exposed to products of gradually slipping quality. That makes the need of alternative ways of assessing quality apparent\textsuperscript{43}.

**FACTORS IN "SCALING UP" SHELF LIFE DATA**

Another problem in shelf life testing relates to whether the samples used in the test will be representative of the actual product which will be made. It is obvious that one cannot test the real final product during the R&D stage because that product has not been yet produced on a regular basis in the processing plant. Thus, several factors come into play which will create a larger (but unknown) window on the true shelf life of the product.

One major factor will be initial ingredient quality. The more that ingredients are bought in bulk, the greater the possibility that they will degrade over time in storage at the processors level and thus reduce final shelf life of the finished product. Another factor is processing conditions. If the shelf life must be known early on, in order to make marketing decisions; then the test product will be made in the lab or pilot plant. Thus, the time/temperature/mixing etc conditions the ingredients will be subjected to, will be different than those conditions for the final industrial process. Generally the larger the volume, the slower it takes to reach equilibrium conditions and thus the product has a greater chance for degradation. For many situations the $x^2$ rule holds; if the vessel diameter increases, and given all else remains the same, it will take $t \cdot \left(\frac{x + \Delta x}{x}\right)^2$ times longer to reach the same temperature condition; i.e.

$$t = 1.56 t \text{ for } x \text{ increasing by } 25\%, \ t = 4 t \text{ for } x \text{ doubling in size.}$$

This same rule applies to diffusion, i.e. moisture gain or loss. Thus the process takes away valuable real shelf life which will not be known if the testing is done on lab made or pilot plant made product.

**SHELF LIFE AND OPEN DATING REGULATIONS**

Another driving force for shelf life testing is a legal one. Many government organizations have stipulated that certain foods must have some type of open date. This has been reviewed by the U.S. Congress Office of Technology Assessment\textsuperscript{48} and summarized as an IFT status summary\textsuperscript{49}. In Europe, under new ECC regulations,
all foods must have some type of shelf life date beginning in 1993. These dates may include the following:

a. Pack Date: This can be the actual date the product was processed and packaged and lets the consumer know how old the product is so they can make a selection judgement. However, for some products the pack date can be confusing. For example orange juice which is seasonal may be concentrated and frozen in bulk tanks. It is later thawed and put into consumer packages. What is the pack date? Fish when caught and kept in a boat hold immediately begin to deteriorate. If a boat stays out for 7-10 days, how do we determine when an individual fish was caught? Is the catch date the pack date?

b. Sell by Date: In some U.S. states and in some European countries many perishable processed foods require a sell by date. It is clear that this date is just a qualified guess usually based on prior experience. Abused product will still have the same date as unabused product and thus the consumer could get unacceptable product. One could date all products with the date based on the worst possible ingredient/processing/distribution condition but that means much good product would be discarded based on a given sell by date. One could also use a sell by date but tell the consumer it is good for an additional number of days, weeks, etc. In fact unless the true compositional (C) and environmental (E) factors are known, the date is only a estimate and might be a poor one. This would be true for all other types of dates to be discussed. It should be noted that retail market personnel prefer a sell by date to help them in stock rotation which is better than a first in first out basis. The problem is that consumers pick over and choose the youngest foods thinking they are getting higher quality and thus defeat the rotation system.

c. Use by Date. The sell by date with a warning to consume within ___ days or an actual "use by date" are other approaches that can be used. In addition some companies use a "freeze by date" which ensures the customer of longer shelf life beyond the "use by" date. Consumers look at use by dates as "death" dates, i.e. after that day the food is inedible or unsafe. With foods that have a short shelf life (e.g. milk) in which the route to end of shelf life is an increasing logarithmic function as would occur with microbial spoilage, the shelf life can be stated mathematically as:

$$\ln \frac{N}{N_0} = k_g t$$

(13)

where $N$ is the number of microbes at time $t$, $k_g=\ln 2 / G$, with $G$ the organism generation time and $N_0$ is the initial microbial population. When $N$ reaches $N_F$, the level at which organic unacceptability occurs, the food is spoiled. This is around $10^6$
to $10^7$ cfu/ml. As seen in Figure 5 the time to reach that number agrees with the lower reported times for end of shelf life; also it has the same temperature dependence as the average line for the sensory end of shelf life. Since growth is rapid, foods like milk do "expire" within a very narrow window of time [usually ± 12 hours]. However, for long shelf life foods such as canned vegetables or

