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Dale Frederick Olds
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photostability testing of food model systems**

Olds, Dale Frederick, M.S.

San Jose State University, 1994

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Ann Arbor, MI 48106**

**USE OF A XENON ARC LAMP EXPOSURE SYSTEM FOR ACCELERATED
PHOTOSTABILITY TESTING OF FOOD MODEL SYSTEMS**

A Thesis

Presented to

**The Faculty of the Department of
Nutrition and Food Science
San Jose State University**

**In Partial Fulfillment
of the Requirements for the Degree
Master of Science
in Nutritional Science**

By

Dale Frederick Olds

August 1994

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APPROVED FOR THE DEPARTMENT
OF NUTRITION AND FOOD SCIENCE

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ABSTRACT

USE OF A XENON ARC LAMP EXPOSURE SYSTEM FOR ACCELERATED PHOTOSTABILITY TESTING OF FOOD MODEL SYSTEMS

by Dale F. Olds

A xenon arc lamp exposure system was evaluated as an accelerated photostability test device using three food model systems: soybean oil, a riboflavin solution, and a FD&C Red #3 solution. The model systems were exposed to xenon irradiance conditions ranging from 0.10 W/m² to 0.35 W/m² (measured at 340 nm) over time periods up to 6 hours. The model systems were also exposed to fluorescent light (100 footcandles) as a non-accelerated test condition. Photodegradative changes were assayed at periodic intervals using peroxide value determination (soybean oil), fluorescence spectrophotometry (riboflavin), and spectrophotometry (FD&C Red #3). Results indicated that the xenon exposure system accelerated degradative changes in each of the model systems. Acceleration factors ranged from 70 times for riboflavin photodegradation (0.10 W/m²) to 194 times for FD&C Red #3 color loss (0.35 W/m²). With some modifications, the xenon exposure system could provide the basis of a standard test method for photostability testing of foods.

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I also would like to thank Atlas Electric Devices Company for loan of the SunChex™ xenon exposure device to the National Food Processors Association for the purpose of conducting this thesis study.

PREFACE

This thesis is written in publication style. The second chapter is written in journal format and will be submitted to the Journal of Food Science. The first and third chapters are written according to the guidelines outlined in the Publication Manual of the American Psychological Association, third edition, 1990.

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CHAPTER 1

Introduction and Review of Literature

Introduction

To stay competitive in the marketplace, food companies must respond quick to changing trends. This poses both opportunities and risks for food companies. Fast-paced product development programs may require that new products with expected long shelf-lives are introduced into the marketplace before there is adequate time to conduct full-term storage stability testing on the products. If an inadequately tested new product fails in the marketplace because it did not meet consumer expectations for safety, nutritional content, or palatability, it may result in economic losses to the company or permanent damage to the image of the company. It is possible, however, for food product development scientists to use shelf-life testing techniques to accelerate the degradative changes that occur in the foods and cause products to be unacceptable. Accelerated shelf-life testing techniques can allow a prediction of shelf-life to be made within a shortened timeframe, and the risks to both the producer and the consumer can be reduced.

Labuza (1982) has reviewed some of the methods which are used for accelerated shelf-life testing of foods. He lists temperature, oxygen level, moisture, and light as the major environmental factors which contribute to deterioration of food and which should be considered when conducting

shelf-life tests. There is no mention in this book or in other published literature of a standard methodology for accelerating deteriorative changes in foods due to exposure to light. Existing methods for photostability testing of foods which are mentioned in the literature vary in light source, light intensity, time of exposure and temperature conditions, and generally provide a low factor of acceleration. Accelerated photostability testing devices and test methodologies have been developed in other industries, such as the plastics, textile or paint industries (American Society for Testing and Materials (ASTM), 1990). In these industries, a xenon arc lamp exposure device is often used to provide high irradiance levels under controlled conditions so that high acceleration rates can be attained for photodegradative changes. The intention of this thesis study was to determine if a xenon arc lamp exposure system could be used as an accelerated test device for photostability testing of foods. To test the efficacy of the device, three major modes of photodegradation in food were studied: vitamin degradation, photooxidation of oil, and color loss.

Objective

The objective of this study was to evaluate a tabletop xenon arc lamp exposure system as a potential test device for accelerated photostability testing of foods.

Significance of the Study

There is currently no standardized test method for photostability testing of foods. The xenon arc lamp exposure system evaluated in this study provides a potential means of accelerating photochemical changes in foods using controlled, reproducible conditions. Xenon arc lamp exposure devices, and test methods based on their use, have been accepted for accelerated light exposure testing of non-food materials such as plastics, textiles, or paint (ASTM, 1990). A standardized, accelerated photostability test method for the food industry could provide many benefits. Uniform criteria for performance of ingredients, products, or product protection requirements of packaging materials could be established based on a standard test method. An accelerated test could also shorten test time and reduce expense to the manufacturer. This could lead to a better understanding of the photostability of foods and assist in ways to determine how to protect foods against adverse photodegradative changes which affect nutrient content, consumer appeal, and palatability. Ultimately, this could lead to improved food products for the consumer.

Review of Literature

Light

Definition. Light may be defined as electromagnetic radiation which is capable of stimulating the retina of the eye and producing a visual sensation (Brill, 1980). The portion of the electromagnetic spectrum which produces a

visual response is often called the visible spectrum, and ranges from about 380 to 760 nm. A second definition of light includes all electromagnetic radiation within the ultraviolet, visible, and infrared regions of the spectrum. This is sometimes called the optical radiation spectrum, since it follows the laws of optics (Stimson, 1974). The optical spectrum extends from approximately 10 to 10^6 nm. Both of these definitions of light are relevant to the review of the literature on studies pertaining to photostability of foods. As will be noted in the following sections of the literature review, most studies utilize light measurement devices which are designed to measure light only in the visible spectrum, and specifically, the way that the human eye responds to a lighting source. However, when examining chemical changes which can occur when materials are exposed to light, it is known that degradative photochemical reactions can be produced by light in wavelengths other than the visible range (Stevens, 1988). Since the energy content of light photons varies inversely with wavelength, the shorter wavelengths of light possess the highest quantum energy and produce the greatest effect on chemical reactions (Sattar & deMan, 1975). Numerous studies on various materials, including foods, have verified the deleterious effects of light from the shorter wavelength visible and ultraviolet region of the spectrum (Bekbolet, 1990; Brill, 1980; Sobel, 1987).

Measurement of Light. The measurement of light in the visible region of the spectrum is an aspect of the science of photometry (Stimson, 1974).

Photometry is specifically concerned with measurement of visible light as the human eye responds to it. The response of the human eye is not constant over the range of the visible spectrum. It peaks in the green portion of the spectrum at approximately 550 nm and falls off sharply in the 400 nm (blue) and 700 nm (red) areas of the spectrum. Assessment of the data from the Commission Internationale de l'Eclairage (International Commission on Illumination or C.I.E) "standard observer" curve showing the sensitivity of the standard human eye to the visible spectrum indicates that it takes approximately ten times as many units of blue light at 472 nm as green light at 550 nm to produce the same visibility effect to the human eye (Williamson & Cummins, 1983). Most photometric light measurement meters contain filters to correct the photocell response to a reasonable approximation of the C.I.E. relative photopic luminosity curve which represents how the eye responds to light (Phillips Lighting Company, 1984).

Photometric measurement of lighting is appropriate in merchandising of goods, including foods, since visual appeal has a strong influence on consumer acceptance (Amerine, Pangborn, & Roessler, 1965). In photometry, the process of radiant energy striking a surface is called "illumination." The photometric units of illumination are the footcandle (lumen/ft²) and lux (lumen/m²) (Stimpson, 1974).

When evaluating the influence of total optical energy (ultraviolet, visible, and infrared) emitted by a lighting source upon a substance, it may be more

appropriate to apply the principles of radiometry and photochemistry when measuring radiant energy. The energy of light quanta in the region of the optical spectrum is of importance in the study of photochemistry since the absorption of light, especially from the shorter wavelength visible and ultraviolet regions of the spectrum, excite molecules and produce chemical reactions involving the breaking or formation of chemical bonds or changes in molecular electronic states (Stevens, 1988). Radiometry involves the measurement of the energy which produces these chemical changes. In radiometry, the process of radiant energy striking a surface is called "irradiance." The radiometric unit of measurement of irradiance is watts/cm^2 or watts/m^2 .

The unit of optical power in radiometric terms is the "watt." One watt of infrared radiation is equivalent to one watt of ultraviolet radiation which is equivalent to one watt of radiation in the visible region of the spectrum (Stimson, 1974). In comparing radiometric and photometric measurements, it is apparent that it is difficult to correlate photometric and radiometric terms, unless very specific information at each monochromatic wavelength is determined. As an example, although a light source might produce a high output in ultraviolet or infrared radiation in watts, the photometric measurement in lumens would be zero, due to lack of eye response in these ranges.

Most photostability studies on foods which are reported in the literature use instruments which measure output from a light source in photometric units (footcandles, lumens/m², lux), since retail food stores are concerned with lighting which will provide visual appeal to products. As the science of photochemistry has developed, photostability studies have begun to use radiometric units to measure the optical radiation impacting a food material (Andersen & Rasmussen, 1992). Piechocki and Wolters (1994) have recently proposed that photochemistry terminology currently used by the International Union of Pure and Applied Chemistry (IUPAC) be applied to photostability testing of pharmaceutical products. These recommendations may apply to future food photostability research.

Light Sources. Fluorescent, incandescent, and high intensity discharge lamps, as well as natural daylight are all thought of as sources of white light. However, all of these light sources vary significantly from each other in the relative amounts of power emitted at each wavelength. A plot of the energy emitted at each wavelength for a light source is termed a spectral energy (or spectral power) distribution curve. Spectral power distribution curves are available for most light sources and are a convenient means of assessing the radiant energy profile of a light source. The portion of the spectral power distribution curve which is of most interest for chemical and visual effects on foods due to natural daylight or artificial light sources is radiation in the 300-800 nm region (Brill, 1980). Foods are not generally

exposed to light energy of wavelengths less than 300 nm. Radiation reaching the earth from sunlight is considered negligible at wavelengths less than 300 nm (Tonnesen & Moore, 1993). Radiation from food store light sources (artificial light or sunlight passing through window glass) is reported to be greater than 310 nm (Tonnesen & Moore, 1993). As previously mentioned, the shorter visible and ultraviolet wavelengths (300-500 nm) are generally of most concern since they are potentially the most damaging due to their higher quantum energy. The longer wavelength light in the infrared region does not generally possess sufficient energy to produce photochemical effects, although high infrared intensities may produce heat which can increase the rate of chemical changes in foods (Stevens, 1988).

