FOOD, AGRICULTURE AND FISHERIES, AND BIOTECHNOLOGY

FRISBEE

Food Refrigeration Innovations for Safety, Consumers' Benefit, Environmental Impact and Energy Optimisation Along the Cold Chain in Europe.

Grant Agreement N°245288

Type of funding scheme: Large Collaborative Project

Deliverable D.2.1.2

Temperature monitoring techniques and traceability systems along the cold chain

Deliverable Information
Dissemination : Public
Nature : Report
Contractual Delivery Date : 30/06/2011
Actual Delivery Date : 26/07/2011

Scientific coordinator : Dr. G.Alvarez
CEMAGREF, France
e-mail : graciela.alvarez@cemagref.fr

Document Information

Project	: FRISBEE
Document	: Deliverable 2.1.2
Reference	: DEL2.1.2 S1
Filename	: FRISBEE DEL2 1 2 Temperature monitoring techniques S1.doc
Last saved on	: 23/05/2011 16:47 by Jacques Bertrand

Authorship and Review

	Name/Organisation	Approval Date
Written by	Petros Taoukis (NTUA); George Katsaros (NTUA); Lun Li (CEMA); Evelyne Derens-Bertheau (CEMA)	10/06/2011
For review by	Graciela Alvarez	22/07/2011
	Petros Taoukis	22/07/2011

Release Details

Release	Date	Comments
Draft 01	10/06/2011	First draft
Draft 02	22/07/2011	Second draft after assessment by Project Manager
Release 01	25/07/2011	First release after approval by WP Leader
Submitted	26/07/2011	Submitted to the Commission

Distribution List

- On the project Portal
- On the FRISBEE Intranet (http://www.projects-gateway.com/FRISBEE/)

Table of Contents

1. Aim

The aim of this deliverable is the systematic review of tools and methods used to monitor temperature conditions and assure traceability. Conventional and novel approaches are explored including temperature logging, transmission systems like Radio Frequency Identification (RFID) Technology, intelligent packaging, Time-temperature indicators (TTIs) and Radio Frequency- Time-temperature indicators (RF-TTIs). These techniques in practice have contributed to improve the management of the cold chain with regard to product quality and safety, energy consumption and environmental impact is assessed.

2. Introduction

The last decade, the food industry is facing critical changes with regards to consumer needs, food health benefits and safety issues. The quality of food products might deteriorate, due to the submission to a variety of risks during the whole cold chain. Successful supply logistic chains demand the automated and efficient monitoring and control for all operation steps.

The time/temperature history of a food product is crucial to its quality and safety –during the whole cold chain, including consumer handling- for both chilled and frozen food, as well as for some medical and pharmaceuticals products (Kerry, O'Grady et al., 2006; Estrada-Flores and Tanner, 2008; Montanari, 2008). Actually, food preservation in low temperatures is relatively recent. Until the 19th century, drying, salt, oil, vinegar or still alcohol were used to preserve food. These methods were relatively effective, but would modify the taste, the colour, the odour or the texture of food and could present sanitary risks. Nowadays, effective systems are widely used to store the food in low-temperature from the production to the consumption while simultaneously maintain their nutritional, sanitary qualities and their initial taste. Depending on the preservation temperature, low storage temperature can significantly decrease the growth rate of microorganisms and the rate of chemical and physicochemical reactions affecting quality.

The cold chain consists of various steps: manufacturing, storage, transport, distribution and consumer. Moreover, controlling the cold chain is a regulatory constraint, which professionals from different sectors have to manage. For these reasons, the traceability management is very important and care should be taken to ensure a successful surveillance.

Traceability

According to the ISO 9000 system, traceability has to do with the ability to trace the history, the application or the location of an entity, through specific recorded information. Traceability may be considered for different contents each of which has a different application:

- For products: it creates a link between materials, their origin and processing, distribution and location after delivery.
- For data: it relates the calculations and data generated through a quality loop and may link these back to the requirements for quality.
- In calibrations: it relates measuring equipment to national, international or primary standards, to basic physical constants or properties or to reference materials.
- In IT and programming: it relates design and implementation processes back to the requirements for a system.

Under the European Union law traceability means to track any food, feed, food-producing animal or substance that will be used for consumption, through all stages of production, processing and distribution. Traceability is needed because it is a way to respond potential risks that may arise in food or feed. Therefore, traceability ensures that all food products in the EU are safe for consumption.

The implementation of traceability systems may represent an expensive investment, yet there are several advantages that may be gained from it. If well designed, it may become a potential source of competitive advantage for those firms seeking operational efficiency and strategic effectiveness mainly in logistics and marketing (Montanari, 2008). Thus time/temperature control becomes a critical issue in fresh food logistics, and the efficient and effective tracking of cold chain conditions is one of the main points to be addressed (Montanari, 2008). For this, different traceability tools are currently available such as temperature recorders (logger) and wireless sensor technologies which enable a history tracking. Another type of tool is the Time-Temperature Indicators /or Integrators which can be correlated to the quality status of the product.

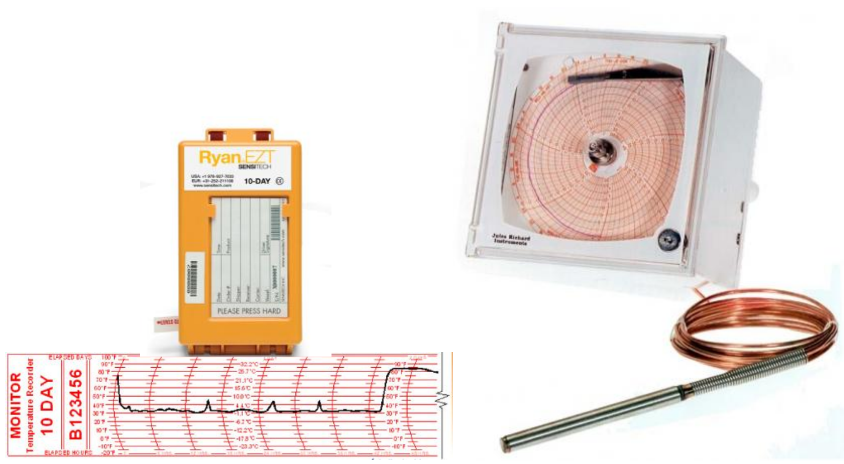
3. Temperature recorders/loggers systems and thermometers

Temperature recorders (mechanical and electronic) may be used for cold chain control. These devices varying in size and shape are composed of an internal and/or external temperature sensor, a measurement transmission system, an electronic memory or a paper plotter. They can record the product temperature or ambient temperature (such as the cold store, the transport vehicle…) at regular intervals and store these temperatures on an electronic memory (Picture 1) or on graph paper for mechanical registers (Picture 2). The output of information obtained by electronic recorders is often made by dedicated software (Ellouze, 2011). In addition, both one-off and reusable systems are available to electronic recorders as well as mechanical ones, in particular for the maritime transport and distant shipment.

Apart from these temperature recorders, thermometers are always used in temperature monitoring management. Thermometers are used as an instant temperature indicator for a specific location and a given time, whereas temperature recorders provide a full time-temperature history, and this is essential in order to detect any changes in environmental conditions that may have altered the quality of the food products.

Temperature recorders are usually used inside the refrigerating equipments, so they are designed to withstand in a range of temperature which may be between -40°C and +30°C. The recorder must be powered independently from the refrigerating system so that it continues to work even if the refrigerating equipment breaks down. In particular, recorders used in refrigerated vehicles must be able to withstand vibrations and shocks. The system should have a current certificate from an accredited laboratory, it should be robust and shock-proof, and the electrical components should be protected against moisture condensation.

Picture 1. Electronic recorders (external sensor and internal sensor)



Picture 2. Mechanical temperature recorders with paper print-out (left: one-off recorder; right: reusable recorder).

