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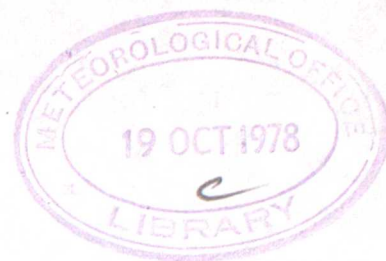
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# METEOROLOGICAL OFFICE

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## MET.O.15 INTERNAL REPORT

No.004

THE EFFECT OF SPLINTERING ON THE INITIATION  
OF THE ICE PHASE IN CUMULONIMBI

by

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Cloud Physics Branch (Met.O.15)



## 1. INTRODUCTION

Glaciation enhances the development of cumulonimbus clouds in a complex manner and it is therefore important to determine the level and stage in the cloud evolution at which significant glaciation occurs.

There is substantial observational evidence (e.g. Mossop, Cottis and Bartlett 1976) that ice crystal concentrations in cumulus clouds of up to  $10^4$  times that expected from the observed number of active ice nuclei, are found at relatively high temperatures, usually above  $-15^{\circ}\text{C}$ . The effect is largest if large droplets and rimed ice particles are also present and the presence of some mechanism of secondary production of ice nuclei has long been suspected. A possible mechanism was recently detected in laboratory experiments by Hallett and Mossop (1974) and substantially confirmed by Goldsmith, Gloster and Hume (1976).

Briefly, a cylindrical rod was rotated through a cloud of supercooled water droplets, and the riming process was found to generate secondary ice crystals by impacts with droplets of diameters  $\geq 24 \mu\text{m}$  in a temperature range of about  $-3$  to  $-8^{\circ}\text{C}$ . Maximum rates of one splinter per 100 to 300 impacts were observed near  $-5^{\circ}\text{C}$ .

The purpose of this report is to describe an attempt to assess, using these laboratory results in a simple numerical model, the possible significance of this process in increasing the temperature at which glaciation occurs in a cumulonimbus updraught.

As a basis for this work one of Jonas' earlier models (1972, unpublished) was taken in which air ascends at a constant rate with no mixing, water droplets growing by condensation only. The ice phase was introduced by letting droplets freeze due to activation of ice nuclei, the number activated varying according to the ice nucleus temperature spectrum after Fletcher (1962). The ice particles soon acquire a significant fall speed, and sweep up water droplets by coalescence. The effects of splintering are included through the introduction of a reasonable number of ice crystals at around  $-5^{\circ}\text{C}$  which could have originated from the Hallett-Mossop splintering effect.

The main limitations of this model are that it is a purely microphysical model with no dynamics included, the neglect of mixing not being serious, as the updraught of a developed cumulonimbus is thought to be fairly well protected from the environment. As such it is to be used to provide input in the form of ice particle numbers and total ice contents for larger models that include a more realistic treatment of the dynamics. The ice nucleus spectrum and splintering rates assumed must be subject to possible future improvements in experimental techniques resulting in better approximations to conditions prevailing in the atmosphere and to a better understanding of the physical mechanism responsible for splintering.

## 2. DESCRIPTION OF THE MODEL

In Jonas (1972, unpublished) water droplets grow by condensation on to sodium chloride nuclei. A fixed nucleus spectrum is assumed with nuclei falling into any one of 18 mass classes over which masses increase exponentially from  $10^{-18}$  to  $1.3 \times 10^{-13}\text{kg}$ . The numbers of nuclei in each class are taken so that they fall off approximately in proportion to the increase in mass from one class to the next. There are 31 drop radius classes with mean class radii increasing exponentially from  $0.1$  to  $102.4 \mu\text{m}$ . Starting from cloud base, air ascends at a constant rate with no mixing, changes in pressure, temperature, drop radii, liquid water content and supersaturation being computed at each time step. Within each radius class all drops of the same nucleus mass have the same radius at any one time and grow at a rate determined by the mean class radius.



To incorporate the ice phase an extra group of classes was added alongside the nucleus mass classes. As before this was divided into radius classes, but with the mean radius of each class ten times that of the corresponding water radius class to cater for larger rates of growth. On freezing, water droplets of radius  $r$  become ice particles of radius  $r/(0.9)^{1/3}$  to allow for the change in density. The growth of ice is determined by the equation

$$r_I \frac{dr_I}{dt} = \sigma_I A (1 + 0.23 Re^{1/2}) + \frac{v_I r_I l_c E}{4 \rho_I}$$

where  $r_I$  = mean radius of ice class,  
 $t$  = time,  
 $\sigma_I$  = supersaturation with respect to ice,  
 $A$  is a function of temperature and pressure derived from

Mason (1971)p.277,

$Re$  = Reynolds number,

$v_I$  = velocity of ice particles having a mean class radius,

$l_c$  = liquid water content in kg per  $m^3$  of air,

$\rho_I$  = density of ice, taken to be  $900 \text{ kg m}^{-3}$ ,

and  $E$  = efficiency factor for water/ice coalescence, assumed to be unity.

The terms on the right hand side are due to sublimation and coalescence with water droplets respectively. Growth of ice takes place at near water saturation until the liquid water content becomes a small fraction of the total water content after which growth occurs at near ice saturation.

The number of ice nuclei active at a temperature  $T^\circ\text{C}$  is assumed to be

$$10^{-2} \exp(-0.6T) \text{ per } m^{-3} \text{ of air}$$

after Fletcher (1962), and since droplet growth is solely by condensation, there is only one nucleus per drop. At each time step the number of ice nuclei activated since the previous time step is calculated and this number of water droplets are taken, in proportion to their numbers in every class, and transferred to ice.

