INFLUENCE OF A PROCESS VARIABLE, TEMPERATURE, AND TWO INGREDIENT VARIABLES, ON EXTRUSION TEXTURIZATION OF WHEAT GLUTEN

by

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INTRODUCTION

Cereals and vegetable proteins have been processed by thermoplastic extrusion for the last thirty years. There has been a great deal of commercial interest in product and process development in this area however, little basic research information is found in the literature.

The protein source most commonly used in extrusion processing is defatted soy flour. This is probably a function of price. Research on extrusion of processing other proteins including wheat gluten is extremely limited. Most available literature on wheat gluten processing is in the form of patent literature which indicates that wheat gluten has been processed in much the same manner as soy protein in thermoplastic extrusion.

The objective of this study was to use the products of a wheat gluten-wheat starch separation as ingredients in the production of a texturized protein product. Vital wheat gluten, starch and peelings are the major fractions from a commercial wheat gluten-starch separation system. Variables of interest in this study were: 1) percent moisture of feed stock and 2) ratio of peelings to gluten. Extrusion temperature was also varied during the study because temperature effects are known to be inversely related to moisture effects when extruding soy protein. Product evaluation criteria involved product rehydration under various conditions as well as density and integrity of the extrudate.

LITERATUE REVIEW

Extrusion is a process by which a material is moved down a barrel and forced through a die. In general food extruders are a viscous drag screw pump equipped with a tightly fitted cylindrical barrel (Rossen and Miller 1973). The flights on the screw force material down the barrel and through a die, such that the extruded material will have the desired shape. In food extrusion there are generally three types of processes used: 1) cold forming, 2) low-pressure cooking and forming, and 3) high-pressure cooking and forming, Conway (1971).

The first process developed using modern extruder technology was a cold forming, low-pressure process. In this process, the material is blended into a uniform dough in the extruder barrel and forced through specially designed dies to create a variety of shapes. Because of the design of the screw, little or no cooking is done in the extruder. After extrusion, further processing usually takes place in the form of baking or frying. Products of this type include pasta, bread sticks and doughnut holes.

The second process is characterized by high-pressure (or high shear) cooking and forming. The earlist extruder developed using this process was the collet extruder (Harper 1981a). With this extruder, no external heat is applied to the barrel. Processing heat comes from viscous dissipation of mechanical energy within the product. The limited versatility of the collet extruder led to the development of cooking extruders with jacketed barrels allowing heat to be added or removed externally. These are known as polytropic barrels. In a cooking extruder, ingredient materials are processed at temperatures above 100°C. Pressure in the extruder is produced by a decrease in screw flight volume as material

proceeds down the barrel and/or by restricting flow at the end of the barrel with a die. Pressure released as the product exits the die causes moisture to evaporate nearly instantaneously and the product to expand as it leaves the die. The high-pressure cooking process is used to produce textured plant protein, ready-to-eat cereals, pet foods and snacks.

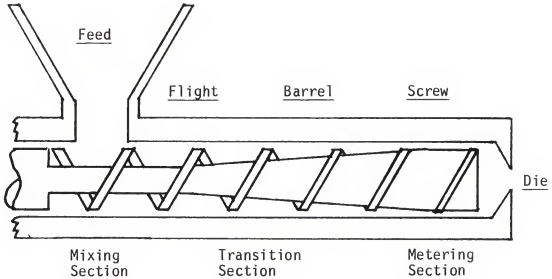
The low pressure cooking and forming process also uses a polytropic barrel. The ingredients are mixed, cooked and then cooled below 100°C before being extruded through a die. Cooling the material below 100°C prevents expansion at the die. The product is then further processed by frying, puffing, toasting or combinations of these. This type of processing is used in the production of some breakfast cereals.

The high pressure (high-shear) cooking process is used for plant protein texturization. Using this process heat can be added by one or more of three mechanisms; (1) viscous dissipation of mechanical energy, (2) heat transfer from steam or electrical heaters surrounding the barrel and/or (3) direct injection of steam into the barrel (Harper 1981a). Considerable mixing takes place in the extruder which together with added heat converts the material into a visous dough-like mass. By constricting the discharge end of the barrel with a die and by using close tolerances between the barrel and the screw elevated pressures of 30-60 atm can be achieved (Harper 1981a). Because the pressure in the barrel exceeds the vapor pressure of water at the temperature reached, evaporation does not occur inside the barrel. When the dough-like mass is forced through the die it is exposed to a large pressure drop causing the dough to expand and moisture to flash off as steam.

Figure 1 shows (schematically) a cooker extruder divided into three sections; mixing, transition, and metering. First the material to be

Figure 1

Schematic of Extrusion Cooker



processed encounters the mixing section, sometimes called the feed section. In this section the screw has deep flights, so the food material can easily be fed and conveyed. If the material has not already been conditioned, water may be added in this section. The function of the mixing section is to mix when water is added, to assure sufficient flow of material down the screw, and to insure that the screw is completely filled (Harper 1981a). No cooking is done in this section preventing interference with feeding of the extruder. This section may be cooled, but is never heated.

The transition section is characterized by rapid rise in temperature and pressure. Before the material leaves this section, it will be changed from a granular or particular state to a dough-like mass. The material at the end of this section usually has a temperature of about 100°C. Some compression takes place in this section. This compression is usually achieved by a gradual decrease in the flight depth along with an increase in the root diameter of the screw. Compression helps change the material into a uniform dough-like mass.

The final section of the extruder is characterized by very shallow flights on the screw, and temperatures well above 100°C. The shallow flights increase the shear rate in the barrel and further mixing assures a uniform temperature in the material. Because of the shallow flights and the high shear rate, viscous dissipation of mechanical energy is the greatest in this section (Harper 1981a), causing a rapid increase in temperature. When material, now called extrudate, moves through the die to atmospheric pressure there is a rapid pressure drop, causing the characteristic expansion.

The whole process from material entering the extruder to the extrudate exiting the die can take less than thirty seconds. Extruders of this type are called high-temperature short-time (HTST) extruders.

Texturization of plant protein using an extruder was begun in the early 1960's, (Harper 1981b) and has grown rapidly into the industry that exits today. Textured plant protein (TPP) has found use as an extender in fresh and processed meat, and as an ingredient in many ready-to-eat or easy-to-prepare processed foods. Extrusion processing of plant protein is used more than other texturization processes because it is cheaper than fiber spinning and has less by-product steam than steam texturization.

Though extrusion processing is used extensively for production of TPP, the mechanism of texturization is not fully understood. The first step in the texturization process is thermal denaturation of protein. Due to high heat and moisture in the extruder barrel there is extensive unfolding of protein molecules. Following denaturation the nearly linear protein chains are free to combine or to become oriented differently (Remsen and Clark 1978). Kinsella (1978) outlined the texturization process within the barrel; first the protein becomes hydrated and unfolds, and is then stretched by the shearing action of the rotating screw flights. The protein molecules then become aligned in the direction of flow and recombine to form fiberous sheaths. When the protein material is forced through the die, moisture flashes off leaving vacuoles within the extrudate. The cooling takes place as the moisture flashes off, which sets the protein in fiberous sheaths.

To achieve a fiberous structure the linear proteins must bind together within the extruder. Chang and Sternbery (1974) and Kelly and Pressey (1966) have submitted data to support disulfide bonding in spun protein. Jenkins (1970, cited by Harper 1981b) obtained U.S. Patent 3,496,858 for the addition of elemental sulfur containing reagents to plant protein before extrusion to improve the structure of TPP. Intermolecular peptide

bonds from free carboxyl and amino groups have been suggested by Burgress and Stanley (1976) to be involved in texturization. They showed evidence that by blocking the formation of amide bonds a less textured product was formed. Weaker bonds, such as hydrogen and hydrophobic bonding and van der Waals' forces, probably also exist to hold the protein in this fiberous state.

