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EVALUATION OF POLYDIMETHYLSILOXANE FLUIDS AS NON-CALORIC FRYING MEDIA

By

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ABSTRACT

EVALUATION OF POLYDIMETHYLSILOXANES AS NON-CALORIC FRYING MEDIA

By

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Polydimethylsiloxane (PDMS) fluids, 35, 100, 350 and 1000 cst. were evaluated for their potential to be used as non-caloric frying media. Three foods of different composition (breaded frozen fish patties, cake doughnut holes and commercially parfried frozen french fries) were fried in each PDMS fluid and corn oil (control). Heat transfer efficiency of each medium was evaluated by an analysis of time/temperature profiles recorded during frying. On the basis of the efficient heat transfer and the acceptable quality assessment for each food product fried in it, the 35 cst. PDMS fluid functioned most effectively as a synthetic frying medium.

It was also hypothesized that PDMS absorption by the food occurs at the product surface in a similar manner that fat does from the control medium. Frying two types of cake doughnuts and four varieties of french-cut potato products of varying surface areas yielded inconclusive results.

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INTRODUCTION

Fat performs a variety of important functions as an ingredient in food products. These include: rich flavor source, tenderizing and shortening agent, contributor of textural characteristics such as smooth mouthfeel, one phase of emulsions and a source of kilocalories (Bennion, 1972). Fat can also be used as a cooking medium, due to its excellent heat transfer properties. This widespread usage has resulted in excessive dietary fat consumption by Americans, a practice associated with increased incidence of obesity and/or atherosclerosis (Rathmann, 1960; Kummerow, 1974; Van Itallie and Hirsch, 1979). Ideally the total caloric content of an individual's diet should be comprised of not more than 30 percent fat; recent estimated levels are 40 percent (Chung and Pomeranz, 1983). This is the equivalent of 130 pounds of fat and oil consumed per person per year (Smith et al., 1986). According to Chung and Pomeranz (1983), the 21 percent increase in per capita lipid consumption which occurred between 1965 and 1979 was a reflection of changing American lifestyle and eating habits. One third of all meals are eaten outside the home (Smith et al., 1986), with consumption of ready-to-eat, convenience food becoming increasingly popular (Gere, 1982; Smith et al., 1986). Chang, Peterson and Ho (1978) stated that doughnut production alone accounts for over 200 million pounds of fat and oil use yearly; potato chips account for 500 million. Fast food restaurants, selling items such as chicken, fish and french fries, increased sales by 87 percent between 1971 and 1973 (Stevenson et al., 1984). In fact, 19.7 percent of all visible fats and oils consumed in 1982 originated from restaurants, mostly the fast food type (Stevenson et al., 1984).

Smith, et al. (1986) analyzed nine commonly consumed snack foods for total lipid content. On a wet weight basis, the results were as follows: potato chips-40 percent, cheese puffs-38 percent, corn chips-35 percent, cheese chips-25 percent, tortilla chips-24 percent, cake doughnuts-22 percent, chicken thighs-14 percent, french fried potatoes-14 percent and fish patties-10 percent. The contribution from the frying medium to this high food fat content is considerable. For example, fresh, raw potatoes contain 0.17 percent lipid whereas potato chips contain 40.4 percent and french fries 13.5 percent (Smith et al., 1986). Development of non-caloric replacements for frying medium fats would thus be beneficial. The hypothesis of this study was that polydimethylsiloxane (PDMS) fluids function similarly to corn oil when used as deep fat frying media. The study was designed to simulate typical household use by an individual consumer.

Specific research objectives included:

(1) to determine the optimum frying conditions for

four PDMS fluids of differing viscosities (35, 100, 350 and 1000 cst.) by comparing the heat transfer rates of these with a standard (corn oil). The time/temperature relationships of all fluids during the heating and frying of three foods--fish patties, french fries and doughnut holes--will be analyzed to accomplish this.

(2) to select one of the four PDMS fluids which had the greatest potential to be used as a frying medium for further study with various french-cut potato products and cake doughnuts. Specifically these potato products were: parfried french fries, parfried shoestring-cut fries, parfried potato coins and fresh-cut french fries. The two types of doughnuts were control cake and high sugar cake doughnuts. Each product was selected on the basis of differing surface area, in order to determine the effect of food product surface area on the amount of frying medium uptake.

REVIEW OF LITERATURE

As recommended in the Surgeon General's U.S. Dietary Guidelines, Americans should decrease the fat content of their diets by 10 percent (Gillis, 1986). One practical approach to achieving this would be to reduce fried food consumption, because of the high fat and calorie content associated with these foods (Smith et al., 1986). The conditions which influence fat uptake by food and the deteriorative changes which occur in the media during frying will be discussed in this literature survey. In addition, the chemical and physical properties of siloxane polymers will be included, along with a review of other fat substitutes currently being studied.

Fat as a Frying Medium

Factors Affecting Fat Absorption During Frying

There are numerous factors which influence the amount of fat absorbed by food during frying. These include: the chemical and physical nature of the fat used, its temperature and length of frying time, the efficiency of draining and the character of the food itself, i.e., the fat and moisture content, the type and amount of breading/batter coating and the total product surface area (Bennion, 1972).

To achieve a high quality product, foods should be fried just until completely cooked at a temperature which will yield a deep, golden brown appearance to the outer surface (Stevenson et al., 1984). A lower temperature will necessitate increased fry time, resulting in a soggy, greasy, unacceptable product caused by the excessive fat absorption. When the temperature is too high, fat uptake may be less than for food fried at an optimum temperature, but coagulation of the food surface takes place so quickly that a black, hardened crust develops before heat penetration is sufficient to completely cook the interior (Bennion, 1972). Frying medium absorption is largely confined to the product surface; the cooking of the internal food is due to heat penetration from the outside (Stevenson et al., 1984).

The total surface area of the food also affects the amount of fat absorbed; the larger the surface area exposed directly to the frying medium, the greater the fat uptake will be (Lowe et al., 1940; Bennion and Park, 1968; Stevenson et al., 1984). Rock and Roth (1964) and McComber and Miller (1976), both using a doughnut system, found that any ingredient change in the dough formulation which caused increased product surface area resulted in increased fat absorption. For example, dough containing additional fat, sugar or leavening agent, or which was held at elevated temperatures, was more stretchy in nature than control formulations. This caused doughnuts to be larger, containing higher amounts of fat.

The nature of fat selected for frying also influences fat absorption by the food product. The harder, less plastic fats are generally more saturated, and therefore, less prone to oxidative deterioration than are the more highly unsaturated fats (Crossley et al., 1962; Kawada et al., 1967; Gere, 1982). The kind and position of fatty acids esterified to the glycerol backbone also affects the oxidation process (Endres et al., 1962). Increased fat absorption results from using deteriorated, oxidized fat (Stern and Roth, 1959).

Meyer (1960) compared the fatty acid composition of several fats and oils commonly used for deep fat frying (Table 1). The oils high in polyunsaturated fatty acids (i.e., soy, corn and cottonseed) tend to have a short shelf life, becoming rancid even when held at room temperature (Stevenson et al., 1984). Because the melting point of these lipids is near body temperature, they impart a good (mouthfeel) upon consumption and contribute an oily surface to the fried food product (Chang et al., 1978).

Fats such as tallow and lard which contain a higher percentage of saturated fatty acids tend to be fairly stable, therefore, foods fried in them have a longer shelf life than foods fried in more unsaturated fats (Stevenson et al., 1984). Product surfaces are also less oily. Fast food restaurants often use animal-based saturated fats for deep

Table 1

Percentages (by weight) of fatty acids in some edible fats and oils (Meyer, 1960)

	Type of Fat or Oil				
FATTY ACID	Soy	Corn	Cottonseed	Lard	Beef Tallow
			%		
C14 (Myristic)			1	1	2
C16 (Palmitic)	9	6	21	28	32
C18 (Stearic)	4	2	2	8	15
C20 (Arachidic)		1	1		
C18:1 (Oleic)	24	37	25	56	49
C18:2 (Linoleic)	51	54	50	5	2
C18:3 (Linoleic)	9				

fat frying, due to the desirable flavor they contribute to the food (Stevenson et al., 1984). Because these fats can form gums during the frying process, either blends of animal and vegetable fats and oils, or sometimes partially hydrogenated soybean oils are used instead (Baeuerlen et al., 1968). Advantages of these media include low cost, resistance to oxidation and favorably long shelf life (Baeuerlen et al., 1968; Barran, 1984).

The fat or oil quality itself influences the length of its use, and hence the fat absorption and overall fried food product quality. As recommended by Stevenson et al. (1984), minimum quality specifications for fats and oils are found in Table 2. Generally those most appropriate for use as a frying medium have a bland flavor, are odorless and light in color with a low melting point (Chang et al., 1978).

Table 2

Common analytical specifications for deep frying fats and oils (Stevenson et al., 1984)

Parameter	Level in Unused Fat/Oil
Free Fatty Acid (FFA	0.05-0.08%
Peroxide Value	1.0 meq/kg
Iodine Value	varies with type of fat
Active Oxygen Method	60 hr or greater if extended shelf life required
Smoke Point	200° C
Moisture	0.10%
Color	light
Melting Point	varies with product being fried
Flavor and Odor	bland

Changes Which Occur in Fat During Frying

During the heating and frying process, lipid deterioration often occurs (Roth and Rock, 1972a; Stevenson et al., 1984; Wu and Nawar, 1986). This degradation is influenced by several factors including: the unsaturated fatty acid content of the fat and its temperature history, presence of contaminating material such as food particles or metal utensils, exposure of the fat to oxygen and the rate at which used fat is replaced with fresh fat (Bennion, 1972; Gere, 1982). The primary chemical reaction responsible for frying fat degradation is autoxidation (Gaddis et al., 1961; Rawls and Van Santen, 1970; Roth and Rock, 1972a), summarized in the following sequence of reactions (Gray, 1978):

Initiation $RH + O_2 \rightarrow R\cdot + \cdot OH$

Propagation $R\cdot + O_2 \rightarrow ROO\cdot$
$ROO\cdot + RH \rightarrow ROOH + R\cdot$

Termination $R\cdot + R\cdot \rightarrow RR$
$R\cdot + ROO\cdot \rightarrow ROOR$
$ROO\cdot + ROO\cdot \rightarrow ROOR + O_2$

The unstable hydroperoxides (ROOH) are formed as a direct result of the interaction between oxygen and a fatty acid (Farmer et al., 1943). They decompose via one of three reaction mechanisms: 1) fission, to form acids, alcohols, aldehydes and ketones; 2) dehydration, to form ketones; or 3) free radical formation to form dimers, trimers, epoxides, alcohols and hydrocarbons (Roth and Rock, 1972a; Fritsch, 1981; Stevenson et al., 1984). These substances can either polymerize or become involved in the free radical chain mechanism leading to further lipid deterioration (Perkins and Kummerow, 1959; Roth and Rock, 1972a). The rate at which this decomposition occurs, and the specific products formed vary with the food being fried, the type of fat used and the frying conditions (Sahasrabudhe and Bhalerao, 1963). Some of the decomposition products are volatile, the majority of which escape from the frying medium with the steam produced (Robertson, 1968; Weiss, 1970). The remaining volatile products may actually be retained by the food itself, contributing characteristic deep fried flavor to these products (Chang et al., 1978).

Nonvolatile decomposition compounds are also formed during lipid oxidation as a result of unsaturated fatty acid polymerization within the frying medium (Stevenson et al., 1984). Because these molecules can accumulate in the fried food, concerns regarding possible health hazards associated with using thermally abused fats have appeared in the literature (Johnson et al., 1957; Artman, 1969). Although the toxicity of these oxidation products is well documented, it is generally concluded that the extent of lipid deterioration which occurs under normal, routine commercial frying processes is not nutritionally damaging (Rock and Roth, 1966; Nolen et al., 1967; Artman and Alexander, 1968; Poling et al., 1970; Waltking et al., 1975). In fact, due to the primarily linear formation rate over time, appearance of these compounds in the oil can be used to indicate frying life endpoint (Paradis and Nawar, 1981). Oil can then be discarded before reaching a dangerously toxic level.

Another chemical reaction occurring during the heating of oil is hydrolysis of fatty acids from glycerol at the ester linkage (Endres et al., 1962; Roth and Rock, 1972a; Fritsch, 1981). Moisture originating from the food being fried increases hydrolytic activity, regardless of the type of fatty acids present (Endres et al., 1962). Resulting molecules formed are glycerol, monoacyl- and diacyl-glycerides and free fatty acids (Stevenson et al., 1984). As the quantity of free fatty acids present in the initial frying media increases, greater amounts of free fatty acids will be formed via hydrolysis, although not to a large enough extent to adversely affect food quality (Fritsch, 1981). Other factors influencing the rate of hydrolysis are unknown (Fritsch, 1981).

The steam produced from the food moisture plays a beneficial role during frying, by accumulating over the fryer surface thereby limiting air exposure (Stevenson et al., 1984). This reduces the rate at which oxidative deterioration can occur. In addition, peroxides and other undesirable volatile decomposition products are carried out of the frying medium by the steam, which prevents their accumulation and subsequent contribution to further lipid oxidation and deterioration (Wishner and Keeney, 1965; Landers and Rathmann, 1981).

Perkins and Kummerow (1959) isolated and characterized many of the polymerization compounds formed in thermally oxidized corn oil. After aerating 200° C oil for 48 hours, viscosity increased and linoleic acid content decreased. This decline was attributed to the oxidation, scission and polymerization which occurred due to the double bonds present in the unsaturated linoleic acid (Perkins and Kummerow, 1959). Other oxygen-containing polymer fractions, in the form of hydroxyl and carboxyl groups, were also found (Perkins and Kummerow, 1959).

Results of this and other early related studies (Johnson and Kummerow, 1957) have been criticized on the basis that the heating and oxidation conditions used in laboratory experiments are too extreme, and therefore not truly representative of actual frying operations (Melnick, 1957a,b). In order to validate this criticism, Wishner and Keeney (1965) analyzed the carbonyl compound content of thermally oxidized corn oil produced under a controlled laboratory situation designed to simulate a typical frying operation. These investigators found that the steam release during frying was indeed effective in removing many volatile monocarbonyl compounds, whereas the larger, less volatile molecules such as deca-2,4-dienal remained in the frying medium. A comparison was also made between the thermal oxidation products of corn oil (containing 55% linoleate when fresh) with lard and hydrogenated vegetable shortening (containing between 8 and 14% linoleate when fresh). The monocarbonyl content of the corn oil after frying was 2-3 times higher than that found in the other two lipid media, indicating that the linoleic acid content of the fresh fat largely determines the monocarbonyl content in used frying fat.

The chemical changes due to oxidative and hydrolytic lipid decomposition are accompanied by many physical changes (Bennion, 1972; Roth and Rock, 1972b). These include alterations in color, flavor and odor, viscosity, heat transfer coefficient, density, surface and interfacial tension, smoke point and foaming (Roth and Rock, 1972b; Landers and Rathmann, 1981; Stevenson et al., 1984). Fresh oil is typically light yellow in color, and with extended use becomes amber-colored, then red-brown and eventually dark black. This color transformation is caused both by food particles leached from the product surface during frying, and also from the presence of various unsaturated oxidation products which absorb differing wavelengths of light (Roth and Rock, 1972b).

As mentioned previously, many of the volatile monocarbonyl compounds formed from oxidation are released with the steam evolved during frying (Zabik, 1962). Those that remain, such as deca-2,4-dienal and other aldehydes and ketones, contribute characteristic fried flavor to food. Unsaturated lactones, being oxidation products of trilinolein and triolein, are the compounds found in corn oil which are responsible for deep fat fried flavor (Krishnamurthy and Chang, 1967; Blumenthal et al., 1976; Chang et al., 1978). Other flavor compounds have also been isolated; some of them are undesirable. For example, untreated soybean oils, containing high amounts of linolenic acid, can undergo a process known as reversion (Roth and Rock, 1972b). By-products of easily oxidized linolenic acid, such as 3-cis-hexenal, contribute off-flavors and odors (Hoffman, 1961; Roth and Rock, 1972b). Most other fats and oils commonly used for frying contain much lesser amounts of linolenic acid, hence development of reverted flavor and odor is not a concern.

Increased viscosity is another physical indicator of oxidative deterioration of the frying medium (Stern and Roth, 1959; Roth and Rock, 1972b). This is a direct result of increased hydrogen bonding, dipole associations and van der Waals forces which occur due to the stereochemistry and polarity of the polymerization products formed (Roth and Rock, 1972b). This increased resistance to shear greatly affects the overall frying process, because of a decreased heat transfer coefficient. In fact, Rock and Roth (1966) stated that a viscosity increase of 3.0 cst. in used oil caused 20 percent less energy to be transferred to the product than if fresh oil were used. Stern and Roth (1959) found that this phenomenon increased fat absorption by the fried product to an undesirable extent, due to longer cooking times and excessive medium coating on the product when removed from the fryer.

Density of the frying medium is determined by temperature, water content, free fatty acid content, degree of unsaturation and molecular weight of the oil used (Timms, 1985). Even though alteration of these medium characteristics occurs during lipid deterioration, density changes are usually slight and do not affect the fried product quality to a large extent (Roth and Rock, 1972b).

Due to the polar nature of many of the oxidative and hydrolytic decomposition products, interfacial tension between the fat and water present and the surface tension of the frying medium itself decreases (Roth and Rock, 1972b). The monoacyl- and diacyl-glycerides, hydroxy acids and free fatty acids formed allow for increased fat absorption by the food product due to lowered interfacial tension. This results in a faster cooking rate due to the increased surface area for heat transfer (Roth and Rock, 1972b).

Another physical indication of fat deterioration is foaming (Chang et al., 1978). This is one of the later signs to become evident, because the other physical changes previously discussed, such as lowered interfacial tension, increased viscosity and increased binding between long chain polymerized molecules, are needed to provide structural support to the bubble (Roth and Rock, 1972b). Without these, gas dispersions within the medium are unstable and would burst. Used fat is thus often discarded before foaming becomes evident (Roth and Rock, 1972b).

The final physical indicator of deteriorated fat is a lowered smoke point caused by the release of volatile decomposition molecules (Bennion, 1972). Production of these increase with increasing deterioration, thus aggregating in large enough quantities to become visible as smoke (Roth and Rock, 1972b). This occurs in fresh fat only when temperatures exceed 400° F, but in used fat it can be visible at much lower temperatures (Zabik, 1962).

The determination of an absolute point when deteriorating frying fat should be discarded is difficult in a practical setting, due to the complex, time-consuming nature of most laboratory analytical methods (Stevenson et al., 1984). Mehlenbacher (1960) and Gray (1978) reviewed many of these.

Because organoleptic evaluation of used oils is relatively insensitive and unreliable, physical indicators are often used in commercial settings to determine the end of frying life (Stevenson et al., 1984). No specific guidelines are routinely followed, however. Most fast food restaurants completely replace frying fat before 100 hours of fry time, even though much variation exists related to fat usage, i.e., cooking temperature, hours used per day, rate of fresh fat replacement, volume of food fried and filtration methods (Smith et al., 1986).

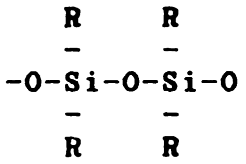
Timms (1985) proposed that the maximum acceptable frying oil viscosity should be 45 cps. at 50° C. This represents almost twice fresh oil viscosity. Smith et al. (1986) stated that a common procedure in the U.S. is to discard used fat when the free fatty acid content increases over one percent. Recommendations for used frying fat evaluation do exist in Germany. As cited by Stevenson et al. (1984), Billek et al. (1978) stated that these include: 1) odor and flavor judged as unacceptable, 2) concentration of petroleum ether insoluble oxidized fatty acids in 0.7 percent or higher or the smoke point is lower than 170° C, or 3) the concentration of petroleum ether insoluble fatty acids is one percent or higher.

Chemical and Physical Properties of Siloxane Polymers

Chemistry of Silicon and Siloxane Polymers

Oxygen and silicon are the two most abundantly found elements in the earth's crust (Bowen and Peggs, 1984). Today compounds produced from these two elements, known as siloxanes, have many important technological uses, as evidenced by several industrial corporations whose existence is based solely on monomeric and polymeric siloxane manufacture.

The term "silicon" has been defined by Noll (1968) as "those organosilicon polymers in which the silicon atoms are bound to each other through oxygen atoms, the silicon valences not taken up by oxygen being saturated by at least one organic group." Linear polymers with the following structure form the basis of this class of compounds:



$$-O-\underset{\underset{R}{-}}{\overset{\overset{R}{-}}{Si}}-O-\underset{\underset{R}{-}}{\overset{\overset{R}{-}}{Si}}-O \qquad (R_2SiO)_n$$

These polymers are also called polyorganosilanes, or siloxanes. Chemically speaking, the silicon atom resembles that of carbon, with one important difference. Instead of forming double bonds with oxygen, silicon tends to form single bonds, i.e., -Si-O-Si- (Noll, 1968). The chemical properties of these siloxane polymers result from their electron configuration and subsequent ability to form hybrid orbitals.

Several important structural properties are characteristic of siloxane compounds including:

(1) polymeric nature, indicating similarity to organic macromolecules,

(2) Si-O bonds, indicating similarity to inorganic silicates (SiO_4), and

(3) hydrocarbon moities are directly bound to silicon, contributing organic character to the molecules.

This blending of inorganic and organic components determines the unique, technologically important properties of the siloxane polymers. The nature of the substituent groups bound to the Si-O backbone via the silicon atom determines the overall siloxane character, which ranges from a viscous fluid to elastic and rubbery to a brittle, crystalline solid. As carbon content of the substituent groups increases, the organic character of the siloxane molecule increases which means polyorganosilanes containing a high number of organic substituents are more compatible with organic compounds. For example, higher molecular weight polymethylsiloxanes are virtually insoluble in lower alcohols, whereas those polymers containing only phenyl groups as substituent groups are miscible with ethanol, and sometimes even methanol and paraffin (Noll, 1968). Gair (1970) gives examples of special polysiloxane properties as related to substituent group composition (Table 3).