The ice particles, as they grow, acquire a fall speed taken to be that of water droplets (Mason 1971 p.594) and so sweep out a volume of air in which all water drops, assumed to have zero fall speed, coalesce on to the ice particles. The ice particles are assumed to remain within the ascending air parcel. This is a reasonable approximation, since their fall speeds, of say  $1$  to  $2 \text{ ms}^{-1}$ , are a small proportion of the updraught speeds of  $5$ ,  $10$  and  $20 \text{ ms}^{-1}$  used in these experiments. Water droplets for this process are taken in proportion to their numbers in each class with the total mass of each ice class being distributed equally amongst the ice particles in that class.

For a few computer runs water/water coalescence is included by coalescing a specified fraction of water droplets in every class. These droplets coalesce in pairs thereby forming drops of double their masses, and so transferring them into the next highest radius class.



### 3. RESULTS OF ICE NUCLEUS SPECTRUM WITH WATER/ICE COALESCENCE

In all computer runs the cloud base level was at 850 mb with a temperature of  $10^{\circ}\text{C}$ , and except where stated otherwise a maritime spectrum of condensation nuclei was taken containing  $1.23 \times 10^8$  nuclei per kg of air. Since droplet growth is by condensation only, they soon all acquire similar radii, reaching  $20 \mu\text{m}$  in radius at 660 mb by which time the temperature has fallen to  $-1^{\circ}\text{C}$ .

Fig 1 shows the variation in ice and water contents as the air ascends to the  $-40^{\circ}\text{C}$  level. The dotted line gives the combined solid and liquid water content, seen to increase steadily at first then more slowly up to a final value of around 9 g per kg of air. It is given here for an updraught of  $10 \text{ ms}^{-1}$ ; for different updraughts this dotted curve is identical except in the region of rapid glaciation where a temporary increase in the slope of the curve is caused by the change from water to ice saturation.

The full lines show how the ice content increases, 50% glaciation being achieved by  $-31$ ,  $-35$ , and  $-36^{\circ}\text{C}$  in updraughts of 5, 10 and  $20 \text{ ms}^{-1}$  respectively. Liquid water contents, now shown here, are found by subtracting the ice curves from the dotted curve. Above  $10 \text{ ms}^{-1}$  the ice nucleus spectrum dominates the freezing whereas in weaker updraughts, with more time in which to act, the coalescence process quickly takes over and becomes dominant.

It is necessary to point out that water/water coalescence has very little effect on water/ice coalescence. This is because the total mass of water swept out by the ice particles does not alter, the result of water/water coalescence being to decrease droplet numbers at the expense of their masses. Also since water/water coalescence is a much slower process than water/ice coalescence, there is not time for coalesced water drops to acquire terminal velocities comparable with those of ice particles.

### 4. SPLINTERING

As a means of splinter production, hail is assumed to fall from an external source through the cloud at a velocity  $v_H = 10.6(l_H)^{1/5}$  where  $l_H$  is the mass of hail in  $\text{g kg}^{-1}$ . The splintering rate is then

$$n_H \pi r_H^2 v_H n_c \rho / N \quad \text{per kg of air per second.}$$

with  $r_H$ , the radius of hail, taken to be  $1000 \mu\text{m}$   
 $n_H$ , the number of hailstones per kg of air,  
 $n_c$ , the number of water droplets per kg of air,  $\geq 12 \mu\text{m}$  in radius,  
 and  $\rho$ , the density of air.

$N$ , the number of droplets required to produce one splinter is taken, see fig 2, to peak near  $-5^{\circ}\text{C}$  at a value of 150, which lies between the 250 and 100 obtained in laboratory experiments by Mossop (1976) and Goldsmith, Gloster and Hume (1976) respectively. Fig 2 also shows splintering rates from  $1 \text{ g kg}^{-1}$  of hail. All splinters are introduced at a radius of say  $10 \mu\text{m}$ , as the time to grow to this size is very short.

The effect of adding splintering from  $1 \text{ g kg}^{-1}$  of hail is shown in fig 3. At each of three updraught speeds, namely 5, 10 and  $20 \text{ ms}^{-1}$  curve B shows the effects of coalescence and the ice nucleus spectrum whereas in curve A splintering is added. At  $20 \text{ ms}^{-1}$  ice appears in low concentrations sooner with splintering than without, the difference being equivalent to  $3^{\circ}\text{C}$  at  $0.5 \text{ g kg}^{-1}$ . However, the ice nucleus spectrum soon dominates curve A with the result that by the time much of the cloud is ice the curves only differ by about  $\frac{1}{2}^{\circ}\text{C}$ .



For  $10 \text{ ms}^{-1}$  there is a much greater difference, but with the non-splintering curve B, due mainly to the ice nucleus spectrum, catching up somewhat on curve A, dominated by splintering combined with coalescence. The decrease in the slope of curve A as the cloud becomes nearly fully glaciated is due to the supply of water, for coalescence on to ice, running out. With splintering, 50% glaciation is achieved at  $-23^\circ\text{C}$  (430 mb), this being  $12^\circ\text{C}$  warmer than without splintering.

By  $5 \text{ ms}^{-1}$ , with splintering having had longer to act, the gap between the curves has further increased, 50% glaciation occurring at  $-13^\circ\text{C}$  (520 mb) for curve A,  $18^\circ\text{C}$  warmer than without splintering. For both curves the rates at which freezing occurs for the bulk of the cloud are similar.