Processing conditions can have a great affect on the characteristics of TPP. Some of the processing conditions that have been shown to affect TPP are moisture content, ingredients, temperature, screw speed and residence time (Kinsella 1978). These conditions are often interrelated. Processing conditions for production of good quality TPP are outlined in the patent literature, but there is little data on how variation in the process conditions affect TPP quality.

Moisture content of a material before extrusion can affect the degree of expansion, density and water absorption of the extrudate. Faubion et al (1982) showed that increasing the moisture content of wheat starch from 17-24% was accompanied by a 20% decrease in expansion. Similar results were reported by Seiler (1980) and Park (1976). Aguilera and Kosikowski (1976) reported lower water absorption upon rehydration for soy protein when extruded at high moisture (above 30%) levels.

Ingredient particle size can affect final product structure and uniformity. Ingredients used must make a uniform, homogeneous mix or the final product will be nonuniform and weak (Hauck 1979). Specific properties of ingredients can also change the characteristics of an extrudate. Flour with a low gluten content will produce a weak, light product. The addition of wheat gluten will produce a stronger more dense product (Smith 1975). Fat is used to weaken doughs, but provides plasticity and hardness in the

extrudate (Smith 1975). The use of full fat vegetable proteins will yield a poor quality TPP. Hauck (1979) states that the high fat content reduces the amount of stretching and twisting occuring in the barrel. This stretching and twisting is necessary to align the protein and produce the chewy, gel products whose mouth feel after rehydration is similar to that of meat protein.

The protein of ingredient materials must be undenatured and capable of forming a gel. Proteins that have been denatured before extrusion will not make good quality TPP (Williams et al 1977). Williams defined good quality TPP as that which obtained a layered sheet structure rather than a porous structure.

Ingredient temperature reached in the extruder may be the most important processing variable. Product expansion and flash evaporation of water from the extrudate require temperatures over 100°C (Harper 1981a). Cumming et al (1972) studied the relationship between production temperature and product density, and between production temperature and water absorption of soy protein extrudate. As process temperature increased, product density decreased and water absorption increased.

Most textured soy proteins are not pH modified, and the extrudate exhibits a light density. Density can be increased by adjusting pH to between 5 and 6.5 (Kinsella 1978, Smith 1975). This produces a dense and chewy product much like the product formed with low processing temperatures and high moistures. Alkaline pH (above 8.5) will make a less chewy, more tender product which will rehydrate rapidly, but with a bitter taste (Harper 1981b).

It should be made clear that even though these process conditions are sometimes studied and looked at separately, they are interrelated. Process conditions need to be managed simultaneously to produce the desired product.

Aguilera and Kosikowski (1976) attempted to optimize moisture content, screw speed and processing temperatures to produce TPP with good water rehydration characteristics. The best water absorption occurred when the product was extruded above 145°C and the moisture content was below 30%. The density of glandless cotten seed meal extrudate was shown to decrease as process temperature and screw speed were increased. Increasing screw speed and processing temperature also increased water absorption (Taranto et al 1975).

Wheat Gluten

Wheat gluten is an artifact protein formed by the washing step used to separate starch from endosperm proteins. Gluten is obtained by washing flour in excess water or dilute salt solution. Washing removes much of the starch and soluble material leaving a rubbery mass called gluten, which contains about 80% of the total endosperm protein, and is itself 75-85% (d.b.) protein. Gluten also contains about 5-10% (d.b.) lipid and between 10-15% (d.b.) carbohydrate (Karsarda et al 1971, 1976).

Wheat gluten is mainly made up of storage proteins with the two major fractions being gliadin and glutenin. Other proteins found in gluten are albumins (Woychik et al 1961), and membrane proteins (Simmonds 1972). Gliadin has the lower molecular weight of the two major protein fractions found in gluten and is a sticky, extensible protein. It is this cohesiveness that keeps gliadin from being washed away from the glutenin during the washing process (Kent-Jones and Amos 1967). Glutenin is an elastic and cohesive protein, but not as cohesive as gliadin. These two proteins give gluten its unusual properties. Gliadin and glutenin can be extracted from either gluten or flour.

The amino acid composition of gluten, gliadin and glutenin are shown in Table 1. As can be seen from the table there is an unusually high amount of glutamic acid (present largely in the form of glutamine) and proline in gluten. About one out of every three amino acids is glutamine and about one out of every seven is proline (Kasarda et al 1971). The large number of glutamine side chains gives gluten a great potential for hydrogen bonding causing its strong aggregation tendencies. Hydrophobic bonding is also a possibility due to the large number of non-polar side chains. The ionization potential of wheat gluten is low. The reason for this is the carboxyl groups of glutamic and aspartic acid are not free to ionize, and there is a low amount of amino acids (lysine histidine and arginine) with side chains capable of acquiring a positive charge (Wu and Dimler 1963a, 1963b cited by Kasarda 1976). This gives the gluten complex an unusually wide isoelectric point between pH 6 and 9. At pH values below 4 or 5 gluten becomes moderately soluble. At pH values above 11 gluten also becomes moderately soluble, but at this elevated pH disulfide bonds can be broken.

Vital wheat gluten finds its major use in the baking industry, where its most valuable properties are: (1) dough strengthening, (2) gas retention and controlled expansion resulting in uniform shaped products, (3) structural enhancement due to thermosetting, and (4) water absorption and retention allowing improved yield, product softness and extended shelf life, and natural flavor enhancement (Anonymous 1981). Wheat gluten is used most often to add strength to and increase water absorption of bakery products, such as variety breads and hinged buns.

Magnuson (1977) estimated that about 100 million pounds of vital wheat gluten is used each year in the United States. About 60% goes into

Table 1

Amino Acid Composition of Gluten, Gliadin and Glutenin[a]

(moles amino acid per 10^5g of protein)

Amino Acid	Gluten	Gliadin	Glutenin
Arginine	20	15	20
Histidine	15	15	13
Lysine	9	5	13
Threonine	21	18	26
Serine	40	38	50
Aspartic acid	22	20	23
Glutamic acid	290	317	278
Glycine	47	25	78
Alanine	30	25	34
Valine	45	43	41
Leucine	59	62	57
Isoleucine	33	37	28
Proline	137	148	114
Tyrosine	20	16	25
Phenylalanine	32	38	27
Tryptophan	6	5	8
Cystine/2	14	10	10
Methionine	12	12	12
Ammonia	298	301	240

[a]Data of Wu and Dimler (1963)

bakery foods with the remainder used in prepared cereals, pet food, pasta and meat analogues.

Wheat gluten is not a good protein supplement because of a deficiency in some of the essential amino acids, particularly lysine. The protein efficiency ratio (PER) for wheat gluten ranges from 0.7 to 1.0, or about 28 to 40% of the value of casein (Anonymous 1981). Vegetable proteins generally have low PER values. Even with the addition of optimal amounts of lysine the PER of wheat gluten becomes only 1.7. The blending of different types of vegetable proteins can sometimes give a higher PER than the arithmetic average would suggest. Such is the case with a blend of wheat gluten and soy flour. Soy flour has a PER of 2.0. A 45/55 wheat gluten to soy flour blend has a PER of 2.3 (Anonymous 1981). The use of textured wheat gluten as a meat extender would give the extender itself a low PER value; however since the finished food product would only be 15-20% textured wheat gluten its nutritional quality would not be greatly reduced.

John Harvey Kellogg did some of the first work on fabricated plant proteins in this country. Kellogg was trying to develop palatable diets devoid of meat, one example of which was a texturized product developed from wheat gluten. The gluten was texturized by boiling. This denatured and expanded the protein into a chewy product. The product was then used in bouillon-type broth, or minced and used as imitation meat (Hartman 1976, cited by Kinsella 1978). A patent (U.S. Patent 869,371) was obtained by Kellogg in 1907 for processing a meat-like product from a mixture of wheat gluten and casein.

