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# Design and Control of Energy Efficient Drying Processes with Specific Reference to Foods

Quarterly Report
for the Period
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# A. Summary

Work on Phase II of the drying project was started during the last quarter. Progress on Task 10 (Revision of Drying Models) included a review of fundamental drying theory, and an investigation of experimental methods to determine model coefficients. Models for a drum dryer were also analysed this quarter. Progress on Task 11 (Dryer Studies) included an analysis of a pressurized drying chamber, and installation of a vacuum drum dryer. Further work is needed to prepare both systems for experimental drying studies. Progress on Task 12 (Food Quality Studies) included collection of data on browning and vitamin A degradation in nonfat dried milk. Analysis and interpretation of the data are planned for the next quarter. Thermal property tests on porous food materials were also investigated during the past quarter. Progress on Task 13 (Recommendations/Strategies for Dryer Design and Control) included a review of dryer control strategies presented in the literature. A survey of available sensors for dryer control is planned for the next quarter.

# B. Task 10. Revision of Drying Models

## B.1. Fundamental Drying Models

### B.1.1. Introduction

In the first phase of this study, mass transfer in extruded durum semolina during drying was analyzed. Unique coefficients for an irreversible thermodynamics model could not be determined. A simple diffusion equation was used together with experimentally determined effective diffusivity values and isotherm relations to predict drying rates and moisture profiles. The model underpredicted the drying rate at high temperatures (60-125°C) and at partial vacuum pressures. It was postulated that a pressure gradient existed within the extruded material at these conditions resulting in higher rates of mass flux and flatter moisture profiles than those predicted by the diffusion model.

### B.1.2. Objective

Task 10 states that the fundamental drying models developed in Task 5 will be revised to more accurately predict the results of Task 8.

Task 5: Develop fundamental drying models, based upon moisture transfer mechanisms and generalized energy, mass, and fluid flow equations. Data obtained in Tasks 1, 2, and 8 will be used to calculate the values of the constants used in these models.

Task 8: Perform the Food Properties Studies as described in the test plan (Task 6).

B.1.3. Progress

In order to suggest meaningful revisions to existing drying models, a comprehensive review of fundamental drying theory has been undertaken. Rather than chronologically reviewing the drying literature, previous studies have been examined with the objective of making the following comparisons:

1. Mass transfer **driving forces** proposed.

   Proposed driving forces include gradients in total moisture concentration, liquid concentration, vapor pressure, capillary pressure, temperature, equilibrium moisture content, chemical potential, and total pressure, and gravity.

2. Mass transfer **mechanisms** proposed.

   Moisture transfer is separated into liquid and vapor fluxes in some studies, and is combined as one flux in others. Molecular diffusion, capillarity, and mass flow have been suggested as transfer mechanisms. A distinction between hygroscopic and nonhygroscopic materials is often made. Rotstein and Cornish (1978) suggested a moisture transfer mechanism based on a cellular model. The main source of water in a tissue is taken to be the cell. The transport of water in a cell to the ambient atmosphere is proposed to occur by movement through the cell, through the enveloping cell structure, through the porous structure of the tissue, and finally through the outside boundary layer. Roman et al. (1979) assumed that vapor-phase diffusion through the porous structure of the tissue was the controlling mass transfer step.

3. Important assumptions and considerations made in modeling approaches.

   Assumptions of some kind are made in every modeling approach. In many cases the solid material and water are assumed to comprise homogeneous body for modeling purposes. It is often assumed that no shrinkage occurs during the drying process. The internal transfer of moisture to the material surface, or the external transfer of moisture from the surface through a boundary layer to the surrounding medium may be assumed to be the controlling step in the transfer process. One of the simplest drying models (Keen, 1914) uses an empirical relationship to express the drying rate of soil as a function of the soil moisture content and specific gravity.

Most drying models attempt to relate the drying rate to one or more fundamental driving forces. The theory of irreversible thermodynamics has been applied to the modeling of drying phenomena when more than one driving force is present in the process. For example, in coupled heat and mass transfer processes, gradients of moisture concentration and temperature can be assumed to be direct driving forces for mass and energy transfer. The theory of irreversible thermodynamics accounts for cross-effects that occur between driving forces (e.g. Soret and Dufour effects). The application of Onsager's reciprocal relations reduces the number of unknown model coefficients when a process is modeled within the irreversible thermodynamics framework.

4. Methods of obtaining model coefficients.

Application of theoretical drying models requires the determination of model coefficients. Model coefficients relate the transport rates of energy and mass to the pertinent driving forces. In some cases, model coefficients can be determined theoretically (e.g., from the kinetic theory of gases). For most models, coefficients are determined experimentally. Mass transfer coefficients can be determined from desorption rate tests and from permeation tests using a material membrane.

In addition to a review of drying theory, the development of experimental techniques to determine model coefficients was considered this quarter. A diffusion cell with a food membrane has been proposed as a possible method to measure transfer coefficients. Total pressure, vapor pressure, and temperature could be controlled on either side of the membrane, and the moisture flux due to various driving forces could be studied. Two important questions have arisen regarding the determination of model coefficients:

1. Could the desired coefficients be feasibly obtained with a diffusion cell type of approach?
2. Could the desired coefficients be obtained more easily and accurately with a desorption approach using a Cahn balance?

These questions need to be given more thought before further development of experimental equipment is undertaken.

It is most desirable to obtain independent experimental measurements of model coefficients. Comparison of predicted drying rates with actual drying rates then gives a measure of model validity. When model coefficients are determined by fitting the model predictions to actual drying data, the general model validity is uncertain.

5. Methods of model solution.

The modeling of coupled heat and mass transfer phenomena gives rise, in general, to a system of nonlinear partial differential equations which is difficult to solve. Numerical techniques such as the method of lines have been used to solve these systems of equations.

