# THERMAL EXPOSITION MONITORING OF FIREFIGHTERS

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This paper describes progress of project focused on health management and occupational safety of firefighter units' members, especially from thermal exposition point of view. After introduction is described evolution of design of the prototypes of a pocket personal measurement device. The next part deals with the selection of precise temperature, humidity and body activity sensors. Attention is also given to power consumption of the device. There were made many various tests of this measurement prototype device, mostly at real case scenarios, like measurements at a thermal chamber used for firefighter's suit testing. The last part of the paper describes software support for configuration and wireless monitoring and supervision of multiple members of a rescue team by an assigned overseer in real time. This provides additional level of safety and can greatly help to reduce the risk of health damage caused by extreme conditions.

**KEYWORDS**

measurement, safety, firefighters, thermal exposition

## 1 INTRODUCTION

Firefighter units' members are mostly exposed to dangerous conditions during their duty [KARTER 2003], [FAHY 2003]. At present, there is not available any compact system for measuring and assessing working heat stress and others health-care parameters. But it is important to measure thermal exposure on the surface of protective clothing and internal temperature. Based upon these needs a project was started with the goal to develop a personal device for monitor these risks. The system will measure, archive and analyze actual temperatures and it will warn the person in an appropriate way about reaching/exceeding the pre-set boundary values at which there is a danger of damage to health and clothing (protective clothing will lose its heat resistance). The system will also allow monitoring of movement activities and the person's body position in relation to the ground. The solution involves a unique way of controlling the whole system without using fingers at the time of emergency. This paper is dealing with progress in the project; initial stage is described at [NOVAK 2016].

## 2 STATE OF ART

According to the research that has been carried out, the proposed solution is unique. So far, conventional laboratory dataloggers have been used for testing - bulky, low mechanical endurance, necessity of finger control, they have not been compatible, high price, higher consumption, etc. Another unique feature is incorporating intrinsic safety of the system, which will make it absolutely unique and it will enable to use it also in explosion hazard area (chemical industry accident, mines, etc.) according to the ATEX directive [EU].

There are some other solutions, for example the QUESTemp°™ II. This personal heat monitor is a belt or pocket worn device with a thin, flexible cable leading up to a small ear mold containing the sensor and a small speaker [3M]. The QUESTEMP°II personal monitor is intended to be a part of a well-managed heat stress program. It is an alerting device which warns the user that their body temperature has risen above the "safe" level and that action should soon be taken to allow the body to cool. The QUESTEMP°II monitor acts as an aid and does not replace the individuals own feelings and judgment.

Many manufacturers produce devices called *Personal Alert Safety System (PASS)* (see Figure 1), which are designed to signal dangerous situations via an audible alarm. Typically, PASS devices sense movement or lack of movement and activate an alarm signal if the lack of motion exceeds a specific time period. The loud alarm signal alerts other personnel that a firefighter has become incapacitated and it helps to guide rescue personnel to the location of the incapacitated firefighter. Parameters and testing of some of these devices are described at NIST Interagency/Internal Report [BRYNER 2005].


**Figure 1**. Different PASS devices from various manufacturers.

## 3 TECHNICAL SOLUTION

The output of this project is a functional sample of the system for monitoring thermal exposure of firemen and rescuers, adjusted for tests in simulated and laboratory conditions. This monitoring system must meet the following requirements: The device is able to measure external (from -20 to +400 °C) and internal (up to 50 °C) thermal exposure of person's clothing and body and to archive the measured values for the subsequent analysis. In case of exceeding of the pre-set values, it will warn the person in an appropriate way about reaching this state (this is the primary purpose of the system). The device must fit in protective clothing breast pocket, weighs less than 300 g, and works within the temperature range from -20 °C to +50 °C. In electronics design the intrinsic safety is implemented, which enable to use the system also in explosion hazard areas including coal mines. The device must be customizable for individual persons, must provide data logging for potential off-line analysis and must be extendable by additional external sensors – like heart rate Bluetooth sensor.

