# ADIABATIC STORAGE TRIALS AS AN EXPERIMENTAL TOOL FOR PREDICTING STORABILITY IN ARTIFICIAL CONTROLLED ATMOSPHERES.

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## ABSTRACT

An experimental apparatus designed to follow autocatalytic phenomena which cause production of even very low quantities of heat (down to approx 0.07 W) is described. Such phenomena may occur inside industrial grain or oil seed storage bins, causing very damaging hot spots.

The results obtained with the described instrumentation thus permit to predict the behaviour of the stored products and their storability in various practical situations.

The behaviour of sunflower seeds at various moisture contents, initial temperatures and interstitial gas composition was studied in the apparatus. The existence of autocatalytic phenomena was observed. They increased in function of the level of the initial moisture content of grain, of the initial temperature and the oxygen content in the interstitial atmospheres.

Even in nearly complete anoxia (residual oxygen lower than 0.1% vol) heat development in the sunflower seed mass was observed. However the induction time was found to be significantly longer in this condition as compared to the corresponding tests in air.

## INTRODUCTION

The argument faced in the present work is to study and to simulate the thermal behaviour of grains stored in a silo.

It is well known that the axial part of a silo the grain is in quasi-adiabatic conditions owing to the low thermal conductivity of the surrounding grains. The heat generated by the grain, even at very low rate, can increase the temperature in a sensible manner. At this increased temperature the heat generation rate increases so that an autocatalytic process can be activated, able to produce hot spots in the bulk of grain.

In order to study the conditions of hot spot generation, an experimental apparatus has been designed able to measure heat production rate of very low intensity.

The induction time and the heat production of sunflower seeds at various moisture contents, initial temperatures and interstitial gas compositions has been measured with the apparatus.These values are compared to the heat lost by the bulk of the seeds at steady state: only if heat production is equal to heat loss a steady state condition is possible. On this basis a simple storability criterium may be considered to predict the possibility of hot spot generation.

## EXPERIMENTAL APPARATUS

The experimental apparatus is a microsilo with a double PVC wall with an air interspace. (Fig. 1).

The internal diameter is 20 cm, the height is 50 cm, the capacity is 5 kg of sunflower seeds.

The microsilo is immersed in a thermostatic stired water bath having a controlled and homogeneous temperature: the difference in temperature at different positions and/or different time is less than 0.1°C. The bath has an external 3 cm thick rock wool thermal insulation and is heated by four electrical radiators of 85 W and 0.3 $m^2$ of surface each. An air flow is supplied at the bottom of the bath through a perforated tube in order to increase the heat exchange between radiator-water and water-microsilo and to homogenize the temperature.

Two temperature probes (calibrated resistances) are placed at the same height on the wall of the microsilo: the first ($T_1$) on the internal wall in contact with the stored product, the second ($T_2$) on the external wall, in contact with the bath. When the internal wall

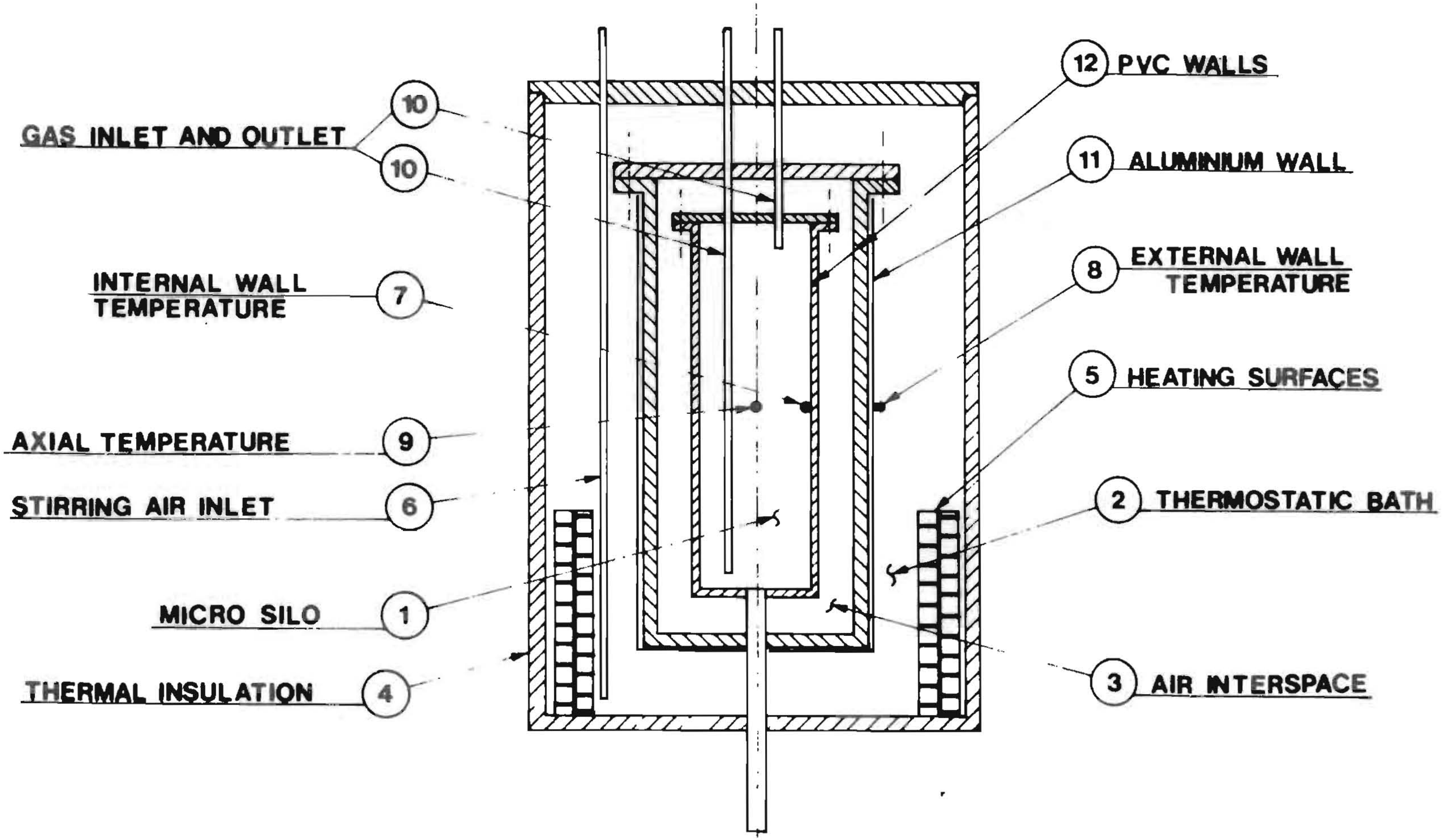


Fig.1. Experimental apparatus for adiabatic storage tests.

temperature $T_1$ is greater than $T_2$, the temperature control system actions the electrical heating until equalization of the two temperatures is reached.

