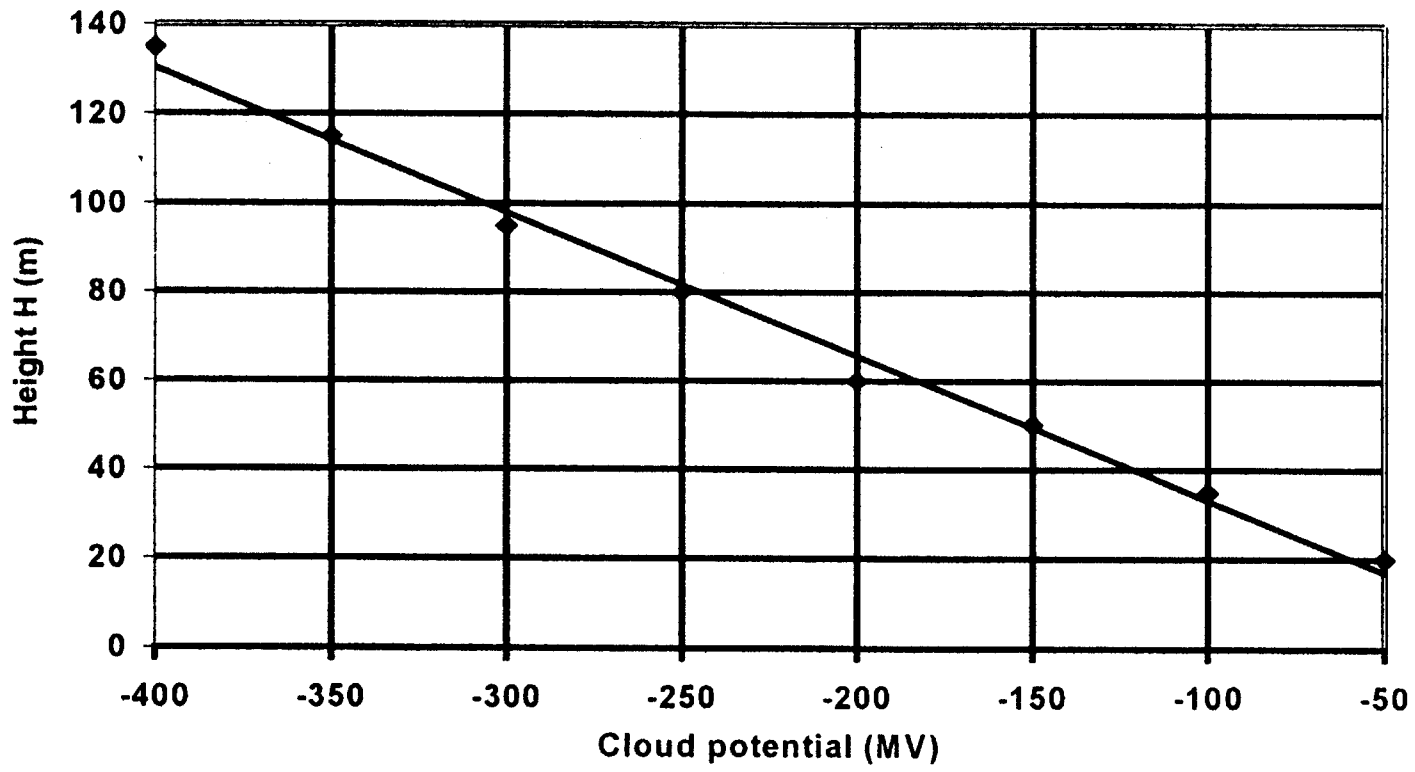

Fig. 2. The height of the stepped leader tip from ground level when a connecting leader is incepted (both Conditions 1 and 2 are satisfied) at the Franklin rod (height 10 m, radius 0.03 m).