For all temperature measuring systems, it is important to carry out periodic checks/calibrations to ensure proper functioning and accurate measurement. This could be done by checking against a calibrated thermometer (a reference thermometer). The frequency of calibration must be defined by the user according to the equipment's operation conditions, but at least once a year (Bogh-Sorensen, 2006).

Two categories of measuring systems are used in the food industry regarding the sensor type (probe): the mechanical system and electronic system. Their specifications and accuracies are detailed below.

Mechanical system:

Glass bulbs filled with alcohol (accuracy: 0.1 to 1°C). Their use is limited to stationary thermometers in cold stores; they must not be in contact with foodstuffs, unless they are placed in a steel duct; the response time is long.

Vapour pressure or liquid expansion (accuracy: 1 to 2°C). A transducer transfers the variations of pressure or volume in the detector bulb to a remote indicator dial.

Bimetallic blades or coils (accuracy: 2 to 4°C). The distortions caused by the different between the expansions of the two metals are mechanically transferred to a graduated mobile paper print-out or to the needle of an indicator dial.

Electronic system:

Today electronic thermometers are used much more widely than the "mechanical" thermometers mentioned above.

Contact systems use the following types of sensors (probes); it could be internal or external:

- Variable-resistance sensor made of platinum wire (PT100, PT1000);
- Variable-resistance semiconductor sensor (thermistor);
- Thermocouples based on the occurrence of an electrical potential at the junction of two dissimilar metallic wires;
- Semiconductor probes supplying current or voltage proportionally to the temperature; accuracy from 0.5 to 2°C;
- Integrated circuits designed specially to measure the temperature. They include the probe and the measurement and memory functions, accuracy from 0.5 to 2°C.

Electronic sensors, controllers and transmitters are commercially available with differing accuracies. Standard commercial PT100 sensors, 4 to 20 mA transmitters and controllers have accuracies of 0.3°C for each component. Probes with a component accuracy of 0.03°C are only marginally and significantly more expensive than standard equipment.

Non-contact systems (Picture 3) that measure infrared radiation are often included in electronic thermometers. The advantage is that the product temperatures are measured "without contact". Nevertheless, the accuracy of measurement can vary from ±2 to ±6°C depending on the distance between sensor and product, the product temperature, the characteristics of the surface, and on the emissivity of the surface (packaging material). It is significant to notice that such instruments measure the surface temperature, which may be different from the temperature in the centre of the food.

A non-invasive internal frozen temperature detector (NIFT-D^{TM}) system exists for boxed frozen foods (Picture 3). It is a continuous on–line system that shines a beam of microwaves through each box of product and detects the level of transmitted microwaves that pass through. The system can be calibrated to infer both the thermal centre and the bulk average temperature of the product to an accuracy of ±2°C over a temperature range of -25 to +10°C and it can operate at sustained production rate of about 20 boxes per minute with no operator intervention (Clarke, 2007).

Picture 3. NIFT-D^{TM} system (Clarke, 2007)

European Regulations

Furthermore, it is easier to check the temperature of the surrounding environment in order to ensure that has reached the predefined conditions. The regulation for frozen foods requires only the air temperature recording. Air temperature can be measured using the previous devices. Temperature recorders and thermometers standardisations are available. European Commission Regulation 37/2005 requires temperature recorders and thermometer for means of transport, warehousing and storage of quick-frozen foods to conform to EN 12830 (recorder specifications), EN13485 (thermometer specifications) and EN 13486 (recommendation for periodic verification to recorders and thermometers). In addition, for product temperature control, the devices used should have a better accuracy than that for air temperature monitoring. It is recommended that:

- the accuracy should be ±0.5°C, and should be checked with regular intervals;
- the response time should achieve 90% of the difference between initial and final reading within 3 minutes.

4. Wireless Sensor Technologies (WST)

WST refers to Radio Frequency Identification (RFID) based on sensor devices and Wireless Sensor Network (WSN). RFID were initially developed for identification purposes, but the growing interest and potentials for other applications has led to the development of wireless sensor devices that can measure different parameters. The essential difference between a WSN and a RFID system is that RFID devices have no cooperative capabilities, while WSN allow different network topologies and multi-hop communication (Ruiz-Garcia, Lunadei et al., 2009; Faouzi, 2009).

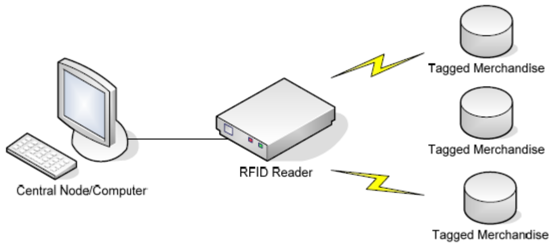
Many research efforts were attracted by these technologies during the last decade with an increasing maturity and adoption of standards, such as various ISO (International Organization for Standards) standards for RFID (ISO 15693, ISO/IEC 18000, ISO 11784, etc.) and Bluetooth and ZigBee for WSN (Ruiz-Garcia, Lunadei et al., 2009; Bhattacharyya et al., 2010). RFID-based technologies are being widely developed to all kinds of products' shelf life tracking. It is a potential tool for cold chain management in the food industry.

4.1. Radio Frequency Identification (RFID)

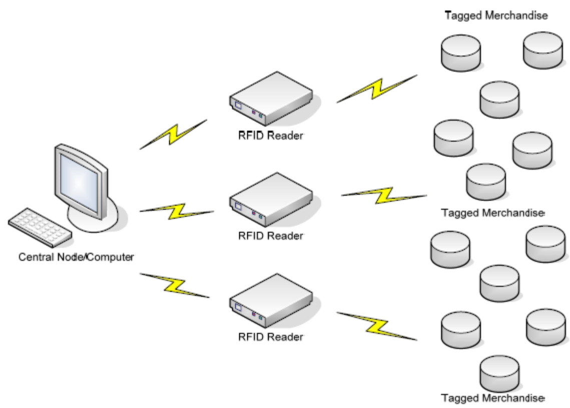
Radio Frequency identification (RFID) is an emerging wireless communication technology. Its protocol was built for short range product identification covering the 2 mm – 2 m read range with use of Electronic product Code (EPC). RFID is a generic term for technologies that use radio frequency waves to identify an object. This technology was developed as the replacement for the optical bar-code. It can overcome the barcode limitations: reading operation is typically performed manually and needs an unobstructed line sight. Moreover, thanks to RFID's anti-collision protocols, several items (up to 1000) can be identified concurrently; its reliability and accuracy are considerably higher than barcode technology (Montanari, 2008). In addition, RFID could be particularly used in cold chain management (using temperature sensors) for temperature sensitive products since it can record simultaneously the geographical track and the temperature of a food product. By recording the geographical track/position of the individual packaging, palettes or containers, one can identify the weak links through the whole cold chain (Estrada-Flores and Tanner, 2008). The continuous R&D and cost decrease of RFID systems will lead to a more effective use in the near future. Real-time data recording concerning environmental parameters (including temperature and humidity) and real time data transmission allow for corrective actions of the weak links before the products are significantly deteriorated. RFIDs are already being used in cold chains for temperature monitoring of perishable food (Montanari, 2008; Abad, Palacio et al., 2009; Jedermann, Ruiz-Garcia et al., 2009; Martinez-Sala, Egea-Lopez et al., 2009; Liu, Hu et al., 2010; Wang, Kwok et al., 2010; Wang, Zhang et al., 2010), however there are still potentials for a wider use of that kind of systems.

