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CALCULATION OF LIGHTNING CHANNEL CHARACTERISTICS: COMPARISON OF EXISTING MODELS

L. Baker
R. L. Gardner
M. H. Frese
A. L. Paxton

Mission Research Corporation

ABSTRACT

We compare a number of models for the development of a lightning channel during the return stroke. These models are the simple model of Strawe, that of Braginskii upon which it is based, the CHANNL-1 code developed at Mission Research Corporation (based on an earlier code by R. L. Gardner), and the model of Plooster, upon which CHANNL-1 is based. The CHANNL-1 model is the most ambitious of the models considered and includes detailed simulation of the channel hydrodynamics as well as a multigroup radiation transport routine. The agreement between the models is qualitative. We discuss directions for future development of models of this type and the need for such enhancements.

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I. INTRODUCTION

In order to determine the currents and radiated fields of a lightning return stroke, it is necessary to know the characteristics of the current carrying channel. This requires a nonlinear model capable of determining how the passage of the large return stroke current modifies the channel properties. In this report we compare two such models, the relatively simple model employed by the RSTRAW code (Ref. 1) and a more complex model called CHANNL-1 (Ref. 2). We will not compare in this report the complete transmission-line models in which these models supply the channel parameters (resistivity per unit length and, through the channel radius, the inductance and capacitanace per unit length), but limit the discussion to the comparison of the computation of channel properties themselves.

II. DESCRIPTION OF THE MODELS TO BE COMPARED

The RSTRAW model of Strawe is a development of the model of Braginskii (Ref. 3). The CHANNL-1 model is a development of a code originally by Gardner (Ref. 4), which was in turn based on the computer model of Plooster (Refs. 5, 6, 7). CHANNL-1 is a much larger and hence more expensive and slower code to run than RSTRAW, but contains a more complete treatment of the relevant physical processes. It is of interest to compare the results of the models. If it could be established that the former is reasonably accurate, for example, it could be used for parameter surveys while the CHANNL-1 code could be used for studying extreme cases and studying the role of various physical processes. The comparison could also lead to improvements in the simple model, through improved choices of various phenomenological coefficients used in the RSTRAW model.

Both computer codes model and solve the same continuum equations, with some difference in the physical processes considered. Cylindrical geometry is used with all variables functions of the radial variable r alone. The one-dimensional equations for conservation of mass, momentum, and energy are then modeled and these approximate equations solved. In RSTRAW the channel is divided into three zones: a hot central core, a cooler, dense shell, and the ambient atmosphere outside. Nothing happens in the outermost ambient layer, since the channel expansion is assumed to be supersonic at all times and the thermal conduction and radiative processes are assumed not to affect this layer. The "shell" is not explicitly treated as a separate layer, its dimensions neglected as well as any kinetic or internal energy deposited in it. Consequently, all variables, density, temperature, etc. are assumed constant within the channel and the channel expansion is treated by a "slug" model in which force balance at the channel edge is used to obtain the channel expansion. This is one respect in which the RSTRAW model differs from Braginskii's; in the former the ambient pressure was neglected, in this the balance taken is of the form

$$A(p-P) = d/dt\,[vM]$$

where a is the channel radius, $A = \pi a^2$ the area/length of the channel, $v = da/dt$ the expansion velocity, and M the "moving" channel mass, which is taken as $\pi \times (a^2 - a_0^2) \times \rho \times K$, where a_0 is the initial channel radius, ρ the density, and K is an efficiency factor. It is clear that this assumes that the material within a_0 never moves and that the efficiency factor K, which was defined by Braginskii to relate the pressure behind the shock to the shock velocity, also relates the mean velocity of the material behind the shock to the shock velocity as well. This factor may be considered an adjustable parameter which could be used to "tune" the model. Comparisons with the hydrocode simulations discussed below suggest that the model used in RSTRAW expands too slowly, implying that this constant K is too large. Note that the model in RSTRAW may be said to be a one-zone model, since the behavior of the outer two zones is not calculated.

CHANNL-1 models the same continuuum equations. Rather than reducing the system to one or two zones, which when modeled yield a set of ordinary differential equations, it employs finite-difference methods to solve these partial differential equations. The hydrodynamic conservation equations are solved in the conventional manner following Richtmyer and Morton (Ref. 8), using Lagrangian coordinates in which the "grid" moves with the material. Both models use the electrical and thermal conductivities of Plooster, although RSTRAW uses a simpler fit to this data. The other major difference between models lies in the treatment of transport phenomena. RSTRAW uses approximate models for radiative power loss and thermal conduction loss from the channels. As with the momentum equation, a phenomenological factor called m is used with the thermal conduction loss term: the temperature gradient at the channel periphery is taken to be mT/a where m is between 2 and 3. Radiation losses are treated as a channel emission corrected by reabsorption. The emission is a fit to data while the reabsorption in the shell (which is assumed to "ablate" into the channel, and hence return the energy to the channel, instantly, in the form of internal energy) is assumed to take place for photons of energy exceeding 6.67 eV and is fit to data accordingly. Note again that these terms are not allowed to change the assumed properties of the outer layers and merely act as losses in the energy balance of the central channel.

CHANNL-1 presently uses a multigroup radiation transport model (Ref. 9). This is described in Reference 9, and has been used successfully in hydrocode simulations of plasma channels, for example. For air eight photon groups are used. These are chosen to correspond to spectral regions with relatively little variation in opacity. The P1 approximation of the spherical harmonics method is then used. This method may be shown to be exact (for "grey" or frequency-independent opacities) in both the optically thick and optically thin limits. Reciprocal opacity means are used; while Rosseland and Planck mean opacities can vary widely when determined over the entire frequency spectrum, over the bands considered the average opacities differ relatively little (about a factor of two) depending upon the method of averaging used. The mean employed is most appropriate for the optically thick limit. Errors in the optically thin limit are of less importance because the emission is relatively small and consequently even a large error in the relative amount of emission would cause a small error in the energy balance. The opacities used to form the band averages are taken from the work of the Lockheed group (Refs. 10, 11). These opacities include contributions from lines and molecular bands as well as continuum opacities. Of course, resonance lines are not accurately treated but again, due to the large optical depths in these lines and the consequent photon trapping, their effect on the net energy balance is not important for most cases. We note that the energy scheme used in a previous version of CHANNL-1 (Ref. 2) seems to have caused large errors in central channel temperature. These preliminary results should be disregarded, and are superceded by the results presented here. The radiative transport dominates the electron thermal conduction, and the latter may be safely neglected. It was found that the inclusion of the thermal conduction model in CHANNL-1 by the time-splitting of the energy equation (i.e., successively treating separately the various terms of the equation) resulted in a numerical instability, and so thermal conduction was neglected in the runs discussed below.

The equation-of-state used by RSTRAW is that of Braginskii (Ref. 3), which is of an ideal gas with constant ratio of specific heats, $\gamma = 1.22$ for air. The model used in CHANNL-1 is that of Plooster (Ref. 5). A fictitious gas called AIR_2 which has properties that are weighted averages of those of nitrogen and oxygen is used. Dissociation as well as single and double ionization are considered. Further, all molecules are assumed dissociated before ionization begins, and all atoms are assumed to be singly ionized before any are doubly ionized. This equation of state should be accurate above 10,000 degrees Kelvin. Plooster (Ref. 5) acknowledges that his model "misrepresents the thermodynamic properties of real air in the temperature range 3000 to 9000 K, since the dissociation energies of O_2 and N_2 are very different. In addition, substantial quantities of nitrogen oxides are present at equilibrium in this temperature range. Nevertheless, the total energy required to dissociate one mole of AIR_2 is the same as that required for a like quantity of real air." Consequently, while the computed temperature of a zone is unreliable if that temperature is in the range of 3000 to 9000 degrees, it should be reasonably accurate above and below that temperature regime. Further, the transport coefficients and opacities are independent of the AIR_2 model's calculated electron densities, but rely upon tables or formulae as a function of temperature and density. This is important, for ionization of NO can be the principal source of electrons in the temperature regime mentioned and if the conductivity model were to rely AIR_2 to provide electron density for this purpose it could seriously underestimate the electrical conductivity. We emphasize this problem does not occur. The model was also shown by Plooster (Ref. 5) to be thermodynamically consistent, which is often difficult to achieve in practice with tabular equations-of-state. The AIR_2 model has the advantage that modification into a two-temperature model, for example, is much simpler than for an equation-of-state based upon tabular data, although Plooster (Ref. 6) has argued that electron and ion temperatures should be rather similar for conditions expected in the lightning channel.