Two primary factors influencing the selection of food supermarket lighting are good color rendition to provide visual appeal to products and high energy efficiency to provide functional lighting at a low cost. Incandescent lights are not commonly used for general store lighting due to their low efficiencies (low amount of light produced for total amount of energy radiated). The spectral power distribution curve for a tungsten filament incandescent lamp shows that 75% to 85% of the energy is released as heat in the infrared region (Brill, 1980). Fluorescent lighting is most commonly used for store lighting due to its higher energy efficiency and good color rendition properties. Although the emission of radiation within the fluorescent tube, caused by collision of electrons with mercury

atoms, is mainly in the ultraviolet region at 253 nm, the fluorescent powders coating the tube absorb the radiation and transform it into visible light. The radiant energy emitted by fluorescent lights used for store lighting is generally in the 350 to 700 nm region (General Electric, 1974). Fluorescent lamps with different phosphor coatings will provide different spectral power distribution curves and may be used in different areas of food supermarkets to enhance visual appeal of various products. Differing lamps may be used in the dairy, meat, and general store shelf areas.

The spectral energy distribution of sunlight depends on a wide variety of factors including season, time of day, weather conditions, latitude and altitude (Brill, 1980). Photostability test methods for materials exposed to sunlight have used xenon arc lamps to simulate natural daylight at repeatable light output conditions (ASTM, 1992). The higher output of ultraviolet and infrared emissions from the xenon lamp can be controlled by using filters to eliminate ultraviolet radiation below 290-320 nm and using cooling to reduce sample temperatures caused by the higher infrared content. When properly filtered, xenon arc light is reported to closely simulate photodegradative effects of natural daylight without production of unnatural artifacts (Thoma, 1991). When simulating daylight passing through window glass, as in a store front window, filters are used to duplicate the cut off all radiant energy below 310 nm (Kinmonth & Scott, 1984).

Photodegradative Changes in Foods

Overview. The energy of light quanta can be absorbed by foods exposed to light or foods in packages which allow the passage of light. This energy can catalyze chemical reactions in foods and result in a loss of product quality. Bekbolet (1990) has recently reviewed many of the degradative changes which can occur in foods exposed to light. The photosensitized oxidation of food components due to the interaction of light, photosensitizers, and oxygen may account for many of the light-induced photodegradative changes in foods (Bradley & Min, 1992). However, in some cases, photodegradative changes are complex in nature and not fully understood.

For the purposes of this literature review, photodegradative changes which occur in foods will be organized into three major categories: color degradation, flavor degradation, and nutrient degradation. Some food components may undergo photodegradative reactions which would place them in more than one of these categories. An example would be the photodegradation of beta-carotene which would represent a food component which experiences both color loss and nutritional loss (as a Vitamin A precursor) during photodegradation. These components may, therefore, be noted in more than one section of the review. The intent of the review on photodegradation is to illustrate the variety of food components which are affected by exposure to light and the variety of test methods that are used

to evaluate effects of light on food. This will lead to the final section of the review of the literature on photostability test methods and a discussion concerning a need for standard method for accelerated photostability testing of foods.

Color degradation. Color and appearance characteristics of a food can have a strong influence on consumer acceptance of the food (Amerine et al., 1965). Light can negatively affect the appearance of food products by catalyzing degradative changes in their coloring components. Fading or discoloration of pigments are examples of some the undesirable changes in appearance which can occur.

Coloring components of food are generally either intrinsic to the food or added as food colorants. Examples of food colorants which are intrinsic to food are chlorophyll in vegetable products and myoglobin in meats. Examples of added colorants are the synthetic certified food dyes and the colorants which are extracted from plant or animal sources.

Of the synthetic Food, Drug, and Cosmetic (FD&C) certified food colors, erythrosine (Red No. 3) and indigotine (Blue No. 2) are known to have poor light stability (Krahler, 1955). Erythrosine, in addition to being subject to color fading, has been reported to act as a photosensitizer which will initiate oxidation in unsaturated lipids (Chan, 1976). The mechanism for erythrosine photosensitized oxidation has been described by Rosenthal, Yang, Bell, and Scher (1988) and Bradley and Min (1992). Erythrosine strongly absorbs

radiant energy at 526 nm. As light energy is absorbed, an electron is raised to a higher energy level and the "excited" dye is transformed to a singlet-excited state. This excited singlet state is converted to a triplet-excited state by intersystem crossing. There is then an energy transfer from the excited triplet sensitizer (dye) to molecular oxygen in the ground state (triplet state) to generate singlet state oxygen. This singlet state oxygen is highly reactive with the electron-rich double bonds of unsaturated fats. The reaction of singlet state oxygen with linoleic acid is reported to occur 1450 times faster than triplet state oxygen (Bradley & Min, 1992). Little additional information has been published in the last 20 years on light stability of the synthetic dyes and the mechanism by which color fading occurs. Fading rate curves for colorants, which plot of concentration of colorant against time of irradiation, are often first order (Zollinger, 1987).

Of the naturally occurring pigments, the anthocyanins, betalains, and carotenoids all experience color loss when exposed to light. Palamidis and Markakis (1975) reported up to 70% destruction of anthocyanins from grape skin extract in a carbonated beverage stored 135 days under fluorescent lights (80 footcandles). Studies by Attoe and von Elbe (1981) indicated that degradation of anthocyanins may be a photooxidative process since photodegradation of anthocyanin was not noticed unless a trace amount of oxygen was present.

Sapers and Hornstein (1979) and Attoe and von Elbe (1981) reported significant destruction of the betalain pigments from red beets when exposed to fluorescent light ranging in intensity from 90 to 400 footcandles. The mechanism of photodegradation of the pigment was not determined. Rate of reaction of pigment loss due to light exposure was first order.

Pesek and Warthesen (1987) found significant photodegradation of α -carotene, β -carotene, and lycopene carotenoids in a vegetable juice system exposed to fluorescent light at an intensity of 230 footcandles. Further studies by Pesek and Warthesen (1988, 1990) on photoisomerism and photodegradation of β -carotene indicated that temperature, physical state, and matrix of the β -carotene dispersion all affected photodegradation rate. Losses after 5 days of fluorescent light exposure at 250 footcandles ranged from 10% to 50%. Pesek and Warthesen (1990) concluded that although trans-cis photoisomerization of β -carotene was occurring, the predominant reaction was photodegradation of all-trans- β -carotene. Of the isomers that were formed during irradiation, the 9-cis isomer was the predominant isomer formed and the 13-cis isomer was the most sensitive to light. In these studies, the photodegradative reaction followed first order kinetics.

β -carotene has also been shown to act as a singlet oxygen quencher and an inhibitor of photooxidative singlet oxygen reactions (Bradley & Min, 1992). β -carotene quenches singlet oxygen by a physical quenching process. This involves an energy transfer from singlet oxygen to the low

singlet energy state β -carotene molecule. Rawls and van Santen (1970) speculated that a function of β -carotene in nature may be to protect the lipids or chlorophyll in plants from photooxidation. There is also considerable current interest in use of β -carotene as an antioxidant in foods (Tee, 1992).

The exposure of meats to light can result in color deterioration which can strongly influence consumer perception of the quality of meats (Bekbolet, 1990). The color of meats is largely dependent on the chemical state of myoglobin, the major pigment molecule in meat (Clydesdale & Francis, 1971). Oxygenation of the purple-colored myoglobin produces oxymyoglobin, the bright red form of the pigment which appeals to consumers. Oxidation of oxymyoglobin results in the formation of metmyoglobin, the undesirable brown color. Studies on fresh meats by Setser, Harrison, Kropf, and Dayton (1973) and Satterlee and Hansmeyer (1974) indicate that there is a significant increase in metmyoglobin content in meats exposed to light. Light energy in the region of 400 nm to 590 nm was found to induce discoloration. Other studies by Bertelsen and Skipsted (1987) indicate that the rate of photooxidation of oxymyoglobin to metmyoglobin was greatly increased by shorter wavelength light in the ultraviolet region of the spectrum (primarily 254 nm).

Frozen meat is also subject to discoloration when exposed to light (Lentz, 1979). Zachariah and Satterlee (1973) found that short wavelength

fluorescent light (400-590 nm) at an intensity of 250 to 300 footcandles enhanced the oxidation of oxymyoglobin at freezing temperatures.

Color stability of cured meats is also affected by light (Bekbolet, 1990). Nitrite cured meats form nitrosylheme pigments which provide the pink color in cured meat and inhibit lipid oxidation (Andersen, Bertelsen, Ohlen, & Skibsted, 1990). Light exposure combined with trace amounts of oxygen can cause discoloration due to photooxidation of the nitrosylheme pigments resulting in the fading of the pigments. Andersen and Rasmussen (1992) noted that this discoloration, which can occur within the first 24 hours of display in illuminated (650 lux) refrigerated cases, can be eliminated by using oxygen absorbers and low oxygen transmission rate packaging materials. Kinetic studies by Andersen and Skibsted (1992) using monochromatic light of different wavelengths indicated that, in contrast to frozen beef, improvements in color stability would not be expected by addition of ultraviolet absorbers to the packaging material.

Flavor degradation. Light can induce formation of undesirable flavors and odors in foods which can make the products unpalatable. Two well documented examples are photochemically induced off-flavors in dairy products and lipids (Bekbolet, 1990).

The effects of light on flavor degradation of milk has been extensively studied (Bradley, 1980; Dimick, 1982; Olsen & Ashoor, 1987; Sattar & deMan, 1975). Off-flavor development in milk is primarily associated with

blow-molded polyethylene containers which allow light transmission (Hoskin, 1988). Two types of flavor changes are reported to occur in milk which is exposed to light. "Light-activated" off-flavors have been attributed to degradation of proteins, amino acids, or riboflavin, or the combined effects of photochemical degradation of these components (Hansen, Turner, & Aurand, 1975). Oxidized or rancid off-flavors are attributed to the oxidation of milk lipids (Bekbolet, 1990). Studies on flavor evaluation of retail milk using a trained taste panel have indicated that 86.1% of the milk in blow-molded plastic bottles contained oxidized off-flavors while 12.7% of milk packaged in paperboard (impermeable to light) had an oxidized flavor defect (Barnard, 1972).

Studies have also been conducted on the effects of light on butter and cheeses. Light-induced flavor changes may occur in butter when it is not adequately protected from light (Bekbolet, 1990). No significant changes occurred in the flavor or aroma of Colby, Mozzarella, or Cheddar cheese stored for 14 days under fluorescent illumination ranging from 50 to 500 footcandles (Deger & Ashoor, 1987).