Table 3

Distinctive properties of various polysiloxanes as related to substituent group composition (Gair, 1970)

Substituent Group	Characteristics
Methyl	Thermal stability, least expensive, release water repellency, lowest percent organic
Phenyl	Oxidative stability, disrupts crystallinity
Vinyl	Improves cure, "bridge" in glass fiber treatment
Tetrachlorophenyl	Lubricity
Aminopropyl	Water solubility, "bridge" to organics
Phenylethyl	Organic compatibility
Amyl	Enhanced water repellency
Alkoxy	Replaces corrosive chlorine group
Carbethoxyethyl	"Bridge" to organics

Polymers may be linear (fluids), branched chain (rubbers), cyclic or cross-linked (crystalline solids), however this literature review will focus solely on the linear polymers. The shortest chain possible consists of two silicon atoms held together by an oxygen bridge (Noll, 1968):

$$R_3Si\text{-}O\text{-}SiR_3$$

The chain length can be increased by adding siloxane units which contain two functional sites in a progressively increasing manner, as follows:

$$R_3SiO[R_2SiO]_nSiR_3$$

The size of "n" determines the resulting fluid viscosity according to Staudinger's law (Noll, 1968):

$n = K \cdot M$ where

M = molecular weight
$K = 1.43 \times 10^{-5}$ (siloxane-specific)
n = viscosity

This relationship is valid up to a molecular weight of 2500, or 34 siloxane units. Viscosities of compounds with higher molecular weight can be calculated using the following exponential function (Flory et al., 1952):

$$n = K \cdot M^{n}$$

Other empirical relationships between molecular weight and viscosity have also been reported (Warrick et al., 1955). As cited by Noll (1968), polydimethylsiloxanes of various viscosities have differing molecular weights (Table 4).

Table 4
Viscosities, calculated weight-average molecular weights $\bar{M}$ and average number of siloxane units $\bar{N}$ per molecule in a series of linear polydimethylsiloxanes (Noll, 1968)

VISCOSITY (CST)	$\bar{M}$	$\bar{N}$
60	3600	50
140	8000	110
440	17000	230
680	21000	280
1440	30000	400
10000	60000	800
50000	88000	1200
100000	103000	1400
300000	143000	1900

The viscosities of polydimethylsiloxanes currently used technologically range from 0.65 cst. to 1,000,000 cst. (Noll, 1968).

Various structural configurations of the siloxane polymer are possible because of rotation about the siloxane bond. This is attributed to the relatively constant interatomic distances, bond strengths and valence angles present among the silicon, carbon and oxygen atoms (Noll, 1968). The distance between the silicon and oxygen atoms is 1.645 A°; the large area occupied by the silicon atom results in the silicon-carbon bond being 15 percent longer at 1.88A° (Noll, 1968). The valence angle of the siloxane oxygen is 130°. Although oxygen has a great affinity for silicon, relative strengths of the Si-O-Si and Si-C bonds vary, depending on the organic substituent group's ability to accept or donate electrons. In polydimethylsiloxanes, the methyl group acts as a weak electron donor, which results in increased polarity of the Si-O bond (Noll, 1968). Energy of the $Si-CH_3$ bond is 74 kcal/mole (Tannenbaum, 1954), as compared to the Si-O bond at 88.2 kcal/mole (Pauling, 1960).

The number of polymer configurations possible increases with increasing chain length, however the most common linear formation is a ball. In this form, methyl groups are oriented away from the Si-O-Si axis providing maximum free rotation around the siloxane bond (Noll, 1968). This lack of steric hindrance by the methyl groups allows for great polydimethylsiloxane chain mobility (Noll, 1968). When dissolved in organic solvents, linear polydimethylsiloxanes assume this randomly coiled configuration, but spread out in monomolecular layers when in contact with polar surfaces (Noll, 1968). When spread out, the siloxane bonds and methyl groups are oriented in opposite directions giving a zigzag appearance to the chain. This "stretching" is prevented by steric hindrance when larger substituent groups are present.

When no external force is exerted upon the linear siloxane chain, the most stable molecular configuration is assumed, which is the helical structure (Noll, 1968). This stability is due to the polar component of the siloxane bond, which creates a weak dipole. The chain tends to compensate for this dipole internally by facing it with a dipole of opposite polarity. The helical structure thus formed possesses weak forces for intermolecular associations.

As cited by Noll (1968), Fox et al. (1947), using force/area isotherms, investigated the surface pressure exerted by various polysiloxane molecules when spread on a monolayer of water as a function of the molecule's area. They discovered that hydrogen bonds are formed between the water molecules and the siloxane oxygen as shown in Figure 1 (Noll, 1968):

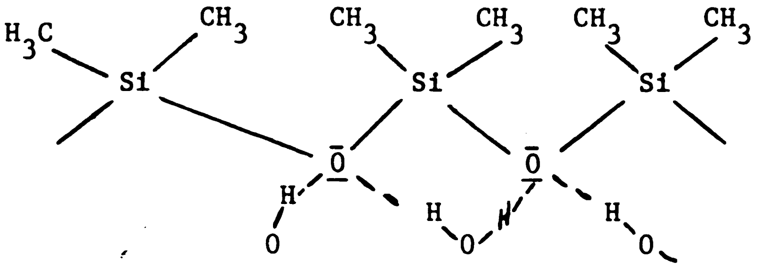


Figure 1. Bonding of a polysiloxane molecule with water molecules

The partially polar Si-O-Si bonds are oriented to lie on the water surface with water molecules contained between chain members. When these intra-chain water molecules are squeezed out, the polymer return to its' helical structure because of lower surface area requirements (Noll, 1968).

On non-polar surfaces the molecule remains in a helical configuration constantly, as shown by force/area isotherm analysis. This structure can be destroyed when dissolved in suitable solvents, however (Noll, 1968).

Physical Properties of Siloxane Polymers

The siloxane backbone along with the content and orientation of its' substituent groups determine the physical properties of the siloxane polymers. From a technological point of view, the most important classes of compounds are the polymethylsiloxanes and the polymethylphenylsiloxanes. They possess the following characteristics: resistance to high and low temperature with little physical change occurring as temperature fluctuates, resistance to weathering, sunlight and ozone, stable to oxygen, good electrical insulators, ability to form films, biologically inert and "non-sticking," hydrophobic nature (Noll, 1968; Gair, 1970).

Thermal Resiliency. The temperature resistance of the polymethylsiloxanes is exceptional and is far better than most plastics, rubbers and oils (Noll, 1968). Most can be heated in the presence of air from 180-200° C for one year without undergoing much physical change. Temperatures as high as 350-450° C can be withstood for short periods of time.

When subjected to extreme adverse thermal conditions, the bond most susceptible to rupture is the Si-C bond, however depolymerization also occurs (Noll, 1968). In the presence of oxygen, degradation begins on the organic group with the oxygen atom attached first. The degradation can be prevented by several antioxidants, including p-amino-phenol, phenyl-1-naphthylamine, diphenylamine, substituted catechols, pyrene and fluoranthene, however iron is used most commonly (Gair, 1970). The incorporation of phenyl groups can also increase oxidative stability, but incorporation of this substituent decreases antioxidant effectiveness (Torkelson, 1970).

In thermal degradation, the siloxane bond is preferentially ruptured, forming cyclic trimers and tetramers as decomposition products (Noll, 1968). When both thermal and oxidative deterioration occur simultaneously, formaldehyde, formic acid, carbon dioxide and carbon monoxide are formed in addition to the siloxane-containing cyclic molecules (Noll, 1968; Torkelson, 1970). The susceptibility to thermal and oxidative deterioration increases with increasing substituent group chain length, thus methylsilicones have better resistance than ethyl- or butylsilicones (Noll, 1968). Straight-chain siloxane molecules also have better heat resistance characteristics than cross-linked molecules with the same substituent group composition (Noll, 1968).

Linear polydimethylsiloxanes are also relatively unaffected by cold temperatures, as evidenced by freezing or pour points ranging from -60° to -40° C for fluids with viscosities between 60 and 300,000 cst. (Noll, 1968; Gair, 1970). This is attributed to the slight tendency for weak intermolecular forces to associate. When the same molecule becomes branched or cross-linked, however, the tendency for chains to associate is increased causing loss of this cold-resistant property (Noll, 1968).

A viscosity which remains constant despite fluctuations in temperature is another important characteristic of the polydimethylsiloxanes. This can be explained by the occurrence of two opposing changes in chemical structure. As temperature increases, intermolecular distances increase; however, this is compensated for by a simultaneous expansion of the helices (Noll, 1968). This important property enables the siloxanes to be used as hydraulic fluids in airplane instruments and controls (Gair, 1970).

At ambient temperatures, polydimethylsiloxanes are stable to air, oxygen, plastics, paper, wood and also ammonia and metal salt solutions. Explosive substances result when siloxanes are mixed with hydrogen peroxide, however (Noll, 1968). Polydimethylsiloxanes can be decomposed at high temperatures by hydrofluoric acids, concentrated nitric acid or elemental chlorine. Good solvents are hydrocarbons or chlorinated hydrocarbons, ethers, esters and higher alcohols containing at least four carbon atoms. Isopropanol, n-propanol, n-butanol, acetone and dioxane can solubilize siloxanes with viscosities less than 140 cst. (Noll, 1968).

Film-Forming Ability. As discussed previously, methylsiloxane fluids spread out into molecular layers when placed on various surfaces. This results in water-repellency preventing adherence of sticky substances. This film-forming ability is important in the car and furniture polish industries (Gair, 1970). When the methyl substituent groups are replaced by larger aliphatic or aromatic groups, the spreading ability greatly decreases, however (Noll, 1968). Mineral oil or other such compounds require 40 percent more effort to spread out and rub than siloxanes do, mainly because the semi-polar siloxane bond is lacking (Torkelson, 1970). The average surface tension of methylsilicones is 20 dynes per centimeter, and the degree of surface adherence is affected by reactions which occur between the surface and substituent groups (Noll, 1968). For example, hydrogen bonds form between gases and polydimethylsiloxane molecules which remain intact even when subjected to high temperatures. Removal of siloxanes from such surfaces is thus rather difficult, requiring solvents such as hexane or methyl ketones (Noll, 1968).

Siloxanes are also capable of forming surface solutions in aqueous media. This indicates lowered surface tension of water, which is the basis for silicone use as a defoaming agent (Noll, 1968). Attributes such as little compatibility with most substances, spreadable nature and only low concentrations necessary also contribute favorably to this antifoaming ability. As chain length of the substituent group increases, spreading ability decreases, resulting in decreased capability to combat foam formation (Noll, 1968).

Hydrophobic Nature. Siloxanes are also hydrophobic in nature, although permeable to water vapor to a certain extent (Noll, 1968). This enables easy clean-up of liquid spills on the siloxane surface (Gair, 1970).

Thermal Conductivity. The thermal conductivity of polydimethylsiloxanes is dependent upon molecular weight and viscosity, ranging from 2.36 x 10^{-4} cal sec^{-1} $cm^{-1}deg^{-1}$ (hexamethylsiloxane) at 50° C to 3.7 x 10^{-4} cal sec^{-1} cm^{-1}

deg^{-1} for a 100 cst. fluid. This latter figure remains fairly constant for fluids of higher viscosity (Noll, 1968).

Vapor Pressure. Only the low molecular weight siloxanes are distillable, but the vapor pressure of high molecular weight silicone fluids does remain fairly constant at a low level, providing no low molecular weight volatiles are present (Noll, 1968).

Dow Corning 200 Polydimethylsiloxane Fluid Specifications. Specifications on the Dow Corning 200 polydimethylsiloxane fluids used in this study can be found in Table 5.

Industrial Processing Methods of Siloxane Polymers

Three main industrial processes are currently used to manufacture siloxane compounds. These are: 1) direct synthesis, in which silicon reacts directly with organic halides, 2) organometallic synthesis, in which organic radicals are transferred to the silicon atom by organometallic compounds, and 3) synthesis by reacting hydrocarbons with silanes (Noll, 1968). The type of process selected is determined largely by the final functional characteristics desired in the synthesized polymers (Noll, 1968). Direct synthesis is most commonly used for methylchlorosilane and phenylchlorosilane preparation. As described by Noll (1968), a flow diagram of the direct synthesis process can be found in Figure 2.

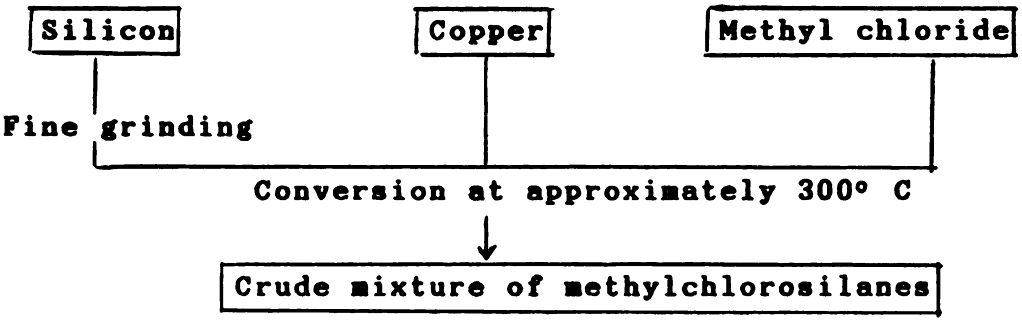


Figure 2. Direct synthesis method (Noll, 1968)

Metallic silicon and methylchloride are combined in the presence of a copper catalyst. High temperatures of 250-400° C are also required because commercially available silicon does not readily react with organic halides. The specific temperature selected depends upon the catalyst used, although it is usually as low as possible since the reaction is exothermic (Noll, 1968). The resulting product composition can be monitored by adjusting reaction conditions, such as temperature, type of catalyst and gases present (Noll, 1968). The silicon is ground to a fine powder in order to provide the maximum surface area possible. Complete homogenization of the silicon and catalyst then takes place before synthesis begins. Copper and silver are the two most commonly used catalysts, in amounts ranging from 5-10 percent of the total silicon used. The reaction products are separated by fractional distillation (Noll, 1968).

Table 5

Typical physical properties of Dow Corning 200 PDMS fluid

As Supplied	Dow Corning 200 fluid 50 cst.	Dow Corning 200 fluid 100 cst.	Dow Corning 200 fluid 200 cst.	Dow Corning 200 fluid 350 cst.	Dow Corning 200 fluid 500 cst.	Dow Corning 200 fluid 1000 cst.
Appearance	Crystal clear liquid free from suspended matter and sediment					
Specific Gravity @ 25°C	0.960	0.964	0.967	0.968	0.969	0.970
Refractive Index @ 25°C	1.4022	1.4030	1.4032	1.4034	1.4034	1.4075
Color, APHA	5	5	5	5	5	5
Flash Point, open cut, °F	605	>620	>620	>620	>620	>620
Acid Number, BCP	trace	trace	trace	trace	trace	trace
Pour Point, °C	-70	-65	-65	-65	-50	-50
Surface Tension @ 25°C, dynes/cm . . .	20.8	20.9	21.0	21.1	21.1	21.2
Volatile Content, @ 150°C, percent	0.3	0.02	0.07	0.09	0.15	0.11
Viscosity Temperature Coefficient . .	0.59	0.60	0.60	0.60	0.60	0.61
Coefficient of Expansion, cc/cc/°C . .	0.00104	0.00096	0.00096	0.00096	0.00096	0.00096
Thermal Conductivity @ 50°C, gm cal/cm.sec.°C . . .	---	0.00037	---	0.00038	---	0.00038
Specific Heat @ 25°C, cal/gm/cm . . .	---	0.352	---	0.350	---	0.349
Solubility Parameter*	7.3	7.4	7.4	7.4	7.4	7.4
Solubility in Typical Solvents						
Chlorinated solvents	High	High	High	High	High	High
Aromatic solvents	High	High	High	High	High	High
Aliphatic solvents	High	High	High	High	High	High
Dry alcohols	Poor	Poor	Poor	Poor	Poor	Poor
Water	Poor	Poor	Poor	Poor	Poor	Poor
Fluorinated propellents	Poor	Poor	Poor	Poor	Poor	Poor
Dielectric Strength @ 25°C, volts/mil	400	400	400	400	400	400
Volume Resistivity @ 25°C, ohm-cm . .	1.0x10^{15}	1.0x10^{15}	1.0x10^{15}	1.0x10^{15}	1.0x10^{15}	1.0x10^{15}

*Fedors Method: R.F. Fedors, Polymer Engineering And Science, Feb. 1974.

The second method used for siloxane polymer production is organometallic synthesis, a process outlined in Figure 3 (Noll, 1968). The Grignard reaction is the theoretical basis of this reaction which allows for the transfer of organic groups to silicon by organomagnesium compounds in order to form the Si-C bond (Noll, 1968). The advantage of this process over direct syntheis is versatility, which enables easy direction and control over the specific reation products generated (Noll, 1968).

The least common type of siloxane polymer synthesis involves the production of Si-C bonds through various addition and subtraction reactions. Noll (1968) outlines these. The specific reaction conditions vary depending on the reactions and catalysts required.

Use of Silicones in Food Products

Silicones are currently being used by commercial food processors as defoaming agents, however FDA regulations restrict usage to 10 parts per million (Anon., 1983). Silicones are commonly added to frying oils in order to inhibit oxidation through suppression of foaming. A concentration as low as 0.03 parts per million can reduce the appearance of many physical and chemical changes associated with frying oil deterioration (Freeman et al., 1973). The mode of action appears to be the formation of a siloxane molecule monolayer on the frying oil surface which creates a physical boundary between the oil and air. This

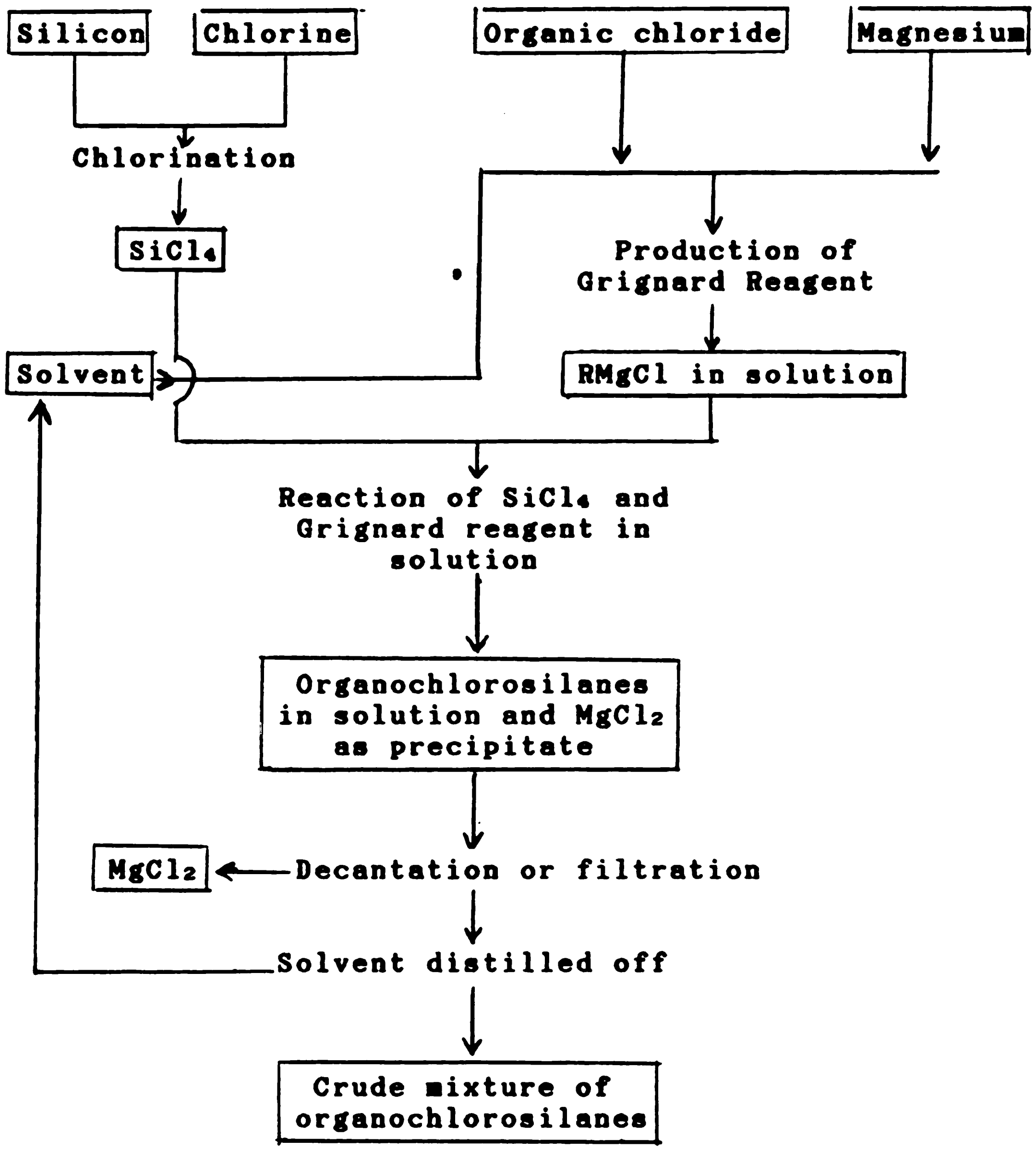


Figure 3. Organometallic synthesis method (Noll, 1968)

limits air exposure somewhat, but more importantly interferes with the convective mixing of the air within the oil. Freeman et al. (1973) found that during frying of potato chips in oil containing 2 parts per million silicone, the silicone content of the oil was reduced by half; the remainder being picked up by the chips.

Several analytical techniques have been described in the literature for quantitating the siloxane content of both the frying medium and the fried food. Utilizing the low melting point characteristic of polydimethylsiloxanes, Neal et al., (1969) described a low temperature extraction procedure for siloxane material using petroleum ether followed by either visible or ultraviolet spectrometry or atomic absorption. Criticisms of this method have been raised due to its tedious, time-consuming nature (Doeden et al., 1980). Freeman et al. (1973) reported on a workable, direct aspiration flame atomic absorption technique which is only applicable to lightly hydrogenated oils. Doeden et al. (1980) refined this, developing a direct aspiration flame atomic absorption method that can be used with heavier hydrogenated products also. A modification of this procedure was used for silicon analysis in this study.

Biological and Dietary Sources of Silicon

Trace amounts of silicon are contained in most animal tissues, and it has been theorized that silicon, along with magnesium and fluorine, plays a role in bone formation (Carlisle, 1971). Silicon is considered to be an essential element for skeletal development in both chicks and rats (Carlisle, 1971; Schwartz and Milne, 1972). Milk is a rich source of dietary silicon, presumably due to its requirement for growth (Archibald and Fenner, 1975).