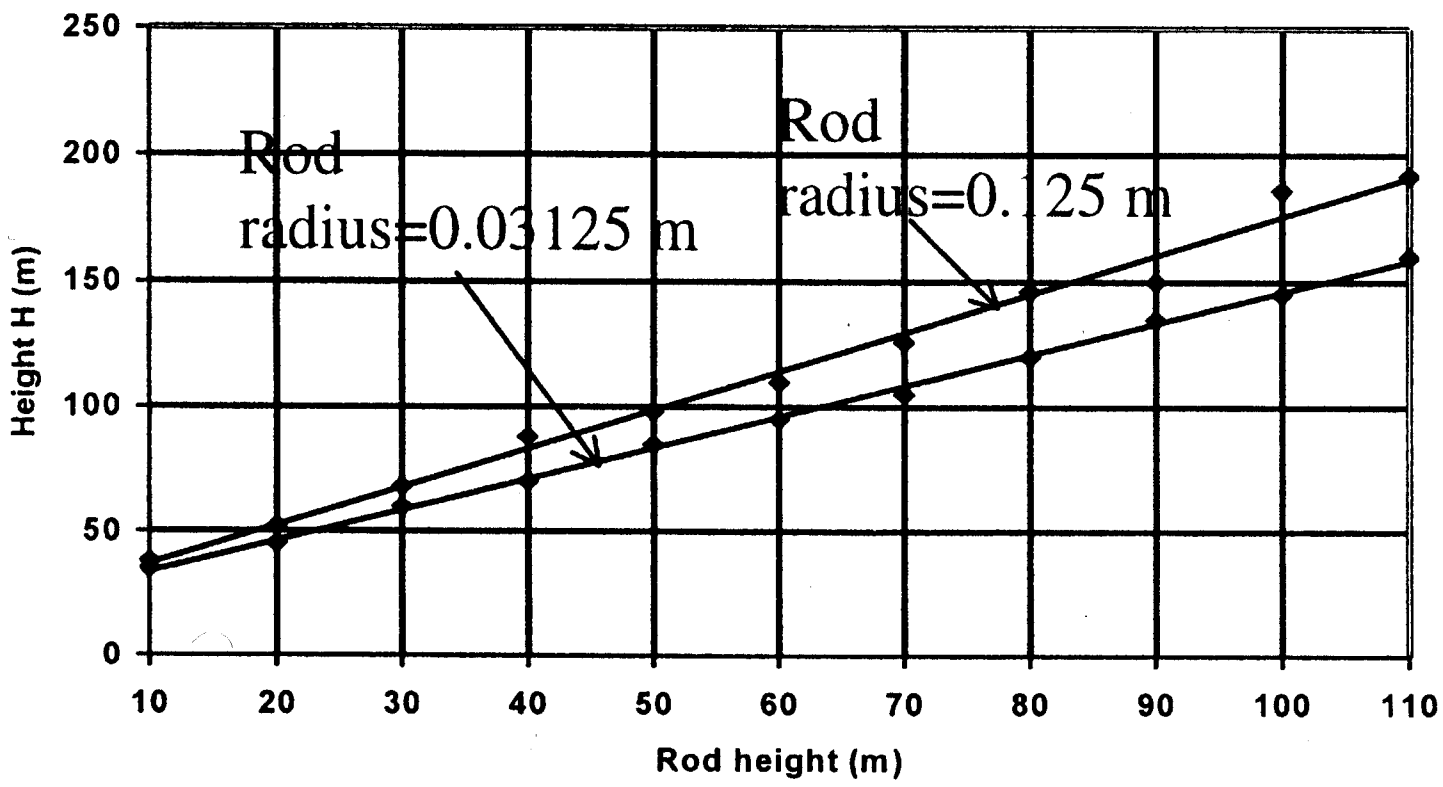

Fig. 3. The height of the stepped leader tip from ground level when a connecting leader (both Conditions 1 and 2 are satisfied) is incepted at the Franklin rod as a function of the rod height. Results are given here for two rod radii.

The results in Fig. 4 show the height of the stepped leader when Conditions 1 (thin line) and 2 (thick line) are satisfied as a function of the rod radius. The same data is depicted in Fig. 5 with a different scale. Note that below a critical radius, Condition 1 is satisfied before Condition 2. For example consider a rod radius of 0.1 m. Streamers are incepted at the tip of the rod when the stepped leader is about 160 m but they will not transform into a leader. The optimum field conditions necessary for streamer to leader transition is achieved only after the stepped leader has reached a height of 40 m. Thus, any streamers that are incepted at the tip of the rod when the leader is at a height of 160–40 m will die out without giving rise to a leader. When the radius of the conductor is about 0.37 m both conditions are satisfied at the same time.