The time of transit from around the  $-2.5^\circ\text{C}$  level to 50% glaciation (about 5 minutes) is roughly independent of updraught speed, because increasing speed is offset by increasing height at which glaciation occurs.

Fig 4 gives a breakdown of the effects of splintering and coalescence for an updraught of  $10 \text{ ms}^{-1}$ . In curve D, for the ice nucleus spectrum alone, significant amounts of ice are not produced until after  $-30^\circ\text{C}$ , but once they occur glaciation becomes rapid; at  $-33^\circ\text{C}$  there is  $1 \text{ g kg}^{-1}$  of ice and by  $-37^\circ\text{C}$  glaciation is complete. Curve C shows that the effect of coalescence is to make freezing occur more rapidly at concentrations of ice less than  $1 \text{ g kg}^{-1}$ . With splintering added, curve B shows that low ice concentrations are formed significantly earlier than with the ice nucleus spectrum alone, but that the time at which the cloud becomes fully glaciated is unaltered. Curve A shows that only when the combined effects of splintering and coalescence are included, does the bulk of the cloud become glaciated significantly earlier than with the ice nucleus spectrum acting alone.

Splinters are also produced in the water/ice coalescence process. This is termed resplintering, occurring at a rate given by

$$\sum_I \frac{n_I \pi r_I^2 v_I n_c \rho}{N} \quad \text{per kg of air per second.}$$

with  $n_I$ , the number of ice particles per kg of air in ice class I,

and  $\sum_I$ , the sum over all ice radius classes.

The effect of adding resplintering is to produce curves negligibly different from those with splintering. This is reasonable, since only when the concentration of cloud ice exceeds that of hail, will resplintering exceed splintering. These small secondary splinters will then remove much less water than the now larger far more numerous splinters produced around the peak rate at  $-5^\circ\text{C}$ .

## 5. VARYING THE HAIL CONCENTRATION

As the hail concentration determines the splintering rate, it is instructive to see what happens when different hail concentrations are taken. Fig 5 shows the results for 2.0, 1.0, 0.5 and  $0.1 \text{ g kg}^{-1}$  of hail falling through an updraught of  $10 \text{ ms}^{-1}$ . Also shown is the curve with hail not present, that is with freezing determined by coalescence and the ice nucleus spectrum. The cloud becomes 50% glaciated by  $-20$ ,  $-23$ ,  $-25$ ,  $-30$  and  $-35^\circ\text{C}$  for 2.0, 1.0, 0.5, 0.1 and  $0.0 \text{ g kg}^{-1}$  of hail respectively. Since it was stated in the previous section that the cloud took about 5 minutes to become 50% glaciated after reaching the  $-2.5^\circ\text{C}$  level, it is interesting to note that the corresponding times for 2.0, 1.0, 0.5 and  $0.1 \text{ g kg}^{-1}$  of hail are 270, 300, 330 and 390 seconds. By comparing the temperatures at which freezing occurs with those for curves A in fig 3 it is seen that the model is more sensitive to changes in updraught speed than in hail concentration.



Although coalescence amongst water droplets has been shown to have very little effect with splintering excluded, it is necessary to see whether it has any effect with splintering present. A computer run was performed for  $1 \text{ g kg}^{-1}$  of hail falling through an updraught of  $10 \text{ ms}^{-1}$ ; the results of coalescing  $10^{-3}$  of the water droplets per second, a value based on other numerical models (eg. Miller and Pearce 1974), is given by the dotted line in fig 5. There is a small delay, about 5 seconds in the glaciation, this being a consequence of the reduction in the numbers of water droplets leading to less splinters being produced.

## 6. VARYING THE SPECTRUM OF CONDENSATION NUCLEI

In fig 6 the result is seen at  $10 \text{ ms}^{-1}$  of increasing the number of condensation nuclei to continental values. Curves labelled with a 1, 2 or 3 correspond to  $1.23 \times 10^8$ ,  $4.0 \times 10^8$ , or  $9.0 \times 10^8$  nuclei per kg of air. Based on the work of Mossop (1976) splintering is allowed to occur when droplets radii exceed  $12 \mu\text{m}$ . Curves B, with splintering excluded, show that an increase in droplet numbers delays the freezing process. This is because in this case freezing is due largely to the ice nucleus spectrum; more droplets require more ice nuclei to be activated, hence the delay.

In curves A, with splintering allowed, an increase in droplet numbers initially leads to more splinters being produced with the result that glaciation sets in earlier. However, as droplet numbers continue to increase, they will compete more for the same amount of water made available by moist adiabatic ascent. This will lead to slower growth so that at some stage their radii will fail to reach  $12 \mu\text{m}$  causing splintering to stop with the result that freezing is much delayed, 50% glaciation occurring at  $-20$  and  $-37^\circ\text{C}$  for  $4 \times 10^8$  and  $9 \times 10^8$  condensation nuclei respectively.

This sudden cut off in splintering is artificial in that in the model all water droplets have nearly equal radii. In real clouds the spectrum is much broader so that the change to a more continental cumulus cloud will result in a smoother decrease in the temperature of glaciation, as compared with the model.