According to Schwartz (1971), the average American diet contains approximately 10 mg silicon day^{-1}, assuming a 1.5 kg freshweight intake. Individual foods vary widely in silicon content, partly attributable to differences in the analytical techniques used for quantification (Bowen and Peggs, 1984). Using direct aspiration flame atomic absorption spectroscopy, Bowen and Peggs (1984) analyzed various foods for silicon content (Table 6). These authors concluded that the major dietary contributors of silicon are cereals followed by vegetables.

Table 6

Mean values of silicon mg kg^{1} dry matter in foods[1]
(Bowen and Peggs, 1984)

Material	mg Si kg^{-1} by AAS[2]
Barley	2610 ± 25
Maize	44
Oats	4310
Rice, polished	57
Rye	70
Sorghum, red	762
Sorghum, white	431
Wheat	65
Wheat flour, white	103 ± 3
Broad bean	84 ± 3
Cabbage	115 ± 3
Carrot	68
Kale, reference material	403
Peanut	50
Potato	59 ± 3
Raisin	141
Milk	25 ± 2
Chicken bone ash	50
Chicken cartilage ash	95

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[1] All values are means of duplicate determinations of a single sample taken through the whole procedure.

[2] Atomic Absorption Spectroscopy

Fat Substitutes Currently Under Investigation

For years researchers nationwide have been studying a variety of substances for their potential to be used as fat substitutes. Currently none possess all the requirements necessary to be successfully marketed and manufactured. In order to substantially reduce the fat and calorie content of an individual's diet, the fat replacement should contain no more than four to five kilocalories per gram, it must have similar functionality to normal fats and it must be non-toxic with no metabolite accumulation occurring in the body (Merton, 1970).

Generally, fat substitutes are one of two types, either the result of dilution of a fat with a non-caloric substance or the chemical alteration of the fat or synthetic fat-like material (Merton, 1970). There are several available fat substitutes produced via the first approach. Most use water and a diluent and are ultimately used as spreads. In this technique, water-in-oil emulsions are produced with thickeners such as carboxymethylcellulose or gelatin to provide the desired texture (Merton, 1970). Fat-in-water emulsions have also been produced; the aqueous phase containing 7-8 percent protein and the fatty phase containing an emulsion of vegetable oils with vitamins and flavors (Kaunitz, 1966).

Hannigan (1981) reported on an East German discovery, Starch Hydrolysis Product. This maltodextrin derivative, produced from commercial white potato starch, produces a gel containing approximately 75 percent water, and can be used to replace part of the fat and sugar in many foods. Favorable characteristics of this potential fat extender include its miscibility with water and most lipid materials and its fat-like mouthfeel.

Other fat replacers are being developed and tested for their use as frying media. One material which has been used clinically for patients with fat malabsorption diseases has been medium chain triglycerides (Isselbacher, 1964; Hashim, 1964). These synthetic fat substitutes differ from normal fats in their fatty acid chain lengths, containing only eight to ten carbon atoms each. This allows for only a slight reduction in energy content - 8.3 kilocalories per gram compared to "normal" fats and oils with nine kilocalories per gram. These substances can also be used as spreads or incorporated directly into bakery products.

A natural substance, jojobas oil, has also received much attention in the literature, however results have not been too promising. As reported by Hamm (1984), this potential fat replacer is sensitive to hydrolysis in the gut, thus rendering it at least somewhat absorbable.

Hamm (1984) also studied two tricarboxylate esters, trialkoxycitrate and trialkoxytricarballylate. He concluded that the caloric contribution of these substances is probably quite small, however they are hydrolyzable in the gut. Concerns over possible toxicological effects due to either free alcohols or tricarballylic acid release in the intestine have been raised. In rat feeding studies conducted with these compounds, anal leakage was another problem noted. This occurred at substitution levels in excess of 9 percent weight/weight of the diet. This may be the physiological limit for any nondigestible, nonabsorbable oil, as similar findings have been reported with liquid sucrose polyester (Glueck et al., 1979).

Probably the most promising fat replacement substance to date is sucrose polyester (Hamm, 1984). This sugar derivative is produced by replacing glycerol in normal triglycerides with alternate alcohols. Although currently approved for review by the FDA, it is not known how long before a decision regarding marketability will be reached.

Results of studies conducted with polydimethylsiloxane substances have not yet appeared in the literature. Unpublished testing conducted at Michigan State University has demonstrated acceptable functionality when these fluids were substituted for fat in various baked products and ice cream. The toxicological hazards of these substances along with associated anal leakage problems are currently being investigated.

MATERIALS AND METHODS

Frying Media and Conditions

Frying Media

Polydimethylsiloxane (PDMS) fluids with viscosities of 35, 100, 350 and 1000 cst. (Dow Corning Corporation, Midland MI) were evaluated for their potential to be used as deep fat frying media. Corn oil (Archer Daniels, Decanteur, IL) served as a control for all experiments.

Frying Conditions

Hamilton Beach "Tall Fry" household fryers (1.34 liter capacity) were used to fry a variety of foods. Separate fryers were used for each corn oil and PDMS fluid.

Time/Temperature Measurement During Frying

Time/temperature histories were recorded for each frying medium during heating and frying using a Honeywell multiple-point potentiometer with three attached thermocouples placed in the fryer's geometric center and two points located equidistant from center (Figure 4). Depth of thermocouple immersion was 3.8 cm into the 6.2 cm total oil depth (total fryer height = 14.1 cm).

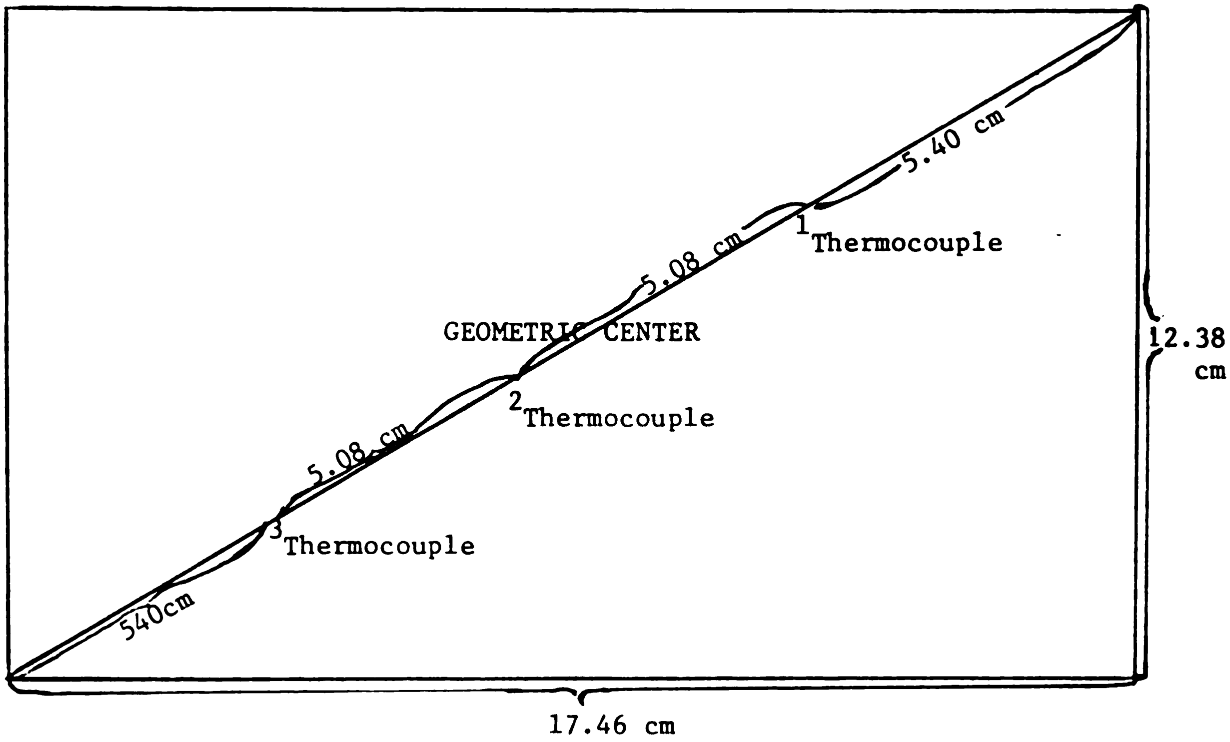

Figure 4. Positioning of thermocouples as seen from fryer surface

Subjective product evaluations from pre-testing trials determined the specific frying conditions used. Products were fried to a constant internal temperature whenever possible; constant frying time was used as a cooking endpoint for foods whose physical nature prevented thermocouple insertion during frying. For these products, internal temperature was recorded upon removal from frying media. All products were drained for a constant time on wire racks prior to objective evaluations. Five consecutive fries were conducted for the first three products tested (i.e., fish patties, french fries and cake doughnut holes), whereas three consecutive fries were used in further experiments with only the 35 cst. fluid and corn oil.

Food Products Deep Fat Fried

Information regarding the composition of each product can be found in the Appendix section. The manufacturer's name and address are included also.

Fish Patties

Commercially breaded, frozen 3 oz. cod patties (Appendix A) obtained from Michigan State University Food Stores were fried in all frying media at 182-4°C to an internal endpoint temperature of 99-100°C. A thermocouple inserted in the product's geometric center and one in the frying medium (position 1--see Figure 4) recorded time/temperature histories during both the heating and frying periods. Five consecutive fries were conducted for each type of medium; individual patties were drained in a fryer basket for fifteen seconds after which they were drained for an additional minute on wire racks before evaluating objectively. A second replication of the first five consecutive fries (i.e., 10 samples total) was conducted after fryers had been thoroughly cleaned and refilled with fresh media. Data generated from the first fry series included: fluid loss during frying, product cooking loss, color and shear. Samples from the second fry series were ground then analyzed for moisture, fat and PDMS content after product weight and oil weight were measured. Time/temperature histories and visual observations of both the product and oil were recorded during both fry series.

French Fries

Commercially parfried, frozen french fries (Appendix G) obtained from Michigan State University Food Stores were fried in all media for ten minutes at 186-8°C. For each replication, five potatoes of comparable size and shape (2.0 cm x 7.5-9.0 cm each) were fried, then drained first in the fry basket for fifteen seconds then for an additional one minute on wire racks before conducting objective evaluations. Fryers were cleaned and refilled with fresh frying medium before conducting a second frying series identical to the first five. Data obtained from the first five replicates included: cooking loss, fluid loss during frying, color and shear; second series data included: cooking loss, fluid loss during frying, moisture, fat and PDMS content. Time/temperature histories of the fluids during the frying process and product endpoint temperatures were also recorded.

Doughnut Holes

A commercial doughnut mix, Dawn Doughnut "Majestic," was obtained from the Michigan State University Bakery. Doughnut holes were prepared according to manufacturer's instructions (Appendix C) and fried in all media types at

186-8°C for three and one half minutes. Because the thin dough consistency prevented thermocouple insertion into the product during frying, only product endpoint temperature and oil temperature during frying were recorded. Doughnut holes were drained fifteen seconds in the fryer basket immediately after removal from the fryer, then cooled on wire racks for one hour at room temperature before evaluating. Two fry series consisting of five consecutive fries each were conducted (i.e., 20 total doughnut holes - 2 per fry). Data obtained from the first fry series included: fluid loss during frying, product weight gain, compression and shear. Samples from the second fry series were ground and analyzed for moisture, fat and PDMS content after product weight and oil weight were measured. Time/temperature histories and visual observations of both the product and oil were recorded during both fry series.

Cake Doughnuts

Two different cake doughnut formulations were prepared and fried in both corn oil and 35 cst. PDMS fluid (Appendix D). The control formulation used is described in Table 7; a high sugar cake doughnut was also prepared by incorporating 50 percent additional sugar to the control formulation. Based on flour weight, this represented a 15.92 percent increase.

For both formulations, three consecutive replications of one doughnut each were fried for three minutes at 190-

Table 7

Formulation for cake doughnuts (control)

Ingredients	% of Flour Weight
All Purpose Flour	100.0
Granulated Sugar	31.7
Homogenized Milk	38.7
Hydrogenated Vegetable Shortening	4.1
Eggs	15.2
SAS Baking Powder	3.8
Salt	1.3
Nutmeg	0.3
Cinnamon	0.3
Mace	0.2

2°C. Frying medium temperature was recorded during both the heating and frying periods; product endpoint temperature was taken upon doughnut removal from fryer. After draining fifteen seconds, doughnuts were transferred to wire racks and cooled for an additional hour at room temperature before conducting objective evaluations. A second fry series, consisting of three replications identical to the first three, was conducted after cleaning fryers and refilling with fresh media. Data obtained from the first fry series included: fluid loss during frying, product weight gain or loss, shear and compression; second series data collected included: fluid loss during frying, product weight gain or loss, moisture, fat and PDMS content. Visual observations of both the frying media and the product were also noted. Due to problems with raw dough adherence to fry baskets, these were not used.

Potatoes

Four different types of french fried potato products were evaluated, each of differing size. These included: french fries cut from fresh potatoes (Michigan Russets), parfried potato coins (Appendix E), parfried shoestring-cut fries (Appendix F) and parfried regular-cut french fries (Appendix G).

Fresh-cut French Fries. In order to simulate household preparation, Michigan Russet potatoes were purchased at a local grocery store in February, 1987. From the thirty pounds obtained, potatoes of roughly the same shape and size (9-10 cm long and 5-6 cm wide) with minimal defects were selected. Two of these pre-selected potatoes were used for each replication fried. Potatoes were washed thoroughly and peeled, then soaked in cold water for two to three minutes. After slicing off both ends, the potato was cut into pieces of uniform size and shape (8.7 cm x 1.2 cm x 1.2 cm) using a Pomfri-Perfect cutter (Westmark). Cut fries were then placed in cold water for an additional minute, removed and blotted dry with paper toweling. Ten fries were placed in a strainer and immersed in boiling water for two minutes. Upon removal, fries were dried with paper toweling prior to frying at 196-8°C for six minutes in both corn oil and 35 cst. PDMS fluid. Fries were drained first for fifteen seconds in the fry basket held over the fryer, then for an additional minute on wire racks. Product weight was taken both before and after boiling and frying. Temperature of both frying media during the heating and frying periods as well as product endpoint temperature was monitored. Visual observations were also recorded. Three consecutive replications were fried in both media evaluated; fryers were cleaned and refilled with fresh fluid before conducting a second frying series identical to the first three. Data from the first fry series included: product weight loss during parboiling, cooking loss, fluid loss during frying, color and shear; second series data included product weight loss during parboiling, cooking loss, fluid loss during frying, moisture, fat and PDMS content.

Potato Coins. Parfried, frozen potato coins (Appendix E), purchased in a local grocery store, were fried at 188-90°C for two minutes in both corn oil (control) and 35 cst. PDMS fluid. Three replications consisting of twelve round potato pieces (averaging 2.9 cm x 3.1 cm and 0.9 cm thick each) were fried in both media. Upon frying completion, potatoes were drained fifteen seconds in a fry basket held over the fryer, then for an additional minute on wire racks prior to evaluation. Endpoint temperature was recorded immediately after removing product from the medium; a time/temperature history during the heating and cooking periods was also recorded for each frying fluid. A second fry series, identical to the first three, was conducted for each medium after fryers had been cleaned and refilled with fresh fluid. Data generated from the first three replicates included: cooking loss, fluid loss during frying, color and shear; second series data included: cooking loss, fluid loss during frying, moisture, fat and PDMS content.

Shoestring-Cut Potatoes. Parfried, frozen shoestring-cut potatoes (Appendix F) obtained form Michigan State University Food Stores, were fried at 186-8°C in corn oil (control) and 35 cst. PDMS fluid. Fry time was four minutes and thirty seconds for both media, immediately after which product endpoint temperature was taken. A replication consisted of twenty potato pieces, each averaging 9.4 cm x

0.7 cm x 0.7 cm; three replications completed one fry series. Fryers were cleaned and refilled with fresh media before frying a second set of replications. Product cooking loss, fluid loss during frying, color and shear data were obtained from the first fry series; second series data included: product cooking loss, fluid loss during frying, moisture, fat and PDMS content. Evaluations were conducted after thorough draining; for each replication this consisted of fifteen seconds in the fry basket held over the fryer, then for an additional minute on wire racks. Visual observations of the fried product and both media during the heating and frying processes were also recorded.

Objective Evaluations

Frying Media

In addition to time/temperature histories, the objective evaluation of medium changes during frying included:

Fluid loss during frying - This was calculated as the percent change in weight of the frying medium pre- and post-fry.

Food Products

For each product fried, the following objective evaluations were conducted:

Cooking loss/weight gain. This was calculated as the percent change in weight of the food product pre- and post-fry.

Color. Tristimulus color was measured as a function of wavelength using the Hunter Color Difference Meter, Model D25. The three scales used included:

(1) L. This scale measured the degree of lightness or darkness of a sample, with results ranging from zero for black to one hundred for pure white.

(2) a_L. This scale measured the degree of redness or greenness of a sample, with negative results corresponding to green hues and positive results corresponding to red hues.

(3) b_L. This scale measured the degree of yellowness or blueness of a sample, with negative results corresponding to blue hues and positive results corresponding to yellow ones.

For each product evaluated, standardization of the instrument was conducted using a manufacturer's color tile which most closely matched the sample color. The pink tile (C2-15325; $L=66.1$, $a_L=19.7$, $b_L=10.1$) was used for cake doughnut color evaluations; the yellow tile (C2-15327; $L=78.5$, $a_L=-3.2$, $b_L=23.4$) was used for color evaluations of all other food products fried.

Shear. This was measured as the amount of force in pounds required to shear a specified weight of sample. Results were converted to kg/g.. The Allo Kramer

Texturecorder model TR5 (3000 pound transducer) was used with either a single blade or multiple blade shear compression cell.

Compression. This was measured as the amount of force in pounds required to compress the sample. Results were converted to kilograms.. The Allo Kramer Texturecorder model TR5 (3000 pound transducer) was used with the compression cell.

Moisture. AACC method 44-40 (1983) was used to determine the moisture content of each sample, expressed as a percent of product weight. This procedure involved drying ground samples for twelve hours in a vacuum oven.

Fat. A modification of AOAC method 24.005 (1980), combined with a six hour Soxhlet extraction using hexane, was used to determine the fat content of each food product fried. Due to the solubility of polydimethylsiloxane polymers in hexane, the final reported fat value was derived from the difference between the total amount of extract obtained and the polydimethylsiloxane content. This was expressed as a percent of product weight on a dried weight basis.

Polydimethylsiloxane (PDMS). The atomic silicon content of each fried sample was quantitated using a Perkin Elmer Atomic Absorption Spectrophotometer, model 380, with a silicon hollow cathode lamp and a nitrous oxide/acetylene flame at a wavelength of 251.6 nm. Slit width was 0.2 nm. Silicon content was then converted to polydimethylsiloxane value represents a percent of product on a dried weight basis.

Absorbed Medium. Absorbed fat was calculated as the fat content of the fried product minus the fat content of the raw product. Absorbed PDMS was calculated as the difference between the PDMS content of the fried product and the PDMS content of the raw product.

Heating Characteristics. Time/temperature curves were obtained for each oil variable during the frying of fish patties, french fries and cake doughnut holes. Specific data points plotted represent the means of temperatures recorded for each fry.

Product Surface Area. The surface areas of the control and high sugar doughnuts and the four french-cut potatoes were calculated using the formulas described in Appendix H. The potato products were fresh-cut, shoestring-cut, regular-cut and potato coins.

Statistical Analysis

MSTAT (Michigan State University, 1982) was used to analyze significant differences among the parameters used to evaluate product quality and medium changes during frying. This included one-way analyses of variance with replicates for all data except cake doughnuts. For the cake doughnuts, two-way analyses of variance with replicates were calculated for all objective measures except percentage fat and percentage PDMS; Duncan's Multiple Range Test (1957) was used to sort out significant differences among the means. Since no significant difference ($P < 0.01$) existed between any one of the consecutive fries for any one food product, each fry was treated as a replication in subsequent analysis.

RESULTS AND DISCUSSION

The overall goal of this study was to evaluate the potential of polydimethylsiloxane (PDMS) fluids to be used as non-caloric frying media. The research was divided into two main sections; the first involved an investigation of the heat transfer properties of four PDMS fluids of differing viscosity. As discussed previously, this variation in viscosity resulted from PDMS polymer chain length differences, rather than changes in molecular structure or composition. Corn oil was used as a control frying medium.

Heat transfer efficiency is an important characteristic of the frying medium, because of its direct influence on fried food product quality (Stern and Roth, 1959; Bennion, 1973). Increased viscosity of the frying medium causes a decrease in energy transfer to the food, which results in increased fat absorption because of the longer cooking time which is needed (Stern and Roth, 1959).

Based on these evaluations, the PDMS fluid which functioned optimally was selected for further evaluation in the second segment of the study. The focus of the second section was the determination of a mode for PDMS absorption onto the food product from the frying medium. Medium uptake as a function of food product surface area was quantitated in order to accomplish this. Analyses of variance for all these data are included in Appendix I.

Use of 35, 100, 350 and 1000 cst. Polydimethylsiloxane (PDMS) Fluids as Frying Media

In this section of the study, three foods of different composition were fried in 35, 100, 350 and 1000 cst. PDMS fluids. A control frying medium of corn oil was also used. The foods were breaded, frozen fish patties, commercially parfried frozen french fried potatoes and cake donut holes which had been prepared from a commercial bakery mix. Product quality of each of these foods after frying was objectively measured and compared to a control. Formal sensory analysis was not conducted, as use of PDMS as a frying medium has not yet received Food and Drug Administration approval. Informal sensory testing and visual observations were conducted by the study investigator, however.

FISH PATTIES

Visual Observations During Frying

Corn Oil (Control)

Medium: As each frozen fish patty was lowered into the corn oil via a frying basket, bubbling up of the medium occurred. This was caused by the release of moisture from the food, as the frozen mass came in contact with the heated oil. Even though this rapid boiling appearance continued for the majority of fry time, no increase in medium volume or frothy foam formation was observed. Steam release was noticed above the fryer surface midway through frying. As fish temperature approached 900 C, boiling intensity and steam escape subsided. Batter particles which had sloughed from the fish breading were observed at the fryer bottom.

Fish Patties: Patties fried in the corn oil were of high quality - deep golden brown in color with a slightly soft yet non-greasy texture. Internal edges of the breading was sufficiently soaked after six and one half minutes of cooking. This frying endpoint was determined when internal fish patty temperature reached 99-100° C. Some of the breading particles which had remained in the fryer from previous replications adhered to the surface of the fourth and fifth replicates, however not to a large enough extent to adversely affect product quality.

