A Product Development Study: Rainbow Trout Bologna

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A PRODUCT DEVELOPMENT STUDY:

RAINBOW TROUT BOLOGNA

by

Marshall Dean Smith

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ABSTRACT

A Product Development Study:

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Department: Nutrition and Food Sciences

Mechanically deboned rainbow trout (*Oncorhynchus mykiss*) was analyzed and then used in texture studies. The meat contained a moderately low amount of fat (10% ± 2%, x ± SD). Pre-deboned meat had more calcium than deboned meat ($P<0.001$). Sausages were made of fish and various non-meat ingredients including egg white, collagen, soy protein isolate, starch, cellulose, and wheat gluten. Adhesiveness, cohesiveness, hardness, shear, and springiness of the cooked sausages were measured to describe texture. The data were fit to linear and quadratic models. Adhesiveness data did not fit the model ($F(6,50)=1.1$, $P>|F|=0.37$). A combined response model predicted formulations for fish sausage that would closely duplicate the texture of commercially available processed meats. A thermal model was developed that helped verify the thermal

properties of rainbow trout. Thermal conductivity was measured ($k = 0.48$ W/m·K) and specific heat was calculated ($C_p = 3200$ J/kg·K).

(104 pages)

DEDICATION

The completion of this research may be attributed to my wife, Allison. Her help and patience saw me through times of trouble and triumph. It is to our children that I dedicate this thesis. Erika and Clayton, may you enjoy a good life through our hard work.

ACKNOWLEDGMENTS

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Marshall D. Smith

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INTRODUCTION

Fish is a protein-rich food of great nutritional and economic importance. Value varies from specie to specie and depends on factors like availability, flavor, texture, meat content, bone content, and oil content. Rainbow trout, *Oncorhynchus mykiss*, are fish native to North American mountain streams and lakes. They are considered a valuable game fish. High protein content makes trout desirable from a nutritional standpoint. Table 1 compares red meat and fish.

Table 1--Composition of raw meat. Fish is similar to red meat

Meat	Water	Protein	Fat
Red meat	70%	20%	8%
Flounder	83%	15%	1%
Trout	71%	18%	10%

Statement of Problem

Fish may be processed into many different forms. Common forms are fillet, chunk, paté, and surimi. In all cases the head, tail, and viscera are removed. In many cases, fillets are cut, and the bones are discarded. The meat that remains on the bones represents a valuable resource.

One way to salvage meat is with a mechanical deboner. Such a machine uses pressure to separate muscle from bone. By running trout frames through a deboner, finely minced meat is obtained that may be further processed into a meat product. A possible use for this meat is to make a bologna-like product. Development of such a product is the focus of this research.

Sausage cookery affects product texture. Changes in heating rate, final cook temperature, cooking time, and size affect products differently. Cooking models simulate actual cooking cycles. By preparing a computer solution to the heat transfer problem of cooking a bologna-like sausage, multiple variables may be studied rapidly, and cook cycles may be predicted quickly.

Objectives

The overall objective of this research was to develop a fish product from mechanically deboned meat. Specific objectives included:

(1) Characterize mechanically deboned rainbow trout in terms of yield, proximate analysis, and mineral content.

(2) Develop a deboned trout product with a texture like bologna.

(3) Prepare a closed-form model of heat transfer for the bologna-like product. Validate the model by comparing analytical results to experimental results.

LITERATURE REVIEW

This section summarizes research pertinent to restructured trout bologna. Six areas are discussed: characteristics of deboned meat, products made with mechanically deboned meat, product development experimental design, texture, non-meat ingredients used in processed meat, and cooking models.

Two comprehensive project summaries review similar product development work. The Alaska Fisheries Development Foundation (1987) conducted a 6-year study on the manufacture of surimi. They focused on product quality measurement and production methods. The other summary was prepared by Berry (1987), who reviewed research relevant to USDA work on restructured meat. Some of the themes he studied were bind problems, inconsistent texture, crust formation, and air pockets. Process variables included particle size, addition of non-meat ingredients, and mixing. Berry also studied a wide range of instrumental measurements that provided insight into texture problems. Those two works provide an excellent foundation for product development research.

Characteristics of Deboned Meat

Mechanical deboning is the process of separating meat from bones. The principle behind deboning involves forcing meat, which is softer than bone, through a perforated chamber. The quality of the mince depends on both the species of fish and the portion of the fish being deboned. Possible raw materials include whole fish, fillets, trimmings, and back bones. The amount and quality of minced fish in a meat product greatly affects sensory results (Babbitt, 1986). Regenstein (1986) suggested the following factors for improved quality of mechanically recovered meat: premium starting materials, reduced yields, meat with minimal color, and proper frozen storage.

Mechanically deboned meat may be added to food products. Fish may not be added to processed meat products; however, the following restrictions apply to other forms of deboned meat: (1) calcium levels must be below 0.75% for red meat and below 0.175% for poultry; (2) it may not be added to baby, junior, or toddler foods, ground beef, fabricated steaks, or similar foods; (3) it must be labeled as "mechanically separated," and (4) 20% is the maximum level at which it may be added (CFR, 1996). The regulations imply that calcium levels increase as bone enters the product; however, Field et al. (1974) found that deboning decreased the calcium levels in pre- and post-rigor lamb.

Products Made with Mechanically Deboned Meat

A variety of products can be made from minced meat. Salt soluble proteins bind water and fat together and form excellent gels. Bind and gel formation enable minced meat to be used in products like hot dogs (Lanier, 1985). Other possible products include surimi, paté, ethnic foods, breaded or battered products that are deep fried, and puffed snack products.

Processed Meat

Salt soluble meat proteins have a great effect on the texture of processed meat. Grinding is a common manufacturing process that exposes extractable proteins. Those proteins congeal after cooking and bind meat particles together. For this reason, the final texture of processed meat depends on the particle size of the raw material. Emulsions utilize the exposed proteins to hold products together. Coarse-ground products often use finely ground meat (with ample protein) for bind. In a loaf product, ground meat binds large chunks together.

Perhaps the single most important attribute in determining the quality of a restructured product is particle size. Berry et al. (1987) studied beef and pork steaks and found that visually detected fibrousness, first bite hardness, cohesiveness, and shear force increased with increasing flake size. Penfield et al. (1992) compared steaks with flake widths of 1.295 and 1.905-cm and found that larger flakes produced more acceptable steaks.

Another processing method used in restructured products is tumbling. The mechanical action of tumbling exposes proteins that improve bind. Depending on the meat block and the desired effect of the tumbling action, the process may proceed for minutes or hours. Formed hams are tumbled for at least an hour. A catfish hot dog became rubbery when tumbled for more than 5 min (Abide et al., 1990).

Surimi

"Surimi is prepared by fresh water leaching of mechanically deboned fish muscle" (Lanier, 1986, p. 107). The leaching process removes all water soluble components and leaves behind a high concentration of functional proteins. Such a high concentration of proteins makes surimi an excellent candidate for use as a meat binder.

Many of the ingredients used in surimi are for preservation. A typical recipe consists of 4% of both sorbitol and sucrose. Dextrose has also been used. Those sugars act as cryoprotectants and help preserve proteins in their native state during frozen storage. Lanier (1985) suggested that meat scientists should learn the cryoprotective practices of surimi manufacturers. By so doing, they could better utilize meat protein.

As noted previously, proteins form gel structures. Peculiarly, cold water fish proteins gel at low temperatures as well as heat setting. Given enough time, gels will form at temperatures as low as 0°C. Low temperature setting might be due to hydrophobic interactions between amino acids. High temperature setting results from disulfide bonding (Lanier, 1986). Given the functional properties of fish protein at low temperatures, Lanier (1985) proposed replacing the process of tumbling with the addition of surimi to the meat batter. Various other thermal transition stages have been documented for fish (Wu et al., 1985) and other meat proteins (Lan et al., 1995). These properties open many avenues to the processed meat industry.

Surimi has many functional properties. They include binding water, foaming, emulsifying, and forming a stable dispersion (Lanier, 1986). The functionality of the proteins depends on non-meat ingredients and processing. Lanier (1985) showed that slow heating allows proteins to form a more ordered gel matrix. He also documented (Lanier, 1986) factors affecting gel quality. Gel rigidity is a function of protein concentration, and cohesiveness is a function of the quality of proteins.

Various applications exist for surimi in the food industry. Artificial crab legs and fish cakes are commercially manufactured. Surimi could be added to hot dogs and other processed meat products with the advantages of low cost and high functionality.

Extruded Foods

With the recent onset of extrusion technology, mechanically deboned meat was introduced to the world of snack foods. Puffed products can be easily made. A filler for meat loaf was made through extrusion processing (Murray et al., 1980).

Product Development Experimental Design

Response surfaces are valuable tools for product development research. Response surfaces present regression results on contour maps. Those maps illustrate the effect of response variables on the model. Murray et al. (1980) used response surfaces to understand the interaction of protein level and temperature on an extruded fish product.

Texture

Texture evaluation in meat products is done by sensory and mechanical tests. Sensory tests measure consumers' opinions and preferences. Mechanical tests should correlate to sensory test results quickly and without the added variables of human bias and error.

Contributions to the field of texture studies are numerous. Chrystall (1994) discussed how texture relates to meat products. His discussion focused on factors that affected texture like breed, fatness, sex, growth promoter, and connective tissue. Dransfield (1994) reviewed more than 30 different tests.

Mechanical tests fall under three main categories. Imitative tests like Texture Profile Analysis (TPA) mimic the processes they evaluate. Empirical tests, such as shear, have little scientific basis but have proven to be closely correlated to a selected property. Fundamental tests measure well defined rheological properties (Claus, 1995).

Shear

The force required to cut is defined as shear. Consumers find connective tissue objectionable because it increases toughness in meat. The difference in texture between meat and connective tissue would show up in shear tests. Claus (1995) compared shear test guidelines of national (AMSA, 1995) and international committees (Chrystall et al., 1994). Table 2 describes the guidelines suggested by each committee.

Texture Profile Analysis

Texture Profile Analysis (TPA) is a test that replicates the chewing motion. Samples are compressed twice while force and deformation data are collected. Bourne

Table 2--Recommendations for shear testing

Guideline	National committee	International committee
sample configuration	1.27-cm core	square sample
shear speed	200 to 250 mm/min	50 to 100 mm/min
blade	G-R Electric, Manhattan, KS "V" shaped blade	1.2 mm thick blade with rectangular hole
muscle fiber orientation	perpendicular	perpendicular
number of samples	six	six
shear rate important	likely	not likely

(1978) described the procedure and made recommendations for such a test. Plotting force against time produces a useful curve for evaluating texture. Associated variables are listed below.

Fracturability . .	the force at the first break in the curve
Hardness	maximum force during compression
Cohesiveness. . .	ratio of the second positive force area to the first
Adhesiveness. . .	maximum negative force
Springiness	height recovered between the end of the first and the start of the second compressions
Gumminess	product of hardness and cohesiveness
Chewiness	product of hardness, cohesiveness, and springiness

Olkku and Sherman (1979) described the mechanics and energy considerations of TPA testing in a very complete review. They related TPA data to stress-deformation and stress-strain curves.

Texture profile parameters vary between tests. Compressions between 25% and 75% are accepted. There is an equally broad range of test speeds. Each test depends on the material being tested. The critical factor is how far samples are compressed. The structure must be disrupted, but it must not be destroyed.

Other Tests

Three other types of tests have proven meaningful in evaluating meat texture: torsion, stress-relaxation, and tensile tests. Torsion tests twist products and collect force and torque angle data. With definable equations, torsion tests are an excellent way to measure actual cohesiveness and bind values in products like hot dogs (Hamann, 1987).

Stress-relaxation tests induce stress in a sample. Force measurements are taken as the sample "relaxes" under pressure. A stress-relaxation test was documented by Weinberg and Angel (1995) who varied probe speed, level of deformation, and sample thickness. The purpose of the test was to study the effects on bind of NaCl replacement by $CaCl_2$. When they compared the two salts, they found that fewer proteins were extracted with $CaCl_2$. That caused the $CaCl_2$ samples to yield to compressive forces more than the NaCl samples, particularly when long samples (>1.5-cm) were compressed by less than 50%.

Another test is the tensile test. Samples are gripped on both ends, and the force required to break the sample is recorded. Measurements from those tests relate to cohesiveness of a sample. MacNeil and Mast (1989) developed a "Resistance to Tear" device for tensile testing.

Non-Meat Ingredients Used in Processed Meats

Non-meat ingredients play a significant role in processed meat texture. The effect of those ingredients varies according to their function. Proteins strengthen the gel structure and carbohydrates bind water. Both ingredients increase hardness but in different ways.

Many summary papers have focused on the effects of non-meat ingredients and their effects. The most comprehensive review of non-meat ingredients was provided by Keeton (1996). He presented many types of carbohydrates and proteins and focused on how they can be used as fat replacers in processed meat. Purge controllers like modified food starch, sodium caseinate, isolated soy protein, and carrageenan, function by finding water to make meat more appealing. Lanier (1986) summarized the effects of ingredients and noted that they work separately rather than in conjunction with meat proteins.

Egg White

Egg white is an animal protein that forms a strong gel. Research has focused on the gel strength of egg whites, although they are seldom used in meat. It is known that large amounts of egg whites do not have the expected additive strength (Burgarella et al., 1985). Since egg whites are more than 85% protein, the resulting gels are very strong.

Milk Proteins

Milk proteins come in the form of whey proteins and casein proteins. Whey is a by-product of cheese manufacture and may be prepared as isolate or concentrate. Concentrated forms contain up to 40% protein. With both hydrophobic and hydrophilic regions, whey is a good fat emulsifier. Lactalbumin is a heat denatured whey protein concentrate. The use of lactalbumin in meat is limited because the heat treated proteins self-aggregate and are less soluble than other proteins.

Caseinates are separated directly from milk. Giese (1994) noted that casein emulsified fat and improved moistness and smoothness in processed meat. When used in emulsion products, they are absorbed onto fat globules better than onto myofibrillar proteins and help to stabilize the emulsion.

Collagen

Collagen is an animal protein that contributes to toughness in meat. It is a major component of connective tissue and makes beef chucks tough and is an undesirable constituent in steaks. Ranges of collagen in muscle vary from 1% in skeletal muscle to 27% in gristle. Meat from older animals is tougher due to permanent cross-links that form in collagen. Collagen-rich meat may be tenderized by processing methods like blade tenderizers (Flores et al., 1986), enzymes (Rolan et al., 1988), and acids (Wenham and Locker, 1976).

The functional properties of collagen make it a candidate for addition to processed meat. Whiting (1989) reviewed those properties and noted some of the associated problems. Collagen is toughest at 40°C, but melts and loses all strength at temperatures above 80°C. At low levels it stabilizes batters, minimizes shrinkage, and improves texture. Large amounts congeal after cooking to form undesirable gel pockets. Whiting recommended that a meat block should not contain more than 3% collagen by weight.

Two forms of collagen may be added to meat. Raw materials high in collagen may be added to a meat block or collagen may be processed into fibers. Typical uses include low-fat applications (Eilert et al., 1993) and hot dog products (Meullenet et al., 1994).

Soy

Soy proteins are available in flour, grits, concentrates, isolates, and textured forms (Giese, 1994). Due to the distinctive odor of soy beans, the most commonly used forms are flavorless isolates and concentrates. Isolates differ from concentrates in that isolates have no fibrous residues or non-protein components. Textured products are made by combining isolates and fibers in an extruder.

Uses for soy proteins depend on the form involved. Textured proteins "are most often used in coarse chopped or ground meats such as pizza toppings, taco meats, meat balls, meat patties, and Salisbury steaks. In those products, soy protein provided structure, reduced cooking loss, and extended freshness" (Keeton, 1996, p. 27). Jin and Lee (1988) used 10% textured protein in pork steaks. Pure soy protein forms an excellent gel and has been combined with chicken meat (Megard et al., 1985).

Hydrocolloids

Hydrocolloids are long-chain polymers that thicken in aqueous systems. Many edible gums are classified as hydrocolloids. They are used primarily as fat substitutes. Like fats, they melt when heated and reform into gels when cooled. Glicksman (1985) used hydrocolloids in restructured seafood to provide shape, form, and texture. Their use should be monitored since carbohydrate gums give mushy textures (Lanier, 1986).

Cellulose

Cellulose is a plant-derived carbohydrate polymer made of glucose. Types of food grade cellulose include microcrystalline cellulose, carboxy methyl cellulose (CBMC), methyl cellulose, and hydroxypropyl methyl cellulose. Cellulose has been used in two types of meat products. CBMCs softened the texture of notoriously tough reduced fat franks (Lin et al., 1988). Microcrystalline cellulose, when used in a ground pork product, increased hardness (Todd et al., 1989) but produced an unacceptable grainy texture (Todd et al., 1990). Cellulose was also added to surimi to improve freeze-thaw stability and improve firmness (Yoon and Lee, 1990).