## 7. CONCLUSIONS

Except at an updraught of  $20 \text{ ms}^{-1}$  where the ice nucleus spectrum dominates the freezing process, the effect of splintering is to cause freezing to occur at a significantly higher temperature than with just coalescence and the ice nucleus spectrum acting. Provided some hail is present, the temperature at which glaciation occurs is closely determined by the updraught speed, the hail concentration being less critical. For 5, 10 and  $20 \text{ ms}^{-1}$  updraught, 50% of the cloud is glaciated at  $-13$ ,  $-23$  and  $-36^\circ\text{C}$  respectively with  $1 \text{ g kg}^{-1}$  of hail falling through the cloud. As a reasonable guide the splintering-coalescence process takes some 5 minutes to glaciate the cloud once it has reached the  $-2.5^\circ\text{C}$  level.

The results suggest that in real clouds splintering is likely to be important when the updraught velocity is less than  $20 \text{ ms}^{-1}$ . This is especially likely to occur near the cloud boundaries.



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FIG. 1

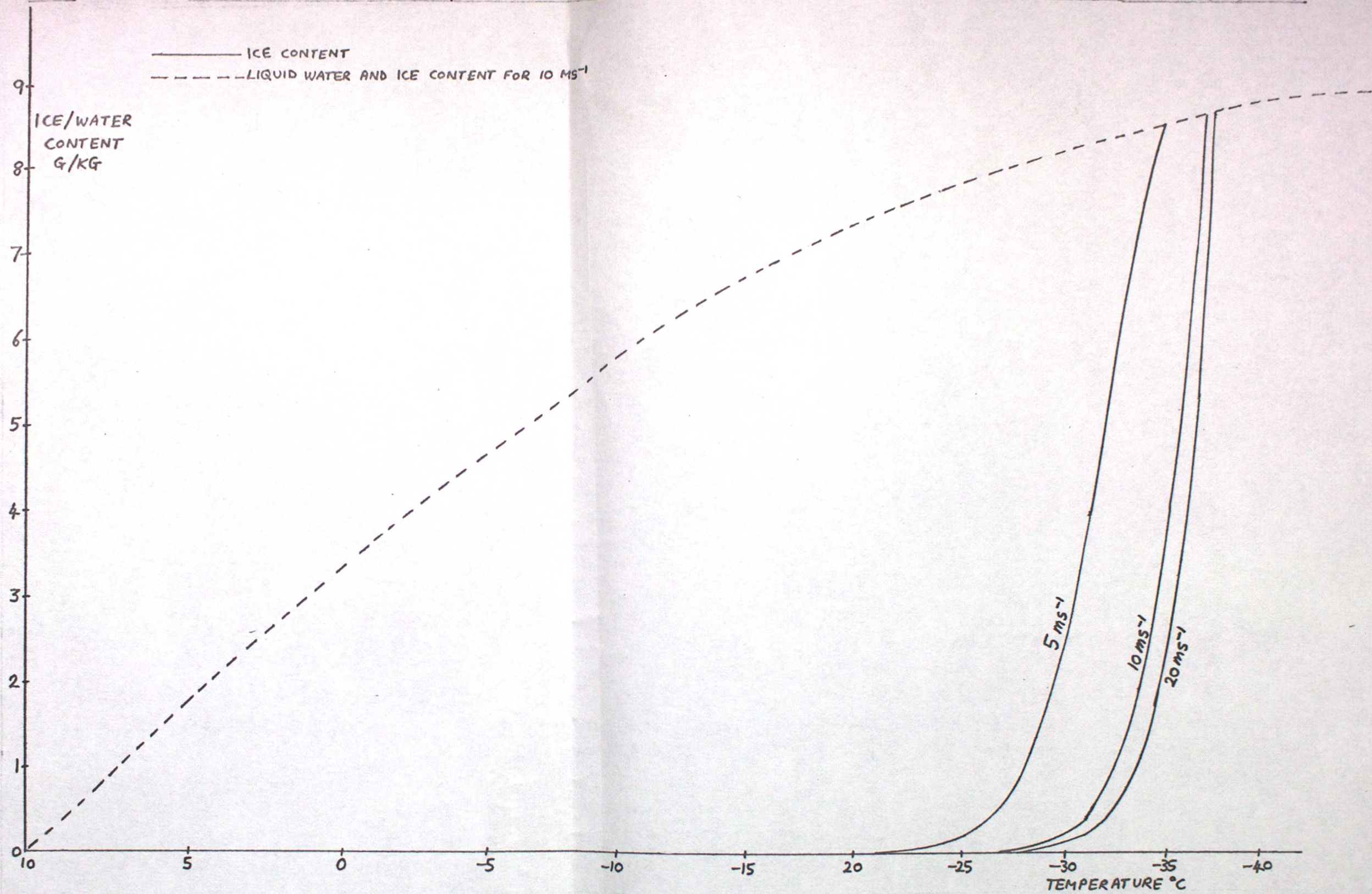
FREEZING BY ICE NUCLEUS SPECTRUM AND WATER/ICE COALESCENCE FOR UPDRAUGHTS OF 5, 10, 20  $\text{ms}^{-1}$ 