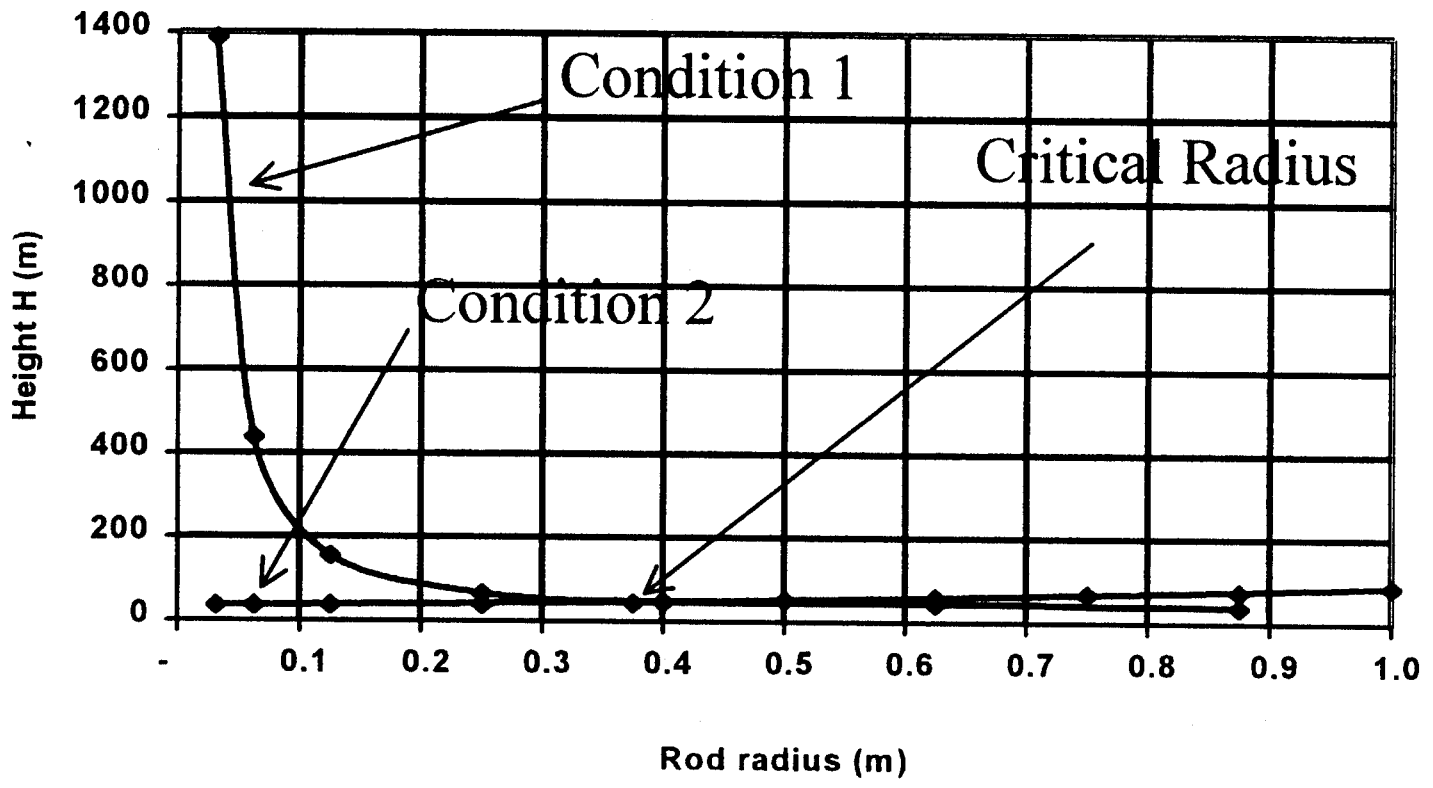

Fig. 4. The height of the stepped leader tip from ground level when Conditions 1 and 2 are satisfied at the Franklin rod as a function of the rod radii. At the critical radius both conditions are satisfied simultaneously. In this region to the right of the critical radius, once a streamer is created it will lead immediately to the inception of a leader.