6. Attempts made to validate models.

Comparison of predicted drying rates with experimental rates gives one a measure of model validity. Further validation of the model involves comparison of actual and predicted moisture profiles. Experimental measurements of moisture profiles is difficult, and has limited the ability to validate drying models.

### B.1.4. Future Work

Many technical publications, books, and theses have been collected and examined. Computerized searches of available databases have been made in an effort to locate relevant literature sources. In the next quarter, additional publications will be reviewed, and a more detailed comparison of previous studies within the framework cited above will be made. Ultimately, a careful review of previous modeling approaches, and interpretation of new experimental data, will enable selection of a revised drying model for food materials. The revised model should account for the experimental drying data obtained under vacuum and high temperature conditions in Phase I.

## B.2. Drum Dryer Model

By using the drum drying model developed in Task 5, two computer programs were developed. One used a "tray dryer approach". In this approach, the whole surface of the drum was considered as a continuous tray dryer which is exposed to the same initial and boundary conditions. Another approach used the characteristic of constant rotary speed of the drum dryer, i.e., $V = \frac{dz}{dt}$ = constant, to omit the $dt$ from the heat transfer equation. Both computer programs applied the finite difference method and the Gauss-Seidel iteration method. The results from the computer programs did not yield a good agreement with the data collected earlier from drum drying of mashed potatoes. Further revision will be necessary. The two programming approaches are as follows:

1. Tray dryer approach.

In the development of the drum drying model, several assumptions were made. They were: (1) infinite slab approximation, (2) homogeneous physical properties, (3) negligible heat loss, (4) constant heat transfer coefficient, (5) uniform film thickness, and (6) uniform drum surface temperature.

Under these assumptions, the drum drying process has many things in common with tray drying such as heat transfer path, water evaporizing path, etc. From this viewpoint, the process of drum drying may be considered as tray drying. This approach will simplify the computing method, and more importantly, it will support the thought of collecting drum drying data from a modified tray dryer. This makes accurate control and measurement of experimental variables possible.

A computer program was developed based on this approach. Figures B.1 and B.2 show the comparison of the predicted results to experimental data. A large deviation can be seen and the potential causes include the method of calculating the saturation pressure and the assumption of a constant heat transfer coefficient. These wil be explained later in this section.

2. Simplified approach.

One characteristic of drum drying is that the drum speed is uniform and remains unchanged during the drying process. From the definition of speed, one may use the expression, $v = \frac{dz}{dt}$ throughout the calculation of drum drying. The time variable, $dt$, in the heat transfer equations can be omitted and the computational work is simplified. Figures B.3 and B.4 show the comparison of the predicted values by this approach to experimental data. A large deviation exists.

3. Further work.

Since large deviations exist, more accurate methods of calculating model properties should be applied before one gives an evaluation of these approaches. Possible sources of the deviations are as follows:

