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WHITE PAPER

Fresh Food – Dynamic Expiration Dates Using Auto-ID Technology and Analytic Shelf Life Models

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ABSTRACT

Foodborne disease accounts for a large percentage of human illness, while at the same time edible and safe foods and medicines are unnecessarily thrown away. In many cases, this is a result of poor storage conditions on the one hand and waste and ignorance on the other. If we could somehow determine the actual state of the food or drug – whether it was "good" or "bad" – we could save millions of lives and billions of dollars. While it is not yet possible to completely determine the condition of a perishable item, we may be able to approximately infer its state. In this paper, we propose to use automatic identification and wireless temperature measurement coupled with computer modeling to determine the condition of a perishable item in real-time. The direct application of this approach is a dynamic measurement of food quality and a variable expiration date that depends on actual food storage conditions.

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Biography

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Co-Director

Dr. David Brock received Bachelors degrees in theoretical mathematics and mechanical engineering from MIT, and his Masters and Ph.D. degrees from the Department of Mechanical Engineering at MIT with an affiliation to the Artificial Intelligence Lab. He is currently a Principal Research Scientist in the Laboratory for Manufacturing and Productivity and Co-Director of the MIT Auto-ID Center. Dr. Brock is also the Founder of Brock Rogers Surgical, a manufacturer of robotic medical devices. Dr. Brock has worked with a number of organizations including the Artificial Intelligence Laboratory, the Massachusetts Eye and Ear Infirmary, DARPA, Lockheed-Martin, Loral, BBN and Draper Laboratories.

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Contents

1. INTRODUCTION

We propose to replace the expiration date as a fixed number with a dynamic function whose outcome depends on the actual storage conditions of the food or medicine. By applying Auto-ID Electronic Product Code (EPC) tags on food items coupled with wireless temperature telemetry, food quality and safety can be much more accurately predicted [1, 2, 9].

We have combining automatic identification and temperature measurement with computer modeling to infer the quality of the food in real-time. Short lived temperature variations, for example, were recorded and their impact was integrated with on-going calculations of shelf-life.

This concept was applied first to the United States Department of Defense combat rations – the MRE (Meals Ready to Eat), but could be easily generalized to all perishable foods and medicines, as well as non-consumable chemicals and materials.

The extraordinary dependence of chemical, biological or mechanical reactions on temperature has been well characterized by the Arrhenius equation, which was suggested by Svante August Arrhenius, a Swedish chemist in 1889. It was this equation we applied to determine the current product quality and the remaining shelf-life.

The general application of this idea could, potentially, reduce illness resulting for foodborne disease as save valuable food from unnecessary disposal.

2. BACKGROUND

An estimated 76 million cases of foodborne disease occur each year within the United States resulting in 325,000 hospitalizations and 5,000 deaths [3, 4]. Food related illness worldwide is even larger. In 1998, according the World Health Organization (WHO), an estimated 1.8 million children in developing countries died from diarrheal disease, and the primary cause of this being contaminated food and water [5].

On the other hand, vast amounts of food and medicine are wasted daily – much of it simply because it has past its expiration date. In many cases, this material is perfectly safe and edible. An estimated 96 **billion** tons of edible food – or 26 percent of the United States production – is thrown out each year and disposed into landfills [6].

The expiration date is, in fact, a “rule of thumb.” A product’s safety may last long after the expiration date has transpired – particularly if it is properly stored. Improper storage, elevated temperatures or excess humidity may significantly reduce the product’s safety and efficacy long before the expiration date is reached.

Selling food past its expiration date does not necessarily violate the FDA’s regulations or law. The FDA’s regulations relate primarily to food safety. The quality of the food, its taste, texture, aroma and appearance, is greatly affected by age and temperature, which is distinct from safety. However, all aspect of food and medication are affected by storage.

Storage has a profound impact on product quality and safety. When storage conditions are ideal – when the temperature and humidity are low – food may retain its quality for significant periods – long after the date printed on the label has past. However, with elevated temperatures food quality may deteriorate very rapidly.