A third temperature probe is placed in the centre of the microsilo in order to measure the bulk temperature.

Three identical instruments with the above mentioned characteristics have been built in order to test at the same time the same product in different experimental conditions.

CALIBRATION OF THE APPARATUS

The principle of the set up is to maintain at every time the temperature of the bath at the same value as the temperature of the stored product, in order to achieve adiabatic conditions.

To approach these conditions we tried to minimize the heat loss by the product ($Q_1$) and the heat gained by the product ($Q_2$). The heat lost by the product is:

$$Q_1 = \alpha S(T_1 - T_2)$$

where S is the microsilo wall area and $\alpha$ is the thermal conductivity trough the walls. We tried to minimize $\alpha$ by the two PVC walls with air interspace, and to minimize $(T_1 - T_2)$ by the temperature control. Nevertheless $\alpha$ and $(T_1 - T_2)$ are not equal to zero so that $Q_1$ is equal to the heat conducted through the microsilo walls with a temperature gradient less or equal to the sensibility of the temperature control. The sensibility is equal to 0.1°C. The value of $Q_1$ was measured by calibration tests performed with electrical heating sources of known values.

The heat gained by the product is:

$$Q_2 = \alpha S(T_2 - T_1)$$

During the operation of the apparatus the thermal control system heats the bath until the temperature $T_2$ becomes equal to $T_1$. But the heating of the bath may generate temperature gradients so that at the time when heating stops some parts of the bath may have a temperature greater than $T_2 = T_1$. The water of these parts mixes with the bulk and a mean temperature $T_2' = T_2 + \Delta T$ greater than the product temperature $T_1$ may build up in the bath (overshot), and heat is gained by the product.

The above mentioned reduction of the thermal conductivity to minimize $Q_1$, contributes to minimize $Q_2$ too. To reduce $\Delta T$ the bath is homogenized by air bubbling; besides heat exhange is enhanced by the large area of the heating surface. In this way we obtained values of $\Delta T$ smaller than 0.1°C in the bath.

$Q_1$ and $Q_2$ were measured by calibration tests performed by operating the apparatus with simulation of heat generation by a 0.82 $\Omega$ electrical resistance supplied by direct current of measured intensity. The resistance was placed in a 5 kg wheat bulk in the microsilo, having a very low moisture content (8%) in order to be sure that the heat generated by the product is zero.

The product temperature was measured as function of time at a 0.03, 0.07 and 0.20 W electrical power supply (Fig.2). The temperature of the product ($T_3 \simeq T_1$) is constant at the lowest power supplied (0.03 W), it is a straight line function of the time at the other values of the power supplied. This behaviour is in agreement with the hypothesis of quasi - adiabatic conditions with a constant power supply. The heat adsorbed by the product was calculated by means of the measured temperature increase using a value of 0.5 Kcal/kg°C as specific heat of the grain. The values of the heat absorbed by the grain are 0, 0.04 and 0.23W, when the values of the heat supply are respectively 0.03, 0.07 and 0.20 W.

It apperas that the sensibility of the thermal control system is about 0.03 W. In other words at a very low heat production rate the system is not perfectly adiabatic and loses about 0.03 W ($Q_1$ = 0.03 W), at high values of heat production rate the tested product gains from the sorrounding about 0.03 W ($Q_2$ = 0.03 W).

In conclusion the experimental apparatus appears to be able to study and to measure heat production rates in the field of 0.07 - 0.20 W with a ± 0.03 W error.

