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DEVELOPMENT OF RFID TEMPERATURE TRACKING SYSTEMS FOR COMBAT FEEDING LOGISTICS

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ABSTRACT First Strike Rations (FSR) military meals are shelf-stable products able to withstand a wide range of temperatures along their supply chain. Nonetheless, once their temperature thresholds have been surpassed, their expected shelf-life is reduced considerably. If inadequate temperature management of FSR loads is not detected, its consumption could diminish the nutritional status of the military forces deployed and pose a food safety threat for them. Therefore, a reliable temperature tracking system must be in place during combat feeding logistic operations. RFID temperature tracking presents superior performance than conventional monitoring methods in food supply chains; however, cost-efficiency and consistent readings must be obtained. This is achieved by minimizing the number of sensors employed, monitoring only thermally relevant locations and by surpassing the interactions between the systems' radio frequency waves and the product and its environment. The objective of this research was to develop a RFID temperature tracking system for FSR logistics by finding a thermally relevant location able to represent 85% of the temperatures present inside a pallet of FSRs when subjected to conditions similar to the ones faced along its supply chains, and by determining the readability of a commercially available RFID battery assisted passive tag in this particular location. The thermally relevant location pursued was not detected. Thus, a system where instrumentation takes place in the middle point of an interval that gathers the temperature readings of 85% of the locations measured was proposed. Lastly, the outcome of the readability study is reported, and the monitoring system is finalized.

Keywords: RFID, Temperature tracking, Environmental monitoring, Food logistics, Combat feeding.

INTRODUCTION Current US Military operations require the deployment of millions of men and women around the world. Daily, the Department of Defense (DoD) feeds more than two million people, becoming one of the largest foodservice providers in the globe. In the field, during warfare operations, the use of shelf-stable Meals, Ready-to-Eat (MRE) has provided for many years a viable option for combat feeding without the time and temperature constraints imposed by most perishable food supply chains. First Strike

Rations (FSR) were first introduced into the mix of shelf-stable military feeding by the DoD in 2008 as a way of reducing the waste of food existent with MREs and the weight Warfighters had to carry, while still fulfilling their nutritional requirements. Unlike MREs, that provide sustenance on a meal-basis, FSRs are able to supply the soldier the energy requirements of the entirety of the day (DoD Live, 2009).

Being shelf-stable, FSRs are able to withstand a wide range of temperatures along their supply chain. Nonetheless, once their temperature thresholds have been surpassed (26.67°C), the deterioration rate of the product is accelerated, reducing considerably its expected shelf-life (DoD Live, 2009). High temperature abuse could not only generate nutritional changes in it, such as the loss of certain vitamins, and sensory changes in color, texture and flavour, which impact the acceptability of the product (Ross et al., 1985; Ross et al., 1987; Narayan et al., 1997; Ross et al., 1997; Shaw et al., 1997; Natress et al., 2009); but could also favor the development of spoilage microorganisms and dangerous pathogenic growth (Banwart, 1989; Ng et al., 2002). Taking into account the fact that shelf-stable meals are transported without refrigeration, and the wide array of environmental conditions encountered along combat feeding logistics, it is then imperative to monitor the temperature conditions of FSR loads along their supply chains. If inadequate temperature management of FSRs is not discovered in a timely manner, their consumption could diminish the nutritional status of the military forces deployed, affect their morale, and, moreover, pose a food safety thread for them. Therefore, a reliable temperature tracking system must be in place during combat feeding logistic operations in order to detect the thermal abuse of FSR loads.

Radio Frequency Identification (RFID) is a wireless auto-id technology that has recently gained popularity as an asset tracking tool, mostly due to the DoD and Wal-Mart's initiative to use it for this purpose in their supply chains since 2005. In food supply chains, RFID's potential lies in the possibility of a conjoint collection of pedigree data and time/temperature information able to satisfy the current needs of the industry for trace-back and process traceability (Karkkainen, 2003; Gaukler and Seifert, 2007; Montrucchio et al., 2007; Perez-Aloe et al., 2007). Furthermore, previous research (Amador et al., 2009) indicates that RFID temperature tracking performs better when compared to conventional temperature tracking systems; providing enhanced accuracy while increasing the simplicity of the sensing system.

