Considerations for the Application of Time-Temperature Integrators in Food Distribution

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Introduction

Today, consumers demand safe, natural, healthy and convenient food products. Fresh and/or minimally-processed foods using controlled/modified atmospheric packaging (CAP/MAP) with refrigeration are developing rapidly. The safety and quality of foods depends on ingredient selection, control of processing conditions and maintenance of distribution conditions. The current U.S. distribution system cannot adequately meet the requirements for the safety and quality maintenance of extended shelf life refrigerated (ESLR) products. For example, the Fresh Chef line of salads and the soups and sauces of Campbell Soup Co. was pulled out of the market in 1987 due to lack of temperature control and subsequent abuse. Culinary Brands used Federal Express to deliver its fresh products to overcome this problem. Kraft did a survey, the result of which showed that although the average temperature was 45°F, the maximum temperature was 59.7-62°F and 4-16 percent of their products exceeded 55°F during distribution. That led Kraft to install its own cooler cases at retailer locations (36±4°F) for their CAP/MAP line (Rice, 1989). Temperature abuse may exist at any point in the perishable food distribution chain and jeopardize the product, such as loading/unloading, temperature cycling in walk-in coolers, storage displays and home transport. The International Institute of Refrigeration (IIR, 1985) estimated current losses of perishable foods of at least 10 percent due to physical damage and inadequate temperature control; and the National Academy of Sciences (NAS, 1987) reported that 1-16 percent of food losses (1-3% in frozen food, 1-4% in dairy products, 10-16% in fresh produce) occurred during distribution.

Legally, food manufacturers are considered responsible for the ultimate quality and product safety even when they have no control of the distribution chain based on the Food, Drug and Cosmetic (FD&C) Act. In addition, loss of quality leads to loss of sales and thereby loss of profit. A cost effective system to monitor the temperature conditions of individual products throughout distribution and to indicate their remaining shelf life and any potentially unsafe condition would be the use of time-temperature integrators/indicators (TTIs). The proper use of a TTI tag could facilitate scheduling of distribution so that products approaching the end of their shelf life are moved first at the warehouse and retail level; a TTI tag could indicate problem areas in the distribution system so that they could be resolved; and, by replacing and/or complementing open date labeling at the point of purchase, it could reduce food waste and ensure that a consistent quality food product reaches the consumer (Taoukis and Lubuza, 1989a,b).

This paper will mainly present the kinetic basis for correlation of TTIs with foods and considerations for applying a TTI tag as well as several application examples.

Time-Temperature Integrators

Broadly speaking, a time-temperature integrator/indicator is a device or tag that can keep track of an accumulated time-temperature distribution function to which a perishable product is subjected, from the point of manufacture to the display shelf of the retail outlet, or even to the consumer. The operation of a TTI is based on mechanical, chemical or enzymatic systems that change irreversibly from the time of their activation. The rate increases at higher temperatures in a manner similar to most chemical reactions. The change is usually expressed as a visible response, in the form of a mechanical deformation, color development and/or color movement. Technical and practical requirements for an ideal TTI have been discussed in detail (Renier and Morin, 1962; Sanderson-Walker, 1975; Taoukis, 1989).

TTIs come in various sizes and shapes. They vary in cost from a few pennies for a TTI tag to more than several hundred dollars for an electronic device. A variety of TTIs based on different physicochemical principles were described by Schoen and Byrne (1972), Byrne (1976), Singh and Wells (1985), Taoukis (1989) and Taoukis et al. (1991).

Among all of those patented, only three types of non-electronic, individual package TTIs have ever been commercialized and evaluated extensively. TTI type I is the 3M Monitor Mark™(Manske, 1983). It is based on a time-temperature dependent diffusion of a blue dyed fatty acid ester through a porous wick made of a high quality blotting paper. The measurable response is the distance of the advancing easily visible diffusion front of the blue dye from the origin, much like reading a thermometer. A scanner could be used to record and calculate the distance traversed. Before use, the dye/ester mixture is separated from the wick by a barrier film so that no diffusion occurs. To activate the indicator, the barrier is pulled off and diffusion starts if the temperature is above the melting point of the ester. The melting point of the fatty acid ester used in a particular MonitorMark tag determines its response temperature. MonitorMark tags are available with response temperatures ranging from -17°C to 48°C and maximum running time of up to one year (Manske, 1983; 1985).