In recent years there has been a renewed interest in the use of wheat gluten for the production of meat analogues. Tanaka et al (1976) produced

a meat analogue by blending a foaming agent with vital wheat gluten. The product had the fine fiberous structure of crab meat. Palmer (1972) patented a process to make simulated meat by heat coagulation of wheat gluten. The wheat gluten was hydrated into a thin dough, placed in a pan and heated to 400°F. The dough quickly forms a skin and then expands by internal steam generation. When the protein reaches its coagulation temperature the dough sets. After the product cools it can be rehydrated and substituted for chopped meat.

Blends of wheat gluten and other vegetable proteins have been used in the production of meat analogues. Arima and Harada (1971) used a blend of proteins from wheat, soy, milk and eggs to produce a meat analogue. The proteins were coagulated into a soft curd with the addition of calcium salts. The curd was then hardend with the addition of an acid and the protein structure set by boiling. Nagasawa et al (1972) also produced a meat analogue from a blend of proteins, soy, casein and wheat gluten. They used a divalent cation to coagulate the protein. The protein was set by heating to 85°C.

Meat extenders have been produced from wheat gluten. MacAllister and Finucane (1963) described a method by which a dry mix of wheat gluten, soy flour, albumin and starch was used to produce a meat extender. The mix was formed into a dough with the addition of water and vegetable oil. The dough was extruded through a pasta extruder, cut into short pieces and dried. The rehydrated pieces had a meat-like appearance and could be used in chopped meats.

High temperature, high pressure extrusion can also be used to texturize wheat gluten. Wheat gluten is named as a possible protein source in some patent literature dealing with high temperature, high pressure extrusion.

Atkinson (1970) claims a process which is not limited to any particular type of protein, and in which any type of vegetable or animal protein can be used. Baker et al (1975) lists vital wheat gluten as a possible protein source in a patent for the production of a meat-like product. Both of these patents call for high compression and a pressure drop at the die of at least 100 psi. Atkinson claims the pressure drop should be between 250 and 900 psi. Wheat gluten is mentioned as the preferred vegetable protein in some patents where the extrusion process is used. These processes use a low pressure drop at the die and have little compression within the barrel. Hayes et al (1975) suggested using 1.5:1 compression screw with a pressure drop less than 200 psi. Feldbrugge et al (1975) recommended using a 2:1 compression screw with a pressure drop of less than 100 psi. Both of these processes give a product which is relatively dense and absorbs less water than products made with high pressure and high compression.

There are a variety of tests that have been designed to characterize texture and other physical properties of TPP. Some of these tests can be used to monitor effects of process conditions on TPP characteristics. There are no standardized tests or no procedures for testing TPP quality.

Water absorption or rehydration value is a common physical test for TPP. The TPP is placed in excess water of specified temperature and allowed to rehydrate for a specified time. Following rehydration the TPP is drained. Water absorbed per unit of TPP is calculated to give water absorption. Water absorption may be given as a percent increased in weight (percent rehydration). This type of test is not standardized as various laboratories use different rehydration conditions. Samples can be retorted (Harper 1981b), rehydrated in 25°C water for 15 minutes (Aguilera and Kosikowski 1976), rehydrated in boiling water for 5 or 10 minutes (Cumming

et al 1972) or rehydrated for 5 minutes in 4°C, 24°C or 100°C water (Taranto et al 1975).

Bulk density (Harper 1981b) and density (Stearns 1974; Taranto et al 1975) have both been used to indicate degree of expansion of extruded products. Bulk density is determined by obtaining the weight of TPP which occupies a given volume. The second test, density, assumes that the shape of an extrudate approximates a simple geometric shape. The volume is calculated and divided into the weight of the extrudate. The density measurement of a TPP gives a better estimate of expansion than does bulk density, but not all extrudates approximate a simple geometric shape.

An test for TPP integrity was proposed by USDA (1974) and was subsequently improved by Bird (1975, cited by Harper 1981b). The sized TPP (-4 +20 mesh) is thoroughly hydrated with water and then retorted for 15 minutes. The cooled TPP is placed on a 20 mesh screen and rinsed with a constant spray for one minute. The integrity index is the weight of the TPP remaining on the screen divided by the weight of the original hydrated TPP.

Instrumental methods for measuring TPP texture include; Kramer Shear Press (KSP), Warner-Bratzler Shear Instrument (WBS) and the Minnesota Texture Method (MTM) (Harper 1981b). KSP is used to determine shear force and work of shearing (Cumming et al 1972), measure compressibility and shear of TPP. WBS relates more directly to shear than does KSP, because the blades are thinner with WBS (Cumming et al). The MTM measures the textural parameters hardness, cohesiveness, chewiness, packability and extrudability (Breene 1977). The texture is determined by extruding a sized (-4 +20 mesh) and hydrated TPP through an Ottawa Texture Measuring System. The system is a 10 cm^3 cell with an 8-wire grid. The textural properties of TPP are correlated with force displacement curve.

MATERIALS AND METHODS

Vital Wheat Gluten

Vital wheat gluten was donated by Midwest Solvents Co. Inc., Atchinson, Kansas. The gluten had a protein content of 75.5% (db, N x 5.7) and had an average particle size of 180 microns and a geometric standard deviation (sgw) of 1.52.

Peelings

Peelings is the name of screenings obtained during the wet milling of whole wheat in a commercial separation system. Proximate analysis values for peelings are shown in Table 2. Due to limited availability of actual peelings in this country a simulated peelings fraction was prepared from a mixture of bran, shorts and germ collected from the Kansas State University pilot flour mill. Each of the three fractions were finely ground through an Alpine pin mill (model 160 z; Augsbrug, Germany). Simulated peelings were a blended mixture of 87.0% bran, 8.0% shorts and 5.0% germ. Proximate analysis values of the simulated peelings are shown in Table 2. The simulated peelings had an average particle size of 300 microns and a sgw of 1.65, actual peelings had an average particle size of 411 microns and a sgw of 1.28.

Particle Size Determination

Particle size determinations were done by the method of Pfost and Headley (1976).

Tempering

Tempering was carried out in a Hobart mixer (model A-200; Troy, OH) using a McDuffey bowl and fork. The mixing bowl was fitted with a stainless steel cover to prevent excessive sample loss during mixing.

Table 2

Proximate Analysis of Wheat Gluten, Peelings and Simulated Peelings

Sample	Crude protein	Ash	Ether extract	Crude fiber	Nitrogen free extract
Wheat Gluten	75.5	0.9	1.1	0.3	22.3
Peelings	16.7	6.1	3.1	11.2	62.9
Simulated Peelings	17.9	6.7	3.4	9.8	62.2

Data reported on dry matter basis.

Distilled water necessary to bring 1500 g of sample (gluten plus peelings) to the desired moisture level was added while the mixer was running. Mixing was continued for five minutes after all water was added. The sample was immediately extruded to prevent agglomeration. Actual moisture values (AACC method 44-31) after tempering averaged 1.5 percent lower than calculated values.

Extruder

All runs were carried out on a laboratory scale, single screw, Brabender extruder (Model 2403; South Hackensack, NJ).

Specifications

Barrel Diameter	1.905 cm
Barrel Length	47.65 cm
Barrel Length to Diameter Ratio	25:1
Number of Temperature Control Zones	3
Compression Ratio	5:1
Cooling	compressed air

The extruder was equipped with a stainless steel screw, fitted with a torpedo point to fill the void volumn at the end of the extruder.

Die

A carbon steel side discharge die, designed and built at Kansas State University, was used in this study. The discharge opening of the die was 3.81 cm from the extruder barrel and had a square opening 0.635 cm on a side. A side discharge die has its discharge opening perpendicular to the barrel axis.

Extruder Operation

Processing temperatures were fixed in zone 1 (25°C) and zone 2 (100°C). The temperature of zone 3 was varied over 5 different levels between 130 and 190°C. Screw speed was maintained at 150 RPM.