As this paper illustrates, temperature is the predominate factor determining the longevity and quality of stored food, medicine and perishable products. Temperature, as we will see, has an **exponential** impact on the viability of a product.

Using temperature measurement – whether on the product or within the environment – coupled with automatic identification technologies, such as RFID and the Electronic Product Code, we can much more accurately determine the state of the product. In this way, we can properly dispose of the product when it is no longer viable, but, as importantly, retain the product while it is good – irrespective of a fixed expiration date.

3. SHELF LIFE MODEL

Food quality and safety is an aggregate of characteristics that affects the product's ability to satisfy the needs of the customer [7]. Quality may be affected by a number of factors that may be physical, chemical or biological in nature, and that act in complex and interconnected ways. Food quality may change in short time scales as a function of food processing or on long as a result of storage and refrigeration.

Although many agents affect food quality, temperature is often the single, dominant factor. Here we present the equations that determine food quality as a function of the single variable – temperature.

3.1. Chemical Kinetics

The reaction rate is the speed of a chemical reaction. The general form of a chemical reaction is

$$aA + bB \rightarrow cC + dD \,,$$

where A and B are generic reactants and C and D are products, and a, b, c, and d the quantity of each.

Given the stoichiometry we have

$$-\frac{1}{a}\frac{d[A]}{dt} = -\frac{1}{b}\frac{d[B]}{dt} = \frac{1}{c}\frac{d[C]}{dt} = \frac{1}{d}\frac{d[D]}{dt}$$

and the **differential rate law** is

$$-\frac{1}{a}\frac{d[A]}{dt} = k[A]^n[B]^m$$

where n is the **order of the reaction** with respect to A and m is the order of the reaction with respect to B. The sum $n+m$ is called simply the order of the reaction. The order of the reaction with respect to each reagent must be found experimentally and cannot be predicted or deduced from the equation for the reaction.

The constant k is the **rate constant**, or more formally, the specific-reaction rate constant, since it is numerically equal to the rate the reaction would have if all concentrations were set to unity. Each reaction is characterized by its own rate constant whose value is determined by the nature of the reactants and the **temperature**.

3.2. Food Quality

A mathematical model of the change in **food quality** follows the general form of the chemical kinetics equation presented above. We can simplify and generalize the chemical kinetics, and use this to determine the rate of food degradation. Let us define a single variable Q to describe quality then $Q(t)$ as a function of time is

$$D(Q)(t) = -kQ(t)^n$$

where k is the rate constant and n is the order of the reaction. If we assume an arbitrary initial value for "goodness" of 1; that is, $Q(0) = 1$, we then have the following simple equations as given below.

3.3. Arrhenius Kinetics

The most common assumption about the behavior of k is embodied in **Arrhenius kinetics**, that is the assumption that

$$k = k_1 e^{\left[-\frac{E_a}{R_g T(t)}\right]}$$

where k_1 is the pre-exponential constant, E_a is the activation energy, and R_g is the **universal gas** constant.

Thus the equation of **food quality** is given as

$$D(Q)(t) = -k_1 e^{\left[-\frac{E_a}{R_g T(t)}\right]} Q(t)^n$$

3.4. Parameters

The food quality equation given above depends on three unknown parameters besides temperature. These include n the **order of the reaction**, k_1 the pre-exponential constant and E_a the activation energy of the reaction. The R_g is the well know **universal gas constant**

$$R_g = 8.314\left[\frac{m^2 kg}{s^2 K mol}\right]$$

3.5. Examples

Example 1: Rate Constant
The Arrhenius equation for the rate constant is given by