FIG. 2

## SPLINTERING AS A FUNCTION OF TEMPERATURE

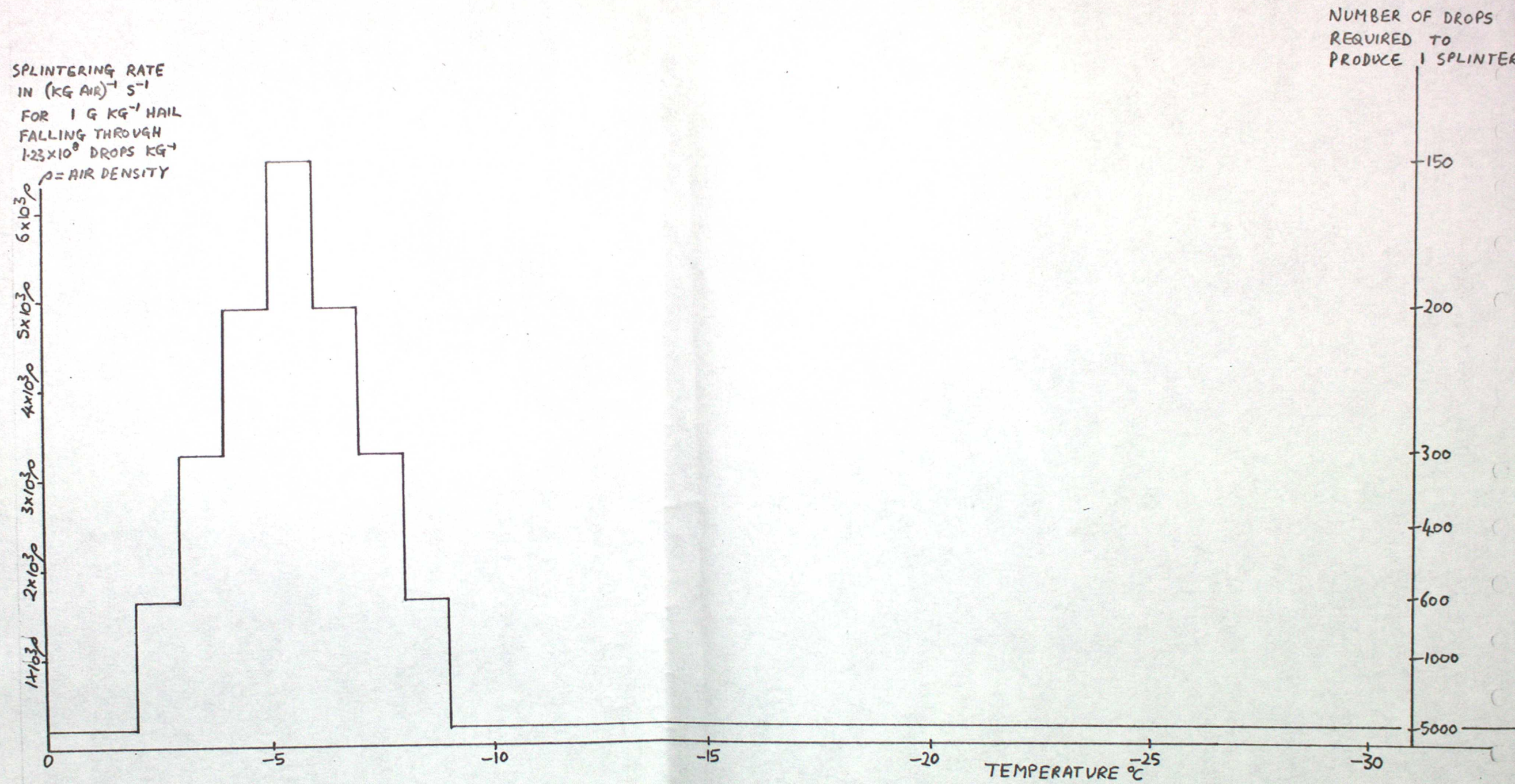




FIG 3 THE EFFECT OF SPLINTERING  