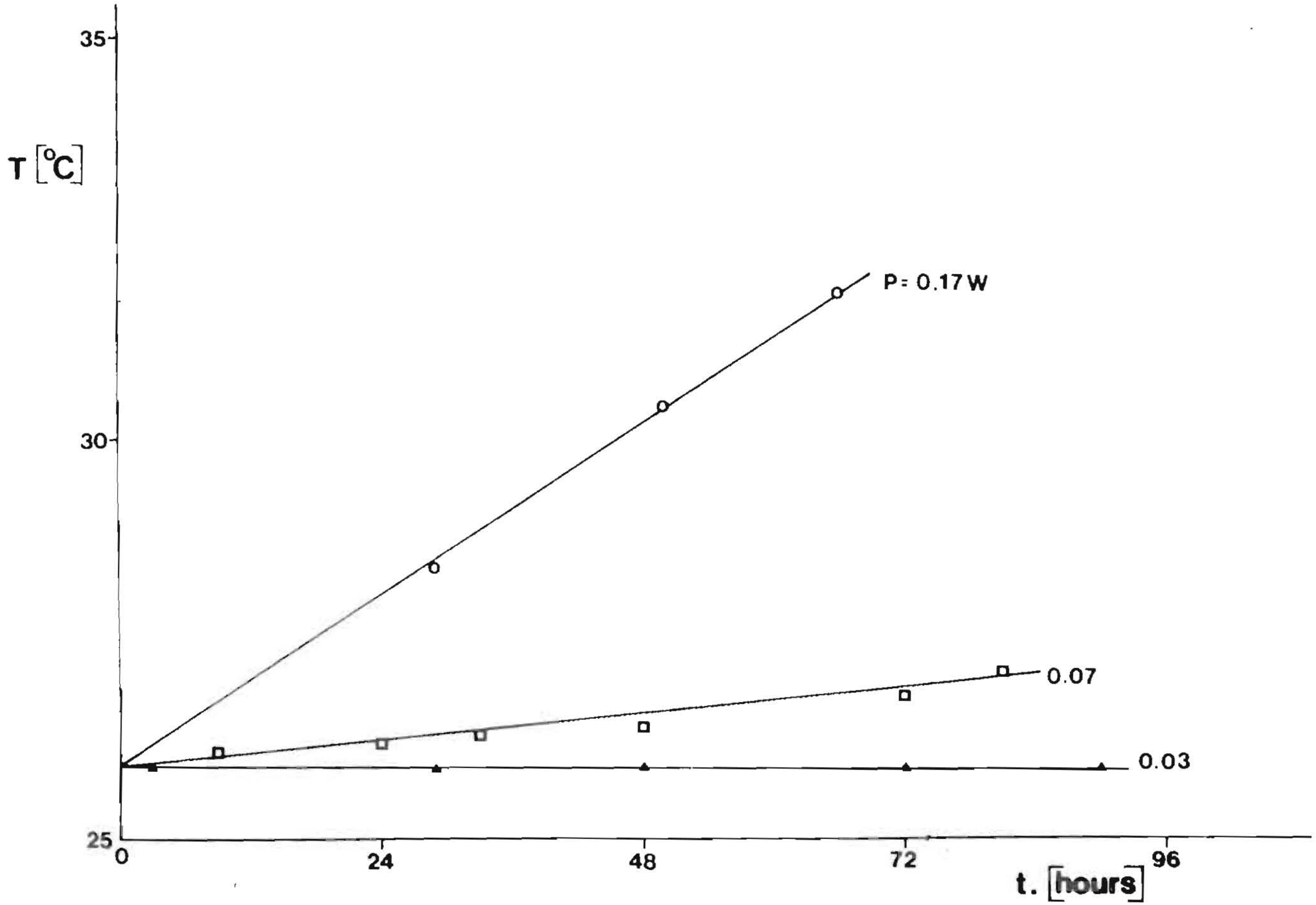


Fig.2. Calibration tests. Product temperature versus time at different values of the external power supplied (P).

EXPERIMENTAL RESULTS

The apparatus was used to study the behaviour of third grade sunflower seeds.

The moisture content of some lots of the seeds was increased by a slow addition of water in order to have three lots of products to be tested with 8.4, 9.3 and 12.6% moisture content. The time necessary for moistening was about 24 hours.

Two different preservation systems were tested:

(1) Controlled atmosphere (ACT): the interstitial atmosphere of the seeds was pure nitrogen (the residual oxygen content was 0.05% vol) the microsilo was purged with UPP nitrogen and maintained at a slight positive pressure for the whole test time.

(2) Confined atmosphere (ACF): the interstitial atmosphere of the seeds was nitrogen with a decreasing oxygen content in function of the time owing to the activity of the seeds contained in the gas tight microsilo.

Such behaviour is shown in fig. 3 where the decreasing oxygen content is shown simultaneously with the increasing temperature.

In fig. 4 the results of the ACF tests at 26°C and 21°C initial temperature are shown: the seed temperature versus time sharply increases after an induction time $t_i$ that increases with decreasing moisture content of the seed. The time $t_i$ is approx. 0 at 12.3% moisture content, approx. 2 days for 9.3% m.c., approx. 5 days for 8.4% m.c., at 26°C initial temperature.

At 21°C a very different behaviour appears and the seed at 9.3% m.c. does not show any increase in temperature for the whole test time (about 22 days).

In fig. 5 the results of the ACT tests at 26°C initial temperature are shown: the seed temperature increases in function of time in about the same way as in the ACF tests, but the induction times are much longer: $t_i$ is greater than the test duration (100 days) at 8.4% m.c.; it is approx. 25 days at 9.3% m.c., and approx. 15 days at 12.6% m.c.

The comparison between ACF and ACT the preservation technologies is shown in fig.6 for sunflower seeds 9.3% m.c.