$$k = k_1 e^{\left[-\frac{E_a}{R_g T(t)}\right]}$$

Suppose the activation energy E_a is

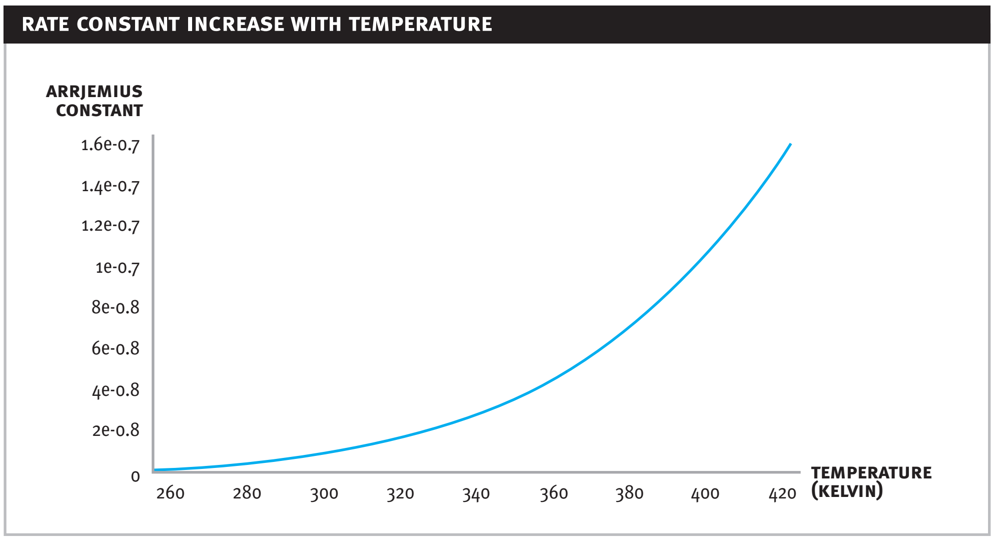
$$E_a = 25000\left[\frac{m^2 kg}{s^2 mol}\right]$$

the pre-exponential constant k_1 is

$$k_1 = 0.0002 s^{-1}$$

If we plot the rate constant as a function of temperature, given the above equations, we have the following graph.

Figure 1: Rate constant k increases significantly with temperature.



Example 2: Food Quality

Suppose we have two samples of the same food exposed to constant of 40 degrees F and 120 degrees F respectively. Given the assumptions in the previous example and assuming a second order rate of reaction we have the following equations

$$D(Q)(t) = -0.408\times10^{-8} s^{-1} Q(t)^2 \qquad \text{for } 40° \text{ F}$$

and

$$D(Q)(t) = -0.174\times10^{-7} s^{-1} Q(t)^2 \qquad \text{for } 120° \text{ F}$$

Assuming a initial condition of Q(0) = 100%, we have the equation for quality as a function of time (in days) is

$$Q(t) = \frac{0.125\times10^{11}}{0.4406\times10^{7} t + 0.125\times10^{9}} \qquad \text{for } 40° \text{ F}$$

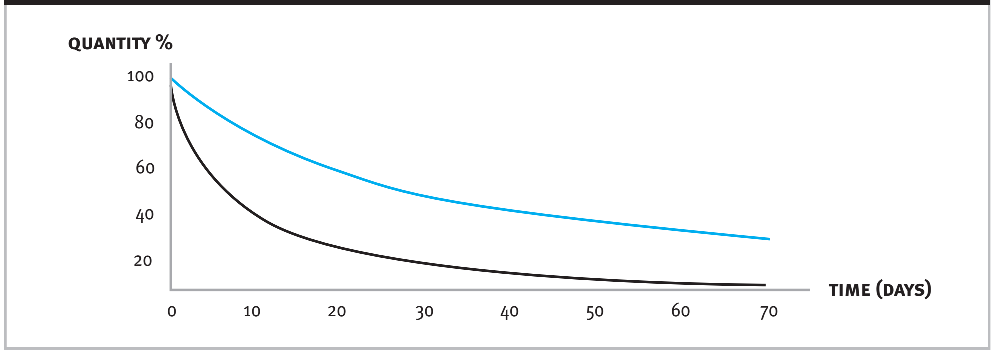
and

$$Q(t) = \frac{0.500\times10^{10}}{0.7517\times10^{7} t + 0.500\times10^{8}} \qquad \text{for } 120° \text{ F}$$

Plotted as a function of time, we see that food quality decreases rapidly with higher temperatures.