Wheat Gluten

Wheat gluten is a plant protein used in many bakery goods and breakfast foods. It retains its viscoelastic characteristics at high temperatures. Wheat gluten was used with pork (Jin and Lee, 1988) and deboned chicken (Alvarez et al., 1990).

Starch

Starches are carbohydrate granules of glucose that usually contain amylose and amylopectin. The ratio of the two components varies from one source of starch to another. When heated, starches form a gel with great water holding capacity. The hydrogen bonding of amylose determines the gel properties. Starches bind water, but they do not emulsify.

Starch has been used as a fat replacer in processed meats and in extrusion experiments. Alvarez extruded a gel composed of 15% corn starch and mechanically deboned chicken (Alvarez et al., 1991). Starches are often modified to alter viscosity, hydration capacity, solubility, and gelatinization properties. Modified starches find use in processed meat as fat substitutes. Lanier (1986) recommended non-pre-gelatinized starch for surimi.

Salt

Salt, like phosphate, has many functions in meat. As people become concerned about what they eat, salt is imminently targeted as an undesirable ingredient. Herring (1995) addressed the salt reduction issue and explained the necessary functions of salt so that producers might not lose quality by reducing salt. Salt helps extract proteins. Those proteins act as binders in processed meat. Salt enhances flavor and suppresses microbial growth.

Phosphates

Phosphates have four functions in meat. The first function, as discussed by Mandigo (1992), is to change the charge potential on the proteins. The result is that charged parts of the protein repel each other and open the protein spatially. The second effect is due to the buffering effect of phosphates. Since the pH changes, so does the charge on the protein, which allows for increased water binding. Third, phosphates sequester metal ions, preventing oxidation. The fourth function is to dissociate actomyosin and tenderize meat. Phosphates are widely used in meat because they minimize lipid oxidation and increase yield by improving the water holding capacity.

Cooking Time Predictions

Cooking time predictions are helpful for at least two reasons. The first is safety. It is necessary to know when harmful microflora have been killed. Second, since texture is a function of the cooking temperature, it may be altered by time-temperature relationships. Both Heisler (1947) and Ball (1923) published charts that predicted time-temperature relationships for general cases. Through the use of computers, cooking models can predict time and temperature for any case.

Computer simulations of the cooking process are helpful to meat processors. With a few simple key strokes, cook schedules can be predicted for various sausage sizes and oven temperatures. Geometry often presents a problem to cooking models. Complex problems, like irregular product shape or strange boundary conditions, are best solved by numerical methods. Closed form solutions exist for simple problems that are very well defined.

Numerical Solutions

Numerical methods are used to solve problems involving phase changes, irregular boundaries, and nonstandard boundary conditions. The two most common numerical methods are finite element and finite difference. Both methods work by breaking a problem down into small sections. Finite element methods are particularly suited for nonuniform shapes. Finite difference methods require fewer computations, but applications are limited to uniformly sectioned products. Finite difference methods were used to predict mass transfer and temperatures during forced convection, natural convection, and boiling (Huang and Mittal, 1995).

Analytical Solutions

Solutions exist for many standard shapes and conditions. Heisler's solutions to heat transfer problems (in the form of charts and equations) may be programmed into a computer. Those closed-form solutions to heat transfer problems are well suited for cooking a long, round fish bologna in a smokehouse.

MATERIALS AND METHODS

Trout bologna product development studies focused on the following three areas: characterization of mechanically deboned meat, product development, and cook process modeling.

Materials

The following sections describe processing equipment, analysis equipment, ingredients, and software used to develop rainbow trout bologna.

Processing Equipment

Paradise Farms in Paradise, Utah, supplied rainbow trout. In the course of one day, fish were filleted, brought to USU, deboned, and frozen. The procedure was repeated on three separate days. The average trout was one year old and weighed one pound. Trout frames were deboned using the twin screw mechanical deboner shown in Fig. 1 (model RSTC-02BX-V05, Beehive, Inc., Sandy, UT). Holes in the chamber were 0.031 inches in diameter. Immediately after deboning, 5-pound bags of meat were collected and frozen. Meat was held in storage at -20°F until needed.

Time and temperature data were collected during cooking. Temperature data were recorded on a six-channel datalogger (CR10WP, Campbell Scientific, Logan, UT) with the use of type T thermocouples. Thermal conductivity was measured with a conductivity probe (TC-22, Campbell Scientific, Logan, UT) and recorded on the six-channel datalogger. The datalogger programs are included in Appendices A and B.

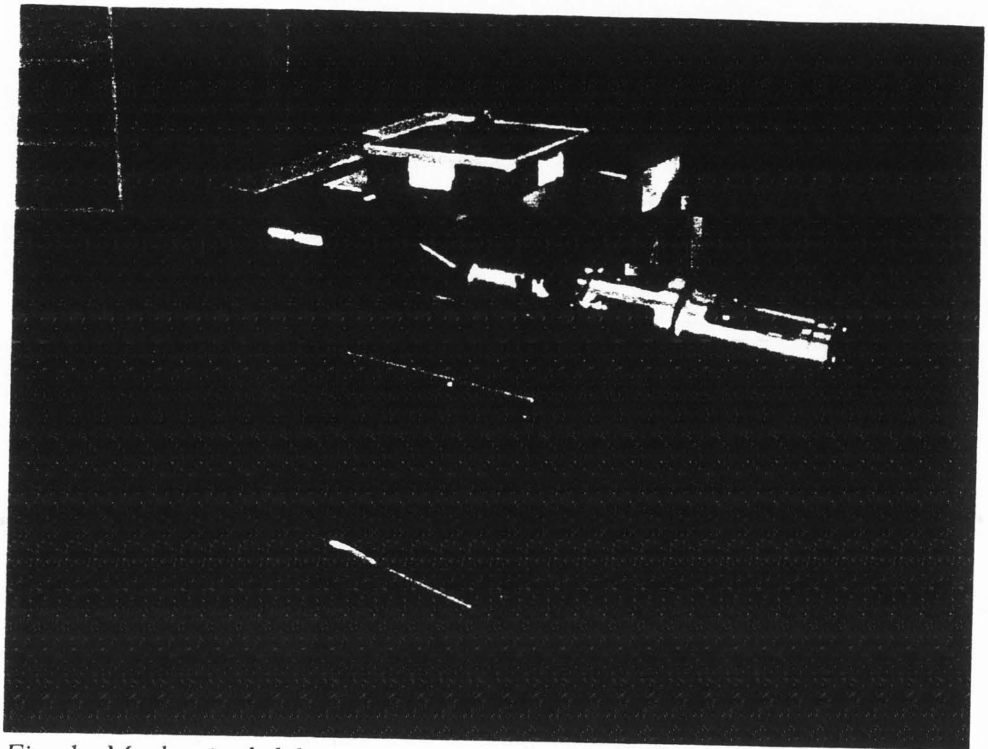


Fig. 1--Mechanical deboner.

Sausages were cooked in a 500-pound capacity thermal processing oven (TR2-1700, Vortron Inc., Beloit, WI).

Analysis Equipment

Fat, moisture, and ash were determined by procedures that were published by the American Organization of Analytical Chemists (AOAC) in 1990. Fat was determined by ether extraction (Procedure 960.39B). A vacuum oven was used for moisture determinations (Procedure 950.46A). The percentage of dry ash was calculated after complete oxidation in a muffle furnace (Procedure 920.153).

Albion Laboratories (Clearfield, UT) determined mineral content through Inductively Coupled Plasma (ICP) spectrophotometry. The ICP equipment (model

Accuris ARL, Fisons, Inc., Georgia, AT) created a plasma field in which electrons from a sample were excited from their ground states. A computer analyzed the characteristic energy fingerprint of each mineral to determine identity and quantity.

Texture was analyzed with the Stevens Farnell Quality Testing System (QTS25, Leonard Farnell & Company Limited, Herts, England). Note from Fig. 2 that the mobile portion of the analyzer, called the beak, contained both the probe and the load cell. Sensitivity of the load cell was one gram.

Ingredients

All ingredients used in this project were shelf stable. Two animal-based products were used: powdered egg whites (Standard egg whites, Siouxpreme Egg Products, Sioux Center, IA) and collagen (Collagen, Devroe Inc., Somerville, NJ). Plant products

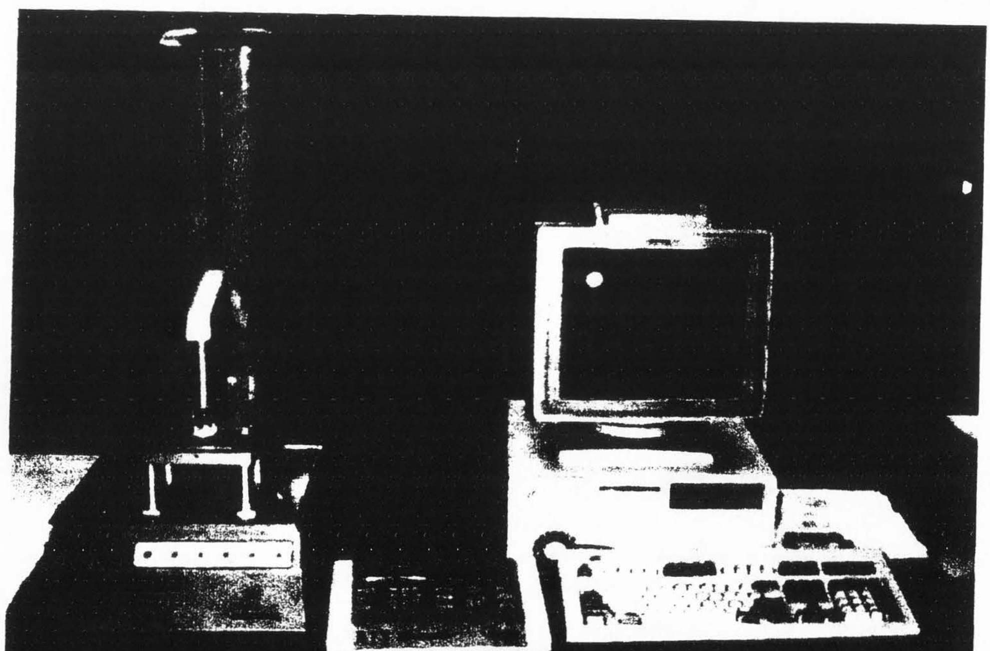


Fig. 2--Texture analyzer.

included isolated soy protein (Supro 500E, Protein Technologies, St. Louis, MO), Solka-Floc cellulose (Solka-Floc 40-FCC, Fiber Sales and Development, St. Louis, MO), vital wheat gluten (Provim ESP, ADM/Ogilvie, Decatur, IL), and modified corn starch (Purity®W, National Starch and Chemical Company, Bridgewater, NJ). Table salt was added to all formulations (Morton International Inc., Chicago, IL).

Software

Computer software aided in the design and the analysis of experiments. ECHIP designed and prepared graphical output (version 6.0 for Windows™, Echip, Incorporated, Hockessin, DE). The statistical results were generated with SAS (release 6.09 of SAS for AXP, SAS Institute Inc., Cary, NC). QTS software controlled the texture analyzer and stored the requisite data (version 1.1WT, Leonard Farnell & Company Limited, Herts, England).

Methods

The following section details the methods and preparation for each experiment. In all cases, statistical significance was based on $\alpha = 0.05$.

Product Development

The aim of the texture studies was to achieve a desired texture by adding specified amounts of various ingredients. The method, which led to texture manipulation, involved texture analysis and response surfaces. A texture analyzer measured how non-meat ingredients affected texture parameters. Regressions run on the data led to response surfaces that mapped the effects of ingredients on texture.

Design of Experiments

Two sets of experiments were designed using ECHIP: preliminary experiments and final experiments. The design of the experiments was central composite in cube.

Preliminary experiments. Screening experiments were designed to evaluate the effect of ingredients on texture. The six ingredients tested were wheat gluten, egg white, collagen, soy protein isolate, cellulose, and starch. Individual ingredients were added in the range of 0 to 3% of the total formulation, as listed in Table 3. The collected data were fitted to the following first order equation.

$$\begin{aligned} Y = \beta_0 + \beta_1 * \%\ \text{wheat gluten} + \beta_2 * \%\ \text{egg white} + \beta_3 * \%\ \text{collagen} + \\ \beta_4 * \%\ \text{soy protein isolate} + \beta_5 * \%\ \text{cellulose} + \beta_6 * \%\ \text{starch} \end{aligned} \qquad \text{Eq. (1)}$$

where:

Y = the predicted value of the particular response variable
β_0 = the intercept of the equation, the response due to fish and salt alone
$\beta_{1\text{-}6}$ = the corresponding coefficients resulting from a linear regression

Egg white, collagen, wheat gluten, and soy protein isolate had the greatest effect on texture. Wheat gluten had an unfavorable odor.

Final experiments. Complex relationships between ingredients were investigated. Egg white, collagen, and soy protein isolate were added in combination according to Table 4.

Table 3--Formulations for preliminary experiments. For each treatment, the composition is shown as the percentage of the total weight for each ingredient. In addition to the mid-point, two levels were tested, all or nothing, to allow effects to be accentuated

Treatment #	%Salt	%Wheat gluten	%Egg white	%Collagen	%Soy protein	%Cellulose	%Starch	% Fish
15	1.0	1.5	1.5	1.5	1.5	1.5	1.0	90.5
6	1.0	0.0	3.0	3.0	0.0	0.0	0.0	93.0
5	1.0	3.0	0.0	0.0	3.0	3.0	2.0	88.0
1	1.0	0.0	3.0	3.0	3.0	0.0	2.0	88.0
1	1.0	0.0	3.0	3.0	3.0	0.0	2.0	88.0
11	1.0	3.0	3.0	0.0	3.0	0.0	0.0	90.0
8	1.0	3.0	0.0	3.0	3.0	0.0	0.0	90.0
13	1.0	3.0	3.0	3.0	0.0	3.0	0.0	87.0
3	1.0	0.0	0.0	3.0	3.0	3.0	0.0	90.0
14	1.0	0.0	0.0	0.0	0.0	0.0	0.0	99.0
7	1.0	0.0	3.0	0.0	0.0	3.0	2.0	91.0
10	1.0	0.0	3.0	0.0	3.0	3.0	0.0	90.0
2	1.0	3.0	0.0	0.0	0.0	3.0	0.0	93.0
4	1.0	3.0	3.0	0.0	0.0	0.0	2.0	91.0
12	1.0	0.0	0.0	3.0	0.0	3.0	2.0	91.0
9	1.0	3.0	0.0	3.0	0.0	0.0	2.0	91.0
3	1.0	0.0	0.0	3.0	3.0	3.0	0.0	90.0
2	1.0	3.0	0.0	0.0	0.0	3.0	0.0	93.0

Table 4--Formulations for final experiments. The makeup of each treatment is shown as the percentage of each ingredient by weight. Ingredients were tested at three levels in combination with each other to allow complicated relationships between ingredients to be detected

Treatment #	%Salt	%Collagen	%Soy protein	%Egg white	%Fish
14	1.0	0.0	0.0	0.0	99.0
4	1.0	2.0	3.0	1.5	92.5
8	1.0	0.0	3.0	3.0	93.0
15	1.0	2.0	1.5	1.5	94.0
11	1.0	4.0	3.0	0.0	92.0
15	1.0	2.0	1.5	1.5	94.0
3	1.0	2.0	0.0	1.5	95.5
6	1.0	2.0	1.5	3.0	92.5
15	1.0	2.0	1.5	1.5	94.0
12	1.0	0.0	3.0	0.0	96.0
15	1.0	2.0	1.5	1.5	94.0
9	1.0	4.0	0.0	3.0	92.0
13	1.0	4.0	0.0	0.0	95.0
7	1.0	4.0	3.0	3.0	89.0
1	1.0	0.0	1.5	1.5	96.0
2	1.0	4.0	1.5	1.5	92.0
5	1.0	2.0	1.5	0.0	95.5
10	1.0	0.0	0.0	3.0	96.0
15	1.0	2.0	1.5	1.5	94.0

The purpose of the final experiments, as stated previously, was to examine complex relationships between ingredients. To that end, the test data were fitted to the equation that follows.

$$\begin{gathered} Y = \beta_0 + \beta_s*\%soy + \beta_e*\%egg + \beta_c*\%collagen + \\ \beta_s*\beta_e*\%soy*\%egg + \beta_s*\beta_c*\%soy*\%collagen + \beta_e*\beta_c*\%egg*\%collagen + \\ \beta_s*\beta_s*\%soy*\%soy + \beta_c*\beta_c*\%collagen*\%collagen + \beta_e*\beta_e*\%egg*\%egg \end{gathered} \qquad \text{Eq. (2)}$$

where:

Y = the predicted value of the particular response variable
β_0 = the intercept of the equation, the response due to fish and salt alone
β_s = the coefficient for soy protein isolate
β_e = the coefficient for egg white
β_c = the coefficient for collagen

Linear terms appear in the first row. Interactions between ingredients are listed in the second row. The last row contains quadratic responses involving a single ingredient. For the second and third rows, nonzero coefficients represent nonlinear responses.