There is extensive literature on the deteriorative effect of light on edible fats and oils. Exposure of lipids to light can induce lipid oxidation which leads to the formation of compounds which impart undesirable flavors. The photooxidation of fats and oils is believed to be initiated by a photosensitized reaction (Bradley & Min, 1992; Chan, 1976; Rawls & van

Santen, 1970). Unsaturated fatty acids which are prone to oxidation do not absorb visible light and are not subject to exposure conditions where there is a significant amount of ultraviolet irradiation. Therefore, the photooxidation process is believed to be initiated by means of a photosensitizer which absorbs light energy and is transformed into an unstable "excited" reactive state which can supply the energy required to initiate the oxidative reaction process. The photosensitized reaction ultimately leads to production of free radicals and hydroperoxides and perpetuation of the oxidative chain reaction process. Two pathways for photosensitized oxidation have been proposed (Bradley & Min, 1992). In the Type I pathway, the sensitizer absorbs light energy and transfers energy to a substrate to activate free radicals. The free radicals can then react with ground state oxygen (triplet state) to produce oxidation products. In the Type II pathway, molecular oxygen, rather than the substrate, reacts with the excited sensitizer. The transfer of energy from the sensitizer to oxygen generates a singlet oxygen state, which is a more highly reactive state. The singlet state oxygen rapidly reacts with unsaturated fatty acids to produce hydroperoxides that readily decompose to off-flavor compounds. It is currently believed that the Type II pathway is the most common pathway for photosensitized oxidation of foods (Bradley & Min, 1992). Chlorophyll, hematoporphyrins, riboflavin, and erythrosine are some the known photosensitizers found in food (Nawar, 1985).

In the photooxidative process, once hydroperoxides are formed, the free radical chain reaction proceeds rapidly in manner typical of autoxidation. Photooxidation is reported to differ from thermal oxidation primarily in the initiation step of the reaction where some differences in the formation and decomposition of hydroperoxides have been noted (Clements, van den Engh, Frost, Hoogenhout, & Nooi, 1972; Sonntag, 1979).

Photooxidative rancidity of oils has been reported for most food oils, including corn oil (Chahine & deMan, 1971), olive oil (Kiritsakis & Dugan, 1985), butterfat, coconut oil, and rapeseed oil (Sattar, deMan & Alexander, 1975), and soybean, sunflower, and peanut oil (Neumann, Fusero & Garcia, 1991). Components naturally found in the oils may play an important role in the photostability of the oils. Photosensitizers such as chlorophyll and pheophytin will function as photosensitizers and promote oxidation via singlet oxygen generation while β -carotene and tocopherols may act as singlet oxygen quenchers and provide protective effects against photooxidation (Jung, Lee, & Min, 1991; Kiritsakis & Dugan, 1985; Warner & Frankel, 1987).

Analytical techniques for measuring oxidation such as peroxide value, oxygen uptake, and pentane levels have shown good correlation to flavor scores of photooxidized oils (Fiorti, Kanuk & Sims, 1974; Waliking & Goetz, 1983). In soybean oil, a peroxide value of 10 to 15 or greater is regarded an upper acceptance limit for oxidation (American Oil Chemists' Society,

personal communication, 1993; Bekbolet, 1990).

Off-flavor development in foods containing oils which are exposed to light have also been reported. Potato chips are highly susceptible to photooxidation because of their large surface area and high fat content. Light-shielding packages have been recommended to protect the flavor of potato chips (Kubiak, Austin, & Lindsay, 1982; Quast & Karel, 1972).

Nutrient Degradation. The primary purpose for consumption of food is for nutrition. Retention of nutrients in foods is of concern to the food scientist, nutritionist, and the consumer. Light is an environmental factor which can cause significant loss of some nutrients found in foods, especially certain vitamins.

Degradation of riboflavin (vitamin B₂) in milk has been studied extensively since riboflavin is very sensitive to light and since milk is the source of approximately 40% to 50% of the total dietary riboflavin in the United States (Allen & Parks, 1979). Riboflavin loses its biologic activity when it is degraded by light to lumichrome (neutral or acid systems) or lumiflavin (alkaline systems) (Wagner-Jauregg, 1972). Riboflavin is excited by visible light wavelengths in the range of 440 to 500 nm and emits a yellow-green fluorescence at 530 nm (Schanderl, 1970). Riboflavin losses of approximately 11% have been reported in milk held for 48 hours under fluorescent lights at 300 footcandles light intensity (Singh, Heldman, & Kirk, 1975).

Riboflavin has been implicated as both a Type I and Type II photosensitizer which can promote oxidation of other milk components. Riboflavin-sensitized photooxidation of amino acids, most notably methionine, and oxidation of milk lipids can lead to development of off-flavors in milk (Bekbolet, 1990; Dimick, 1982). The photosensitizing effect of riboflavin may be responsible for the destruction of other vitamins in milk, such as Vitamin A and ascorbic acid (Bekbolet, 1990).

Significant loss of riboflavin has also been reported in pasta products exposed to fluorescent light. Woodcock, Warthesen, and Labuza (1982) reported a 72% loss of riboflavin in macaroni held for 21 days under fluorescent light at 300 footcandles illumination. 60% loss of riboflavin has been reported in pasta held for only 2 days at 100 footcandles (Furaya, Warthesen, & Labuza, 1984). The rate of riboflavin loss was first order in these studies.

Ascorbic acid (vitamin C) is also readily degraded by exposure to light. The photochemical mechanism involves conversion of ascorbic acid to dehydroascorbic acid, which in a neutral pH such as milk, is rapidly converted to the biologically inactive compound, diketogulonic acid (Bradley, 1980). 80% to 90% losses have been noted in milk subjected to fluorescent illumination of 100 footcandles for 24 hours (Dimick, 1982). 40% to 90% losses have been reported in orange drinks exposed to fluorescent illumination of 104 footcandles for 144 hours (Ahmed, Watrous,

Hargrove, & Dimick, 1976). Sahbaz and Somer (1993) have recently elucidated the reaction mechanisms for riboflavin-sensitized photodecomposition of ascorbic acid.

Vitamin A has also been shown to be susceptible to destruction by light. Losses up to 50% were found in milk packaged in blow-molded polyethylene bottles and exposed to fluorescent light. (Dimick, 1982). Nonfat dry milk exposed to fluorescent light illumination of 325 footcandles for 16 weeks incurred vitamin A losses as high as 70% (deBoer, deMan, & deMan, 1984).

Other nutrients which have been reported to be degraded by light are vitamin K (Indyk, 1988), vitamin B₆ (Saidi & Warthesen, 1983), the essential fatty acids in polyunsaturated fats (Bekbolet, 1990), β -carotene (as a vitamin A precursor) (Pesek & Warthesen, 1987), and tryptophan (Kanner & Fennema, 1987).

Photostability Test Methods

Photodegradation is influenced by many factors including light source, wavelength, light intensity, exposure time, temperature, the material characteristics of the food container, and surface area of the food in relation to volume of the container. As noted in the experimental studies which have been reviewed, illumination or irradiance and light source used in research on photodegradation of foods can vary considerably. Incandescent and natural daylight are sometimes used (von Elbe, Maing, & Amundson,

1974; Zachariah & Satterlee, 1973). Fluorescent light sources are used in most studies, however, the type of fluorescent bulb used may vary (cool white, warm white, daylight or other) or may not be reported. Although supermarket lighting conditions are often reported to be in the range of 100 to 200 footcandles (Dimick, 1982; Furaya et al., 1984; Phillips Lighting Company, 1984), illumination in experimental studies may range from as low as 20 footcandles to over 700 footcandles. In some cases, the higher illumination may have been used to accelerate degradative changes and shorten experimental timeframes. In most cases, the acceleration factor was not high. Two studies from the literature reported use of high intensity illumination devices to accelerate photodegradation of oils (Moser, Evans, Cowan, & Kwolek, 1965; Ostic-Matijasevic, Turkulov, Karlovic, & Radenkovic, 1982). No reference was made concerning use of these methods on other food components or food products. Fluorescent lighting was used in both studies. Daylight fluorescent bulbs were used in the study by Moser et al. (1965) and cool white fluorescent bulbs were used in the study by Ostic-Matijasevic et al. (1982). Methods for controlling light output to a constant level, and procedures for testing the reproducibility of the methods were not reported.

Although an accelerated method for light stability testing of foods would appear to be of value to the food industry, a standardized test method for performing such testing has not been established. Photostability test

devices and standard test protocols have been established for photostability testing of materials such as paints, plastics, textiles, and agricultural chemicals. These test devices and methods have been developed to control irradiance level at a repeatable spectral energy distribution under standard, reproducible test conditions. Xenon arc lamp test devices are specified in some of these test methods. ASTM G26 "Standard Practice for Operating Light Exposure Apparatus (Xenon-Arc Type) With and Without Water for Exposure of Nonmetallic Materials" describes the use of xenon arc devices (ASTM, 1990). The SunChex™, manufactured by Atlas Electric Devices Company, is a benchtop scale xenon arc lamp test device which was designed for accelerated photostability testing of materials. This device was acquired for this thesis study to evaluate its feasibility as a potential standard test device for photostability testing of foods.

CHAPTER 2
Journal Article

Author's Title Page

**USE OF A XENON ARC LAMP EXPOSURE SYSTEM FOR ACCELERATED
PHOTOSTABILITY TESTING OF FOOD MODEL SYSTEMS**

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RUNNING HEAD: ACCELERATED PHOTOSTABILITY TEST

ABSTRACT

A xenon arc lamp exposure system was evaluated as an accelerated photostability test device using three food model systems: soybean oil, a riboflavin solution, and a FD&C Red #3 solution. Tests compared xenon irradiance levels ranging from 0.10 W/m² to 0.35 W/m² (at 340 nm) for time periods up to 6 hours against fluorescent illumination conditions (100 footcandles). Results indicated that the xenon exposure system accelerated photochemical changes in each of the model systems. Acceleration effects varied with irradiance level and model system. Acceleration factors ranged from 70 times for riboflavin (0.10 W/m²) to 194 times for FD&C Red #3 (0.35 W/m²).

INTRODUCTION

Light is a form of radiant energy which can catalyze chemical reactions in foods. Bekbolet (1990) has recently presented a review of the many foods and food components which are affected by exposure to light. Among the food products which are affected by light, milk products have been extensively studied (Sattar and deMan, 1975; Bradley, 1980; Dimick, 1982; Olsen and Ashoor, 1987). Light-induced off-flavors in milk have been attributed to degradation of proteins, amino acids, or riboflavin, or the combined effects of photochemical degradation of these components. Oxidized or rancid flavors in milk products have also been attributed to the photooxidation of milk lipids. Photodegradation of riboflavin in milk has been a subject of research interest since riboflavin is very sensitive to light and since milk is the source of approximately 40% to 50% of the total dietary riboflavin in the United States (Allen and Parks, 1979).