RFID systems mainly consist of the following components: the tag (or transponder), the reader, and the eventual sensor for environmental parameters tracking, which communicate with each other thanks to the radio transmission (Kumar, Reinitz et al., 2009). Five frequency ranges are commonly used by RFID systems: low frequency (9 to 135 KHz), high frequency (13.553 to 15.567 MHz), amateur radio band (430 to 440 MHz), ultra high frequency (860 to 930 MHz), and microwave frequency (2.45 and 5.8 GHz) (Kumar, Reinitz et al., 2009).

A simple RFID system operation begins with a reader interrogating the tagged merchandise by sending and receiving radio frequency signals to and from the tag, via their antennas. The tags respond back to the reader with a unique identification code assigned to it (EPC). The reader then transmits this data to the central node where a database is created. Typically, systems transmit data collected by the RFID reader to the central node over a wired Ethernet connection (LAN) (Picture 4). The implementation of such a system involves expanding it to the level of scale necessary (a retailer at the storefront or distribution level). Depending on the size of scale, installing the necessary wired infrastructure may outweigh the few benefits of wired networking, such as reliability and low power consumption. Coupled with the high installation cost, the implementation of a wired network infrastructure may not be justifiable. Another option would be to enable the reader and the server to communicate wirelessly via digital mobile telephony (GSM) or local area networks such as Zigbee (Picture 5). This may overcome the difficulty and cost of implementation.



Picture 4. Typical RFID System (Bellantoni, 2005)



Picture 5. Wireless-Enabled RFID System (Bellantoni, 2005)

4.1.1. RFID tags categories

RFID tag is a small device which can store data via a microchip. It could be attached to an object for logistics management purposes with the help of an antenna which transmits and receives the data. The size of a tag often depends on the size of the antenna because the microchip is usually very small (Picture 6); the smallest commercial tags are thinner than a sheet of paper (0.4×0.4 mm^2) (Roberts, 2006; Kumar, Reinitz et al., 2009).

Picture 6. Examples of RFID tag: Left: Courtesy of Behnam Jamali, the University of Adelaide; right: Courtesy of Mark Lohmann, CHILL-ON project (Estrada-Flores and Tanner, 2008)

RFID tags can be classified into the following categories according to their power source:

- Passive RFID tags

Passive tags don't require any power source. These tags rely on the power supplied by the reader. They transmit the information only when they are in the field where the reader's radio waves can attach. These tags are less expensive (approximately 10 cents per tag for large quantities), have a very long operational life, and are small enough to fit onto an adhesive label. Even this price, passive tags are more expensive than a barcode label (less than 1 cent). They typically operate at frequencies of 128 KHz, 13.6 MHz, 915 MHz, or 2.45 GHz. These tags can communicate with readers for a distance ranging from a few centimeters to 10 m (Weinstein, 2005).

- Active RFID systems

These tags need a battery to power up its microchip. They have a higher reliability, longer range of operation and greater operating frequency. Nevertheless, its battery lead to a larger size and shorter battery life make these active tags impractical for label application, their higher cost ($20 to $100) is their disadvantage as well. Active tags operate at frequencies of 433 MHz, 2.45 GHz, or 5.8 GHz. Readers can communicate with active tags from a distance ranging from 20 to 100 m (Weinstein, 2005).

- Semi-passive tags

These tags are also battery powered. The battery is used only to run the microchip, the signal transmission use the same method as the passive tags. The battery size is therefore smaller than in the active tags; moreover these tags can be read more rapidly compared to the passive tags. They can also monitor and record environmental condition using sensors, which are powered by the battery.

Tags can be also classified according to their read-write capabilities as read-only, write-once read-many (WORM), electronically erasable programmable read-only memory (EEPROM), and read-write tags based on their read–write capabilities (Kumar, Reinitz et al., 2009).

4.1.2. Tag reader and Antenna

The tag reader is in charge to power and communicate with the RFID tags. The reader consists of a high frequency (HF) interface (consisting of a transmitter and a receiver), antenna, and a control unit. The HF interface generates power to activate and supply the tag, sends and receives data with the tag. The reader can have one or more antennas which emit radio waves and receive signals sent from the tag. The control unit is based upon a microprocessor in order to control communication with the tag. The performance of a reader is usually measured in terms of the range and rate the reader can identify. The antenna is a conductive element which transmits the information between the tag and an RFID reader. The reader and tag both have antennas for data transmitting and receiving. The reader antenna converts the electricity to radio waves and transmits the waves to the tag. The tag antenna receives the radio waves and converts them to electricity for powering the microchip if it is a passive tag (Kumar, Reinitz et al., 2009).

4.2. Wireless Sensor Network (WSN)

WSN can operate in a wide range of environmental conditions and provide advantage in cost, size, power, flexibility and distributed intelligence, compared to wired ones. By auto configuration set up, the network could continue to operate as nodes are moved, introduced or removed. Monitoring applications have been developed in medicine, agriculture, environment, military, etc… and in many others fields (Ruiz-Garcia, Lunadei et al., 2009). A sensor node consists of four basic components: a sensing unit, a processing unit, a transceiver unit and a power unit (Akyildiz, Su et al., 2002). A variety of sensors like temperature, humidity or volatile compound detection could be monitored at different environmental conditions.

Nowadays, two standard WSN technologies are available: Zigbee and Bluetooth. Both run within the Industrial Scientific and Medical (ISM) band of 2.4 GHz, which provides license free operations, huge spectrum allocation and worldwide compatibility (Ruiz-Garcia, Lunadei et al., 2009). Comparing these two technologies, Bluetooth has higher data rates; however, Zigbee has the advantage in power consumption which is of primary importance and should be extremely low in a sensor network. Moreover, Bluetooth devices have lower battery life than Zigbee (1 week to >1 year). In addition, Zigbee can provide a higher network flexibility allowing different topologies (more than 65 000 nodes according to specification). Various authors showed the suitability of Zigbee monitoring in the food and agriculture field (Ruiz-Garcia, Barreiro et al., 2007; Montanari, 2008; Ruiz-Garcia, Barreiro et al., 2008; Ruiz-Garcia, Lunadei et al., 2009).

4.3. WSTs application in the Food Industry's traceability – present actors

Most fresh food products are perishable and their quality can be affected by temperature condition in the supply chain. In particular, vegetables, fruits, meats or fish and all their products require low temperature storage. Therefore, temperature is the most important factor when prolonging the practical shelf life of perishable food products. Numerous applications in the food industry, including those for supply chain management, temperature monitoring, and food safety assurance are available.

4.3.1. RFID-based and varied WSTs technologies application

4.3.1.1. RFID system application

RFID tags are used to track food products during distribution and storage in supply chain management. Readers can simultaneously communicate with several RFID tags which can store more data compared to a barcode. An RFID system implemented in a store can be used to maintain an accurate database of its inventory that automatically alerts a warehouse management system once the inventories are low. Wal-Mart stores Inc. was the 1st major company to push RFID implementation in their supply chain management. Wal-Mart demands its top 300 suppliers to place RFID tags which would store an Electronic Product Code (EPC) on all pallets and cases of products. These tags would be used to track products at the moment of their entrances in Wal-Mart's distribution centers and during shipments to individual stores (Jones, Clarke-Hill et al., 2005). British Telecommunications has launched an online real-time food traceability system based on RFID technology (read/write tags combined with the barcodes) via a secure data exchange platform on the Internet. This online network provides a real-time data on the current and historical status of all stock items from manufacturer to the point of sale. This system tracks products in real-time to speedup the recalling products and reduce the cost (Connolly, 2007). A French company, e-Provenance (France) has developed a tracking system based on RFID technology to preserve the quality of fine wines and trace their origin. Three (3) components (a semi-active RFID tag placed inside each case of wine, a passive RFID tag with a unique code attached to the base of each bottle and a proprietary and tamper-proof neck seal at the base of the capsule of each bottle) are coordinated in an encrypted Internet database (Launois, 2008). The Spanish company ECOMOVISTAND collaborated with the Polytechnic University of Cartagena (Spain) has involved an intelligent returnable and transport units with active RFID tags for tracking of the grocery supply chain (Martínez-Sala, Egea-López et al., 2009). This ecological packing, called MT, can provide the information via a data system called MEGASTAND, which allow to track MTs over the entire supply chain. RFID technology has also been adopted for the ripening of climacteric fruits monitoring during transport and vending. Vergara et al., (2007) developed an RFID reader system with onboard micro-machined metal oxide gas sensors for monitoring climacteric apples. They combined a commercial inductive coupling radio frequency transceiver operating at 13.56 MHz (ISO 15693 compatible), micro-hot plate gas sensors, driving and readout electronics to evaluate apples conservation stage.