Preparation of Fish Bologna

Prior to use in experiments, frozen deboned fish meat was thawed at 47°F for 24 hr. Sample preparation proceeded according to the formulations listed in Tables 3 and 4. All ingredients were combined and mixed by hand with a spoon until a cohesive mass formed. The average mixing time was 1 min. The batter was then stuffed by hand into 2 1/2 inch fibrous casings (2 1/2 x 20 inch fibrous mahogany casing, Vista International Inc, Kenosh, WI) and tied with string. Care was taken to eliminate air and stuff casings as tightly as possible. That procedure produced one bologna. Three separate and unique bolognas were made for each treatment. All bolognas were hung vertically by strings and cooked in the smokehouse to an internal temperature of 180°F.

Texture Analysis

After cooking, fish bolognas were immediately refrigerated until texture could be tested. All tests were completed within 24 hr of cooking. Texture was analyzed using a Stevens Farnell Texture Analyzer. Analysis samples were 15 mm long and 14 mm in diameter. Ends were cut perpendicular to the axis using a miter box. From each bologna, two analysis samples were tested by compressing each twice at a speed of 50 mm/min to 60% (40% compression) of the original height. The reported replicate value was the average of the responses from the analysis samples. Two additional samples from each bologna were sheared using a "V" shaped blade moving at 600 mm/min. Again, the average value was recorded. The definitions of each of the response variables are listed in Table 5.

In summary, there were 15 unique treatments for both the preliminary and the final experiments. Each prescribed treatment was prepared three times (n=3). From each of those preparations, two analysis samples were tested. The average of the two data points was recorded as the replicate value.

A method was needed for evaluating the feasibility of manufacturing a desired product. All of the responses were combined into a comprehensive variable, the Combined Response Variable, that measured how well a specific target could be reproduced. The Combined Response Variable was defined by the following equation.

Table 5--Definitions of the variables used in texture studies

Variable	Definition
Shear	Force required to cut through a sample
Hardness	Maximum force measured during the first compression
Cohesiveness	Positive force*time area of cycle two divided by cycle one
Springiness index	Ratio of the recovered height after cycle one to the original height
Adhesiveness	Maximum negative force

$$\sum_{i=1}^{p} k_i w_i \left| \frac{(x_i - g_i)}{r_i} \right| \qquad \text{Eq. (3)}$$

k_i = -2, as defined by ECHIP
w_i = user specified weight for response i
r_i = range of response
g_i = target goal
x_i = simulated value for response i
p = number of response variables

All variables except w_i were predetermined by experiments or definitions.

The premise of texture studies was that variation in texture properties could be measured by response variables. By inference, a variable's importance depended on its capacity to distinguish different textures. Hence, response variable weights should reflect how well a response variable measured different textures. Weights were determined by testing several commercial meats. Texture of those meats varied, most notably, due to the size of the meat particles (from formed products to comminuted). Variability was calculated by taking the range and dividing by the average value, as defined by the following equation.

$$\%\,variation = \frac{maximum - minimum}{mean} * 100\% \qquad \text{Eq. (4)}$$

Weights were assigned by taking the percent variation and scaling them to sum to ten, e.g., a 118% variation was given a weight of 3.0.

Cook Process Modeling

Time-temperature profiles were recorded while cooking fish bologna. Thermocouples were inserted into the bologna at specific distances. Those distances were measured before and after cooking to verify location. A Fortran program modeled the bologna cooking process as an infinitely long cylinder. Equations used in the program and the associated derivations are included in Appendix C. The program itself is in Appendix D. Heisler (1947) charts were used to verify the computer data.

Program operation required four variables to be known. Density was measured as weight divided by the volume of water displaced. Thermal conductivity was measured with a probe. Specific heat was calculated according to the following equation (Toledo, 1994).

$$C = (1674.72 \times \%\text{Fat}) + (837.36 \times \%\text{Non-fat solids}) + (4186.8 \times \%\text{Moisture}) \text{ in J / (kg} \cdot \text{K)} \qquad \text{Eq. (5)}$$

The heat transfer coefficient was determined by fitting simulation curves to actual data. Since variables could introduce error to the model, robustness was studied. This was done by considering a range of values and figuring the correlation coefficient (R^2), the root mean squared error (RMS), the maximum deviation, and the minimum deviation. R^2 and RMS were defined as follows.

$$R^2 = 1 - \frac{\sum_{i=1}^{n} (Y_i - Y_i^*)^2}{\sum_{i=1}^{n} (Y_i - \bar{Y})^2} \qquad \text{Eq. (6)}$$

$$RMS = \frac{1}{n} \sum_{i=1}^{n} \sqrt{(Y_i - Y_i^*)^2} \qquad \text{Eq. (7)}$$

Y_i = true temperature at time i

Y_i^* = predicted temperature at time i

$\bar{Y}$ = average temperature

n = number of data points

Those combined statistics measured how well the model fit the data and, by comparing the results of different test values, the robustness of the model.

RESULTS AND DISCUSSION

Characterization of Mechanically Deboned Fish

Three types of analysis helped define the properties of rainbow trout meat and the deboning process. First, yield measured how much meat could be salvaged. Second, proximate analysis results showed the general composition of the meat. Third, bone content was examined through mineral analysis.

Yield

Three batches of fish frames were processed on a mechanical deboner. Seventy percent of the infeed weight was recovered as meat. Standard deviation was 10%.

Proximate Analysis

Standard AOAC procedures were used to test moisture, fat, and ash. Five analysis samples (n=5) were drawn from one batch of fish. Table 6 lists the results. Deboned rainbow trout meat was 71% water, as determined with a vacuum oven. Ether extracted fat amounting to 10% of the total composition. The level of ash was 1.1%. Only trace amounts of carbohydrates are present in meat. Given that carbohydrates in fish are negligible, protein was determined by subtracting the sum of the different components from 100. Deboned skinless rainbow trout was high in protein content relative to fat.

Table 6--Proximate analysis showed high protein content relative to fat

Component	Percentage of composition	Standard deviation
Moisture	71%	1%
Fat	10%	2%
Ash	1.1%	0.1%
Carbohydrates*	trace	
Protein**	18%	

n=5
* Carbohydrates in fish, like other types of meat, are negligible.
** Protein was calculated by subtracting the different components from 100%.

Mineral Content

Albion Laboratories in Clearfield, UT performed the mineral analysis on pre- and post-deboned meat. Table 7 shows the results of one trial replicated three times. Mineral content differed, as reflected by P-values, in every case. Unexpectedly, calcium levels were down, but phosphorus increased in deboned meat. Those two minerals are common in bone, and levels should have changed in tandem. The calcium decrease was unexpected since some bone was inherently mixed with the meat. The only way to decrease calcium was to either dilute the meat, which would drop the level of all the elements, or remove a high calcium component along with the waste. Since there was not a general decrease in mineral content, something must have been removed from the meat.

Table 7--Mineral composition for deboned and fresh rainbow trout. Deboned trout had less calcium but more phosphorus and iron than fresh fish

Mineral	Non-Deboned (ppm)	Deboned (ppm)	P ($\bar{x}_1=\bar{x}_2$)
Phosphorus	1800 ± 100	2030 ± 20	0.001
Potassium	3410 ± 10	3450 ± 10	0.049
Magnesium	189 ± 1	207 ± 2	0.001
Calcium	430 ± 10	330 ± 10	0.001
Sodium	470 ± 10	450 ± 10	0.009
Iron	6.7 ± 0.1	8.8 ± 0.2	0.001
Aluminum	0.0 ± 0.1	0.40 ± 0.02	0.001
Manganese	0.11 ± 0.01	0.09 ± 0.01	0.001
Boron	0.35 ± 0.01	0.5 ± 0.1	0.009
Copper	0.41 ± 0.01	0.35 ± 0.01	0.001
Zinc	4.4 ± 0.1	4.5 ± 0.1	0.035

n=3, $\bar{x}$ ± S.D.

The calcium decrease in deboned fish was unexpected but there are a couple of factors to consider. All three analysis samples came from a single batch of fish. Analysis of another batch of fish might produce different results. USDA regulations for red meat stipulate that calcium levels must be lower than 0.75%. The amount of calcium detected was minuscule at less than 0.04%. Also, the decrease in calcium was consistent with Field and associates' deboned mutton studies (Field et al., 1974).

Texture Studies

TPA Validation

The theory behind TPA studies, as explained in Materials and Methods, was to compress a sample and disrupt the physical structure, decompress the sample, and repeat the cycle. In order for test data to be meaningful, structural failure had to begin before the end of the first compression; however, extreme failure would void results that depend on the second compression. The test variables were compression range and test speed.

Force-time graphs illustrated how samples responded to force and were useful in determining test parameters. Figure 3 showed a sample that settled during testing. The plateau at the top of the first cycle showed the structure failing. The lower peak on the second compression indicated that the sample was still intact. That sample, the control treatment (Preliminary Test #14), failed due to insufficient bind, but it successfully completed the two-cycle test. Figure 4 was an ideal test. The nonlinear curve on the first compression showed the sample yielding to force; however, the peak of the second test was only slightly lower than the first. Figure 5 was a sample for which failure was insufficient. The three sources of added protein bound the sample tightly and prevented failure. Profiles of the first and second compressions were almost identical. Figure 6 is an overlay of the different tests. The magnitude of the failure varied according to the amount and type of added protein. Comparisons between trials showed the TPA parameters of compression and test speed to be adequate.

Preliminary Experiments

The purposes of the preliminary experiments were to evaluate dependent variables and to identify the effects of the independent variables. To accomplish the task, a linear model was employed to efficiently evaluate the main effect of each ingredient. Other models would have required more extensive testing and may not have improved the

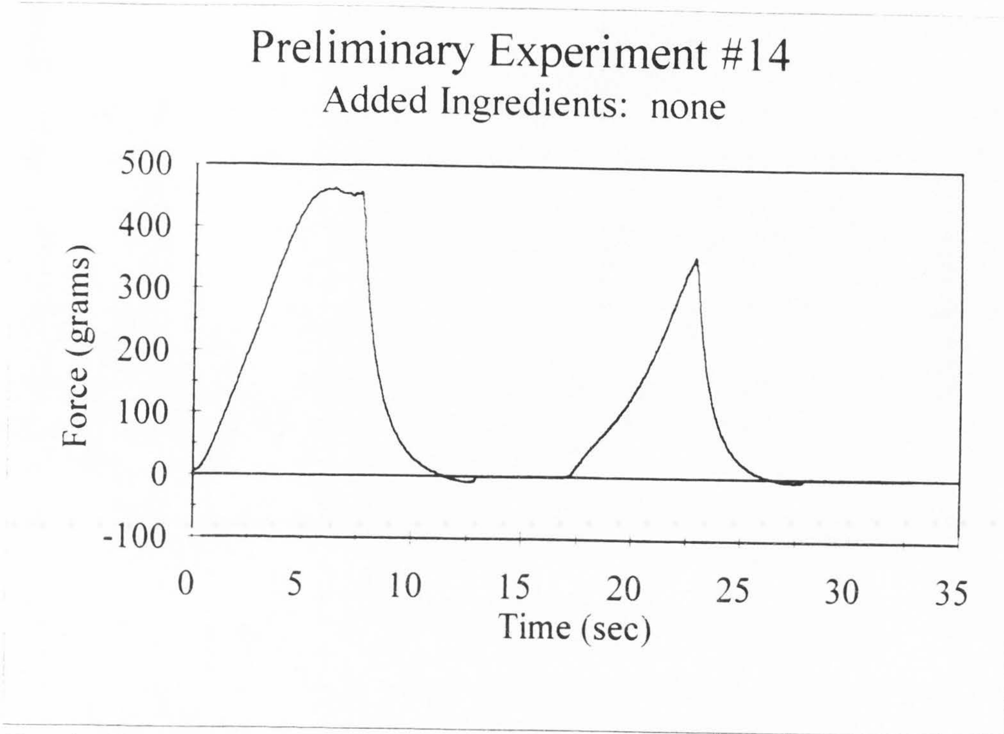


Fig. 3--TPA of sample with no added ingredients. Failure was too extensive during the first compression.

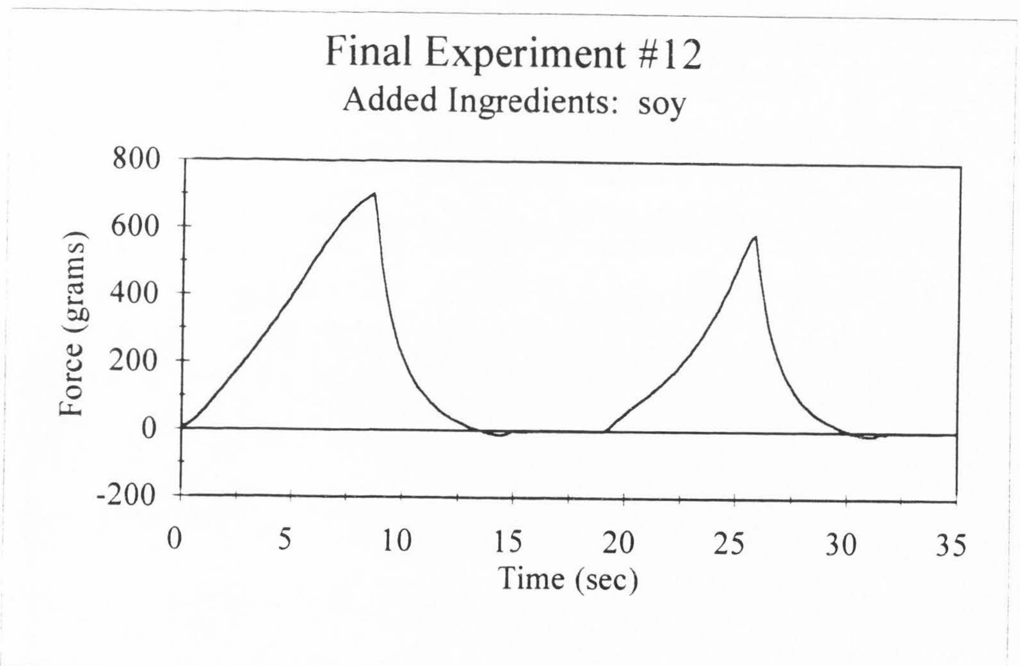


Fig. 4--TPA showing product breaking down. The nonlinear curve at the end of the first compression shows that the sample yielded to force. The sample was still intact for the second compression.

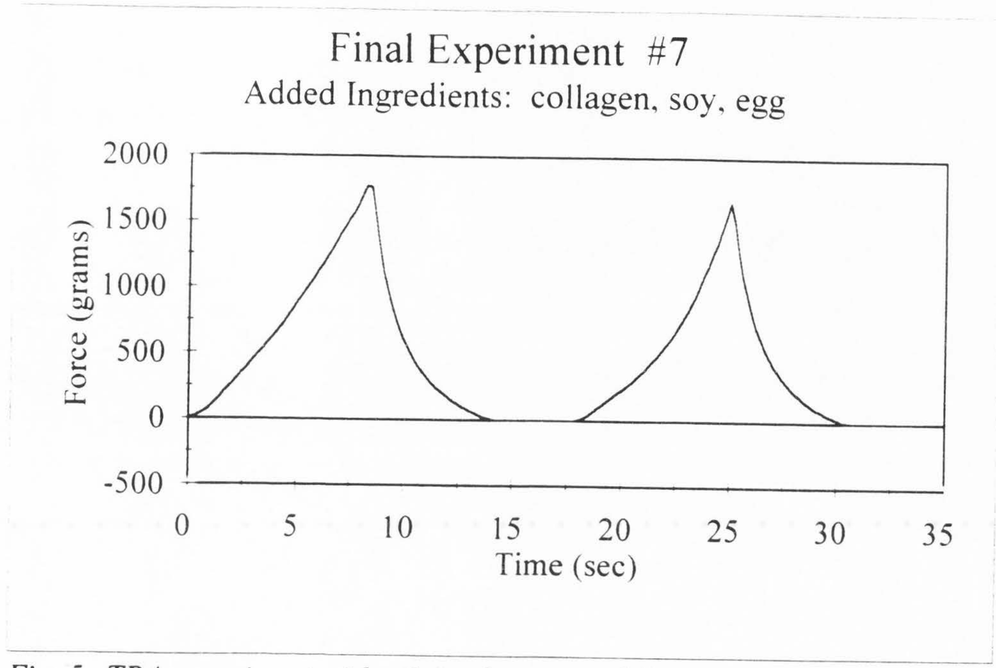


Fig. 5--TPA experiment with minimal structural damage. TPA parameters were not sufficient to break down the structure.