Prior to each sample run, ground corn (25% moisture) was extruded to establish a uniform flow. The sample material followed the corn and was extruded for about two minutes prior to sample collection to avoid contamination.

Between sample runs zones 2 and 3 were cooled to 75°C, the screw and die removed and the barrel cleaned. Following cleaning, zones 2 and 3 were reheated and the extruder readied for the next sample.

Approximately 1 kg of sample was collected for each run. Samples were air dried overnight at room temperature and stored at room temperature in sealed polyethylene bags following drying.

Sizing

Samples were ground through a laboratory Ross roller mill (size 9" x 6"; Oklahoma City, OK). Samples were sized on a Gyro-Lab sifter (size 100; Richmond Manufacturing Co., Lockport, NY). Sampled material passed through a number 3 1/2 (5.66 mm opening) and remained on a number 8 wire mesh (2.38 mm opening) screen.

Bulk Density

Bulk density of the sample was determined by weighing the sample material required to fill a container of known volume.

Rehydration

Rehydration studies using water at each of three temperatures were performed on each extrudate. The water temperatures used were 100°C (boiling) 25°C (room temperature) and 2°C (cold). A five g sample was placed in a styrofoam cup and fifty milliliters of water added. After a 10 minute rehydration excess water was removed through a Buchner funnel lined with Whatman number 4 filter paper. The sample was reweighed and percent rehydration calculated as follows:

$$\% \text{ Rehydration} = \frac{\text{Wt. rehydrated sample} - \text{Wt. original sample}}{\text{Wt. original sample}} \times 100$$

Twelve Hour Rehydration

A five g sample was placed in a 235 ml glass container and 50 milliliters of 25°C (room temperature) water was added. The container was sealed and the sample was allowed to rehydrate for 12 hours at room temperature. Percent rehydration was calculated as before.

Rate of Rehydration

Three extrudate runs were selected, on the basis of density, for determination of the effect of rehydration time on percent rehydration. Eight, 5 g, subsamples were taken from each of the three extrudate runs and rehydrated in 50 milliliters of 25°C (room temperature) water. The subsamples were rehydrated for various time intervals from five minutes to 360 minutes. Percent rehydration was graphed against time in Figure 8.

Cooking Rehydration

A 10 g sample was placed in a 235 ml glass container and combined with 160 ml of water. The sample was heated in a sealed vessel until 1.68 atm of steam pressure was obtained. Temperature and pressure were maintained for 15 minutes. After cooling excess water was removed using a Buchner funnel lined with Whatman number 4 filter paper. The sample was reweighed and percent rehydration calculated.

Integrity Test

A twenty-five g sample was added to 150 ml of distilled water in a glass container. The sample was then cooked under pressure as described for cooking rehydration.

The cooled sample was decanted. The solid fraction was transferred to a 1000 ml boiling flask and stirred at 500 RPM for 10 minutes. The

sample was then spread evenly over a number 6 Tyler screen. Five, 500 ml aliquots of water were poured evenly over the sample. Material retained on the screen was placed in a 10.2 x 5.1 x 5.1 centimeter pan and dried at 130°C for 15 hours. Percent dry matter loss was calculated as follows:

$$\text{\% dry matter loss} = \frac{\text{dry matter before}^* - \text{dry matter after}}{\text{dry matter before}^*} \times 100$$

*Dry matter of extrudate samples were determined by drying at 130°C for 3 hours.

Experimental Design

Five treatment levels of temperatue (130, 142, 160, 178 and 190°C), moisture (20.5, 22.5, 25.5, 28.5 and 30.5%) and peelings (0, 3, 7.5, 12 and 15%) were studied (Table 3). Fifteen of the possible 125 combinations were selected for testing according to a central composite rotational design (Cochran and Cox 1957). Product data was analyzed by the Regression analysis portion of the SAS program (SAS Institute Inc; Raleigh, NC, 1982 release). The regression equations were plotted with the GContour option of the SAS/ Graph program.

Table 3

Run Order and Variables for Extrusion

Run order	Temperature^{o}C	% Peelings	% Moisture
1	142	3.0	22.5
2	178	12.0	22.5
3	160	15.0	25.5
4	178	12.0	28.5
5	160	7.5	25.5
6	178	3.0	25.5
7	130	7.5	25.5
8	160	7.5	25.5
9	160	7.5	25.5
10	142	12.0	22.5
11	160	7.5	25.5
12	142	12.0	28.5
13	160	7.5	25.5
14	190	7.5	25.5
15	142	3.0	28.5
16	160	7.5	20.5
17	160	0.0	25.5
18	160	7.5	25.5
19	160	7.5	30.5
20	178	3.0	28.5

RESULTS AND DISCUSSION

Bulk Density

The results of the fitted regression model for bulk density of the extrudate are summarized in Table 4. Peelings quantity did not have a significant ($P<0.05$) affect on the regression and was therefore left out of the regression model. Figure 2 is the graph of the regression model and depicts the effect of process temperature and percent moisture of the feedstock upon the bulk density of the extrudate. The bulk density of the extrudate decreases as process temperature increases. Cumming et al (1972), with soybean meal and Taranto et al (1975), with cottonseed meal, found a similar relationship. Taranto suggests that at low processing temperatures the extrudate is undercooked, brittle and tightly compacted. As the temperature is increased the material is more fully cooked and becomes more plastic. The more fully cooked, more plastic material allows for more expansion and reduced density. Cumming et al (1972) suggested that physical changes affecting density occur prior to the die. They found marked changes in density as process temperature was increased, but the net diameter of the extrudate remained constant.

Figure 2 shows that as moisture content of the feedstock increases the bulk density of the extrudate also increases. Pressure in the barrel is caused by the compression of the material as it moves down the barrel and by the temperature in the barrel. The driving force for expansion is the difference between pressure within the barrel and atmospheric pressure. Increases in processing temperatures alter the characteristics of the material in process making it more plastic. This allows for greater expansion. Since the amount of expansion depends on the pressure across the die, a high moisture sample should expand to the

same degree as a low moisture sample, up to some moisture optimum, if the process temperatures are equal.

The elastic nature of gluten and the fact that high moisture samples extruded at low temperatures were observed to be wet after extrusion may provide an explanation of expansion. When material exits the die flash evaporation takes place which dries the extrudate. Low moisture samples flash off enough water to allow the gluten to set in the expanded state. A sample of higher moisture would expand initially to the same degree as the lower moisture sample, but since the sample is of higher moisture, a smaller percentage of the water would be driven off by flash evaporation, leaving more water in the extrudate. This may allow the gluten to contract into more dense extrudate.

Rehydration

The cooking rehydration (CR) was significantly correlated with process temperature and percent moisture of the feedstock. The results of the regression model are summarized in Table 5. Peelings did not significantly affect ($P<0.05$) the regression model for CR and was therefore left out of the model. Figure 3 depicts the effect of process temperature and percent moisture of the feedstock on CR. Percent rehydration varied directly with temperature and inversely with moisture. A 30 minute cooking rehydration was also done, with little or no increase in rehydration, indicating that the extrudates were fully rehydrated at 15 minutes. If this is the case then all the extrudates should absorb the same amount of water if the absorption capacity of the feedstock was not altered during the extrusion. The difference, then, in the percent rehydration between the high and low (331.42% and 212.76%) values was due to some structural change in the extrudate.

Bulk density (Table 6) is inversely correlated with percent rehydration. The change in bulk density is caused by structural changes in the extrudate. Figure 4 shows that the low bulk density extrudates have larger cells with thinner cell walls. The lower bulk density extrudates also appear to have more cells per unit weight giving a more sponge like structure. The increased surface area of this sponge like structure allows for greater absorption. Cumming et al (1972) found similar results for defatted soybean meal using a boiling water rehydration. They concluded that the more sponge like the structure the more water that is imbided by the product.