35 cst. PDMS

Fluid: As each patty was immersed in the heated siloxane, small bubbles were evident surrounding the fish. These bubbles appeared to originate from the fryer bottom, move upward then erupt at the fluid surface. This quickly developed into a white foam layer (0.5 cm thick, or 8.06% of the original medium volume) which coated the entire surface. Bubbling intensity accompanied by a crackling noise developed as the fish patty temperature reached 65-75° C, but no increase in frothy volume was observed. A "rolling boil" appearance was characteristic as fish temperature reached 88-90° C, increased crackling and some splashing out of fluid was evident. No additional frothiness or escape of steam was observed.

Fish Patties: Fish patties fried in 35 cst. PDMS fluid appeared similar to control fish patties, although somewhat lighter in color. All replicates had an acceptable, light golden brown color with discreet surface granules noted. Outer surfaces were slightly crispy with a more dry appearance toward the outside; internally, the fish was flaky and the edges of the batter coating appeared sufficiently cooked. Mouthfeel of the battered fish patty was not excessively greasy, however slight PDMS drainage form the batter was noted during cooling. Some adherence of batter coating to the fry basket bottom was also observed. Batter particles were evident in the fryer after fish removal; these particles became blackened with time and some adhered to subsequently fried replications. Cooking time was 15.4 percent longer than for the patties fried in corn oil.

100 cst. PDMS

Fluid: This fluid appeared to behave very similarly to the 35 cst. fluid during the initial minutes of frying, however when the fish patty temperature reached 70-80° C, a large increase in frothy volume and bubbling intensity occurred. Maximum frothiness (104.84% of the initial medium height) with a "rolling boil" appearance occurred as fish patty reached 90-92° C; froth volume subsided at approximately 95° C. Periodic bursts of steam every 3-5 seconds were also observed.

Fish Patties: Patties fried in 100 cst. PDMS did not appear as similar to controls as did the patties fried in 35 cst. PDMS. Generally, the fish patties were tender and moist, light golden brown and had slightly less cooking loss than those fried in corn oil. Edges were crispier and slightly darker than interior surfaces. The batter coating cooked as discreet granules, causing the outer surface to appear rough and "pebbly-looking." The fourth and fifth replicates were slightly more puffed in shape than the first three, caused by several air pockets (2.5 cm diameter) which formed between the batter coating and the enclosed fish. DArk brown batter particles from previously fired fish patties adhered to the surface of later replicates. The PDMS fluid drained from all breaded patties efficiently; excessive greasiness was not noticed. Cooking time was 46.2 percent longer than for the controls, 26.7 percent longer than fish patties fried in 35 cst. PDMS.

350 cst. PDMS

Fluid: Bubbling and frothy foam formation was observed during frying with this siloxane fluid also, but not to the great extent described for the 100 cst. fluid. Maximum foam volume, equivalent to 69.36 percent of the initial medium height, was reached when fish patty temperature approached 92-95° C. This foaminess then slowly subsided during the remainder of frying.

Fish Patties: Fish patties fried in the 350 cst. fluid were of less acceptable quality than fish patties fried in either the corn oil, 35 or 100 cst. media. Pools of PDMS fluid remained on the product surface after draining time had elapsed, while interior edges of the batter coating appeared undercooked despite a cooking time which was 46.2 percent longer than the controls. Internally, fish was flaky and appeared sufficiently cooked. The surface was golden brown in color with a darker, crispy appearance on the outer 0.5 cm. of fish perimeter. The fourth and fifth replicates contained surface-adhering dark particles from previously fried replicates; the texture appeared slightly rubbery.

1000 cst. PDMS

Fluid: During the initial frying stages, this PDMS fluid resembled a thick, fairly clear boiling syrup. Even though small bubbles emerging from the fryer bottom were observed, white frothy foam characteristic of the other PDMS fluids never developed even though fluid clarity decreased. Batter particles lost from the fish remained suspended within the fluid upon cooling.

Fish Patties: Patties fried in 1000 cst. PDMS were of such poor quality that frying was discontinued after the third replication. Even though much lighter in color than previously fried samples, exterior edges were slightly darker. The fluid was so resistant to draining that pools of PDMS remained on the fish patty surface even after objective testing had been completed. Product texture was very soggy, in fact, difficulties arose in keeping the thermocouple inserted in the patty during the late stages of frying. The batter coating looked very thick and rubbery on the internal edges. Cooking time was 76.9 percent longer than for the controls.

Heating Curve Analysis

As seen in Figure 5, corn oil (control) exhibited the most fluctuations in temperature during the frying process, although overall temperature remained higher than the PDMS variables during the latter half of frying. The 35, 100 and 350 cst. fluids all exhibited a sharp drop in temperature immediately after the fish was immersed and maintained this lower temperature throughout the frying process. Similar, smooth heating patterns were characteristic of all the siloxane fluids, however the 35 cst. fluid temperature was higher at the cessation of frying than any of the other PDMS variables.

Figure 6 shows the internal temperature of the fish patties during frying. As expected, higher internal

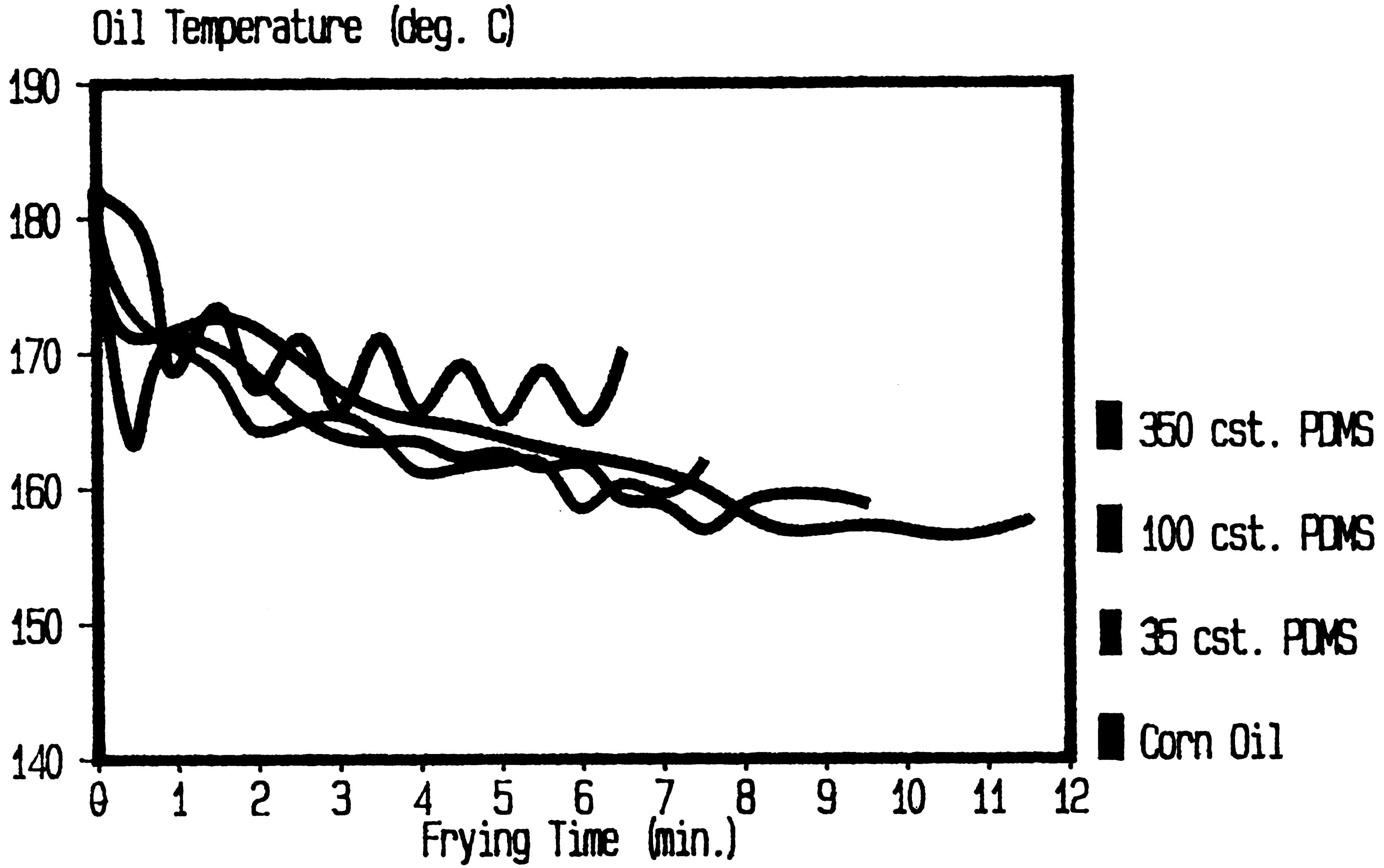

Figure 5: Changes in frying media temperatures (n=10) during frying of fish patties in corn oil (control) and three polydimethylsiloxane (PDMS) fluids of differing viscosities

Fish Temperature (deg. C)

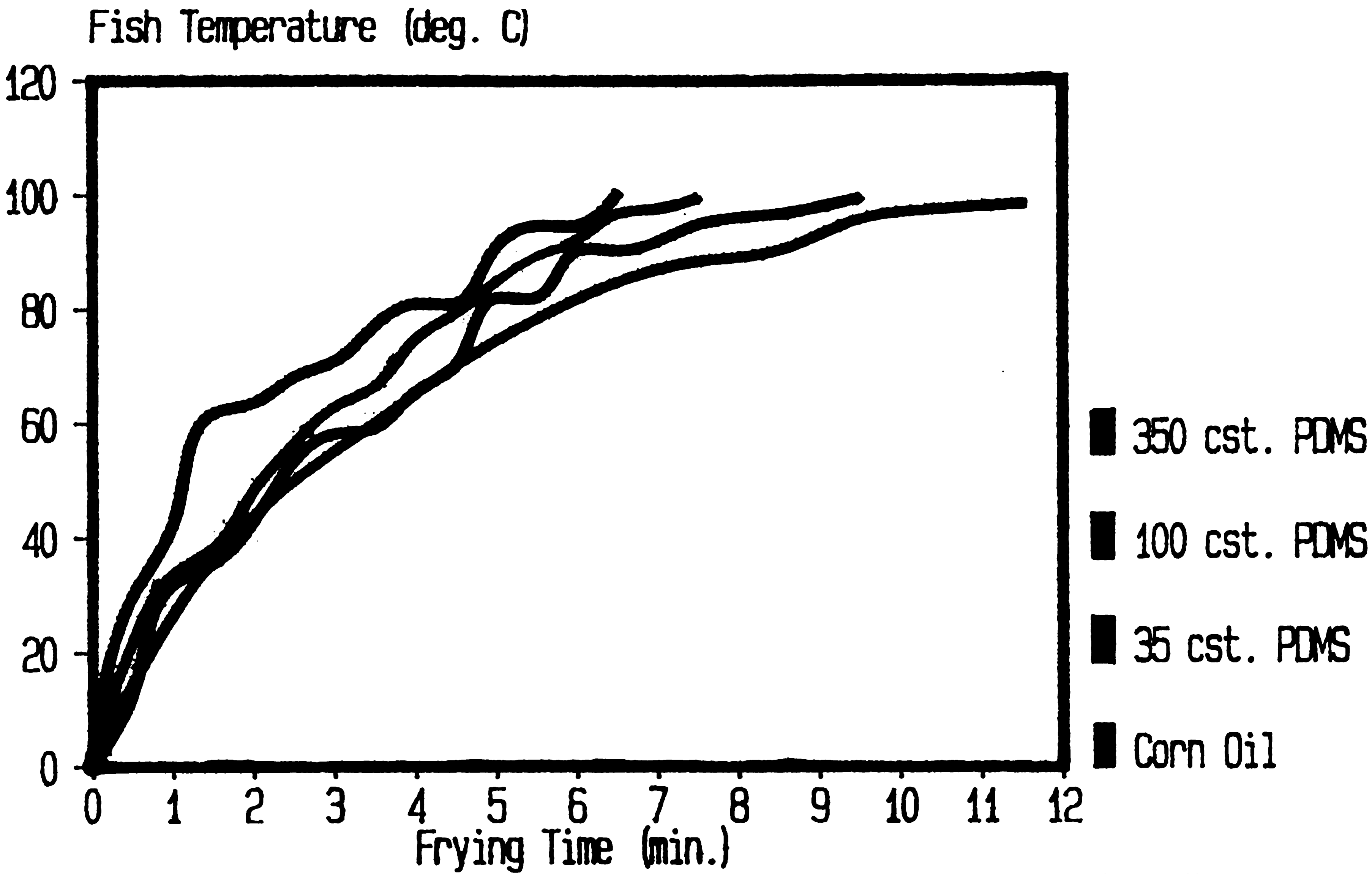

Figure 6: Changes in internal fish patty temperature (n=10) during frying in corn oil (control) and three polydimethylsiloxane (PDMS) fluids of differing viscosities

temperatures were obtained for the fish fried in corn oil than for fish fried in PDMS media at each point recorded. As the viscosity of the PDMS fluid increased, internal temperatures of the fish patties were generally lower. This is consistent with the longer cooking times needed, i.e., compared to the control which was fried six and one half minutes, the 35 cst. treatment was fried 15.4 percent longer to reach 99-100° C; the fish fried in the 100 and 350 cst. media took substantially longer to cook, 46.2 percent and 76.9 percent longer, respectively.

Evaluation of Fish Patty Quality

As evidenced in Table 8, the fish patties fried in the 35 cst. PDMS fluid were more similar to the controls than any of the other siloxane fluids. No significant differences were established between any of the products for fluid loss, cooking loss, shear, moisture or absorbed medium content, however subjectively fish patties became softer and more rubbery when fried in any siloxane fluid of higher viscosity.

The quality parameter most variable among products was color. Fish patties fried in each of the PDMS media were significantly lighter than those fried in corn oil; those fried in the 35 cst. medium were evaluated as lightest in color. Redness scores did not differ among any of the fish patties fried in siloxane, but all were significantly lower than the controls. Fish fried in the 35 cst. medium was

Table 8

Objective measurements of fish patties[1] fried in corn oil (control) and three polydimethylsiloxane (PDMS) fluids of differing viscosities

Quality Parameter	Control (corn oil)	PDMS Fluids		
		35 cst.	100 cst.	350 cst.
Fluid loss (%)	1.32 ± 0.16	1.05 ± 0.12	1.29 ± 0.14	1.66 ± 0.23
Cooking loss (%)	21.40 ± 0.98	18.20 ± 3.48	18.01 ± 3.88	18.28 ± 0.80
Color: L	42.5 ± 2.9^a	58.8 ± 0.9^b	53.5 ± 2.9^c	52.3 ± 2.7^c
a_L	9.3 ± 1.7^a	1.8 ± 0.8^b	1.9 ± 0.8^b	1.6 ± 0.6^b
b_L	21.2 ± 1.3^b	16.5 ± 1.4^a	21.0 ± 1.7^b	21.1 ± 0.9^b
Shear (kg/g)	2.63 ± 0.46	2.76 ± 0.47	2.45 ± 0.39	2.36 ± 0.28
Moisture (%)	47.99 ± 2.63	53.06 ± 2.23	54.37 ± 2.19	53.18 ± 1.45
Fat (%)[2,3]	31.81 ± 2.54	3.60 ± 0.71^b	2.47 ± 1.35^b	8.01 ± 2.24^a
PDMS (%)[2,3]	0.01 ± 0.01	20.50 ± 1.63	18.96 ± 4.27	21.11 ± 0.91
Absorbed Medium (%)[4]	21.02 ± 2.05	20.49 ± 1.49	18.95 ± 4.09	21.10 ± 0.62

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[1] means and standard deviations, n=5. Values marked with different superscripts are significantly different using Duncan's Test at $P \leqslant 0.01$.

[2] dry weight basis; statistical analysis among PDMS frying media only

[3] raw product contained 10.79% fat and 0.01% PDMS on a dry weight basis.

[4] dry weight basis; statistical analysis among all four frying media

also evaluated as significantly less yellow than any other variables, while no significant differences were found among the fish fried in the higher viscosity siloxanes and the control. Apparently the synthetic, experimental medium influences the type and/or extent of browning which occurs during frying. Browning reactions are complex; the types which occur depend upon the chemical composition of the food, as well as temperature, pH and presence of catalysts (Bennion, 1972). Both caramelization and Maillard browning probably occurred in this frying of breaded fish patties, because the essential conditions for both were present. It is quite possible that the lower temperature exhibited by the PDMS frying media decreased the amount of Maillard browning, since rate of this reaction is temperature-dependent (Meyer, 1960). The necessary amino acids and reducing sugars were provided by the bread coating of the fish patty (Unfortunately no information on specific ingredients contained in the fish patties was available from the manufacturer. Normally bread coating consists of starch, flour, water, dried milk, salt and spices (Suderman and Cunningham, 1983). The frying temperature of 184-6° C was high enough for caramelization to occur; the necessary sugars for this reaction supplied by the flour in the breading.

Fat content of the fish patties fried in the 350 cst. PDMS medium was significantly higher than that of the products fried in the 100 or 35 cst. media. Several explanations for this are possible. First, the amount of surface fat (10.79%) present on the raw product as a result of commercial processing may inhibit the longer chain siloxane polymer from adsorbing. The lower molecular weight siloxanes are known to be more miscible with fat (Noll, 1968). These smaller PDMS molecules might also have been more successful at dislodging surface fat molecules. Another possibility lies with the composition of the bread coating, perhaps it contained an ingredient which was incompatible with the larger siloxane polymer. Since no incompatibility problems were evident in other food products which contained similar ingredients, the relative immiscibility of the 350 cst. siloxane with surface fat appears to be the most likely explanation.

No differences were found among the frying media for amount of medium uptake. This could indicate that siloxane is absorbed to the food product surface in the same way that fat from a corn oil medium is absorbed.

FRENCH FRIED POTATOES

Visual Observations During Frying

Corn Oil (Control)

Medium: Rapid boiling of the corn oil occurred as the fries were immersed in the medium, caused by moisture release from the food. Steam release was also observed directly above the fryer surface. Frying time was ten minutes; boiling intensity decreased for the latter third of this. As this physical change in medium appearance occurred, fries were visible floating near the oil surface. No product debris was observed in the fryer after frying completion.

French Fries: Potatoes fried in corn oil were of high quality, both visually and organoleptically. The outer surface was a light, golden brown color and just slightly crisp. The interior was creamy white in color with a soft, moist texture. Mouthfeel was not excessively greasy, however flavor was rich. Very little drip was observed during the draining period.

35 cst. PDMS

Fluid: Immediately upon immersion of french fries into the frying media, intense bubbling occurred accompanied by development of a white frothiness which covered the fluid surface completely. This layer remained approximately 0.5-1.25 cm in depth during the initial minute of frying, then began to slightly increase in volume (13.85% of initial oil height) while maintaining a "rolling boil" appearance. No escape of steam was noticed. After approximately three additional minutes of frying, the frothiness began to subside and a clearing of the fluid surface was evident. French fries floated just under the surface as the white bubble layer thinned to less than 0.5 cm in thickness. With approximately 3-4 minutes fry time remaining, the fluid became so clear that the bottom of the fry basket was visible. During the last two minutes of frying very little of the white frothy layer remained, although small, clear bubbles continued to form despite erupting quickly and disappearing, leaving a clear frying medium.

French Fries: All five replications were very similar in appearance and were of acceptable quality. Generally, the potatoes fried in 35 cst. PDMS were slightly less golden brown in color than controls, with a light, crispy surface and a slightly soft interior. Fries appeared to be sufficiently cooked. Excessive siloxane uptake did not occur, as mouthfeel was not overly greasy. Only very slight drip was evidenced during the draining period.

100 cst. PDMS

Fluid: As frying began, small streams of bubbles surrounded each potato. This bubbling developed into a white, frothy foam which increased in volume 104.84 percent of the initial medium height after 3-4 minutes of frying. Foam remained at this height for 1-2 minutes while exhibiting a "rolling boil" appearance. Periodic bursts of steam were also evident. Frothy volume then subsided slowly and eventually dissipated with 4-5 minutes of frying time remaining. This resulted in a fairly clear medium containing some surface bubbles; fries were noticeable floating on the fluid surface at this point.

French Fries: Potatoes fried in 100 cst. PDMS were of comparable quality to the ones fried in 35 cst. PDMS, although slightly lighter and less red in color. Overall texture was acceptable also, however a slight oily surface was noted. Draining appeared to be efficient; the amount of drip appeared similar to that observed for fries cooked in the 35 cst. siloxane fluid.

350 cst. PDMS

Fluid: Bubbling and foam formation during frying with the 350 cst. fluid appeared very similar to the 100 cst; the only noticeable difference was in maximum foam height reached. The 350 cst. was 80.46 percent lower than the 100 cst. fluid.

French Fries: The potatoes fried in 350 cst. PDMS were not of acceptable quality. Generally, fries were a deep golden yellow color in the center and slightly brown toward the edges, although overall still lighter than potatoes fried in any of the other media. The 350 cst. fluid adsorbed to the potato surface to a much greater extent than with the other fluids; increased drip during draining and excessive product greasiness was noted. Oozing of PDMS from the fries during shearing occurred. Siloxane pools also were evident in Hunter Color Difference Meter dishes after color evaluation had been completed.

Heating Curve Analysis

As evidenced in Figure 7, the heating pattern of the 35 cst. fluid was more similar to the corn oil than any of the other PDMS fluids. The corn oil temperature dropped quite low initially after the fries were immersed in the medium, however it increased at a faster rate than the PDMS fluids, especially during the latter half of frying. In conventional frying, oil temperature normally drops when frozen food is immersed in it. Additional heat loss occurs as moisture from the food evaporates through boiling (Weiss, 1983). The 35 cst. fluid retained the highest temperature throughout the frying process, with the least overall fluctuations. The 100 cst. fluid exhibited the most temperature variations, while the 100 and 350 cst. media retained the lowest temperatures throughout frying. Nevertheless, the temperature of the highest viscosity PDMS fluid was greater than any of the other media for the first three minutes of frying, this being the period when foam formation reached its maximum. As the foam layer subsided and dissipated, the fluid temperature dropped lower than the other variables.