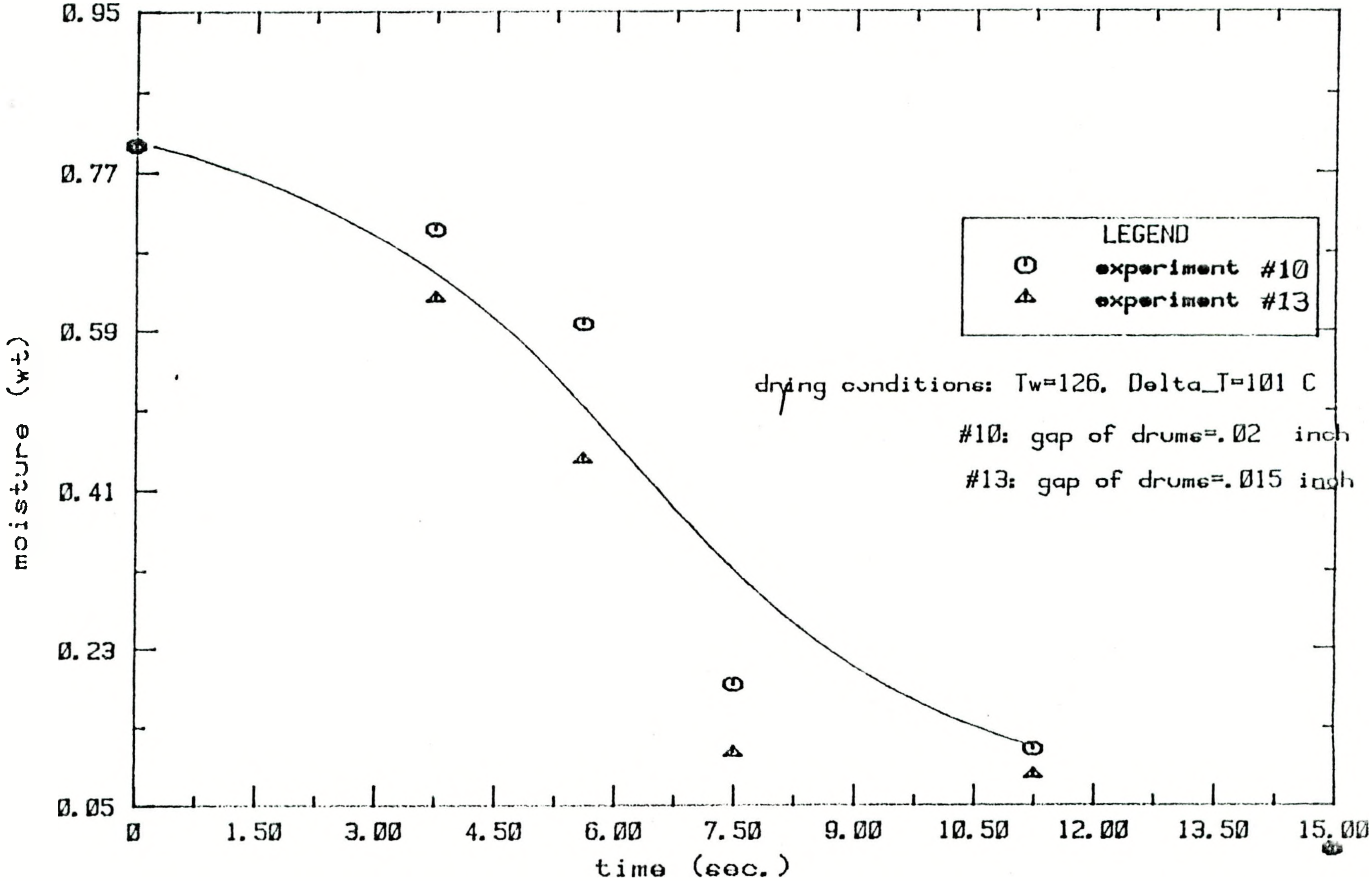


Fig. B.1 Comparison of predict value VS. experiment data

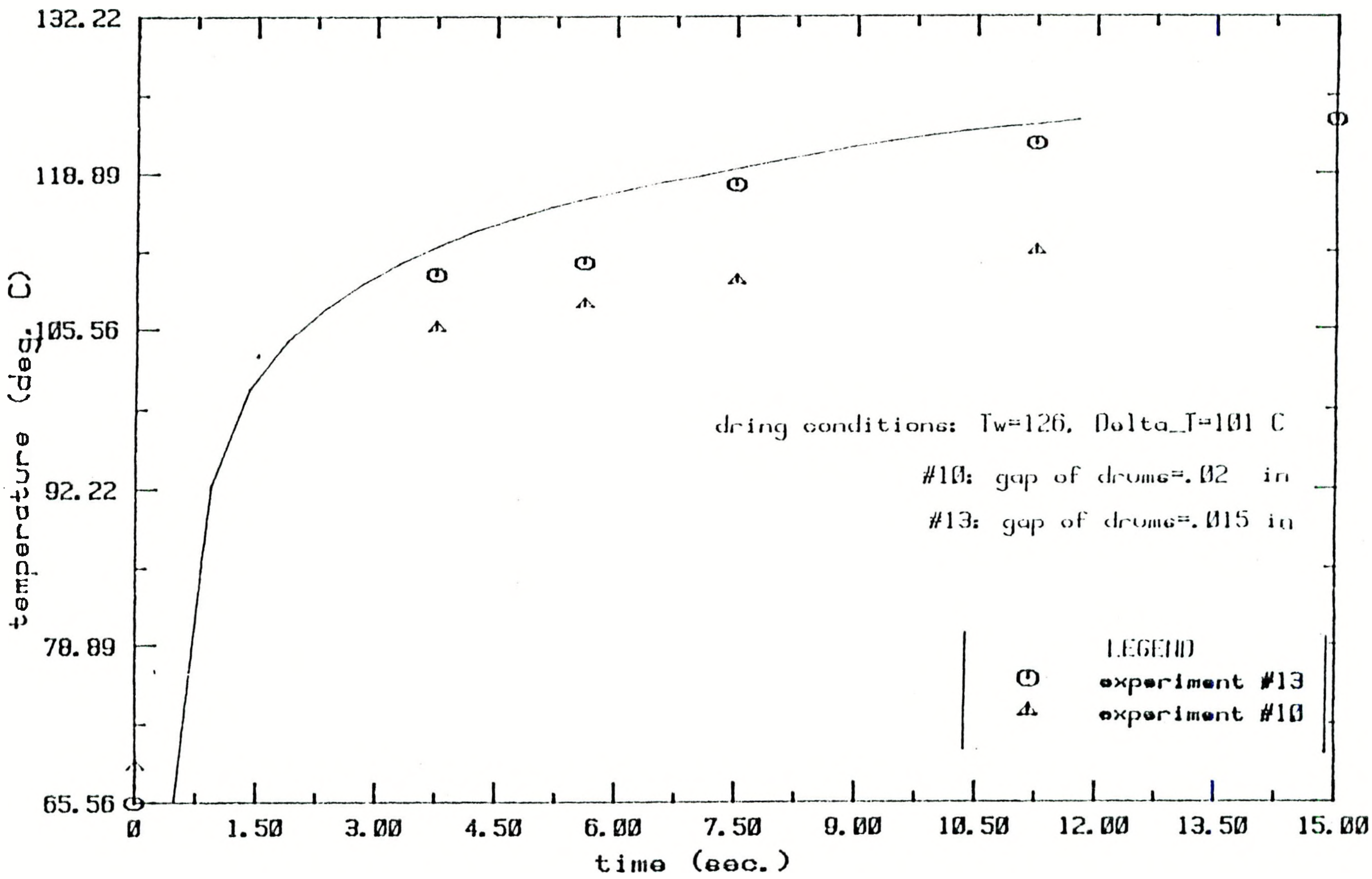


Fig.B.2. Comparison of predict value VS. experiement data

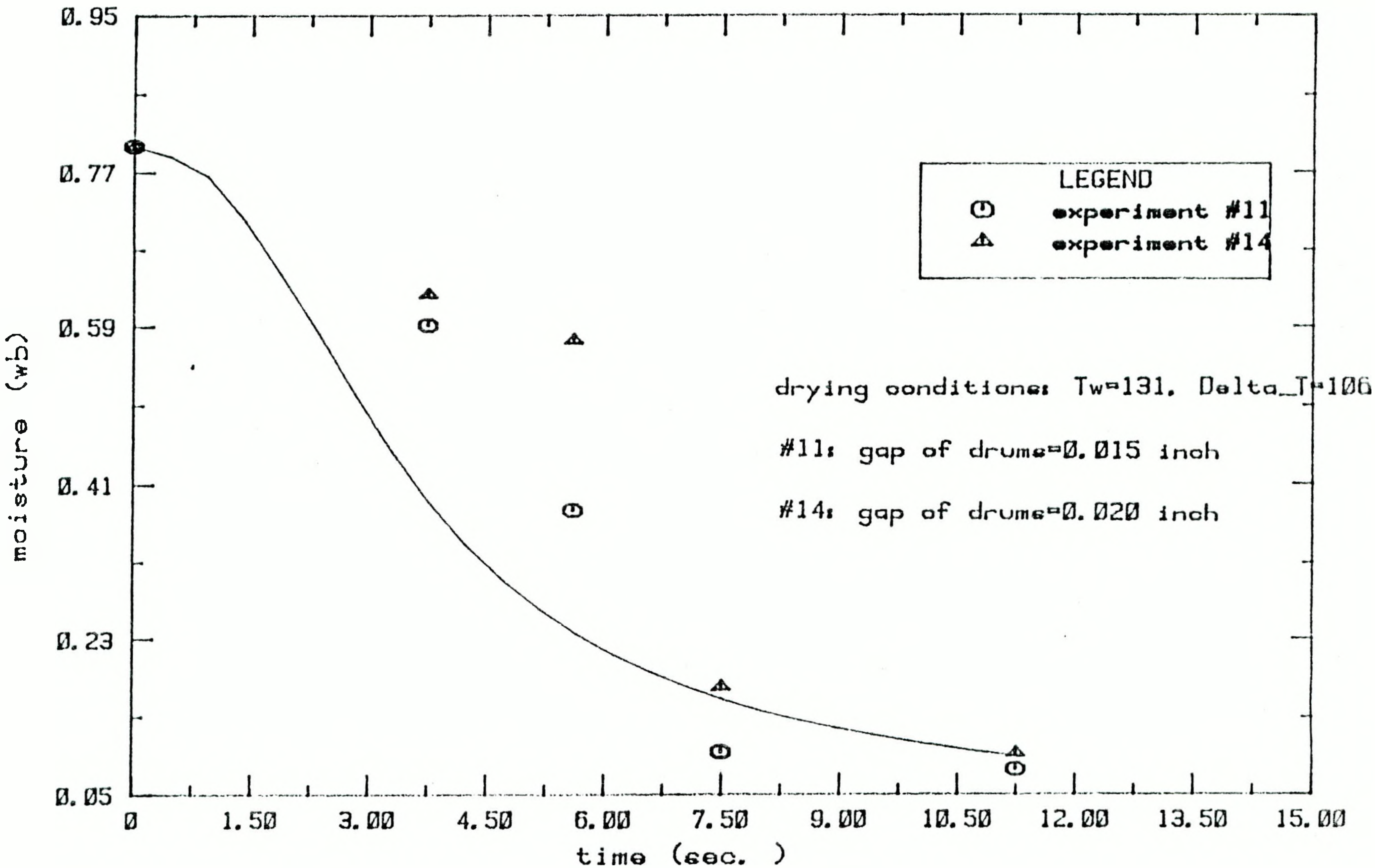


Fig. B.3 Comparison of predict data VS. experiment data

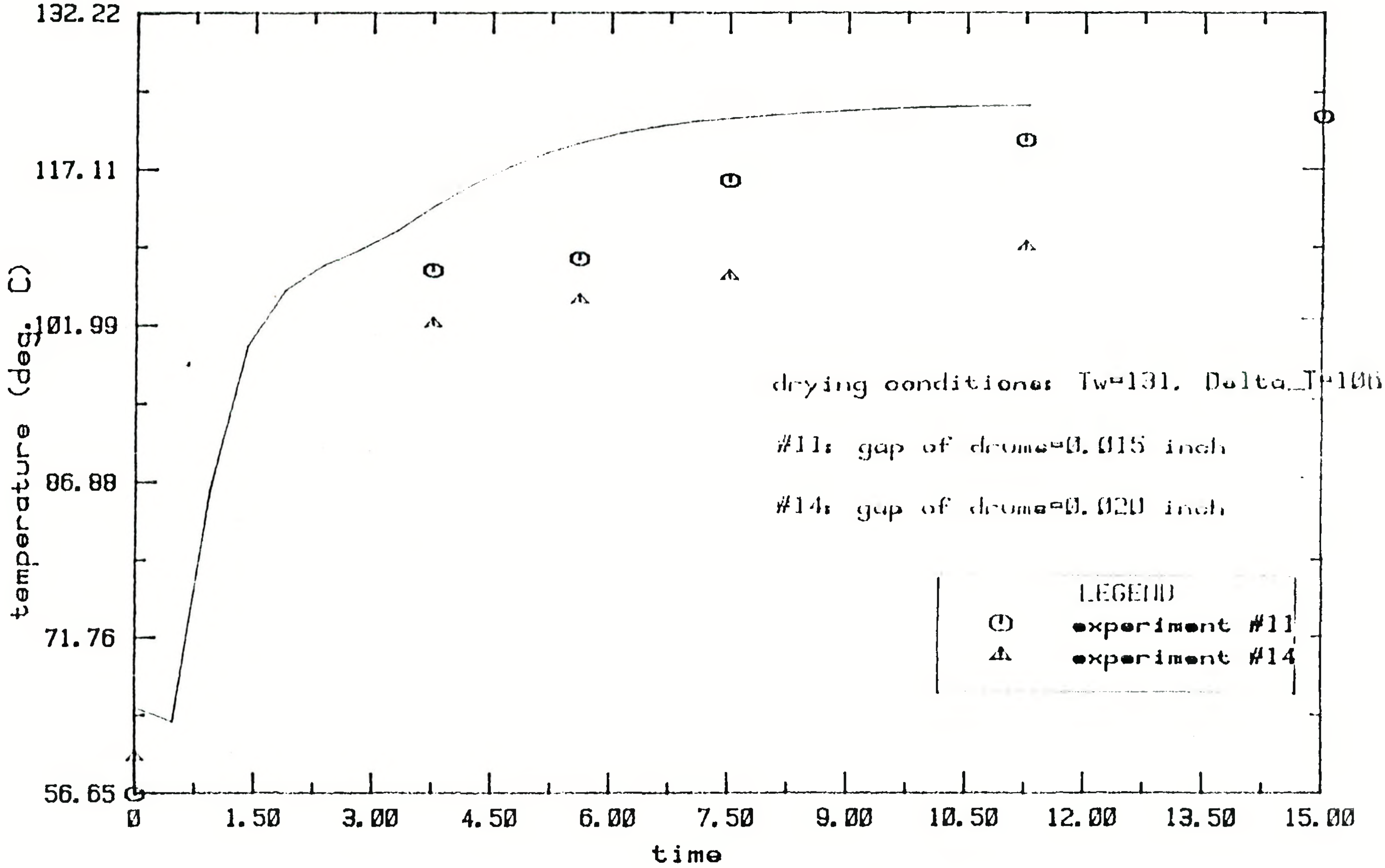


Fig.B.4. Comparison of predict value VS. experiement data

- The method of calculating the saturation vapor pressure on the film surface: The film surface vapor pressure was calculated by a regression equation which was taken from tabulated saturated steam data. If the temperature is above the boiling point of the material, or if the ambient pressure is below one atmosphere, special phenomena may occur and the regression equation may no longer be suitable. Unfortunately, these are the situations which exist frequently during drum drying.
- The assumption of a constant heat transfer coefficient: Since the drums are continuously rotating, the heat transfer coefficient could be different at each spatial position. The assumption of a uniform film thickness is valid only if the drying material does not shrink or swell to a large extent. For most food materials, this assumption may not be proper.

Further work is also needed to develop methods to calculate the surface vapor pressure and the heat transfer coefficient.

## C. Task 11. Dryer Studies

### C.1. Dryer Studies Related to Model Validation

One measure of validation for the revised drying model to be developed in Task 10 could come from comparison of actual and predicted drying rates. Experimental drying rate measurements on pasta slabs were made in Phase I for vacuum and high temperature conditions. Experimental data under elevated pressure conditions would give additional insight into the model validity. Drying equipment suitable for high pressure operation is available in LORRE (Laboratory of Renewable Resources Engineering) on the Purdue