CHANNL-1 requires initialization with a temperature and density profile as a function of radius. Since the conductivity model does not model avalanche breakdown phenomena, one cannot start with ambient conditions, but rather an elevated temperature of order 1 eV is needed to allow a "seed" conductivity to permit current flow. The density is typically assumed ambient, under the assumption that between breakdown and the start of significant channel current little time has elapsed for the channel to rarefy (Plooster (Ref. 7) has considered constant pressure as well as constant density initial conditions). The velocity distribution is similarly assumed initially zero and computed self-consistently from the equations of motion. RSTRAW, by model assumptions, must start with a shock already formed (this shock in effect defines the boundary between the ambient zone and the channel zone). From the shock strength follow the conditions behind the shock.

Each code follows Plooster's model in assuming that current diffusion into the channel is rapid compared to changes in the current, so that one may treat the radial zones as resistors in parallel across the same voltage gradient (analagously, in RSTRAW, the current is taken as uniform in the channel). Braginskii justifies this assumption for a specific choice of channel parameters of 1 mm radius, computing a skin depth of 1 cm. This calculation did not take into account either channel expansion, or an increase in channel conductivity resulting in a decrease in skin depth. It appears for rise times of the order of 1 μs and for typical estimates of conductivity the skin depth can be of the order of or less than a typical channel radius. Then the skin depth is given by the expression $\delta = \sqrt{T\rho/\pi\mu_0}$ where δ is the skin depth, ρ the resistivity, T the timescale and μ_0 the permeability. From the data of Reference 4 the typical channel resistivity may be estimated as 0.3 Ω-cm or 30 Ω-m. This yields 3 mm as the skin depth. Braginskii (Ref. 3), in his estimate of the channel skin depth, found 1 cm as a typical value. If the channel has expanded to a radius of about 1 cm before the first return stroke or between return strokes, we see that the approximation of instantaneous diffusion may be violated. Therefore, it is desirable to develop models which can treat in a self-consistent manner the diffusion of current into the channel. Fortunately, MHD codes with such a capability have been in existence for decades and there should be no problem, in principle, in applying similar methods to obtain the current distribution in the channel. We consider this to be desirable in futher development of channel modeling capability.

Each code neglects the magnetic pressure, i.e. the Lorentz force, due to current flow. This could become significant for channels in which large currents (of order 100 kA) flow, as shown by CHANNL-1 runs in which the magnetic pressure at the channel edge was computed as a diagnostic. The calculation of the magnetic field distribution is the same as that of the current distribution described above. Consequently, adopting the techniques of MHD codes would provide the field distribution for the inclusion of Lorentz forces. Such MHD codes regularly neglect the displacement current term. As the lightning channel is often a strong emitter of electromagnetic radiation, this omission may be difficult to justify in the present circumstances. However, inclusion of such terms would greatly complicate the model. In fact, such radiation terms would couple the various portions of the channel, and a one-dimensional model would no longer apply. The loss due to electromagnetic radiation cannot simply be treated as a loss per unit channel length, as say Ohmic losses may be treated, because of the coupling of channel regions through the radiation field. For example, the radiation loss term for a dipole is not proportional to the dipole length but to the square of the length. If we assumed that the lightning channel were composed of a random linking of radiators (e.g., dipoles of specified lengthor perhaps monopoles), we could calculate an average loss per unit length, assuming the fields were incoherently superimposed and hence the radiating segments were decoupled. This would give a phenomenological model for the effect of electromagnetic radiation losses on the channel. To summarize, a computational model employing the techniques of MHD codes would address the problems of magnetic pressure and current distribution in the lightning channel. An attempt to include radiation terms would require at least a two-dimensional model and would greatly complicate matters. Such a model is probably unjustified at this time.

Neither code explicitly considers the tortuous nature of the channel as it would affect the hydrodynamic evolution of the channel. In transmission line models the parameters used are the inductance, capacitance, and resistance per unit length. In the CIRCUS model of the transmission line, the first two quantities listed above are fixed, and subroutine RSTRAW supplies the resistance per unit length. In an attempt to account for torturosity, this resistance per unit length is multiplied by a factor accounting for the ratio of channel length to the straight-line distance between two points on the channel. This is correct if the inductance and capacitance per unit length are based upon the straight-line distance between points. If all of the parameters L, C, R are per the same unit of length, i.e., that following the channel (and not the smaller straight-line distance), then any one of them (e.g., the resistance) should not be multiplied by any factor. In practice, this caveat is probably unimportant due to the uncertainties in L and C are as large as uncertainties due to the ratio of straight-line to along-channel distances between points. Conceptually, it is clear that R, L, and C must be per the same unit of length, whether that be straight-line or along-channel lengths. It appears that CIRCUS does this by taking L and C as per unit straight-line distance, and converts the R of RSTRAW (which clearly must give resistances per along-channel length) to per straight-line length by multiplying R with phenomenological constant representing the ratio of the two lengths. The uncertainty in estimating L and C per unit length is probably as large as the uncertainty in such a factor.

Table 1 compares the physical models employed by the CHANNL-1 and RSTRAW codes.

TABLE 1. COMPARISON OF CHANNL-1 AND RSTRAW MODELS

PHYSICS	CHANNL-1	RSTRAW
Transport:	Multigroup Photon	Phenomenological Conduction + Radiation
Equation of State	Plooster AIR_2	Ideal Gas =1.22
Zones	Arbitrary (typically 100)	3 (only one fully modeled)
Initial Condition	Temp., Density variation	Shock position

Both models attempt to describe essentially the same continuum equations with similar physics. The difference is the extent to which these continuum equations are modeled, and also whether the electrical resistivity, etc. are modeled by simple fits as in RSTRAW or the more detailed formulae as in CHANNL-1. In RSTRAW quantities such as channel temperature are treated as averaged quantities, with gradients treated by using a fraction of the channel radius as a lengthscale. In CHANNL-1, finite-difference approximations are used which, in the limit of infinitesimal zone size (which in practice means scales smaller than the physical lengthscales), should exactly model the desired equations. Consequently, if RSTRAW should get more accurate answers than CHANNL-1 on some problem, this could only be fortuitous, i.e. a consequence of the neglect of some important physical effect in both models which causes a less accurate solution of the equations to give better agreement with experiment. This assumes that the differences in radiation transport between the two models is not significant. We would expect the multigroup transport model used in CHANNL-1, which has been benchmarked against numerous experiments, to do a good job of treating the net energy losses of the channel. At some increase in complexity and running time, the RSTRAW model could be enhanced through the use of more complete models for the equation-of-state, resistivity, etc. More accurate relationships for the shock could be used. Somewhat more costly would be explicit consideration of the region between the hot channel and the shock. This would allow the channel and shock to separate at late times, as they should. It would also allow a more complete treatment of the transport (reabsorption in the intervening layer) and possibly an improvement of the treatment of momentum balance near the shock and channel boundaries.