TTI type II is the I-point® TTI (Blixt, 1983). It is based on a color change caused by a pH decrease, due to a controlled enzymatic hydrolysis of a lipid substrate. Before activation the lipase and the lipid substrate are in two separate compartments, one of which has a visible window. At activation, the barrier that separates them is broken, enzyme and substrate are mixed, the pH drops and the color change starts as shown by the presence of an added pH indicator. The TTI is triggered with a special activating device and can be applied manually or mechanically, depending on the packaging line. The color change can be visually recognized and compared to a color band surrounding the window (e.g. green-good, yellow-caution, red-don't use). The change can also be measured continuously using an electronic color scanner and compared to an internal standard.

TTI type III is the Lifelines™ Fresh-Scan and Fresh-Check systems (Fields, 1985). It is based on the solid state polymerization of thinly coated colorless acetylenic monomer that changes to a highly colored opaque polymer. The measurable change is the reflectance which is measured with a laser optic wand with the information stored in a hand held computer. The indicator tag has two bar codes, one for identification of the product and the other for identification of the indicator model. The indicators are active from the time of production and have to be stored in the freezer before use.

Another type of TTI is a consumer readable TTI or consumer tag. It is a simple circular device that reflects the product's time-temperature history by producing a color change in the inner circle. When the center is darker than the outer circle printed color, the product has passed end of shelf life. Two types of consumer readable TTIs have been studied more extensively (Sherlock et al., 1991).

Kinetic Basis for TTI Applications

Food Kinetics

Usually, a distribution expert considers food shelf life as the storage period at 73°F and 50 percent RH for shelf stable foods, 5°F for frozen foods and 40°F for refrigerated foods (Labuza, 1982), within which the product remains at an acceptable sensory, nutritional and microbial quality level. However, in real life, variable distribution and storage conditions may result in lesser or greater shelf life for a particular food product.

Loss of shelf life in a food or an individual ingredient is usually evaluated by the measurement of a characteristic quality index, "A." The quality index for foods includes flavor, color, nutrients level, texture, and sensory quality as well as microbial load and toxin production. The change of quality index A with time t can usually be expressed as:

$$f(A) = k_A t \qquad (1)$$

where f(A) is the food quality function and k_A is the rate constant for the food quality loss reaction. The form of a food quality function depends on the reaction order. In general, the change in quality follows either a simple constant rate of change at constant temperatures (zero order) or an exponential change (first order) as follows:

$$f(A) = A_o - A_t = k_z t \qquad \text{zero order} \qquad (2a)$$

and

$$f(A) = \ln A_o - \ln A_t = k_f t \qquad \text{first order} \qquad (2b)$$

It should be noted that most chemical reactions leading to quality loss in food systems are much more complex. However, the reaction kinetics can be simplified into either pseudo-zero order or pseudo-first order (Benson, 1960; Frost and Pearson, 1961; Connors, 1990). In the case of complex reaction kinetics with respect to reactants, an intermediate or a final product (e.g. peroxides or hexanal in lipid oxidation) could be used as a quality index.

Sometimes, there is an induction period or lag time (t_{lag}) before the quality deterioration begins (e.g. amino acid and reducing sugar depletion or browning pigment formation in the Maillard reaction, microbial growth lag). The length of t_{lag} depends on many factors, but temperature is the predominant factor. Given this, modeling of both the induction or lag period and deterioration phase are necessary for accurate prediction of quality loss and/or shelf life remaining. An example of such work has been demonstrated by Fu et al. (1991).

With respect to the temperature dependence of the reaction, the rate constant usually follows the Arrhenius relationship, as shown below:

$$k_A = k_{oA} \exp\left[-\frac{E_{A(food)}}{RT}\right] \qquad (3)$$

where k_{oA} is the pre-exponential factor, $E_{A(food)}$ is the activation energy (temperature sensitivity) of the reaction that controls food quality loss, R is the universal gas constant and T is the absolute temperature (K), which may be constant or variable. This says that the rate is an exponential function of absolute temperature. It should be noted that the rate constant may be modeled by other temperature sensitivity models, such as the square root model for microbial growth

(Ratkowsky et al., 1982). The Q_{10} approach is also used sometimes, in which the rate is assumed to be increased by a constant factor, e.g. 2 to 3 times, for every 10°C increase in temperatures. It should be noted that the higher the temperature sensitivity (E_A) of the reaction, the faster the reaction goes when temperature is increased.