campus. The hangdown tube and housing for the Cahn 1000 balance are made of 3/4 inch stainless steel. Pressurized nitrogen gas passes through a flow control valve and then to the hangdown tube. The system is not yet operational. A system to humidify the nitrogen gas stream is under development. The system does not currently allow pressure control. A search is presently being conducted for a suitable pressure sensor and proportional control pressure valve.

Comparison of actual and predicted moisture profiles would provide further validation of the revised drying model. New techniques to measure moisture profiles have been explored. A Fast Fourier Transform IR sensor coming to the Agronomy Department at Purdue has potential for moisture profile measurement. The IR sensor could also measure the surface moisture content of the sample during drying. The surface moisture content is an important parameter in most drying models and is often assumed to equal the equilibrium moisture content of the food at the ambient drying conditions. Funding for the IR sensor has been approved, but the actual sensor has not been selected or ordered. During the next quarter, contact with the Agronomy Department will be maintained regarding the choice of sensor, and the possibility of use of its use in this project.

### C.2. Drum Dryer Studies

A vacuum drum dryer donated by Blaw Knox was installed and tested in the past quarter. The system will enable one to conduct a drum drying experiment under a vacuum of from 0 to 28 inch Hg. The drum rotary speed may be varied from 0 to 20 rpm. A water heating system in which the water temperature and flow rate can be controlled and measured was connected to the dryer. The water removed from food is collected in the condenser. The product temperature will be measured by an IR-500 thermometer and several thermocouples. The moisture content of product will be measured by 2 standard oven techniques. More calibration work needs to be done before actual drying studies begin. The skim milk drying studies may be conducted under the conditions listed in Table C.1.