The system was developed in two basic variants – a simpler and cheaper one without intrinsic safety and another one with it. The output in the area of intellectual property protection will be a submitted patent application. At the end of this project, testing of a few samples by a particular fire brigade was realized.

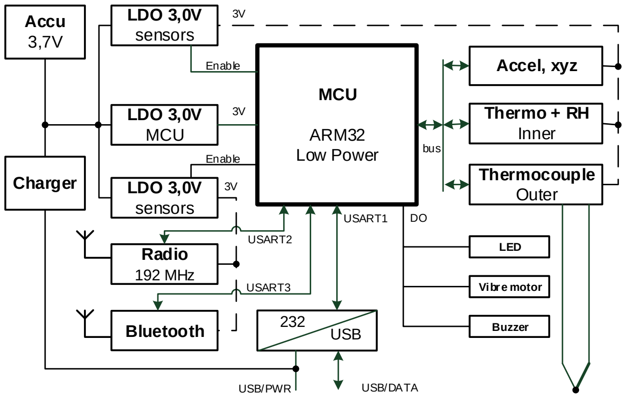


**Figure 2.** Functional diagram of measurement device

A functional diagram of the measurement device (prototype III) is presented on Figure 2. This measurement device is based on the advanced ultra-low-power 32bit MCU from Cortex-M3 ARM family STM32L152. Reason for choosing this microcontroller is its low consumption (0.9 µA at standby mode + RTC and 9 µA low-power run mode) what is almost the best consumption on the market, according EEMBC metrics [EEMBC]). This is ideal for battery application and intrinsic safety (ATEX).

Device for internal temperature and humidity measurement is SHT21 from Sensorion. The SHT21 has become an industry standard in terms of form factor and intelligence: Embedded in a reflow solderable Dual Flat No leads (DFN) package of 3 x 3 mm foot print and 1.1 mm height it provides calibrated, linearized sensor signals in digital, I2C format. The SHT2x sensors contain a capacitive type humidity sensor, a band gap temperature sensor and a specialized analog and digital integrated circuit – all on a single CMOSens® chip. This yields in an unmatched sensor performance in terms of accuracy and stability as well as minimal power consumption.

For external temperature measuring, the K thermocouple sensor is used. For digitalizing of the value from this sensor is used the MAX31855 from Maxim Integrated. The MAX31855 performs cold-junction compensation and digitizes the signal from a K-, J-, N-, T-, S-, R-, or E-type thermocouples. The data is output in a signed 14-bit, SPI-compatible, read-only format. This converter resolves temperatures to 0.25 °C, allows readings as high as +1800 °C and as low as 270 °C, and exhibits thermocouple accuracy of ±2 °C for temperatures ranging from -200 °C to +700 °C for K-type thermocouples.

Movement activity of equipped person is measured by the accelerometer ADXL345 from Analog Devices. The ADXL345 is a small, thin, low power, 3-axis accelerometer with high resolution (13-bit) measurement at up to ±16 g. Digital output data is formatted as 16-bit twos complement and is accessible through either a SPI (3- or 4-wire) or I2C digital interface. The ADXL345 is well suited for mobile device applications. It measures the static acceleration of gravity in tilt-sensing applications, as well as dynamic acceleration resulting from motion or shock. Its high resolution (4 mg/LSB) enables measurement of inclination changes less than 1.0 °. This 3-axes accelerometer also offers smart functions for internal data analyses. It can provide notification about lack of movement, free fall of firefighter etc.

Firmware at this MCU is responsible for data acquiring from all the external sensors and evaluate eventual alarm condition. Next task of MCU is store measured data to external EEPROM for data logging purposes and communication with PC-based application for data downloading and customization for individual needs of the specific user.

Some techniques were used at the initial stage of hardware design for power optimization reasons. The most important is usage of low power devices with software controlled powering (only when this device is necessary).

The system functionality can be enhanced by two communication channels. One is used for communication with some additional personal measurement device – for example Heart Rate (HR) sensor belt. For this close range communication is used low power Bluetooth 4.0 module (BlueGiga BL112). For communication with the command station is used a high-power radio module working on a lower frequency (192 MHz), which is suitable for communication throughout obstacles (like urban structures etc.).