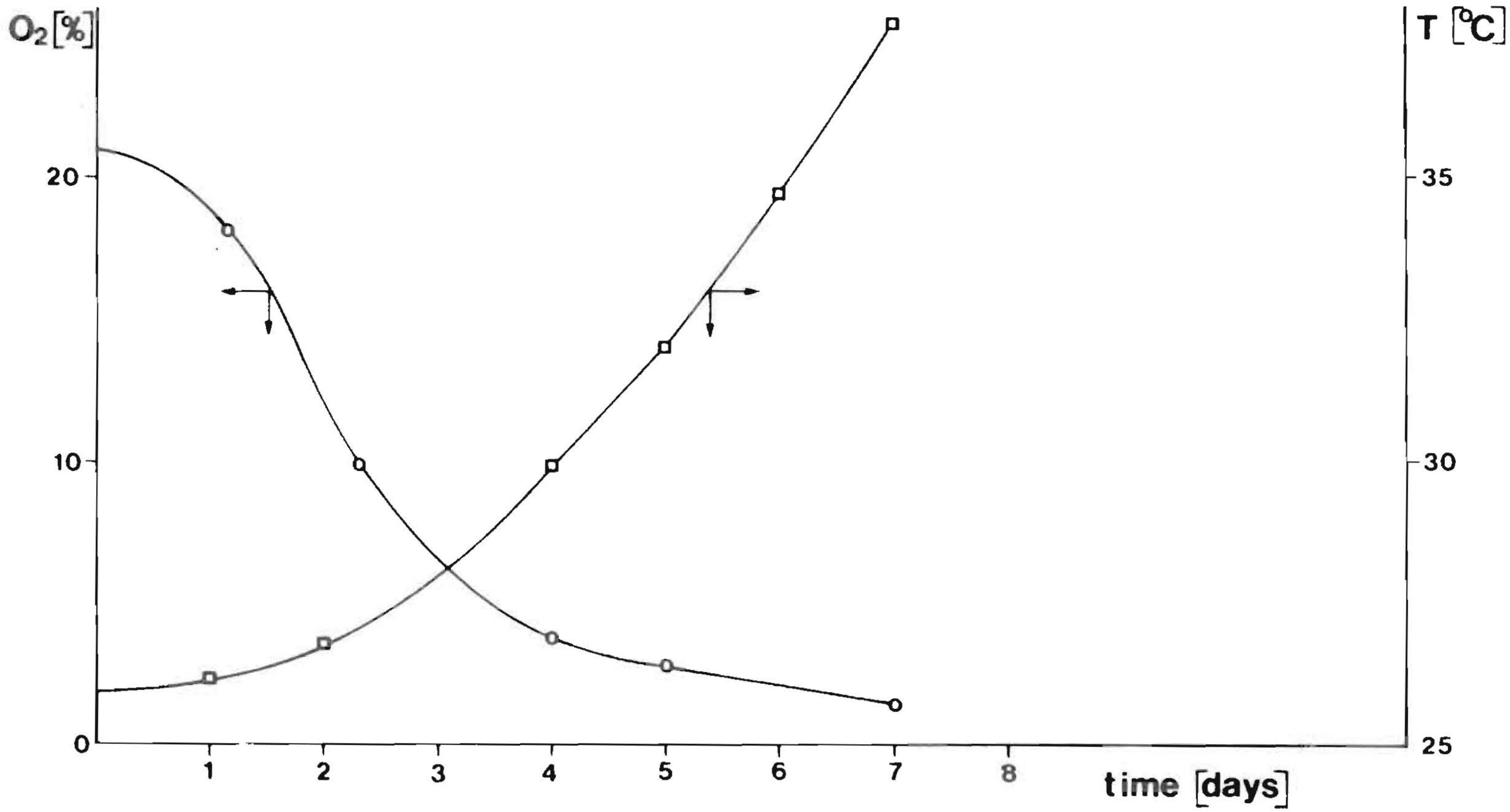


Fig.3. Confined Atmosphere tests. Temperature and oxygen content versus time for sunflower seeds at 9.3% moisture content.

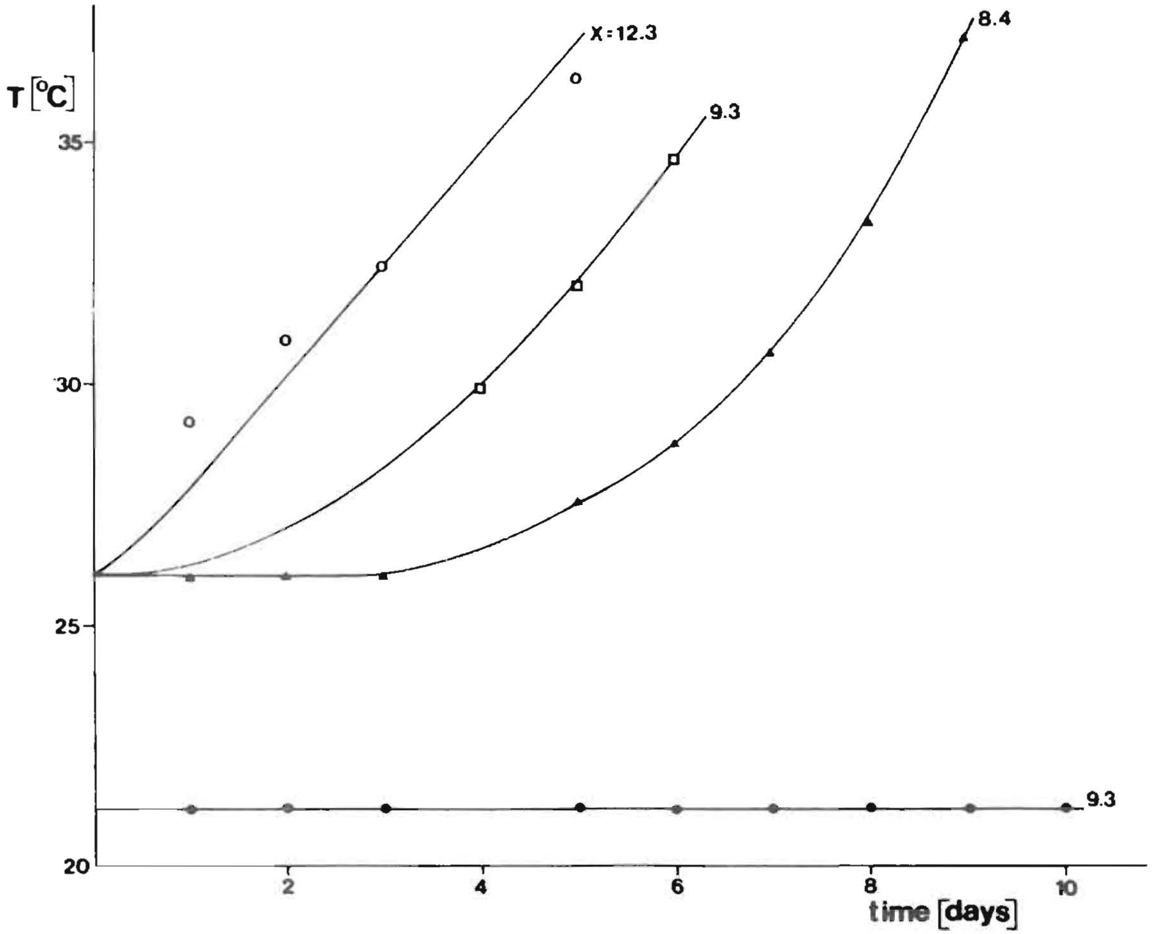


Fig.4. Confined Atmosphere tests. Temperature versus time for sunflower seeds at different moisture contents (X).