Evaluation of French Fry Quality

Few statistically significant differences were found between the potatoes fried in corn oil and those fried in the siloxane media (Table 9). The quality of the french fries fried in the 35 cst. medium was more similar to those

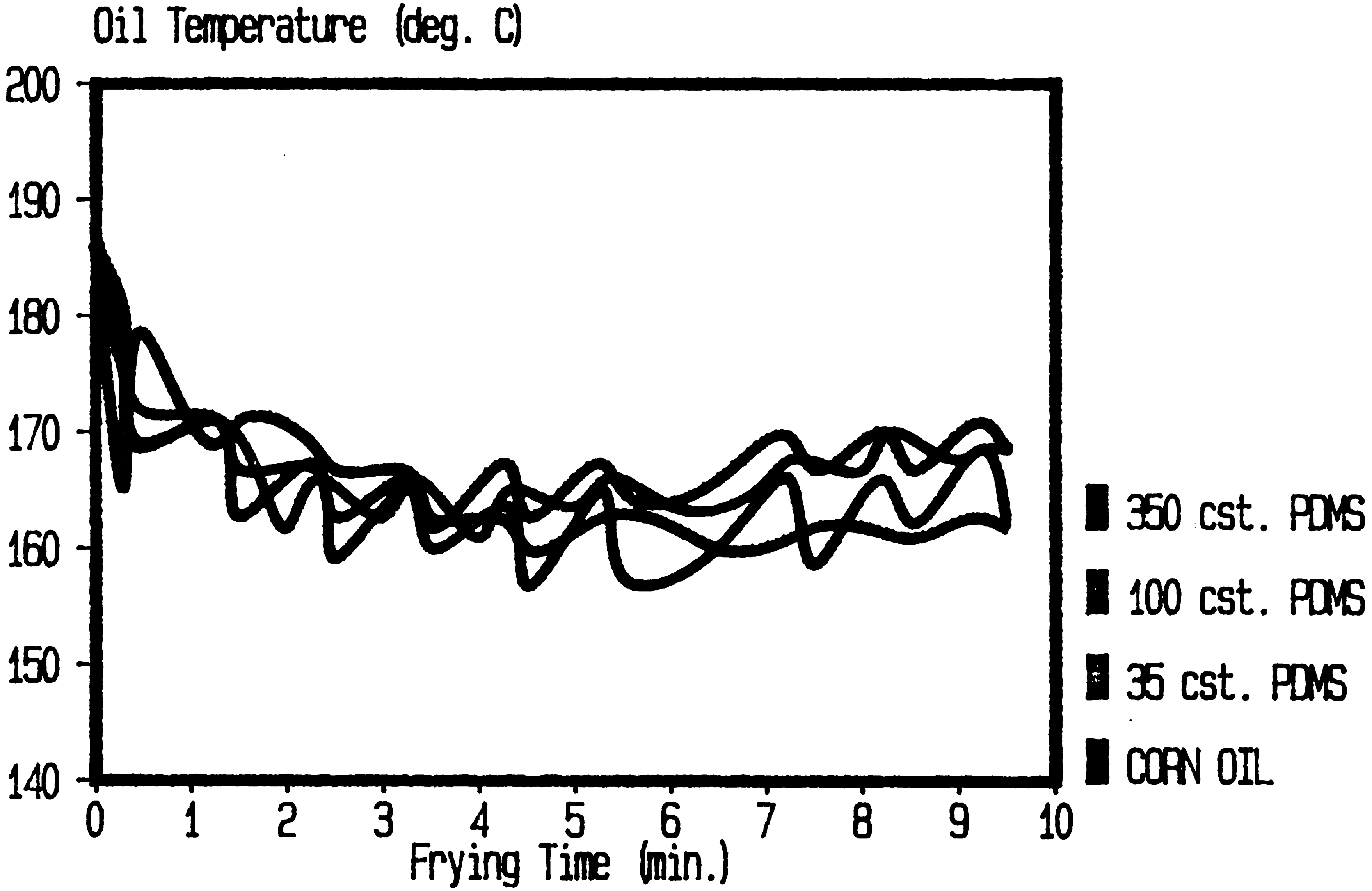

Figure 7: Changes in frying media temperatures (n=10) during frying of french fries in corn oil (control) and three polydimethylsiloxane (PDMS) fluids of differing viscosities

Table 9

Objective measurements of french fries[1] fried in corn oil (control) and three polydimethylsiloxane (PDMS) fluids of differing viscosities

Quality Parameter	Control (corn oil)	PDMS Fluids 35 cst.	PDMS Fluids 100 cst.	PDMS Fluids 350 cst.
Fluid loss (%)	0.87 ± 0.20^{ab}	0.84 ± 0.13^{b}	0.94 ± 0.19^{ab}	1.12 ± 0.27^{a}
Cooking loss (%)	37.00 ± 1.37^{a}	34.77 ± 2.04^{b}	33.04 ± 1.08^{c}	29.72 ± 1.37^{d}
Color: L	54.0 ± 1.8	56.4 ± 1.3	57.1 ± 0.9	60.4 ± 3.3
a_L	8.6 ± 0.7^{a}	4.7 ± 0.9^{b}	5.3 ± 0.8^{b}	1.5 ± 1.1^{c}
b_L	19.3 ± 1.7	18.1 ± 0.9	19.2 ± 0.6	18.2 ± 0.8
Shear (kg/g)	0.54 ± 0.14	0.43 ± 0.02	0.52 ± 0.16	0.54 ± 0.10
Moisture (%)	48.50 ± 4.09^{a}	41.55 ± 2.50^{b}	55.27 ± 2.43^{c}	54.71 ± 2.12^{c}
Fat (%)[2,3]	28.10 ± 3.27	5.59 ± 1.77^{ab}	7.13 ± 1.67^{b}	3.34 ± 1.33^{a}
PDMS (%)[2,3]	0.00 ± 0.02	19.42 ± 2.47	19.57 ± 1.21	21.58 ± 4.62
Absorbed Medium (%)[4]	7.51 ± 3.03^{a}	19.42 ± 2.47	19.57 ± 1.21	21.58 ± 4.62

[1] means and standard deviations, n=5. Values marked with different superscripts are significantly different using Duncan's Test at $P \leqslant 0.01$.

[2] dry weight basis; statistical analysis among PDMS frying media only

[3] raw product contained 22.59% fat and 0.00% PDMS on a dry weight basis.

[4] dry weight basis; statistical analysis among all four frying media

fried in corn oil, however. Generally as viscosity of the PDMS fluid increased, cooking loss decreased and moisture content increased. This is consistent with the inverse relationship which typically exists between these two parameters (Stevenson et al., 1984). The largest differences found among variables were in color; all potatoes fried in PDMS were significantly less red than the control, with the 350 cst. being the least red. No differences were found in lightness evaluations.

A significant difference was found to exist among the fat contents of the french fries fried in PDMS. Those fried in the 350 cst. siloxane fluid retained significantly less fat than the french fries cooked in 35 or 100 cst. PDMS The high amount of surface fat present on the frozen fries as a result of commercial parfrying could have been displaced by the large, adsorbing siloxane polymers. The smaller PDMS molecules may not have functioned in the same way. Consistent with this, the total amount of media uptake by the product fried in the 350 cst. fluid was slightly, although not significantly, higher than the other PDMS fluids. Shearability of the fries did not differ significantly among variables, however the potatoes fried in the 350 cst. medium were excessively greasy and had a slight rubbery texture when evaluated subjectively by the study investigator.

DOUGHNUT HOLES

Visual Observations During Frying

Corn Oil (Control)

Medium: As doughnut batter was placed in the heated corn oil, small bubbles formed and erupted surrounding the doughnut hole perimeter. The rapid boiling medium appearance observed during fish patty and french fry frying was not observed. No foam formation or increase in medium volume occurred. No product debris was observed in the fryer after frying completion.

Doughnut Holes: For the first few seconds of frying, dough remained at fryer bottom but then rose to the medium surface and floated there until frying completion. Volume expansion of the product began to occur during the first thirty seconds of frying and continued halfway through frying duration. Cooking time was three and one half minutes, after which the doughnut holes were drained on wire racks. Product quality appeared comparable to similar items available commercially. Outer surface was a deep, dark golden brown with a crisp, slightly crunchy character. Mouthfeel was slightly greasy, however. Internally the doughnut was pale yellow in color with an even distribution of small, thin-walled air cells.

35 cst. PDMS

Fluid: As doughnut holes were immersed in the 35 cst. medium, small, thin streams of bubbles formed surrounding the dough. The white frothy foam layer formed during fish patty frying was not evident; PDMS surface remained relatively clear. No product debris was evident in the medium after frying, either.

Doughnut Holes: Generally, all replications were very similar in appearance-deep golden brown in color with a slightly dry-looking outer surface, even though an excessively greasy mouthfeel was noted. EAch sample was not completely round as with control samples, instead the surface cracked allowing interior dough to emerge after one to two minutes of frying. Apparently the outer surface of the doughnut cooked more quickly than the interior dough, causing the final product to have the following general shape (Figure 8):

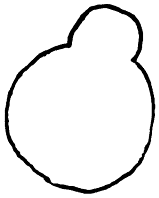

Figure 8. Shape of doughnut hole fried in 35 cst. PDMS fluid

Additional testing with alternate frying times and temperatures was unsuccessful in improving product quality. Color was a much lighter golden yellow in the crevice separating the two sections. Very little drip was evident during draining.

100 cst. PDMS

Fluid: Bubbling and foaming of this PDMS fluid was observed during frying, although no large increase in foam volume occurred. Foam layer remained approximately 0.5 cm thick covering the fluid surface completely. No product debris was evident in the medium after frying completion.

Doughnut Holes: Doughnut holes fried in 100 cst. PDMS behaved very similarly to products fried in the 35 cst. PDMS during frying. The dough remained at fryer bottom for the first 10-15 seconds after immersion n the medium, then rose to the surface and floated during the remainder of the cooking process. Color and surface appearance closely approximated the doughnut holes fried in 35 cst. siloxane. Little drip was evidenced during draining and overall greasy mouthfeel of the product approximated the 35 cst. variables.

350 cst. PDMS

Fluid: Overall appearance during frying was very similar to the 100 cst. fluid. A 0.5 cm thick white foam layer covered the fluid surface completely during frying which never increased in volume.

Doughnut Holes: PDMS adsorption appeared to be greater with the 350 cst. fluid than with either of the lower viscosity fluids, as the PDMS appeared to completely coat the product during the first minute of frying. Each variable developed large surface cracks through which siloxane bubbles emerged and surrounded, giving an "oozing" appearance. Final products had a characteristic crispy fried texture and were golden brown in color with a lighter, lemon yellow coloring in between surface cracks. Overall the doughnut holes were round and of low volume; the misshapen form characteristic of the doughnut holes fried in the lower viscosity siloxane media was not observed.

1000 cst. PDMS

Fluid: Foaming was not evident with this PDMS fluid. SMall, thin streams of bubbles formed surrounding the doughnut holes, but these dissipated quickly.

Doughnut Holes: Doughnut holes fried in 1000 cst. PDMS differed from the controls more than the other experimental doughnut holes. These were much softer, more moist and gained more weight during frying. However, the doughnuts fried in 1000 cst. PDMS fluid did not puff out into a circular shape. Instead the doughnut holes expanded one side at a time causing the product to sit on the fluid surface rather than rolling over on all sides. For several variables, raw dough was evident emerging from surface cracks at the end of frying. To compensate for this, the fourth and fifth replicates were fried for an additional thirty seconds which resulted in fully cooked interior dough much like other replicates, although the surface was crispier and darker golden brown in color. (NOTE: Due to the poor quality of these samples, further objective analysis was discontinued.)

Heating Curve Analysis

Although similar heating curves were obtained for each of the frying media evaluated (Figure 9), the corn oil (control) retained a consistently lower temperature than any of the PDMS variables. This was in sharp contrast to the temperature profiles obtained during fish patty and potato frying. For these foods, the heating curves for all the media showed more fluctuations in temperature, with the corn oil retaining the highest temperature overall. Apparently the temperature and composition of the food being fried directly affects the siloxane fluids' heat transfer efficiency.

Evaluation of Doughnut Hole Quality

The doughnut holes fried in the 35 cst. PDMS fluid had a more acceptable overall quality than the other experimental variables (Table 10), however all doughnuts, including the control, had a high fat content and were noticeably greasy. For most of the quality parameters evaluated, few significant differences were found between the doughnut holes fried in any of the siloxane fluids and those fried in corn oil.

Weight gain tended to be lower for the controls than for doughnut holes fried in PDMS fluid, however this was not statistically significant due to large variability among replications. Texture of the doughnut holes fried in the

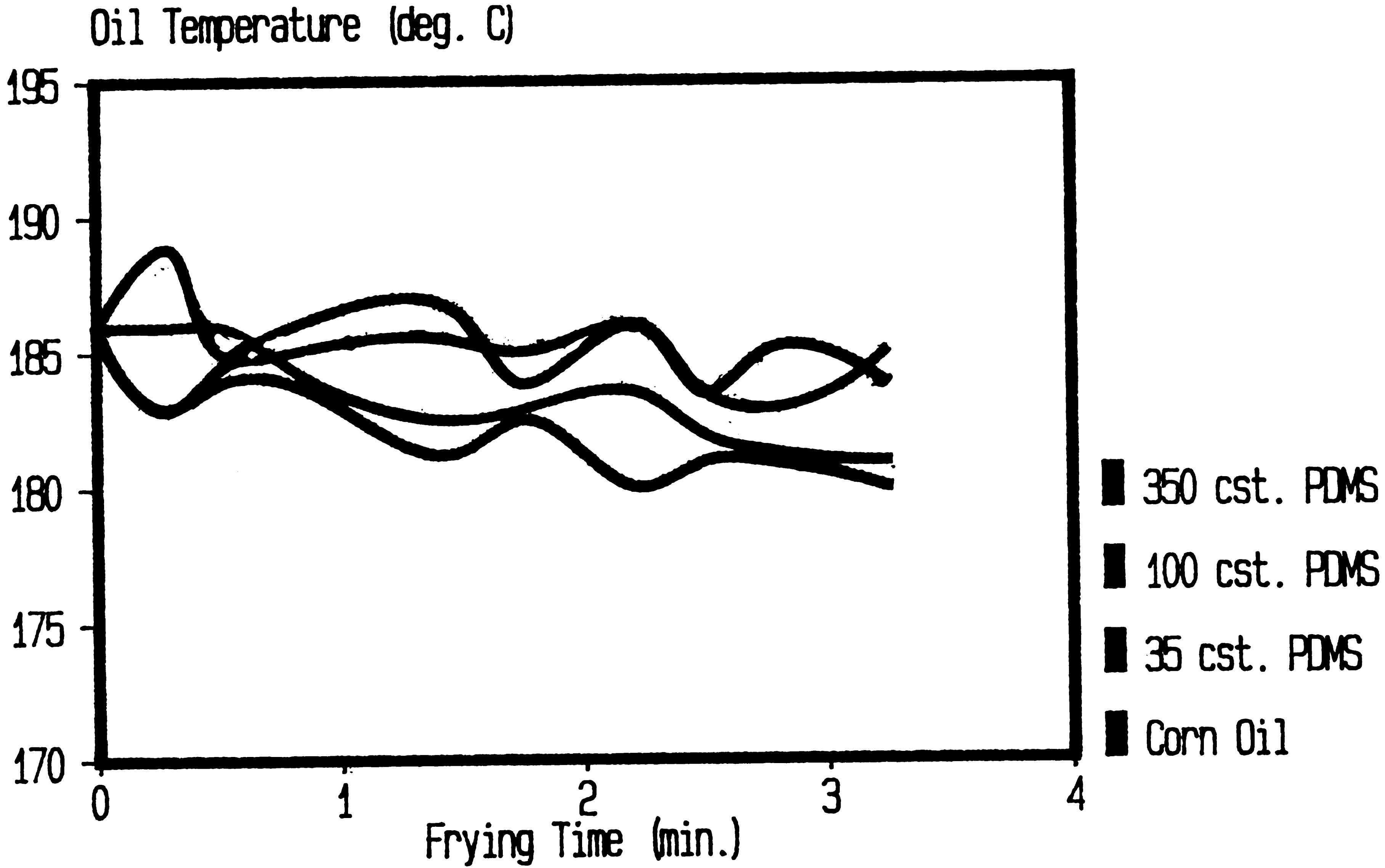

Figure 9: Changes in frying media temperatures (n=10) during frying of doughnut holes in corn oil (control) and three polydimethylsiloxane (PDMS) fluids of differing viscosities

Table 10

Objective measurements of doughnut holes[1] fried in corn oil (control) and three polydimethylsiloxane (PDMS) fluids of differing viscosities

	Control (corn oil)	PDMS Fluids 35 cst.	PDMS Fluids 100 cst.	PDMS Fluids 350 cst.
Fluid loss (%)	1.80 ± 0.61^{a}	2.12 ± 0.29^{b}	1.99 ± 0.34^{ab}	2.25 ± 0.20^{b}
Weight gain (%)	22.73 ± 0.62	31.77 ± 8.71	30.47 ± 3.72	33.69 ± 4.19
Compression (kg)	14.0 ± 1.9^{ab}	16.8 ± 3.5^{a}	12.3 ± 3.6^{b}	11.6 ± 0.09^{b}
Shear (kg/g)	1.79 ± 0.12^{a}	1.83 ± 0.07^{a}	1.78 ± 0.14^{a}	1.47 ± 0.11^{b}
Moisture (%)	17.48 ± 2.58	17.50 ± 1.34	17.06 ± 1.67	16.49 ± 0.66
Fat (%)[2,3]	45.00 ± 7.10	8.03 ± 1.98^{a}	4.60 ± 1.88^{b}	4.33 ± 1.26^{b}
PDMS (%)[2,3]	0.04 ± 0.03	42.59 ± 4.65	36.72 ± 2.19	38.44 ± 3.92
Absorbed Medium (%)[4]	39.01 ± 7.06	42.55 ± 4.41	36.68 ± 1.91	38.40 ± 3.83

[1] means and standard deviations, n=5. Values marked with different superscripts are significantly different using Duncan's Test at $P \leqslant 0.01$.

[2] dry weight basis; statistical analysis among PDMS frying media only

[3] raw product contained 5.99% fat and 0.04% PDMS on a dry weight basis.

[4] dry weight basis; statistical analysis among all four frying media

350 cst. PDMS fluid was softer than those fried in any other medium, evidenced by significantly lower shear values. Visual observations of a softer, less crisp external surface were consistent with these measurements. Statistically significant differences were also found among compression scores; the doughnut holes fried in the 35 cst. PDMS fluid were less easily compressed than those fried in the other two PDMS media, reflective of a crisper, less compact product consistency. No statistical significant differences were found among compressibility of doughnut holes fried in the two higher viscosity PDMS fluids and those fried in the control medium, however. Moisture content and PDMS content among the variables fried in siloxane did not vary significantly, however differences were measured in fat content. The doughnuts fried in the 35 cst. fluid retained significantly more fat than the products fried in the higher molecular weight siloxane fluids. Presumably this may be attributed to the greater miscibility property of the lower viscosity siloxane polymers with fat (Noll, 1968). If the PDMS molecules penetrate into the interior of the food, it is possible that the more immiscible, longer chain PDMS polymers may have displaced some of the internal fat. The total amount of PDMS and the amount of medium uptake for all variables was similar, however. This again indicates that the mode of PDMS absorption onto food from the experimental medium may be similar to fat absorption from the control corn oil medium. For conventional types of frying media,

fat absorption by food is a surface phenomenon (Stevenson et al., 1984).

It should be noted that a slight amount of PDMS (0.04%) was detected in the control samples. Presumably this was caused by contaminated glassware, as the problem was corrected after changes in cleaning were initiated.

Selection of the Optimum PDMS Fluid for Further Evaluation

On the basis of the data collected, it appeared that the 35, 100 and 350 cst. PDMS fluids could function well as non-caloric frying media. The high viscosity of the 1000 cst. siloxane limited its heat transfer efficiency, resulting in poor quality of the food products fried in it. The characteristics most affected by the siloxane media were color and texture. Generally the foods fried in the lower molecular weight siloxanes were lighter and less red in color with a softer, more moist consistency than the control products fried in corn oil. These differences were minimal with cake doughnut holes and french fries, but became more pronounced with the fish patties. This could be a function of the bread coating or the proteinaceous nature of the fish itself, however the former cause is most likely. If the siloxane medium adsorbs on the food surface in the same manner as the corn oil medium does, either the breading itself or one of the ingredients used in it limits the effectiveness of PDMS frying.

Of the viscosities evaluated, the 35 cst. PDMS had the best potential to be used as a frying medium, due to its efficient heat transfer and the acceptable quality of the foods fried in it. It was thus chosen as the experimental medium in which to investigate a relationship between product surface area and amount of media uptake.

Frying Medium Uptake as a Function of Product Surface Area: 35 cst. PDMS and Corn Oil (Control)

The direct relationship between fat absorption from the frying medium and food product surface area has long been known. Lowe et al. (1940) and Bennion and Park (1968) have shown that as the surface area of a given food increases, the amount of medium adsorption by that product increases to a similar degree. As part of this study then, it was hypothesized that this phenomenon also occurs with the 35 cst. PDMS frying medium.

Two food systems were selected to test this, cake doughnuts and french fried potatoes. While mode of PDMS ad/absorption was the primary focus of this segment of the research, data were also collected relative to food product quality. These evaluations will be included and discussed first.

CAKE DOUGHNUTS

Two cake doughnut formulations were prepared, a control and a high sugar variable. The control formulation contained 31.7 percent sugar based on flour weight. the high sugar variable contained 50 percent additional sugar, or 46.6 percent based on flour weight. The increased sucrose content provides increased water holding capacity, which in turn causes dough character to be thinner and more stretchy (Bennion, 1972). This results in increased doughnut surface area (Roth and Rock, 1964; McComber and Miller, 1976). Theoretically this type of doughnut should absorb more frying medium than the control doughnut.

Visual Observations of Media During Frying

Corn Oil (Control)

Medium: As doughnuts were immersed into the heated oil, small, clear bubbles formed in the medium around the outer doughnut perimeter and also in the center hole. Generally these bubbles formed and erupted quickly, with no intense boiling or increase in medium volume occurring. Splashing of the corn oil outside the fryer was not observed. No escape of steam was evident above the fryer during cooking. Medium remained clear and light amber in color after frying completion; no doughnut particles remained in the fryer.