ON THE GROWTH OF ICE FOR  
UPDRAUGHTS OF 5, 10, 20  $\text{ms}^{-1}$

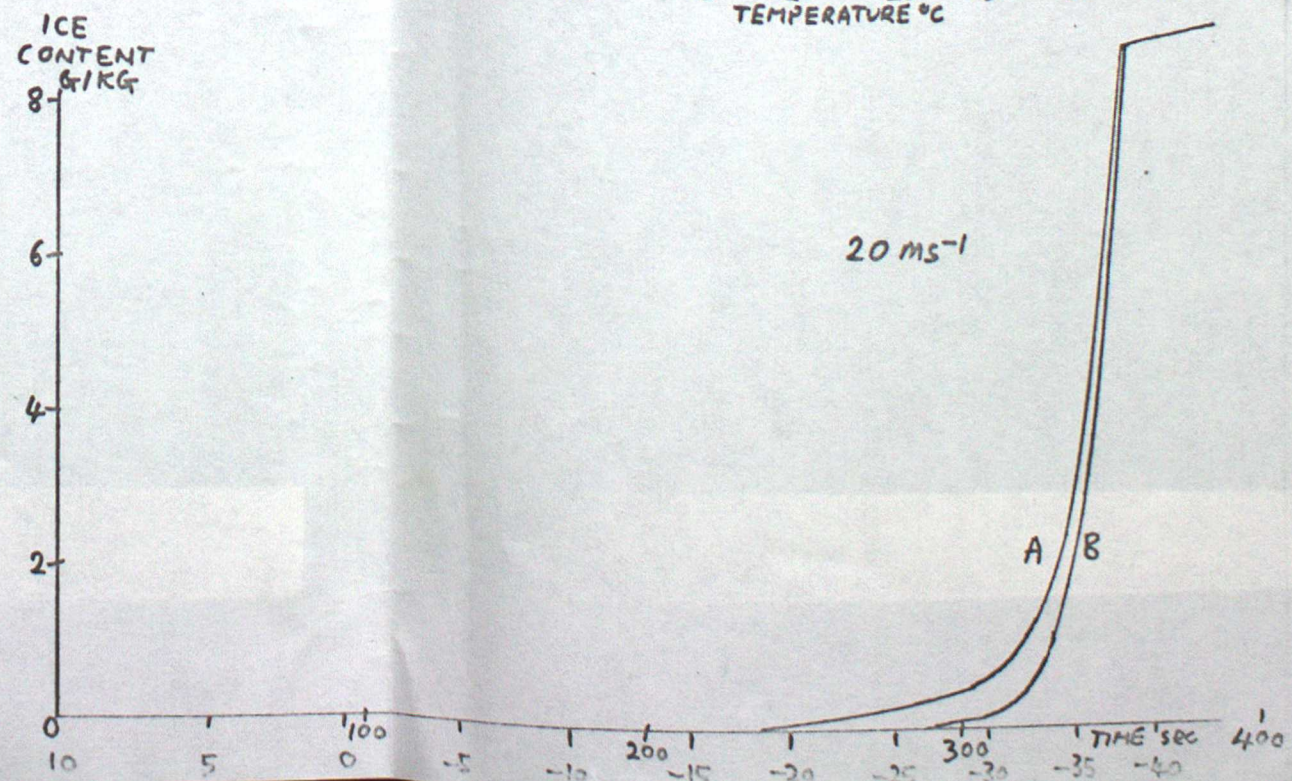