Table C.1 Experiment conditions for drum drying of skim milk

| drying | vacuum (inch Hg) | | | |
|---|---|---|---|---|
| temp. (°F) | 0 | 5 | 10 | 15 |
| 150 | | | x | x |
| 180 | | x | x | x |
| 212 | x | x | x | |
| 240 | x | | | |

## D. Task 12. Food Quality Studies

### D.1 Browning and Vitamin A Degradation

The procedures being used to measure quality of NFDM were described in the Phase I final report (April, 1987). Table D.1 shows the sets of constant temperature, constant moisture samples for which nonenzymatic browning measurements have been: 1) completed and included in the Phase I final report, 2) completed since the final report, and 3) planned for future tests. After analysing the results of Phase I, it was found that more data is needed at temperatures greater than 100°C.

Table D.1. Non-enzymatic Browning Measurements

| Moisture (%) | Temperature (°C) | | | | | |
|---|---|---|---|---|---|---|
| | 35 | 70 | 80 | 90 | 110 | 130 |
| 3-4 | //// | //// | | //// | * | * |
| 8-10 | //// | * | | * | * | * |
| 20 | • | • | | //// | | |
| 30-32 | | • | • | • | * | * |
| 50 | | • | | | | |

//// Included in the final report

• Completed since the final report

* To be completed in the future

Figures D.1-3 are plots of the raw data obtained since the Phase I final report (some of the previous data is also included). Data analysis will be performed and regression lines fit to the data. Most of the literature to date has indicated that the browning reactions follow zero order kinetics. However, a recent study of reaction kinetics indicated that browning in lactose-glycerin solutions was best described by a fractional reaction order (~0.5) (Buera et al, 1987). The data of this study will be analyzed with respect to both zero and fractional reaction order kinetics to determine the best fit.