III. COMPARISON OF RESULTS

A. COMPARISON OF PLOOSTER AND CHANNL-1 WITH EXPERIMENTS

It is of interest to compare the CHANNL-1 model with the experiments discussed in Plooster (Ref. 6). This will allow us to estimate the significance of radiation transport and the effect of using the multigroup transport in place of simpler treatments. It will also allow us to benchmark the CHANNL-1 code against experiment.

The channel radius of the the Higham and Meek (Refs. 12, 13) experiments is given in Figure 1; this may be compared to the results plotted in Figure 5 of Plooster (Ref. 6). Although we have initialized the channel to 1 mm diameter, which is larger than the (unspecified) inital radius used by Plooster, the agreement is good in that by 12 μs the channel radius agrees well with both that of Plooster and the experimentally observed luminous channel radius. Plooster does not give the peak channel temperature although in our simulations it is 20,000 K and falls rapidly to about 16,000 K. Figure 2 plots the channel voltage gradient and compares it to Plooster's calculated values and the results of Higham and Meek. The results seem in general marginally better than Plooster's but not convincingly so, being closer to Plooster's values than the experiment and somewhat below the experimental values, as Plooster's voltage gradients are.

The other comparison of interest is with the work of Orville, Uman and collaborators on a laboratory measurements of a 4-m length spark at Westinghouse Research Laboratories (Refs. 14, 15, 16). This experiment had much larger currents than that of Higham and Meek. Figures 3 through 6 show the voltage gradient, channel radius, core temperature, and energy balance, respectively. The voltage gradient is significantly higher than

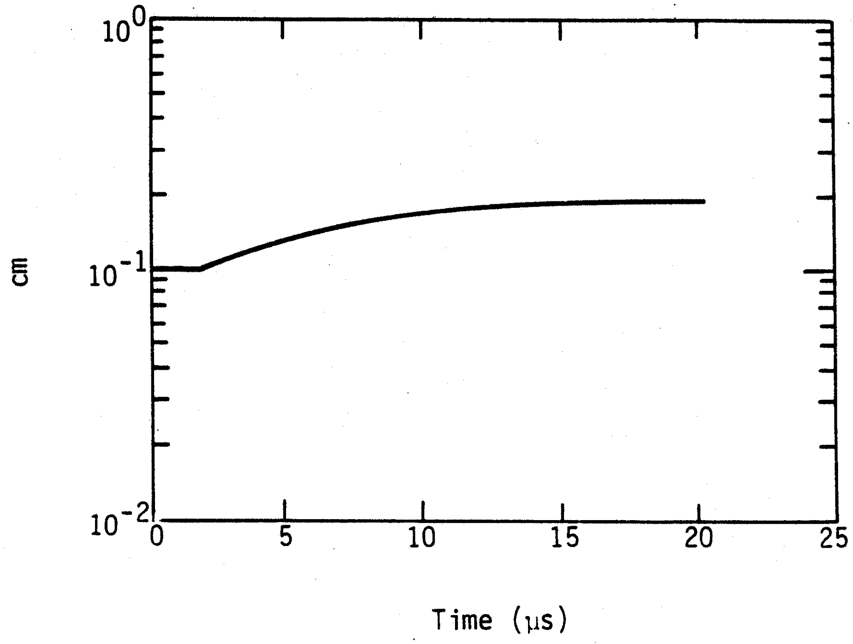

Figure 1. Channel radius as a function of time, calculated by CHANNL-1, for the experiment of Higham and Meek discussed in Plooster (Ref. 6). Initial channel radius is 1 mm.

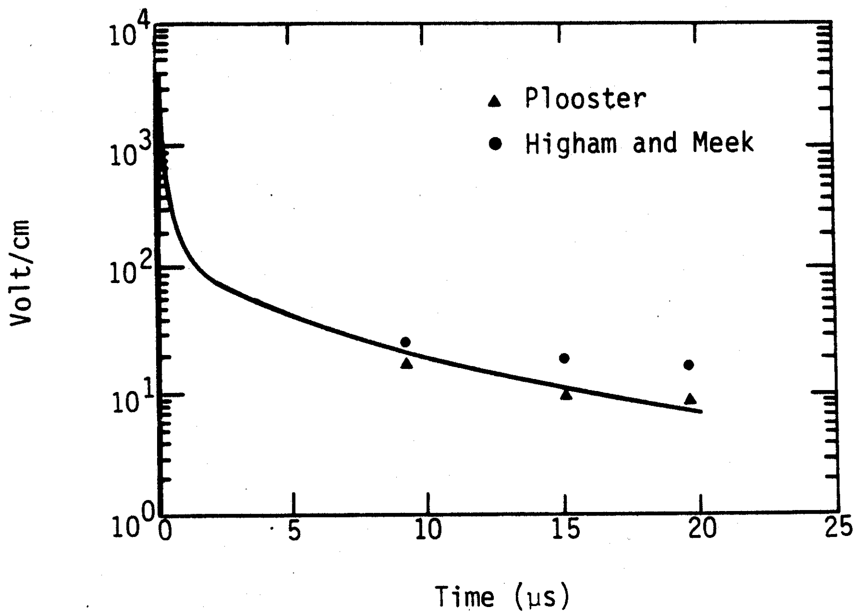

Figure 2. Voltage gradient along the channel for the experiment of Higham and Meek discussed by Plooster(Ref. 6), as calculated by CHANNL-1. The results of Plooster's calculations and the experimental data points are shown for comparison.

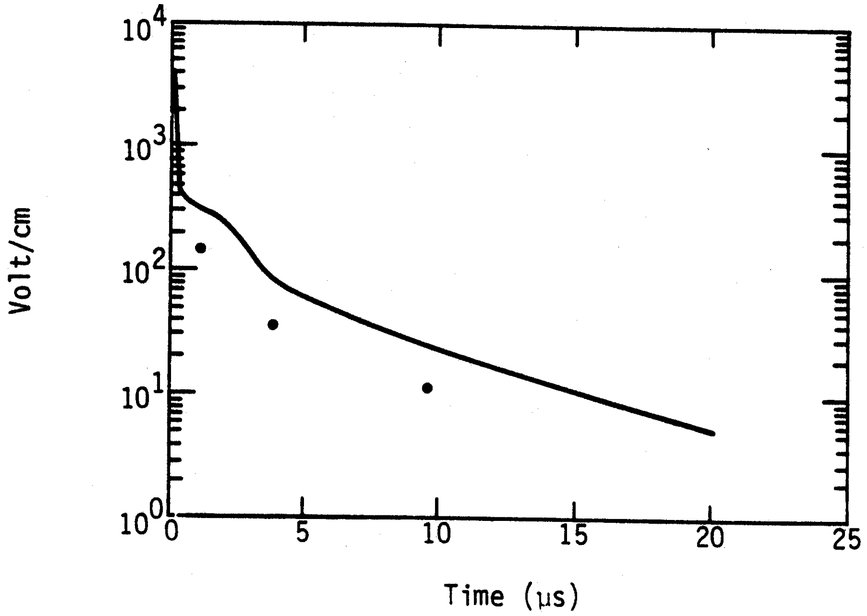

Figure 3. Voltage gradient along the channel for the Westinghouse 4-m spark experiments, as calculated by CHANNL-1, compared with the calculations of Plooster.