Numerous pilot trail studies (commercial or non commercial) regarding RFID technology application are also available. Auburn Univ. Detection and Food Safety (AUDFS) project uses the combination of RFID technology and sensors to detect pathogens in food. The objective of this project was to develop the microscopic structures coating with bacteriophages or viruses which can bind to pathogens. A signal will be sent to a RFID reader if a pathogen binds with the coating (Nambi, Nyalamadugu et al., 2003). A real case application in an Italian fruit cold chain has been developed to compare two management approaches based on RFID technology with two different measuring systems regarding the cost analysis. Temperature-humidity data are monitored in real-time (Montanari, 2008). For fish supply chain management, a RFID smart tag instrumented with light, temperature and humidity sensors was suggested (Abad, Palacio et al., 2009). Real-time traceability information could be provided by this system for different fish distribution chain steps. ID-TAG project launched by CRYOLOG (France) uses the RFID technology to monitor the temperature variations in the food with a combination of quality indicators. Possibility of RFID technology adoption for Perishable foods during sea transportation which regularly involves long transit times has also been studied. A 12 m long refrigerated sea container (68 m^3) and a 915 MHz RFID system were used. The implementation of a real time-temperature monitoring system within a container can provide a good tool to address food quality losses (Laniel and Emond, 2010). Other examples of commercial trail of RFID application include: Ballantine (US) tracks fresh fruit shipments from packing house to retail display cabinets in order to increase their competitive advantage. Manor supervises their supermarket freezers and refrigerators. Unilever tracks ice cream temperatures throughout the cold chain in order to ensure quality assurance. In retail filed, after Wal-Mart stores, more recently Carrefour and Metro have adopted digital-tagging technologies, including RFID. The third largest retailer in the US, Kroger Co. has tested RFID temperature monitoring with their suppliers. However, the business case for RFID remains to be proven (Estrada-Flores and Tanner, 2008).

Numerous commercial manufacturers offer RFID systems for the supply chain management. Evidencia (USA) has developed a radio frequency identification (RFID) logger (ThermAssureRF™) combining tracking and tracing with temperature readings. This RFID logger integrates an electronic in-transit temperature sensor, advanced micro-chip and wireless technologies to track inventory throughout an entire facility giving processors a way to identify when food safety may have been compromised. The passive RFID tags store a 96 bit EPC code for logistics, and can log 4,000 temperature readings to an accuracy of about 0.3°C. The tags with programmable alarms, are tamper-proof, and water and shock resistant (ElAmin, 2007). Programmable temperature RFID logger

(Easy2Log) from Caen RFID (Italy) can identify problems incurred with product during cold chain storage and transit. Easy2Log uses the ultra high frequency (UHF) technology to monitor temperature sensitive products during transportation or storage providing an improved quality control system for food manufacturers. Easy2Log can be used as both a pallet tag and a case tag, which it can provide localized temperature measurement, including the monitoring of several areas within a single cargo or truck. This logger features a sensor that can accurately detect temperature changes by 0.5 °C. It can be set at a reading rate of between eight seconds to half hour intervals. Easy2Log functions in the range of -20°C to +70°C, thus enabling critical temperature control for perishable products such as fresh food, seafood, meat and poultry, milk-based products and frozen food. This temperature logger (semi-Passive Tag) has a memory capacity of 8000 temperature samples with a long life battery of either three or five years. It costs 32€ a unit for retailing (Byrne, 2008). An Austria company (Identec Solutions) has developed an RFID-based temperature data logger (i-Q32T) which is capable of storing up to 13000 temperatures. Information can be retrieved using a reader at distances of up to 100 m. The data logger can be used to monitor the food products during processing and cool-down periods. The range of operation for this data logger is from -40 to 85◦C (±0.25◦C) and it has a battery life of over 6 years. The logging intervals can range from 1 min to 18 h (ElAmin, 2005). Infratab Inc. (U.S.A.) provides Freshtime™ semi-active RFID tags to monitor the shelf life of foods with a battery as the power source. The tag can detect temperature and integrate it over time to determine the shelf life of a product. The temperature operation range of these tags is from -25 to 70◦C. These tags have also an optional visual display that provides green, yellow, and red indicators depending upon the status of the product (Kumar, Reinitz et al., 2009). Other RFID tags are also available on the market regarding temperature monitoring such as VarioSens® RFID tag from KSW Microtech AG (Germany) which operates from -20 to 50◦C; Turbotag™ developed by Sealed air (U.S.A.) which captures and delivers the tagged product temperature history; TempTale/TagAlert from Sensitech (USA) which tracks the temperature and humidity for logistic chain optimization; TempAlarm from Bioett (Sweden) which monitors the temperature history for different logistic steps; @Trace from KBS (France) which can measure different parameters such as temperature, relative humidity, shock and acceleration with an operation temperature range from -30 to 80 °C; TempSens/VarioSens from KSW Microtec (Germany) for temperature and humidity tracking which is RFID-based; FreshTime from Infratab (USA and Ireland) which tracks the temperature in real-time with a data storage and transmits the information via EPC Gen2 and ISO standard.

4.3.1.2. Limitation and challenges of RFID system application

Despite of RFID technology advantages, a number of limitations have been raised regarding their practical applications.

It is very difficult to read ultra high frequency tags near a human body because of the interference from the high water content of humans (Roberts, 2006). This is one of the main technical challenges in implementing RFID technology. Tags on the products with large amount of liquid or metals can not be read easily because liquids absorb signals while metals reflect them (Kumar, Reinitz et al., 2009).

The lack of uniformity in global standards is also one of its limitations. Numerous standards and regulations on frequencies and radio spectrum have been adopted in different countries, which have inhibited development of a global standard for RFID. Two main global organizations EPC global and the International Organization for Standardization working on RFID standards are endeavoring to unify the standards (Estrada-Flores and Tanner, 2008).

Read range is considered as another limitation for RFID technologies. Most of the low frequency RFID systems have an operating range of about 1 m and ultra high frequency systems extend the operating range to 3 to 4 m. For example, Amador et al. (Amador, Emond et al., 2009) showed the use of RFID for temperature tracking in a commercial shipment of pineapples from Costa Rica to the USA. Jedermann et al. (Jedermann, Ruiz-Garcia et al., 2009) monitored 16 refrigerated trucks using semi-passive RFID instrumented with temperature sensors (Turbo Tag) following the temperature gradients. But these temperature recording applications during transportation and distribution have a transmission range less than one meter and they are not able to develop advanced network topologies compared to ZigBee devices that have the potential to do it. Moreover, because of their low reading range, they require manual handling although RFID data loggers are available in high quantities. Another disadvantage is that temperature loggers are only available for the 13.56 MHz HF band which limits the reading range of about 20 cm (Ruiz-Garcia, Lunadei et al., 2009).

Accuracy: Although RFID readers don't need line of sight of the object for operation, if the tag is oriented perpendicular to the antenna of the reader, the reader cannot communicate accurately with it. Moreover, for most cold chain applications regarding to the temperature trucking, a sensor accuracy of ± 0.5°C or better is expected. However, in the mass production of RFID tags, calibration method should be simple and inexpensive; calibration procedures may be different between manufacturers and models.