35 cst. PDMS

Fluid: White, slightly frothy bubbling of the 35 cst. fluid appeared surrounding the doughnut upon its immersion into the medium. These bubbles came up through the doughnut center, although never flowed out over the doughnut surface. The bubbles around the doughnut perimeter slowly spread out, covering the fluid surface with a 0.1 cm thick layer. After doughnut removal most of the bubbles dissipated, however some still remained clinging to the fryer walls until the beginning of the following replication. After completion of frying, the used siloxane medium appeared much like the fresh fluid, clear with no product debris or cloudiness noticeable.

Visual Observations and Evaluation of Doughnut Quality

The two types of cake doughnuts prepared, control and high sugar, were both of acceptable overall quality, regardless of the type of frying medium used. Two-way analyses of variance between doughnut formulation and type of medium were calculated for all quality characteristics except the fat and PDMS content. Because of the obviously large difference in these latter two parameters depending on the type of frying medium used, the effect of ingredient variation in the doughnut formulation was determined for each medium separately.

Frying in PDMS affected color and texture to the largest extent. This was consistent with the results found in the first section of this study. The external appearance of the control doughnuts fried in PDMS was sandy-looking with a deep brown color, slightly darker on center edges than on the top and bottom surfaces. The control doughnuts fried in corn oil exhibited the same general appearance, however they were deeper golden brown in color. This visual observation made by the study investigator was substantiated by the analysis of variance, which indicated significant differences between doughnut formulations for lightness (L values), redness (A_L values) and tenderness values. Significant differences in frying media were found for lightness, redness and tenderness (Table 11). For the PDMS frying medium only, the high sugar doughnuts were found to be significantly darker in color than the control doughnuts, evidenced by lower L values. This same occurrence was expected with the control doughnuts, too, due to the additional sucrose which hydrolyzes to provide reducing sugars for involvement in Maillard browning (Bennion, 1972). Increased carbonyl-compound browning may have occurred, also. No differences were found in yellowness evaluations between either of the doughnut types in either of the two media.

For control doughnuts fried in each medium, a broken, uneven surface appearance was characteristic. This was evident on one surface of each doughnut only, and occurred consistently for all replications fried. This cracking appeared to be the result of steam release during the initial half of dough cooking, as it was apparent on the top doughnut surface prior to flipping the doughnuts midway through frying. The bottom surface remained smooth. This did not adversely affect overall doughnut appearance and quality, however, and was also characteristic of the high sugar doughnuts fried in both media.

As observed by the study investigator, control doughnuts fried in both media had soft exteriors when pierced with a thermocouple immediately upon removal from the fryer, but surfaces toughened slightly after cooling. Apparently this physical change in external surface character was greater for the control doughnut fried in corn oil, as the control doughnut fried in PDMS had a significantly softer character, evidenced by lower shear values (Table 11). Due to the tenderizing effect that sugar has in baked products (Bennion, 1972), it was expected that the high sugar doughnuts would be softer than the controls. This was found to be true for the doughnuts fried in corn oil, however similar shear values for control doughnuts and doughnuts with increased sugar were obtained when fried in PDMS. The analysis of variance for shear showed a significant interaction, which may indicate the presence of an unknown factor which influenced doughnut tenderness evaluations.

Results of the analysis of variance for compression measurements showed significant differences between the two types of doughnuts for any one medium used, however no differences were found between the medium types for either

Table 11

Objective evaluation of two cake doughnut types[1] (control and high sugar) with different surface areas fried in corn oil (control) and 35 cst. polydimethylsiloxane (PDMS) fluid

	Corn oil (control)		35 cst. PDMS	
Quality Parameter	Control Cake Doughnut	High Sugar Cake Doughnut	Control Cake Doughnut	High Sugar Cake Doughnut
Fluid Loss During Frying (%)	0.90 ± 0.06^{a}	1.15 ± 0.29^{a}	0.95 ± 0.09^{a}	1.43 ± 0.07^{b}
Color: L	32.9 ± 2.0^{ab}	30.4 ± 0.1^{a}	37.2 ± 1.4^{b}	30.7 ± 1.1^{a}
a_L	9.5 ± 0.5^{b}	10.7 ± 0.3^{b}	4.5 ± 1.2^{a}	10.8 ± 0.5^{b}
b_L	14.7 ± 0.7	15.5 ± 2.7	16.6 ± 0.4	13.8 ± 0.5
Shear (Kg/g)	7.83 ± 0.38^{c}	1.66 ± 0.19^{a}	5.85 ± 0.30^{b}	5.41 ± 0.25^{b}
Compression (Kg)[2]	7.2 ± 2.3	4.6 ± 0.0	5.9 ± 0.4	4.3 ± 0.2
Cooking Loss (%)	13.82 ± 1.41^{a}	24.63 ± 3.56^{b}	18.65 ± 3.13^{a}	34.67 ± 3.58^{c}
Moisture (%)[2]	14.17 ± 0.81	9.42 ± 0.81	14.88 ± 1.75	9.25 ± 0.51
Fat (%)[3]	30.26 ± 1.35	37.80 ± 1.97	3.98 ± 0.43	9.11 ± 2.08
PDMS (%)[4]	0.00 ± 0.01	0.00 ± 0.00	29.18 ± 3.64	36.34 ± 0.87
Abs. Medium (%)[5]	22.52 ± 1.33^{a}	33.03 ± 1.80^{c}	29.18 ± 3.64^{b}	36.34 ± 0.87^{c}

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[1] Means and standard deviations, n=5. Values marked with different superscripts are significantly different using Duncan's Test at $P \leqslant 0.01$.

[2] significant difference ($p \leqslant 0.01$) occurred between doughnut formulations for either one of the media

[3] dry weight basis; significant difference ($p \leqslant 0.01$) occurred between fat content of doughnut formulations for either one of the media. Raw product contained 7.47% fat.

[4] dry weight basis; significant difference ($p \leqslant 0.01$) occurred between PDMS content of doughnut formulations fried in 35 cst. PDMS. Raw product contained 0.00% PDMS.

[5] dry weight basis

doughnut formulation. This indicated that differences in the interior dough compactness existed between the two doughnut types. This finding was consistent with expectations, as the higher sucrose content provided greater potential for air incorporation causing a less compact dough to result (Bennion, 1972).

Doughnuts with increased sugar fried in either media lost significantly more weight than the control doughnuts fried in the same medium. The same pattern was observed with moisture content; for each medium, the high sugar doughnuts lost significantly more moisture than did the control doughnuts.

Evaluation of Medium Uptake and Product Surface Area: Control and High Sugar Varieties

Table 12 summarizes surface area measurements for the control and high sugar doughnuts. Prior to frying, the high sugar doughnut had a smaller surface area (1.299 cm^2/g) as compared to the control doughnut (2.036 cm^2/g). Results after frying were not consistent with findings reported by other researchers (Lowe et al., 1940; Roth and Rock, 1964; McComber and Miller, 1976). After frying, no significant differences among surface areas of all four doughnut varieties were found, i.e., the control doughnuts fried in the corn oil and PDMS and the high sugar doughnuts fried in the same two media. The combined analysis of variance for surface area showed a statistically significant interaction

Table 12

Frying medium uptake by two formulations of cake doughnuts[1] (control and high sugar) fried in corn oil (control) and 35 cst. polydimethylsiloxane (PDMS) fluid

	Total Surface Area(cm^2)	Surface Area (cm^2/g)	Medium Absorbed[2] (g/cm^2)
Control (Corn Oil)			
Control Doughnut	122.88 ± 6.28^{b}	3.05 ± 0.27^{a}	0.064 ± 0.006^{a}
High Sugar Doughnut	115.15 ± 6.51^{b}	3.04 ± 0.17^{a}	0.099 ± 0.054^{b}
35 cst. PDMS			
Control Doughnut	98.90 ± 1.49^{a}	2.41 ± 0.07^{b}	0.103 ± 0.003^{b}
High Sugar Doughnut	100.12 ± 2.54^{a}	3.05 ± 0.17^{a}	0.109 ± 0.006^{b}

[1] n=3; Values marked with different superscripts are significantly different, $p \leq 0.01$.

[2] dry weight basis

term, indicating that the two variables, doughnut formulation and frying medium, were not acting independently of each other relative to their influence on surface area. This is consistent with the findings shown in Table 12. The high sugar doughnut retained a larger surface area than the control doughnut during frying in siloxane, but frying in corn oil produced the opposite effect. It is possible that limitations inherent in calculating surface area could be responsible for this deviation from expectations. Measurements of doughnut dimensions made with a ruler were somewhat crude; slight differences in surface height and in frequency and/or depth of surface cracking were unmeasureable. Additional doughnut varieties with different surface areas should be prepared and fried in both media to clarify this. Experimentally this could be accomplished by altering the amounts of flour, egg or baking powder in the original formulation (Bennion, 1972). Additional replications should also be conducted.

A combined analysis of variance was also calculated for the amount of medium taken up by each of the four doughnut types during frying (Table 11). No statistically significant differences were found between high sugar doughnuts fried in corn oil and those fried in PDMS, however the medium absorbed for these variables was significantly higher than the control doughnuts fried in either medium. The control cake doughnut fried in corn oil took up significantly less frying medium than a similar doughnut fried in PDMS.

Since these results do not account for the differences in doughnut surface area which were obtained, the medium absorption was converted to grams of medium uptake per cm^2 doughnut surface. Results are shown in Table 12. The analysis of variance showed statistically significant differences between both the types of doughnuts for the corn oil medium only. A statistically significant interaction was also found, visually illustrated by the plot of means for each of these conditions (Figure 10). In actuality, the control doughnuts fried in corn oil took up significantly less medium than any of the other doughnut variables. When fried in the siloxane medium, the high sugar doughnuts did not have a significantly larger surface area than the control doughnuts did. No differences were found in amount of medium uptake between the two doughnut formulations, either.

While these results indicate that a consistent relationship between doughnut surface area and medium uptake for the siloxane frying medium was not apparent, the statistically significant interaction found indicates that unknown factors may be influencing medium uptake. As mentioned previously, physical limitations in measuring doughnut dimensions may have occurred. Even though cooking times were constant, the slightly lower temperature of the siloxane medium maintained during frying may have influenced the amount of medium uptake which occurred. Another possibility may be differences in doughnut porosity.

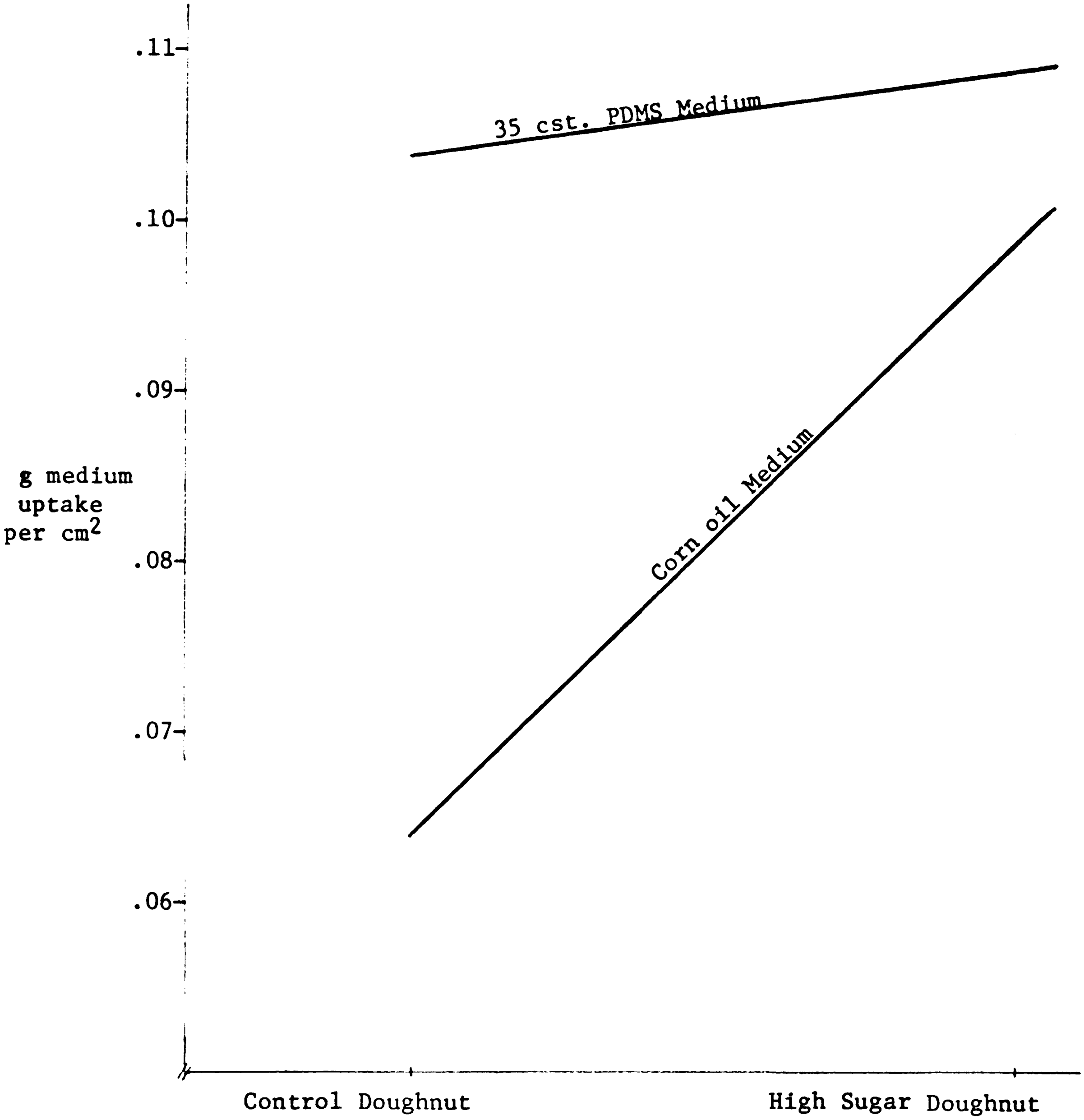

Figure 10: Means of medium uptake (g/cm^2) for control and high sugar donuts fried in corn oil and 35 cst. PDMS fluid (n=3)

Visually no differences in doughnut porosity were observed by the study investigator, however if subtle differences did actually exist this could have affected the amount of medium uptake. Additional frying experiments with doughnuts of varying surface area are needed. Performing additional replications of all variables would also provide further information useful in pinpointing the influencing factor.

FRENCH FRIED POTATOES

Four types of french fried potatoes, each with a different surface area, were fried in the corn oil and 35 cst. PDMS medium in order to further investigate the relationship between food product surface area and medium uptake. As stated previously, for conventional frying media, fat absorption by the food product increases as the product's surface area increases (Lowe et al., 1940; Bennion and Park, 1968). The four french-cut potatoes evaluated in this study and their respective surface areas are found in Table 13.

Table 13

Surface areas of four varieties of french-cut potatoes

Type of Potato	Total Surface Area (cm^2)	Surface Area (cm^2/g)
Regular-Cut French Fries	132.80	1.65
Potato Coins	898.81	12.07
Shoestring-Cut Fries	522.13	6.80
Fresh-Cut Fries	444.40	4.17

Theoretically, the potato coins should absorb the most fat from the corn oil medium, since surface area is largest. The regular-cut fries should absorb the least. If PDMS is absorbed by the product surface in a similar manner as fat from the control medium, one would expect to see the same relationship; highest PDMS uptake by the potato coins, and least from the regular cut french fries. Product quality parameters were also measured for all potato products. These attributes will be discussed separately for each potato type before comparing amounts of media uptake.

Regular-Cut French Fries

French fry data were collected for the initial section of this thesis when two fry series of five replications each were conducted. Since no difference was found to exist among replicates, the data analyzed in this section consist of results obtained from the first, third and fifth replicates (Table 14). Observations of frying media behavior and a detailed discussion of quality parameters measured can be found on pages 64 and 68 of this thesis.

As discussed previously in the first section of this study, few quality differences were measured between the french fries cooked in PDMS and those cooked in corn oil (Table 14). Cooking loss and moisture content and shearability were not significantly different. Color was the only parameter affected by frying in siloxane, as

Table 14

Objective evaluation of french fries[1] fried in corn oil (control) and 35 cst. polydimethylsiloxane (PDMS) fluid

Objective Measure	Control (Corn Oil)	35 cst. PDMS
Cooking Loss (%)	38.07 ± 1.15	36.58 ± 2.36
Fluid Loss (%)	0.73 ± 0.14	0.73 ± 0.14
Color: L	55.1 ± 0.9	56.3 ± 1.4
^{a}L	8.1 ± 0.3	5.3 ± 0.7**
^{b}L	19.9 ± 1.8	18.5 ± 1.0
Shear (kg/g)	0.49 ± 0.08	0.42 ± 0.02
Moisture (%)	46.60 ± 3.19	50.59 ± 1.24
Fat (%)[2]	28.10 ± 3.27	5.52 ± 1.77*
PDMS (%)[2]	0.02 ± 0.04	19.48 ± 2.47*
Absorbed Medium (%)[2]	7.49 ± 3.01	19.47 ± 2.31*

[1] n=3

[2] dry weight basis. Raw product contained 22.61% fat and 0.01% PDMS.

*significantly different, $p \leq 0.01$

**significantly different, $p \leq 0.05$

evidenced by the significantly less red hue measured on the potatoes fried in siloxane. No statistically significant differences were found for lightness or yellowness evaluations.

Statistically significant differences in medium uptake by french fries cooked in the two fluids were found, however. Absorbed PDMS from the siloxane medium was significantly lower than absorbed fat from the corn oil medium, 19.47 percent versus 7.49 percent. The total fat content of the potatoes fried in corn oil (frozen plus absorbed) was 28.10 percent, compared to the 24.99 percent combined raw fat and absorbed PDMS content of the potatoes fried in siloxane. It is probable that dislodgement of some of the surface fat molecules by absorbing PDMS molecules occurred, thereby accounting for this difference.

Potato Coins

Potato coins fried in 35 cst. PDMS fluid scored similarly to those fried in corn oil for most of the quality parameters evaluated (Table 15). Visually observed, the potato coins fried in corn oil were deep golden brown in color, somewhat darker on the outside edges than on the top or bottom surfaces. Hunter color evaluations showed these potatoes to be significantly darker in color than the ones fried in 35 cst. PDMS fluid. This was observed visually by the investigator; diminished browning on the edges was evident, also. No statistically significant differences were found between the redness and yellowness evaluations of the two samples, however. Although not measured objectively, the interiors of both potato types were very similar - white in color with a characteristic soft, moist cooked potato appearance.

Outer surfaces of the potato coins fried in corn oil appeared rough with slight oiliness noted. Some oozing of fat was evident upon breaking and shearing. Shear values for the potato coins fried in PDMS and those fried in corn oil were not significantly different. Oozing of siloxane occurred as the potato was sheared, however excessive PDMS surface adsorption was not visually apparent to the investigator. Cooking loss exhibited by the potatoes fried in PDMS was significantly less than that measured for the potatoes fried in corn oil. Moisture contents did not differ significantly between potato coins fried in each medium, but the amount of medium uptake from siloxane was over 50 percent higher than that taken up from corn oil. This contradicts the previously cited evidence for a similar mode of media absorption to the product surface from the two frying fluids examined. Apparently the surface fat present on the raw product due to commercial parfrying influenced the amount of medium uptake which occurred from both media. The fat content of the coins fried in the 35 cst. PDMS fluid was actually lower than the frozen product fat content. Since most of this fat is contained on the surface due to parfrying, some may have been displaced by the absorbing

Table 15

Objective evaluation of potato coins[1] fried in corn oil (control) and 35 cst. polydimethylsiloxane (PDMS) fluid

Quality Parameter	Control (Corn Oil)		35 cst. PDMS	
Cooking Loss (%)	10.34	1.16	4.39	3.76**
Fluid Loss	1.08	0.08	0.97	0.33
Color: L	45.4	0.3	47.7[b]	0.6**
aL	9.2	0.7	8.3	0.4
bL	11.3	0.4	12.7	0.3
Shear (kg/g)	0.60	0.11	0.72	0.04
Moisture (%)	41.67	2.33	43.24	2.70
Fat (%)[2]	52.97	2.23	26.78	1.56*
PDMS (%)[2]	0.03	0.02	25.91	1.20*
Absorbed Medium (%)[2]	12.98	1.83	25.86	1.05*

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[1] n=3

[2] dry weight basis. Raw product contained 39.99% fat and 0.05% PDMS

*significantly different, $p \leq 0.01$

**significantly different, $p \leq 0.05$

siloxane molecules. This is the most reasonable explanation, since the total fat content of the coins fried in corn oil, i.e. 52.97 percent, equivalent to the frozen fat content plus the fat taken up from the medium, was roughly equivalent to the combined fat and PDMS content of the coins fried in siloxane, i.e. 52.64 percent. No physical evidence of this leached fat was observed in the medium after frying completion, however. Another possible explanation lies in non-representative frozen product sampling, however this is unlikely because identical results were obtained from two additional extractions conducted subsequent to initial data compilation.

Visual Observations of Media During Frying

Corn Oil Medium: Rapid boiling and development of large, clear bubbles which erupted quickly occurred as potato coins were lowered into the medium. Oil drops splashed outside the fryer, too. This behavior can be attributed to the ice which adhered to the frozen product. Although it was impossible to remove all the ice without handling the sample excessively, attempts were made to keep adhered ice at a consistently low level for each replication.

35 cst. PDMS Fluid: The PDMS fluid underwent extensive bubbling and foaming with a consequent volume increase during product frying. Immediately upon immersion into the frying medium, a white frothiness became apparent which progressively increased in height with each successive replication. Maximum changes from the initial foam height were 47.18 percent for the first replicate, 62.90 percent for the second and 104.84 percent for the third. Splashing out of PDMS was noted for the last replication, when foam volume reaches its' maximum at the top edge of the fry basket. Moisture from the adhered ice on the frozen potato coin surface probably accounted for this.

Shoestring-Cut French Fries

As evidenced in Table 16, the overall quality of shoestring-cut potatoes fried in siloxane measured very similarly to those fried in corn oil. Cooking loss, color and shearability measurements did not significantly vary for products fried in both media. Statistically significant differences were found between moisture contents, however, with the potatoes fried in PDMS being more moist. Visual observations by the study investigator showed each variable had a slightly crisp exterior, with a soft, moist interior, quite characteristic of shoestring-cut french fries. Excessive greasiness was not detected in potatoes fried in either media. Draining for each was thorough and efficient, with the same amount of frying medium loss measured for both fluids evaluated.