The change of a food quality function $f(A)_t$ for a known variable temperature exposure, T(t), can be calculated through Eqs. (1) and (3) where:

$$f(A)_t = \int_{t_1}^{t_2} k_{Adt} = k_{oA} \int_{t_1}^{t_2} \exp[-\frac{E_{A(food)}}{RT(t)}]dt \qquad (4)$$

The integral can be calculated analytically for simple T(t) functions or numerically for more complex ones, such as a sine wave temperature function. The concept of an effective temperature (T_{eff}) is also introduced to calculate the quality change under a variable time-temperature condition. T_{eff} is defined as the constant temperature that results in the same quality change as the variable temperature distribution over the same time period. Thus, $f(A)_t$ can be expressed as:

$$f(A)_t = k_{oA} \exp[-\frac{E_{A(food)}}{RT_{eff(food)}}]\ t \qquad (5)$$

TTI Kinetics

The same kinetic approach can be used to model the measurable change, x, of TTIs. Similarly, a TTI response function f(x) can be defined as:

$$f(x) = k_I t \qquad (6)$$

where k_I is the rate constant for the TTI response.

Different forms of f(x) for each type of TTI are shown in Table 1. It can be seen that TTI type I and the consumer tags follow a pseudo-zero order and type III follows pseudo-first order kinetics. TTI type II is a complex one, which was modeled by a first order kinetics by Wells and Singh (1988a).

The rate constant for a TTI response also follows the Arrhenius theory,

$$k_1 = k_{oI} \exp[-\frac{E_{A(TTI)}}{RT}] \qquad (7)$$

where k_I, k_{oI} and $E_{A(TTI)}$ are the rate constant, the pre-exponential factor and the activation energy of TTIs, respectively.

Table 1 summarizes the kinetic results of the three types of TTI and consumer tags studied by Taoukis and Labuza (1989a) and Sherlock et al. (1991). As noted, the $E_{A(TTI)}$ values of the indicators cover the range of the most important deteriorative reactions in foods. Wells and Singh (1988b) found similar activation energies for the tags they studied.

For an indicator exposed to the same variable temperature distribution, T(t), as the food product, the response function can be expressed by the following equations:

$$\begin{aligned} f(x)_t &= \int_{t_1}^{t_2} k_I dt = \\ & k_{oI} \int_{t_1}^{t_2} \exp[-\frac{E_{A(TTI)}}{RT(t)}]dt \end{aligned} \qquad (8)$$

With the concept of an effective temperature, then:

$$f(x)_t = k_{oI} \exp[-\frac{E_{A(TTI)}}{RT_{eff(TTI)}}]t \qquad (9)$$

Thus, $T_{eff(TTI)}$ can be calculated from the TTI response:

$$T_{eff(TTI)} = \frac{E_{A(TTI)}/R}{\ln[k_{oI}t/f(x)]} \qquad (10)$$

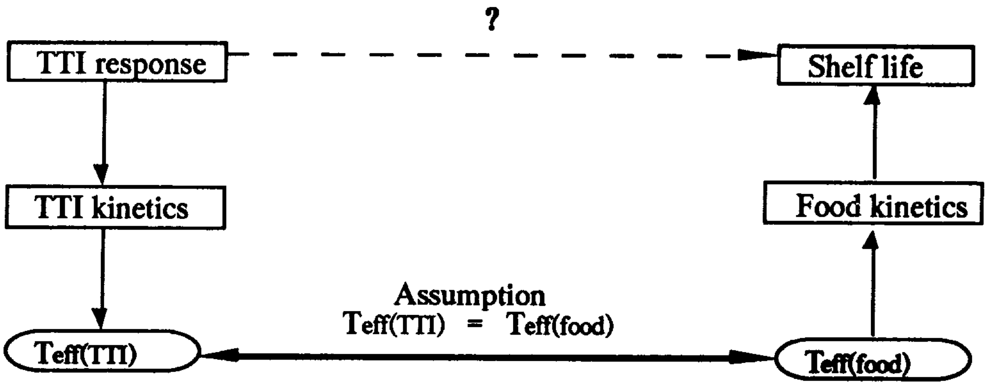
Table 1. Kinetics Parameters for Several TTIs