Exposure of foods to light can also result in degradation of pigments which can negatively influence visual appeal of foods. Photodegradation of heme pigments can cause undesirable colors in fresh (Clydesdale and Francis, 1971), frozen (Lentz, 1979), or cured meats (Andersen and Rasmussen, 1992). Other pigments which undergo discoloration when exposed to light include anthocyanins (Palamidis and Markakis, 1975), betalains (Attoe and von Elbe, 1981) and carotenes (Pesek and Warthesen, 1987). Food pigments such as chlorophyll and hematoporphyrins, and

synthetic dyes such as erythrosine (FD&C Red #3), may also act as photosensitizers which can catalyze oxidation of other food components through formation of singlet oxygen (Bradley and Min, 1992). Singlet oxygen oxidation of food fats and oils may be strongly influenced by the presence of photosensitizers (Rawls and van Santen, 1970; Clements et al., 1973). Photooxidative rancidity of oils has been reported for most food oils, including corn oil (Chahine and deMan, 1971), olive oil (Kiritsakis and Dugan, 1985) butterfat, coconut oil, and rapeseed oil (Sattar et al., 1975), and soybean oil (Clements et al., 1973).

Other nutrients which have been reported to be degraded by light are ascorbic acid (Ahmed et al., 1976; Dimick, 1982), vitamin K (Indyk, 1988), vitamin B₆ (Saidi and Warthesen, 1983), and tryptophan (Kanner and Fennema, 1987).

Although the deleterious effects of light on food are well known, there is currently no standard industry test method for evaluating the stability of foods exposed to light. Existing methods for photostability testing of foods which are mentioned in the literature vary in light source, light intensity, time of exposure and temperature conditions, and generally provide a low factor of acceleration. Accelerated photostability testing devices and test methodologies have been developed in other industries, such as the plastics, textile or paint industries (ASTM, 1990). In these industries, a xenon arc lamp exposure device may be used to provide high irradiance levels under

controlled conditions so that high acceleration rates can be attained for photodegradative changes. The objective of this study was to determine if a xenon arc lamp exposure system could be used as an accelerated test device for photostability testing of foods. To test the efficacy of the device, three major modes of photodegradation in food were studied: vitamin degradation, photooxidation of oil, and color degradation.

MATERIALS AND METHODS

Experimental Design

Three food ingredients, riboflavin, soybean oil, and FD&C Red #3 were used in model systems to study vitamin, oil, and color photodegradation.

Model systems were selected since it was easier to evaluate photodegradative changes in simple systems rather than in more complex food systems.

Each model system was exposed to the xenon arc light accelerated test conditions at varying irradiance levels and was sampled at five different time intervals during the total exposure time (Table 1). Irradiance levels ranged from 0.1 W/m² to 0.35 W/m² (measured at 340 nm). Total test exposure time ranged from 30 minutes to 6 hours. The food models were also exposed to one non-accelerated fluorescent lighting condition (100 footcandles). Total exposure time to the fluorescent light ranged from 72 hours to 408 hours. Samples were taken at five time intervals. Samples of each model system were also wrapped in foil and placed next to the

irradiated sample during each exposure test to serve as non-irradiated controls. Tests were replicated three times for each model system.

Light Exposure Systems

A 1500 watt xenon arc lamp exposure device (SunChex™, Atlas Electric Devices Co., Chicago, IL) was used to produce the accelerated light exposure conditions. Irradiance level was measured at 340 nm using the exposure device monitoring system. A soda-lime filter was used during all exposure testing for cut-off of all radiant energy below 310 nm. To reduce potential degradative effects of heat produced by the exposure device upon the food models, the unit was operated in a 4° C cold room and the fan unit and pulse heater system in the exposure unit were used to control the test chamber temperature to $22^{\circ} \pm 2^{\circ}$ C.

Non-accelerated lighting conditions consisted of four 40 watt fluorescent tubes (SP-35, General Electric Co., Hendersonville, NC) connected to a dimmer system to produce a constant illuminance of 100 footcandles on the samples. These lighting conditions were reported to represent "average" supermarket shelf lighting conditions (personal communication, Safeway Stores lighting engineer). Illuminance was measured with a Minolta T-1 illuminance meter (Minolta Corp. Instruments Systems Div., Ramsey, NJ). In this study, the photometric measurements (footcandles), which are typically used to measure visual response in supermarket lighting, were not correlated to a radiometric measurement

(W/m²) for the fluorescent light source. Temperature in the fluorescent light chamber was controlled to 22° ± 2° C by placing the unit in a 20° C controlled temperature room and circulating air through the light chamber with a small fan unit.

Food Model Systems

The model systems used in the study were: a 18.5 mg/l solution of Red #3 prepared from 90% pure dye (Warner Jenkinson, St. Louis, MO) and deionized water; a 4.0 mg/l solution of riboflavin (USP, Takeda USA Inc., Orangeburg, NY) and deionized water with glacial acetic acid added (0.01%, v/v) to acidify the solution to pH <4.0; and refined soybean oil (Archer S, Archer Daniels Midland Co., Decatur IL).

Sample containers for the FD&C Red #3 and riboflavin solutions during exposure testing were 40 ml borosilicate glass vials with lined screw caps. Sample containers for the soybean oil were 9mm x 49 mm polystyrene petri dishes with a 1/16" hole drilled in the cover to allow a constant exposure of the oil to atmospheric oxygen. Stock solutions of each model system were held refrigerated in sealed, foil-wrapped containers between replications, and stirred prior to testing. Headspace of the stock soybean oil container was flushed with nitrogen between samplings.

Chemical Analysis

Color fading of the FD&C Red #3 dye was monitored by spectrophotometric measurement of absorbance at 526 nm (Model DU-8

UV-VIS, Beckman Instruments, Inc., Fullerton, CA) according to AOAC method 955.39 (AOAC, 1990). Riboflavin loss was monitored fluorometrically (Model 204-A Fluorescence Spectrophotometer, Perkin Elmer Corp., Norwalk, CT) according to AOAC method 970.65 (AOAC, 1990) using an excitation wavelength of 440 nm and emission wavelength of 530 nm. Soybean oil degradation was measured according to The American Oil Chemists Society method Cd 8-53 for peroxide value determination (AOCS, 1993).

Triplicate assays were performed on all FD&C Red #3 and riboflavin samples. Single assays were performed on each soybean oil sample.

Data Analysis

Data were analyzed by linear regression of relative measured change versus exposure time. Rate constants for the photodegradative reaction at each light exposure level were derived from the slope of the best fit regression lines. Assessment of whether the photodegradative reaction best fit zero or first order pseudo-kinetics was by comparison of correlation coefficients from the regression of the data for assayed attribute versus exposure time (zero order), or the natural logarithm of the assayed attribute versus exposure time (first order). The highest correlation coefficient represented the best fit of the data to the reaction order.

Acceleration rates were established by comparing rate of change for the xenon light accelerated test conditions versus rate of change for the non-

accelerated conditions. Comparisons were made at 50% loss of FD&C Red #3 and 50% loss of riboflavin, since a 50% loss is generally regarded to represent a substantial change in concentration (e.g. half-life). Comparison point for the soybean oil was a peroxide value of 10 which is generally regarded by the oil industry as being unacceptable quality (oxidized) for soybean oil (personal communication, American Oil Chemist's Society).

RESULTS AND DISCUSSION

The xenon arc lamp exposure system accelerated degradative changes in each of the food model systems. Acceleration effects varied with irradiance level and model system.

FD&C Red #3

The effect of time of exposure on Red #3 color loss at each xenon arc irradiance level is shown in Figure 1. Higher irradiance levels in the xenon system resulted in increased rates of color loss. Based on the regression data, the times to 50% color loss were 42.5, 30.0, and 16.4 minutes for xenon irradiance levels of 0.10, 0.20, and 0.35 W/m², respectively.

Samples exposed to the non-accelerated fluorescent exposure condition exhibited a slower rate of color loss (Figure 2). The calculated time for 50% color loss due to fluorescent light at 100 footcandles illumination was 3168 minutes. A comparison of the data for time to 50% color loss for samples exposed to the xenon arc lamp versus the fluorescent light conditions indicated that the xenon arc device accelerated color loss approximately 75

to 194 times, depending on irradiance level (Table 2). In both the xenon and fluorescent light exposure conditions, photodegradation of FD&C Red #3 best fit first order reaction kinetics ($r^2 \geq 0.94$ for all xenon exposure conditions; $r^2 = 0.96$ for fluorescent conditions). Although foods research literature in the last 20 years is limited in the area of the chemistry of photodegradation of FD&C Red #3, photochemical destruction of dyes is generally reported to follow first order reactions (Zollinger, 1987). There were no significant degradative changes in the control samples shielded with foil and subjected to the xenon or fluorescent light exposure test conditions ($p < 0.05$).

Riboflavin

Riboflavin degradation was extremely rapid when subjected to the xenon exposure conditions (Figure 3). At the highest xenon exposure condition (0.30 W/m^2), riboflavin losses greater than 70% occurred after only 10 minutes of irradiation. Calculated time to 50% loss of riboflavin, based on regression of the test data, was 13.5, 9.6, 7.6, and 5.8 minutes for xenon irradiance conditions of 0.10, 0.15, 0.20, and 0.30 W/m^2 , respectively. Rate of degradation for the reference samples exposed to the fluorescent light conditions is shown in Figure 4. Calculated time to 50% loss of riboflavin subjected to the fluorescent exposure condition, based on regression data, was 955 minutes. Degradation of riboflavin was accelerated approximately 70 to 165 times by the xenon exposure system,

depending on irradiance level (Table 2). Regression data indicated that photodegradation of riboflavin best fit first order kinetics ($r^2 \geq 0.98$ for xenon exposure conditions; $r^2 = 0.99$ for fluorescent conditions). These findings are in agreement with previous photostability studies on riboflavin in milk (Singh et al., 1975) and pasta (Furaya et al., 1984) which reported photodegradation of riboflavin as a first order reaction. There were no significant degradative changes in the control samples wrapped in foil which were subjected to the xenon or fluorescent light conditions ($p < 0.05$).

Soybean Oil

Figures 5 and 6 illustrate rate of photooxidative change as measured by peroxide value in the soybean oil exposed to xenon arc and fluorescent light. Time of exposure to produce a peroxide value of 10, as derived from regression analysis, was 91.6, 61.9, and 56.2 minutes for xenon irradiance levels of 0.15, 0.25, and 0.35 W/m², respectively. Calculated time required to produce a peroxide value of 10 in the soybean oil exposed to the reference fluorescent light condition was 6767 minutes. Acceleration of photooxidative change due to exposure to the xenon exposure conditions ranged from 74 to 120 times, depending upon irradiance level (Table 2). Regression analysis indicated that the photooxidative reaction best fit zero order kinetics ($r^2 \geq 0.97$ for xenon exposure conditions; $r^2 = 0.98$ for fluorescent conditions). Peroxide values for the control samples wrapped in foil and subjected to the xenon and fluorescent exposure conditions showed

little change during the course of the study (all control samples were ≤ 0.4 meq/kg).