Cost: The “cost” of this technology has been cited frequently as a reason for the slow uptake. Electronic Article Surveillance (EAS) tags are the most widely used tags, which cost between 1 and 6 US cents each. Over 6 billion of them are used annually. Passive tags, which have some data storage capability, cost between 5 to 10 cents each with large quantities manufactures. However, they are still expensive as compared to a barcode label (less than 1 cent). Active tags which are used for tagging high value items, costs can be up to $100 per tag. This high cost of the tags makes it uneconomical to use tags into every retail item (Roberts, 2006). Despite of this constraint, the actual information may be much more valuable than the cost of the tags in the case of cold chain traceability application. Price reduction of the tags could lead to a widespread adoption of RFID technology with the help of manufacturing technologies improves.

Another limitation regarding to this technology is consumer's privacy concerns. This topic includes issues about the disclosure of private information (such as buying habits, movement tracking…) and health cancers. Deactivation of the tag at the point of sale can be a solution to counter such privacy concerns. Security issues should be also drawn the public attention due to the unauthorized scanning of the tags regarding the shipments or inventory details of products.

4.3.2. Varied WSTs technologies application

In addition to the classical RFID technologies application, there are other applications which use the wireless sensors or RFID-integrated for supply chain management in the perishable food field.

Use of wireless sensors in the refrigerated vehicles was proposed. The vehicles can host a variety of sensors to communicate what happens during the transport journey, monitoring the status of perishable products (Shan, Liu et al., 2004). Intermodal refrigerated fruit transport which integrate wireless sensor networks with multiplex communications, fleet management systems, and mobile networks was studied and analyzed (Ruiz-Garcia, Barreiro et al., 2007). ZigBee motes were proved as suitable for their use under cooling conditions in warehouses and fruit chambers. A WSN based system was also studied for the fresh fish logistic chain monitoring. This system uses SMS to send warnings and to monitor recent temperature data. The system is based on a web server and bespoke wireless data loggers operating over a GSM network (Hayes, Crowley et al., 2005). An intelligent containers system RFID-based was presented combining wireless sensor networks. It can be placed in transport vehicles in order to monitor the ongoing environmental conditions and simultaneously process the received data (Jedermann, Behrens et al., 2006). A real-time monitoring solution for cold chain distribution by integrating RFID, sensor, and wireless communication technologies has been suggested. In addition, the economic benefits of real-time information on product quality can be quantitatively evaluated by the multi-stage planning model and this has been verified by numerous case studies (Shi, Zhang et al., 2010).

Applicable food logistic monitoring requires a sufficient memory for measurements. Specialized WST monitoring devices allow giving continuous and accurate information throughout the distribution process to suppliers and distributors for perishable products. Precise, frequent and automated monitoring should permit a more intelligent supply chain management. They could be useful to remedy the cause of the problem. Online notifications offer new opportunities for transport improving. An integration of WSN and RFID seems interesting and complementary, which allow synergies. WSN uses a variety of sensors, but they cannot identify objects individually while RFID allow the identification of items such as container, pallet, boxes or bottles. For this reason, combination of them provides a significant progress on monitoring. Currently, the RFID technology evolution has been developed very fast. Semi-passive tags can be used to monitor environmental parameters, such as the temperature, humidity, to alert the supply chain problem. RFID loggers are available in high quantities and are cost-effective. Despites of advantages, they require manual handling because of their low reading range. The main gains of WSN are its longer reading range, the flexibility and different network topologies that can be configured, the variety of sensors that are already implemented and their low power consumption. In 2009, a complete program has been proposed to makes full use of RFID tags, temperature sensors, GPS systems and other technical advantages, including the cold chain temperature monitoring system architecture, software design and system flow procedure, etc... The system can real-time monitor the location and the temperature of cold-chain products, to achieve quality assurance of cold-chain products in the supply chain process (Yan and Lee, 2009).

Other new developments like the combination of RFID technology and time-temperature indicator (TTI) should be considered also. This potential integration permits the tracking of the shelf life of chilled and frozen products. In Europe, a prototype device delivered by a European project ("CHILLON") permits the connection of chemically based TTI to RFID transponders.

5. Time-temperature indicators

Temperature is usually the most important environmental factor influencing the kinetics of physical and chemical deteriorations, as well as microbial growth in food products as mentioned above. Time-temperature indicators (TTIs) are typically small self-adhesive labels attached onto shipping containers or individual consumer packages. They are inexpensive, active "smart labels" that can easily show measurable, time- and temperature-dependent changes that reflect the full or partial time-temperature history of a food product to which it is attached. This technique is particularly useful for warning of temperature abuse for chilled or frozen food products (Taoukis and Labuza, 1989). They are also used as "freshness indicators" for estimating the remaining shelf life of perishable products. The responses of these labels are usually some visually distinct changes that are temperature dependent, such as an increase in color intensity and diffusion of a dye along a straight path.

TTIs are based on mechanical, chemical, enzymatic or microbiological changes that are irreversible and expressed usually as a response in a visually quantifiable identifier in the form of mechanical deformation, color development or color movement. The rate of change in the system underlying the TTI is temperature dependent, increasing with higher temperatures, in a manner similar to the deteriorative reactions responsible for food spoilage. Overall, the visible response of the TTIs reflects the cumulative time-temperature history of the food products they accompany. TTIs are an integral part of an interactive intelligent package and can serve as part of an active shelf life signal in conjunction with the "use-by-date" on the label (Taoukis, 2011).

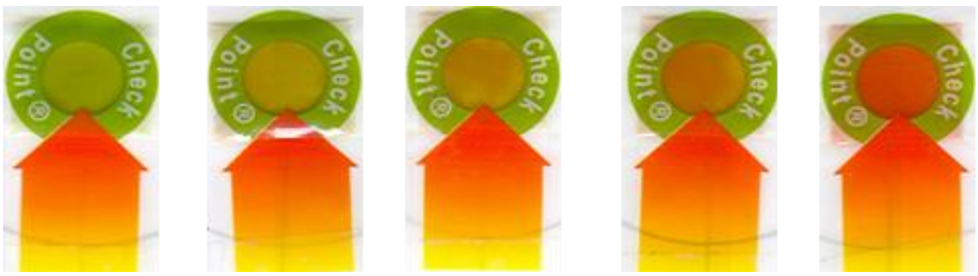
TTI response has to match the behaviour of the food, since there is no correlation algorithm used but a single visual end point which should indicate closely the end of shelf life at any temperature. The ideal TTI should be applicable to the targeted food product, practical as a shelf life management tool and cost effective (Taoukis and Labuza, 2003; Taoukis, 2010). Such a TTI should:

- Be based on a continuous time-temperature dependent change that is expressed in a response that is easily measurable and irreversible.
- Have a response rate and identifier that mimics or closely correlates to the food's extent of quality deterioration and residual shelf life.
- Be reliable and reproducible, to give consistent responses when exposed to the same or equivalent temperature conditions and temporal profiles.
- Have low cost.
- Be flexible, adaptable to various temperature ranges (e.g., frozen, refrigerated, room temperature) with adjustable temperature sensitivity, and be useful for response periods of a few days up to several months.
- Be small, easily integrated as part of the food package and compatible with a high speed packaging process.
- Have a long shelf life before activation for use and be easily to activate.
- Be unaffected by ambient conditions other than temperature, such as light, relative humidity (RH) and air pollutants.
- Resist normal mechanical abuses and have a response that is unalterable by mishandling or tampering.
- Be nontoxic and pose no safety concern in the unlikely situation of contact with product.
- Be able to transmit in a simple, clear way the intended message to its targets, including distribution handlers, inspectors, retail store personnel or consumers.
- Have a response both visually understandable and adaptable to measurement by electronic equipment for easier and faster information, acquisition, storage and subsequent use.