Hot water (boiling) rehydration (HWR) was significantly correlated with process temperature and percent moisture of the feedstock. The results of the regression model are summarized in Table 7. As before, peelings, did not have a significant effect ($P<0.05$) on the regression model and was not included in further calculations. Figure 5 depicts the effect of process temperature and percent moisture on HWR. Percent rehydration varied directly with process temperature and inversely with percent moisture. Since this was a short time rehydration (10 minutes), the increase in the amount of water absorbed could be due either to the rate at which the water is absorbed or to the sponge like structure, which allows the extrudate to absorb and hold more water.

A similar rehydration was also performed with room temperature water ($25^{o}C$). The room temperature water rehydration (RWR) was also significantly correlated with process temperature and percent moisture of feedstock. The results of the regression model are summarized in Table 8. Peelings did not have a significant effect ($P<0.05$) on the regression model and was left out. Figure 6 depicts the effect of process temperature and percent moisture on RWR. Percent rehydration increased directly with

process temperature and inversely with percent moisture. As with HWR the amount of water absorbed could depend on the rate of absorption or on the absolute capacity of the extrudate.

Cold water (2°C) rehydration (CWR) was also significantly correlated with process temperature and percent moisture of feedstock. The results of the regression model are summarized in Table 9. Peelings did not significantly effect ($P<0.05$) the regression model and was therefore left out of the model. Figure 7 depicts the effect of process temperature and percent moisture on CWR. As can be seen these effects are similar to those seen with HWR and RWR.

The sponge like structure of extrudates allows the greater total absorption, and may influence the rate of absorption. Extrudate with more cells per unit weight will have more surface area. The greater surface area would allow for faster absorption, because there is more area for absorption to take place. Because of the time involved with these rehydrations (10 minutes), the rate of absorption might have an effect on the amount of absorption.

Figure 8 depicts the rate of absorption of three extrudates, the least dense, the most dense and an extrudate of intermediate density. There is a large difference in the amount of water absorbed between the highly expanded extrudate and the dense extrudate. Clearly, the highly expanded extrudate does absorb water faster. In Figure 9 where the rehydration time is 12 hours, the extrudates should be fully rehydrated and the rate of absorption would not be a factor. The relationships between percent rehydration and process temperature and percent moisture are the same as for 10 minute rehydration of these samples. Thus while rate of absorption varies between extrudates it is closely related to total absorptive capacity.

Physical Integrity of Extrudates

Table 11 is a summary of the results of the fitted regression model for dry matter loss of extrudates. Moisture did not have a significant ($P<0.05$) affect on extrudate integrity and was not included in the regression model. Figure 10 illustrates the effect of process temperature and percent moisture on the integrity of the extrudate. Dry matter loss increased with both increased peelings and process temperature.

Figure 11 shows that particles of peelings did not lose their integrity and remained as individual particles throughout extrusion.

As material leaves the transition section of the barrel it has been changed from a particulate state into a dough-like mass. Protein molecules unfold and become aligned in the direction of flow and form fiberous sheaths (Kinsella 1978). Since peelings retained their integrity it forces the dough-like mass to align around the peelings particles, leaving the peelings imbedded in the extrudate matrix. Having these large individual particles in the extrudate matrix could weaken the extrudate by destroying the continuity of the aligned mass. The weakened extrudate would then be expected to break up more during the integrity test giving a higher dry matter loss.

Process temperature was also shown to increase dry matter loss. The cell walls of lower bulk density, extrudate were thinner than those of higher bulk density (Figure 4). Process temperature influenced the amount of expansion that took place at the die, and therefore, the bulk density of the extrudate. The degree of expansion, therefore, influences the cell wall thickness. The thin cell wall extrudates had greater dry matter loss indicating a relationship between temperature, cell wall thickness and dry matter loss.

CONCLUSION

Process temperature, percent moisture and percent peelings were significantly related to physical properties of the extrudate. Process temperature appeared to have the greatest effect. It was a significant variable for all three extrudate properties examined. Process temperature was the only variable with an independent effect on bulk density and rehydration. Temperature is thought to be a major controlling factor for expansion. Moisture content of the feedstock is inversely related to process temperature in its effect on expansion. High moisture samples showed decrease expansion by allowing the gluten to contract before it sets, after expansion.

Expansion influences bulk density by producing an extrudate of varying volume per given weight. Increased expansion also effects rehydration in two ways. Expansion gives the extrudate a more sponge like structure. This structure then allows the extrudate to absorb and hold more water. Secondly, expansion gives the extrudate more surface area, so absorption can occur faster. The expansion can then influence the amount of rehydration in a short time test. Because the rate of absorption is dependent upon the structure of the extrudate, the ranking in terms of absorption does not change. The extrudate that absorbs the most water also absorbs water the fastest, and the extrudate that absorbs the least amount of water absorbs water the slowest. Rehydration was highly corrlelated with bulk density. This was to be expected since expansion is the major controlling factor for both of these properties. Expansion is also thought to be responsible for magnifying the amount of dry matter loss of the extrudate. Expansion produces thinner cell walls which could break easier than thick cell walls.

The distruction of the extrudate would produce some pieces small enough to be lost during the screening part of the integrity test. The thin cell wall extrudate could also let more soluble material diffuse out of the extrudate during the cooking part of the integrity test, thus causing greater dry matter loss.

Peelings was shown to be significant for dry matter loss. It was thought that the peelings, being able to retain their integrity in the extruder, disrupt the continuity of the extrudate mass, thereby weakening the extrudate. This was the only property affected by percent peelings and the effect was not large. Since peelings are not a significant factor in rehydration, they can be added at low levels to gluten without adversely effecting the rehydration of the extrudate.

Obviously more work would have to be done with this product before it could be used as a meat extender. The textural properties of the extruded gluten would need to be studied, along with how these textural properties are effected by peelings. The extruded gluten product would also have to be tested against textured soy products for acceptance.

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Table 4

Summary of Bulk Density Data for Regression Model

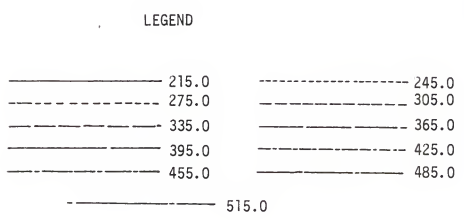
Source	Degrees of freedom	Sum of squares	Mean square	F	Prob>F
Regression	2	81277.58	40638.79	49.16	0.0001
Error	17	14053.09	826.65		
Total	19	95330.66			

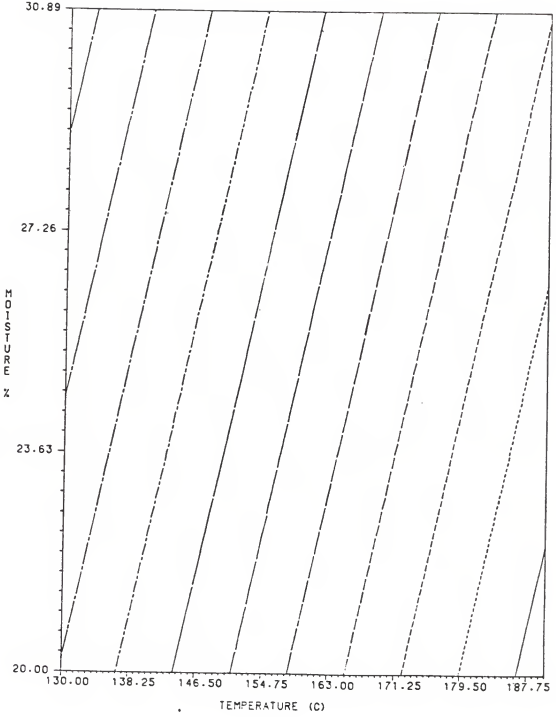
	B-value	T-test for parameter=0	Prob > T
Intercept	862.86400	11.122	0.0001
Temperature	-4.22604	-9.610	0.0001
Moisture	6.96405	3.977	0.001

Model Y = 862.864 -4.22604 x Temperature +6.96405 x Moisture

R^2 = 0.8526

Figure 2. Bulk density of extrudate, contours as a function of process temperature and moisture content of feedstock. Bulk density in kg/m^3.