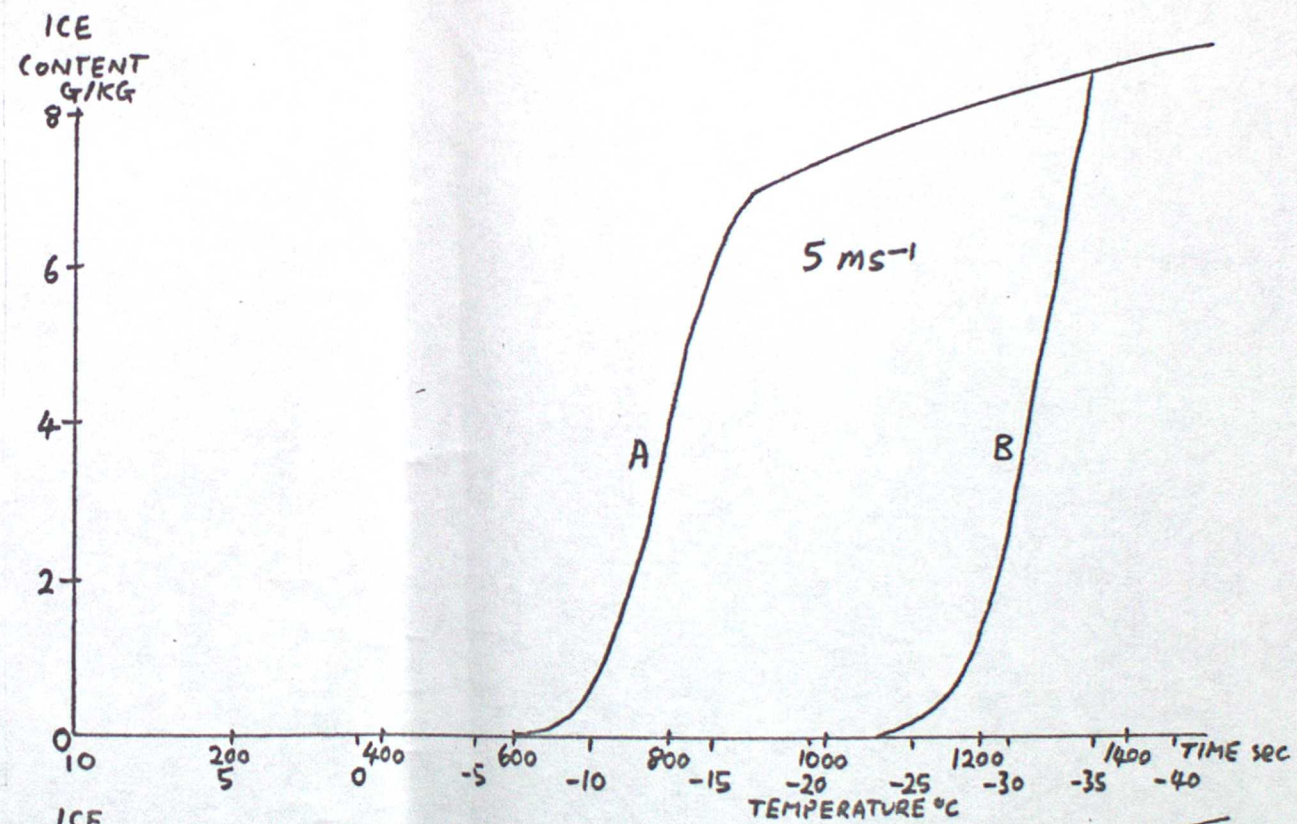
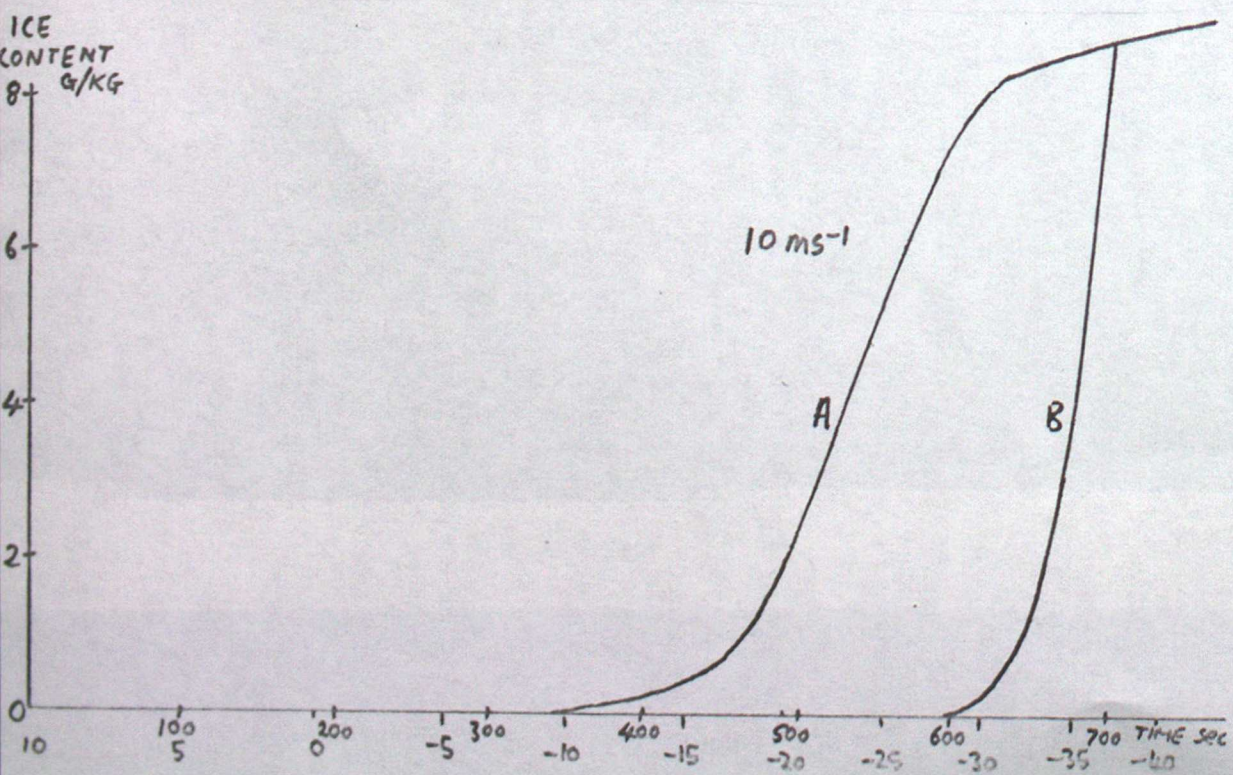
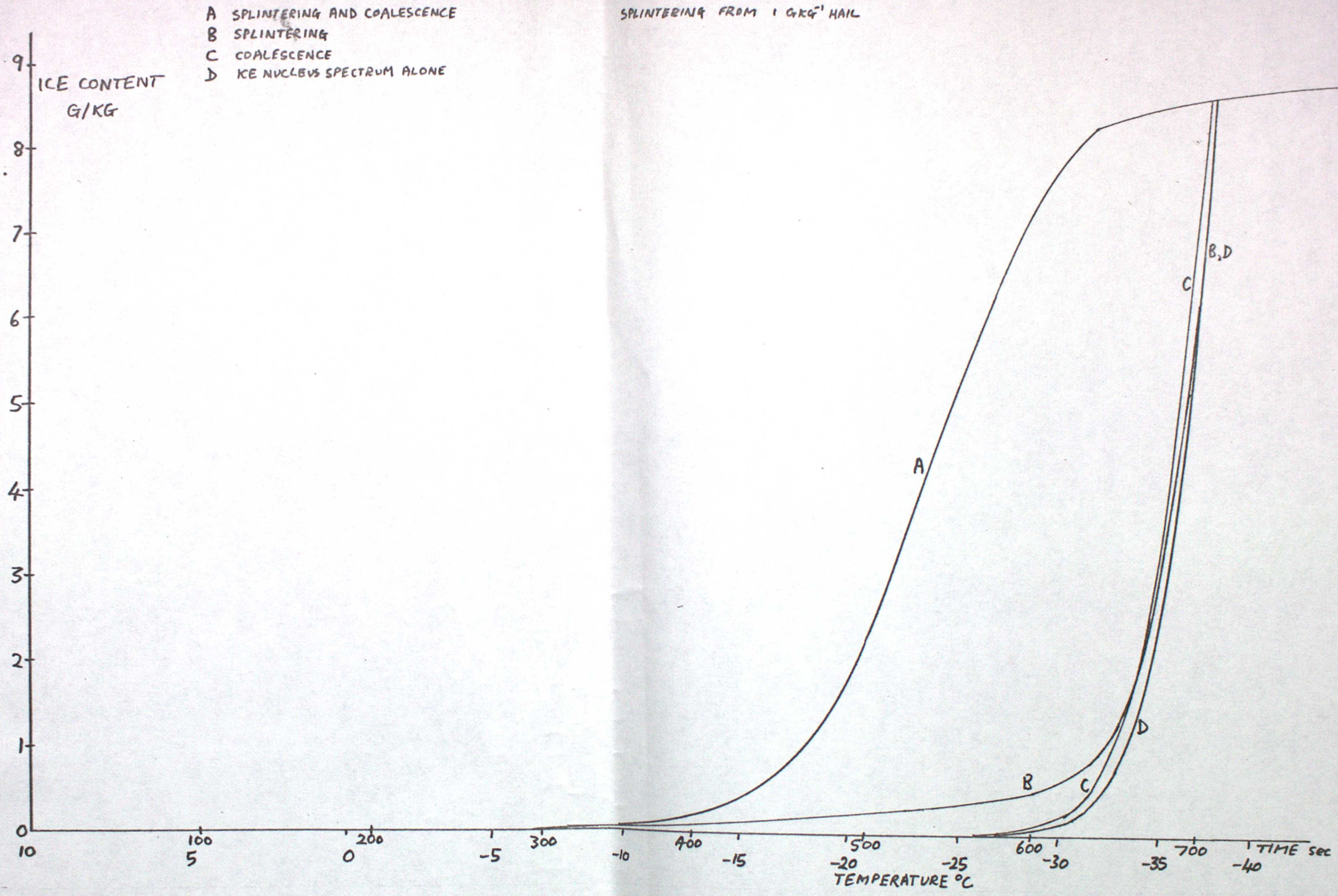