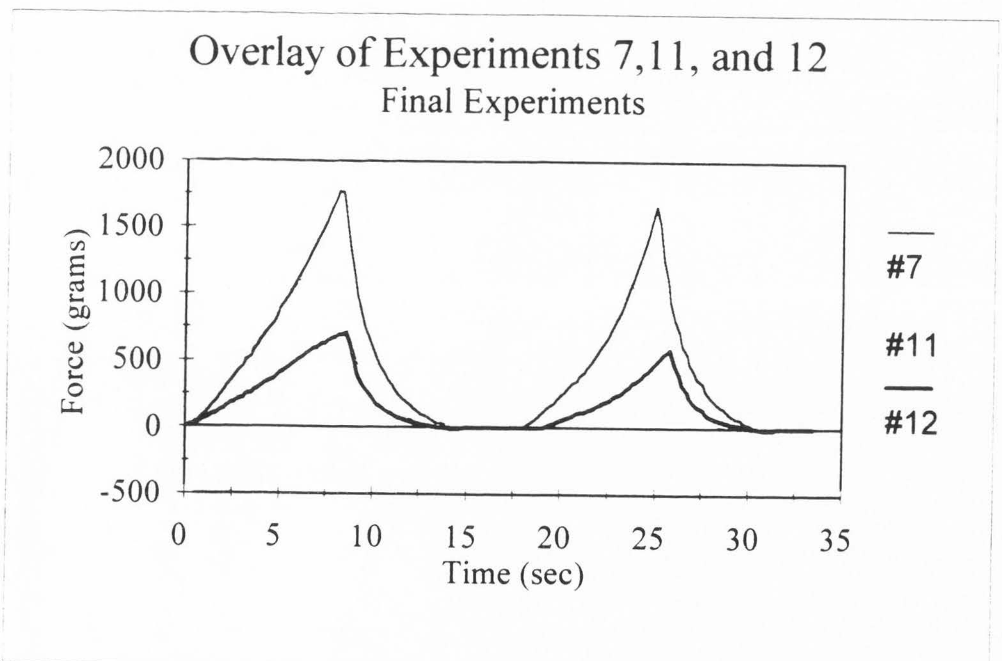


Fig. 6--Overlay of three TPA experiments. #7 shows the product breaking down very little. The sample in #11 weakened or shifted during the first compression. #12 settled greatly and the hardness is much lower than in the other tests.

results. TPA tests were conducted, data were collected, and a model was prepared.

Adhesiveness, cohesiveness, hardness, shear, and springiness were chosen as dependent variables. Examination showed that linear regression models fit the experimental data in every case except adhesiveness. Data for that variable appeared to be very random, and, as listed in Table 8, no ingredient was shown to have a significant effect. Adhesiveness, which would relate to how well bologna sticks to teeth, was not considered to be a key variable. Given the lack of significant results, adhesiveness was not studied in further experiments.

Shear responses were the most predictable. In addition to having the highest correlation of $R^2 = 0.845$, the probability values in Table 9 also show that every ingredient affected shear.

All of the ingredients affected at least one response. Collagen increased shear (Table 9), springiness index (Table 10), and cohesiveness (Table 11) more than any other ingredient. According to Table 12, the ingredient that most affected hardness was egg white. In general, responses were affected most by collagen and egg white, followed by wheat gluten and soy protein isolate. Curiously, starch either decreased response values or had no effect.

Rank Order

Ingredient effects were evaluated in the preliminary experiments. To make further tests manageable, the number of ingredients in the final experiments was reduced from six to three. Collagen, egg white, soy protein isolate, and wheat gluten seemed to have the

Table 8--Regression results for adhesiveness data using a linear model. No ingredients significantly affected texture

Coefficient (g / %)	SE_{mean}	DF	P	Term
30				Constant
0	100	1	0.258	Wheat gluten
0	100	1	0.354	Egg white
0	100	1	0.441	Collagen
0	100	1	0.322	Soy
0	100	1	0.219	Cellulose
0	100	1	0.417	Starch

C.V. = 590.1	SS_{model} = 168400	SS_{error} = 1274000
F(6,50) = 1.1	MS_{model} = 28100	MS_{error} = 25500
Prob > F = 0.375		
R^2 = 0.117		

Table 9--Linear regression results from shear data. Collagen had the greatest impact on shear

Coefficient (g / %)	SE_{mean}	DF	P	Term
220				Constant
30	10	1	0.001	Wheat gluten
100	10	1	0.001	Egg white
110	10	1	0.001	Collagen
50	10	1	0.001	Soy
50	10	1	0.001	Cellulose
-30	10	1	0.017	Starch

C.V. = 13.2	SS_{model} = 2331360	SS_{error} = 426400
F(6,50) = 45.6	MS_{model} = 388560	MS_{error} = 8530
Prob > F = 0.001		
R^2 = 0.845		

Table 10--Regression data for the linear model of hardness. Egg white increased hardness more than other variables

Coefficient (g / %)	SE_{mean}	DF	P	Term
500				Constant
100	100	1	0.016	Wheat gluten
300	100	1	0.001	Egg white
200	100	1	0.001	Collagen
0	100	1	0.050	Soy
0	100	1	0.060	Cellulose
-100	100	1	0.059	Starch
C.V. = 16.8		SS_{model} = 11729100		SS_{error} =2955100
F(6,50) = 33.1		MS_{model} = 1954800		MS_{error} = 59100
Prob > F = 0.001				
R^2 = 0.799				

Table 11--Linear regression results from cohesiveness. Collagen and soy protein isolate had the greatest effects on cohesiveness

Coefficient (cohesiveness / %)	SE_{mean}	DF	P	Term
0.50				Constant
0.01	0.01	1	0.003	Wheat gluten
0.01	0.01	1	0.001	Egg white
0.04	0.01	1	0.001	Collagen
0.02	0.01	1	0.001	Soy
0.01	0.01	1	0.031	Cellulose
-0.01	0.01	1	0.056	Starch
C.V. = 5.8		SS_{model} = 0.19		SS_{error} = 0.06
F(6,50) = 25.1		MS_{model} = 0.03		MS_{error} = 0.00
Prob > F = 0.001				
R^2 = 0.750				

Table 12--Collagen affected the linear model for springiness index more than any other ingredient

Coefficient (Springiness index / %)	SE_{mean}	DF	P	Term
0.770				Constant
0.006	0.002	1	0.009	Wheat gluten
0.001	0.002	1	0.537	Egg white
0.024	0.002	1	0.001	Collagen
0.005	0.002	1	0.014	Soy
-0.007	0.002	1	0.002	Cellulose
0.000	0.003	1	0.854	Starch
C.V. = 2.7		SS_{model} = 0.084		SS_{error} = 0.025
$F(6,50) = 28.4$		MS_{model} = 0.014		MS_{error} = 0.000
Prob > F = 0.001				
$R^2 = 0.773$				

greatest effect on texture. Wheat gluten had an undesirable odor. Rank order validated the use of collagen, egg white, and soy protein isolate in the final experiments.

Rank order compared responses. Table 13 lists the independent variables and the dependent variables. For a particular model, the largest coefficient ranked first and so on. Where two ingredients had the same coefficient, each was ranked the same, and the subsequent number was skipped. An overall rank was determined by summing the ranks from each model. The ingredient with the lowest overall number had the greatest impact on texture. Accordingly, the effect of the independent variables from greatest to least was: collagen, egg white, soy protein isolate, wheat gluten, cellulose, and starch.

Rank order discounted the accuracy of the models. Rank order did not distinguish between models that fit the data and those that did not. All models were assumed to be of equal importance. Future evaluations might compensate for those factors.

Table 13--Rank order of ingredients. Collagen had the greatest overall effect on texture

	Dependent variable rank					
Independent variable	Shear	Hardness	Cohesiveness	Springiness	Adhesiveness	Score
Wheat gluten	5	3	3	2	1	14
Egg white	2	1	3	4	1	11
Collagen	1	2	1	1	1	6
Soy protein isolate	3	4	2	3	1	13
Cellulose	3	4	3	6	1	17
Starch	6	6	6	5	1	24

Note: Rank corresponded to the size of the linear regression coefficient. The independent variable with the largest regression coefficient ranked first. All ranks for a particular ingredient were summed. The lowest scoring ingredient affected overall texture the most.

Final Experiments

The final experiments were designed to evaluate complex relationships between ingredients. By using the quadratic model, hardness responses could be more closely predicted than with a simple linear model. Correlation between experimental data and the models increased from 0.799 for the linear model to 0.952 for the quadratic model. The linear model discounted soy protein isolate. The quadratic model, as listed in Table 14, identified soy protein isolate as having the greatest effect on hardness. In addition to the linear contribution of soy protein isolate, hardness responses were also shaped by two significant negative interactions, both of which involved soy protein isolate.

Interactions were detected in every response. Table 15 lists the regression results for shear. There was a positive interaction between soy protein isolate and egg white. The linear effect of egg white was the only other significant contribution to shear responses. The cohesiveness model, as reported in Table 16, included the interaction between soy protein isolate and egg white. Springiness was affected by collagen, the coefficient for which was three times larger than any other regression coefficient. In addition, the only significant interaction for springiness was between collagen and egg white. That interaction was negative as listed in Table 17.

Some of the regression results were unexpected. Coefficients for cohesiveness and springiness index changed drastically. Statistics from both the linear and quadratic models were similar, indicating that neither model was better than the other. Another disturbing trend was that very few ingredients significantly affected texture. With five percent probability ($\alpha = 0.05$) as the cutoff, the effects on shear of collagen and soy protein

Table 14--Quadratic regression results for hardness. Five terms were significant, three of which included soy protein isolate

Coefficient (g / %)	SE_{mean}	DF	P	Term
420				Intercept
140	30	1	0.001	Collagen
180	40	1	0.001	Soy
120	40	1	0.007	Egg white
10	10	1	0.364	Collagen^2
-20	10	1	0.005	Collagen*soy
10	10	1	0.236	Collagen*egg white
-30	10	1	0.034	Soy^2
10	10	1	0.097	Soy*egg white
10	10	1	0.277	Egg white^2
C.V. = 7.0	SS_{model} = 6099700			SS_{error} = 307600
F(9,47) = 103.6	MS_{model} = 677700			MS_{error} = 6500
Prob > F = 0.001				
R^2 = 0.952				

Table 15--Quadratic regression statistics for shear. One of the two significant responses was the interaction between soy protein isolate and egg white

Coefficient (g / %)	SE_{mean}	DF	P	Term
220				Intercept
0	100	1	0.088	Collagen
100	100	1	0.059	Soy
100	100	1	0.042	Egg white
10	10	1	0.079	Collagen^2
0	10	1	0.850	Collagen*soy
0	10	1	0.601	Collagen*egg white
-10	10	1	0.334	Soy^2
10	10	1	0.031	Soy*egg white
0	10	1	0.880	Egg white^2
C.V. = 11.7	SS_{model} = 1454000			SS_{error} = 200400
F(9,47) = 37.9	MS_{model} = 161600			MS_{error} = 4300
Prob > F = 0.001				
R^2 = 0.879				

Table 16--Cohesiveness regression results for a quadratic model. All interactions were negative

Coefficient (cohesiveness / %)	SE_{mean}	DF	P	Term
0.514				Intercept
0.03	0.01	1	0.012	Collagen
0.05	0.01	1	0.002	Soy
0.03	0.01	1	0.079	Egg white
-0.001	0.002	1	0.824	$Collagen^2$
-0.003	0.002	1	0.086	Collagen*soy
-0.000	0.002	1	0.884	Collagen*egg white
-0.005	0.004	1	0.287	Soy^2
-0.006	0.003	1	0.033	Soy*egg white
-0.000	0.004	1	0.958	Egg $white^2$
C.V. = 4.4	SS_{model} = 0.102			SS_{error} = 0.037
F(9,47) = 14.6	MS_{model} = 0.011			MS_{error} = 0.001
Prob > F = 0.001				
R^2 = 0.736				

Table 17--The quadratic springiness index model was most affected by collagen

Coefficient (Springiness index / %)	SE_{mean}	DF	P	Term
0.759				Intercept
0.03	0.01	1	0.001	Collagen
-0.01	0.01	1	0.367	Soy
0.01	0.01	1	0.285	Egg white
-0.003	0.002	1	0.163	$Collagen^2$
0.000	0.001	1	0.775	Collagen*soy
-0.003	0.001	1	0.050	Collagen*egg white
0.003	0.003	1	0.414	Soy^2
0.004	0.002	1	0.075	Soy*egg white
-0.002	0.003	1	0.461	Egg $white^2$
C.V. = 2.6	SS_{model} = 0.058			SS_{error} = 0.021
F(9,47) = 14.2	MS_{model} = 0.006			MS_{error} = 0.000
Prob > F = 0.001				
R^2 = 0.731				

isolate, two of the three key ingredients, were not significant in the quadratic model. It seemed that in some cases the quadratic model was less beneficial than the linear model.

Multiple regressions, and particularly multiple nonlinear regressions, have the potential of including so many terms that any variation in the data could be explained. No attempt was made at parsimony, which would have required insignificant terms to be eliminated to balance simplicity and fit. For that reason, F-statistics often indicated that a model was good even if most terms were not significant.

Combined Responses

A special variable helped evaluate the feasibility of attaining a certain texture, such as, the texture of commercial bologna. After all the regression models were examined and a recipe was proposed, the Combined Response Variable gauged the plausibility of reproducing the desired texture.

Determination of Weight Values

As discussed in Material and Methods, the numeric value of the Combined Response Variable was defined by Eq. (3). If the value of w_i changed from one dependent variable to the next, then the value of the Combined Response Variable would be influenced by one variable more than another. Since no two dependent variables evaluated the same properties, weights should be different.

Experiments were conducted to determine weights. Several meats were purchased and tested. Those meats ranged in texture from ham, a formed product, to bologna, a comminuted product. Weights were determined according to percent variation as defined by Eq. (4). To establish a range for comparison, weights were multiplied by a scaling factor. The results of those experiments are shown in Table 18.

Shear responses varied more than those of any other dependent variable. By the method of Eq. (4), shear was assigned the greatest weight. It was followed by hardness, springiness, and cohesiveness.

Comparison of products and responses led to three observations. First, formed products made of large chunks responded similarly to texture tests. Response values from turkey breast and ham were closer than values from any other two products. Second, fermented and dried products, like salami, had texture properties very dissimilar to other sausages. Third, the smallest coefficients of variation for three out of the four response variables came from hot dog data. Hardness, springiness index, and cohesiveness data were more consistent for hot dogs than for any other product.

Comparison of Commercial Products

The last step of the texture studies was to determine what types of products could be made from deboned rainbow trout. The tools used to accomplish the task were the quadratic models and the Combined Response Variable with the assigned weights. Targets were established by testing commercial products including emulsions, coarse-ground, restructured, and semi-dry sausages.

The Combined Response Variable was used to gauge how effectively texture could be reproduced. By establishing a target and setting the sum of the weights to ten, the range of the Combined Response Variable became negative twenty to zero [-20,0] as

Table 18--Determination of weight values for use in the Combined Response Variable. Shear values varied more than those of the other response variables for the variety of meat tested. The assigned weight for shear was the largest

Commercial product	Hardness (g)	Cohesiveness $\frac{(N \cdot s)_2}{(N \cdot s)_1}$	Springiness index $\frac{(mm)_2}{(mm)_1}$	Shear (g)
Smoked turkey breast	969.3 ± 172.3	0.737 ± 0.025	0.883 ± 0.031	526.2 ± 86.0
Ham	949.0 ± 250.6	0.727 ± 0.013	0.880 ± 0.029	504.2 ± 35.3
Smoked sausage	495.7 ± 122.2	0.668 ± 0.054	0.748 ± 0.049	281.2 ± 45.0
Salami	1534.3 ± 147.4	0.632 ± 0.016	0.654 ± 0.014	1787.7 ± 485.5
Bologna	770.0 ± 138.7	0.647 ± 0.099	0.835 ± 0.035	341.5 ± 29.6
Hot dogs	599.1 ± 45.0	0.753 ± 0.009	0.885 ± 0.014	447.9 ± 40.5
Weight*	3.0	0.4	0.7	5.9

n=5, $\bar{x} \pm$ S.D.

*Weights were calculated by taking ($\bar{x}_{max}$ - $\bar{x}_{min}$)/average * scaling factor. A scale factor of 2.53 made the weights sum to ten.

defined by Eq. (3). Reproducible textures scored close to zero. The combined response results are presented in Table 19.

Two factors influenced the likelihood of texture reproduction: capability of the ingredients to achieve a response value and contradictory criteria. Salami texture could not be reproduced. Adding all ingredients at the maximum level would still cause shear and hardness values to fall far short of experimental data. For hot dogs, shear values were disproportionately lower than hardness values when compared to other products. Since no ingredient affected shear without affecting hardness and since shear had the greater weight, the Combined Response Variable would tend to satisfy the shear requirement.

The texture of semi-dry sausage would be the most difficult texture to imitate. The low score of -13.33 was nearly a full order of magnitude lower than any other score.