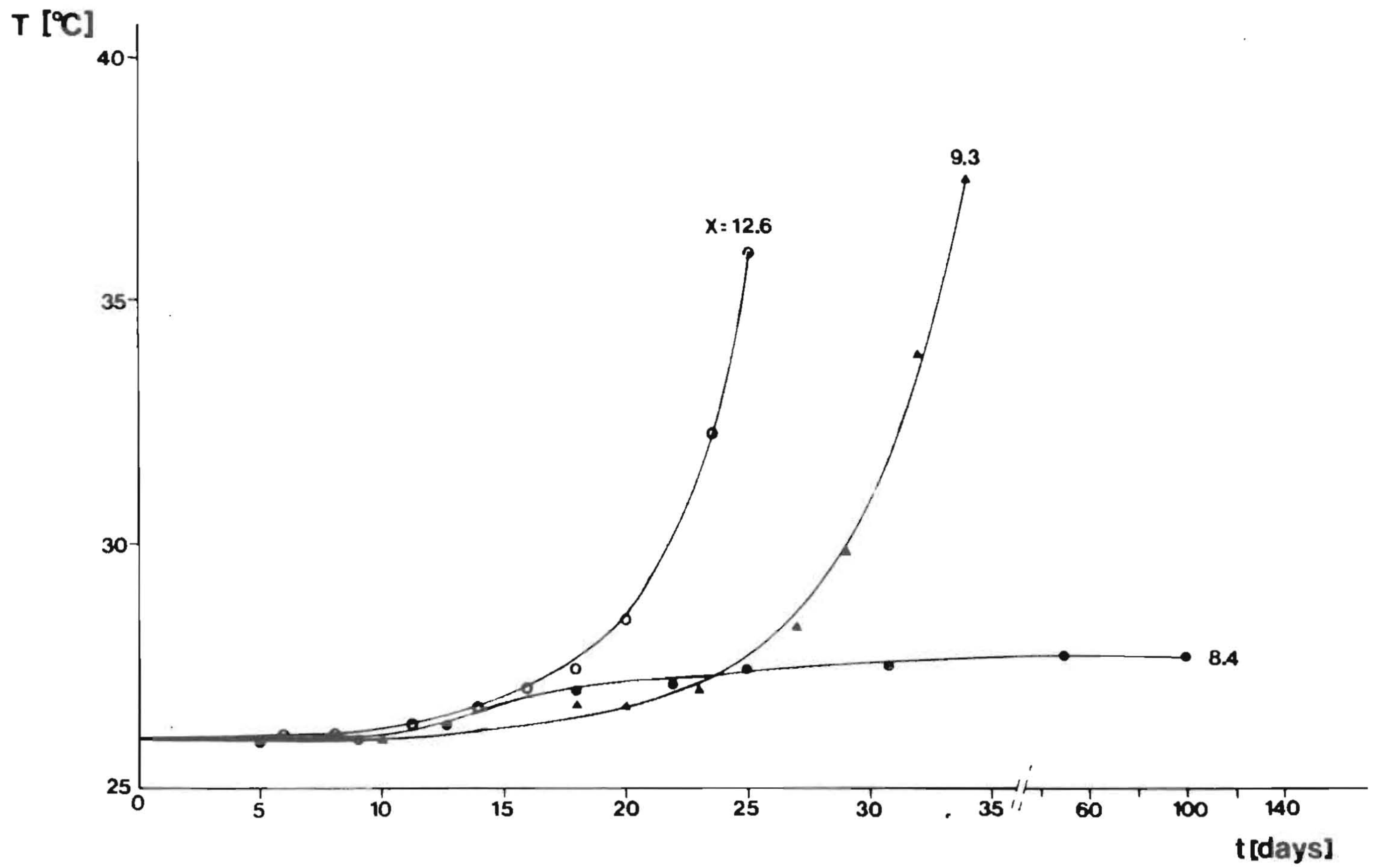


Fig.5. Controlled Atmosphere tests. Temperature versus time for sunflower seeds at different moisture contents (X).