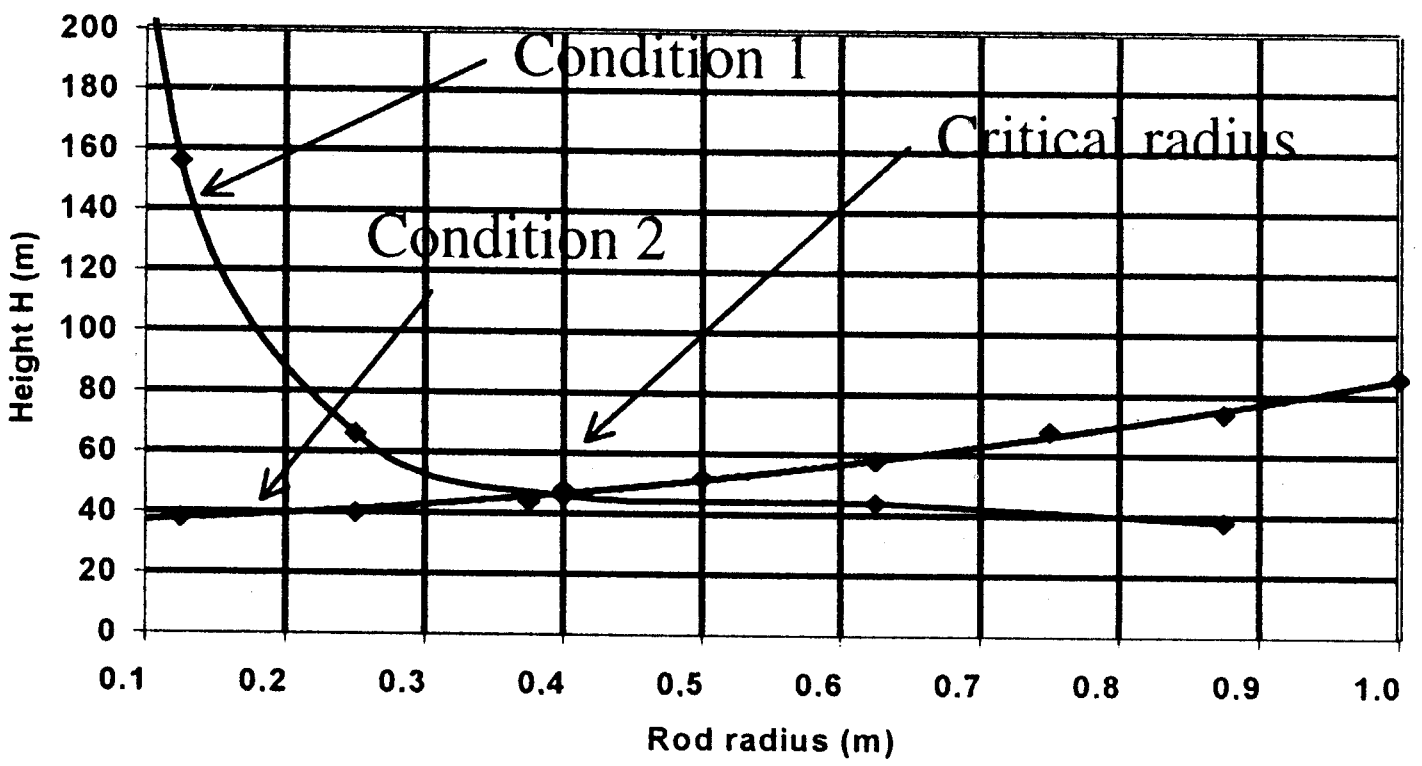

Fig. 5. Same as Fig. 4 except at a different scale.

In this case the streamer will be directly converted to a leader. For conductor radii larger than this critical value Condition 2 is satisfied first and Condition 1 later. For example consider a conductor radius of 0.7 m. When the stepped leader is about 63 m from ground level the optimum field configuration necessary for the streamer to leader transition is achieved. However, the electric field strength in the vicinity of the conductor tip is not high enough to give birth to a streamer. The condition necessary for the streamer inception is reached only when the stepped leader is about 42 m from ground level. This result shows that with Franklin rods of radius less than about 0.35 m, any attempt to artificially initiate a streamer will not result any increase in the attractive radius (the height of the stepped leader tip when a connecting leader is initiated from the Franklin rod) because the artificially initiated streamer will not be converted into a connecting leader. According to the data given in Fig. 4, artificially