Influence of Irradiance Level on Rate Constants

Increasing irradiance levels resulted in an increased rate of change for the photodegradative reactions which occurred in each of the model systems. Best fit linear regression of the rate constants for the photodegradative reactions versus $1/\text{irradiance}$ indicated a good linear fit ($r^2 \geq 0.87$) for each model. These results imply that a similar photodegradative mechanism was occurring over the range of irradiance levels which were tested, and that varying degrees of acceleration could be achieved by the xenon device for the same photochemical reaction.

CONCLUSIONS

The xenon arc lamp exposure system induced high rates of acceleration for photodegradative changes in the three food components examined in this study. The accelerated photochemical changes in each model system exposed to the xenon exposure conditions followed similar reaction kinetics to the same model exposed to the non-accelerated light exposure condition. These results suggest that the xenon exposure system shows promise as a test device for predicting photodegradation in foods. Further testing would be recommended to determine if the test method is applicable to a wider range of food ingredients and packaged food products. Modifications to the existing device which would enhance its application for routine testing of

food products would be to increase the size of the test chamber to accommodate multiple or larger packaged food items, and to add a cooling unit to the device to allow the air temperature to be controlled to 20°C or lower while operating the unit at room temperature. Development of a standard test method using a xenon arc lamp exposure system specifically engineered for foods testing could potentially provide food companies with a rapid, uniform performance standard for photostability testing of their products.

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TABLE 1. EXPERIMENTAL DESIGN

Exposure Condition	Color Degradation Model System	Vitamin Loss Model System	Lipid Oxidation Model System
	FD&C Red #3/Water 18.5 mg/l solution	Riboflavin/Water 4.0 mg/l solution	Soybean oil
<u>Xenon Arc Light</u>			
Irradiance Level (W/m ² at 340 nm)	0.10 0.20 0.35	0.10 0.15 0.20 0.30	0.15 0.25 0.35
Exposure Time * (minutes)	180 90 45	50 30 30 30	360 360 360
<u>Fluorescent Light</u>			
Exposure Time at 100 footcandles *	144	72	408
Control samples - Wrapped in foil and placed next to irradiated samples			
Replicates - Each test was replicated 3 times for each model system			
* Samples taken at 5 time intervals over total exposure time

FIGURE 1. FD&C Red #3 Color Loss Vs. Time at Different Irradiance Levels - Xenon Exposure System

FIGURE 2. FD&C Red #3 Color Loss Vs. Time at 100 Footcandles
Fluorescent Illumination

Table 2. Calculated Acceleration Factors - Xenon Arc vs. Fluorescent Light Exposure Conditions

FD&C RED #3		
Light Source/ Exposure Condition	Time to 50% Loss	Acceleration Factor
Fluorescent = 100 Footcandles	3168.4 minutes	
Xenon = 0.10 W/m ²	42.5 minutes	74.6
Xenon = 0.20 W/m ²	30.0 minutes	105.8
Xenon = 0.35 W/m ²	16.4 minutes	193.7

RIBOFLAVIN		
Light Source/ Exposure Condition	Time to 50% Loss	Acceleration Factor
Fluorescent = 100 Footcandles	955.3 minutes	
Xenon = 0.10 W/m ²	13.5 minutes	70.7
Xenon = 0.15 W/m ²	9.6 minutes	99.1
Xenon = 0.20 W/m ²	7.6 minutes	125.2
Xenon = 0.30 W/m ²	5.8 minutes	165.0

SOYBEAN OIL		
Light Source/ Exposure Condition	Time to Peroxide Value = 10	Acceleration Factor
Fluorescent = 100 Footcandles	6766.6 minutes	
Xenon = 0.15 W/m ²	91.6 minutes	73.9
Xenon = 0.25 W/m ²	61.9 minutes	109.4
Xenon = 0.35 W/m ²	56.2 minutes	120.4

FIGURE 3. Riboflavin Loss Vs. Time at Different Irradiance Levels - Xenon Exposure System

FIGURE 4. Riboflavin Loss Vs. Time at 100 Footcandles - Fluorescent Illumination

FIGURE 5. Peroxide Value of Soybean Oil Vs. Time at Different Irradiance Levels - Xenon Exposure System

FIGURE 6. Peroxide Value of Soybean Oil Vs. Time at 100 Footcandles Fluorescent Illumination

CHAPTER 3

Summary and Recommendations

Summary

A xenon arc lamp exposure system was evaluated as an accelerated test device for determining the photostability of foods. Three model food systems were evaluated for photodegradative changes: a FD&C Red #3 solution, a riboflavin solution, and refined soybean oil. The food models were exposed to the xenon arc light at irradiance levels ranging from 0.10 W/m² to 0.35 W/m² over time periods up to 6 hours. The model systems were also exposed to fluorescent light (100 footcandles) as a non-accelerated test condition. Results indicated that the photochemical changes which occurred in the model system exposed to the xenon exposure conditions appeared to follow similar reaction kinetics to the same model exposed to fluorescent light conditions. Photodegradation of FD&C Red #3 and riboflavin best fit first order reaction kinetics (r^2 of 0.94 or greater for all xenon and fluorescent exposure data). Photooxidation of the soybean oil best fit zero order kinetics (r^2 of 0.97 or greater for all xenon and fluorescent exposure data). The xenon arc lamp exposure system accelerated degradative changes in each of the model systems. Acceleration effects varied with irradiance level and model. Acceleration factors ranged from approximately 70 times for riboflavin degradation (0.10 W/m²) to 194

times for FD&C Red #3 loss (0.35 W/m^2). The xenon exposure system shows promise as a device for accelerated photostability testing of foods, however some modifications would be recommended to improve the effectiveness of the device for routine test purposes.

Recommendations

The xenon arc light exposure system induced high rates of acceleration for chemical degradative changes in the food components examined in this study. However, further testing is recommended to determine if the test method is applicable to a broader range of packaged food items or food ingredients. Further testing would also be required to determine the correlation of rate of degradation induced by the accelerated test to photochemical degradation experienced under actual light exposure conditions in the food handling and distribution environment.

Certain modifications to the SunChex™ xenon system would improve the ability to use the unit for routine food testing. Addition of a cooling unit to the device would be recommended to allow the air temperature in the test chamber to be controlled to 20°C or lower. It is not feasible to routinely operate the device in a walk-in refrigerated room to control air temperature, as was done in this study. Another recommended modification to the unit would be to increase the test chamber size to accommodate multiple or larger packaged food items. If these modifications were incorporated into a

xenon arc exposure system, subsequent testing could be done to determine the reproducibility of the test device and the potential for establishing a standard accelerated photostability test method for the food industry.

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Appendices

Appendix A
FD&C Red #3 Color Loss at 0.10 W/m² Xenon Exposure
FD&C Red #3 Solution (18.5 mg/L)
Xenon Irradiance Condition = 0.10 W/m² (@ 340 nm)

Irradiance Level	Exposure time (min)	Test Sample		Dark Sample	
		Absorbance at 526 nm	% of Original Concentration	Absorbance at 526 nm	% of Original Concentration
0.10 W/m ²	0	1.8000	99.69		
	15	1.5272	84.58		
	15	1.5509	85.90		
	15	1.5282	84.64	1.7893	99.10
	15	1.5342	84.97		
	15	1.5343	84.98		
	15	1.5350	85.02	1.7788	98.52
	15	1.4779	81.85		
	15	1.4801	81.97		
	15	1.5095	83.60	1.7849	98.86
	30	1.2608	69.83		
	30	1.2823	71.02		
	30	1.2457	68.99	1.7753	98.33
	30	1.1875	65.77		
	30	1.1886	65.83		
	30	1.1994	66.43	1.7890	99.08
	30	1.2592	69.74		
	30	1.2264	67.92		
	30	1.1931	66.08	1.7844	98.83
	60	0.7762	42.98		
	60	0.7606	42.12		
	60	0.7247	40.13	1.7877	99.01
	60	0.6946	38.47		
	60	0.6945	38.46		
	60	0.6947	38.47	1.7780	98.48
	60	0.6550	36.28		
	60	0.6755	37.41		
	60	0.7116	39.41	1.7780	98.48

Appendix A (continued)
FD&C Red #3 Color Loss at 0.10 W/m² Xenon Exposure
FD&C Red #3 Solution (18.5 mg/L)
Xenon Irradiance Condition = 0.10 W/m² (@ 340 nm)

Irradiance Level	Exposure time (min)	Test Sample		Dark Sample	
		Absorbance at 526 nm	% of Original Concentration	Absorbance at 526 nm	% of Original Concentration
0.10 W/m ²	120	0.1357	7.51		
	120	0.1742	9.64		
	120	0.1556	8.61	1.7870	98.97
	120	0.1463	8.10		
	120	0.1451	8.03		
	120	0.1481	8.19	1.7780	98.48
	120	0.1492	8.26		
	120	0.1320	7.30		
	120	0.1650	9.13	1.7834	98.77
	180	0.0337	1.86		
	180	0.0316	1.74		
	180	0.0315	1.74	1.7882	99.04
	180	0.0344	1.90		
	180	0.0341	1.88		
	180	0.0340	1.88	1.7775	98.45
	180	0.0342	1.89		
	180	0.0372	2.06		
	180	0.0388	2.14	1.7870	98.97

Appendix B
Regression Data
Time of Exposure vs. % of Original Concentration
FD&C Red #3 Solution
Xenon Irradiance Condition = 0.10 W/m²

Zero Order (Time of Exposure vs % of Original Concentration) Regression Output:	
Constant	81.8269
Std Err of Y Est	10.9205
R Squared	0.8956
No. of Observations	46
Degrees of Freedom	44
X Coefficient(s)	-0.5074
Std Err of Coef.	0.0261

First Order (Time of Exposure vs ln % of Original Concentration) Regression Output:	
Constant	4.8969
Std Err of Y Est	0.1206
R Squared	0.9933
No. of Observations	46
Degrees of Freedom	44
X Coefficient(s)	-0.0233
Std Err of Coef.	0.0003

Appendix C
FD&C Red #3 Color Loss at 0.20 W/m² Xenon Exposure
FD&C Red #3 Solution (18.5 mg/L)
Xenon Irradiance Condition = 0.20 W/m² (@ 340 nm)

Irradiance Level	Exposure time (min)	Test Sample		Dark Sample	
		Absorbance at 526 nm	% of Original Concentration	Absorbance at 526 nm	% of Original Concentration
0.20 W/m ²	0	1.8000	99.70		
	15	1.2523	69.36		
	15	1.2766	70.70		
	15	1.2612	69.85	1.7808	98.636
	15	1.3532	74.95		
	15	1.3278	73.54		
	15	1.2941	71.67	1.7967	99.516
	15	1.3214	73.18		
	15	1.2935	71.64		
	15	1.2583	69.69	1.7913	99.217
	30	0.8448	46.78		
	30	0.8285	45.88		
	30	0.7927	43.90	1.7889	99.084
	30	0.8130	45.02		
	30	0.8074	44.71		
	30	0.7800	43.20	1.7895	99.118
	30	0.8098	44.85		
	30	0.7762	42.99		
	30	0.8328	46.12	1.7880	99.034
	45	0.4573	25.32		
	45	0.4668	25.85		
	45	0.4145	22.95	1.7860	98.924
	45	0.4389	24.30		
	45	0.4138	22.91		
	45	0.3872	21.44	1.7848	98.857
	45	0.4454	24.66		
	45	0.4442	24.60		
	45	0.3895	21.57	1.7860	98.924