However the promises RFID holds in food supply chains; in each implementation, there are two major hurdles that need to be surpassed: Applying the technology in a cost-efficient way, and obtaining consistent readings. In order to achieve the first one, and reduce the cost of the implementation; the use of sensor-enabled battery-assisted passive tags (BAP) and active tags has to be minimized across the load without compromising the accuracy of the system (Amador et al., 2009). Moreover, if the thermal and perishability characteristics of the product being handled permit it, this can be easily obtained by monitoring only the relevant locations able to provide a general view of the thermal reality of the load or, its Points of Relevance (PoR) (Amador and Emond, 2010). Attaining consistent readings, nonetheless, is a more complicated matter; for it depends considerably on surpassing the interactions between the systems' radio frequency (RF) waves and the product and its environment. Previous studies by Dobkin and Weigand (2005), Redemske and Fletcher (2005), and Hartvanyi and Marek (2007) have detailed how, depending on its frequency, the radio frequency (RF) signal gets affected by the

presence of water or metal in the environment. In the ultra high frequency (UHF) spectrum, for example, where most supply chain management applications take place, water absorbs the energy of the RF wave, decreasing communication between the antennas and the tags; while metal acts as a reflector, which sometimes can facilitate or hinder this process (Sydänheimo et al., 2006; Lazaro et al., 2009). Solutions for this problem will then depend on many factors particular to each implementation case, such as the class and configuration of the equipment being used, the reading range available, the components, packaging, and level of aggregation of the product handled, and the presence of any element in the surroundings that might interact with the system (metallic forklifts, sea containers, etc).

The objective of this research was to develop a RFID temperature tracking system for FSR logistics; by finding a thermally relevant location able to represent 85% of the temperatures present inside a pallet of FSRs when subjected to heating and cooling conditions similar to the ones faced along its supply chains, and by determining the level of readability of a commercially available RFID battery assisted passive tag in this thermally relevant position.

MATERIALS AND METHODS

Relevance Study A pallet of 324 FSR packets (0.20 m x 0.14 m x 0.09 m) packed in 36 boxes was instrumented with thermocouples previously calibrated in an ice bath. The pallet consisted of four layers of twelve corrugated boxes (0.42 m x 0.26 m x 0.23 m); and each box contained three layers of FSR packets (four in the bottom, three in the middle, and two in the top), with a total of nine per box. The 142 packets instrumented provided a three-dimensional perspective for the examination of the heat transfer process along the boxes (Figure 1) and the pallet. After instrumentation, the pallet was stored in a temperature controlled chamber. A series of heating episodes followed by cooling ones were staged inside it, with room temperatures ranging from 60°C to -35°C, respectively. Before each heating/cooling episode pallet temperature was stabilized at 25°C. There were eight heating/cooling episodes with different durations: six hours of heating/six hours of cooling, eight hours of heating/eight hours of cooling, nine hours of heating/15 hours of cooling, 18 hours of heating/18 hours of cooling, 1 day of heating/1 day of cooling, 2 days of heating/2 days of cooling, 3 days of heating/3 days of cooling, and 4 days of heating/4 days of cooling. Quantitative analysis was performed using quintiles in Microsoft® Excel (Microsoft Corporation, Redmont, WA).

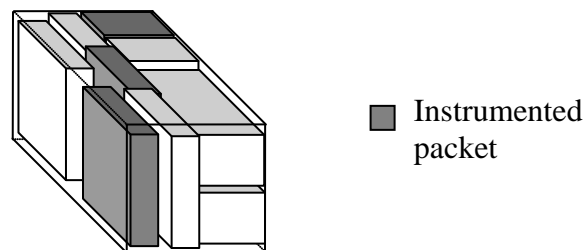


Figure 1. Three-dimensional view of the FSR packets instrumented in each box.

Readability Study Two sides of the pallet were tested for readability of class 3 battery assisted passive tags (BAP) using the Intellex™ DK900 (Intellex Corporation, Santa Clara, CA) RFID system operating at 915 MHz. The pallet was located inside a sea container, near the door, in the middle of it wide-wise (Figure 2). The container had open air surroundings and a metallic door near by. The placement of the tags was determined by the results of the relevance study. Since the four sides of the pallet could be represented by one of the 1.22 m sides (Configuration α) and one of the 1.02 m sides (Configuration β), only these two were tested. Each side was studied independently. The antennas were positioned in the middle point of the front of the side being read. Readings were obtained using six different antenna distances (0.50 m, 1 m, 1.50 m, 2 m, 2.50 m, and 3 m) with respect to the pallet.