## 4 PROTOTYPE EVOLUTION

Three prototypes of the device were made during the project time. The first one (see Figure 3) was designed to verify all technologic components and was used for measurements at the Health Institute in Ostrava. It used a modular system for adding and replacing of all sensors (on development boards).

**Figure 3.** Measurement device prototype version I

The following prototype (see Figure 4) was made with focus on size minimization and was tested at several firefighters' events (for example TFA competitions). All components are fully integrated on the main board. There are no separable modules.

**Figure 4.** Measurement device prototype version II (after an extreme test)

The last functional prototype (see Fig. 5) was designed based on additional needs resulting from the previous testing and consulting with firefighters' authorities. It was equipped with a wireless communication module for data exchange with the base station (typically mounted at firefighter's car cab). Hard metal cover was used for this prototype. This prototype was presented also at firefighter's expositions at Hannover (Germany) and Atlanta (U.S.A.).


**Figure 5**. Measurement device prototype version III (final)

## 5 INITIAL STUDY AND TESTING

The device described above (prototype I) was subject to a complex testing with two volunteers from local firefighter station (professional firefighters aged 32 and 42) who – prior to our testing – successfully passed a stress test in a functional laboratory of the Department of Physiology and Pathophysiology, Faculty of Medicine, University of Ostrava, Ostrava [JIRAK, 2014].

**Figure 6.** Testing at climatic chamber

The device for load measurement of the rescuers was verified in a climatic chamber of the Department of Work Physiology at the Health Institute in Ostrava (See Fig. 6). The climatic chamber has an inner space of 2 x 3 x 2 meters. Conditioned air is conveyed to the chamber from an engine room through a duct hole located in the wall and sized 1 x 1 m, along the chamber longitudinal axis, and removed in the wall on the opposite side. The chamber allows experimenters to adjust the airflow speed, dry air temperature, air relative humidity and intensity of heat or cold radiation.

First of all, these experimental persons completed a continuous load test on a bicycle ergometer (Ergo 900, Ergo-Line) in which the load was increased every minute by 25 W up to maximum. Subsequently, after perfect relaxation, they underwent a submaximal exercise test in which the load was increased every 3 minutes so that a steady state was reached at the end of each load stage. Experimental persons underwent this test in the rescue suit with the same equipment as during the subsequent testing in the climatic chamber.

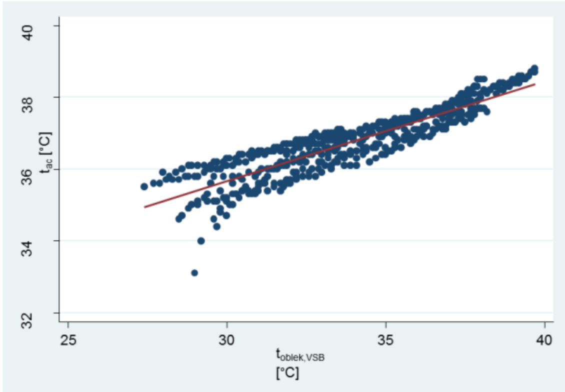


**Figure 7.** The relationship between the body temperature $t_{ac}$ (measured in the ear canal) and the under suit temperature measured by the SAM device

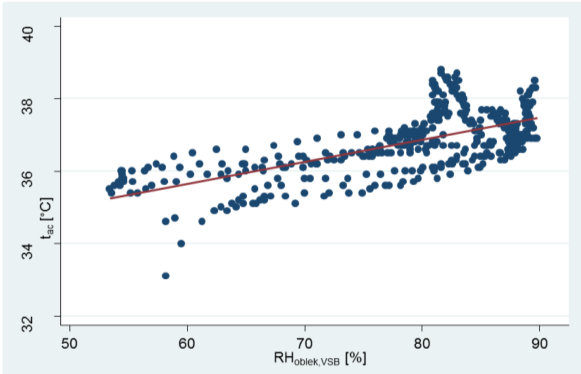


**Figure 8.** The relationship between the body temperature $t_{ac}$ (measured in the ear canal) and the under suit relative humidity measured by the SAM device (R = 0.6651)

Based on our experiments (Figure 7, 8), the air temperature measured under the suit proved to be a very good indicator of the overall load of firefighters or rescuers. The technical solution of sensing the temperature under the suit using the verified SAM technology does not affect or limit fire fighters in their work and minimizes the possibility of damage to the sensor and signaling failures [JIRAK, 2008].