Figure 2. Food quality decreases with time and temperature.

FOOD QUALITY DECREASES WITH TIME AND TEMPERATURE



Example 3: Time and Temperature

Here will illustrate the effects of both time and temperature. It is clear from the model that even a short exposure to high temperatures can severely degrade the quality of the food.

Given the food quality equation

$$D(Q)(t) = -k_1 e^{\left[-\frac{E_a}{R_g T(t)}\right]} Q(t)^n$$

We substitute values from the previous examples

$$D(Q)(t) = -17.28 e^{\left[-\frac{3007}{T}\right]} Q(t)^2$$

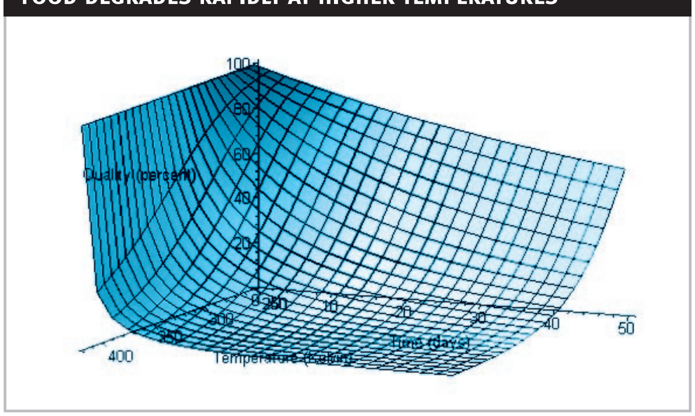
Again given the initial condition of 100% quality food; that is, Q(0) = 100%, we have the following equation for quality as a function of both time and temperature

$$Q(t) = \frac{25}{432 e^{\left(-\frac{15034}{5T}\right)} t + \frac{1}{4}}$$

Plotting quality as a function of time (in days) and temperature (in Kelvin), we have

Figure 3: Food degrades rapidly at higher temperatures.

FOOD DEGRADES RAPIDLY AT HIGHER TEMPERATURES



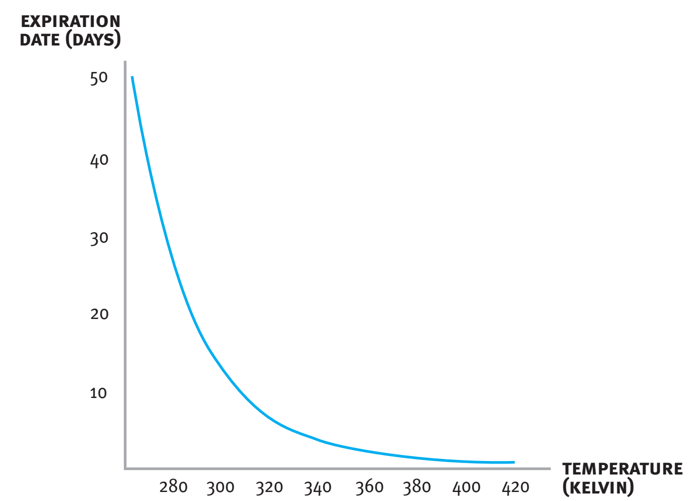
Example 4: Expiration Date
Now if we were to pick a reasonable value of food quality, say 50%, and used this as a measure of expiration, we would see that the expiration data changes drastically depending on the temperature.

Let's pick 50% quality as a measure of expiration. Now assuming the values from the previous example, we have the following plot of expiration date as a function of temperature.

Clearly, it would be impossible to pick **one** fixed value for expiration given its dependence on temperature, but that is what food and drug manufacturers must do.

Figure 4: Depending on the particular rate constants, expiration date varies widely as a function of temperature.