Based on particle size, finely ground rainbow trout should be best suited for emulsion products. Excepting salami, the lowest score unexpectedly corresponded to hot dogs, an emulsion product. That was explained by the two variables with the greatest

Table 19--Combined response results showing the percent composition of each ingredient to imitate the texture of a commercial product

	Composition based on percentage					
Product	Collagen	Soy	Egg white	Fish	Salt	Score[a]
Turkey breast	3.69	0.00	0.00	95.31	1.00	-0.94
Ham	2.00	1.14	1.18	94.68	1.00	-1.23
Salami	4.00	3.00	3.00	89.00	1.00	-13.33
Smoked sausage	0.00	0.50	0.33	98.17	1.00	-0.73
Bologna	0.50	2.62	0.00	95.88	1.00	-0.72
Hot dog	2.00	1.50	0.00	95.50	1.00	-2.40

[a] Scores were calculated according to Eq. (3). Values close to zero indicate that a texture similar to the commercial product could be produced.

weights: shear and hardness. Shear values were approximately half as large as hardness values in every case except salami and hot dogs. Shear values for hot dogs were 75% as large as the hardness scores. High shear values may have resulted from the small diameter which allowed heat and smoke to penetrate rapidly. Smoke would cause a skin to form on the outside of the hot dog and change the texture. Smoke and heat would affect shear more than hardness since the protein skin would resist cutting but bend when compressed.

To enhance comparisons, consideration would have to be given to the importance of texture variations within types of processed meat. Variation, as measured by the standard deviation, should be greatest in formed products followed by ground products. Uniform measurements should come from emulsions, the most homogeneous of all the products. There was certainly a trend with hot dog measurements varying little and formed product measurements varying greatly.

Response Surfaces

Response surfaces aided in understanding combined responses by presenting results on a simulated 3-D surface. Smoked sausage combined response values decreased with the addition of ingredients. That is shown in Figs. 7 and 8, the 3-D and 2-D response surfaces. Some products would be very dependent on a specific ingredient. The 3-D and 2-D response surfaces in Figs. 9 and 10 show a collagen dependent ridge where hot dog properties were most reproducible. The texture of salami could not be mimicked. Figure 11 shows that salami combined response values increased very slowly with the addition of ingredients.

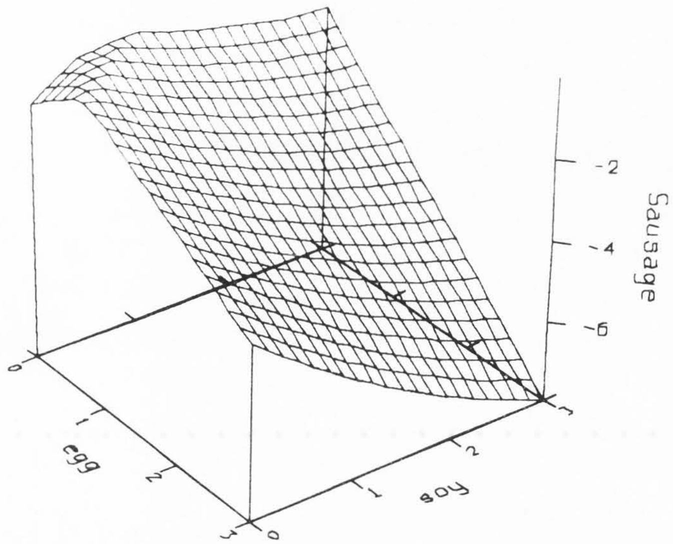


Fig. 7--3-D response surface illustrating the effect of ingredients on the Combined Response Variable. Low amounts of egg white and soy protein isolate would be needed to make a sausage-like texture.

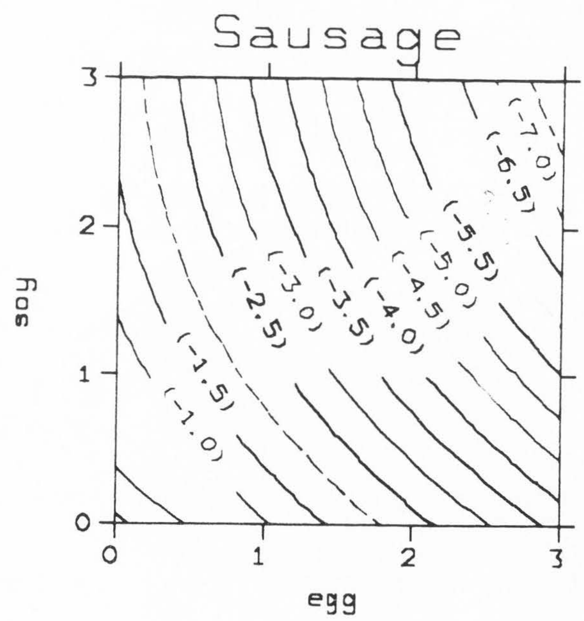


Fig. 8--2-D response surface showing the relationship between soy protein isolate and egg white for smoked sausages. The Combined Response Variable decreased almost equally when soy protein isolate or egg white were added.

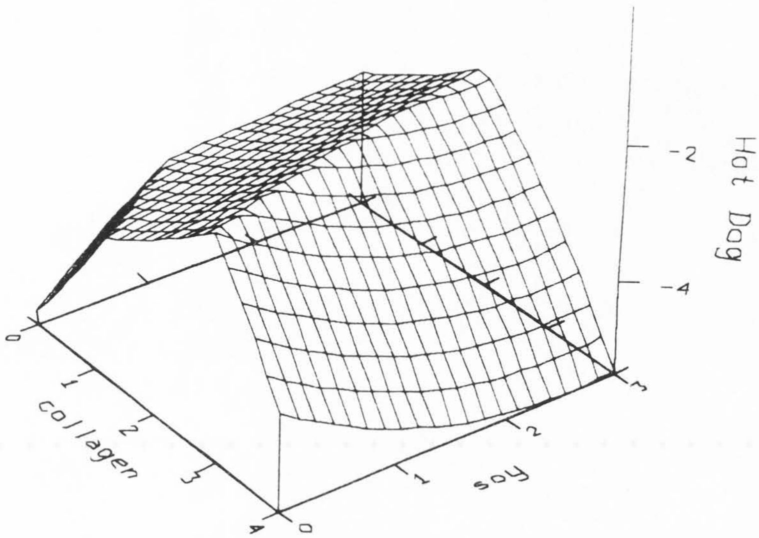


Fig. 9--3-D response surface showing the Combined Response Variable for hot dogs. Collagen is the most important ingredient for imitating emulsion texture.

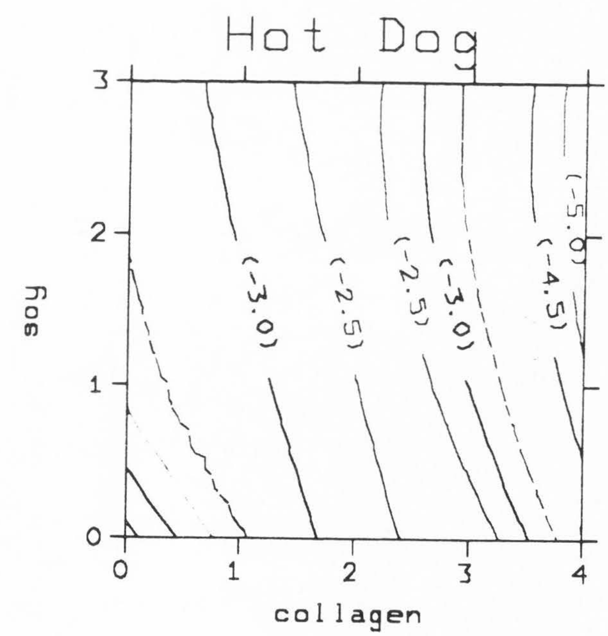


Fig. 10--2-D response surface showing the relationship between the amounts of soy protein isolate and collagen and the Combined Response Variable. The lines are relatively straight meaning that soy protein isolate had little effect.

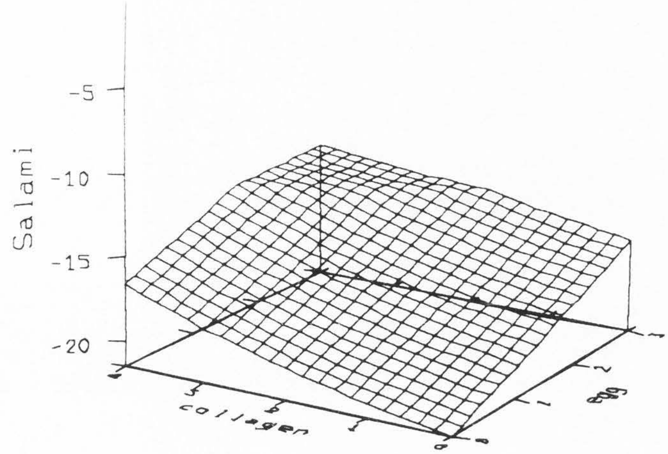


Fig. 11--3-D response surface illustrating how difficult it would be to imitate the texture of salami. Hardness and shear values were unattainable with the processing methods and ingredients considered.

Recipe for Trout Bologna

Rainbow Trout Bologna was prepared and sampled. Salt and cure were important to the recipe as was egg white. Personal preference was for a product that did not crumble, and egg white was the ingredient of choice. The recipe for the bologna is listed in Table 20.

Cook Process Modeling

The final focus of this research was heat transfer during cooking. A model was prepared to predict time and temperature data. The model responded to changes in cook temperature and sausage size.

Heat Transfer Model

Heating of fish bologna proceeded by two heat transfer modes. The first was convection, wherein heat was transferred from the thermal processing unit to the product.

Table 20--Recipe for rainbow trout bologna

Ingredient	Percentage of composition
Fish	86.91
Salt	1.15
Prague powder	0.21
Phosphate	0.25
Erythorbate	0.02
Egg white	3.56
Coriander	0.02
Fennel	<0.01
Garlic powder	0.40
Cheyenne pepper	0.08
White pepper	0.06
Black pepper	0.04
Maple flavor	<0.01
Liquid smoke	<0.01
Brown sugar	7.08
Red food color	<0.01

The second mode was conduction of heat from the outside of the sausage to the center. The general heat transfer equation follows.

$$\nabla^2 T + \frac{q}{k} = \frac{1}{\alpha}\frac{\partial T}{\partial t} \qquad \text{Eq. (8)}$$

where $\alpha = \dfrac{k}{\rho c_p}$ and $\nabla^2 T = \dfrac{\partial^2 T}{\partial r^2} + \dfrac{1}{r}\dfrac{\partial T}{\partial r} + \dfrac{1}{r^2}\dfrac{\partial^2 T}{\partial \phi^2} + \dfrac{\partial^2 T}{\partial z^2}$.

Three assumptions were made to simplify the problem. First, no heat was generated from within the sausage. Second, the sausage was infinitely long. Third, the energy source delivered heat uniformly to the entire exterior surface of the sausage. The model had no capacity for phase changes so it would not be valid for freezing or boiling. Initially, the sausage was the same refrigerated temperature throughout.

Validation

In order to solve the heat transfer problem, several variables had to be known. Two properties, specific heat ("C_p") and thermal conductivity ("k"), depended on the meat. Radial position of the temperature probe ("r"), oven temperature ("T"), and heat transfer coefficient ("h") were specific to the cooking process; "h" and "C_p" were not measured directly.

None of the variables were known with absolute certainty. "C_p" was calculated using equations from Toledo's food engineering text (1994). "h" values were determined by adjusting an educated guess to fit experimental data. "T" varied slightly from one thermocouple to the next. Unfortunately, the signal from the thermocouple could not be conditioned to eliminate error. The radius of the sausage changed during cooking, and the probe could have moved slightly. Errors may have been introduced with every variable.

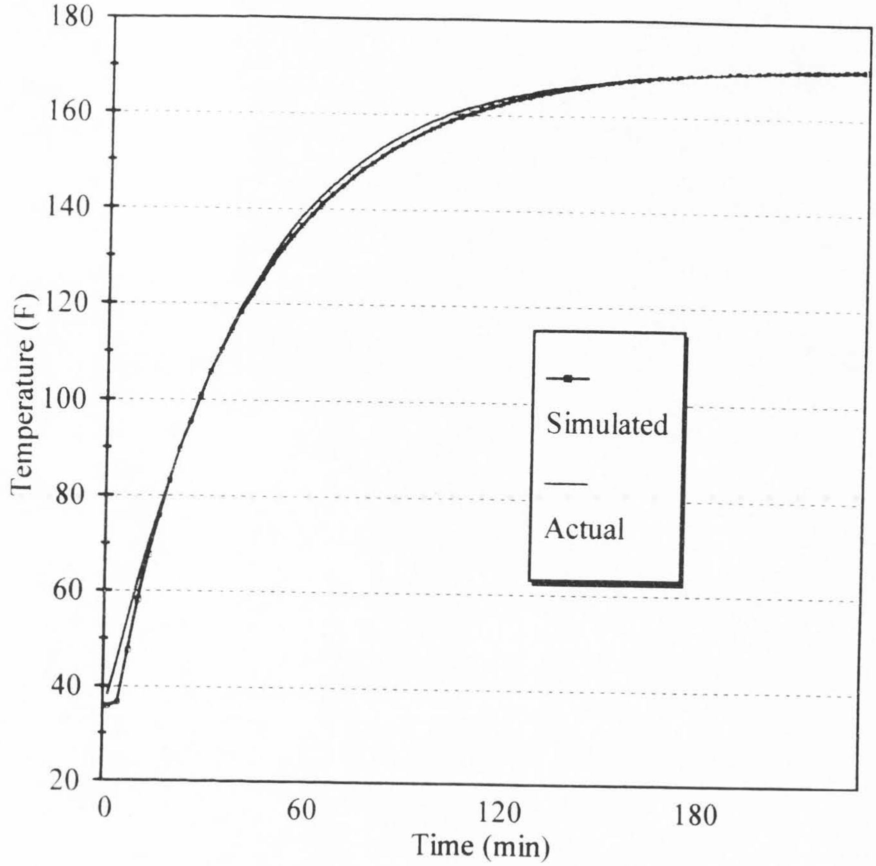
Two statistics aided in gaging the robustness of the model. RMS, as defined by Eq. (7), measured the average error between sets of data. The correlation of experimental data to model data was quantified by R^2 according to Eq. (6). Limitations to those statistics involved the number of data points. R^2 and RMS depended heavily on the number of data points and how long the test was allowed to progress. Additional statistics of "Min" and "Max" measured extreme differences between the sets of data. "Min" subtracted simulated from actual data while "Max" subtracted actual from simulated.

Three types of data sets were of interest in evaluating errors. The "best-fit" set was used as a standard. Data from that model were mapped against the actual data in Fig. 12. The next set used in "error tests" included all credible values. The final data set was calculated such that RMS would be less than five times greater than the standard.

Table 21 lists the range of values tested by the computer program. Percent variation, which measured range on a relative scale, showed that "T" values varied the least and "k" values varied the most.

The computer model allowed different test conditions to be studied. Simulated tests covered a range of values for each variable. As the data were plotted on a graph, trends emerged in three regions: the initial one third of the test, a center band covering approximately two thirds of the test, and the latter two thirds of the test. By varying "r", large temperature differences occurred during the initial stages. Data from different values for "h", "k", and "C_p" had similar beginning and ending temperatures; however, temperatures during the rest of the cycle were different. The effects of "T" were apparent at the latter stages of cooking.

Simulation tests revealed information relevant to the standard value for each variable. The standard for "r" was established by measurement. Figure 13 showed how mislocating the probe would cause errors near the beginning of the cycle. All simulations reached the same temperature within 120 minutes. "h" was obtained by examining different transfer rates from the smokehouse to the sausage. Error patterns like those in Fig. 14 emerged, wherein the largest errors occurred in the middle of the cycle. A heat transfer rate of 40 $W/m^2 \cdot K$ fit the actual cook data most closely. Figure 15 showed the



Diameter of sausage = 6.2-cm	
Distance from center = 2.3-cm	$R^2 = 0.997$
Length of sausage = 20-cm	RMS = 1.05 °F
Oven temperature = 171 °F	Max = 0.30 °F
Heat transfer coefficient (h) = 40 W/m^2·K	Min = -9.46 °F
Thermal conductivity (k) = 0.48 W/m·K	
Specific heat (C_p) = 3200 J/kg·K	

Fig. 12--Best-fit values for the heat transfer model. This model had the best correlation (R^2 = .997) to the actual data and the lowest error (RMS = 1.28 °F).