Appendix C (continued)
FD&C Red #3 Color Loss at 0.20 W/m² Xenon Exposure
FD&C Red #3 Solution (18.5 mg/L)
Xenon Irradiance Condition = 0.20 W/m² (@ 340 nm)

Irradiance Level	Exposure time (min)	Test Sample		Dark Sample	
		Absorbance at 526 nm	% of Original Concentration	Absorbance at 526 nm	% of Original Concentration
0.20 W/m ²	60	0.2162	11.97		
	60	0.2437	13.49		
	60	0.2202	12.19	1.7876	99.012
	60	0.2160	11.96		
	60	0.2435	13.48		
	60	0.1820	10.07	1.7897	99.129
	60	0.2254	12.48		
	60	0.2521	13.96		
	60	0.2111	11.68	1.7880	99.034
	90	0.0441	2.44		
	90	0.0463	2.56		
	90	0.0437	2.42	1.7881	99.040
	90	0.0438	2.42		
	90	0.0460	2.54		
	90	0.0468	2.58	1.7895	99.118
	90	0.0455	2.51		
	90	0.0459	2.54		
	90	0.0444	2.45	1.7880	99.034

Appendix D
Regression Data
Time of Exposure vs. % of Original Concentration
FD&C Red #3 Solution
Xenon Irradiance Condition = 0.20 W/m²

Zero Order (Time of Exposure vs. % of Original Concentration) Regression Output:	
Constant	76.4215
Std Err of Y Est	9.5747
R Squared	0.8748
No. of Observations	46
Degrees of Freedom	44
X Coefficient(s)	-0.9352
Std Err of Coef.	0.0533

First Order (Time Of Exposure vs. ln % of Original Concentration) Regression Output:	
Constant	5.0554
Std Err of Y Est	0.1460
R Squared	0.9855
No. of Observations	46
Degrees of Freedom	44
X Coefficient(s)	-0.0444
Std Err of Coef.	0.0008

Appendix E
FD&C Red #3 Color Loss at 0.35 W/m² Xenon Exposure
FD&C Red #3 Solution (18.5 mg/L)
Xenon Irradiance Condition = 0.35 W/m² (@340 nm)

Irradiance Level	Exposure time (min)	Test Sample		Dark Sample	
		Absorbance at 526 nm	% of Original Concentration	Absorbance at 526 nm	% of Original Concentration
0.35 W/m ²	0	1.8000	99.70		
	10	1.3198	73.10		
	10	1.2927	71.59		
	10	1.2493	69.19	1.7881	99.040
	10	1.3067	72.37		
	10	1.3358	73.98		
	10	1.2970	71.83	1.8011	99.760
	10	1.2703	70.35		
	10	1.2497	69.21		
	10	1.2351	68.40	1.7849	98.863
	15	1.0165	56.30		
	15	1.0164	56.29		
	15	1.0145	56.19	1.7892	99.101
	15	1.0685	59.18		
	15	1.0877	60.24		
	15	1.0739	59.48	1.8040	99.921
	15	0.9675	53.58		
	15	1.0123	56.06		
	15	0.9551	52.89	1.7853	98.885
	20	0.8267	45.79		
	20	0.8708	48.23		
	20	0.8198	45.40	1.8000	99.699
	20	0.7711	42.71		
	20	0.8414	46.60		
	20	0.8009	44.36	1.8014	99.777
	20	0.6825	37.79		
	20	0.7458	41.30		
	20	0.6858	37.98	1.7868	98.968

Appendix E (continued)
FD&C Red #3 Color Loss at 0.35 W/m² Xenon Exposure
FD&C Red #3 Solution (18.5 mg/L)
Xenon Irradiance Condition = 0.35 W/m² (@340 nm)

Irradiance Level	Exposure time (min)	Test Sample		Dark Sample	
		Absorbance at 526 nm	% of Original Concentration	Absorbance at 526 nm	% of Original Concentration
0.35 W/m ²	30	0.2552	14.13		
	30	0.2785	15.42		
	30	0.2357	13.05	1.7892	99.101
	30	0.3530	19.54		
	30	0.3922	21.72		
	30	0.3181	17.61	1.8033	99.882
	30	0.3228	17.87		
	30	0.3251	18.00		
	30	0.3590	19.88	1.7807	98.630
	45	0.0470	2.60		
	45	0.0539	2.98		
	45	0.0420	2.32	1.7839	98.807
	45	0.0862	4.77		
	45	0.0935	5.17		
	45	0.0823	4.55	1.8079	100.137
	45	0.1051	5.82		
	45	0.2004	11.09		
	45	0.0930	5.14	1.7832	98.769

Appendix F
Regression Data
Time of Exposure vs. % of Original Concentration
FD&C Red #3 Solution
Xenon Irradiance Condition = 0.35 W/m²

Zero Order (Time of Exposure vs. % of Original Concentration) Regression Output:	
Constant	86.0250
Std Err of Y Est	6.9474
R Squared	0.9312
No. of Observations	46
Degrees of Freedom	44
X Coefficient(s)	-1.9584
Std Err of Coef.	0.0803

First Order (Time of Exposure vs. ln % of Original Concentration) Regression Output:	
Constant	5.1754
Std Err of Y Est	0.2627
R Squared	0.9397
No. of Observations	46
Degrees of Freedom	44
X Coefficient(s)	-0.0795
Std Err of Coef.	0.0030

Appendix G
FD&C Red #3 Color Loss at 100 Footcandles Fluorescent Illumination
FD&C Red #3 Solution (18.5 mg/L)
Fluorescent Light Illumination = 100 Footcandles

Illumination Level	Exposure time (min.)	Test Sample		Dark Sample	
		Absorbance at 526 nm	% of Original Concentration	Absorbance at 526 nm	% of Original Concentration
100 Footcandles	0	1.8000	99.699		
	1440	1.4059	77.86		
	1440	1.4296	79.18		
	1440	1.3999	77.53	1.7731	98.209
	1440	1.3980	77.43		
	1440	1.4217	78.74		
	1440	1.4195	78.62	1.7734	98.226
	1440	1.3890	76.93		
	1440	1.4402	79.76		
	1440	1.4009	77.59	1.7948	99.411
	2880	1.0415	57.68		
	2880	1.0618	58.81		
	2880	1.0194	56.46	1.7798	98.580
	2880	1.0120	56.05		
	2880	1.0309	57.09		
	2880	1.0699	59.25	1.7792	98.547
	2880	1.0699	59.25		
	2880	1.0255	56.79		
	2880	1.0126	56.08	1.7930	99.311
	4320	0.6879	38.10		
	4320	0.6994	38.73		
	4320	0.7056	39.07	1.7798	98.580
	4320	0.6616	36.64		
	4320	0.6396	35.42		
	4320	0.6903	38.23	1.7740	98.259
	4320	0.7021	38.88		
	4320	0.6587	36.48		
	4320	0.6787	37.58	1.8018	99.799

Appendix G (continued)
FD&C Red #3 Color Loss at 100 Footcandles Fluorescent Illumination
FD&C Red #3 Solution (18.5 mg/L)
Fluorescent Light Illumination = 100 Footcandles

Illumination Level	Exposure time (min.)	Test Sample		Dark Sample	
		Absorbance at 526 nm	% of Original Concentration	Absorbance at 526 nm	% of Original Concentration
100 Footcandles	5760	0.3667	20.30		
	5760	0.4056	22.46		
	5760	0.3948	21.86	1.7770	98.425
	5760	0.4580	25.36		
	5760	0.4611	25.53		
	5760	0.4571	25.31	1.7803	98.608
	5760	0.3964	21.95		
	5760	0.3547	19.64		
	5760	0.3657	20.25	1.7933	99.328
	7200	0.2437	13.49		
	7200	0.2523	13.97		
	7200	0.2680	14.84		
	8640	0.1262	6.98		
	8640	0.1317	7.29		
	8640	0.1363	7.54	1.7812	98.658
	8640	0.0932	5.15		
	8640	0.1168	6.46		
	8640	0.1170	6.47	1.7695	98.010
	8640	0.0918	5.08		
	8640	0.0881	4.87		
	8640	0.0861	4.76	1.8012	99.766

Appendix H
Regression Data
Time of Exposure vs. % of Original Concentration
FD&C Red #3 Solution
Fluorescent Light Illumination = 100 Footcandles

Zero Order (Time of Exposure vs. % of Original Conc.) Regression Output:	
Constant	87.7726
Std Err of Y Est	5.7559
R Squared	0.9552
No. of Observations	49
Degrees of Freedom	47
X Coefficient(s)	-0.0102
Std Err of Coef.	0.0003

First Order (Time of Exposure vs. ln % of Original Conc.) Regression Output:	
Constant	4.9993
Std Err of Y Est	0.1758
R Squared	0.9639
No. of Observations	49
Degrees of Freedom	47
X Coefficient(s)	-0.0210
Std Err of Coef.	0.0006

Appendix I
Riboflavin Loss at 0.10W/m² Xenon Exposure
Riboflavin Solution (4.0 mg/L)
Xenon Irradiance Condition = 0.10 W/m² (@ 340 nm)

Irradiance Level	Exposure Time (min)	Test Sample		Dark Sample	
		Riboflavin (mg/L)	% of Original Concentration	Riboflavin (mg/L)	% of Original Concentration
0.10 W/m ²	0	4.000	100.00		
	10	2.747	68.67		
	10	2.678	66.95		
	10	2.678	66.95	3.985	99.211
	10	2.449	61.22		
	10	2.311	57.78		
	10	2.357	58.92		
	10	2.173	54.34		
	10	2.173	54.34		
	10	2.265	56.63		
	20	1.394	34.84		
	20	1.325	33.12		
	20	1.417	35.42	3.962	98.638
	20	1.417	35.42		
	20	1.440	35.99		
	20	1.417	35.42		
	20	1.577	39.43		
	20	1.600	40.00		
	20	1.600	40.00		
	30	0.692	17.30		
	30	0.664	16.61		
	30	0.596	14.89	4.008	99.785
	30	0.499	12.48		
	30	0.541	13.51		
	30	0.637	15.92		
	30	0.472	11.79		
	30	0.479	11.96		
	30	0.430	10.76		

Appendix I (continued)
Riboflavin Loss at 0.10W/m² Xenon Exposure
Riboflavin Solution (4.0 mg/L)
Xenon Irradiance Condition = 0.10 W/m² (@ 340 nm)