Figure 2. Pallet and antenna position during the readability study at an antenna distance of 2 m.

Equipment Configuration In order to maximize the read range of the Class 3 tags inside the pallet, reader output power was set at its maximum and air interface data rates were set at their minimum. Table 1 summarizes the reader's configuration. Once set up, the system was run in five occasions; in each one, 200 attempts of communicating with each one of the tags were made. The level of readability of the tags was determined by averaging the percentage of times a tag was read with respect to the attempts made of contacting it.

Table 1. RFID reader configuration

Protocol	Power (dBm)	Q Value	TX Ant	RX Ant	Forward Link	Reverse Link
C3	30	4	1	1	8 kbps	8 kbps

RESULTS AND DISCUSSION

Relevance Study No thermally relevant position representing 85% of the temperatures of the pallet was detected. A great level of temperature variability was present in the load. This was mostly because of the existence of high temperature differentials due to heat accumulation in the middle of the boxes after the warming episodes. Even though the temperature differentials within boxes and along the pallet were quite significant in all trials, at the end of the 3d/3d and 4d/4d ones these were reduced considerably because the pallet was reaching thermal equilibrium.

An approach previously employed by Amador and Emond (2010) was then applied: The use of a location that has a temperature (n) that represents the middle point of an interval that gathers the temperature readings of 85% of the measured locations was proposed. The suggested range was $[n+8, n-8]$; a total of 16°C of temperature differential. Table 2 displays the likelihood of gathering 85% of the temperature readings in this interval for each heating/cooling episode. No particular trend was found between this particular likelihood and the duration of the episodes.

Table 2. Likelihood of gathering 85% of the temperature readings in the 16°C range proposed.

Episode	Likelihood
6 h, 6 h	96.55%
8 h, 8 h	84.40%
9 h, 15 h	60.20%
18 h, 18 h	60.27%
24 h, 24 h	52.16%
2 d, 2 d	56.28%
3 d, 3 d	69%
4 d, 4 d	76.90%

The temperature profiles obtained in the trials were then compared to the one corresponding to this hypothetical location; resulting in the determination of two Points of Relevance (PoR), where the temperature “ n ” was recorded and where the sensors of the projected system would be placed.

- Point A: Layer 2 (Row 1), $X= 11$, $Y= 5$
- Point B: Layer 4 (Row 2), $X= 4$, $Y= 1$

Where the layers move along the vertical axis (Z) and are labelled, along rows, in an ascending way from the top to the bottom. The locations of these points are represented in Figure 3. Although not shown in the graphic, it is important to remark that, because of thermal symmetry, these thermally relevant locations will also be present in their equivalent positions on the other sides of the pallet (along the X and Y axis).

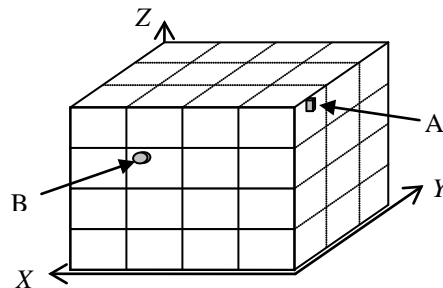


Figure 3. Locations of the Points of Relevance (PoR) detected in the pallet.

The likelihood of gathering 85% of the measured temperatures of the pallet within the 16°C interval that uses these points as middle point was then calculated (Table 3).

Table 3. Likelihood of gathering 85% of the temperature readings in the 16°C range proposed when using the Points of Relevance (PoR) found as the interval's middle points.

Episode	Point A	Point B
6 h, 6 h	72.58%	85.23%
8 h, 8 h	41.24%	35%
9 h, 15 h	63.41%	74.78%
18 h, 18 h	32.15%	48.58%
1 d, 1 d	23.87%	32.45%
2 d, 2 d	49.89%	44.76%
3 d, 3 d	42.32%	32.27%
4 d, 4 d	58.07%	43.11%

As can be seen, Point B gives a higher likelihood during most of the short and middle duration episodes (up to 1d/1d), while Point A performs better during the longest trials. Still, the selection of the best PoR for temperature monitoring will not only depend in this estimate but also on the level of readability of the RF signal obtained in these locations.