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27.26
23.63
20.00
MOISTURE %
130.00
138.25
146.50
154.75
163.00
171.25
179.50
187.75
TEMPERATURE (C)

Table 5

Summary of Cooking Rehydration Data for Regression Model

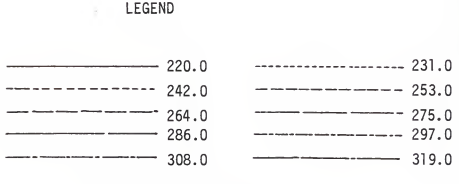
Source	Degrees of freedom	Sum of squares	Mean square	F	Prob>F
Regression	2	9906.84	4953.42	31.47	0.0001
Error	17	2675.89	157.40		
Total	19	12582.73			

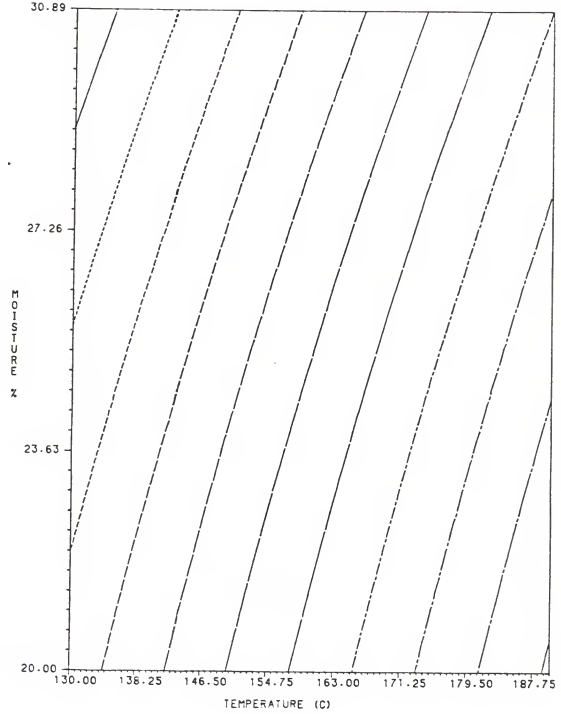
	B-value	T-test for parameter=0	Prob > T
Intercept	89.27204	2.646	0.0170
Temperature	1.40545	7.424	0.0001
Moisture^2	-0.06218	-2.797	0.0124

Model Y = 89.27204 +1.40545 x Temperature -0.06218 x Moisture^2

R^2 = 0.7873

Figure 3. Cooking rehydration of extrudate, contours as a function of process temperature and moisture content of feedstock. Cooking rehydration in percent water absorbed.

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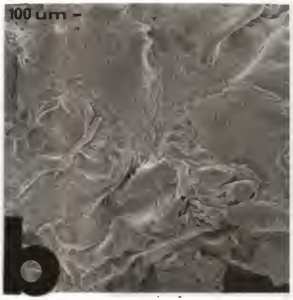
TEMPERATURE (C)

Figure 4. Scanning Electron Micrographs of Extrudates. 4A Cross section of a highly expanded extrudate, 4B surface of a highly expanded extrudate, 4C cross section of a less expanded more dense extrudate, 4D surface of a less dense extrudate.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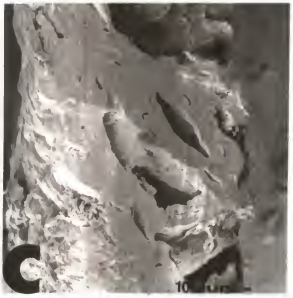
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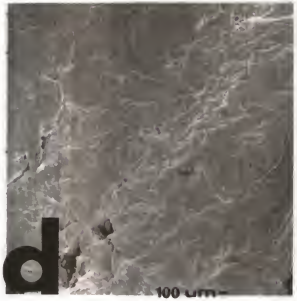
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100 um

Table 6

Correlation Coefficients for Bulk Density vs Percent Rehydration

Type of Rehydration	Bulk Density	
	Pearson Correlation	Spearman Correlation
Cold	-0.9085	-0.9338
Tepid	-0.9313	-0.8815
Hot	-0.9570	-0.9023
Cooking	-0.9085	-0.8647

Table 7

Summary of Hot Water Rehydration Data for Regression Model

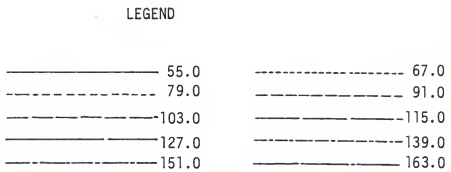
Source	Degrees of freedom	Sum of squares	Mean square	F	Prob>F
Regression	2	12114.12	6057.06	49.81	0.0001
Error	17	2067.10	121.59		
Total	19	14181.22			

	B-value	T-test for parameter=0	Prob > T
Intercept	33.40501	1.785	0.0921
Temperature^2	0.00485	9.345	0.0001
Moisture^2	-0.06849	-3.505	0.0027

Model Y = 33.40501 +0.00485 x Temperature^2 -0.06849 x Moisture^2

R^2 = 0.8542

Figure 5. Hot water rehydration of extrudate, contours as a function of process temperature and moisture content of feedstock. Hot water rehydration in percent water absorbed.



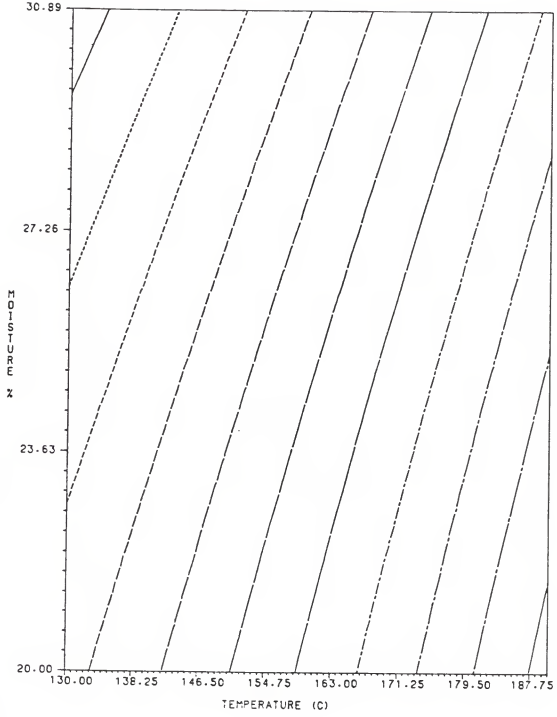

30.89
27.26
23.63
20.00
MOISTURE %
130.00
138.25
146.50
154.75
163.00
171.25
179.50
187.75
TEMPERATURE (C)

Table 8

Summary of Room Temperature Rehydration Data for Regression Model

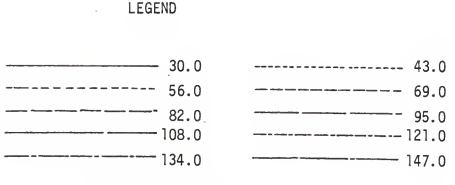
Source	Degrees of freedom	Sum of squares	Mean square	F	Prob>F
Regression	2	12759.58	6379.79	36.49	0.0001
Error	17	2972.15	174.83		
Total	19	15731.73			