Table 21--Computer program variables. The range of credible thermal conductivity values used in error test was smaller than the robust range. Thermal conductivity values could vary greatly without severely affecting the model. The oven temperature must be very accurately known

		Error tests[a]				Robustness	
Variable	Values for standard (measured or best fit)	Minimum value	Maximum value	Maximum deviation (+) (model-standard)	Maximum deviation (-) (standard-model)	Range (5xRMS)	Percent variation for range
Heat transfer coefficient ($h=W/m^2 \cdot K$)	40	20	100	20°F	-23°F	30-72	82%
Thermal conductivity ($k=W/m \cdot K$)	0.48	0.3	0.7	7°F	-13°F	0.35-1.04	99%
Location probe (r=cm)	2.3	1.3	3.3	35°F	-23°F	1.7-3.0	55%
Specific heat ($C_p=J/kg \cdot K$)	3200	2700	3800	8°F	-11°F	2500-3700	39%
Oven temperature (T=°F)	171	164	179	8°F	-10°F	165-177	7%

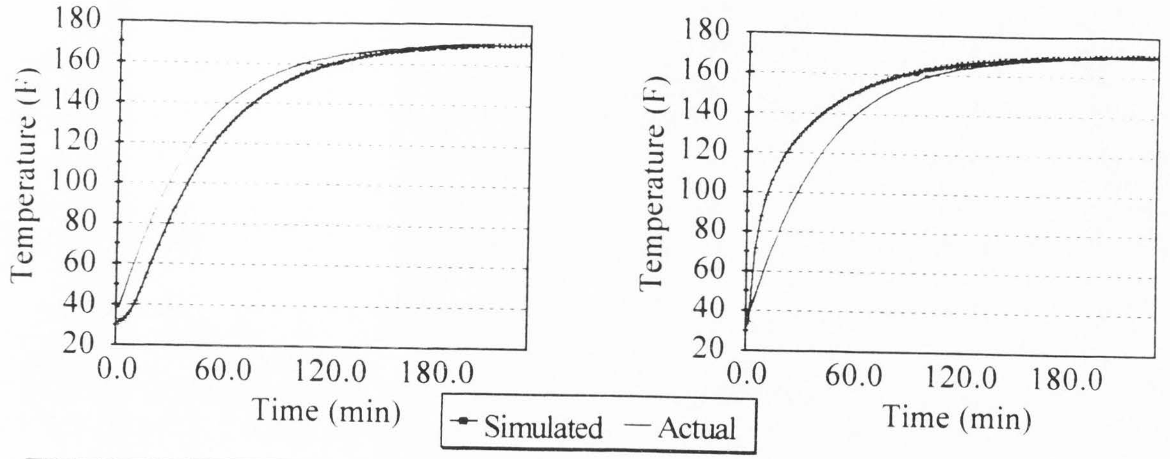
[a]The range of values used in the robustness tests was determined either by experimentation or published data.

effects of "k" to be similar to those of "h". Fortunately, "k" was measured with a probe at 0.48 W/m·K so errors should have been minimal. Heat capacity, as measured by "C_p", also affected the model similarly to "h". The calculated value of 3200 J/kg·K fit the experimental data the best; however, Fig. 16 showed that the model was not greatly affected by the range of values tested. "T" was measured by a thermocouple, but the signal could not be conditioned to eliminate error. Incorrect measurements, as shown in Fig. 17, resulted in blaring errors. Those errors were most pronounced at the end of the cooking cycle.

Size Variations

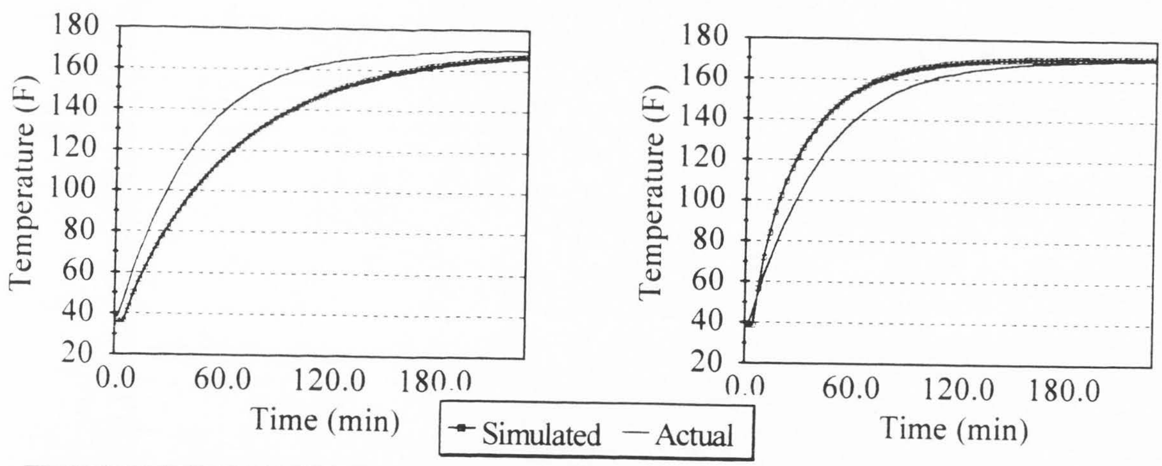
The computer program predicted time and temperature data for both small and large sausages. Figure 18 shows the results of tests performed with 4.0, 6.2, and 10.2-cm diameter sausages. The distance from the center, or "r", measured the distance from the probe to the center of the sausage.

Experimental data from all three sausages agreed very well with simulated data. The best correlation of R^2 =.996 and the smallest average error (RMS=1.56°F) corresponded to the 4.0-cm sausage. The cook temperature of the 6.2-cm sausage never reached the oven temperature, which resulted in the largest RMS of 5.28°F. Simulated data were higher than actual data (Max) on the 10.2-cm sausage. If the experimental data could be shifted to the left, they would match the actual data more closely. A delayed start or an inaccurate starting time could cause the observed temperature differences.



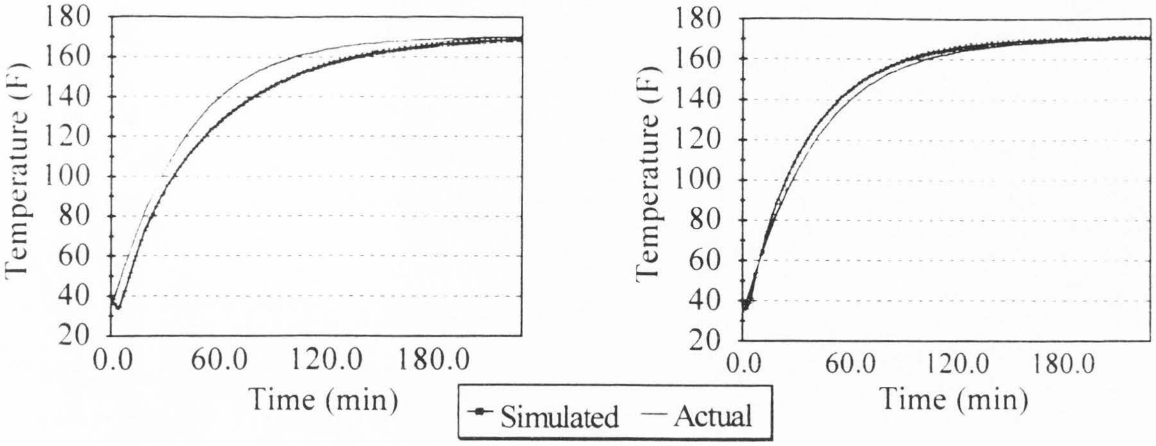
$R^2 = 0.913$	$R^2 = 0.844$
RMS = 6.80°F	RMS = 8.06°F
Max = 0.09°F	Max = 35.27°F
Min = -22.90°F	Min = -5.17°F
r = 1.3-cm	r = 3.3-cm

Fig. 13--Early errors caused by mislocating thermocouple (probe).



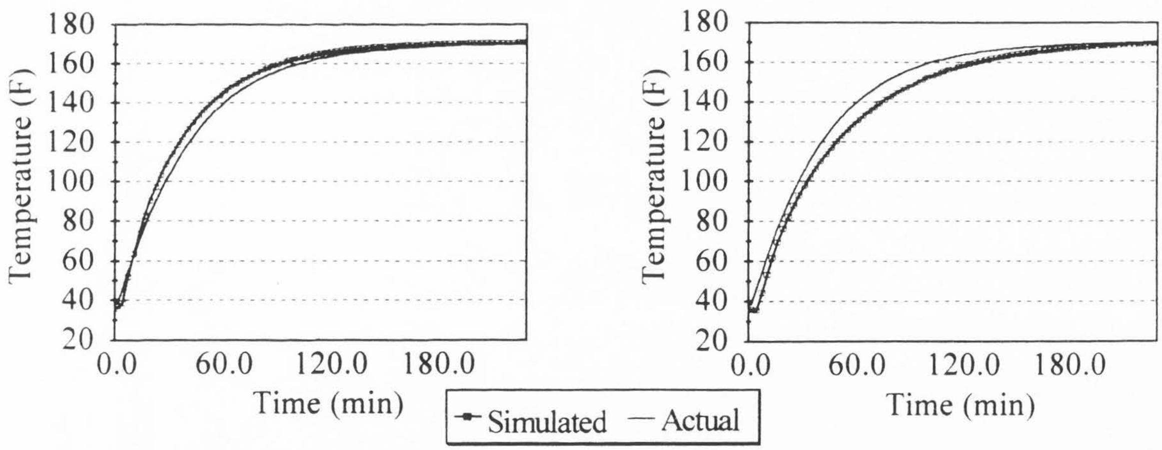
$R^2 = 0.801$	$R^2 = 0.918$
RMS = 13.30°F	RMS = 7.18°F
Max = -2.36°F	Max = 20.28°F
Min = -23.27°F	Min = -7.24°F
h = 20 $W/m^2 \cdot K$	h = 100 $W/m^2 \cdot K$

Fig. 14--Variances in the middle of the cook cycle resulting from different heat transfer rates "h".



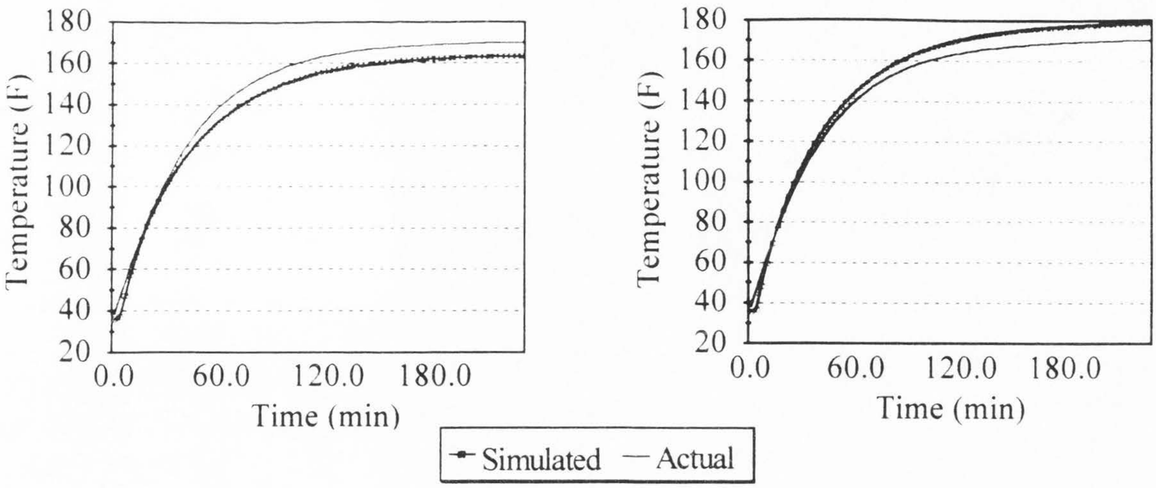
$R^2 = 0.937$	$R^2 = 0.989$
RMS = 7.36°F	RMS = 2.84°F
Max = -1.24°F	Max = 7.04°F
Min = -13.41°F	Min = -5.96°F
k = 0.30 W/m·K	k = 0.70 W/m·K

Fig. 15--Effect of thermal conductivity most evident after the initial cooking stages. Errors were larger for underestimating than for overestimating the standard.



$R^2 = 0.986$	$R^2 = 0.964$
RMS = 3.17°F	RMS = 5.43°F
Max = 8.19°F	Max = -0.59°F
Min = -7.60°F	Min = -10.89°F
C_p = 2700 J/kg·K	C_p = 3800 J/kg·K

Fig. 16--"C_p" representing the amount of heat needed to heat the sausage. High or low values changed the temperatures during the middle of the cycle.



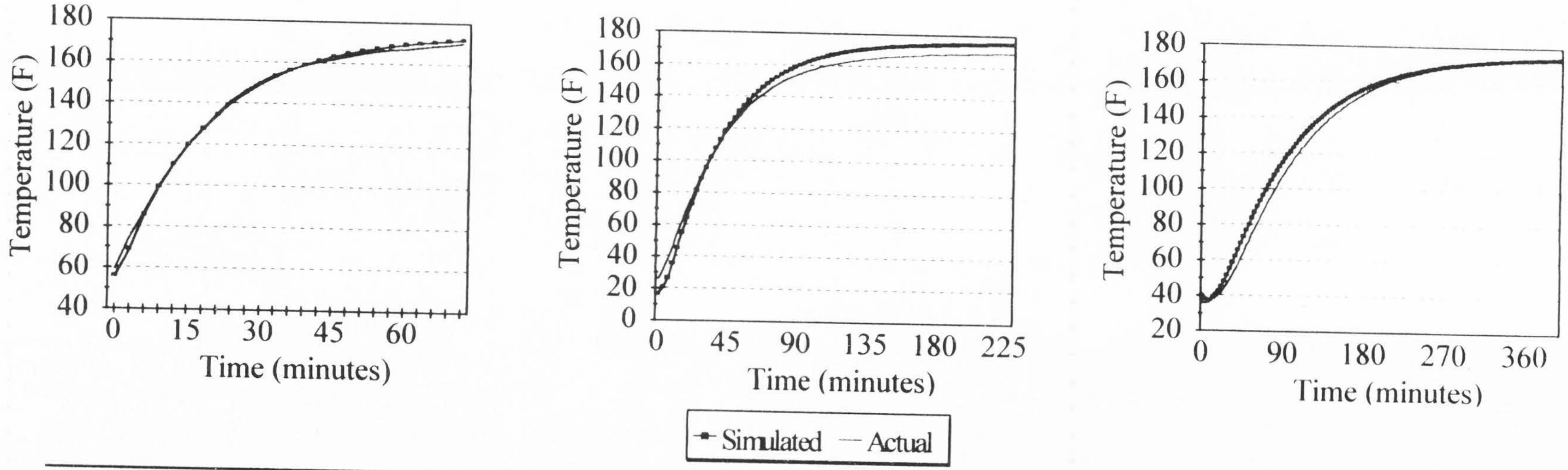
$R^2 = 0.959$	$R^2 = 0.964$
RMS = 6.62°F	RMS = 6.07°F
Max = -2.37°F	Max = 8.26°F
Min = -9.38°F	Min = -9.56°F
T = 164°F	T=179°F

Fig. 17--Final cook temperature depending on the oven temperature. Increasing the oven temperature by 8 °F, produced an average error of 6 °F.

Oven temperature and radial location of the probe were not concretely known. The probes differed by as much as three degrees at room temperature. Unfortunately, the thermocouple signals could not be manipulated to register the same temperature. That difference could explain why the temperature at the 6.2-cm diameter sausage never approached the oven temperature of 175°F. Additionally, the location of the probe may have varied in the cooking process. If the probe moved radially inward during cooking, the measured temperature would be unexpectedly low.

Temperature Variations

Experiments were conducted at two oven temperatures: 175°F and 205°F. Figure 19 presents the results of cooking 4.0-cm diameter sausages. Correlations between

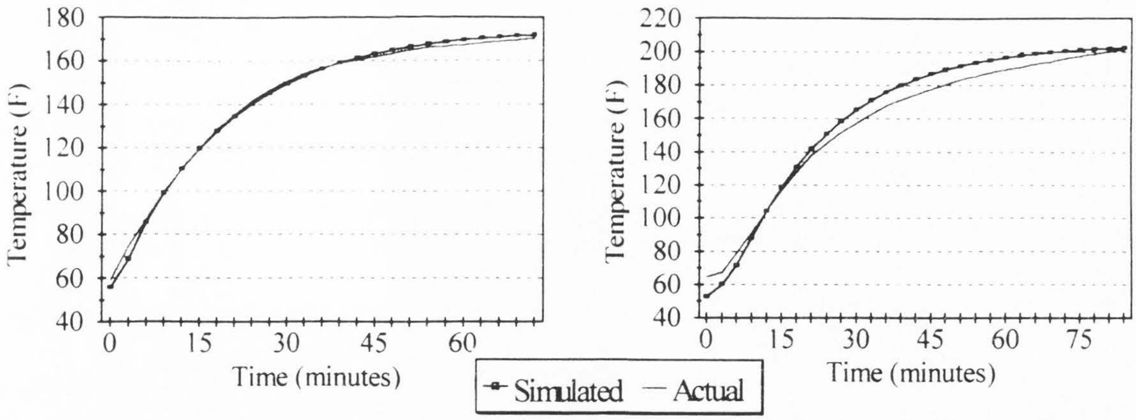


Sausage diameter = 4.0-cm
Distance from center = 1.3-cm
$R^2 = 0.996$
RMS = 1.56°F
Max = 2.22°F
Min = -6.27°F

Sausage diameter = 6.2-cm
Distance from center = 1.3-cm
$R^2 = 0.977$
RMS = 5.28°F
Max = 5.95°F
Min = -12.20°F

Sausage diameter = 10.2-cm
Distance from center = 1.3-cm
$R^2 = 0.990$
RMS = 3.05°F
Max = 9.21°F
Min = -3.30°F

Fig. 18--Comparison of different sausage sizes. The model for the smallest sausage had the best correlation to actual data as well as both the smallest average error and positive error.