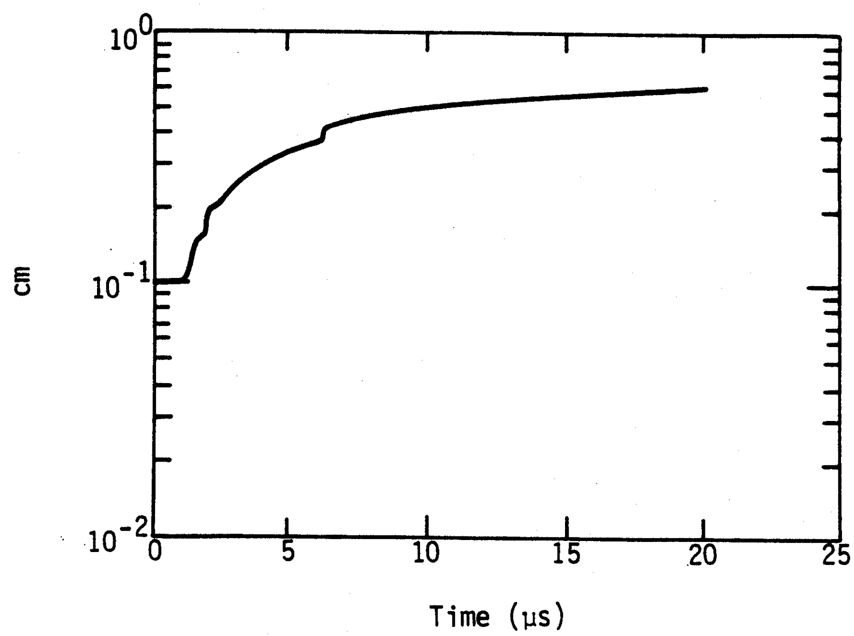

Figure 4. Channel radius as calculated by CHANNL-1 for the Westinghouse experiments.

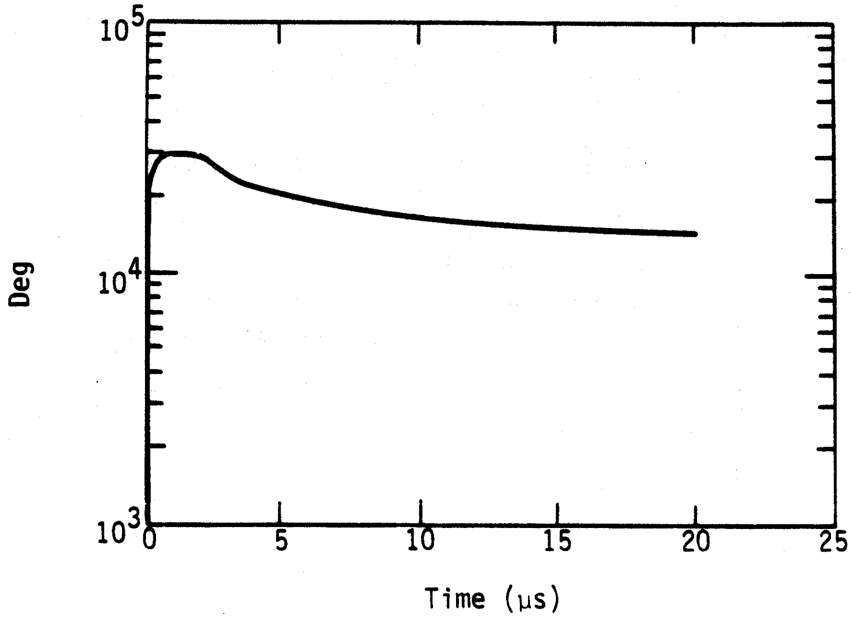

Figure 5. Core temperature of the Westinghouse experiments, calculated by, CHANNL-1. The temperature of the innermost zone of the calculation is used.

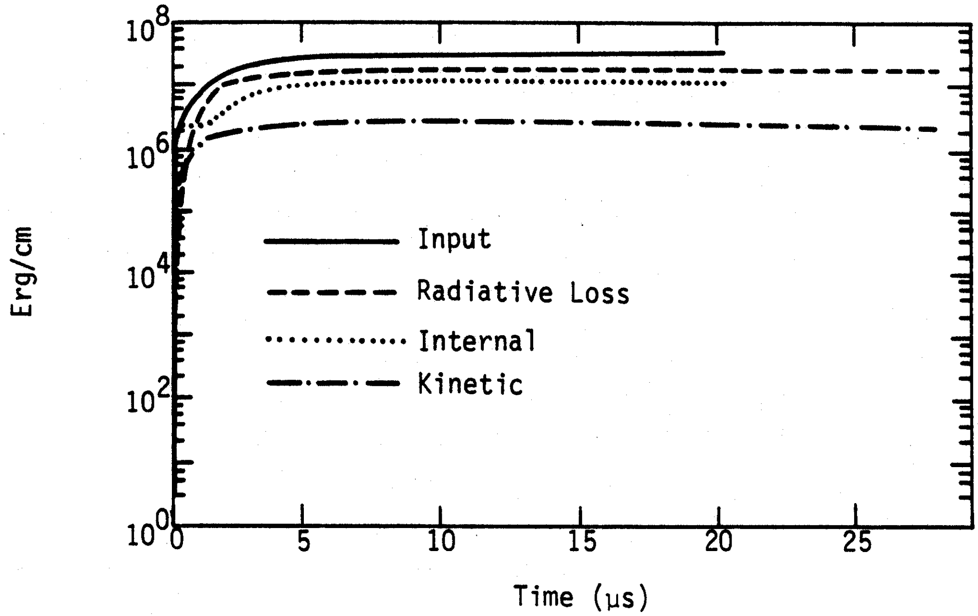

Figure 6. Energy balance (cumulative) for the Westinghouse experiments, as calculated by CHANNL-1. The solid curve is the total energy input and is the highest curve. The lowest curve, dash-dot, is the kinetic energy of the channel (includes acoustic energy). The dotted curve is the radiated energy lost to the channel. The dashed curve is the internal energy deposited in the channel (i.e., that which goes into dissociation, ionization, and increased temperature). The remaining curve is a plot of channel energy which is the sum of internal and kinetic energies, and is almost coincident with the internal energy as the kinetic energy is small compared to the internal energy.

that of Plooster at late times and hence in much better agreement with experiment. This must be attributed to larger radiative cooling due to the multigroup transport treatment of the radiation field (see below). This results in a cooler channel, also in somewhat better agreement with the experiment. As Plooster's values are about one order of magnitude below experiment and these values are about 4 to 5 times his, they are now only a factor of 2 to 2.5 below experiment. Note that the total energy input into the channel does not increase in this proportion since the current has fallen significantly at this time and consequently the effect on the energy balance is negligible. Note also that neither numerical model treats the energy deposited in the channel during the breakdown process, which is not modeled. The peak core temperature of 30,000 K is between the ion and atom temperatures of Plooster and are somewhat closer to the experimental measurements than the results of Plooster. The channel radius is in good agreement with Figure 10 of Plooster and hence the limited experimental data on this variable, in that the channel radius at 15 μs is 0.6 cm compared to the experimental value of 0.6 to 0.9 and Plooster's value of 0.7 cm. At earlier times the channel radius is smaller than Plooster's being slightly less than 0.3 cm at 5 μs compared to the radius 0.42 cm as calculated by Plooster. Finally, the energy balance is of some interest for this experiment. The experiment had a calculated energy input to the spark as 50 J/cm (with an uncertainty of about 25 J/cm), while measurements of the channel radius and temperature suggested about 2 J/cm resided in channel internal energy. Radiant energy losses in the spectral region of 4000 to 11000 Å are an order of magnitude below this. The experimenters concluded the remainder appeared as acoustic emission. Plooster disagrees, calculating that the acoustic energy loss is small and that the radiant energy loss over the entire spectrum is about 1 J/cm, giving about 2 J/cm in internal energy as measured, and a total energy input into the channel of about 4 J/cm. This last number is below the experimenter's calculated value, which is nonetheless rather uncertain. Note that about 25 percent of the energy input to the channel is radiated away. With the multigroup transport model, this loss is roughly 50 percent of the energy input. The bulk of this energy is not radiated in the spectral regime of 4000 to 11000 Å, accounting for the experimental results. The total energy input to the model is comparable to that of Plooster, and hence stil an order of magnitude below the experimental value. On the whole, the agreement with Plooster is still good, and the figure of 2 J/cm for the energy appearing as internal channel energy is still correct. In summary, the CHANNL-1 model is in good agreement with both Plooster and even better agreement with experiment, suggesting that the multigroup transport model in the cases considered gives a more correct treatment of the energy balance. This difference can be significant but is not orders of magnitude.