![Graph](image)

**Figure 5.** End of shelf life of pasteurized milk at different storage temperatures compiled from many sensory shelf life studies from the literature. The time for the psychrotrophic microbial count to reach $10^7$ cfu/ml is superimposed.

ready to eat cereals there is a much wider window of when they become unacceptable. The above equation also relates shelf life to the quality factors introduced earlier; $N_o$ is dependent on ingredient selection and control as well as on processing while $k_g$ is a function of compositional factors such as $a_w$, nutrients, and pH as well as environmental factors such as % RH, temperature and gas composition that can change with packaging and distribution. $N_F$ the final quality level can only be found however, by testing the food under given conditions and relating the microbial
level to some sensory score. In many cases the sensory quality and time to the end of shelf life have different \(Q_{10}\) values as in Figure 2 making quality prediction difficult.

d. Best if Used by Date. Given the fact that some products will have a window on time with respect to acceptability, another approach is to use a "best if used by" date. This is similar to the EEC date called "minimum durability". This is good for products which deteriorate more slowly and are not subject to dramatic extremes in distribution. It has been used in the U.S. for canned foods, cereals, and salad dressings. This date is also subject to the same caveats discussed earlier.

Since each type of open dating has some disadvantages it has been proposed by OTA that a combination of two dates as well as information on home storage conditions would be the most appropriate. For example, a "best if used within ___ days of date stamped on the package" gives the food retailers a "sell by" date (the date stamped) and a date for the consumer's guidance. A step further would be similar to the approach that was adopted by the United Kingdom in 1964 and later by other European countries, for frozen food storage. The "star marking" system required home freezer manufacturers to mark different compartments of the equipment according to the temperature they maintain. The same symbols were used in frozen food packaging with recommended storage time at each condition. An example of two Danish products labeled with the star system is shown in Table 3.

**Table 3. Frozen Foods Labeled with the "Star System".**

<table>
<thead>
<tr>
<th>Star code</th>
<th>Avg. Temp.</th>
<th>Remaining shelf life after &quot;sell date&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mixed vegetables</td>
</tr>
<tr>
<td>Refrig.</td>
<td>+5 °C</td>
<td>1 day</td>
</tr>
<tr>
<td>*</td>
<td>-6 °C</td>
<td>4 days</td>
</tr>
<tr>
<td>**</td>
<td>-12 °C</td>
<td>14 days</td>
</tr>
<tr>
<td>***</td>
<td>-18 °C</td>
<td>60 days</td>
</tr>
</tbody>
</table>

It is clear that even if the most appropriate combination of open dating is employed and is used as suggested above, it falls short from giving any information on the actual distribution conditions and thus the real quality state of individual products. Significant waste of food occurs in the distribution chain. It is very difficult to obtain an accurate estimate of what this waste amounts to. The food industry has been very reluctant to disclose quantitative information on losses due to spoilage, let alone finance relevant studies. A major report was published by the National Science
Foundation in 1979, under the title "Food Losses and Wastes in the Domestic Food Chain of the United States". From this report, estimated losses during distribution for four food categories are listed in Table 4.

Table 4. Food losses during distribution (Source: NSF, 1979)

<table>
<thead>
<tr>
<th>Food Type</th>
<th>Percent Loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frozen Foods</td>
<td>1.0 - 2.9%</td>
</tr>
<tr>
<td>Dairy Products</td>
<td>0.7 - 3.5%</td>
</tr>
<tr>
<td>Fresh Beef</td>
<td>4.8%</td>
</tr>
<tr>
<td>Fresh Produce</td>
<td>9.1 - 16.6%</td>
</tr>
</tbody>
</table>

The numbers in Table 4 refer to losses occurring from the time a product leaves its major processor or producer until it enters the supermarket. Substantial losses can happen subsequently in transport to the home and during home storage. Little information is available on this further loss. Ideally, what would be needed is a cost effective way to individually monitor the conditions of the products throughout distribution all the way to final point of consumption and continuously indicate the remaining shelf life. Such a system could lead to effective quality control of the distribution, optimized stock rotation, reduction of waste and some meaningful information on product "freshness," much sought by the consumer. Time-Temperature Indicators (TTI) are a step towards this direction.