For more than three decades, numerous TTI systems have been proposed, of which only a few reached the industrial prototype and even fewer the commercial application stage. Commercially available Time-Temperature Indicators are based on various reaction mechanisms (polymerisation, thermochromic/photochromic reactions, diffusion or enzyme reaction). A common feature for all concepts is the temperature dependent reaction kinetics of the indicator and activation of the indicator at the moment of packaging (Petersen and Kreyenschmidt, 2004).

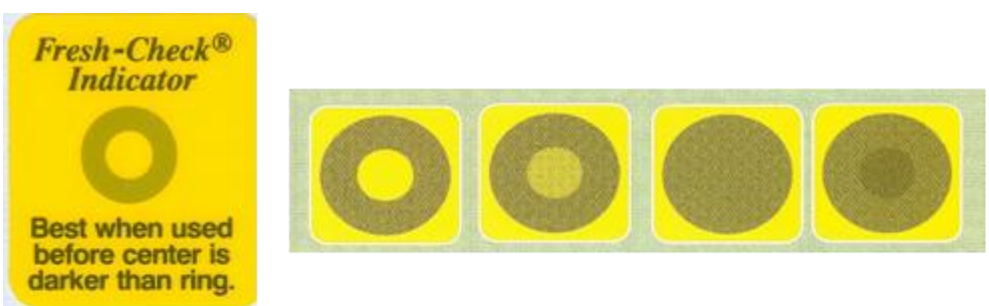
Systems that are currently available commercially are the following:

- The CheckPoint® TTI (Vitsab AB, Malmö, Sweden) is an enzymatic system. This TTI is based on a colour change caused by a pH decrease which is the results of a controlled enzymatic hydrolysis of a lipid substrate. Different combinations of enzyme-substrate and concentrations can be used to give a variety of life response and temperature dependencies. Upon activation, the enzyme and substrate are mixed by mechanically breaking a separating barrier inside the TTI. Hydrolysis of the substrate (e.g. tricaproin) causes acid release (e.g. caproic acid) and the corresponding pH drop indices a colour change in a pH indicator from deep green to bright yellow to orange-red (Picture 7). A visual scale of the colour change facilitates visual recognition, magnitude evaluation and significance of the colour change. The continuous colour change can also be measured with instrumentation and the results can be used in a shelf life management scheme.



Picture 7. Response scale of enzymatic CheckPoint® TTI from green at time of application (left) to orange-red (right) indicating the end of shelf life.

- The Fresh-Check® (Temptime Corp, NJ, USA) (successor to Fresh-Check of Lifelines) is build on a solid state polymerization reaction. The TTI function is based on the property of disubstituted diacetylene crystals (R-C=C-C=C-R) to polymerize through a lattice-controlled solid-state reaction, resulting in a highly colored polymer. The response of the TTI is the colour change as measured in terms of a decrease in reflectance. The colour of the “active” center of the TTI is compared with the reference colour of a surrounding ring (Picture 8). Before using the indicators, which are active from the time of their production, the TTIs have to be stored at deep frozen temperatures where the colour change is very slow.

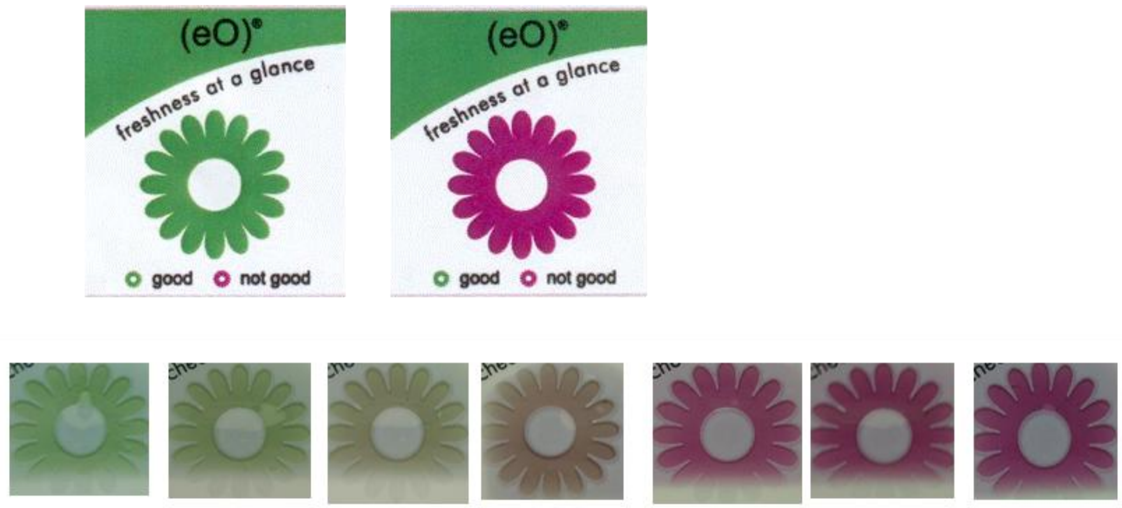


Picture 8. Polymer-based Fresh-Check® TTI.

- The OnVu™ TTI (Ciba Specialty Chemicals & Freshpoint, SW) is a newly introduced solid state reaction-based TTI. It is based on the inherent reproducibility of reactions in crystal phase. Photosensitive compounds such as benzylpyridines are excited and colored by exposure to low wavelength light. This colored state reverses to its initial colorless state at a temperature-dependent rate (Picture 9). By controlling the type of photochromic compound and the time of light exposure during activation, the length and the temperature sensitivity of the TTI can be set. This TTI can take the form of a photosensitive ink and be very flexible in its application.

Picture 9. Solid state photochromic OnVu™ TTI.

- The (eO)® TTI (Cryolog, Gentilly, France) is based on a time-temperature dependent pH change that is expressed as colour changes using suitable pH indicators. The pH change is caused by controlled microbial growth occurring in the gel of the TTI (Louvet et al., 2005; Ellouze et al., 2008). The parameters of the TTI are adjusted for select microorganisms by appropriate variations in the composition of the gel. The response of the TTI is claimed to mimic microbiological spoilage of the monitored food products, as its response is based on the growth characteristics of similar microorganisms, such as select patented strains of the microorganisms *Carbonbacterium piscicola*, *Lactobacillus fuchuensis* and *Leuconostoc mesenteroides*. The pH drop occurs with a colour change of the pH indicator from green to red (Picture 10). This visual scale of colour change can assists the visual recognition and the evaluation of the colour change significance. We can also measure instrumentally this continuous colour change and use it in a shelf life management scheme.

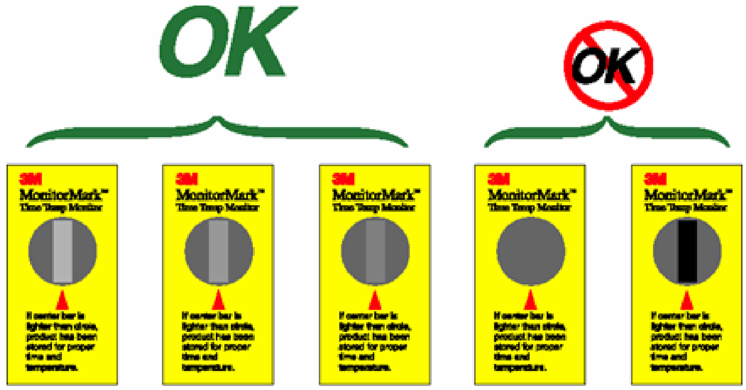


Picture 10. Response scale of Microbial TTI (eO)®.

- The TT sensor™ TTI (Avery Dennison Corp., USA) is based on a diffusion-reaction concept. A polar compound diffuses between two polymer layers and the change in its concentration causes the colour change of a fluorescent indicator from yellow to bright pink (Picture 11).