The largest difference found between the potatoes was in the amount of medium uptake. Similar to the results obtained with the potato coins, significantly more PDMS was taken up from the siloxane medium than fat from the corn oil medium. The 31.54 percent total fat content of the control potatoes (raw plus absorbed) approximated the combined fat and absorbed PDMS content of the potatoes fried in siloxane, 31.72 percent. This indicates that some of the absorbed surface fat present in the frozen product from parfrying was displaced by PDMS from the medium during frying. No physical evidence of this was observed in the medium after frying completion, however.

Table 16

Objective evaluation of shoestring-cut fries[1] fried in corn oil (control) and 35 cst. polydimethylsiloxane (PDMS) fluid

Objective Measure	Control (Corn Oil)		35 cst. PDMS	
Cooking Loss (%)	40.12	0.75	39.31	0.81
Fluid Loss (%)	0.78	0.07	0.76	0.12
Color: L	57.8	1.7	61.2	0.7
a_L	2.9	0.4	2.0	0.1
b_L	21.4	0.9	22.7	1.0
Shear (kg/g)	0.89	0.16	0.98	0.14
Moisture (%)	42.06	0.99	45.24	0.85*
Fat (%)[2]	31.54	2.10	10.26	1.47*
PDMS (%)[2]	0.01	0.01	21.50	1.70*
Absorbed Medium (%)[2]	14.72	1.86	21.46	1.38*

[1] n=3

[2] dry weight basis. Raw product contained 16.82% fat and 0.04% PDMS.

*significantly different, $p < 0.01$

Visual Observations of Media During Frying

Corn Oil (Control) Medium: Boiling and bubbling of the corn oil started as the product was immersed in the medium and began to lose moisture. No frothiness or increase in volume was noted, however. Intensity of boiling was not sufficient to cause splashing of the medium outside the fryer. No product debris was observed remaining in the fryer after completion of frying.

35 cst. PDMS Fluid: Frothy white foam formation, similar to that described previously for other food products, occurred during frying with the 35 cst. PDMS fluid. Maximum foam height reached the top of the fry

basket, or 104.84 percent of the initial frying medium height, for all replications. Small quantities of PDMS splashed up outside the fryer when fluid levels were elevated. Some escape of steam was observed during the period of maximum foam height.

Fresh-Cut French Fries

Based on the parameters evaluated, product quality of the fresh-cut french fried potatoes fried in the 35 cst. PDMS fluid was excellent. In fact, very little difference was discernable between these experimental fries and the control ones, either by visual or objective evaluation (Table 17). Potatoes fried in both media were light, golden brown in color with a moist, slightly soft texture characteristic of french fries. No statistically significant differences in Hunter color evaluations or shear values were found between potatoes fried in each media. This is in contrast to the color and texture differences found among the other french-cut potatoes fried in corn oil and PDMS.

The only statistically significant differences found between fresh-cut potatoes fried in both media were in cooking loss and moisture content. The potatoes fried in siloxane retained significantly more moisture, which accounted for the smaller cooking loss measured. The amount of medium uptake by potatoes fried in each variable was similar, which indicates that the original hypothesis of a

Table 17

Objective evaluation of fresh-cut fries[1] fried in corn oil (control) and 35 cst. polydimethylsiloxane (PDMS) fluid

Quality Parameter	Control (Corn Oil)		35 cst. PDMS	
Cooking Loss (%)	39.98	0.45	37.76	1.19*
Fluid Loss (%)	0.55	0.31	0.52	0.08
Weight Loss During Parboiling (%)	2.20	0.50	2.27	0.47
Color: L	59.2	1.5	59.8	1.4
a_L	-2.9	1.0	-3.0	0.5
b_L	23.1	0.9	23.3	0.3
Shear (kg/g)	18.27	2.35	21.13	0.32
Moisture (%)	63.83	1.25	66.45	1.10**
Fat (%)[2]	19.62	1.31	7.83	1.17*
PDMS (%)	0.01	0.01	9.77	0.79*
Absorbed Medium (%)[2]	10.35	0.67	9.76	0.79

[1] n=3

[2] dry weight basis. Raw product contained 9.27% fat and 0.01% PDMS.

*significantly different, $p \leqslant 0.01$

**significantly different, $p \leqslant 0.05$

similar mode of adsorption onto the food product from the frying medium may be true. These potatoes did not have a high surface fat content prior to frying, as did the other three french-cut potato products previously discussed, so apparently no physical interference with PDMS absorption was present. This resulted in similar amounts of medium uptake. The fat content of these potatoes fried in corn oil was consistent with other values reported in the literature (Stevenson et al., 1984; Smith et al., 1986).

Visual Observations of Media During Frying

Corn Oil (Control) Medium: The corn oil underwent noticeable change, particularly during the initial thirty seconds of fry time. Boiling up of the medium occurred due to loss of product moisture, however thick, white frothiness never developed to the extent observed with the siloxane fluid. This does not mean the corn oil was transparent, because bubbling was rapid enough to cloud over the surface. Fries did become visible approximately halfway through the frying process, however. Frying medium appeared like fresh oil at the completion of three french fry replications.

35 cst. PDMS Fluid: Even though quality of the potatoes fried in the 35 cst. fluid was acceptable, the frying medium itself underwent frothing and foam formation which may be considered undesirable. Immediately upon product immersion, rapid boiling accompanied by crackling noises and some splashing out of the medium occurred. As soon as fifteen seconds into the frying period, frothy volume reached the top of the fry basket (a 104.84% increase of the initial oil height). This level remained constant for approximately one minute and thirty seconds before subsiding 1.3 cm every 8-9 seconds. Clearing occurred with nearly two minutes of fry time remaining. Even though fries were visible floating on the fluid surface at this point, some white frothiness was still apparent. This fluid volume increase and foam development was fairly consistent among replications fried.

Evaluation of Medium Uptake as a Function of Product Surface Area: French-Cut Potato Products

Table 18 shows the amount of medium taken up by four french-cut potato products during frying. Due to the apparent influences of potato product surface fat on the amount of siloxane uptake, a direct, statistical comparison between surface area and medium uptake would not be valid. In order to successfully do this, either unprocessed, common lot potatoes of varying size and shape should be evaluated or processed potatoes of similar composition and fat content could possibly be used. The former alternative is preferable, however time limitations prevented this from being incorporated as part of this thesis.

Table 18

Amount of medium absorbed by four french-cut potato products during frying

Potato Product	Total Surface Area (cm^2)	Surface Area (cm^2/g)	Fat Content Prior to Frying (%)[1]	Medium Absorbed (%)[1] Corn Oil (control)	Medium Absorbed (%)[1] 35 cst. PDMS
Regular-Cut French Fries	132.80	1.65	20.59 ± 0.83	7.49 ± 3.01	19.47 ± 2.31[a]
Potato Coins	898.81	12.07	39.99 ± 2.05	12.98 ± 1.83	25.86 ± 1.05[a]
Shoestring-Cut Fries	522.13	6.80	16.82 ± 0.82	14.72 ± 1.86	21.46 ± 1.38[a]
Fresh-Cut Fries	444.40	4.17	9.27 ± 3.08	10.35 ± 0.67	9.76 ± 0.79

[1] Means and standard deviations, n = 3. Values marked with different superscripts are significantly different, $p \leq 0.01$.

SUMMARY AND CONCLUSIONS

The overall goal of this study was to determine the feasibility of using polydimethylsiloxane (PDMS) fluids as non-caloric frying media. In order to accomplish this, four PDMS fluids of differing viscosities (35, 100, 350 and 1000 cst.) were evaluated for their heat transfer efficiencies. Results were obtained by analyzing time/temperature relationships of each media during the heating and frying of the following three foods: breaded, frozen fish patties; frozen, parfried french fried potatoes and cake doughnut holes. Comparisons were made to a control medium, corn oil.

Frying studies indicated that the least viscous PDMS fluid, the 35 cst., exhibited a heating pattern most similar to corn oil. As viscosity of the PDMS medium increased, longer fry times were needed for the foods to reach the same, pre-determined internal endpoint temperature. During frying, the PDMS media maintained lower overall temperatures than did the corn oil. It took longer for these synthetic media to reach frying temperature during initial heating, also. Perhaps slightly higher frying temperatures for PDMS media could be used to shorten overall frying time.

Bubbling and frothy foam formation was a problem observed during frying with the PDMS media. This did not occur consistently for each food fried, but appeared to be related to the moisture loss by the food product. For example, increased foaming and large changes in medium height were observed with the frozen fish patties and french fries; much less was evident with the doughnut holes.

With the exception of the 1000 cst. PDMS medium, the product quality of each food fried in PDMS was generally comparable to identical foods fried in corn oil. Foods fried in this high viscosity medium were unacceptably soggy, due to excessive PDMS saturation. Product quality assessment was based on a variety of objective measurements; formal sensory analysis was not conducted because use of PDMS as a cooking medium has not yet received approval from the Food and Drug Administration. Generally foods fried in PDMS were found to be lighter and less red in color, with a soft, more moist texture. Apparently using PDMS as a frying medium interferes with the normal browning reactions which occur during frying. This could be due to the lower temperatures maintained by the synthetic media throughout frying.

Of the four PDMS fluids examined, the 35 cst. fluid had the best potential to be used as a frying medium, due to its efficient heat transfer and the acceptable quality of the foods fried in it. Thus, the 35 cst. fluid was chosen as the sole PDMS fluid in which to investigate how siloxane is taken up by the food product.

Initially it appeared that PDMS absorbed to the food surface during frying in a similar way that fat from the corn oil medium did. If this is true, one would expect that an increase in food product surface area should cause an increase in PDMS uptake from the medium during frying. Results from the two food systems selected to test this, i.e., cake doughnuts and french-cut potatoes, were inconclusive. Two types of cake doughnuts with different surface areas were fried in corn oil and PDMS. The doughnuts with larger surface areas absorbed more fat during frying in corn oil than the other doughnut variables did, however frying in PDMS did not yield similar results. Uptake from this medium was similar for both doughnut types, regardless of surface area. Several limitations inherent in the experiment and its' analyses may have been responsible for this deviation from expectations. These included: physical limitations in measuring doughnut dimensions, approximations in calculating surface area, and undetectable differences between the surface character of the two doughnut types, either in extent of surface cracking or in porosity. The slightly lower temperature maintained by the PDMS medium during frying may also have influenced medium uptake. Further studies with additional doughnuts of varying surface areas are needed to either substantiate or refute these results. Additional replications should be conducted, also.

Frying studies conducted with the four types of french-cut potato products did not substantiate a relationship between food product surface area and amount of PDMS medium uptake, either. Unfortunately none of the potato products selected were of identical composition; thus a valid comparison between these for medium uptake was impossible. Analysis of fat and siloxane content did indicate that the amount of surface fat present on a commercially parfried product influences the amount of PDMS which is taken up from the siloxane medium. For each of the commercially parfried products, significantly more medium was absorbed to the food from the PDMS medium than from the corn oil medium. Fresh-cut potatoes absorbed similar amounts of media from both the corn oil and siloxane medium, however. Further experimentation needs to be conducted before any definitive conclusions can be reached. This could be achieved by cutting unprocessed, common-lot potatoes into french-cut fries of various surface areas and frying in the corn oil and PDMS. Medium uptake could then be quantitated and results analyzed in relation to potato surface area.

In order to obtain more precise information relative to the mode of PDMS adsorption from the frying medium onto food, depth of PDMS penetration should be determined. This could be achieved in one of two ways, however a combination of both would be optimal in order to compensate for any possible experimental error which may be associated with any one method. The preferred approach would be a scanning electron microscopic evaluation of various food samples fried in the PDMS medium. Using an x-ray detector, elemental silicon could be quantitated and a plot of its location within the specimen made. Transmission electron microscopy probably could not be used, due to the disruption of sample structure that occurs as a result of the fixation techniques needed.

The second approach would involve ultra-thin sectioning of the food fried in PDMS with a microtome. Each section thus obtained would be analyzed for elemental silicon content using atomic absorption spectroscopy. This would enable quantification of silicon as a function of penetration depth into the food. This technique would require that the food sample be frozen prior to slicing, due to the "creeping," spreadable nature of the siloxane polymers. Freezing the food sample by dipping it in liquid nitrogen could be done.

These two methods of quantifying depth of silicon penetration into a sample should be employed on a variety of fried food products, enabling a conclusion to be reached regarding the mode of siloxane ab/adsorption onto food from the frying medium.

APPENDICES

APPENDIX A

3 oz. Breaded Frozen Cod Patty (Frionor): Nutritional Composition[1]

per 100 g product:

Protein, g	14.7
Fat, g	0.5
Moisture, g	57.2
Ash, g	1.0
Carbohydrate, g	26.8
Kilocalories	146
Sodium, mg	68
Calcium, mg	10.8
Potassium, mg	250
Iron, mg	1.15

[1] Supplied by Frionor, P.O. Box A-2087, New Bedford, Mass. 02741

APPENDIX B

Dawn "Majestic" Regular Doughnut Mix: Nutritional Composition[1]

per 100 g fried product:

Protein, g	5.9
Fat, g	18.6
Carbohydrate, g	49.1
Moisture, g	6.0
Fiber, g	0.18
Kilocalories	375
Sodium, mg	640
Potassium, mg	110
Vitamin A, IU	203.42
Vitamin C, mg	0.10
Thiamine, mg	0.46
Riboflavin, mg	0.32
Niacin, mg	3.5
Calcium, mg	38.5
Iron, mg	3.2

[1] Supplied by Dawn Food Products, Inc., 2032 Micor Drive, Jackson, MI 49203-9989

APPENDIX C

Preparation Procedure: Dawn "Majestic" Cake Doughnut Holes

1. Ingredients weighed - doughnut mix = 227.5 g
   distilled water = 102.38 ml

2. Above ingredients blended for 5 seconds on speed 1 (80 rpm) of Hobart Kitchen Aid K-5 Mixer using paddle attachment.

3. Speed increased to 2 (88 rpm) and blending continued for an additional minute.

4. Bowl scraped down.

5. Batter mixed on speed 4 (144 rpm) for 2 minutes.

6. Bowl scraped down; batter left standing 10 minutes before frying.

Frying Procedure:

1. Doughnut holes were dropped into heated oil (186-8°C) two at a time using #40 scoops (approximately 25 gms batter) - one doughnut in lower right corner of fryer and one in upper left.

2. Thermocouples in positions 1, 2 and 3 (as per Fig. 4).

3. Doughnut holes fried for 3 1/2 minutes while turning continuously.

APPENDIX D

Formulation and Procedure for Cake Doughnuts
(Homemade Formulation)

Ingredients	Weight (g)	% of Flour Weight
All Purpose Flour	157.50	100
Granulated Sugar	50.0	31.7
Homogenized Milk	61.00	38.7
Hydrogenated Shortening	6.50	4.1
Eggs	24.00	15.2
SAS Baking Powder	6.00	3.8
Salt	2.00	1.3
Nutmeg	0.50	0.3
Cinnamon	0.50	0.3
Mace	0.25	0.16

Procedure:

1. Flour, baking powder, salt and spices sifted together.
2. Fat creamed for 1 minute on speed 4 (144 rpm) of Hobart KitchenAid K-5 Mixer using paddle attachment.
3. Half of the sugar added to fat gradually over a 30 second period while mixing on speed 4 (144 rpm); mixing continued for an additional 1 1/2 minutes. Bowl scraped.
4. Egg and remaining sugar added alternately in two portions - mixed 30 seconds and bowl scraped after each addition.
5. Milk and half of dry ingredients blended in on speed 4 (144 rpm) for 30 seconds. Bowl scraped before blending for an additional minute on speed 4 (144 rpm).
6. Dough placed on lightly floured board and patted to approximately 1 inch thickness then placed through lightly floured sheeter (National Manufacture Co.) at 3/8" two times.
7. Dough placed on lightly floured board; 5 doughnuts cut and weighed prior to frying.

Appendix D

Frying Procedure:

1. Doughnuts dropped one at a time into heated oil (190-2°C) in lower right hand corner of fryer.

2. Thermocouples in positions 1, 2 and 3 (as per Fig. 1).

3. Doughnuts fried for a total of 3 minutes; flipped over halfway through frying period.

APPENDIX E

Crispy Crowns (Ore-Ida): Ingredients[1]

Potatoes, Vegetable Oil Shortening (contains one or more of the following: Palm Oil or Partially Hydrogenated Soybean Oil), Salt, Precooked Wheat Flour, Yellow Corn Flour, Monosodium Glutamate, Natural Flavoring, Dehydrated Onion, Dextrose, Disodium Dihydrogen Pyrophosphate (to retain natural color).

[1] As listed on package
Ore-Ida Foods, Inc. (Heinz), Boise, Idaho, USA 83706

APPENDIX F

Shoestring Potatoes (Big Beaver) Ingredients[1]

Potatoes, Shortening consisting of one or more of the following: Beef Fat, Hydrogenated Soy and/or Palm Oil; Dextrose, Disodium Dihydrogen Pyrophosphate and/or Yellow #5 and #6 Certified Food Coloring.

[1] As listed on package
Big Beaver Shoestrings Straight Grade "A" Long Fancy,
Mid-America Potato Co., Grand Rapids, MI 49501.

APPENDIX G

French Fried Potatoes (Snowflake) Ingredients[1]

Potatoes, Vegetable Oil Shortening (contains one or more of the following: Palm Oil, Partially Hydrogenated Soybean Oil, Dextrose, Dihydrogen Pyrophosphate (added to preserve natural color). Cooked in Vegetable Oil.

[1] As listed on package. McCain Foods, Easton, ME.

APPENDIX H

Formulas used for food product surface area calculations

__Potatoes:__

1) __Regular-cut:__ Trace on cardboard/weigh

$\boxed{g/cm^2}$ proportion to wgt of $5cm^2$ square

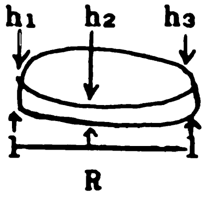
$SA = 2(x) + t\,(\text{perimeter})$ t = thickness
$x = cm^2$

2) __Shoestring-cut and Fresh-cut:__

(length x height) 4
2 (area of end $\underset{w}{\square}$ w)

$SA = 4(l \times h) + 2(w^2)$

3) __Potato Coins:__



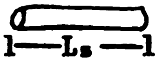
$$\bar{h} = \frac{h_1 + h_2 + h_3}{3}$$

$$SA = 2(\pi R^2) + \bar{h}\,(2\ 11\ R)$$
$$= 2\pi R\,[\bar{R} + \bar{h}]$$

Appendix H

Doughnuts: $SA = \frac{\pi d}{4}\,[(A-2d) + (B-2d) + (A+B)]$

$\frac{\text{height}}{3} \approx d$

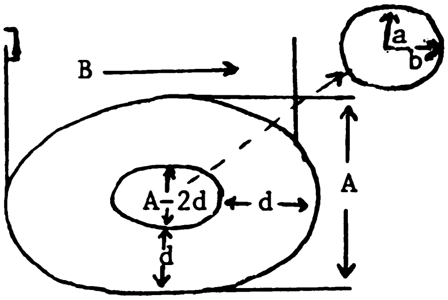


$$\boxed{SA = \pi d L_s}$$

$$\bar{L}_s = \frac{(\text{Perimeter inside ellipse})=(\text{Perimeter of Outside ellipse})}{2}$$

$$\bar{L}_s = \left[\frac{[(A-2d)+(B-2d)]}{2}\,\pi + \pi\,\frac{(A+B)}{2}\right] 1/2$$

$$\bar{L} = \frac{\pi}{4}\,[(A-2d)(B-2d)+(A+B)]$$



$$\text{Area} = \pi ab$$

$$= \pi r^2 \text{ where } a = b$$

$$2\pi r \approx 2\pi\left(\frac{a+b}{2}\right) =$$

$$\boxed{\pi\,(a=b) = \text{perimeter}}$$

APPENDIX I

Table 19. Analyses of variance for fluid loss and cooking loss of fish patties fried in corn oil and three polydimethylsiloxane (PDMS) fluids of differing viscosities

		Mean Squares	
Source	df	Fluid Loss	Cooking Loss
Total	41		
Medium	4	0.49**	47.29
Replications	9	0.08	9.91
Interaction	28	0.02	11.33

**p $\leq$ 0.01

Table 20. Analyses of variance for color of fish patties fried in corn oil and three polydimethylsiloxane (PDMS) fluids of differing viscosities

		Mean Squares		
		Color		
Source	df	L	a_L	b_L
Total	22			
Medium	4	186.83**	63.29**	20.51**
Replications	4	11.93	0.82	5.53
Interaction	14	4.08	1.15	0.99

**p $\leq$ 0.01

Appendix I

Table 21. Analyses of variance for moisture of fish patties fried in corn oil and three polydimethylsiloxane (PDMS) fluids of differing viscosities

Source	df	Mean Squares Moisture
Total	39	
Medium	3	70.18**
Replications	9	11.69**
Interaction	27	6.93

$^{**}p \leq 0.01$

Table 22. Analyses of variance for shear, fat, PDMS and absorbed medium of fish patties fried in corn oil and three PDMS fluids of differing viscosities

		Mean Squares			
Source	df	Shear	Fat	PDMS	Absorbed Medium
Total	19				
Medium	3	0.77	1030.92**	548.79**	4.16
Replications	4	0.87	1.33	2.73	1.48
Interaction	12	0.86	2.32	6.19	9.06

Appendix I

Table 23. Analyses of variance for fluid loss, cooking loss and moisture of cake doughnut holes fried in corn oil and three PDMS fluids of differing viscosities

		Mean Squares		
Source	df	Fluid Loss	Cooking Loss	Moisture
Total	49			
Medium	4	0.38	195.77**	3.80
Replications	9	0.14	80.40	5.68
Interaction	36	0.15	30.34	2.24

**p $\leq$ 0.01

Table 24. Analyses of variance for shear and compression of cake doughnut holes fried in corn oil and three PDMS fluids of differing viscosities

		Mean Squares	
Source	df	Shear	Compression
Total	24		
Medium	4	0.93	155.58
Replications	4	0.03	49.98
Interaction	16	0.06	33.94

Appendix I

Table 25. Analyses of variance for fat and PDMS content of cake doughnut holes fried in corn oil and three PDMS fluids of differing viscosities

		Mean Squares	
Source	df	Fat	PDMS
Total	20		
Medium	4	1579.43**	1610.90**
Replications	5	18.42	24.65
Interaction	11	19.77	6.07

$^{**}p \leqslant 0.01$

Table 26. Analyses of variance for absorbed medium of cake doughnut holes fried in corn oil and three PDMS fluids of differing viscosities