B. COMPARISON OF CHANNL-1 AND RSTRAW

Before turning to the comparison of CHANNL-1 and RSTRAW we should review the comparison of Plooster's and Braginskii's results of Reference 7. Since CHANNL-1 is based upon the former and RSTRAW the latter model, this will shed some light on how much of the variations between the "children" is due to differences between the "parents". Table 2 of that paper shows that the Braginskii model consistently overestimates the channel radius relative to the (presumably) more accurate results of Plooster. This error is not more than about 20 percent, however. The differences in energy input in each of the models is larger up to about 40 percent, but not systematically so; for longer rise times the energy input is larger in the Plooster model, while for short rise times it is larger in the Braginskii model. The difference in energy input is due to the fixed conductivity in the Braginskii model, whereas the conductivity is a function of temperature in the model of Plooster, and also the RSTRAW model. Consequently, we would expect the differences between the RSTRAW and Plooster models to be fairly small, and by extension the differences between the RSTRAW and CHANNL-1 to be relatively small.

We have compared the models on the two cases discussed in Reference 2. These cases were a 10 kA return stroke in a narrow (1 mm initial radius, 15000 K initial temperature) channel and a 20 kA return stroke in a broad channel (1 cm initial radius, 10000 K initial temperature). Each stroke had a linear rise to peak current (1.5 and 1 μs, respectively), and an exponential fall with time constants of 40 and 50 μs, respectively, as in Reference 2. The results were not sensitive to the initial temperature, i.e. channels initialized to 10000 K and 15000 K behaved quite similarly. As might be expected the order of magnitude difference in initial channel radius is important; the larger channel does not reach as high a temperature as the narrower one, and its expansion on the same timescale is negligible. Part of the difference is due to the lower current in the latter case, of course, but not all. There is at present considerable uncertainty in the diameter of lightning channels. Figures 7 through 9 compare results for the first case. The core temperatures and are fairly close, with CHANNL-1 being somewhat hotter at late times. The channel radius is overestimated by RSTRAW, due to the approximation that the shock and channel radii are equal. This results in a channel of much larger cross section and consequently much lower resistance per unit length, so that CHANNL-1 is rather more resistive, especially at late times. Figures 10 through 13 give typical radial profiles for temperature and pressure in the channel, and Figure 14 displays the energy balance. Figures 15 through 16 compare the temperatures and resistances, with Figures 19 and 20 plotting typical radial temperature and pressure profiles of the other comparison case. Again CHANNL-1 gives a channel slightly hotter in the center and yet somewhat more resistive. The channel radius in both codes remains relatively constant at the initial value. A comparison of Figures 12 and 13 reveals significant separation of the shock from the channel radius on the timescale of interest. In RSTRAW these radii are equated. There is a "shoulder" in the temperature profile; comparison of the pressure and temperature profiles show that this is in fact the region between the shock

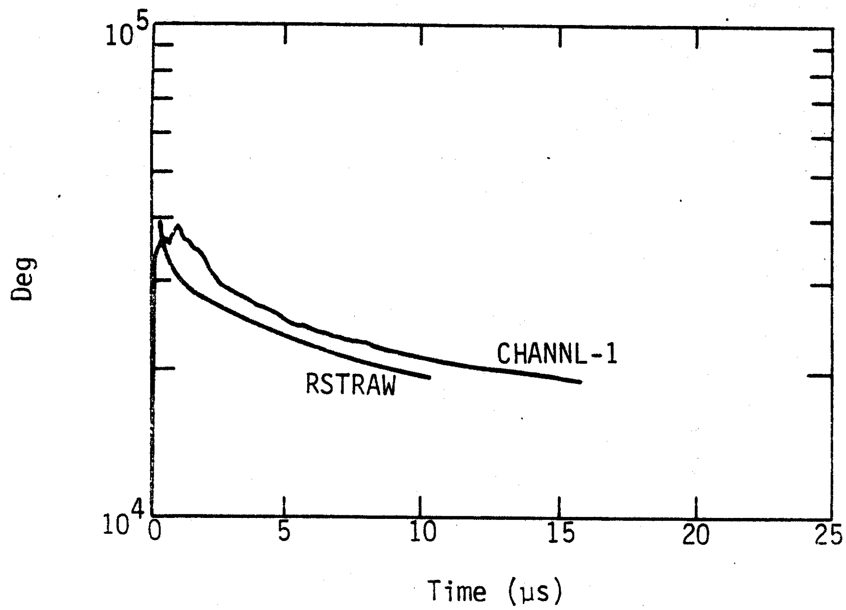

Figure 7. Same as Figure 5 but core temperature.

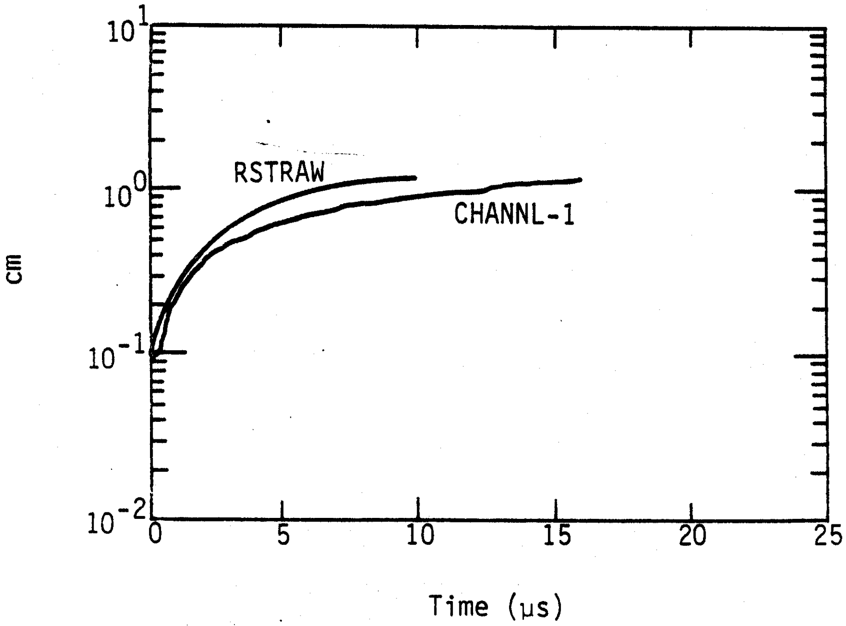

Figure 8. Same as Figure 4 but channel radius. This is defined in CHANNL-1 as the outermost zone whose temperature exceeds 9500 K. For RSTRAW this is the same as the channel and shock radii, which are equal.

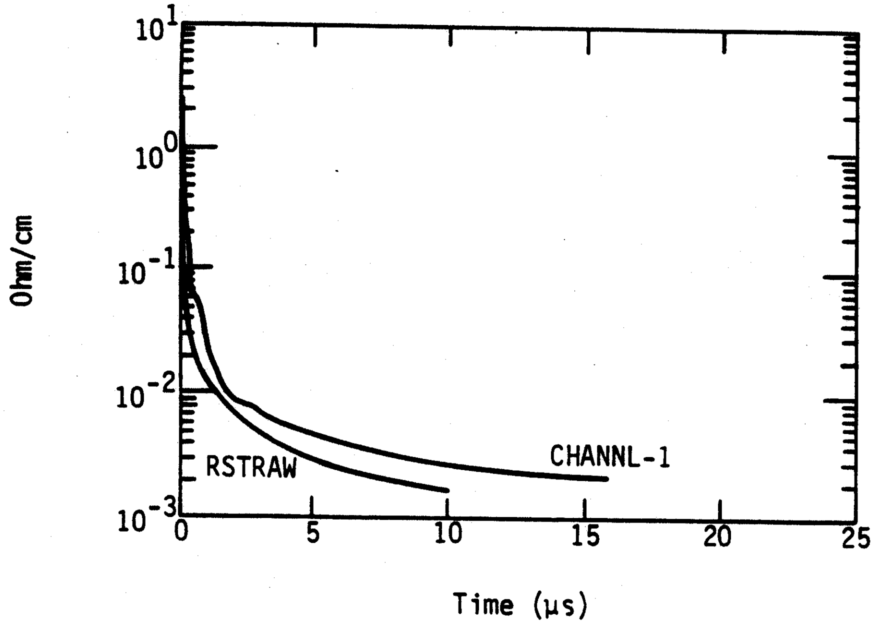

Figure 9. Resistance of the lightning channel with 1 mm initial radius, 20 kA peak current, as calculated by CHANNL-1 and RSTRAW.