Picture 11. TT Sensor™ TTI.

- The 3M Monitor Mark® (3M Co., St.Paul, MN, USA) is based on diffusion of proprietary polymer materials. A viscoelastic material migrates into a light reflective porous matrix at a temperature dependent rate. This causes a progressive change in the light transmissivity of the porous matrix and provides a visual response (Picture 12). The TTI is activated by adhesion of the two materials that, before use, can be stored separately for a long period at ambient temperature.



Picture 12. Diffusion-based 3M Monitor Mark® TTI.

Despite the TTIs potential to substantially contribute to improving food distribution, reducing food waste, and benefiting the consumer with more meaningful shelf life labeling, their applications up to now have not lived up to initial expectations. The food producers' reluctance to accept the benefits of the TTI have been questions of cost, reliability, and applicability. The cost is volume dependent, ranging from $0.02-0.20 per unit. If the other questions were resolved, the cost-benefit analysis would certainly favor the adoption of the TTI. The reliability question is the roots in the TTIs history, due partly to exaggerated claims by manufacturers of some early models and partly to lack of sufficient data, both from studies and from the suppliers. Some of the early attempts in using TTIs as quality monitors were not well designed, not based on the fundamentals involved, and thus were unable to establish the reliability of the TTI systems in the real cold chain. Re-emerging discussions by regulatory agencies to make the use of TTIs mandatory, before the underlying concepts were understood and their reliability was demonstrated, resulted in resistance by industry, which may have hurt TTI adoption and use up to the present time. Current TTI models have achieved high standards of production quality assurance to provide reliable and reproducible responses according to required specifications. Testing standards have been issued by the BSI (BSI, 1999) and can be used by the TTI manufacturers and the TTI users.

Therefore, TTIs can be used for continuous, overall monitoring of the distribution system, leading to recognition and correction of weak links in the chain. Furthermore, it serves as a proof of compliance with contractual requirements for handling by the producer and distributor. It can guarantee that a properly handled product was delivered to the retailer, thus eliminating the possibility of unsubstantiated rejection claims by the latter. The presence of the TTI itself could improve handling, by serving as an incentive and a reminder of the importance of proper temperature control and storage to the distribution employees throughout the distribution chain.

Cases of TTI application

The first TTIs application of significant scale has been the use on vaccines distributed by the WHO. For this application, different TTI technologies have been employed. The Fresh-Check® TTI is used currently on all of the vaccines supplied to the UNICEF Children's Vaccine Campaigns worldwide. Fresh-Check® TTIs have been in recent years reported their uses on food products by several customers including the Monoprix retail chain (France) on several of their own label perishable packed products, the Carrefour retail chain on packed fruits and salads distributed via e-shopping, and Milco® dairy and juice products.

The (eO) ® TTI (CRYOLOG, France) has been applied by Monoprix on packed fresh pork products, by LECLERC retailer in Bretagne on «Marque Repère» fresh packed sandwiches, by Auchan, Cora and Elior.

The CheckPoint® TTI, (VITSAB A.B., Malmö, Sweden) has been used on vacuum or modified atmosphere (MA) packaged fresh seafood imported to USA by several importing companies. This is an interesting case that has been encouraged by regulation. The import of these products are covered by FDA’s Import Alert # 16-125 (last publication 22/12/2009). In 1992, the National Advisory Committee for Microbiological Criteria for Foods (NACMCF) evaluated the microbiological safety issues associated with vacuum or MA packaged of raw fish and fishery products and found that the primary preventive measure (critical control point) against the growth and toxin production of non-proteolytic strains (those strains that grow at refrigeration temperatures) of *Clostridium botulinum* was temperature control. All such products are placed on detention unless importers are on the Green List. To qualify for the Green List, manufacturers, shippers, or importers should provide the information to FDA to establish that controls are in place to either prevent *C. botulinum* toxin formation or provide a visual indication of a potential problem. As set out in the Fish and Fishery Products Hazards and Controls Guidance, one of the potential controls acceptable by FDA as evidence is that the individual products bear a validated TTI which indicates by a color or other visual change, whether the product has been exposed to a time and temperature combination that could result in an unsafe product. This application is based on the fact that potential toxin production is highly temperature sensitive. The time-temperature combinations that could result in toxin production have been illustrated in a single curve based on a set of over 1800 data points by Skinner and Larkin (1998). TTIs' responses that closely match this curve are suitable for this application. The required temperature dependence of the rate constant determining the response of suitable TTIs should be in the range of Ea = 150-200 kJ/mol. The L5-8 CheckPoint® TTI response conforms to the above requirements and is being applied for the import of fresh vacuum- or MA packaged seafood.

Another application reported by VITSAB is Flight Labels; TTIs are used on board British Airways flights for monitoring temperature for proper handling of served meals. The response of the TTI is checked before the serving of each meal and a simple record keeping procedure is followed. Flight Label 1 was based on enzymatic TTI Checkpoint

B7-24 and was used on UK originating flights. For longer flights, Flight Label 2, a diffusion-based TTI produced by Avery-Dennison and converted by VITSAB to use a manual activation system suitable for small local activation stations, was used. Moreover, it is currently supplied by VITSAB for all British Airways flights.

For OnVu^{TM} TTI application, it is currently used on all packages of Kneuss fresh chicken produced and distributed by Ernst Kneuss Geflügel A.G. (Switzerland) (Taoukis, 2010).

6. Conclusions

The literature review with regards temperature monitoring techniques and traceability systems along the food cold chain has shown the necessity for continuous monitoring of the temperature history of food products. Lots of systems have been used for monitoring the cold chain, depending on the food product, the storage conditions, the shelf-life of the product and the cost of the systems. RFIDs and TTIs are devices with significant potentials for their application in the food chain assuring food safety and maximum quality by identifying and controlling the weak links of the whole cold chain. The combination of TTIs and RFIDs is one of the most promising technologies to be applied in the near future for optimum management of all stages of the cold chain.

7. References

Abad, E., F. Palacio, et al. (2009). "RFID smart tag for traceability and cold chain monitoring of foods: Demonstration in an intercontinental fresh fish logistic chain." Journal of Food Engineering 93(4): 394-399.

Akyildiz, I. F., W. Su, et al. (2002). "Wireless sensor networks: a survey." Computer Networks 38(4): 393-422.

Amador, C., J.-P. Emond, et al. (2009). "Application of RFID technologies in the temperature mapping of the pineapple supply chain." Sensing and Instrumentation for Food Quality and Safety 3(1): 26-33.

Bhattacharyya Rahul, Floerkemeier Christian and Sarma Sanjay (2010). RFID Tag Antenna Based Temperature Sensing, IEEE RFID 2010, 8-15.

Bellantoni, J. (2005). ZigBee-Enabled RFID Reader Network.: P 494.

Bogh-Sorensen, L. (2006). Recommendations for the processing and handling of frozen foods. Paris, International Institute of Refrigeration (IIR).

BSI BS 7908: Packaging - Temperature and Time-Temperature Indicators - Performance Specification and Reference Testing.

Byrne, J. (2008). "RFID temperature logger could enhance cold chain quality control." Retrieved 27 April 2011, from http://www.foodproductiondaily.com/Supply-Chain/RFID-temperature-logger-could-enhance-cold-chain-quality-control.

Clarke, R. (2007). "NIFT-DTM and FoodQSMTM." Retrieved 2011, from http://www.wronz.org.nz/mirinz/docs/11-latest-measurement-technology-r-clarke.pdf.

Connolly, C. (2007). "Sensor trends in processing and packaging of foods and pharmaceuticals." Sensor Review 27(2): 103-108.

ElAmin, A. (2005). "RFID tag tracks temperature for food processors." Retrieved 27 April 2011, from http://www.foodproductiondaily.com/Supply-Chain/RFID-tag-tracks-temperature-for-food-processors.