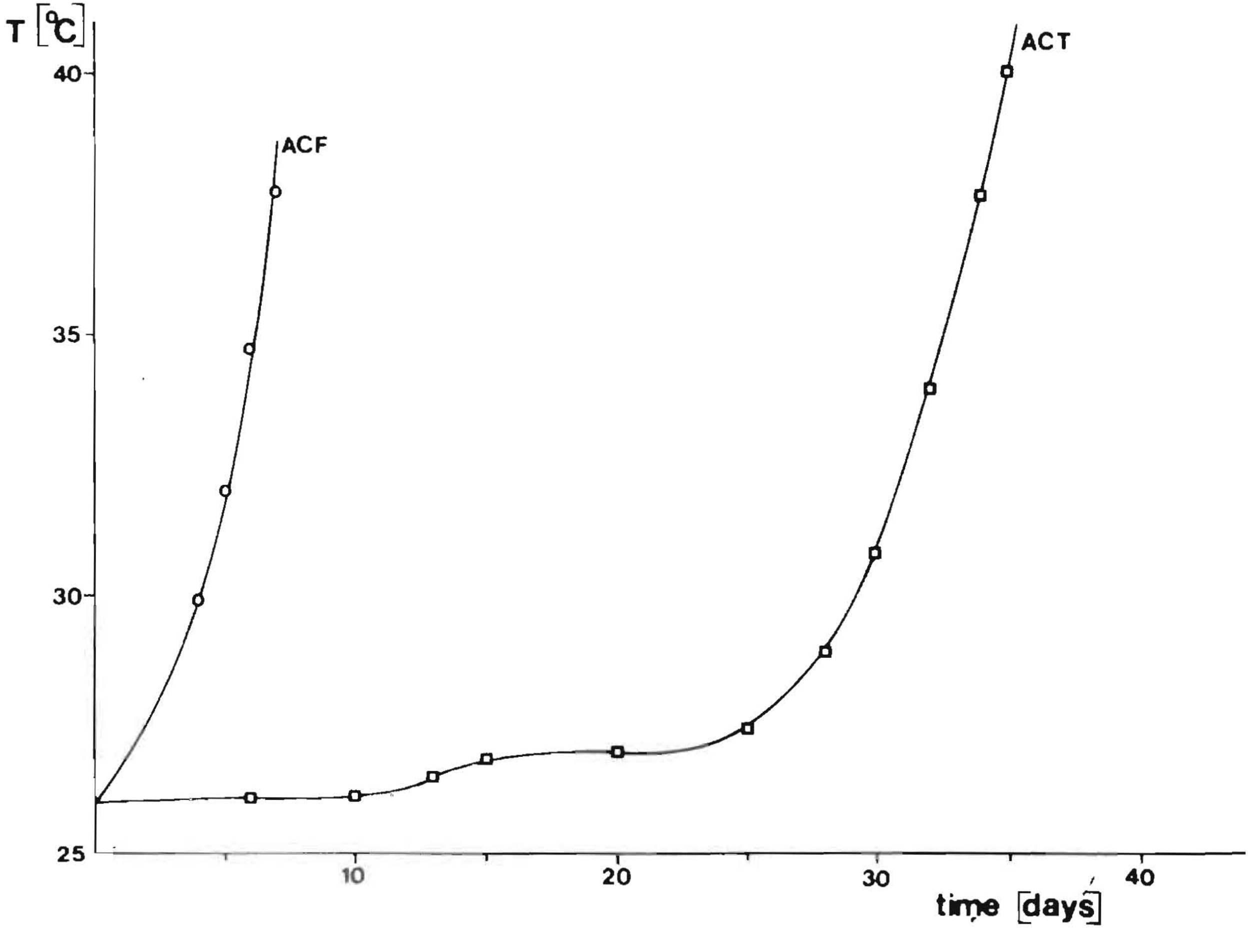


Fig.6. Comparison between confined (ACF) and Controlled (ACT) atmosphere preservation of sunflower seeds at 9.3% moisture content.

DISCUSSION OF THE RESULTS

The results obtained allow to calculate the heat generation rate $S_g$ at the tested conditions.

In adiabatic conditions:

$$S_g = C_p \frac{dT}{dt} \qquad (1)$$

where $S_g$ is measured as cal/(h x kg) and $C_p$ is the specific heat of sunflower seeds assumed to be equal to 500 cal/kg °C.

The temperature T and the gradient dT/dt measured during the described tests change in function of time. The gradient values may be assumed to be function of temperature alone, so that $S_g$, as function of T may be calculate. The calculated values of $S_g$ for 9.3% m.c. sunflower seed preserved in ACF and ACT are shown in figure 7. These values, together with the induction times are the fundamental parameters required to predict storability of a product in a given condition.

An exact prediction may be possible only with a detailed and complicated model. But if we need only a rough storability prediction we can utilize a simple model, here described, that allows anyhow to evaluate the influence of the more important variables:

- product characteristics, summarized by the $S_g = f(T)$ function
- silo diameter (2R)
- ambient temperature ($T_o$)
- preservation technology (ACF or ACT).

The model examines whether the system may attain a steady state condition. If it is not possible, the system has the trend to generate hot spots in oposite case no heating will occur.

The steady state conditions for a cylindrical homogeneous system having a thermal conductivity K and a heat generation rate $S_g$ are represented by the following temperature distribution (Bird et al. 1960):

$$T - T_o = \frac{S_g R^2}{4K}\left[1 - \left(\frac{r}{R}\right)^2\right] \qquad (2)$$

where the sunflower seed thermal conductivity K is assumed to be equal to 1.44 cal/cm.h.°C, T is the temperature at a given distance r from the axis of the cylinder, $T_o$ is the external temperature corresponding to the cylinder radius R, $S_g$ is the heat generation rate at each particular temperature T. The maximum temperature occurs at the axis of the cylinder (r = 0):

$$T_{max} = T_o + \frac{S_g R^2}{4K} \qquad (3)$$

At steady state the heat generation rate is equal to the heat dissipation rate in every position and every time. So that from equation (3) we can calculate the steady state heat dissipation rate ($S_d = S_g$) as function of the maximum temperature $T = T_{max}$

$$S_d = \frac{4K}{R^2}(T_{max} - T_o) \qquad (4)$$

In other words steady state conditions are possible if the heat dissipation rate, indicated by equation (4), may equalize the heat generation rate measured in the present work for sunflower seed and having the temperature dependence shown in figure 7:

$$S_g = f(T_{max}) \qquad (5)$$

From a graphic point of view steady state is possible if the straight line represented by equation (4) intercepts the curve represented by equation (5).

This analysis is performed in figure 7 for 9.3% m.c. sunflower seed for the ACF and ACT preservation technologies. The diameter of the silo is assumed equal to 1 m; the external sorrounding temperature is assumed to be equal to 23, 25 and 27°C for the three conditions