## 6 NEXT TESTING AND VERIFICATION

After finalizing the first testing prototype (Figure 3) and its calibration, further testing was made. First of all was tested behavior at full working temperature range and then was performed test at Mannequin Men (PyroMan™) while some firefighter suit was attempt to achieve the certification.

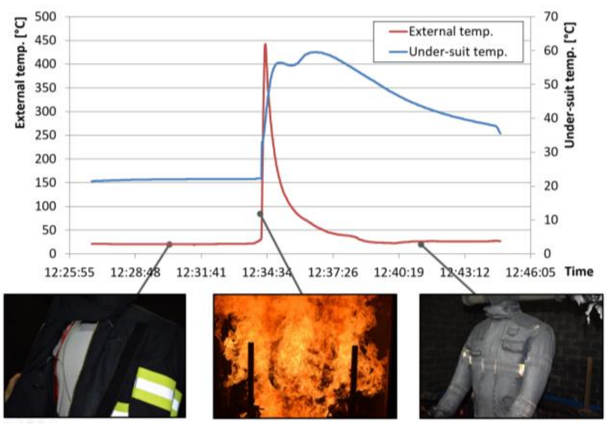


**Figure 9.** Test result at firefighter's suit mannequin test (Spain)

Figure 9 shows the results of the "mannequin test". This test has three phases: initialization with temperature stabilization on normal condition; next is seven-second-long part with applying flames from gas burner and the last phase is thermal stabilization after this thermal shock.
Another very important testing was made at Firefighters Training Centre equipped by Flashover Container Trainer. Experimental Person (instructor of this facility) was equipped with the third version of SAM prototype installed in a special pocket in their firefighter suit (see Figure 10) and was exposed to thermal source (regular fire from wood pallets) – see Fig. 11.

**Figure 10.** Installed measuring device

**Figure 11.** Flashover Container Trainer

The result of this test is a log with record of external and internal (under-suit) temperature and internal relative humidity progress during test. On Figure 12 is displayed the temperature from the external sensor (higher, orange color) and the internal temperature (blue). Maximal temperature was measured during direct facing to the fire.

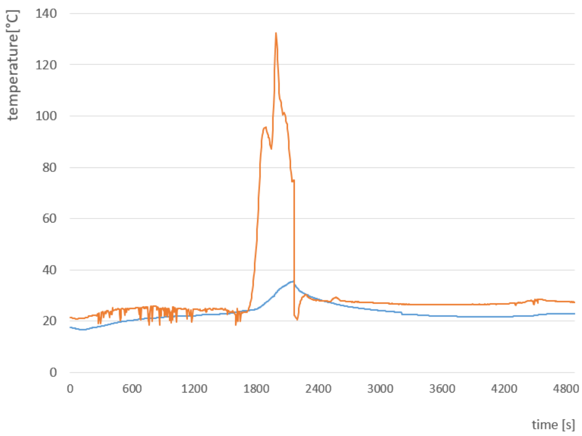


**Figure 12.** Flashover test result – external and internal temperatures

Accuracy of this measurement system depends on accuracy of individual sensors integrated into the system. The external thermocouple thermometer provides accuracy of ±2 °C. Accuracy of the sensor for internal (under-suit) temperature and relative humidity depends on the actual value and is described at Figure 13.