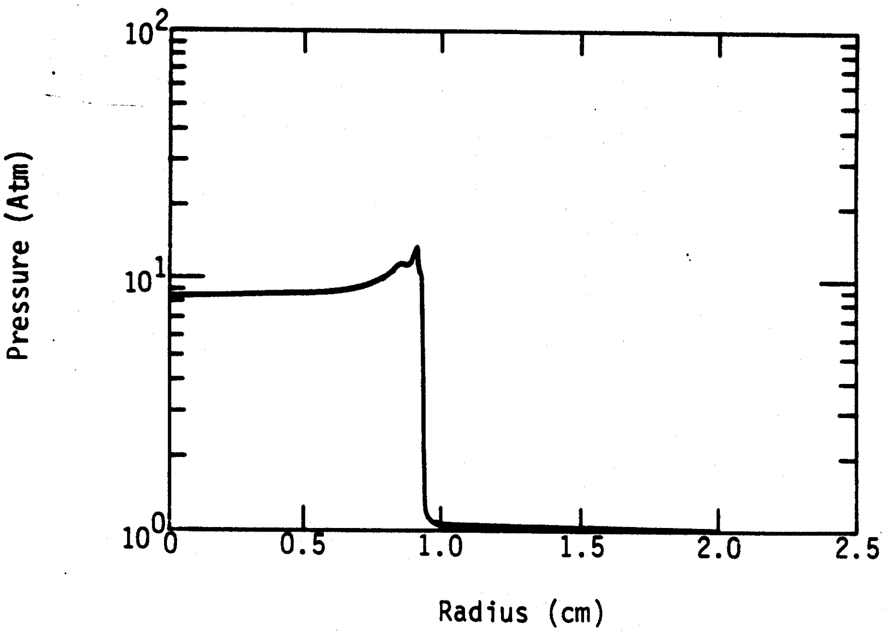

Figure 10. Pressure profile as a function of radius for the same case as Figure 7 at 5.2 μs into the simulation. Note the shock has almost reached 1 cm radius.

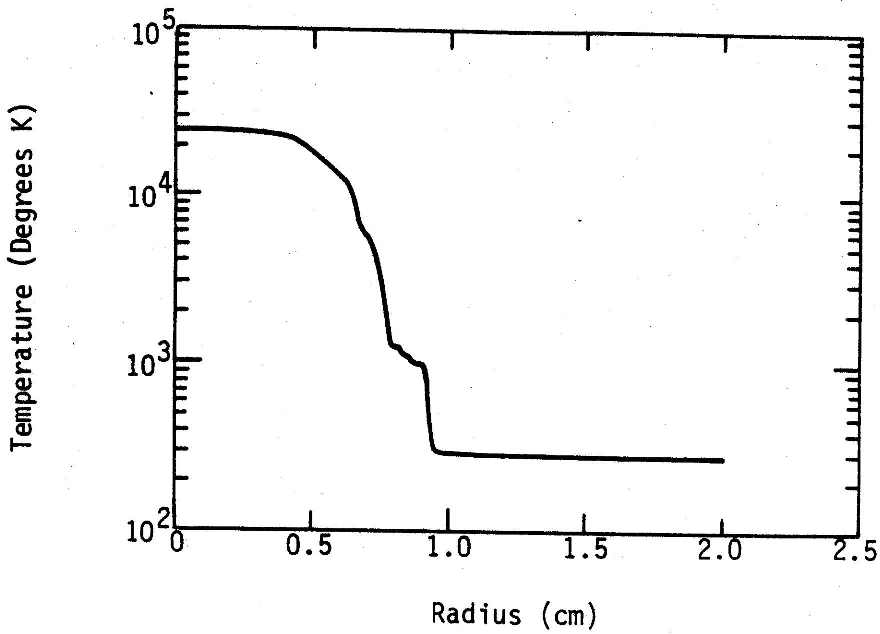

Figure 11. Same as Figure 10 but the temperature profile. Peak temperature is roughly 25,000 K.

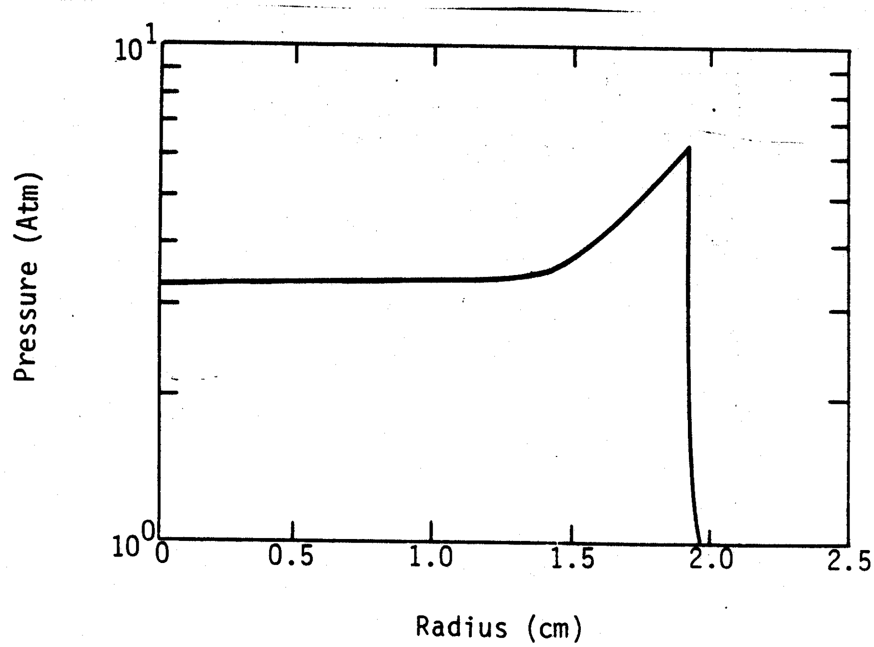

Figure 12. Same as Figure 10 but at 16 μs. The shock has reached to almost 2 cm radius.