**Time-Temperature Indicators**

Generally a *Time-Temperature Indicator* (TTI) can be defined as a simple, inexpensive device that can show an easily measurable, time-temperature dependent change that reflects the full or partial temperature history of a (food) product to which it is attached. TTI operation is based on mechanical, chemical, enzymatic or microbiological systems that change irreversibly from the time of their activation. The rate of change is temperature dependent, increasing at higher temperatures in a manner similar to most physicochemical reactions. The change is usually expressed as a visible response, in the form of a mechanical deformation, colour development or colour movement. The visible reading thus obtained gives some information on the
storage conditions that have preceded it. The ability of TTI to function as cumulative
recorders of temperature history from their activation time to the time each response
measurement is taken, make them useful for two types of applications.

TTI can be used to monitor the temperature exposure of individual food
packages, cartons or pallet loads during distribution up to the time they are displayed
at the supermarket. By being attached to individual cases or pallets they can give a
measure of the preceding temperature conditions at each receiving point. These
points would serve as information gathering and decision making centres. The
information gathered from all stations could be used for overall monitoring of the
distribution system, thus allowing for recognition and possible correction of the more
problematic links.

The second type of TTI application involves their use as quality monitors.
With quality loss being a function of temperature history and with TTI giving a measure
of that history, their response can presumably be correlated to the quality level of the
food. If that can be achieved, TTI can be used in either (or both) of two ways. The first
would be as an inventory management and stock rotation tool at the retail level. The
approach used presently is the First In First Out (FIFO) system according to which,
products received first and/or with the closest expiration date on the label are
displayed and sold first. This approach aims in establishing a "steady state" with all
products being sold at the same quality level. The assumption is that all products
have gone through uniform handling, thus quality is basically a function of time. The
use of the indicators can help establish a system that does not depend on this
unrealistic assumption. The objective will again be the reaching of a "steady state"
situation with the least remaining shelf life products being sold first. This approach
could be coded LSFO (Least Shelf-life First Out). The LSFO system could
theoretically (although not proven) reduce rejected products and eliminate consumer
dissatisfaction since the fraction of product with unacceptable quality sent into the
distribution system will be eliminated. Secondly, TTI attached on individual packaged
products, can serve as dynamic or active shelf life labeling instead of (or in
conjunction with) open date labeling. The TTI would assure the consumers that the
products were properly handled and would indicate remaining shelf life. Use of TTI as
"consumer indicators" is the ultimate goal of these systems.

A variety of TTI based on different physicochemical principles have been
described by Byrne (1976)\textsuperscript{52} and Singh and Wells (1986)\textsuperscript{53}. Statistical correlations of
TTI performance and product quality characteristics have been reported for a variety of
perishable and frozen foods\textsuperscript{54,55,56}. A general approach that allows the correlation of
the response of a TTI to the quality changes of a food product of known deterioration modes, without actual simultaneous testing of the indicator and the food, was developed by Taoukis and Labuza (1989)\textsuperscript{57}.

Use of TTI on food products is still in the exploratory stage. Part of the problem is that accurate shelf life characterization of the food products by the food manufacturers is for the most part missing. The value of such information is becoming more clear with novel products of prolonged shelf life such as extended shelf life refrigerated products (ESLR). A second problem is that the TTI activation energy must be within 5 to 10 kcal/mol of the activation energy of the food to be used as distribution monitors\textsuperscript{57} and much closer for a consumer tag. The available TTI limit the choice of $E_A$. Methods of correcting the error in quality loss prediction caused by the difference in $E_A$ are currently under development in our laboratory. A third problem is related to the so called "history effect" discussed by Labuza (1984)\textsuperscript{7}. It refers to the behaviour of some foods that show a different reaction rate at a given temperature than the one predicted from the Arrhenius relation when they were previously exposed to higher temperatures for various periods of time. This effect cannot be accounted for with TTI that do not show a history effect. Microbial growth is also difficult to monitor with TTI. Microbes go through a lag and log phase on which the effect of temperature needs to be better characterized mathematically. Solutions to these problems combined with a better understanding of the TTI and lower cost makes the widespread use of TTI a safe prediction for the near future. Ideally the consumer of the 1990's will have an active shelf life labelling assuring him of the quality of the food product.