Current US military operations have a focal interest the Middle East. Therefore, the results obtained in this relevance study have to be applicable to the varied conditions of such environment. A review of the year-round weather conditions of Baghdad and Kabul (BBC, 2010) show the existence of considerable temperature differentials, which average 34.50°C, and can reach up to 44°C during certain fall and winter months. These differentials will also depend on where the FSRs are stored, and in which phase of the transportation process is the load. For example, if the pallets are being transported by land to be placed inside a cave, the differentials could be greater, because the temperatures inside this will be considerably lower than the ones registered by the weather services. Likewise, these temperature differentials could decrease if the load is being transported by sea, and protected from solar radiation. From a heat transfer perspective, the worst case scenario for a temperature tracking system like the one being designed is when the temperatures in the pallets are quite variable, due to a high temperature differential between the pallet and the environment. The temperature differential of 95°C used in these trials represents then, an extreme situation very rare to find under normal circumstances; but that gives a safety factor even for the outlier observations encountered in real-life situations. Consequently, it is expected that under normal supply chain conditions, the likelihood of gathering 85% of the temperature readings present in the pallet within the 16°C range proposed when using the PoRs found as middle points of this interval will increase.

The use of a 16°C temperature range as a reference for quality and shelf-life assessments along this supply chain will not be a major concern, because FSRs are shelf-stable products. However, if a component of the ration has a characteristic particularly sensitive to heat or cold (degradation of vitamins, color and texture changes, etc) that might happen within that range under ordinary storage and transport conditions; then, a higher level of quality variability in the pallet is expected, and the application of this system could derive in the incorrect acceptance of a faulty load. As well, a stronger level of sampling and quality control of the load before acceptance should be established when exposure to high temperatures (over 26.67°C) is recorded. Mainly, because the 15% of

temperatures inside the pallet that are not represented by this temperature tracking system might promote pathogen growth, and create food safety hazards for the troops.

Readability Study Figure 4 shows the placement of the tags for Configuration α (1.22 m). These were placed both in the PoRs found, as in their thermally equivalent positions inside the pallet. For Configuration β , the pallet was rotated 90° clockwise.

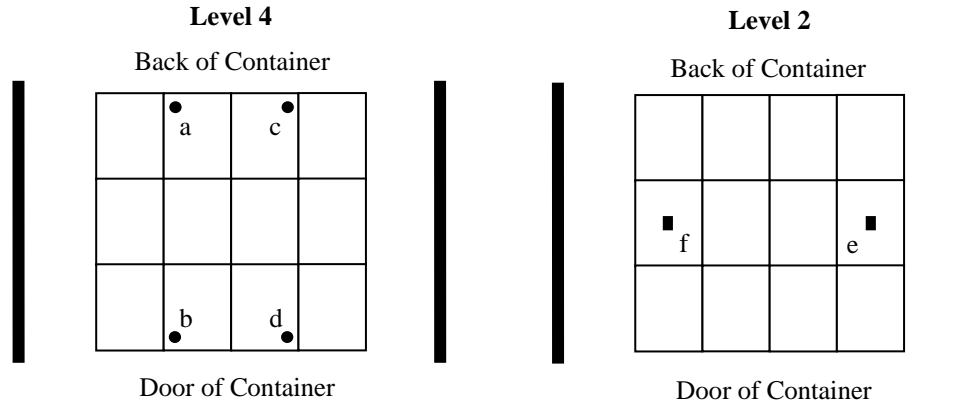


Figure 4. Locations of the RFID tags during the readability study for Configuration α . Where ■ represents PoR A, and ● represents PoR B.

Configuration α provided the highest number of tags read: A minimum of five for each distance (a, b, c, d, e), and six during two of the repetitions held at one meter. With Configuration β , four tags were read during the first five distances tested (b, c, d, e), but only three were recorded at three meters (b, c, e). The location with the highest readability of PoR A was position “e”; whereas for PoR B, the highest reading percentages were distributed in locations “b” and “c” in Configurations α and β , respectively. Tables 4 and 5 summarize the highest readability levels for each PoR in each one of the configurations studied at different reading ranges.

Table 4. Maximum readability values for both Points of Relevance (PoR) in Configuration α .