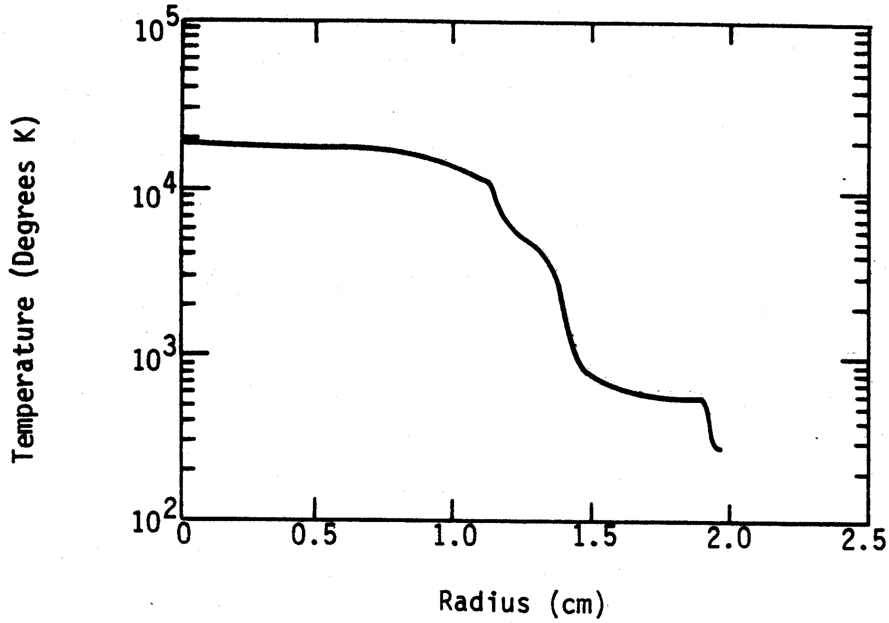

Figure 13. Same as Figure 12 but temperature profile. Note that while the shock has reached 2 cm, the channel radius is roughly 1.5 cm.

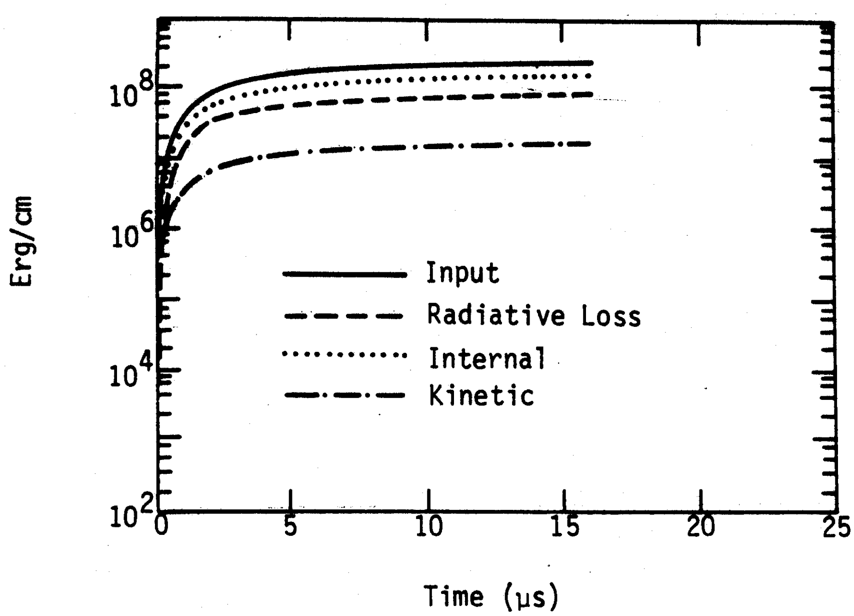

Figure 14. Same as Figure 6 but for the case of Figures 7 through 13.

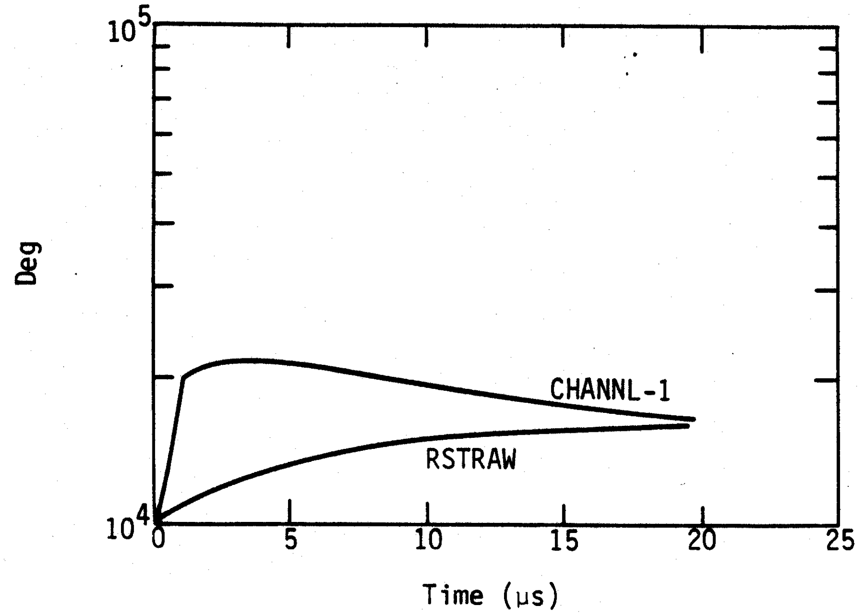

Figure 15. Core temperature for the case of 10 kA peak current, initial radius 1 cm lightning channel. Comparison of results of CHANNL-1 and RSTRAW.

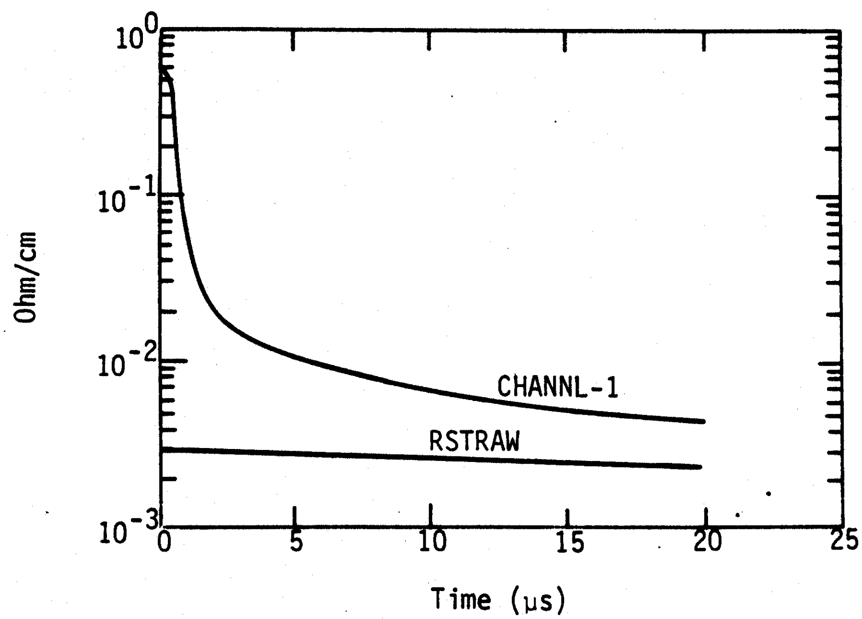

Figure 16. Resistance of the lightning channel for the case of Figure 15, CHANNL-1 and RSTRAW results.

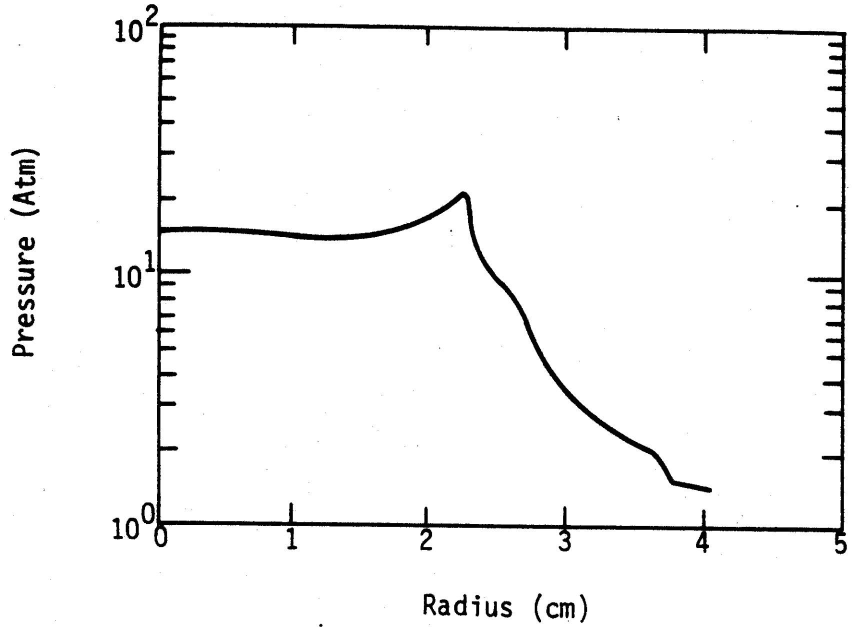

Figure 17. Pressure profile at 6.4 μs for case of Figure 15.