Other alternatives to monitoring temperature during food distribution include the use of flexible, miniaturised electronic temperature recording devices\textsuperscript{59}. They can be as small as 2 in$^3$ and are battery powered. They record time-temperature information that can be displayed and processed at the receiving end by interfacing with a microcomputer. Examples of such devices are the Temp Mentor and Data Mentor (Ryan Instruments Inc., Redmond, WA) and the Datatrace Micropack Tracer (Ball, Broomfield, CO). Recently a satellite tracking system (Geostar Satellite Tracking Service, Geostar Corp., Washington, D.C.) was introduced\textsuperscript{60}. It continuously monitors location, time and temperature of refrigerated and frozen foods during distribution by truck, tracking shipments and transmitting real-time data to shipper and customer via two geostationary satellites positioned 22,300 miles in space above the U.S.
FUTURE DEVELOPMENTS

The drive to achieve higher quality and extended shelf life products will come closer to realization in the near future. The areas in which improvement or innovation will contribute to this goal in the 1990's are outlined below.

a. Improvement in analytical procedures and better understanding of food quality factors as related to their organoleptic characteristics, defined by sensory evaluation.

b. Just in time ingredient supply to ensure high initial quality. This will be coupled with optimized or novel processing to minimize quality losses in the finished product.

c. Lower cost and larger selection of packaging materials with specified barrier properties for O₂, H₂O and CO₂, possibly in conjunction with "in package" scavengers of these gases. Also better temperature insulating packages.

d. Education of scientists in food quality modeling and ASLT procedures. Education of the marketing sector on the limitations of ASLT.

e. Better food distribution control. This will be based on electronic or satellite temperature monitoring and reliable TTI with consumer readable endpoints. Those TTI will be designed to achieve any desired activation energy. Distribution data will be tabulated on a universal scale and will be available on CD ROMs. Such information will be used for accurate estimates of the expected shelf life of food products. In addition to temperature, monitoring of exposure to relative humidity of moisture sensitive foods will be incorporated. Combined Time Temperature/ Relative Humidity Indicators (TTI/RHI) can be developed that will integrate quality loss of a food/package system exposed to variable temperature and RH conditions based on the discussed computer models.

Even with use of all the mentioned distribution concepts for an optimized distribution, especially of refrigerated products, a producer owned and operated system may still be required, similar to the "Cold Chain" of Marks & Spencer PLC of UK\textsuperscript{61}.

Successful implementation of the above points will give the consumer of the 1990's food products of superior quality with the added convenience of extended shelf life.
product its final form and characteristics (except in the relatively few cases where post processing aging is necessary, e.g. in wines and hard cheeses).

Once the food leaves the processing stage its keeping properties and the extent to which it will retain its intended attributes is a function of the microenvironment in the package. The important parameters are gas composition (oxygen, carbon dioxide, inert gases, ethylene, etc.), the relative humidity (%RH), pressure or mechanical stresses, light and temperature. These parameters are dependent on both packaging and storage conditions, the other two factors. It is interesting to note that in many large U.S. food companies the shelf life testing function was (or still is) the domain of the packaging research group based on the erroneous assumption that packaging changes are all that is needed to increase product life. This assumption completely ignores the interactivity of the four factors delineated above.

In the modern, largely urbanized society, food products are often manufactured thousands of miles away from their final destination and perishables formerly available only in season are being demanded and supplied year around. Today’s consumers are more sophisticated and increasingly expect food products with more sensory appeal, that are convenient to prepare and use, nutritionally superior and longer lasting. At the same time consumers want less additives and optimized, minimal processing. The seemingly incompatible objectives of the longer shelf life but less processed (fresher) foods require intense optimization at all the preservation parameters and possibly innovative approaches to ensure minimum food degradation.

In the actual process of designing and introducing a new food product additional parameters play a major role in the optimization scheme, namely cost and marketing considerations. The latter introduce constraints that preclude the use of certain ingredients or processes and in some cases dictate the use of particular alternatives. These requirements are based on real or perceived consumer attitudes on what constitutes a nutritious and healthy diet and in many cases they restrict the use of formulas that would otherwise be the choice of an optimum product from a cost/quality standpoint. A very recent example is the trend in which "tropical" fats (coconut and palm oils), because of their supposedly unhealthy image because they are highly saturated, are being replaced with polyunsaturated vegetable oils in formulated foods. The substitution not only is cost ineffective, but also adversely affects the shelf life of the product, introducing increased susceptibility to lipid oxidation. Thus, the change of a single processing parameter will lead to complete reevaluation of the optimum production scheme, possibly requiring reformulation (e.g. addition of antioxidants), changes in processing and especially new packaging or an