EXPIRATION DATE DROPS WITH HIGHER TEMPERATURES



4. SHELF LIFE DATA

The food quality equation depends on the three unknown parameters: n the order of the reaction, k_1 the pre-exponential constant and E_a the activation energy of the reaction. Thus if we had quantitative measures for food quality over a period of time for **three** constant temperature storage conditions, we could determine the unknowns and produce the general differential equation for quality. This is precisely what is done in practice.

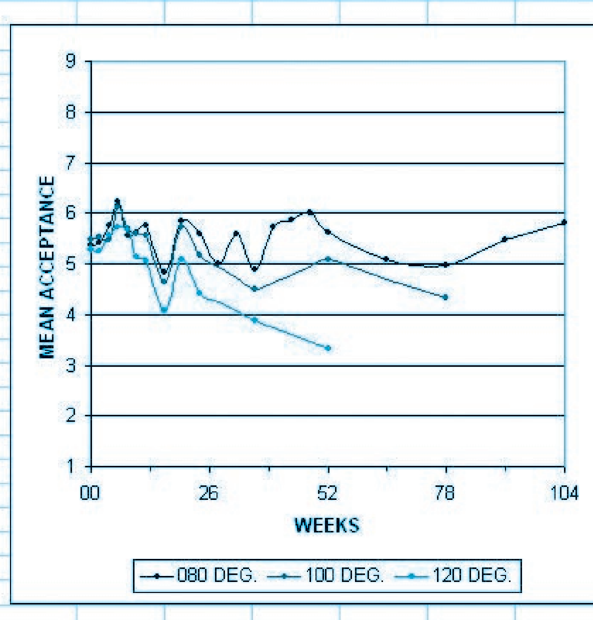
In order to test quality and to determine numeric values for the food quality equations, manufacturers and research centers store samples at three constant temperatures. These samples are then presented to groups of subjects who qualitatively rate the product. This is term a hedonic measure.

The figure below shows a typical sample from food quality testing [8].

Figure 5. Food quality is tested empirically for three constant storage temperatures. These data are sufficient to determine the three unknown parameters of the food quality equation.

Pasta Alfredo

WKS	080 DEG.	100 DEG.	120 DEG.
00	5.375	5.469	5.281
02	5.417	5.528	5.250
04	5.750	5.472	5.556
06	6.222	6.111	5.722
08	5.556	5.694	5.667
10	5.611	5.583	5.139
12	5.744	5.564	5.051
16	4.838	4.649	4.081
20	5.838	5.730	5.081
24	5.595	5.162	4.405
28	5.000		
32	5.579		
36	4.892	4.486	3.892
40	5.732		
44	5.865		
48	6.000		
52	5.629	5.086	3.314
65	5.077		
78	4.975	4.325	
91	5.486		
104	5.821		
130			
156			



<- Product dropped from study

As you might expect some foods become "bad" long before others, as shown in Figures 6 and 7.

Figure 6: Some foods become inedible…

Applesauce

WKS	080 DEG.	100 DEG.	120 DEG.
00	6.622	6.486	6.243
02	6.282	6.359	6.026
04	7.194	6.250	5.972
06	5.949	6.308	5.077
08	6.850	6.350	5.175
10	6.600	6.429	4.286
12	6.944	6.167	4.472
16	7.000	6.947	5.316
20	7.111	6.694	4.361
24	6.300	6.000	3.667
28	6.579		
32	7.189		
36	6.694	5.944	3.028
40	6.730		
44	6.730		
48	6.703		
52	6.583	5.944	3.056
65	6.316		
78	6.583	5.889	
91	6.842		
104	6.300		
130			
156			