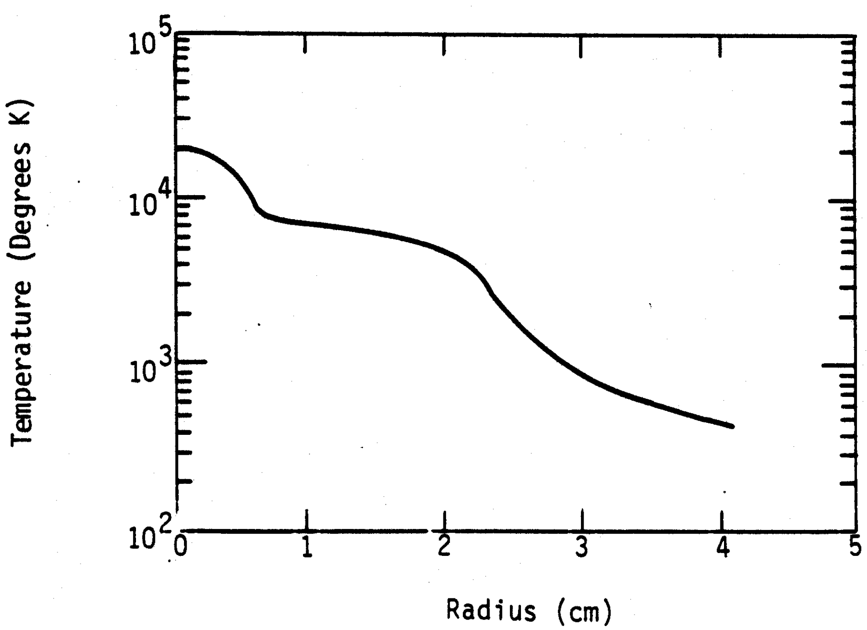

Figure 18. Same as Figure 17 but temperature profile.

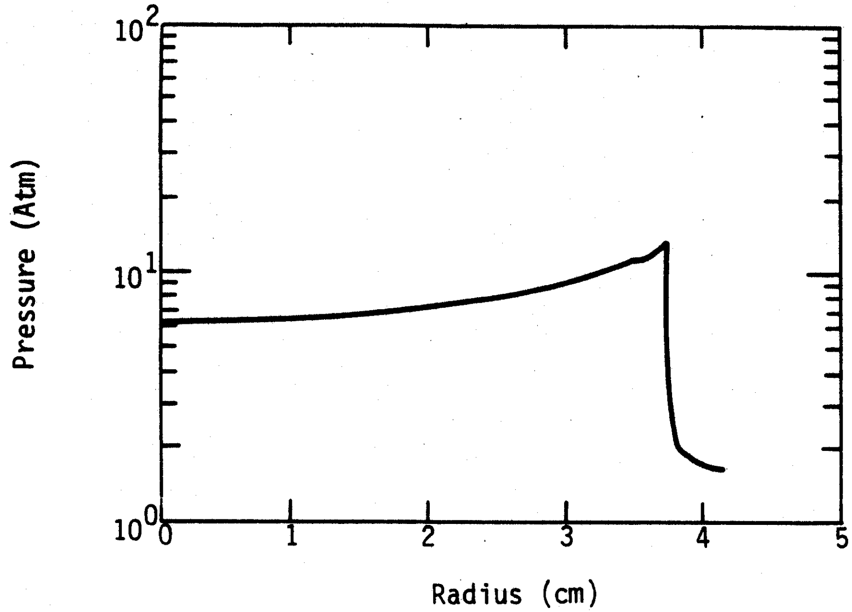

Figure 19. Same as Figure 17 but at 17 μs.

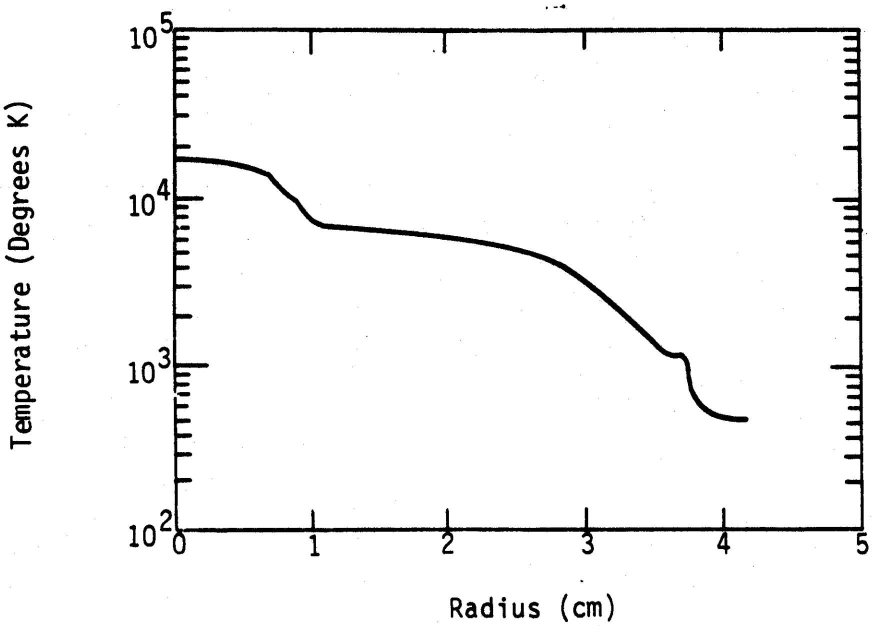

Figure 20. Same as Figure 19 but temperature profile.

and the channel proper, the intervening material being cooler and denser. Please note that the channel resistances reported for CHANNL-1 in Reference 2 are substantially below those being reported for CHANNL-1 at present; this is due to the erroneously high core temperature calculated in that report, and should be considered superceded by this report. Note also that the case illustrated in Figures 15 and 16 has an initial radius of 1 cm, not 1 mm as in the other case or in typical cases run at Boeing. Therefore, the current density $j = I/A$ is decreased by a factor of 100 and the volumetric heating-rate ηj^2 is reduced by 10,000. This accounts for the slow rise, which Strawe has criticized.

IV. DISCUSSION AND CONCLUSIONS

Comparison of the results of CHANNL-1 runs with the calculations of Plooster, the experiments described, and the simple RSTRAW channel model suggests that:

1) the use of multigroup transport improves the agreement of this class of models with experiment

2) the models are in fairly close agreement among each other and with experiment, given the uncertainties in each. RSTRAW seems to overestimate the channel radius and consequently underestimates the channel resistivity significantly, however.

As to future directions for work in this field, we suggest:

1) RSTRAW could probably be substantially improved at a moderate cost in increased complexity. The improved model should treat the channel core and the region between the core and the outgoing shockwave as two separate regions of different radii. The energy accounting of the intermediate region could then be done, rather than assuming that material in that region is instantly ablated into the channel. The shock could be treated more accurately.

2) Self-consistent treatment of current diffusion into the channel should be included in models, especially for narrow channels (at early times) or high current, highly conductive channels.

3) Magnetic Pressure (Lorentz force) effects will have to be considered for high current channels.

Adoption of the techniques current in MHD (Magnetohydrodynamics) codes would address items 2 and 3 above.

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