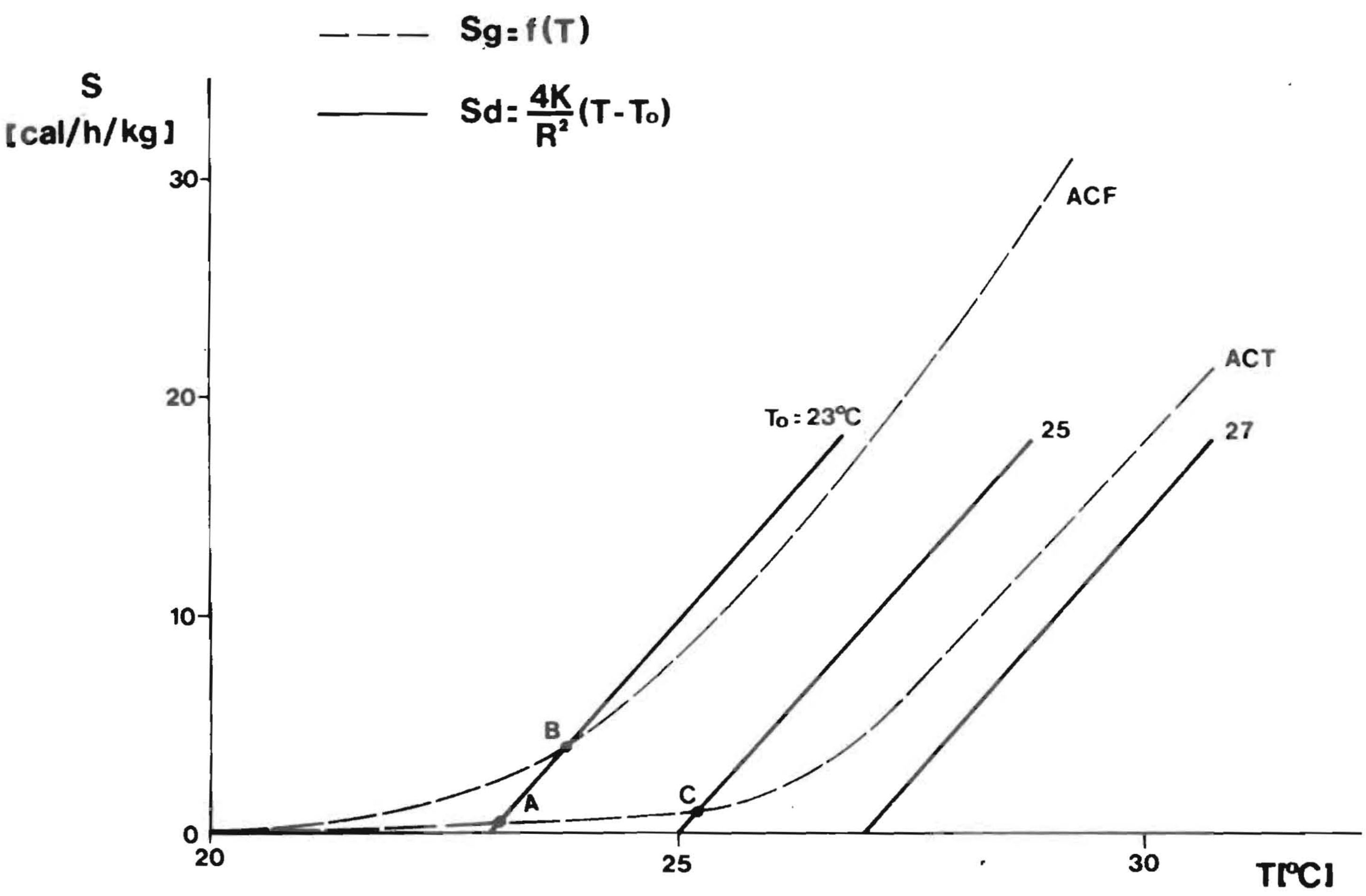


Fig.7. Heat generation rate ($S_g$) and heat dissipation rate ($S_d$), function of the product temperature of sunflower seeds at 9.3% moisture content at different surrounding temperatures $T_o$ and 1 m silo diameter.

examined.

When $T_o$ is equal to 23°C the straight line (4) intercepts the ACF and ACT curves (5) in the A and B points. The system has the trend to attain steady state condition for both the ACF and ACT technologies with the maximum temperatures equal to the coordinates of the A and B points.

When $T_o$ is equal to 25°C the straight line (4) intercepts the ACT curve only (point C). It means that in controlled atmosphere the system has the trend to attain a steady state, in confined atmosphere it has not.

At last when $T_o$ is equal to 27°C it is impossible to equalize the heat generation rate to the heat dissipation rate.

This analysis is performed again in figure 8 with a constant external sorrounding temperature $T_o$ = 25°C and three values of the silo diameter: 0.6, 1 and 2 m.

The system appears stable (steady state possible) for both ACF and ACT conditions at 0.6 m diameter (points A' and B'); it is stable in ACT conditions only at 1 m silo diameter (point C); it is unstable in both cases when the silo diameter is greater than about 2 m.

The extension of this analysis allows to determine the trend of the system as function of the silo diameter and the external surrounding temperature for 9.3% m.c. sunflower seeds (figure 9).

Silos of low diameter allow to preserve the product at high external sorrounding temperature without any trend to hot spot formation. Increasing the silo diameter, the maximum safe sorrounding temperature decreases. Furthermore it appears that the ACT preservation technique extends the conditions for the safe preservation of the product in comparison with the ACF preservation system.

The above described model considers only the existence of a steady state, but it does not evaluate the way and the velocity of the system development.Therefore a system does not generate any hot spot, although it is in conditions of hot spot trend, if the preservation time is less than the induction time.