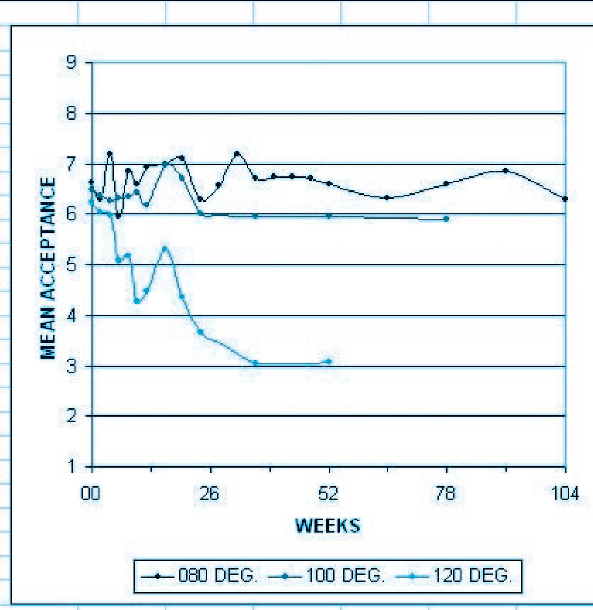
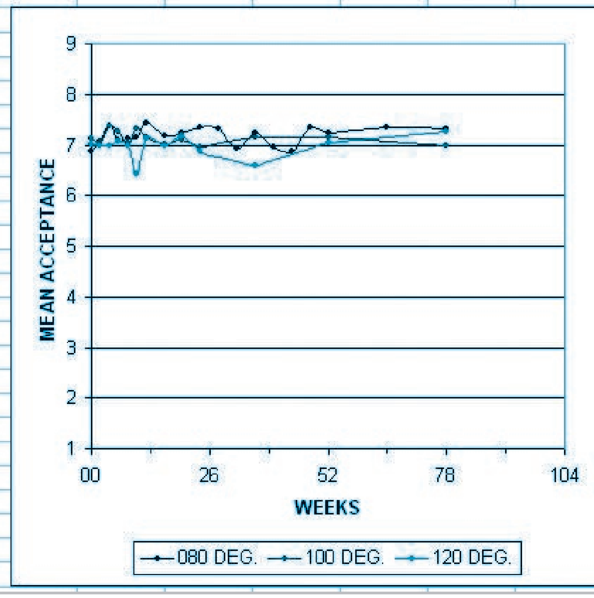


Figure 7: …long before others.

Peanut Butter

WKS	080 DEG.	100 DEG.	120 DEG.
00	6.878	7.122	7.024
02	7.083	7.028	7.000
04	7.385	7.385	6.974
06	7.108	7.270	7.081
08	7.135	7.054	6.973
10	7.158	7.316	6.421
12	7.444	7.167	7.139
16	7.189	7.027	6.973
20	7.237	7.105	7.184
24	7.361	6.972	6.861
28	7.324		
32	6.917		
36	7.250	7.167	6.583
40	6.946		
44	6.872		
48	7.359		
52	7.233	7.167	7.033
65	7.343		
78	7.333	6.974	7.256
91			
104			
130			
156			



Given the values for Q for the three temperatures, such as 80°F, 100°F and 120°F, as shown above, we may determine n, k_1 and E_a. Typically this involves numerical regressive techniques.

As is often the case, the order of the reaction is assume to be unity and the equation reduces to single exponential. By taking the natural logarithm and applying multiple linear regressive techniques we can find the nearest fit for values of k_1 the pre-exponential constant and E_a the activation energy of the reaction.

5. IMPLEMENTATION

The techniques described here may be applied across a broad range of perishable items from fruits and vegetables to paint and cosmetics. In particular, we wish to implement real-time temperature measurement and dynamic expiration dates to foods and medicines. If a product goes “bad” over time, it is most likely depends on temperature as described by the Arrhenius equation, as presented in the previous sections.

However, the concepts presented in this paper are being applied to “Meals Ready to Eat” (MRE) developed by the United States Department of Defense, as shown in Figure 8 [8].

Figure 8: The MRE, or “Meals Ready to Eat,” is the main United States Department of Defense combat ration. There is a wide variety of foods that make of the MRE and all have somewhat different temperature dependent degradation.

A variation of the Auto-ID EPC tag, as shown in Figure 9, provides not only identity and location, but also temperature measurement. These tags are affixed to the MRE as shown in Figure 10.