ElAmin, A. (2007). "RFID tag a cold chain management tool." Retrieved 27 April 2011, from http://www.foodproductiondaily.com/Quality-Safety/RFID-tag-a-cold-chain-management-tool.

Ellouse M., Pichaud M., Bonaiti J., Coroller L., Couvert O., Thuault D., Vaillant R. (2008). Modelling pH evolution and lactic acid production in the growth medium of a lactic acid bacterium: application to set s biological TTI. International Journal of Food Microbiology 128, 101-107.

Ellouze, M. (2011). "Les outils de traçabilité de la chaîne du froid." Revue générale du froid 1113.

Estrada-Flores, S. and D. Tanner (2008). "RFID technologies for cold chain applications." Bulletin de l'Institut International du Froid 88(4): 4-15.

Faouzi Kamoun (2009). RFID System Management: State-of-the Art and Open Research Issues. IEEE TRANSACTIONS ON NETWORK AND SERVICE MANAGEMENT, VOL. 6, NO. 3: 190-205.

Hayes, J., K. Crowley, et al. (2005). Simultaneous Web-based real-time temperature monitoring using multiple wireless sensor networks. Sensors, 2005 IEEE.

Jedermann, R., C. Behrens, et al. (2006). "Applying autonomous sensor systems in logistics-Combining sensor networks, RFIDs and software agents." Sensors and Actuators, A: Physical 132(1 SPEC. ISS.): 370-375.

Jedermann, R., L. Ruiz-Garcia, et al. (2009). "Spatial temperature profiling by semi-passive RFID loggers for perishable food transportation." Computers and Electronics in Agriculture 65(2): 145-154.

Jones, P., C. Clarke-Hill, et al. (2005). "Radio frequency identification and food retailing in the UK." British Food Journal 107(6): 356-360.

Kerry, J. P., M. N. O'Grady, et al. (2006). "Past, current and potential utilisation of active and intelligent packaging systems for meat and muscle-based products: A review." Meat Science 74(1): 113-130.

Kumar, P., H. W. Reinitz, et al. (2009). "Overview of RFID technology and its applications in the food industry." Journal of Food Science 74(8): R101-R106.

Laniel, M. and J. P. Emond (2010). "Mapping of RFID tag readability in relation to the food content in a refrigerated sea container at 915 MHz." Innovative Food Science & Emerging Technologies 11(4): 703-706.

Launois, A. (2008). "RFID tracking system stores wine bottle data." Retrieved 24 April 2011, from http://www.foodproductiondaily.com/Packaging/RFID-tracking-system-stores-wine-bottle-data.

Liu, L., J. Hu, et al. (2010). "Development of time-temperature data collection program for frozen fish in the cold chain." Sensor Letters 8(1): 47-51.

Louvet O., Thuault D., Vaillant R. (2005). Method and device for determining whether or not a product is in condition to be used or consumed. Patent. International Publication Number WO 2005/026383 Al.

Martinez-Sala, A. S., E. Egea-Lopez, et al. (2009). "Tracking of Returnable Packaging and Transport Units with active RFID in the grocery supply chain." Computers in Industry 60(3): 161-171.

Martínez-Sala, A. S., E. Egea-López, et al. (2009). "Tracking of Returnable Packaging and Transport Units with active RFID in the grocery supply chain." Computers in Industry 60(3): 161-171.

Montanari R. (2008). Cold chain tracking: a managerial perspective. Trends in Food Science & Technology 19, 425-431.

Montanari, R. (2008). "Cold chain tracking: a managerial perspective." Trends in Food Science and Technology 19(8): 425-431.

Nambi, S., S. Nyalamadugu, et al. (2003). Radio frequency identification sensors. 7th World Multiconference on Systemics, Cybernetics and Informatics, Vol Vii, Proceedings. N. Callaos, T. Kitazoe, J. Zhou, F. Zhonghua and M. Mostafa. Orlando, Int Inst Informatics & Systemics: 386-390.

Petersen, B., & Kreyenschmidt, J. (2004). Ein viel versprechendes Hilfsmittel – Einsatzmöglichkeiten von Zeit-Temperatur-Indikatoren zur Überprüfung der Kühlkette; Fleischwirtschaft, 10, 57-59.

Roberts, C. M. (2006). "Radio frequency identification (RFID)." Computers & Security 25(1): 18-26.

Ruiz-Garcia, L., L. Lunadei, et al. (2009). "A Review of Wireless Sensor Technologies and Applications in Agriculture and Food Industry: State of the Art and Current Trends." Sensors 9(6): 4728-4750.

Ruiz-Garcia, L., P. Barreiro, et al. (2007). "Review. Monitoring the intermodal, refrigerated transport of fruit using sensor networks." Spanish Journal of Agricultural Research 5(2): 142-156.

Ruiz-Garcia, L., P. Barreiro, et al. (2008). "Performance of ZigBee-Based wireless sensor nodes for real-time monitoring of fruit logistics." Journal of Food Engineering 87(3): 405-415.

Shan, Q., Y. Liu, et al. (2004). Wireless intelligent sensor networks for refrigerated vehicle. Emerging Technologies: Frontiers of Mobile and Wireless Communication, 2004. Proceedings of the IEEE 6th Circuits and Systems Symposium on.

Shi, J., J. Zhang, et al. (2010). "Optimizing distribution strategy for perishable foods using RFiD and sensor technologies." Journal of Business & Industrial Marketing 25(8): 596-606.

Skinner GE, Larkin JW. (1998). Conservative prediction of time to Clostridium botulinum toxin formation for use with time-temperature indicators to ensure the safety of foods. J Food Prot, 1998, 61(9):1154–60.

Taoukis P.S. (2010). Commercialization of time-temperature integrators for foods. In: Case studies in novel food processing technologies: innovations in processing, packaging, and predictive modeling. Doona, C. J. Kustin, K. Feeherry F. E. (Eds.), Woodhead Publishing Series in Food Science, Technology and Nutrition, No. 197.

Taoukis P.S. (2011). Smart packaginbg for monitoring and managing food and beverage shelf life. In: Food and beverage stability and shelf life. Kilcast D., Subramaniam P. (Eds.). Woodhead Publishing Limited, Cambridge.

Taoukis, P. S., & Labuza, T. P. (1989). Applicability of time temperature indicators as shelf life monitors of food products. Journal of Food Science, 54, 783-788.

Taoukis, P.S. (2010). Commercialization of time-temperature integrators for foods. In C.J. Doona, Kustin K., Feeherry F.E. (eds.), Case studies in novel food processing technologies. Woodhead Publishing Limited, Cambridge, UK.

Taoukis, P.S., & Labuza T.P. (2003). Time-temperature indicators (TTI). In R. Ahvenainen (ed.), Novel Food Packaging Techniques, Woodhead Publishing, Cambridge and CRC Press, Boca Raton, FL, pp. 103-126.

Vergara, A., E. Llobet, et al. (2007). "An RFID reader with onboard sensing capability for monitoring fruit quality." Sensors and Actuators B: Chemical 127(1): 143-149.

Wang, L. X., S. K. Kwok, et al. (2010). "A radio frequency identification and sensor-based system for the transportation of food." Journal of Food Engineering 101(1): 120-129.

Wang, T. M., J. A. Zhang, et al. (2010). "Fish product quality evaluation based on temperature monitoring in cold chain." African Journal of Biotechnology 9(37): 6146-6151.

Weinstein, R. (2005). "RFID: a technical overview and its application to the enterprise." IT Professional 7(3): 27-33.

Yan, B. and D. Y. Lee (2009). "Application of RFID in Cold Chain Temperature Monitoring System." 2009 Isecs International Colloquium on Computing, Communication, Control, and Management, Vol Ii: 258-261.