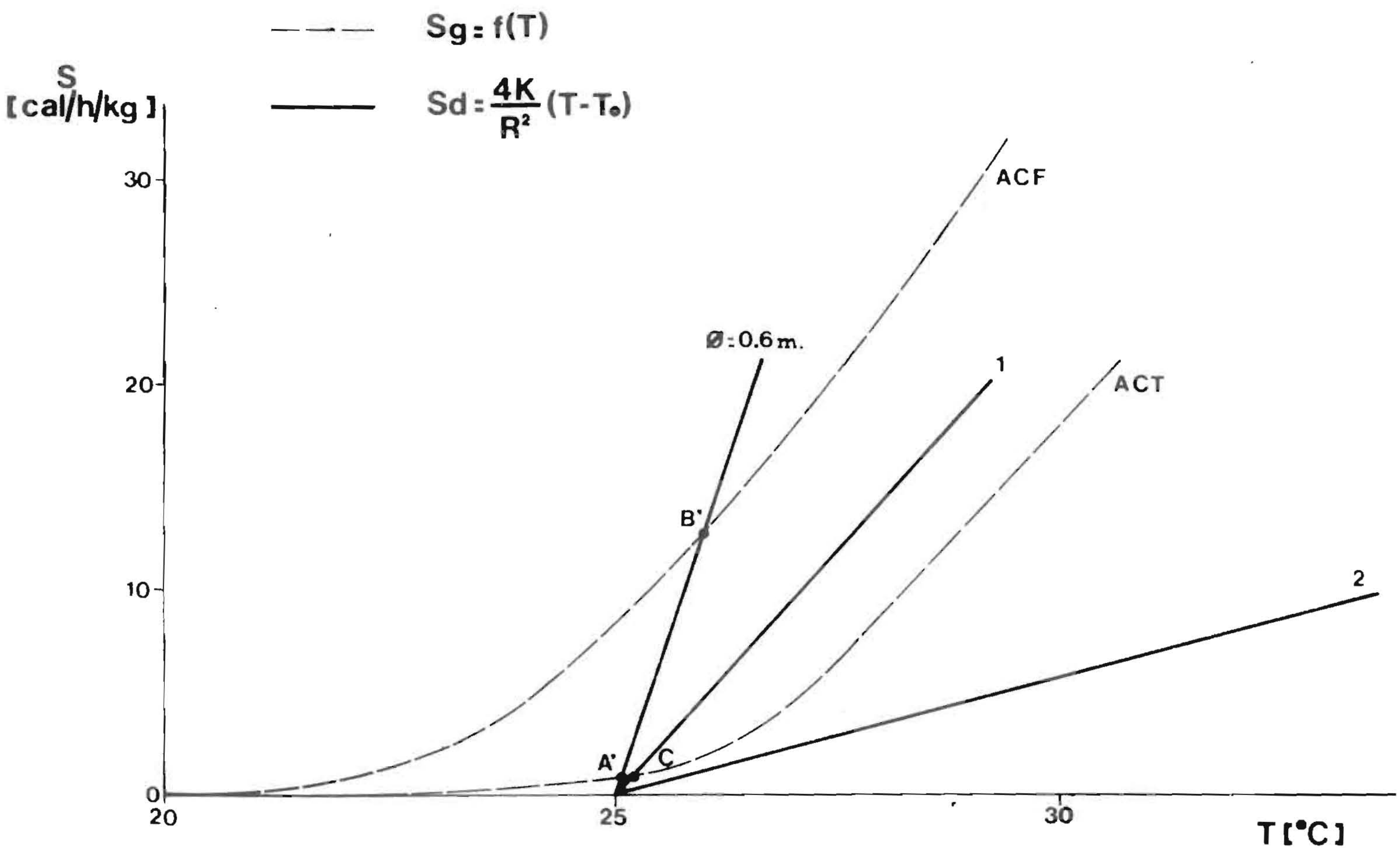


Fig.8. Heat generation rate ($S_g$) and heat dissipation rate ($S_d$), function of the product temperature of sunflower seeds at 9.3% moisture content at different silo diameter and 25°C surrounding temperature.

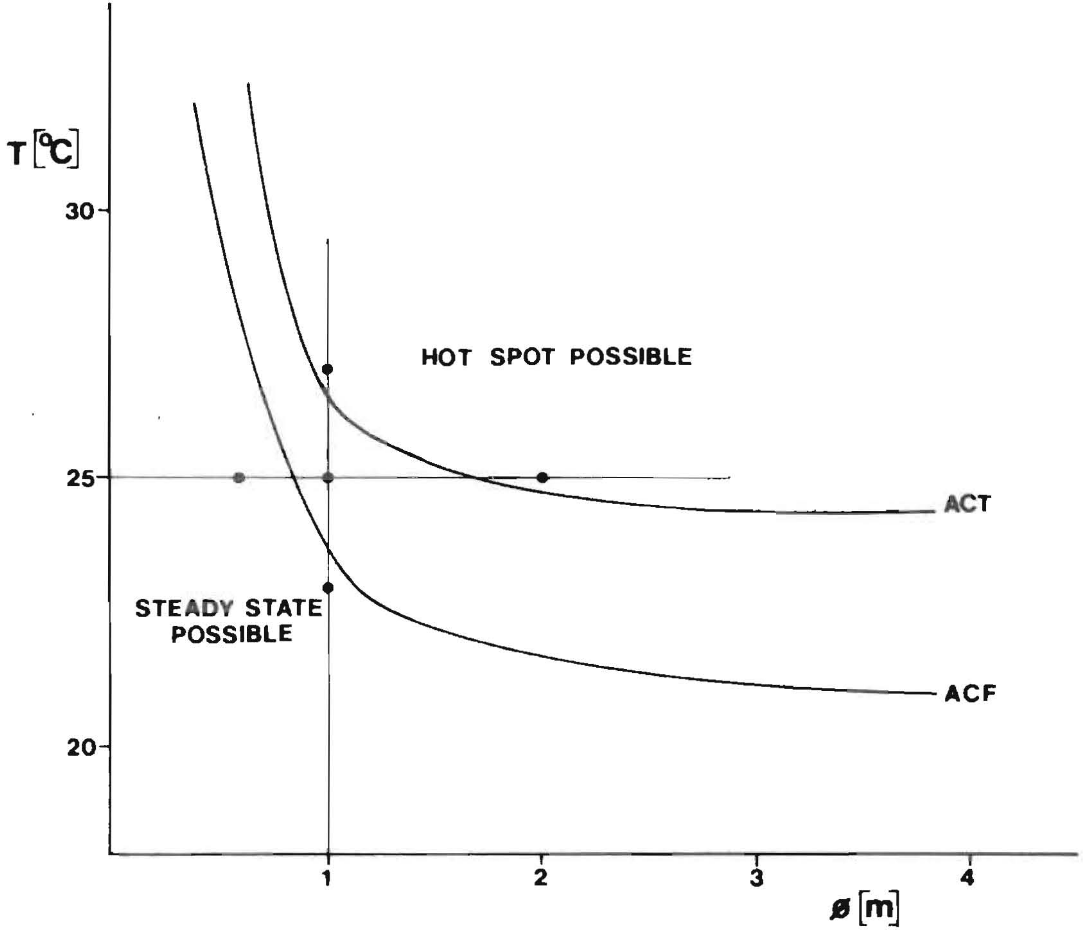


Fig.9. Trend of 9.3% moisture content sunflower seeds as function of silo diameter Ø and surrounding temperature T for confined and controlled atmosphere conditions.

## CONCLUSIONS

The results obtained in the present work allow to draw the following conclusions:

- The above described apparatus is suitable to measure the fundamental parameters required to predict the storability of a product from the point of view of hot spot generation.
- These parameters are: the induction time $t_i$ and the heat generation rate $S_g$.
- For sunflower seeds decreasing values of $t_i$ and increasing values of $S_g$ were measured with increasing moisture content and temperature of the seeds. Even in nearly complete anoxia (residual oxygen content about 0.05%) heat development in the sunflower seed was observed. However the induction time was found to be significantly longer, and the heat generation rate lower than the corresponding values in confined atmosphere conditions.
- A simple storability criterion was presented. It considers the trend of the system, analyzing the heat generation rate and the heat dissipation rate as function of temperature. This criterion allows to understand the hot spot formation in large silos and/or at high surrounding temperatures, while in the same conditions hot spots do not build up at lower silo diameters and/or lower surrounding temperatures. This criterion must be used with precaution because of its simplifying assumptions; but of course it appears more correct than the direct extension of results obtained with laboratory silos of very low diameters.

## ACKNOWLEDGEMENTS

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