Antenna distance	Position	PoR read	Percentage of readings
0.50 m	e	A	17.80%
0.50 m	b	B	80.50%
1 m	e	A	32.20%
1 m	b	B	75.90%
1.50 m	e	A	15.60%
1.50 m	b	B	82.30%
2 m	e	A	18.40%
2 m	b	B	82.60%
2.50 m	e	A	22.40%
2.50 m	b	B	82.60%
3 m	e	A	6.60%
3 m	b	B	82%

Table 5. Maximum readability values for both Points of Relevance (PoR) in Configuration β .

Antenna distance	Position	PoR read	Percentage of readings
0.50 m	e	A	69.50%
0.50 m	c	B	47.80%
1 m	e	A	52.40%
1 m	c	B	69.40%
1.50 m	e	A	45%
1.50 m	c	B	78.40%
2 m	e	A	70.50%
2 m	c	B	88.10%
2.50 m	e	A	28.50%
2.50 m	c	B	68.80%
3 m	e	A	25.60%
3 m	c	B	74.90%

In Configuration α the best reading distance for PoR A is 1 m, and for PoR B is either 2 m or 2.50 m. In configuration β , this distance is 2 m for both PoRs.

These results are quite positive when considering the metallic environment that surrounded the pallet; and the fact that the quad-laminate packaging of the components of the FSRs in direct contact with the tags contained a layer of foil. Furthermore, the high density of the FSR packets inside the boxes restricted the existence of air pockets able to propagate the RF signal and favor tag/reader communication. Since metallic objects reflect RF waves, problems arise whenever the tags need to harvest energy in order to backscatter its information (Sydänheimo et al., 2006). Mo et al., (2007) also reported that whenever there is a metallic object near an antenna, this can change the antenna's radiation pattern, input impedance, radiation efficiency, and resonant frequency; which can decrease the performance of the RFID system. Additionally, Lázaro et al. (2009) accounts that, although challenging, the presence of metallic surfaces near UHF RFID applications can also generate constructive wave interference, and aid the RF system. Nonetheless, a study performed by Laniel et al. (2009) described the existence of signal attenuation at 915 MHz inside a metallic sea container due to path loss, such as multi-path and scattering. Taking into account that the tags utilized in the trial were not designed to work in metallic environments, the existence of favorable results in this readability study could be explained by a combination of factors such as the use of maximum reader output power, and the existence of overall constructive interference.

The system being designed will be used during container unloading operations; and the readings will be taken moments before the pallet is removed from the container by the forklift. Consequently, the space needed between the doors of the container and the antennas must allow the transit of a forklift loaded with a pallet. So, 3 m, the maximum antenna distance tested, will be chosen. At this distance, the readability of PoR A is less than PoR B; thus, the latter will be the thermally relevant point monitored. Given that the orientation of the pallet inside the container might vary according to the stowage pattern

used at the time of loading, the RFID tag in this location must be read from any of the two configurations studied. Locations “b” and “c” are the only two points of PoR B read at 3 m, which are equivalent to each other depending on the rotation of the pallet with respect to the sea container. As a result, instrumenting the pallet in any of them will achieve the systems’ goal. Table 6 shows the readability values of these positions.

Table 6. Readability values of positions “b” and “c” throughout the pallet.

Configuration	Position	Percentage of readings
α	b	82%
α	c	62.60%
β	b	32.60%
β	c	74.90%

As can be seen, the maximum amount of readability existent in the system is 82% while its minimum is 32.60%. Since both tags were detected in all cases, this last value does not imply that the tag will not be read; it only indicates that the reader will take a longer period of time detecting it. Obtaining 32.60% of the 200 reader communication attempts at that particular antenna distance took less than two minutes; so, reading the tag only once will take less than that. However, even if detecting the tag takes two full minutes; this amount of time fits perfectly into this phase of the FSR supply chain, as it uses the dead time when the forklifts are transporting the pallets to their destination after unloading them from the container. Besides, if the readings are done when the forklifts are far away, there are fewer opportunities for negative interactions between its metallic surface and the RF waves.

CONCLUSION A RFID temperature tracking system, able to monitor 85% of the temperatures of a pallet of First Strike Rations (FSR) with only one RFID tag has been successfully designed for combat feeding logistic operations.

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