initiated streamers may lead to connecting leaders only if the radius of the Franklin rod is larger than about 0.35 m. Now, the attractive distance of a Franklin rod is defined as the separation between the tip of the stepped leader and the top of the Franklin rod when a leader is incepted from the latter. In Fig. 5, consider a Franklin rod of radius 0.5 m. The attractive distance of this Franklin rod for the stepped leader under consideration is 32 m (42—the length of the Franklin rod). On the other hand when the stepped leader is at a height of 53 m, an artificial triggering of a streamer from the rod may lead to a connecting leader and may result in an attractive distance of 43 m. That is, the gain in the attractive distance by an artificially initiated streamer will only be about 30%. The situation becomes bleak for smaller conductors and the analysis given here show that with in the approximations made in the paper it is not feasible to increase the attractive radius of conventional Franklin rods by artificially initiating a streamer.

It is important to remember that in this paper we have assumed that the Franklin rod will give rise to a streamer as soon as the criterion necessary for the avalanche to streamer transition is satisfied. That is, we have neglected the statistical time delay necessary for the availability of suitable initiatory electrons. Moreover, as we have mentioned previously, an inception of a connecting leader does not necessarily mean that it will make a successful connection to the down coming stepped leader. For a successful connection the connecting leader should propagate continuously and this requires a minimum field of about 200 kV/m [6]. For this reason, the attractive distances evaluated in this paper should be considered an upper limit. In our calculations we have also neglected the effects of space charge that may accumulate at the tip of the Franklin rod. This space charge may influence the process under consideration to some extent. In the calculations we have assumed the surface of the electrode to be smooth. In reality, the protrusions on the surface can influence the field enhancement factor and hence the streamer inception probability. However, such protrusions cannot influence the electric field over a 3 m distance from the conductor. Thus, the leader inception criterion will not be influenced by them. The results given in Figs. 4 and 5 are valid for a cloud potential of 100 MV. The data depicted in Fig. 1 show, however, that the leader tip height at which Conditions 1 and 2 are satisfied vary more or less linearly with the cloud potential. Thus, the results in Fig. 4 can easily be extended to other cloud potentials using this linear relationship. Finally, according to the results presented in [3,4] the streamer to leader transition criterion used in this paper is independent of the electrode geometry. That is, the same critical streamer length is observed both in sphere-plane gaps and conductor-plane gaps. This makes it possible to apply this criterion, instead of the critical radius concept [5] which depends on the electrode geometry in lightning protection studies in which one has to evaluate the probability of streamer to leader transition in electrical discharges generated by many different configurations.

4. Conclusions

The attachment of a lightning flash to a Franklin conductor takes place through a connecting leader that rises from the Franklin rod towards the down coming

stepped leader of the lightning flash. The successful launching of a connecting leader requires the inception of a streamer discharge from the rod and its transformation into a leader (i.e. streamer to leader transition). Here, the occurrence of these physical processes at the tip of the Franklin rod is investigated. The results show that Franklin conductors of radii less than about 0.35 m artificial initiation of streamers at the conductor tip would not result in any increase in the attractive distance. For rod of radii large than 0.35 m it may be possible to launch a connecting leader by artificially triggering of streamer discharges at the conductor tip but the gain in attractive distance would not be larger than about 30%.

Acknowledgements

Authors thank Dr. Arturo Galvan for many valuable discussions. We also thank Dr. Anders Larsson.

References

[1] Ace, Version 2.51, ABB common platform for field analysis and simulations, ABB Corporate Research Centre, Västerås, Sweden, 1996.
[2] I. Gallimberti, The mechanism of the long spark formation, J. Phys. C40 (1979) 7–193.
[3] Les Renardiers group, Positive discharges in long air gaps at Les Renardieres—1975 results and conclusions, Electra 53 (1977).
[4] Les Renardiers group, Negative discharges in long air gaps at Les Renardieres—1978 results, Electra 74 (1981).
[5] A.J. Ericsson, The ground flash—an engineering study, ELEK 189, National Electrical Engineering Research Institute, Pretoria, South Africa, 1979.
[6] A.B. Clergerie, P. Lalande, P. Laroche, J.C. Willett, D. Davis, I. Gallimberti, The inception phase of positive leaders in triggered lightning: Comparison of modelling with experimental data, in: Proceedings of the 11th International Conference on Atmospheric Electricity, Alabama, 1999.