Two methods of vitamin A analysis have been attempted since the Phase I final report. First an HPLC method was tried. A constant retention time of the vitamin through the column was never achieved. After 2 months of consulting with applications experts and our departmental HPLC expert, no solution was found and the method aborted. Currently, a fluorescence spectrophotometric vitamin A analysis method is being evaluated. Preliminary results are not promising. If success is not found with this method, vitamin A degradation will not be measured and efforts will be concentrated on the browning analysis.

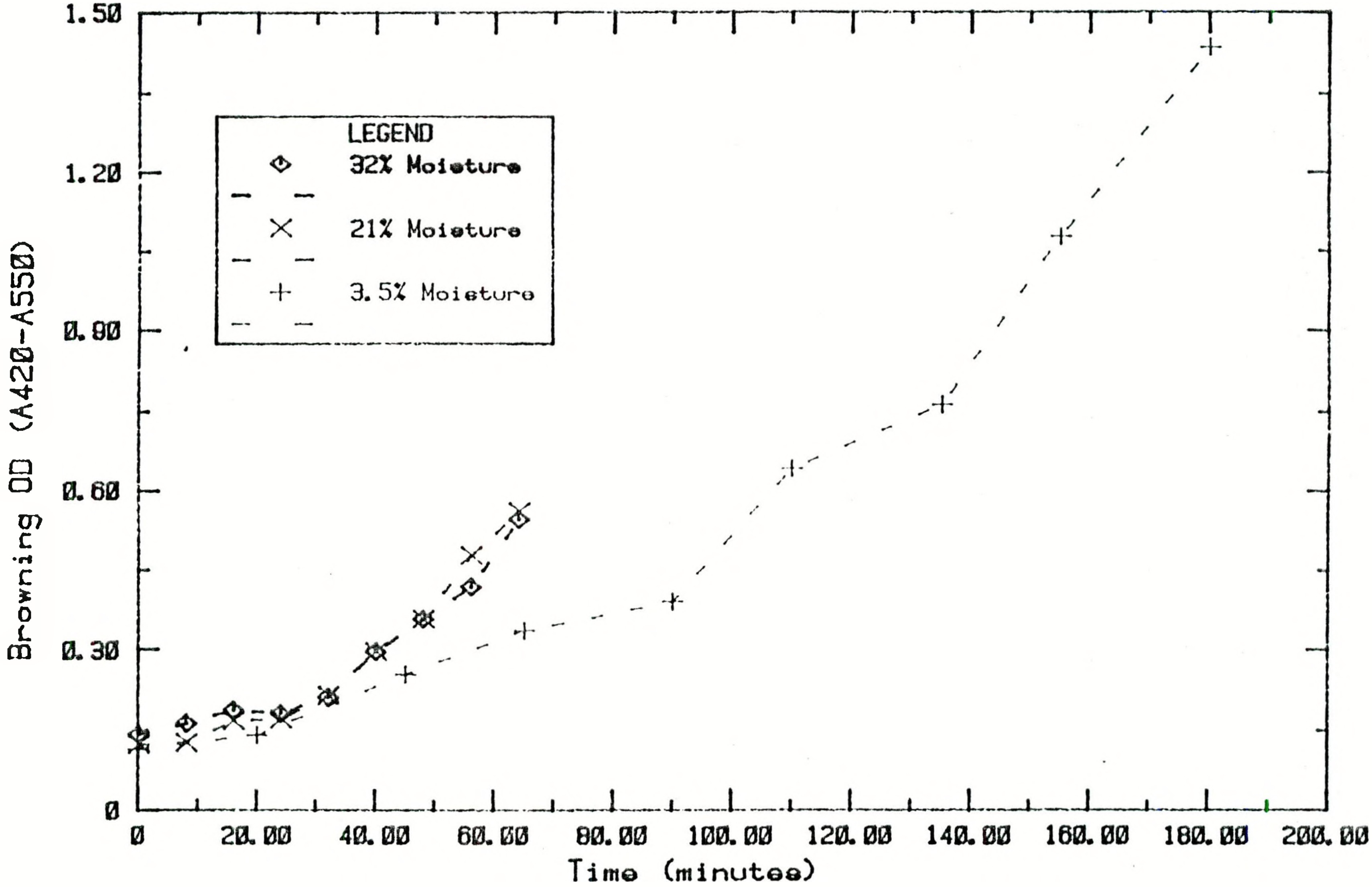


Fig. D.1. Browning of NFDM at 90 C

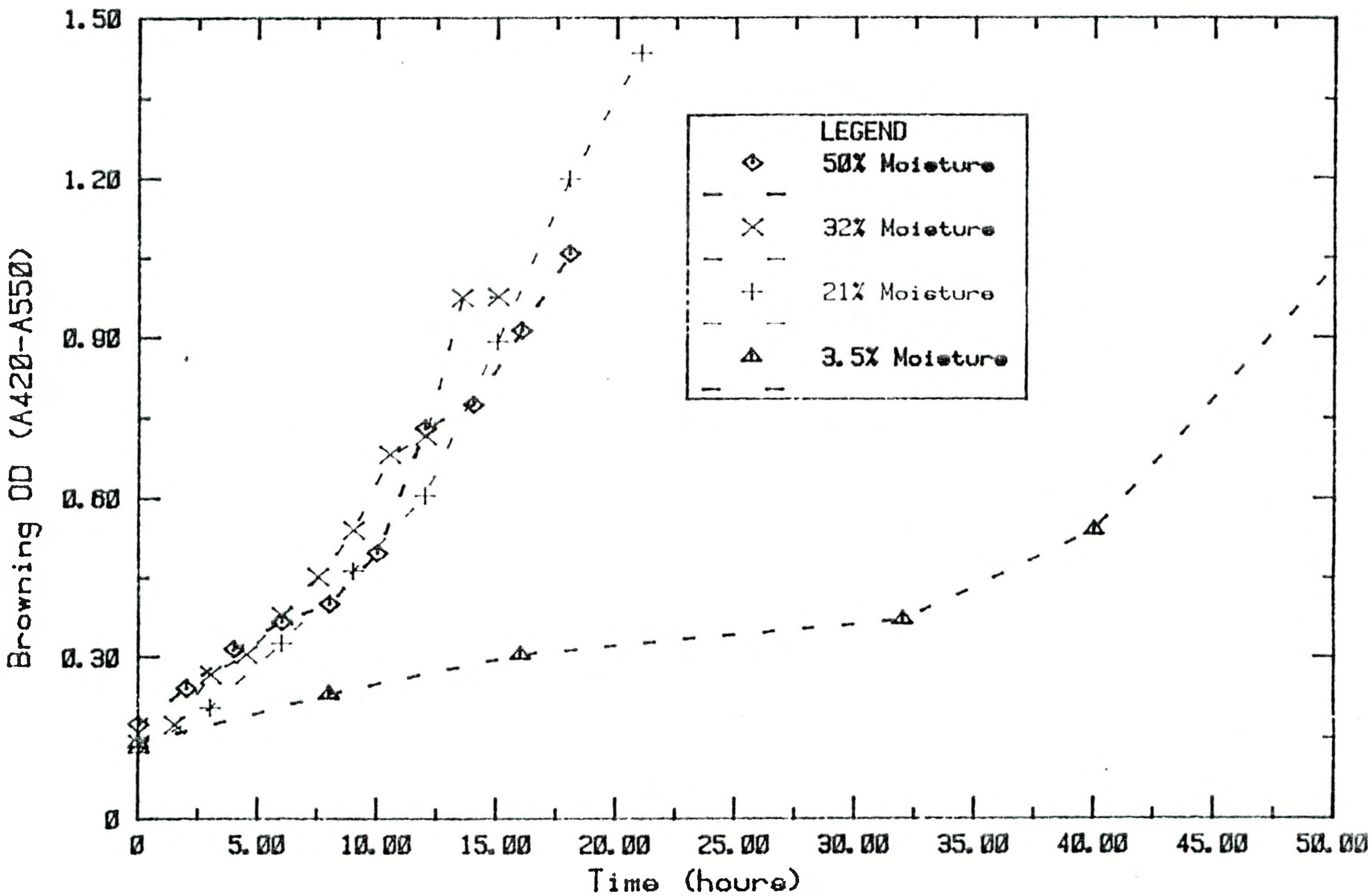


Fig. D.2. Browning of NFDM at 70 C

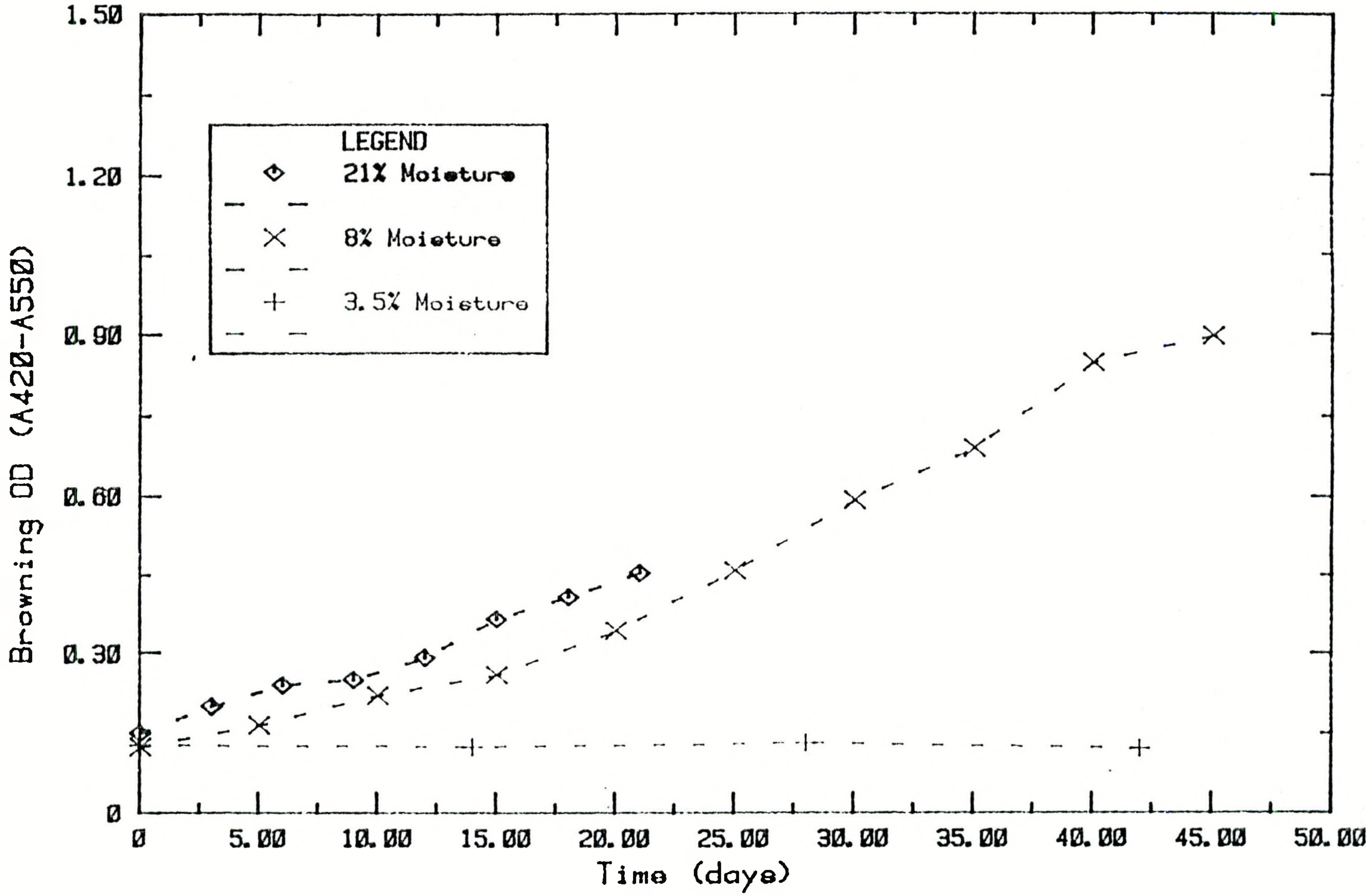


Fig. D.3. Browning of NFDM at 35 C

Progress expected by next quarter:

- All browning analysis completed
- Evaluation of vitamin A method
- Statistical analysis of browning as a function of time.