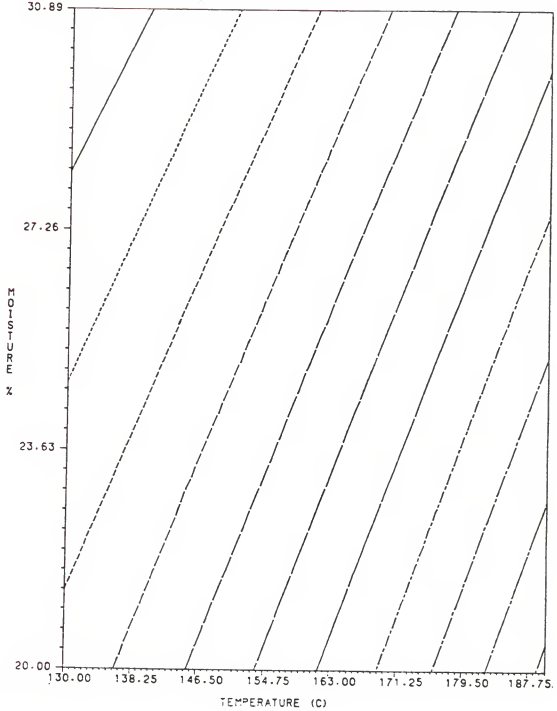
	B-value	T-test for parameter=0	Prob >T
Intercept	16.45531	0.739	0.4697
Temperature^2	0.00706	8.223	0.0001
Temperature x Moisture	-0.02964	-3.982	0.001

Model Y = 16.45531 +0.00706 x Temperature^2 -0.02964 x Temperature x Moisture

R^2 = 0.8111

Figure 6. Room temperature rehydration of extrudate, contours as a function of process temperature and moisture content of feedstock. Rehydration in percent water absorbed.

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23.63
20.00
MOISTURE %
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138.25
146.50
154.75
163.00
171.25
179.50
187.75
TEMPERATURE (C)

Table 9

Summary of Cold Water Rehydration Data for Regression Model

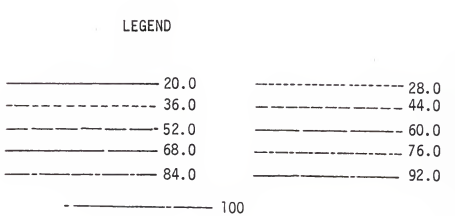
Source	Degrees of freedom	Sum of squares	Mean square	F	Prob>F
Regression	2	5603.81	2801.90	28.69	0.0001
Error	17	1660.22	97.66		
Total	19	7264.03			

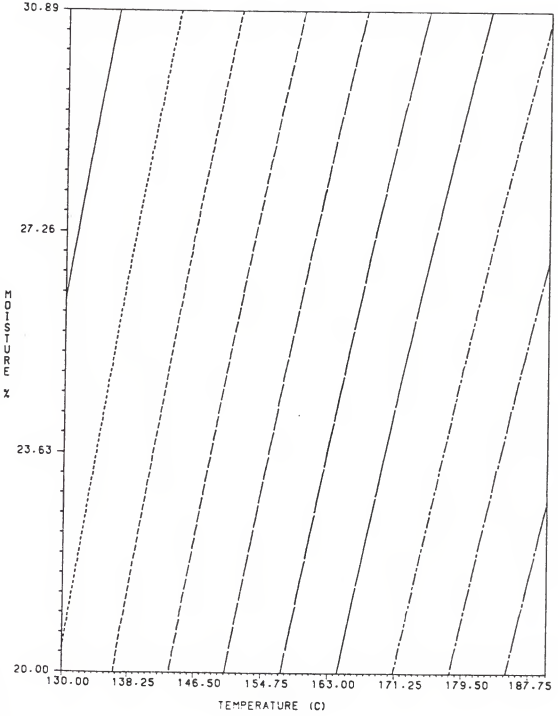
	B-value	T-test for parameter=0	Prob > T
Intercept	-121.48000	-5.007	0.0001
Temperature	1.38627	7.341	0.0001
Temperature x Moisture	-0.01070	-3.029	0.0076

Model Y = -121.48 +1.38627 x Temperature -0.01070 x H_2O x Temperature

R^2 = 0.7714

Figure 7. Cold water rehydration of extrudate, contours as a function of process temperature and moisture content of feedstock. Rehydration in percent water absorbed.

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MOISTURE %
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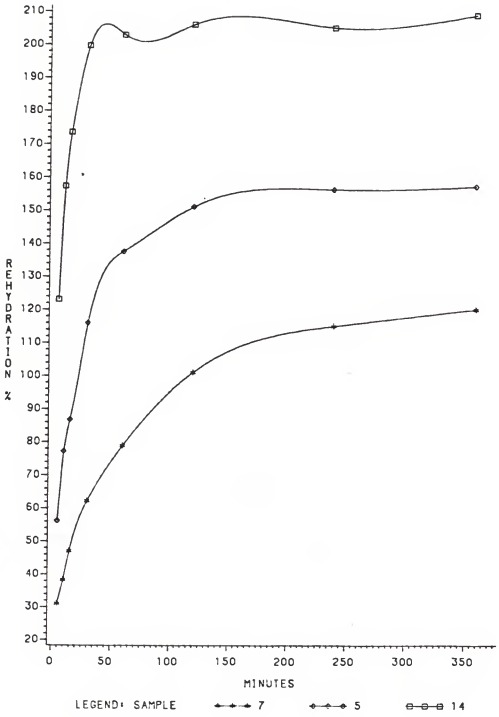
TEMPERATURE (C)

Figure 8. Speed of rehydration for three extrudates. Sample 7 most dense extrudate, sample 5 extrudate of intermediate density and sample 14 least dense extrudate.


REHYDRATION %
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200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
0
50
100
150
200
250
300
350
MINUTES
LEGEND: SAMPLE
7
5
14

Table 10

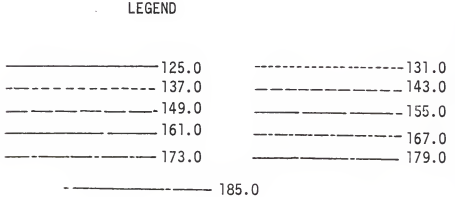
Summary of 12 Hour Rehydration Data for Regression Model

Source	Degrees of freedom	Sum of squares	Mean square	F	Prob>F
Regression	2	4492.095	2246.048	35.410	0.0001
Error	17	1078.298	63.492		
Total	19	5579.393			

	B-value	T-test for parameter=0	Prob > T
Intercept	82.39744	7.792	0.0001
Temperature^2	0.00320	8.394	0.0001
Moisture^2	-0.01814	-2.184	0.0433

Model Y = 82.397 + 0.0032 x Temperature^2 -0.0181 x Moisture^2
R^2 = 0.8064

Figure 9. Twelve hour rehydration of extrudate, contours as a function of process temperature and moisture content of feedstock. Rehydration in percent water absorbed.