Type	Model	f(x)*	$E_{A(TTI)}$ (kcal/mol)	k_{oI}
I	4P	x^2	9.8	$2.03\text{x}10^{8}\text{mm}^{2}/\text{hr}$
II_a	4021	$[\ln 1/(1-x)]^{1/2}$	33.7	$6.70\text{x}10^{23}\text{hr}^{-1}$
II_b	4007	$[\ln 1/(1-x)]^{1/2}$	32.7	$2.62\text{x}10^{23}\text{hr}^{-1}$
III_a	18	$\ln(x_o/x)$	27.0	$1.63\text{x}10^{12}\text{hr}^{-1}$
III_b	41	$\ln(x_o/x)$	20.5	$2.57\text{x}10^{13}\text{hr}^{-1}$
III_c	68	$\ln(x_o/x)$	19.7	$9.42\text{x}10^{12}\text{hr}^{-1}$
Consumer tags				
	A20	$x_o - x_s$	19.4	$2.63\text{x}10^{12}$units/hr
	A40	$x_o - x_s$	19.5	$9.68\text{x}10^{12}$units/hr
	3014	$x_o - x_s$	11.4	$5.40\text{x}10^{6}$units/hr
	4014	$x_o - x_s$	24.3	$5.80\text{x}10^{16}$units/hr

* f(x) form for type II was derived from Gaussian function (Taoukis, 1989).

Figure 1

Correlation Scheme of TTI With Food



Correlation of Food Shelf Life With TTI Response

A kinetically based correlation scheme has been developed by Taoukis and Labuza (1989a) to allow prediction of the shelf life of a product based on the TTI response. The simplified form is shown in Figure 1.

From the measured response of the tag and the tag kinetics (left side of the scheme), one can predict an effective temperature for a variable time-temperature distribution. This value is then used on the right side of the scheme, with the food kinetics, to predict the quality loss or shelf life remaining. This scheme assumes that the effective temperature response of the tag is equal to that of the food. In many cases this may not be true since it also assumes that the activation energies of the food and tag are equal. This can then lead to large prediction errors (Taoukis et al., 1990). Thus, there is a need to have a tag with a temperature sensitivity close to that of the reaction resulting in quality loss.

Considerations for Applying a TTI

Successful application of a TTI depends upon many factors, such as the knowledge of the food product, the type of monitoring required and the potential benefits as well as relative costs and reliability of the system at the temperatures to be encountered. In more detail, the following points have to be considered when employing a TTI:

(1) Deterioration mode: In general, foods deteriorate through several modes: (i) biological respiration, e.g. fresh fruits and vegetables; (ii) microbial growth, e.g. many semi-processed and unprocessed food products; (iii) enzymatic degradation, e.g. polyphenol oxidase, peroxidase, lipoxidase and lipase in some raw and semi-processed products; (iv) chemical degradation, which includes nutrient loss (e.g. vitamin C), color change, lipid oxidation, non-enzymatic browning, flavor (loss or generation); (v) physical degradation, e.g. staling or hardening of bread, softening of a cereal product, melting of a chocolate bar, package ice in a frozen product, cracking of a textured product, and caking of a cake mix; and (vi) a combination of the above. Usually several modes will occur in the same product at the same time with equal importance. It is worthwhile to note that the mode or mechanism for food deterioration may change, depending on the process treatments, package used, and storage and environmental conditions. The food processor and/or distributor must know their products very well and must know the effects of various storage conditions on quality and shelf life.