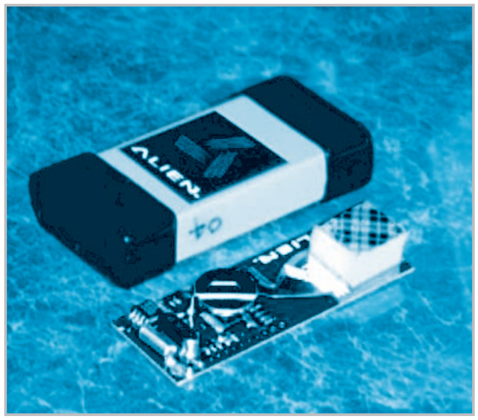


Figure 9: An semi-passive Auto-ID type III tag, shown here, is manufactured by Alien Technology, Inc. with read/write, battery powered, I/O port, temperature integration and a 30-200 meter range [9].

Figure 10: The temperature tag is affixed to the MRE.

Temperature telemetry from the tags can then be read remotely as shown in Figure 11.

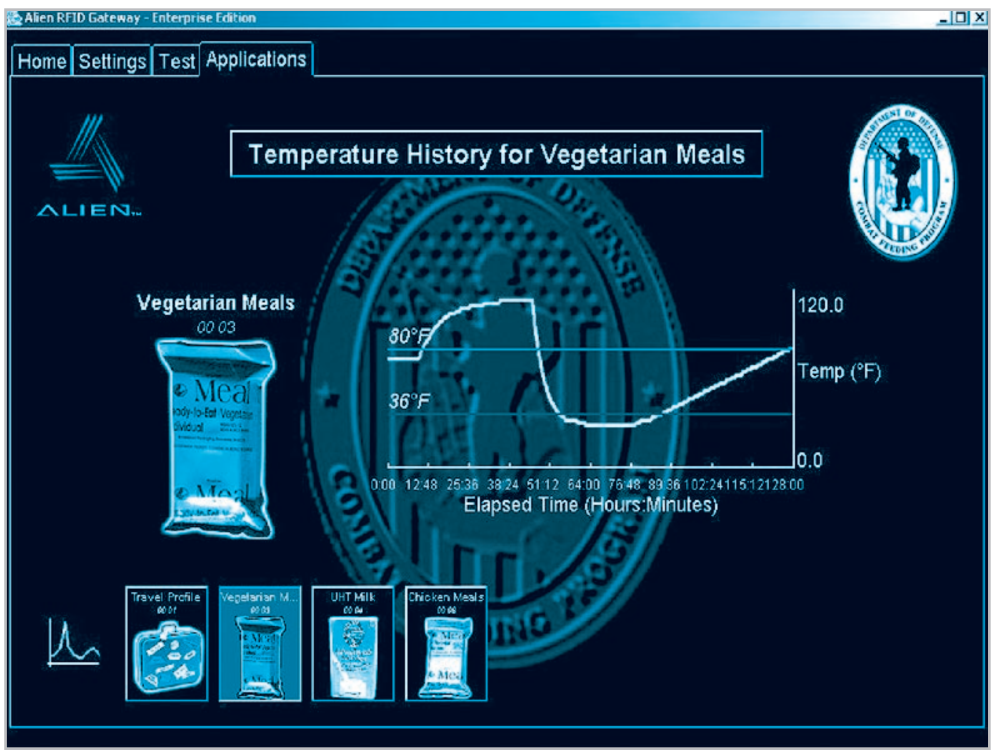
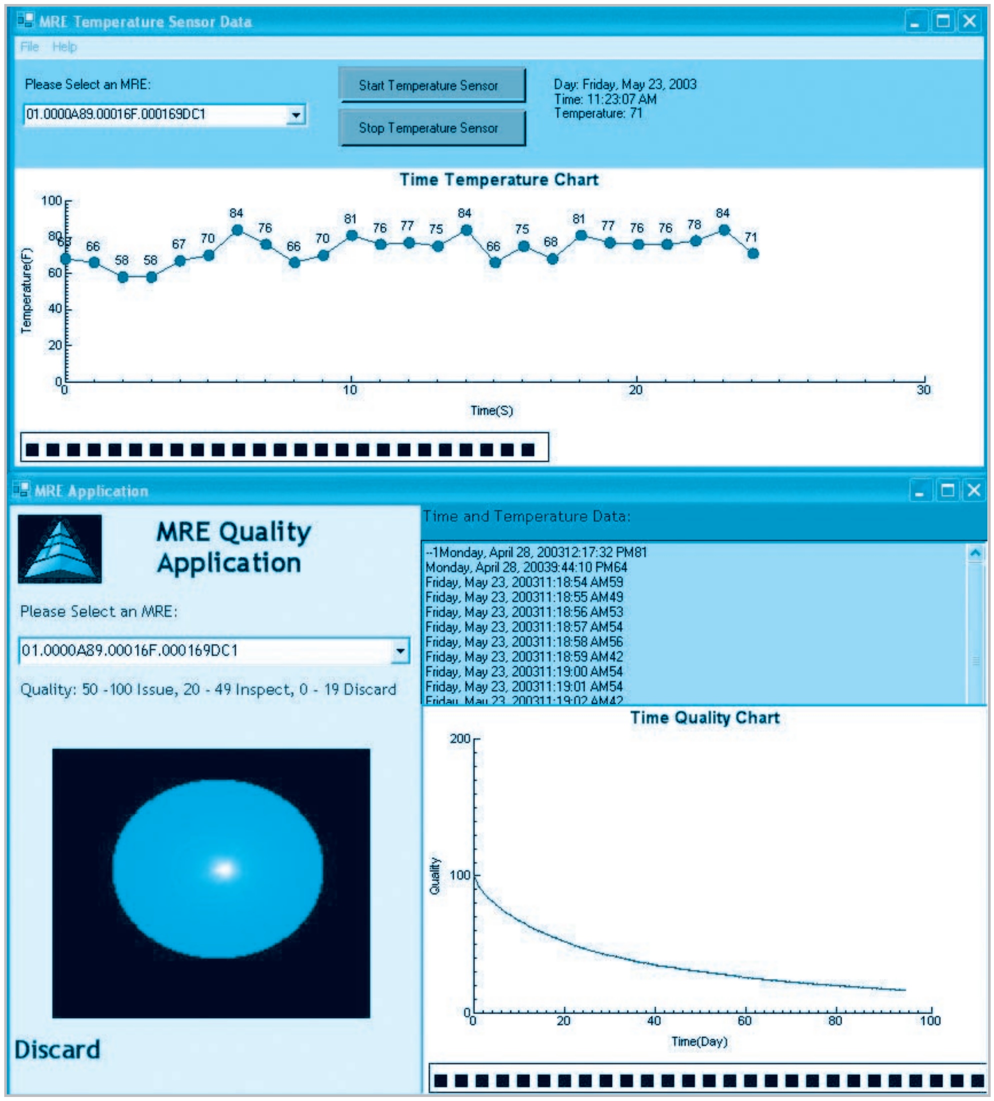


Figure 11: Temperature measurement can be measured wirelessly and in real-time for individual food items.

The temperature profile as measured from the food items are then input into a client process as shown in Figure 12. Here the client application shows not only the approximate food quality based on the temperature history, but also a simple directive to a field inspector – reject, inspect or issue. In this case, "rejection" corresponds to a quality below a minimum threshold and "issue" above a maximum value, while "inspect" is everything in between.

Table 12: Temperature measurement can be measured wirelessly and in real-time for individual food items.



6. CONCLUSION

We have shown here the potential for a revolutionary approach to food safety, in which expiration date varies widely depending on the **actual** storage conditions. Through the combination of automatic identification, wireless temperature telemetry and computer modeling, we have shown it is possible to more accurate model food quality and infer expected shelf-life.

Although the application shown was demonstrated for the combat ration, there is no reason why these results cannot be extended to other foods – or to perishable items in general.

In fact, the wide spread distribution of this technology could have a profound impact on food safety, and could potentially save billions of dollars in otherwise wasted resources.

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