Irradiance Level	Exposure Time (min)	Test Sample		Dark Sample	
		Riboflavin (mg/L)	% of Original Concentration	Riboflavin (mg/L)	% of Original Concentration
0.10 W/m ²	40	76.5	9.21		
	40	76.5	9.21		
	40	73.0	8.81	3.871	96.345
	40	57.0	6.98		
	40	57.5	7.03		
	40	51.0	6.29		
	40	60.0	7.32		
	40	53.0	6.52		
	40	50.0	6.17		
	50	34.0	4.34		
	50	36.5	4.63		
	50	38.5	4.86	3.962	98.638
	50	28.0	3.65		
	50	31.0	3.99		
	50	27.0	3.54		
	50	25.0	3.31		
	50	24.0	3.19		
	50	30.0	3.88		

Appendix J
Regression Data
Time of Exposure vs. % of Original Concentration
Riboflavin Solution
Xenon Irradiance Condition = 0.10 W/m²

Zero Order (Time of Exposure vs. % of Original Conc.) Regression Output:	
Constant	70.8517
Std Err of Y Est	8.9489
R Squared	0.0867
No. of Observations	46
Degrees of Freedom	44
X Coefficient(s)	-1.5226
Std Err of Coef.	0.0900

First Order (Time of Exposure vs. ln % of Original Conc.) Regression Output:	
Constant	4.8325
Std Err of Y Est	0.1615
R Squared	0.9769
No. of Observations	46
Degrees of Freedom	44
X Coefficient(s)	-0.0700
Std Err of Coef.	0.0016

Appendix K
Riboflavin Loss at 0.15 W/m² Xenon Exposure
Riboflavin Solution (4 mg/L)
Xenon Exposure Conditions = 0.15 W/m² (@ 340 nm)

Irradiance Level	Exposure Time (min)	Test Sample		Dark Sample	
		Riboflavin (mg/L)	% of Original Concentration	Riboflavin (mg/L)	% of Original Concentration
0.15 W/m ²	0	4.000	100.00		
	5	2.861	71.51		
	5	2.929	73.23		
	5	2.998	74.95		
	5	3.067	76.67		
	5	3.090	77.25		
	5	3.067	76.67	3.984	99.210
	5	3.021	75.53		
	5	3.021	75.53		
	5	3.044	76.10		
	10	1.851	46.29		
	10	1.897	47.43		
	10	1.783	44.56		
	10	1.897	47.43		
	10	1.966	49.15		
	10	1.851	46.29	3.916	97.490
	10	2.172	54.31		
	10	2.154	53.85		
	10	2.104	52.59		
	15	1.358	33.96		
	15	1.317	32.93		
	15	1.338	33.44		
	15	1.347	33.67		
	15	1.416	35.39		
	15	1.347	33.67		
	15	1.124	28.11	3.893	96.917
	15	1.069	26.73		
	15	0.966	24.15		

Appendix K (continued)
Riboflavin Loss at 0.15 W/m² Xenon Exposure
Riboflavin Solution (4 mg/L)
Xenon Exposure Conditions = 0.15 W/m² (@ 340 nm)

Irradiance Level	Exposure Time (min)	Test Sample		Dark Sample	
		Riboflavin (mg/L)	% of Original Concentration	Riboflavin (mg/L)	% of Original Concentration
0.15 W/m ²	20	0.849	21.23		
	20	0.829	20.71		
	20	0.801	20.02		
	20	0.608	15.21		
	20	0.615	15.38		
	20	0.608	15.21	4.007	99.784
	20	0.794	19.85		
	20	0.829	20.71		
	20	0.787	19.68		
	30	0.310	7.75		
	30	0.308	7.70		
	30	0.308	7.70		
	30	0.319	7.98		
	30	0.318	7.96		
	30	0.295	7.39	3.961	98.637
	30	0.216	5.40		
	30	0.223	5.58		
	30	0.230	5.75		

Appendix L
Regression Data
Time of Exposure vs. % of Original Concentration
Riboflavin Solution
Xenon Irradiance Condition = 0.15 W/m²

Zero Order (Time of Exposure vs. % of Original Concentration) Regression Output:	
Constant	80.6205
Std Err of Y Est	8.5330
R Squared	0.0894
No. of Observations	46
Degrees of Freedom	44
X Coefficient(s)	-2.7443
Std Err of Coef.	0.1426

1st Order (Time of Exposure vs. ln % of Original Concentration) Regression Output:	
Constant	4.8161
Std Err of Y Est	0.1227
R Squared	0.9799
No. of Observations	46
Degrees of Freedom	44
X Coefficient(s)	-0.0950
Std Err of Coef.	0.0021

Appendix M
Riboflavin Loss at 0.20 W/m² Xenon Exposure
Riboflavin Solution (4 mg/L)
Xenon Exposure Conditions = 0.20 W/m² (@ 340 nm)

Irradiance Level	Exposure Time (min)	Test Sample		Dark Sample	
		Riboflavin (mg/L)	% of Original Concentration	Riboflavin (mg/L)	% of Original Concentration
0.20 W/m ²	0	4.000	100.00		
	5	2.563	64.08		
	5	2.563	64.08		
	5	2.655	66.38		
	5	2.302	57.55		
	5	2.357	58.93		
	5	2.242	56.05	3.938	98.064
	5	2.655	66.38		
	5	2.655	66.38		
	5	2.518	62.95		
	10	1.508	37.70		
	10	1.485	37.13		
	10	1.417	35.43		
	10	1.738	43.45		
	10	1.852	46.30		
	10	1.715	42.88	3.870	96.344
	10	1.852	46.30		
	10	1.875	46.88		
	10	1.875	46.88		
	15	0.850	21.25		
	15	0.809	20.23		
	15	0.878	21.95		
	15	0.940	23.50		
	15	0.967	24.18		
	15	0.974	24.35		
	15	0.905	22.63	4.007	99.784
	15	0.885	22.13		
	15	0.898	22.45		

Appendix M (continued)
Riboflavin Loss at 0.20 W/m² Xenon Exposure
Riboflavin Solution (4 mg/L)
Xenon Exposure Conditions = 0.20 W/m² (@ 340 nm)

Irradiance Level	Exposure Time (min)	Test Sample		Dark Sample	
		Riboflavin (mg/L)	% of Original Concentration	Riboflavin (mg/L)	% of Original Concentration
0.20 W/m ²	20	0.547	13.68		
	20	0.485	12.13		
	20	0.554	13.85		
	20	0.575	14.38		
	20	0.575	14.38		
	20	0.554	13.85	3.961	98.637
	20	0.485	12.13		
	20	0.513	12.83		
	20	0.513	12.83		
	30	0.187	4.68		
	30	0.194	4.85		
	30	0.199	4.98		
	30	0.174	4.35		
	30	0.167	4.18		
	30	0.180	4.50	3.870	96.344
	30	0.192	4.80		
	30	0.169	4.23		
	30	0.199	4.98		

Appendix N
Regression Data
Time of Exposure vs. % of Original Concentration
Riboflavin Solution
Xenon Irradiance Condition = 0.20 W/m²

Zero Order	
(Time of Exposure vs. % of Original Concentration)	
Regression Output:	
Constant	68.8542
Std Err of Y Est	9.0654
R Squared	0.8550
No. of Observations	46
Degrees of Freedom	44
X Coefficient(s)	-2.4408
Std Err of Coef.	0.1515

1st Order	
Time of Exposure vs. ln % of Original Concentration)	
Regression Output:	
Constant	4.7115
Std Err of Y Est	0.0889
R Squared	0.9914
No. of Observations	46
Degrees of Freedom	44
X Coefficient(s)	-0.1058
Std Err of Coef.	0.0015

Appendix O
Riboflavin Loss at 0.30 W/m² Xenon Exposure
Riboflavin Solution (4 mg/L)
Xenon Exposure Conditions = 0.30 W/m² (@ 340 nm)

Irradiance Level	Exposure Time (min)	Test Sample		Dark Sample	
		Riboflavin (mg/L)	% of Original Concentration	Riboflavin (mg/L)	% of Original Concentration
0.30 W/m ²	0	4.000	100.00		
	5	2.196	54.90		
	5	2.196	54.90		
	5	2.196	54.90		
	5	2.173	54.33		
	5	2.219	55.48		
	5	2.265	56.63	4.007	99.784
	5	2.196	54.90		
	5	2.219	55.48		
	5	2.311	57.78		
	10	1.022	25.55		
	10	1.125	28.13		
	10	1.139	28.48		
	10	1.146	28.65		
	10	1.180	29.50		
	10	1.215	30.38	3.984	99.210
	10	1.139	28.48		
	10	1.160	29.00		
	10	1.146	28.65		
	15	0.568	14.20		
	15	0.554	13.85		
	15	0.527	13.18		
	15	0.564	14.10		
	15	0.554	13.85		
	15	0.547	13.68		
	15	0.547	13.68	3.870	96.344
	15	0.554	13.85		
	15	0.575	14.38		

Appendix O (continued)
Riboflavin Loss at 0.30 W/m² Xenon Exposure
Riboflavin Solution (4 mg/L)
Xenon Exposure Conditions = 0.30 W/m² (@ 340 nm)

Irradiance Level	Exposure Time (min)	Test Sample		Dark Sample	
		Riboflavin (mg/L)	% of Original Concentration	Riboflavin (mg/L)	% of Original Concentration
0.30 W/m ²	20	0.249	6.23		
	20	0.252	6.30		
	20	0.235	5.88		
	20	0.261	6.53		
	20	0.270	6.75		
	20	0.261	6.53	4.007	99.784
	20	0.256	6.40		
	20	0.274	6.85		
	20	0.270	6.75		
	25	0.148	3.70		
	25	0.155	3.88		
	25	0.144	3.60		
	25	0.130	3.25		
	25	0.135	3.38		
	25	0.125	3.13	3.916	97.490
	25	0.123	3.08		
	25	0.139	3.48		
	25	0.128	3.20		

Appendix P
Regression Data
Time of Exposure vs. % of Original Concentration
Riboflavin Solution
Xenon Irradiance Condition = 0.30 W/m²

Zero Order (Time of Exposure vs. % of Original Concentration) Regression Output:	
Constant	63.8361
Std Err of Y Est	8.9183
R Squared	0.8437
No. of Observations	46
Degrees of Freedom	44
X Coefficient(s)	-2.7655
Std Err of Coef.	0.1794

1st Order (Time of Exposure vs. ln % of Original Concentration) Regression Output:	
Constant	4.7232
Std Err of Y Est	0.0567
R Squared	0.9971
No. of Observations	46
Degrees of Freedom	44
X Coefficient(s)	-0.1406
Std Err of Coef.	0.0011

Appendix Q
Riboflavin Loss at 100 Footcandles Fluorescent Illumination
Riboflavin Solution (4 mg/L)
Fluorescent Illumination Conditions = 100 Footcandles