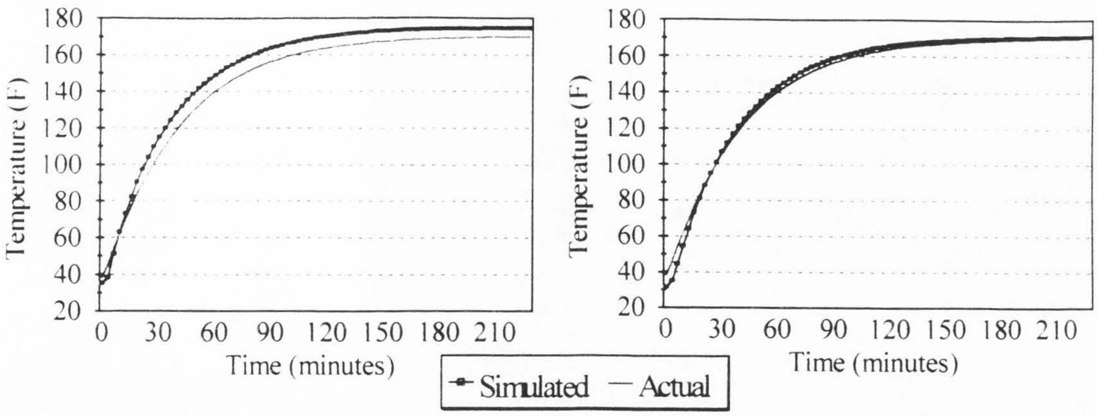
Oven Temperature = 175 °F	Oven Temperature = 205 °F
Diameter of sausage = 4.0-cm	Diameter of sausage = 4.0-cm
Distance from center = 1.3-cm	Distance from center = 0.0-cm
R^2 = 0.996	R^2 = 0.974
RMS = 1.56 °F	RMS = 4.92 °F
Max = 2.22 °F	Max = 9.03 °F
Min = -6.27 °F	Min = -11.78 °F

Fig. 19--Comparison of different cooking temperatures. The model was more effective at lower cooking temperatures.

simulated data and experimental data were very good (R^2 >.97). The average error of the 175 °F sausage was lower than the 205 °F sausage by 3.36 °F.

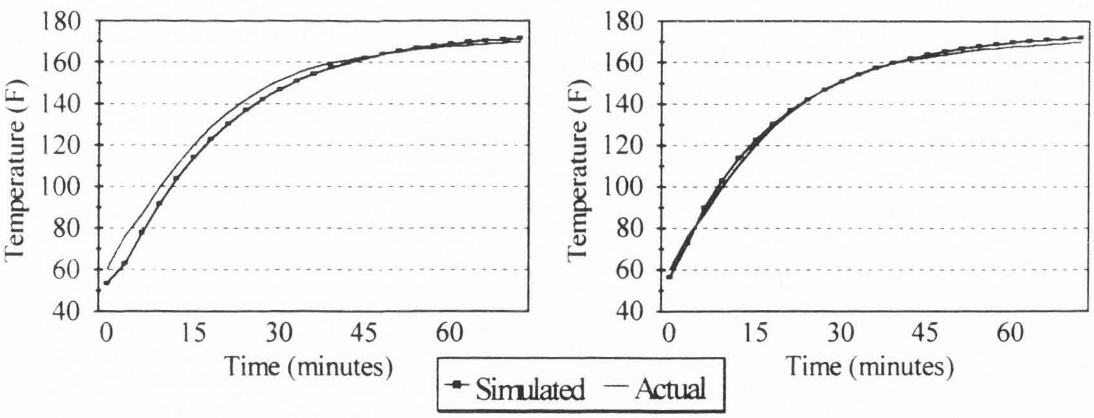
Corrections

Observations made during processing led to concerns about oven temperature and thermocouple location. Two analyses were rerun with minor corrections. Figure 20 reflects a 4 °F temperature change and a 0.3-cm distance differential. RMS dropped from 6.35 °F to 2.10 °F and, even more dramatic, R^2 jumped from 0.961 to 0.993. In the case shown in Fig. 21, moving the probe by 0.4-cm increased R^2 from .975 to .996 and decreased the average error by 4.18 °F. If errors were eliminated, the model could possibly predict the exact experimental time-temperature data.



Actual	Corrected
Diameter = 6.2-cm	Diameter = 6.2-cm
Distance from center = 2.0	Distance from center = 1.7
Temperature = 175 °F	Temperature = 171 °F
R^2 = 0.961	R^2 = 0.993
RMS = 6.35 °F	RMS = 2.10 °F
Max = 9.61 °F	Max = 2.74 °F
Min = -8.02 °F	Min = -11.10 °F

Fig. 20--Effect of temperature and location on heating model. By adjusting those two variables, all of the gauging statistics improved greatly.



Actual	Corrected
Diameter = 4.0-cm	Diameter = 4.0-cm
Distance from center = 1.0-cm	Distance from center = 1.4-cm
R^2 = 0.975	R^2 = 0.996
RMS = 3.89 °F	RMS = 1.71 °F
Max = 1.75 °F	Max = 3.48 °F
Min = -13.34 °F	Min = -3.76 °F

Fig. 21--Effect of location on heating model. Relocation of the probe by 0.4-cm dropped the average error by 2.18 °F.

CONCLUSIONS

The purpose of this research was to find a use for mechanically deboned trout. To help identify possibilities, the composition of trout was determined through proximate analysis procedures. Trout was high in protein (18%) relative to fat (10% ± 2%, $\bar{x}$ ± S.D.). A mineral analysis of pre- and post-deboner meat showed post-deboner meat to have less calcium ($P<0.001$) but more phosphorus ($P<0.001$), magnesium ($P<0.001$), iron ($P<0.001$), and aluminum ($P<0.001$). The composition of all minerals was different in pre- and post-deboner meat at the $\alpha=0.05$ level.

One possible use for deboned meat was the manufacture of a finely chopped emulsion-like product. Ingredients, when added to fish and cooked, affected texture in different ways. Those texture changes were measured by five variables: hardness, shear, cohesiveness, springiness index, and adhesiveness. Adhesiveness was eliminated after the first test when no ingredients were confirmed to have an effect. The model was very inefficient (F-statistic $(6,50) = 1.1$, Probability>F = 0.37).

Collagen, egg white, soy protein isolate, wheat gluten, cellulose, and starch were added with one percent salt to deboned fish. All ingredients affected hardness ($P>|T|=0.06$), cohesiveness ($P>|T|=0.06$), and shear ($P>|T|=0.02$). Egg white and starch were not statistically significant for springiness index. Collagen had the largest coefficient in every case except for hardness. Starch either had no effect or a negative effect on texture.

The comprehensive effect of ingredients was established by rank order. For a particular response, the regression coefficients were ranked first, second, and so forth according to the size of the coefficient. When all the ranks were summed, collagen had the lowest score (6), followed by egg white (11), soy protein isolate (13), wheat gluten (14), cellulose (17), and starch (24).

Interactions, for the most part, had a minimal effect on models. Most interactions were not statistically significant. The only positive interaction was between soy protein isolate and egg white for response shear ($P>|T|=0.03$). All other significant interactions ($\alpha=0.05$) were negative.

Combining responses allowed for the texture of fish products to be compared to commercial products. A technique was devised to weight the four response variables. After testing a variety of products on the texture analyzer, weights were assigned according to the ability of the response variable to detect different textures. Those weights were assigned by taking a scaled value of the percent variation. Shear was assigned the greatest weight (5.9), followed by hardness (3.0), springiness index (0.7), and cohesiveness (0.4). The range of possible scores for the Combined Response Variable was determined by equations (range = [-20,0]). Bologna was the product that could be most closely reproduced (-0.72).

A computer program modeled the process of cooking sausages of different size at different temperatures. Since the exact values of some of the computer-required variables were unknown, two statistics measured robustness of the model: average error (RMS) and correlation coefficient R^2. The range was established for the computer variables wherein the average error was less than five times the error of the best fitting model

(5xRMS). The range of acceptable values for different foods was very similar to the 5xRMS range.

Graphical comparisons of simulated data revealed trends in how a variable affected the model. Each variable created a characteristic error. Oven temperature was the most critical variable to the model. Between possible operator errors and deductions drawn from graphical results, oven temperature and thermocouple location were the variables most prone to error.

Testing showed the model to be accurate over a range of sausage sizes and cooking temperatures. For all sizes of sausage, the best fitting models had low average errors (RMS<5.3 °F) and high correlations to the actual data (R^2>0.97). The model also worked for different cook temperatures. The model was more accurate at low temperatures ($RMS_{175°F}$= 1.6 °F) than at high temperatures ($RMS_{205°F}$= 4.9 °F). Correlations were high at both temperatures (R^2>0.97).

The results of this study showed that mechanically deboned fish can be used to make processed meat products. To better understand the value of deboned fish, it was described in terms of proximate composition and mineral content. Experiments helped determine the ingredients that affected texture. Models were proposed to reproduce the texture of commercial products. A heat transfer model was evaluated in terms of being robust for design variables. The model was effective regardless of sausage size or oven temperature.

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APPENDICES

Appendix A

Datalogger Program for Recording Six Temperatures

```
Program:
   Flag Usage:
   Input Channel Usage:
   Excitation Channel Usage:
   Control Port Usage:
   Pulse Input Channel Usage:
   Output Array Definitions:

 *      1          Table 1 Programs
   01: 60          Sec. Execution Interval

 01:  P17          Module Temperature
   01: 2           Loc :

 02:  P92          If time is
   01: 1           minutes (seconds--) into a
   02: 3           minute or second interval
   03: 10          Set high Flag 0 (output)

 03:  P14          Thermocouple Temp (DIFF)
   01: 6           Reps
   02: 2           7.5 mV slow Range
   03: 1           IN Chan
   04: 1           Type T (Copper-Constantan)
   05: 2           Ref Temp Loc
   06: 2           Loc :
   07: 1.8         Mult
   08: 32          Offset

 04:  P77          Real Time
   01: 0220        Day,Hour-Minute

 05:  P70          Sample
   01: 6           Reps
   02: 2           Loc

 06:  P            End Table 1


 *      2          Table 2 Programs
   01: 0.0000      Sec. Execution Interval

 01:  P            End Table 2
```

```
*      3        Table 3 Subroutines

01:  P          End Table 3

*      A        Mode 10 Memory Allocation
  01: 50        Input Locations
  02: 64        Intermediate Locations
  03: 0.0000    Final Storage Area 2

Page 2   Mode C

*      C        Mode 12 Security
  01: 0         LOCK 1
  02: 0         LOCK 2
  03: 0000      LOCK 3

Page 3    Input Location Assignments (with comments):

Key:
T=Table Number
E=Entry Number
L=Location Number

T:  E:  L:
1:  1:  2:  Loc :
1:  3:  2:  Loc :
```

Appendix B

Datalogger Program for Thermal Conductivity Measurement

```
Program:
 Flag Usage:
 Input Channel Usage:
 Excitation Channel Usage:
 Control Port Usage:
 Pulse Input Channel Usage:
 Output Array Definitions:


*       1         Table 1 Programs
  01: 0.5         Sec. Execution Interval

01:  P17          Module Temperature
  01: 11          Loc [:T panel  ]

02:  P14          Thermocouple Temp (DIFF)
  01: 1           Rep
  02: 1           2.5 mV slow Range
  03: 1           IN Chan
  04: 2           Type E (Chromel-Constantan)
  05: 11          Ref Temp Loc T panel
  06: 3           Loc [:T         ]
  07: 1           Mult
  08: 0.0000      Offset

03:  P14          Thermocouple Temp (DIFF)
  01: 3           Reps
  02: 1           2.5 mV slow Range
  03: 3           IN Chan
  04: 2           Type E (Chromel-Constantan)
  05: 11          Ref Temp Loc T panel
  06: 35          Loc [:T2        ]
  07: 1           Mult
  08: 0.0000      Offset

04:  P91          If Flag/Port
  01: 22          Do if flag 2 is low
  02: 0           Go to end of Program Table

05:  P92          If time is ***************  time interval
  01: 0           minutes (seconds--) into a  time interval
  02: 15          minute or second interval   time interval
  03: 11          Set high Flag 1 **********  time interval

06:  P91          If Flag/Port
  01: 21          Do if flag 1 is low
  02: 0           Go to end of Program Table
```

```
07:  P30         Z=F
  01: 0          F
  02: 00         Exponent of 10
  03: 1          Z Loc [:n        ]

08:  P30         Z=F
  01: 2          F
  02: 00         Exponent of 10
  03: 13         Z Loc [:generator]

09:  P30         Z=F
  01: 0          F
  02: 00         Exponent of 10
  03: 15         Z Loc [:sum      ]

10:  P87         Beginning of Loop
  01: 0          Delay
  02: 15         Loop Count

11:  P30         Z=F
  01: 0          F
  02: 00         Exponent of 10
  03: 17--       Z Loc [:sum q    ]

12:  P95         End

13:  P30         Z=F
  01: 5000       F
  02: 00         Exponent of 10
  03: 10         Z Loc [:mV heater]

14:  P26         Timer
  01: 0          Reset Timer

15:  P86         Do
*****************************************************
  01: 41         Set high Port 1

16:  P87         Beginning of Loop
  01: 1          Delay
  02: 25         Loop Count

17:  P34         Z=X+F
  01: 13         X Loc generator
  02: 0.1        F
  03: 13         Z Loc [:generator]

18:  P41         Z=EXP(X)
  01: 13         X Loc generator
  02: 14         Z Loc [:exp gen  ]

19:  P87         Beginning of Loop
  01: 1          Delay
  02: 100        Loop Count

20:  P34         Z=X+F
  01: 15         X Loc sum
```

```
   02: 0.5      F
   03: 15       Z Loc [:sum       ]

 21:  P88       If X<=>Y
   01: 15       X Loc sum
   02: 3        >=
   03: 14       Y Loc exp gen
   04: 31       Exit Loop if true

 22:  P95       End

 23:  P32       Z=Z+1
   01: 1        Z Loc [:n         ]

 24:  P17       Module Temperature
   01: 11       Loc [:T panel  ]

 25:  P14       Thermocouple Temp (DIFF)
   01: 1        Rep
   02: 1        2.5 mV slow Range
   03: 1        IN Chan
   04: 2        Type E (Chromel-Constantan)
   05: 11       Ref Temp Loc T panel
   06: 3        Loc [:T         ]
   07: 1.0      Mult
   08: 0.0000   Offset

 26:  P14       Thermocouple Temp (DIFF)
   01: 3        Reps
   02: 1        2.5 mV slow Range
   03: 3        IN Chan
   04: 2        Type E (Chromel-Constantan)
   05: 11       Ref Temp Loc T panel
   06: 35       Loc [:T2        ]
   07: 1        Mult
   08: 0.0000   Offset

 27:  P26       Timer
   01: 9        Loc [:timer    ]

 28:  P37       Z=X*F
   01: 9        X Loc timer
   02: 0.1      F
   03: 2        Z Loc [:t         ]

 29:  P2        Volt (DIFF)
   01: 1        Rep
   02: 4        250 mV slow Range
   03: 2        IN Chan
   04: 7        Loc [:V ref    ]
   05: 0.001    Mult
   06: 0        Offset

 30:  P36       Z=X*Y
   01: 7        X Loc V ref
   02: 7        Y Loc V ref
   03: 8        Z Loc [:V ref sq.]
```

```
31:  P37        Z=X*F
  01: 8         X Loc V ref sq.
  02: 31.8      F
  03: 4         Z Loc [:q          ]

32:  P33        Z=X+Y
  01: 17        X Loc sum q
  02: 4         Y Loc q
  03: 17        Z Loc [:sum q      ]

33:  P40        Z=LN(X)
  01: 2         X Loc t
  02: 18        Z Loc [:ln t       ]

34:  P33        Z=X+Y
  01: 19        X Loc sum ln t
  02: 18        Y Loc ln t
  03: 19        Z Loc [:sum ln t ]

35:  P33        Z=X+Y
  01: 20        X Loc sum T
  02: 3         Y Loc T
  03: 20        Z Loc [:sum T      ]

36:  P36        Z=X*Y
  01: 18        X Loc ln t
  02: 3         Y Loc T
  03: 21        Z Loc [:T*ln t     ]

37:  P33        Z=X+Y
  01: 22        X Loc S (T*lnt)
  02: 21        Y Loc T*ln t
  03: 22        Z Loc [:S (T*lnt)]

38:  P36        Z=X*Y
  01: 18        X Loc ln t
  02: 18        Y Loc ln t
  03: 23        Z Loc [:ln t sq. ]

39:  P33        Z=X+Y
  01: 24        X Loc S(lnt sq)
  02: 23        Y Loc ln t sq.
  03: 24        Z Loc [:S(lnt sq)]

40:  P36        Z=X*Y
  01: 19        X Loc sum ln t
  02: 20        Y Loc sum T
  03: 25        Z Loc [:S lnt+S T]

41:  P42        Z=1/X
  01: 1         X Loc n
  02: 26        Z Loc [:1/n        ]

42:  P36        Z=X*Y
  01: 25        X Loc S lnt+S T
  02: 26        Y Loc 1/n
  03: 27        Z Loc [:product  ]
```

```
43:  P35        Z=X-Y
  01: 22        X Loc S (T*lnt)
  02: 27        Y Loc product
  03: 28        Z Loc [:numerator]

44:  P36        Z=X*Y
  01: 19        X Loc sum ln t
  02: 19        Y Loc sum ln t
  03: 29        Z Loc [:(S lnt)sq]

45:  P36        Z=X*Y
  01: 26        X Loc 1/n
  02: 29        Y Loc (S lnt)sq
  03: 30        Z Loc [:product 2]

46:  P35        Z=X-Y
  01: 24        X Loc S(lnt sq)
  02: 30        Y Loc product 2
  03: 31        Z Loc [:denominat]

47:  P38        Z=X/Y
  01: 28        X Loc numerator
  02: 31        Y Loc denominat
  03: 5         Z Loc [:s        ]

48:  P86        Do
  01: 10        Set high Flag 0 (output)

49:  P95        End

50:  P30        Z=F
  01: 0.0000    F
  02: 00        Exponent of 10
  03: 10        Z Loc [:mV heater]

51:  P86        Do
*************************************************
  01: 51        Set low Port 1

52:  P37        Z=X*F
  01: 17        X Loc sum q
  02: 0.04      F
  03: 4         Z Loc [:q        ]

53:  P37        Z=X*F
  01: 5         X Loc s
  02: 12.566    F
  03: 32        Z Loc [:4 pi s   ]

54:  P38        Z=X/Y
  01: 4         X Loc q
  02: 32        Y Loc 4 pi s
  03: 6         Z Loc [:k        ]

55:  P31        Z=X
  01: 6         X Loc k
  02: 1         Z Loc [:n        ]
```

```
56:  P86          Do
  01: 10          Set high Flag 0 (output)

57:  P77          Real Time
  01: 0220        Day,Hour-Minute

58:  P70          Sample
  01: 3           Reps
  02: 4           Loc q

59:  P70          Sample
  01: 3           Reps
  02: 35          Loc T2

60:  P86          Do
  01: 21          Set low Flag 1

61:  P            End Table 1


*      2          Table 2 Programs
  01: 0.0000      Sec. Execution Interval

01:  P            End Table 2


*      3          Table 3 Subroutines

01:  P            End Table 3


*      A          Mode 10 Memory Allocation
  01: 50          Input Locations
  02: 64          Intermediate Locations
  03: 0.0000      Final Storage Area 2


*      C          Mode 12 Security
  01: 0000        LOCK 1
  02: 0000        LOCK 2
  03: 0000        LOCK 3
```

```
Input Location Assignments (with comments):

 Key:
 T=Table Number
 E=Entry Number
 L=Location Number

 T:  E:  L:
 1:  7:  1:  Z Loc [:n         ]
 1: 23:  1:  Z Loc [:n         ]
 1: 55:  1:  Z Loc [:n         ]
 1: 28:  2:  Z Loc [:t         ]
 1:  2:  3:  Loc [:T         ]
 1: 25:  3:  Loc [:T         ]
 1: 31:  4:  Z Loc [:q         ]
 1: 52:  4:  Z Loc [:q         ]
 1: 47:  5:  Z Loc [:s         ]
 1: 54:  6:  Z Loc [:k         ]
 1: 29:  7:  Loc [:V ref     ]
 1: 30:  8:  Z Loc [:V ref sq.]
 1: 27:  9:  Loc [:timer     ]
 1: 13: 10:  Z Loc [:mV heater]
 1: 50: 10:  Z Loc [:mV heater]
 1:  1: 11:  Loc [:T panel   ]
 1: 24: 11:  Loc [:T panel   ]
 1:  8: 13:  Z Loc [:generator]
 1: 17: 13:  Z Loc [:generator]
 1: 18: 14:  Z Loc [:exp gen  ]
 1:  9: 15:  Z Loc [:sum      ]
 1: 20: 15:  Z Loc [:sum      ]
 1: 11: 17:  Z Loc [:sum q    ]
 1: 32: 17:  Z Loc [:sum q    ]
 1: 33: 18:  Z Loc [:ln t     ]
 1: 34: 19:  Z Loc [:sum ln t ]
 1: 35: 20:  Z Loc [:sum T    ]
 1: 36: 21:  Z Loc [:T*ln t   ]
 1: 37: 22:  Z Loc [:S (T*lnt)]
 1: 38: 23:  Z Loc [:ln t sq. ]
 1: 39: 24:  Z Loc [:S(lnt sq)]
 1: 40: 25:  Z Loc [:S lnt+S T]
 1: 41: 26:  Z Loc [:1/n      ]
 1: 42: 27:  Z Loc [:product  ]
 1: 43: 28:  Z Loc [:numerator]
 1: 44: 29:  Z Loc [:(S lnt)sq]
 1: 45: 30:  Z Loc [:product 2]
 1: 46: 31:  Z Loc [:denominat]
 1: 53: 32:  Z Loc [:4 pi s   ]
 1:  3: 35:  Loc [:T2        ]
 1: 26: 35:  Loc [:T2        ]
```