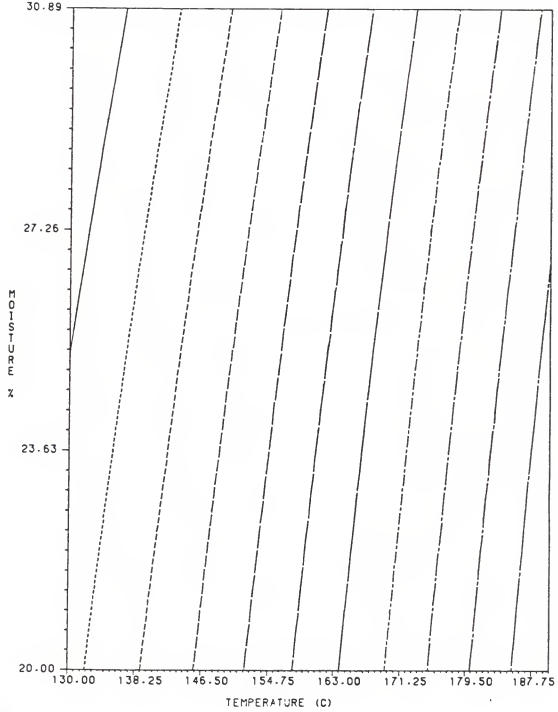

30.89
27.26
23.63
20.00
MOISTURE %
130.00
138.25
146.50
154.75
163.00
171.25
179.50
187.75
TEMPERATURE (C)

Table 11

Summary of Dry Matter Loss Data for Regression Model

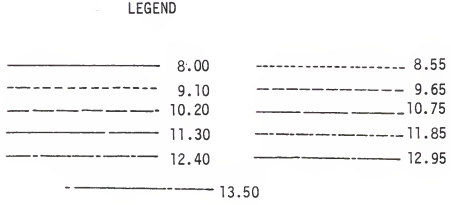
Source	Degrees of freedom	Sum of squares	Mean square	F	Prob>F
Regression	2	26.52	13.26	17.606	0.0001
Error	17	12.80	0.75		
Total	19	39.32			

	B-value	T-test for parameter=0	Prob > T
Intercept	6.45029	5.876	0.0001
Peelings^2	0.01834	5.495	0.0001
Temperature^2	0.00009	2.248	0.0382

Model Y = 6.45029 +0.01834 x Peelings^2 +0.00009 x Temperature^2

R^2 = 0.6744

Figure 10. Dry matter loss of extrudate, contours as a function of process temperature and percent peelings of feedstock. Dry matter as percent loss in extrudate.



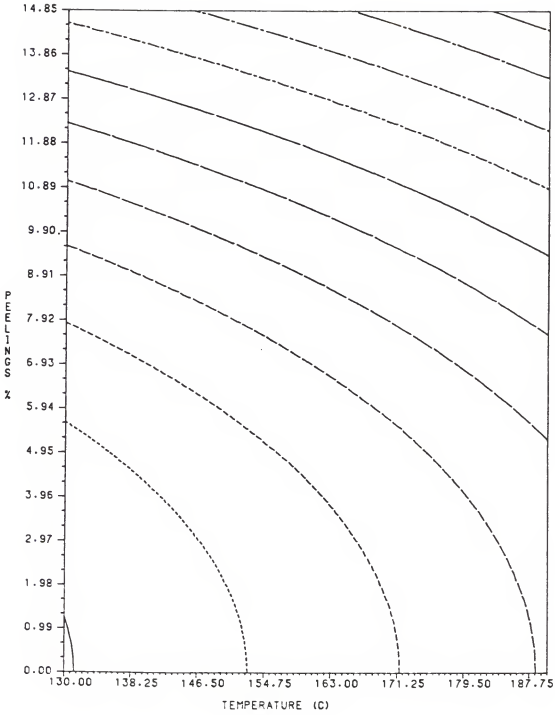
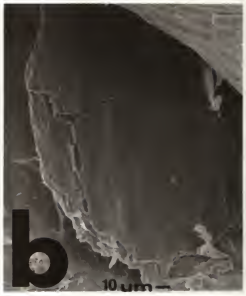
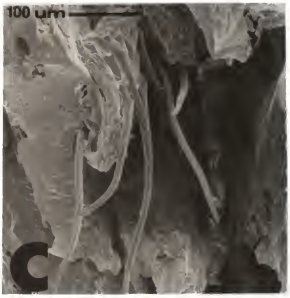

14.85
13.86
12.87
11.88
10.89
9.90
8.91
7.92
6.93
5.94
4.95
3.96
2.97
1.98
0.99
0.00
FEELINGS %
130.00
138.25
146.50
154.75
163.00
171.25
179.50
187.75
TEMPERATURE (C)

Figure 11. Scanning Electron Micrographs of an Extrudate. 11A Cross section of extrudate, 11B, C and D show embedded peelings within the extrudate.


a
100 um


b
10 um


100 um
c


d
100 um

APPENDIX

Sample Number	Cooking* Rehydrtion %	Hot Water* Rehydration %	Room Temperature* Rehydration %	Cold Water* Rehydration %
1	285.01	104.43	72.13	48.64
2	303.52	135.42	101.67	69.02
3	283.73	119.00	75.27	54.42
4	306.44	113.93	95.13	63.16
5	284.10	115.44	77.67	55.43
6	303.20	144.55	115.14	76.04
7	228.04	64.16	38.37	32.00
8	275.79	125.71	88.51	56.53
9	269.49	118.13	75.92	51.60
10	232.80	80.97	47.78	33.70
11	266.60	111.85	78.84	53.17
12	251.48	86.35	52.61	39.09
13	267.35	115.31	78.84	54.11
14	215.64	184.20	157.28	118.75
15	224.17	75.61	39.85	32.91
16	290.96	138.14	111.98	77.24
17	267.29	103.60	61.15	48.34
18	280.99	117.19	72.79	54.40
19	252.81	88.27	48.50	41.53
20	277.23	111.93	66.33	54.16

*Values are an average of three.

Sample Number	Twelve Hour* Rehydration %	Dry Matter# Loss %	Bulk* Density (k/m^3)
1	145.77	9.04	370.00
2	158.41	12.78	320.19
3	151.39	13.75	382.85
4	163.53	10.75	334.77
5	156.17	9.49	356.25
6	171.93	9.12	267.47
7	174.85	9.16	518.11
8	159.53	9.25	346.79
9	154.96	8.92	368.27
10	127.18	9.62	449.04
11	150.87	9.92	374.86
12	138.99	11.19	462.34
13	152.73	9.41	362.66
14	205.53	10.35	225.80
15	136.24	7.74	463.14
16	156.79	11.36	364.90
17	148.76	8.68	366.99
18	154.67	11.43	455.45
19	139.66	9.93	417.79
20	154.95	10.26	347.76

*Values are an averge of three.

#Values are an average of two.

Speed of Rehydration Data

	Sample		
	5	7	14
Time (min)		Rehydration %*	
5	56.24	31.04	123.10
10	77.20	38.37	157.28
15	86.81	47.01	173.61
30	115.96	62.18	199.66
60	137.60	78.90	202.87
120	151.06	101.00	206.13
240	156.22	114.96	205.13
360	157.04	119.94	208.99

*Values are an average of three.

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INFLUENCE OF A PROCESS VARIABLE, TEMPERATURE, AND TWO INGREDIENT VARIABLES, ON EXTRUSION TEXTURIZATION OF WHEAT GLUTEN

by

JOHN WARREN LAWTON JR.

B.S., Kansas State University, 1981

AN ABSTRACT OF A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Grain Science and Industry

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1984

Even though oilseed and cereal proteins have been processed by thermoplastic extrusion for about twenty years, there has been little research done in this area. This study investigated the changes that occur in physical properties of extruded wheat gluten, peelings mixture due to variation of the process temperature and the ratio of two added ingredients. Physical properties examined were bulk density, percent rehydration and integrity of the extrudate. Process temperature was shown to be significant for all three physical properties measured. It appeared that an increase in process temperature enhanced extrudate expansion. Bulk density decreased as process temperature increased and as percent moisture decreased. Expansion decreased bulk density by increasing the volume of extrudate for a given weight. Increased moisture appears to reduce expansion at a given temperature. Higher moisture samples were observed to be wetter than lower moisture samples after extrusion allowing gluten to contract before setting. Percent rehydration was shown to be negatively correlated with bulk density. Percent rehydration was shown to increase with lower bulk density extrudates. This was due to the more expanded extrudate's sponge like structure. It was believed that a sponge like extrudate can absorb and hold more water. Percent rehydration increased with process temperature and decreased with higher moisture. Expansion affected dry matter loss by causing thinner cell walls, which could be expected to produce a weaker extrudate and allow more soluble material to diffuse out of the extrudate. Peelings was only significant for the extrudate integrity. Particles of peelings were thought to disrupt the continuity of the extrudate matrix, thus producing a weaker extrudate. Dry matter loss was shown to increase as both percent peelings and process temperature were increased.