(2) Quality index: Generally, single chemical indices are preferable as they can usually be measured more easily and accurately. For example, the criteria for selecting an appropriate quality index out of the volatile components comprising a food flavor could be based either on their importance to the organoleptic quality of the flavor or on their relative prominence and ease of quantitation and kinetic characterization. Thus, one could follow the decrease of an important desirable component (e.g. citral) or the increase of a developing off flavor (e.g. p-cymene). The initial level of a quality attribute (and its variation) in a food must be known for modeling purposes. The final level (A_s) corresponding to the end of shelf life of a product is determined by legal requirements, consumer preference and/or marketing requirements as well as cost. The error in food quality measurement becomes more important when the measured change causing shelf life is small (Benson, 1960). Improvement in analytical procedures and better understanding of food quality factors as related to their organoleptic characteristics, defined by sensory evaluation, may minimize this error. For some products, such as fresh shrimp, the shelf life differs depending on the quality of either 'prime' or 'mediocre' grade (Haard, 1991). To meet these requirements, the TTI may have to have multi-end points or multi-grade makers on a continuous scale.

(3) Kinetic study: After determining the critical deterioration mode of a food system and its limit quality index. A kinetic experimental study needs to be done to determine the order, rate constant and temperature sensitivity. Data for some foods may be found in the literature, such as the book "Shelf Life Dating of Foods" by Labuza (1982). Methodology for "Accelerated Shelf Life Testing" (ASLT) may be used in collecting the

kinetic data of foods experimentally (Labuza and Schmidl, 1985).

(4) TTI reliability, applicability and cost: Just like everything else, a TTI has its own problems and limitations. The reliability for TTI applications includes its variability in responses within the temperature range encountered, the confidence on the determined kinetic parameters and the difference between $E_{A(food)}$ and $E_{A(TTI)}$. The applicability problem involves deviations from the Arrhenius relationship for both the TTI and food, the heat transfer problem since a TTI tag is usually applied on a package surface and does not reflect the temperature response in the center of a pallet load, and the chemical and light sensitivity of TTIs. The cost of a TTI also depends on the quantity required. All of these aspects and their potential solutions have been discussed in detail by Taoukis et al. (1991).

Examples of TTI Applications

Evaluations of TTIs for a variety of food products have been done by several researchers (Fields and Prusik, 1986; Wells and Singh, 1988a,b,c). However, most studies reported in the literature did not use the above kinetic analysis but relied more on correlation. Such a non-kinetic approach is very limited in its application since the results cannot be extrapolated to other temperature conditions.

Examples of where TTIs have been applied in the past were a supermarket chain that used TTIs to monitor shipments of perishable refrigerated products and for inventory management (Mohel, 1988) and a Massachusetts seafood company who used the enzymatic based TTI on shipping cartons (Densford, 1983). Another large food company has thoroughly tested the use of TTIs on their refrigerated fresh cut salads and sauces and a large soft drink company tested them for their diet drink lines (Anonymous, 1986). Others (Tyson Foods, Yoplait USA) have used the system mainly for profiling the temperature during distribution or for trouble-shooting temperature control problems (Fields, 1991). Other recent applications of FreshCheck include fresh prepared meals, meat products and cultured dairy products, refrigerated salads, cream-based dips, fresh prepared foods, and fresh prepared sous vide meals by several different companies (Fields, 1991).

Current applications are few but important in that they demonstrate the TTI potential as well as highlight the area of existing problems that need to be solved for wider application or other types of applications to be successful. As a matter of fact, TTI applications may be extended to other products, such as health care products, horticultural products, etc. For example, one of the first and most significant applications was the use of the diffusion type TTI (3M) by the World Health Organization (WHO) to monitor refrigerated vaccine shipments (Manske, 1985).

In addition, with the use of TTIs, a new inventory policy has been proposed to replace the traditional first-in first-out (FIFO) issue policy, which is called least shelf life first-out (LSFO) (Taoukis and Labuza, 1989a) or shortest-remaining shelf-life (SRSL) (Wells and Singh, 1989) issue policy. The advantage of this policy is to reduce food waste and to provide more consistent quality at time of issue for food items which have been exposed to fluctuating temperature conditions.

Summary

The use of TTIs is currently being considered by many manufacturers and the USDA as a means to monitor or predict food safety and shelf life based on the temperature history of the food. With the principles and methodology discussed in this paper, one should be able to decide whether one should employ a TTI tag for a particular food, how to choose a TTI tag properly, how to calculate the effective temperature for a variable time-temperature distribution, how to correlate the TTI response with food quality or shelf life, and how to calculate the quality loss or shelf life remaining correctly.

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