FIG. 4

GROWTH OF ICE IN AN. V. DRAUGHT OF 10 MS.

SPLINTERING FROM 1 GKG<sup>-1</sup> HAIL





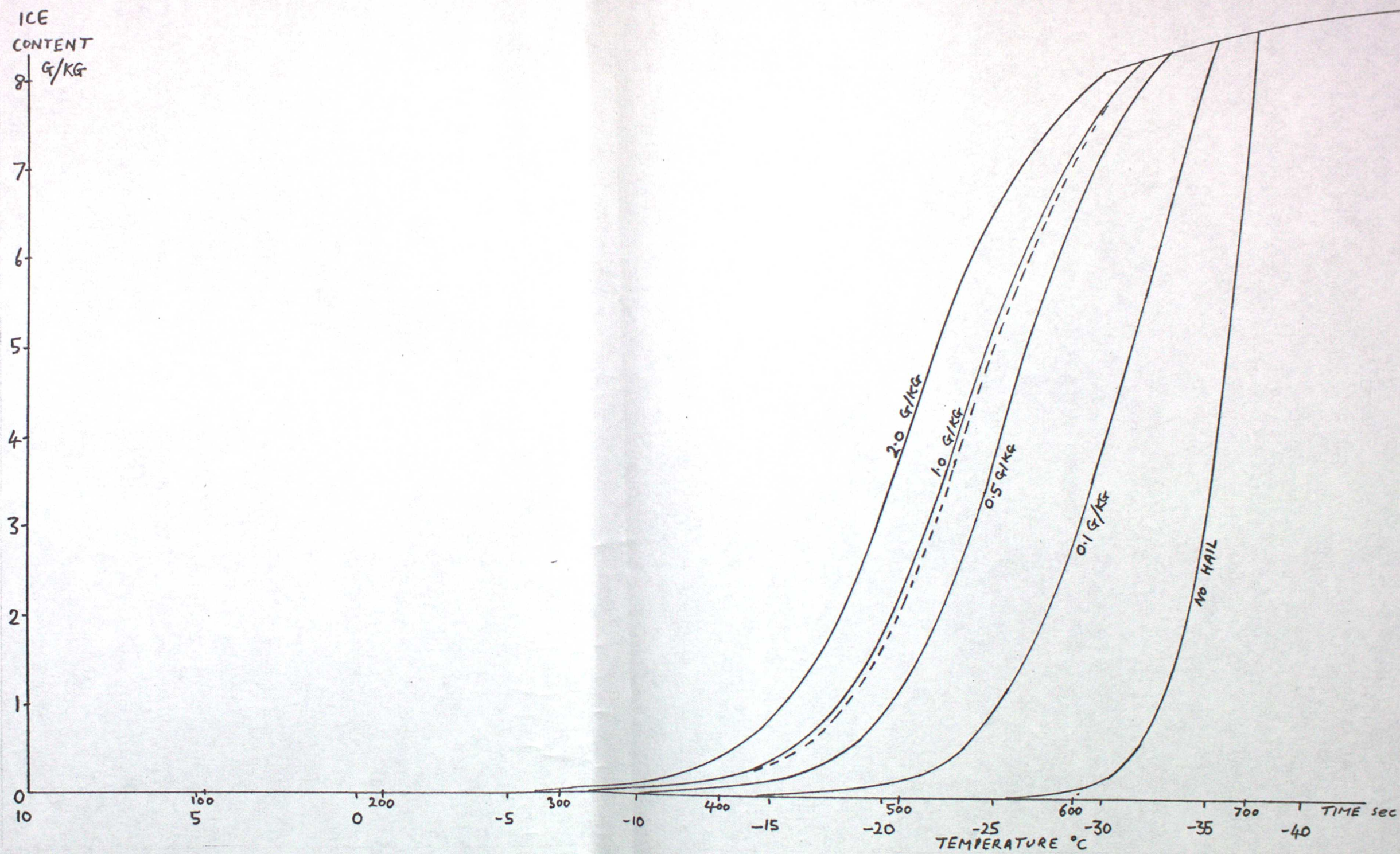
--- WATER COALESCENCE,  $10^{-3} \text{ S}^{-1}$ , ON THE  $1 \text{ G/KG}$  CURVE



FIG 6

VARYING THE CONDENSATION NUCLEUS SPECTRUM FOR AN UPDRAUGHT OF  $10 \text{ MS}^{-1}$ 