Appendix C

Closed Form Solution to Infinitely Long Cylinder

Heating of fish bologna is done by two heat transfer modes. The first is convection; herein heat, is transferred from the thermal processing unit to the product. The second mode is conduction of heat from the outside of the sausage to the center. If thermal conductivity is assumed to be constant throughout the sausage, then the solution to the problem is given by the following general conduction equation

$$\nabla^2 T + \frac{q}{k} = \frac{1}{\alpha}\frac{\partial T}{\partial t} \tag{D.1}$$

where $\alpha = \frac{k}{\rho c_p}$ and $\nabla^2 T$ is the Laplacian operator. Two definitions of that operator follow:

$$\nabla^2 T = \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \quad (\textit{Cartesian Coordinates})$$

Cartesian coordinates describe a typical 3-dimensional space. Cylindrical coordinates are

$$\nabla^2 T = \frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{1}{r^2}\frac{\partial^2 T}{\partial \phi^2} + \frac{\partial^2 T}{\partial z^2} \quad (Cylindrical\ Coordinates)$$

specialized for cylinder-like shapes. The solution for bologna would be best obtained by using the latter set of coordinates.

For the problem at hand, heat transfers in the radial direction only. By defining θ as the time and location dependent temperature difference, $\theta = T(r,t) - T_\infty$, and eliminating the heat generation term of q, (D.1) reduces to (D.2).

$$\frac{\partial^2 \theta}{\partial r^2} + \frac{1}{r}\frac{\partial \theta}{\partial r} = \frac{1}{\alpha}\frac{\partial \theta}{\partial t} \qquad \text{(D.2)}$$

Two numbers need to be defined in order to obtain a solution. Those numbers are the Fourier modulus (Fo) and the Biot number (Bi). In the following equations, x is the characteristic length. For bologna, that length is the radius of the sausage, R.

$$Bi = \frac{resistance\ to\ internal\ heat\ flow}{restiance\ to\ extrnal\ heat\ flow} = \frac{hx}{k}$$

$$Fo = \frac{\alpha t}{x^2}$$

The resulting solution, as defined by Bessel functions of the first kind of the zero (J_0) and first orders (J_1) is (D.3).

$$\frac{\theta}{\theta_i} = 2\sum_{n=1}^{\infty}\frac{1}{\delta_n}e^{-\delta_n^2 Fo}\frac{J_0(\delta_n\frac{r}{R})\ J_1(\delta_n)}{J_0^2(\delta_n)+J_1^2(\delta_n)} \tag{D.3}$$

δ_n is defined by the consecutive roots of the equation:

$$Bi = \delta_n\frac{J_1(\delta_n)}{J_0(\delta_n)}$$

Appendix D

Fortran Code for Predicting Heat Transfer

```
program main
implicit none
real rho, k, h, t, y, c_p, r, radius, t_i, t_inf, t_r
real alpha,theta,sum
real delta, temp,start
real l,length, theta_r, theta_l, time, span,step

open(1,file='n.out',status='unknown')
open(99,file='temp.out',status='unknown')

print*,'ALL DISTANCES AND LENGTHS ARE IN METRIC (cm)'
print*,'IF A VARIABLE IS UNKNOWN, ENTER "0" AND A DEFAULT VALUE'
print*,'WILL BE ASSUMED'
print*,'The output file is temp.out'
print*,'Radius of sausage: (3.5cm)'
read(*,*)radius
if (radius.eq.0.) radius=3.5
radius=radius/100.
print*,'Radial distance from center: (0cm)'
read(*,*)r
r=r/100
print*,'Length of sausage: (20cm)'
read(*,*)l
if (l.eq.0) l=20
l=l/100
print*,'Longitudinal length from center: (0cm)'
read(*,*)length
length=length/100
print*,'Heat transfer coefficient: (40 W/m/K)'
read(*,*)h
if (h.eq.0.) h=40.
print*,'Thermal conductivity: (0.48 W/m^2/K)'
read(*,*)k
if (k.eq.0.) k=.48
print*,'Density: (1000 kg/m^3)'
read(*,*)rho
if (rho.eq.0.) rho=1000.
print*,'Specific heat: (3200 J/kg/K)'
read(*,*)c_p
if (c_p.eq.0) c_p=3200
print*,'Initial temperature: (45 F)'
```

```
      read(*,*)t_i
      if (t_i.eq.0) t_i=45.
      t_i=(t_i-32)*5/9
      print *,'Oven temperature: (180 F)'
      read (*,*) temp
      if (temp.eq.0) temp=180
      t_inf=(temp-32)*5/9
*     print *,t_inf
      print*,'Cook time: (180 min)'
      read (*,*)time
      if (time.eq.0) time=180
      print*,'starting time: (0 min)'
      read(*,*) start
*     print*,time
      print*,'Time interval to be printed: (5 min)'
      read (*,*) span
      if (span.eq.0) span=5.
      print*,'step size: (0.05)'
      read(*,*) step
      if (step.eq.0) step=.05

      alpha=k/rho/c_p

      do 100 y=start,time,span
      sum = 0.
      delta=0.
      t=y*60.
      call cyl(alpha,h,r,radius,k,t,theta_r,step)
      call slab(alpha,h,l,length,k,t,theta_l,step)
      theta = theta_r*theta_l
      t_r=theta*(t_i-t_inf) + t_inf
      write(99,*) t/60,(t_r*9/5+32)
      write(*,*) t/60,(t_r*9/5+32)
100   continue
      end


      subroutine cyl(alpha,h,r,radius,k,t,theta_r,step)
      real alpha,h,r,radius,k,t,theta_r,biot,fourr,j_0,j_1
      real j_0r,j_1r,del,top,step
      real bottom,e_x,sum,l

      sum=0
      delta=0
      biot=h*radius/k
      fourr=alpha*t/radius/radius
```

```
      l=0.
      do 1 x=1,5
      call delta_n(biot,del,j_0,j_1,delta,l,step)
      call xxx(del,j_0,j_1,delta,l)
      call xxx(del,j_0r,j_1r,(delta*r/radius),l)
      top = j_0r*j_1
      bottom = j_0*j_0 + j_1*j_1
      e_x = exp((-1)*delta*delta*fourr)
      sum = sum + e_x*top/bottom/delta
 1    continue
      theta_r = sum*2
      return
      end

      subroutine slab(alpha,h,l,length,k,t,theta_l,step)
      real alpha,h,l,k,t,theta_l,biot,fourr,j_0,j_1,del,top
      real length,bottom,e_x,sum,j_0r,j_1r,step

      sum=0
      delta=0

      biot=h*l/k
      fourr=alpha*t/l/l

      do 1 x=1,5
      call delta_n(biot,del,j_0,j_1,delta,l,step)
      call xxx(del,j_0,j_1,delta,l)
      call xxx(del,j_0r,j_1r,(delta*length/l),l)
      top = sin(delta)*cos(delta*length/l)
      bottom = delta + sin(delta)*cos(delta)
      e_x = exp((-1)*delta*delta*fourr)
      sum = sum + e_x*top/bottom
*     print *,delta, sum,fourr,((-1)*delta*delta*fourr)
 1    continue
      theta_l = sum*2
      return
      end

      subroutine delta_n(biot,del,j_0,j_1,delta_1,l,step)
      implicit none
      real h, j_0, j_1, del, delta_m, delta_1, delta_2, biot
      real l,step

      h=step
 5    call xxx(del,j_0,j_1,delta_1,l)
      if (del.gt.biot)then
      delta_1=delta_1 + h
```

```
      goto 5
      endif
 6    call xxx(del,j_0,j_1,delta_1,l)
      if (del.lt.biot) then
      delta_2=delta_1
      delta_1=delta_1 + h
      goto 6
      endif

 10   delta_m = (delta_1+delta_2)/2.
      call xxx(del,j_0,j_1,delta_m,l)
*     print*,delta_1,del,biot
      if (abs(del-biot)/biot.gt..0001) then
      if ((del-biot).lt.0.) then
      delta_2 = delta_m
      else
      delta_1 = delta_m
      endif
      goto 10
      endif
      return
      end

*********
      subroutine xxx(del,j_0,j_1,delta_1,l)
      real j_0, j_1, delta_1,l

      if (delta_1.lt.3.5) then
      call j_small(delta_1,j_0,j_1)
      else
      call j_big(delta_1,j_0,j_1)
      endif
      del_r = delta_1*j_1/j_0
      del_l = delta_1*sin(delta_1)/cos(delta_1)
      if (l.ne.0) then
      del=del_l
      else
      del=del_r
      endif
      return
      end
*********
      subroutine j_small(delta_1,j_0,j_1)
      real delta_1, x, j_0,j_1

      x=delta_1
```

```
j_0=1
j_0=j_0 - x**2/2**2
j_0=j_0 + x**4/(2*2*4**2)
j_0=j_0 - x**6/(2**2*4**2*6**2)
j_0=j_0 + x**8/(2**2*4**2*6**2*8**2)
j_0=j_0 - x**10/(2**2*4**2*6**2*8**2*10**2)

j_1=x/2
j_1=j_1 - x**3/(2**2*4)
j_1=j_1 + x**5/(2**2*4**2*6)
j_1=j_1 - x**7/(2**2*4**2*6**2*8)
j_1=j_1 + x**9/(2**2*4**2*6**2*8**2*10)
j_1=j_1 - x**11/(2**2*4**2*6**2*8**2*10**2*12)
return
end
**********
subroutine j_big(delta_1,j_0,j_1)
real x,p0,q0,p1,q1
real j_0,j_1

pi=3.14159265
x=delta_1
call q_p(x,p0,q0,p1,q1)
j_0=(p0-q0)/(pi*x)**.5*sin(x) + (p0+q0)/(pi*x)**.5*cos(x)
j_1=(p1+q1)/(pi*x)**.5*sin(x) - (p1-q1)/(pi*x)**.5*cos(x)
end
**********
subroutine q_p(x,p0,q0,p1,q1)
implicit none
real p0,q0,p1,q1,p_0,p_1,q_0,q_1
real p_old,p0n,p1n,q0n,q1n,x
integer n

p_old=5
p0=1.
q0=-1.*1./8./x
p1=1.
q1=3./8./x
p_0=1
p_1=1
q_0=1
q_1=3
p0n=0
p1n=0
q0n=0
q1n=0
p_old=0
```

```
        n=0

*      do 5 n=1,5
5      n=n+1
        p0=p0+p0n
        q0=q0+q0n
        p1=p1+p1n
        q1=q1+q1n

        if ((abs((p_old-p0)/p0)).lt..0005) return
        p_0=p_0*(4*n-3)**2*(4*n-1)**2/2/n/(2*n-1)
        q_0=q_0*(4*n-1)**2*(4*n+1)**2/(2*n+1)/2/n
        p_1=p_1*(4*n+1)*(4*n-1)*(4*n-3)*abs(4*n-5)/2/n/(2*n-1)
        q_1=q_1*(4*n+3)*(4*n+1)*(4*n-1)*(4*n-3)/(2*n+1)/2/n

        p0n=(-1)**n*p_0/(8*x)**(2*n)
        q0n=(-1)**(n+1)*q_0/(8*x)**(2*n+1)
        p1n=(-1)**(n+1)*p_1/(8*x)**(2*n)
        q1n=(-1)**(n)*q_1/(8*x)**(2*n+1)
        p_old=p0

        goto 5
        end
```