Illumination Level	Exposure Time (min)	Test Sample		Dark Sample	
		Riboflavin (mg/L)	% of Original Concentration	Riboflavin (mg/L)	% of Original Concentration
100 Footcandles	0	4.000	100.00		
	570	2.770	69.25		
	570	2.816	70.40		
	570	2.701	67.53		
	570	2.586	64.65		
	570	2.655	66.38		
	570	2.609	65.23	3.961	98.637
	570	2.678	66.95		
	570	2.655	66.38		
	570	2.655	66.38		
	1440	1.554	38.85		
	1440	1.531	38.28		
	1440	1.531	38.28		
	1440	1.417	35.43		
	1440	1.485	37.13		
	1440	1.531	38.28	3.938	98.064
	1440	1.164	29.10		
	1440	1.256	31.40		
	1440	1.187	29.68		
	1860	0.940	23.50		
	1860	0.885	22.13		
	1860	0.981	24.53		
	1860	0.967	24.18		
	1860	0.864	21.60		
	1860	0.953	23.83		
	1860	1.050	26.25	3.870	96.344
	1860	1.063	26.58		
	1860	1.105	27.63		

Appendix Q (continued)
Riboflavin Loss at 100 Footcandles Fluorescent Illumination
Riboflavin Solution (4 mg/L)
Fluorescent Illumination Conditions = 100 Footcandles

Illumination Level	Exposure Time (min)	Test Sample		Dark Sample	
		Riboflavin (mg/L)	% of Original Concentration	Riboflavin (mg/L)	% of Original Concentration
100 Footcandles	2880	0.472	11.80		
	2880	0.472	11.80		
	2880	0.472	11.80		
	2880	0.630	15.75		
	2880	0.609	15.23		
	2880	0.651	16.28	3.870	96.344
	2880	0.451	11.28		
	2880	0.451	11.28		
	2880	0.472	11.80		
	4320	0.208	5.20		
	4320	0.201	5.03		
	4320	0.208	5.20		
	4320	0.187	4.68		
	4320	0.183	4.58		
	4320	0.192	4.80	3.870	96.344
	4320	0.155	3.88		
	4320	0.158	3.95		
	4320	0.153	3.83		

Appendix R
Regression Data
Time of Exposure vs. % of Original Concentration
Riboflavin Solution
Fluorescent Illumination Condition = 100 Footcandles

Zero Order (Time of Exposure vs. % of Original Concentration) Regression Output:	
Constant	65.8947
Std Err of Y Est	10.6699
R Squared	0.8102
No. of Observations	46
Degrees of Freedom	44
X Coefficient(s)	-0.9836
Std Err of Coef.	0.0718

1st Order (Time of Exposure vs. ln % of Original Concentration) Regression Output:	
Constant	4.5808
Std Err of Y Est	0.1104
R Squared	0.9869
No. of Observations	46
Degrees of Freedom	44
X Coefficient(s)	-0.0427
Std Err of Coef.	0.0007

Appendix S
Soybean Oil Photodegradation at 0.15 W/m² Xenon Exposure
Peroxide Value Determinations
Xenon Irradiance Condition = 0.15 W/m²

Irradiance Level	Exposure time (hours)	Test Sample	Dark Sample
		Peroxide Value (meq/kg)	Peroxide Value (meq/kg)
0.15 W/m ²	0	0.2	
	1	7.2	
	1	7.2	
	1	7.2	0.2
	2	12.6	
	2	12.6	
	2	12.8	0.2
	3	19.2	
	3	18.6	
	3	18.4	0.2
	4	22.6	
	4	23.4	
	4	22.6	0.2
	6	28.4	
	6	29.6	
	6	30.4	0.3

Appendix T
Regression Data
Time of Exposure vs. Peroxide Value
Soybean Oil
Xenon Irradiance Condition = 0.15 W/m²

Zero Order (Time of Exposure vs. Peroxide Value) Regression Output:	
Constant	3.0625
Std Err of Y Est	1.5113
R Squared	0.9735
No. of Observations	16
Degrees of Freedom	14
X Coefficient(s)	4.6667
Std Err of Coef.	0.2057

First Order (Time of Exposure vs. ln Peroxide Value) Regression Output:	
Constant	1.1160
Std Err of Y Est	0.8470
R Squared	0.5394
No. of Observations	16
Degrees of Freedom	14
X Coefficient(s)	0.4667
Std Err of Coef.	0.1153

Appendix U
Soybean Oil Photodegradation at 0.25 W/m² Xenon Exposure
Peroxide Value Determinations
Xenon Irradiance Condition = 0.25 W/m²

Irradiance Level	Exposure time (hours)	Test Sample	Dark Sample
		Peroxide Value (meq/kg)	Peroxide Value (meq/kg)
0.25 W/m ²	0	0.2	
	1	10.0	
	1	10.4	
	1	9.0	0.2
	2	17.2	
	2	15.6	
	2	16.8	0.2
	3	23.4	
	3	23.6	
	3	23.6	0.2
	4	28.6	
	4	29.8	
	4	31.6	0.4
	6	38.2	
	6	38.6	
	6	37.6	0.4

Appendix V
Regression Data
Time of Exposure vs. Peroxide Value
Soybean Oil
Xenon Irradiance Condition = 0.25 W/m²

Zero Order (Time of Exposure vs. Peroxide Value) Regression Output:	
Constant	4.1264
Std Err of Y Est	1.9298
R Squared	0.9739
No. of Observations	16
Degrees of Freedom	14
X Coefficient(s)	6.0037
Std Err of Coef.	0.2626

First Order (Time of Exposure vs. ln Peroxide Value) Regression Output:	
Constant	1.3374
Std Err of Y Est	0.9107
R Squared	0.5130
No. of Observations	16
Degrees of Freedom	14
X Coefficient(s)	0.4760
Std Err of Coef.	0.1239

Appendix W
Soybean Oil Photodegradation at 0.35 W/m² Xenon Exposure
Peroxide Value Determinations
Xenon Irradiance Condition = 0.35 W/m²

Irradiance Level	Exposure time (hours)	Test Sample	Dark Sample
		Peroxide Value (meq/kg)	Peroxide Value (meq/kg)
0.35 W/m ²	0	0.2	
	0.5	7.4	
	0.5	7.2	
	0.5	7.4	0.2
	1	12.0	
	1	12.2	
	1	12.6	0.2
	2	20.0	
	2	18.6	
	2	18.4	0.2
	3	27.6	
	3	27.8	
	3	26.8	0.4
	4	34.8	
	4	32.6	
	4	31.2	0.4
	5	41.2	
	5	38.4	
	5	38.0	0.4

Appendix X
Regression Data
Time of Exposure vs. Peroxide Value
Soybean Oil
Xenon Irradiance Condition = 0.35 W/m²

Zero Order (Time of Exposure vs. Peroxide Value) Regression Output:	
Constant	4.0675
Std Err of Y Est	1.6261
R Squared	0.9838
No. of Observations	19
Degrees of Freedom	17
X Coefficient(s)	7.2498
Std Err of Coef.	0.2256

First Order (Time of Exposure vs. ln Peroxide Value) Regression Output:	
Constant	1.4572
Std Err of Y Est	0.8332
R Squared	0.5488
No. of Observations	19
Degrees of Freedom	17
X Coefficient(s)	0.5256
Std Err of Coef.	0.1156

Appendix Y
Soybean Oil Photodegradation at 100 Footcandles Fluorescent Illumination
Peroxide Value Determinations
Fluorescent Illumination Condition = 100 Footcandles

Irradiance Level	Exposure time (hours)	Test Sample	Dark Sample
		Peroxide Value (meq/kg)	Peroxide Value (meq/kg)
100 Footcandles	0	0.2	
	72	6.6	
	72	5.8	
	72	5.8	0.2
	168	15.6	
	168	12.6	
	168	14.0	0.2
	240	26.6	
	240	27.0	
	240	24.8	0.2
	336	40.8	
	336	40.0	
	336	38.4	
	408	50.6	
	408	52.2	
	408	52.0	0.4

Appendix Z
Regression Data
Time of Exposure vs. Peroxide Value
Soybean Oil
Fluorescent Illumination Condition = 100 Footcandles

Zero Order (Time of Exposure vs. Peroxide Value) Regression Output:		
Constant		-4.6662
Std Err of Y Est		2.6050
R Squared		0.9803
No. of Observations		19
Degrees of Freedom		14
X Coefficient(s)	0.1328	
Std Err of Coef.	0.0050	

First Order (Time of Exposure vs. ln Peroxide Value) Regression Output:		
Constant		0.7023
Std Err of Y Est		0.7358
R Squared		0.7425
No. of Observations		16
Degrees of Freedom		14
X Coefficient(s)	0.0090	
Std Err of Coef.	0.0014	

Appendix AA
Regression of Rate Constants (k) vs. 1 / Irradiance

FD&C Red #3			
Xenon Irradiance Condition	1/Irradiance	k	k
		Zero Order	First Order
0.10 W/m ²	10	-0.5074	-0.0233
0.20 W/m ²	5	-0.9352	-0.0444
0.35 W/m ²	2.86	-1.9584	-0.0795
r ² =		0.8030	0.8692
Slope =		0.0903	0.0028

Riboflavin			
Xenon Irradiance Condition	1/Irradiance	k	k
		Zero Order	First Order
0.10 W/m ²	10	-1.5226	-0.0700
0.15 W/m ²	6.67	-2.7440	-0.0950
0.20 W/m ²	5	-2.4410	-0.1058
0.30 W/m ²	3.33	-2.7655	-0.1406
r ² =		0.7332	0.9227
Slope =		0.1753	0.0099

Peroxide Value			
Xenon Irradiance Condition	1/Irradiance	k	k
		Zero Order	First Order
0.15 W/m ²	6.67	4.6667	0.4667
0.25 W/m ²	4	6.0037	0.4760
0.35 W/m ²	2.86	7.2498	0.5256
r ² =		0.95755	0.6774
Slope =		-0.6464	-0.0133

Appendix AB
Specifications: SunChex™ Xenon Exposure System

SunChex™ Specifications

Light Source: 1500 Watt Air Cooled Xenon Arc Lamp

Light Filters: Interchangeable Sharp Cut On

Wattage Range: 1000 to 3200

Wattage Control: Continuous Adjustable, 5-16 Amperes

Irradiance Monitoring: Narrow Band: 320nm, 420 nm
Wide Band: 295 - 400 nm

Temperature Range: 40°C to 90°C

Temperature Control: Continuous Adjustable Set Point

Test Cycling: Programmable Countdown Timer

Exposure Area: 500 cm²

Physical Specifications: Width: 53 cm
Depth: 31 cm
Height: 57 cm
Weight: 30 kg

Electrical Specifications: Voltage: 215 -240
Hertz: 50 or 60
System: Single phase

Source: Atlas Electric Devices Company
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Chicago, IL 60613
312-327-4520