		Mean Squares
Source	df	Absorbed Medium
Total	19	
Medium	3	38.87
Replications	5	77.37
Interaction	11	9.27**

$^{**}p \leqslant 0.01$

Appendix I

Table 27. Analyses of variance for fluid loss and cooking loss of french fries fried in corn oil and three PDMS fluids of differing viscosities

		Mean Squares	
Source	df	Fluid Loss	Cooking Loss
Total	38		
Medium	3	0.07	97.59**
Replications	9	0.12	4.90
Interaction	26	0.02	1.74

**p ≤ 0.01

Table 28. Analyses of variance for color, shear, fat, PDMS and absorbed medium of french fries fried in corn oil and three PDMS fluids of differing viscosities

		Mean Squares						
		Color						Absorbed
Source	df	L	a_L	b_L	Shear	Fat	PDMS	Medium
Total	19							
Medium	3	34.71**	42.57**	2.10	0.06	678.68**	511.06**	214.01**
Replications	4	4.27	0.21	0.24	0.08	1.73	5.54	4.25
Interaction	12	4.25	1.13	1.63	0.05	6.13	8.34	13.91

**p ≤ 0.01

Appendix I

Table 29. Analyses of variance for moisture content of french fries fried in corn oil and three PDMS fluids of differing viscosities

		Mean Squares
Source	df	Moisture
Total	39	
Medium	3	98.94**
Replications	9	9.67
Interaction	27	9.13

**p $\leq$ 0.01

Table 30. Analyses of variance for fluid loss, cooking loss/weight gain, moisture and total absorbed medium for control and high sugar doughnuts fried in corn oil and 35 cst. PDMS fluid

		Mean Squares			
Source	df	Fluid Loss	Cooking Loss/ Weight Gain	Moisture	Absorbed Medium
Total	23				
Doughnut Type	1	0.80	1080.18**	161.57**	467.90**
Medium	1	0.17	332.05**	0.43	148.95**
Interaction	1	0.78	40.80**	1.18	16.78**
Within	20	0.30	11.17**	1.40	4.60*

*p $\leq$ 0.05
**p $\leq$ 0.01

Table 31. Analyses of variance for color, shear, compression, total surface area (cm^2), surface area (cm^2/g) and medium absorbed per cm^2 doughnut surface area for control and high sugar doughnuts fried in corn oil and 35 cst. PDMS fluid

		Mean Squares								
		Color								Medium
Source	df	L	a_L	b_L	Shear	Compression	Total Surface Area	Surface Area (cm^2/g)		Absorbed (g/cm^2)
Total	11									
Doughnut Type	1	60.75**	41.81	3.20	154.44	68.16	32.34	0.07		0.01
Medium	1	15.87*	17.28	0.03	10.18	10.83	1141.65	1.81		0.01
Interaction	1	10.71*	19.25	9.72	123.46	4.81	59.46	1.86		0.01
Within	8	2.65	0.73	8.14	0.62	8.92	271.39	30.10		0.01

Appendix I

Table 32. Analyses of variance for fluid loss of regular-cut french fries fried in corn oil and 35 cst. PDMS fluid

Source	df	Mean Squares Fluid Loss
Total	10	
Medium	1	0.00
Replications	5	0.01
Interaction	4	0.04

Table 33. Analyses of variance for cooking loss, moisture, fat, PDMS and absorbed medium of regular-cut french fries fried in corn oil and 35 cst. PDMS fluid

		Mean Squares				
Source	df	Cooking Loss	Moisture	Fat	PDMS	Absorbed Medium
Total	11					
Medium	1	6.63	47.80*	1529.343	1136.46**	429.60**
Replications	5	5.56	6.75	1.69	3.24	0.97
Interaction	5	2.71	7.30	12.00	3.19	16.50

$^{*}p \leqslant 0.05$
$^{**}p \leqslant 0.01$

Appendix I

Table 34. Analyses of variance for color and shear of regular-cut french fries fried in corn oil and 35 cst. PDMS fluid

		Mean Squares			
		Color			
Source	df	L	a_L	b_L	Shear
Total	5				
Medium	1	2.04	11.76**	2.94	0.04
Replications	2	1.18	0.37	0.47	0.13
Interaction	2	2.93	0.55	6.01	0.03

$^{**}p \leqslant 0.01$

Table 35. Analyses of variance for fluid loss, cooking loss, moisture, fat, PDMS and absorbed medium for potato coins fried in corn oil and 35 cst. PDMS fluid

		Mean Squares					
Source	df	Fluid Loss	Cooking Loss	Moisture	Fat	PDMS	Absorbed Medium
Total	11						
Medium	1	0.04	106.27	7.36	2058.01**	2001.83**	498.20**
Replications	5	0.06	4.76	10.54	2.55	0.80	2.24
Interaction	5	0.07	13.82	4.71	2.93	0.55	3.11

$^{**}p \leqslant 0.01$

Appendix I

Table 36. Analyses of variance for color and shear of potato coins fried in corn oil and 35 cst. PDMS fluid

		Mean Squares			
		Color			
Source	df	L	a_L	b_L	Shear
Total	5				
Medium	1	7.94	1.13	2.94**	0.10
Replications	2	0.27	0.53	0.05	0.05
Interaction	2	0.28	0.35	0.24	0.05

$^{**}p \leq 0.01$

Table 37. Analyses of variance for fluid loss, cooking loss, moisture, fat, PDMS and absorbed medium for shoestring-cut french fries fried in corn oil and 35 cst. PDMS fluid

		Mean Squares					
Source	df	Fluid Loss	Cooking Loss	Moisture	Fat	PDMS	Absorbed Medium
Total	11						
Medium	1	0.00	1.93	30.28**	1358.30**	1384.82**	136.42**
Replications	5	0.02	0.97	0.72	3.92	1.14	4.22
Interaction	5	0.00	0.50	1.32	1.00	1.15	2.30

$^{**}p \leq 0.01$

Appendix I

Table 38. Analyses of variance for color and shear of shoestring-cut french fries fried in corn oil and 35 cst. PDMS fluid

		Mean Squares			
		Color			
Source	df	L	a_L	b_L	Shear
Total	5				
Medium	1	16.67*	1.13	2.80	0.06
Replications	2	1.82	0.11	0.31	0.20
Interaction	2	2.99	0.19	2.16	0.14

*$p \leq 0.05$

Table 39. Analyses of variance for fluid loss, cooking loss, weight loss during parboiling, moisture, fat, PDMS and absorbed medium for fresh-cut french fries fried in corn oil and 35 cst. PDMS fluid

		Mean Squares						
Source	df	Fluid Loss	Cooking Loss	Weight Loss During Parboiling	Moisture	Fat	PDMS	Absorbed Medium
Total	11							
Medium	1	0.00	14.74**	0.02	20.59	416.54**	285.87**	1.00
Replications	5	0.08	1.11	0.41	0.36	1.14	0.21	0.44
Interaction	5	0.04	0.81	0.16	2.97	0.70	0.22	0.53

$^{**}p \leqslant 0.01$

Table 40. Analyses of variance for color and shear for fresh-cut french fries fried in corn oil and 35 cst. PDMS fluid

		Mean Squares			
		Color			
Source	df	L	a_L	b_L	Shear
Total	5				
Medium	1	0.48	0.01	0.03	59.98
Replications	2	5.29	0.58	0.29	24.44
Interaction	2	1.09	1.45	1.12	16.76

$^{**}p \leqslant 0.01$

REFERENCES

REFERENCES

American Association of Cereal Chemists. 1983 (8th edition). Approved methods of the American Association of Cereal Chemists, St. Paul, MN.

Anon. 1983. New food grade silicone antifoams prevent buildup of process foams. Food Eng. 55(3):67.

Anon. 1987. FDA to review P&G's olestra. J. Am. Oil Chemists' Soc. 64:805.

Archibald, J.G. and Fenner, H. 1957. Silicon in cow's milk. J. Dairy Sci. 40:703.

Artman, N.R. 1969. The chemical and biological properties of heated and oxidized fats. Adv. Lipid Rev. 7:245.

Artman, N.R. and Alexander, J.C. 1968. Characterization of some heated fat components. J. Am. Oil Chemists' Soc. 45:643.

Association of Official Analytical Chemists. 1980 (13th edition). Official methods of analysis. William Horwitz, ed., p. 376.

Baeuerlen, R., Brady, H. and Erickson, D. 1968. Frying fats and their uses. Baker's Dig. 42(6):51.

Barran, W.L. 1984. Vegetable oils in fast-food restaurants. J. Am. Oil Chemists' Soc. 61:832.

Bennion, M. 1972. Fats as cooking media, shortening agents, and components of pastry. In "Food Theory and Applications." Paul, P.C. and Palmer, M.M. (ed.), John Wiley and Sons, New York.

Bennion, M. and Park, R.L. 1968. Changes in frying fats with different foods. J. Am. Dietet. Assoc. 52:308.

Billek, G., Guhr, G. and Waibel, J. 1978. Quality assessment of used frying fats: A comparison of four methods. J. Am. Oil Chemists' Soc. 55:728.

Blumenthal, M.M., Trout, J.R. and Chang, S.S. 1976. Correlation of gas chromatographic profiles and organoleptic scores of different fats and oils after simulated deep fat frying. J. Am. Oil Chemists' Soc. 53:496.

Bowen, H.J.M. and Peggs, A. 1984. Determination of the silicon content of food. J. Sci. Food Agric. 35:1225.

Carlisle, E.M. 1970. Silicon: a possible factor in bone calcification. Science 167:279.

Carlisle, E.M. 1971. A relationship between silicon and calcium in bone formation. Fed. Proc. 29:565.

Carlisle, E.M. 1972. Silicon: an essential element for the chick. Science 178:619.

Chang, S.S., Peterson, R.J. and Ho, C. 1978. Chemical reactions involved in the deep fat frying of foods. J. Am. Oil Chemists' Soc. 55:718.

Chung, D.K. and Pomeranz, Y. 1983. Recent trends in usage of fats and oils as functional ingredients in the baking industry. J. Am. Oil Chemists' Soc. 60:1848.

Crossley, A., Heyes, T.D. and Hudson, B.J.F. 1962. The effect of heat on pure triglycerides. J. Am. Oil Chemists' Soc. 39:9.

Doeden, W.G., Kushibab, E.M. and Sugala, A.C. 1980. Determination of dimethylpolysiloxanes in fats and oils. J. Am. Oil Chemists' Soc. 57:73.

Dow Corning Corporation. 1982. Information about silicone fluids (company product information), Midland, MI 48640.

Duncan, D.B. 1957. Multiple range test for correlated and heteroscidastic means. Biometrics 13:164-176.

Eitel, W. 1964. "Silicate Science: Volume 1 - Silicate Structures." Academic Press, New York, p. 1-22.

Endres, J.G., Bhalerao, V.R. and Kummerow, F.A. 1962. Thermal oxidation of synthetic triglycerides. I. Composition of oxidized triglycerides. J. Am. Oil Chemists' Soc. 39:118.

Farmer, E.H., Koch, H.P. and Sutton, D.A. 1943. The course of autoxidation reactions in polyisoprenes and allied compounds. Part VII. Rearrangement of double bonds during autoxidation. J. Chem. Soc. 65:544.

Flory, P.J., Mandelkern, T., Kinsinger, J.B. and Shultz, W.B. 1952. Molecular dimensions of polydimethylsiloxanes. J. Amer. Chem. Soc. 74:3364.

Freeman, P.P., Padley, F.B. and Sheppard, W.L. 1973. Use of silicones in frying oils. J. Am. Oil Chemists' Soc. 50:101.

Fritsch, C.W. 1981. Measurements of frying fat deterioration: A brief review. J. Am. Oil Chemists' Soc. 58:272.

Gaddis, A.M., Ellis, R. and Currie, G.T. 1961. Carbonyls in oxidizing fat V. The composition of neutral volatile monocarbonyl compounds from autooxidized oleate, linoleate, linolenate esters, and fats. J. Am. Oil Chemists' Soc. 38:371.

Gair, T.J. 1970. The spectrum of silicone application. In "Silicone Technology Applied Polymer Symposia No. 14." P.F. Bruins (Ed.). Interscience Publishers, New York, p 1.

Gere, A. 1982. Studies of the changes in edible fats during heating and frying. Die Nahrung 26:923.

Gilman, H. and Dunn, G.E. 1953. Relationship between analogous organic compounds of silicon and carbon. Chem. Reviews 52:77.

Gillis, A. 1986. Dietary guidelines: Not a cure-all for health. J. Am. Oil Chemists' Soc. 63:708.

Glueck, C.J., Mattson, F.H. and Jandacek, R.I. 1979. The lowering of plasma cholesterol by sucrose polyester in subjects consuming diets with 800, 300, or less than 50 mg of cholesterol per day. Amer. J. Clin. Nutr. 32:1636.

Gray, J.I. 1978. Measurement of lipid oxidation: A review. J. Am. Oil Chemists' Soc. 55:539.

Hamm, D.J. 1984. Preparation and evaluation of trialkoxytricarballylate, trialkoxycitrate, trialkoxyglycerolether, jojoba oil and sucrose polyester as low calorie replacement of edible fats and oils. J. Food Sci. 49:419.

Hannigan, K.J. 1981. Fat replacer cuts calories in fatty foods. Food Engin. 53(9):105.

Hashim, S.A., Roholt, H.B. and Babayan, V.K. 1964. Treatment of chyluria and chylothorax with medium-chain triglyceride. New Engl. J. Med. 270:756.

Hoffman, G. 1961. 3-cis-hexenal, the "green" reversion flavor of soybean oil. J. Am. Oil Chemists' Soc. 38:1.

Holzman, G.R., Tauterbur, P.C., Anderoan, J.H. and Koth, W. 1956. Nuclear magnetic resonance field shifts of silicon in various materials. J. Chem. Physics 25:172.

Isselbacher, K.J., Scheig, R. and Plotkin, G.R. 1964. Congenital beta-lipoprotein deficiency: An hereditary disorder involving a defect in absorptiona nd transport of lipis. Medicine 43:347.

Johnson, O.C. and Kummerow, F.A. 1957. Chemical changes which take place in an edible oil during thermal oxidation. J. Am. Oil Chemists' Soc. 34:407.

Johnson, O.C., Sakuragi, T. and Kummerow, F.A. 1946. A comparative study of the nutritive value of thermally oxidized oils. J. Am. Oil Chemists' Soc. 33:433.

Kaunitz, H. 1966. Some etiological factors in obesity. J. Am. Oil Chemists' Soc. 43:1975.

Kawada, T., Kirshnamurthy, R.G., Mookherjie, B.D. and Chang, S.S. 1967. Chemical reactions in the deep fat frying of foods. II. Identification of acidic volatile decomposition products of corn oil. J. Am. Oil Chemists' Soc. 44:131.

King, E.J., Stantial, H. and Dolan, M. 1933. The biochemistry of silicic acid. The presence of silica in tissue; Biochem. J. 27:1002.

Krishnamurthy, R.G. and Chang, S.S. 1967. Chemical reactions involved in the deep fat frying of foods. III. Identification of nonacidic volatile decomposition products of corn oil. J. Am. Oil Chemists' Soc. 44:136.

Kummerow, F.A. 1974. Current studies on relation of fat to health. J. Am. Oil Chemists' Soc. 51:255.

Landers, R.E. and Rathmann, D.M. 1981. Vegetable oils: effects of processing, storage and use on nutritional values. J. Am. Oil Chemists' Soc. 58:255.

Lowe, B., Nelson, P.M., and Buchanan, H. 1940. The physical and chemical characteristics of lards and other fats in relation to their culinary value. III. For frying purposes. Iowa Agri. Expt. Sta. Res. Bulletin, 279.

McComber, D. and Miller, E.M. 1976. Differences in total lipid and fatty acid composition of doughnuts as influenced by lecithin, leavening agent, and use of frying fat. Cercal Chem. 53(1):101.

Mehlenbacher, V.C. 1960. Newer analytical methods for the fat and oil industry. J. Am. Oil Chemists' Soc. 37:613.

Melnick, D. 1957a. Absence of thermal polymers in potato-chip frying oils. J. Am. Oil Chemists' Soc. 34:351.

Melnick, D. 1957b. Nutritional quality of frying fats in commercial use. J. Am. Oil Chemists' Soc. 34:578.

Merten, H.L. 1970. Low calorie lipids. J. Agr. Food Chem. 18(6):1002.

Meyer, L.H. 1960. "Food Chemistry." Reinhold Publishing Corporation, New York, p. 19.

Michigan State University. 1982. MSTAT. A Microcomputer program for the design, management and analysis of agronomic research experiments. Michigan State University, East Lansing, MI.

Neal, P., Campbell, A.D., Firestone, D. and Aldridge, M.H. 1969. Low temperature separation of trace amounts of dimethylpolysiloxanes from food. J. Am. Oil Chemists' Soc. 46:561.

Nolen, G.A., Alexander, J.C. and Artman, N.R. 1967. Long-term rat feeding study with used frying fats. J. Nutr. 93:337.

Noll, W. 1968. "Chemistry and Technology of Silicones." Academic Press, New York.

Paradis, A.J. and Nawar, W.W. 1981. Evaluation of new methods for the assessment of used frying oils. J. Food Sci. 46:449.

Pauling, L. 1960. "The Nature of the Chemical Band." Cornell University Press, Ithaca, NY.

Perkins, E.G. and Kummerow, F.A. 1959. The isolation and characterization of the polymers formed during the thermal oxidation of corn oil. J. Am. Oil Chemists' Soc. 36:371.

Poling, C.E., Eagle, E., Rice, E.E., Durand, A.M.A. and Fisher, M. 1970. Long-term responses of rats to heat-treated dietary fats: IV. Weight gains, food and energy efficiencies, longevity and histopathology. Lipids 5:128.

Rathmann, D.M. 1960. Dietary fat and heart disease. J. Am. Oil Chemists' Soc. 37:601.

Rawls, H.R. and VanSanten, P.J. 1970. A possible role for singlet oxygen in the initiation of fatty acid autoxidation. J. Am. Oil Chemists' Soc. 47:121.

Robertson, C.J. 1968. A review of current deep fat frying practices points the way to new horizons. Can. Inst. Food Sci. Technol. J. 1:A66.

Rock, S.P. and Roth, M. 1964. Factors affecting the rate of deterioration in the frying qualities of fats. I. Exposure to air. J. Am. Oil Chemists' Soc. 41:228.

Rock, S.P. and Roth, M. 1966. Properties of frying fat. I. The relationship of viscosity to the concentration of non-urea abducting fatty acids. J. Am. Oil Chemists' Soc. 43:116.

Roth, H. and Rock, S.P. 1972a. The chemistry and technology of frying fat. I. Chemistry. Baker's Dig. 46(4):38.

Roth, H. and Rock, S.P. 1972b. The chemistry and technology of frying fat. II. Technology. Baker's Dig. 46(5):38.

Sahasrabudhe, M.R. and Bhalerao, V.R. 1963. A method for the determination of the extent of polymerization in frying fats and in fats extracted from fried foods. J. Am. Oil Chemists' Soc. 40:711.

Schwartz, K. and Milne, D.B. 1971. Growth promoting effects of silicon in rats. Nature, Lond. 239-333.

Schwartz, K. 1971. "Newer Trace Elements in Nutrition," Mertz, W. and Cormatzer, W.E. (Ed.) M. Dekker, New York, p. 314-326.

Smith, L.M., Clifford, A.J., Creveling, R.K. and Hamblin, C.L. 1985. Lipid content and fatty acid profiles of various deep-fat fried foods. J. Am. Oil Chemists' Soc. 62:996.

Smith, L.M., Clifford, A.J., Hamblin, C.L. and Creveling, R.K. 1986. Changes in physical and chemical properties of shortenings used for commercial deep-fat frying. J. Am. Oil Chemists' Soc. 63:1017.

Stern, S. and Roth, H. 1959. Properties of frying fat related to fat absorption in doughnut fat. Cereal Sci. Today 4:176.

Stevenson, S.G., Vaisey-Genser, M. and Eskin, N.A.M. 1984. Quality control in the use of deep frying oils. J. Am. Oil Chemists' Soc. 61:1102.

Suderman, D.R. and Cunningham, F.E. 1983. "Batter and Breading," AVI Publishing Company, Inc. Westport, CT, p. 2-5.

Surgeon General's Report on Health Promotion and Disease Prevention. Healthy People. DHEW Publication No. 79-55071, Washington, D.C. 1979.

Tanaka, T. and Watase, T. 1954. Heats of combustion and formation of some methoxy-polysilane and polysiloxane: Si-O bond energy. J. Chem. Physics 22:1268.

Tannenbaum, S. 1954. The Si-C bond energy in alkylsilanes. J. Amer. Chem. Soc. 76:1027.

Thompson, L.U. and Aust, R. 1983. Lipid changes in french fries and heated oils during commercial deep frying and their technological implications. Can. Inst. Food Sci. Technol. J. 16:246.

Timms, R.E. 1985. Physical properties of oils and mixtures of oils. J. Am. Oil Chemists' Soc. 62:241.

Torkelson, A. 1970. Developments and trends in silicone fluids. In "Silicone Technology. Applied Polymer Symposia No. 14." P.F. Bruins (Ed.) Interscience Publishers, New York, p 61.

VanItallie, J.B. and Hirsch, J. 1979. Report of the task force on the evidence relating six dietary factors to the nation's health; appraisal of excess calories as a factor in the causation of disease. Am. J. Clin. Nutr. 32:2648.

Waltking, A.E., Seery, W.E. and Bleffert, G.W. 1975. Chemical analysis of polymerization products in abused fats and oils. J. Am. Oil Chemists' Soc. 52:96.

Warrick, E.L., Piccoli, W.A. and Stark, F.O. 1955. Melt viscosities of dimethylpolysiloxanes. J. Amer. Chem. Soc. 77:5017.

Weiss, T.J. 1970. "Food Oils and their Uses." The AVI Publishing Co., Inc., Westport, CT, p. 157-179.

Wishner, L.A. and Keeney, M. 1965. Comparative study of monocarbonyl compounds formed during deep fat frying in different fats. J. Am. Oil Chemists' Soc. 42:776.

Wu, Pei-fen and Nawar, W.W. 1986. A technique for monitoring the quality of used frying oils. J. Am. Oil Chemists' Soc. 63:1363.

Zabik, M.E. 1962. Correlation of smoke point to free fatty acid content in measuring fat deterioration from consecutive heatings. Food Technol. 16:111.