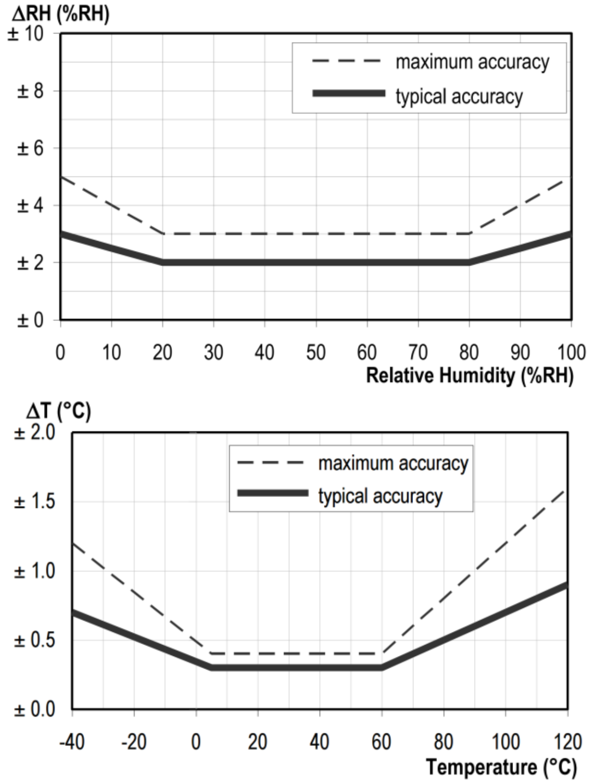


**Figure 13.** Accuracy of the internal sensor (SHT21)

## 7 SOFTWARE SUPPORT

The device offers the ability to customize most of its internal parameters based on the needs of the target application or even for every individual wearer. The device can be connected to a PC or notebook via a standard micro-USB cable and special software developed together with the device can then be used to change the configuration and parameters, check the basic status of the device and read the logs.
Another supplementary system for the device is a remote monitoring tablet (see Figure 14) for an operator commander or any other person that coordinates and monitors team members equipped with the pocket devices. The tablet with integrated communicates with pocket devices of all team members wirelessly.

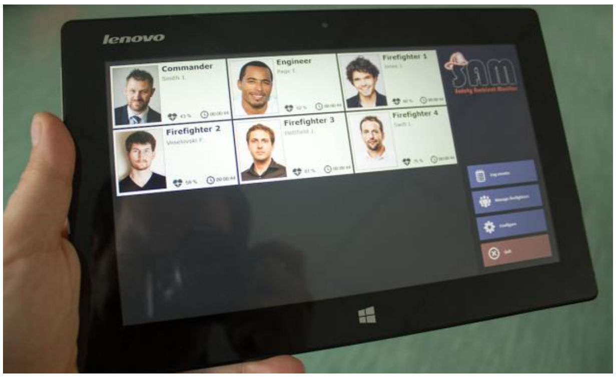


**Figure 14.** Remote monitoring tablet with a special graphical application

The application running on the tablet allows visual supervision over each team member – each of them is displayed in the form of a personal card with basic information and current status.
Each card contains a photograph and name of the person, position in the team, detailed list of values of all sensors of the pocket device, potential warning and status icons, timer monitoring for example the duration of the person's operation and an icon indicating a low battery of the pocket device.

For a very quick overview of the basic status of every monitored team member, the personal cards have color-coded backgrounds:

- green – normal condition, everything is fine,
- yellow – warning of imminent danger (warning status),
- red – critical danger (critical status),
- gray – communication with the pocket device has been lost.

More detailed feedback about the warning or critical status is presented in the form of symbolic status icons – each icon is displayed when the corresponding state has been detected:

- external temperate exceeds its limit,
- internal temperature exceeds its lower limit,
- internal temperature exceeds its higher limit,
- no movement has been detected for a certain time,
- freefall was detected (this icon is displayed only together with the previous one, if freefall was detected and the person is not moving).

## 8 CONCLUSION

The output of this part of this project is a prototype of a portable device enabling to measure external and internal temperature of protective clothing, heart rate and body position in relation to the ground (movement, no movement, standing, lying – injured, unconscious, etc.). The device is designed in two alternatives – a simpler one without intrinsic safety, and another one with intrinsic safety for use in explosion hazard areas. Another part of the project was development and verification of possibilities for wireless communication between each member of firefighter units and a commander.

## CONTACTS

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