### D.2 Thermal Properties

D.2.1. Introduction

Most quality parameters are temperature dependent. Quality attributes such as vitamin content, color, and texture degrade at high temperature.[5] Thus, changes in food quality attributes should be considered in the design of drying systems.

D.2.2. Objectives

1. To develop a comprehensive thermal conductivity model for all food materials.
2. To evaluate the thermal conductivity model at wide ranges of temperature, moisture content and pressure.
3. To write an interactive computer program for predicting thermal properties of food materials.

D.2.3. Accomplishments in Phase I

A model for estimating the thermal conductivity of food materials was developed based on composition using the Keey model. This model was found to give satisfactory results in both liquid and fine porous materials. In non-porous solid materials (i.e. corn kernels and kidney bean catyledons) and in large, non-homogeneous porous materials (i.e. grains, beans), the errors of predicted values were high. These findings were reported by Murakami and Okos (1986).

D.2.4. Progress

The probe apparatus was redesigned to improve durability and to enable measurement of a wide range of thermal conductivity values. The old probe apparatus had the thermocouple and heater wires glued with Epoxy on the surface of a small tube. It was found that the Epoxy glue softened in some liquids (i.e. acetone, benzene, etc.) used for calibration. Thus, in the new probe, the heater wires were inserted into the tubes and the thermocouple wire was soldered on the surface. A thin copper wire was wound around the thermocouple junction and then soldered. The new design has a smaller diameter and thus, has a lower time correction factor. It also requires lower power. The new probe was calibrated with air, benzene, acetone, methanol and water, all without glasswool. It was found that the correction factor (ratio of literature and experimental values) was not constant. However, a plot of these values forms a straight line. Convection was found to significantly increase the measured thermal conductivity values, and was due to the high power input. The optimum power input for a test material could be found by trial and error. This corresponds to the highest power level at which the plot of the measured thermal conductivity values against power input has a zero slope.

The thermal conductivity of chocolate fudge, marshmallow, cooky icing, ground cooky and fig pastes were measured from -20°C to 100°C. Temperature distributions during cooling were also measured for the following samples: marshmallow pies, fig bars and vanilla cookies. These samples were supplied by Ralston-Purina. A finite difference program was written to predict the temperature distribution in composite food materials.

The thermal conductivity model reported by Murakami and Okos (1986) required interpolation and extrapolation. Since the distribution factor of the Key model was expressed in three separate equations. A single new equation was developed which expresses the distribution factor as a function of porosity and moisture content. Initial results showed that this model is valid in liquid and porous foods with small particles (i.e. powders and flours) at a wide range of temperatures, moisture contents and porosities. Like the old model, it doesn't give satisfactory results in porous materials with large non-homogeneous particles like grains. Moreover, the results were poor in meat at temperatures below the freezing point.

The Keey model was found to be the best structural model for predicting thermal conductivity. This model groups the food components into solid (including liquid) and gas. Studies on catalysts (Smith, 1981; Soomro and Hughes, 1979; and Sehr, 1958) indicated that thermal conductivity decreases with pressure, and at vacuum conditions should be equal to the thermal conductivity of the solid component. Therefore, studying thermal conductivity of food materials under a vacuum should be an excellent way to study the validity of the Keey structural model.

D.2.5. Plans for Next Quarter

Thermal conductivity of food materials such as fish, meat, and fruit juices, will be collected from the literature. These materials were not included in the previous study. Together with new data on chocolate fudge, marshmallow, ground cooky, cooky icing and fig pastes, the thermal conductivity model will be evaluated. Data will include several levels of temperature, moisture content and porosity.

A Center for Food Properties will also be initiated. With faculty members from the Departments of Agricultural Engineering and Food Science serving as core members, this center will aim to serve the food industry. This center will provide data on food properties to the food industry and spearhead research on food properties measurement and modelling.

## E. Task 13. Recommendations/Strategies for Dryer Design and Control

The objectives for this part of the study can be given as follows:

1. Develop a valid stress prediction model for products subjected to drying conditions.
2. Develop a valid failure criterion which will allow prediction of stress crack formation based on experimental failure data obtained in Task 8.
3. Develop dryer control strategies utilizing drying models and optimization techniques.
4. Review available sensors from the viewpoint of dryer control application.

Several aspects of the adaptive on-line control scheme application to process control were reviewed from the literature. The advantages of the adaptive on-line control scheme are as follows:

1. It requires very little information on process dynamics.
2. It makes the system converge quickly to the desired state.
3. It adapts to environmental changes and is stable even when operational difficulties are encountered.

The drawback of the adaptive control scheme is that a great amount of numerical calculation for process parameters and manipulated variables is required, and should be repeated at intervals of relatively short time. Therefore, the implementation of the control algorithm is somewhat complicated.

More literature on the application of control schemes to process control will be examined in order to determine their potential in dryer control. Review of the available sensors will also be carried out in parallel with the control strategies study. Review of related literature, including journal publications, theses, and the Phase I final report, is the major objective for the next quarter.

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