EXPERIMENTAL DETERMINATION OF THE THERMAL FLUX DENSITY VARIATION LOST IN TIME BY A DIVER

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Keywords: thermal flux density, diving suit, hypothermia

Abstract: The survival of a person at the prolonged immersion in cold water is managed by many factors. After the determination of the mathematic model of the thermal transfer at the skin level, we will focus on the measurement of the body temperature variation of some subjects and on the calculation of the real thermal flux density lost in time by the divers. The subjects with different biophysical parameters will dive in various conditions (water temperature, depth, time) using minimum two types of suits of different thicknesses. We aim to compare the theoretical determinations to the real heat loss of a diver.

1. INTRODUCTION

The survival of an individual in prolonged cold water immersion are governed by pertinent factors including exposure time in water, roughness of the sea, water temperature, age, gender, fatigue and biophysical parameters of the individual. For example, shipwreck victims immersed in deep cold water and without proper insulation or protection could die of respiratory or circulatory failure at body temperatures below 28°C. Death in this pretext is associated with hypothermia-induced fatty degeneration which is accompanied by series of internal complications, leading to cardio respiratory arrest due to after drop. Although hypothermia is most common in patients exposed to extreme cold environment, it can develop secondary to toxin exposure, metabolic derangements, infections, and dysfunction of the central nervous and endocrine systems.

The choice of the diving suit can do in according to the water temperature at the work depth, the diving during and the diver physiognomy.

2. THEORETICAL CONSIDERATION

In a precedent work paper it was established the calculus formula of the thermal flux density which sweeps the diver body in diverse situations.

$\dot{q} = \Delta t_m \times \frac{m \times C}{S_c \cdot \tau} \left[W/_{m^2} \right]$ (1), where

Δt_m = the variation of the medium temperatures, S_c (m^2) = the body surface from the Dunn diagram– Annex 1;

$\tau(s)$ = diving time, C $\left[Kj/_{kgC^0} \right]$ = caloric coefficient specific for the human body

These theoretical studies were checked this year by an experimental study which pursues to measures the temperatures for the calculus of the real thermal flux density lost by the different subjects. In fact it measured the skin and the core temperature, at time equal intervals and it calculated the C_i in t_i moment for everyone who dived and the thermal flux density $\dot{q}_i$ too.

$\dot{q} = \dot{Q}/S$ (2) - the thermal flux density

$\dot{Q} = \dot{Q}_m - \dot{Q}_r - \dot{Q}_p$ (3) - the thermal flux lost by a diver

$\dot{Q}_r$ = the thermal flux lost by respiration, negative, represents 1/5 $\dot{Q}$

$\dot{Q}_p =$ the thermal flux lost at skin level, by conduction and convection, negative

$\dot{Q}_m$ = the metabolic thermal flux, positive, obtained with the Harris-Benedict relation, for men, in 24 hours:

$\dot{Q}_m = 66{,}473 + 13{,}7516m + 5{,}0033L - 6{,}755a[Kcal]$ (4),

where m = corporal mass in kg, L = high in cm, a = old in years

3. THE INFLUENCE FACTORS OF THE SURVIVAL TIME

3.1. THE WATER TEMPERATURE

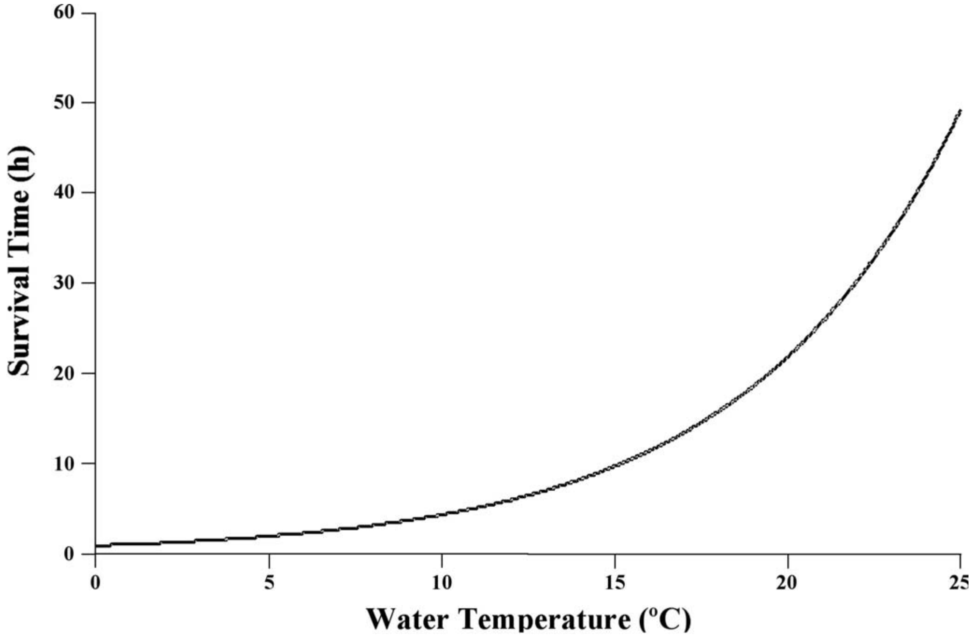

Fig. 1 Variation of the survival time with the water temperature

The curve from Figure 1 was obtained by assuming that the subject did not wear proper protection thermal insulation suit. It shows that the survival time increase exponentially with water temperature, initially very slowly up to 15°C and thereafter increases very rapidly with increase in the water temperature, with low probability of survival below 15°C water.

3.2. THE INSULATION THICKNESS OF THE SUIT

To increasing the probability of survival, it can use a protection suit with different thicknesses. Figure 2 shows that to maintain a core temperature of 28 **°C**, increasing the insulation thickness from 2 to 5 mm can increase the survival time by about 7 hours.

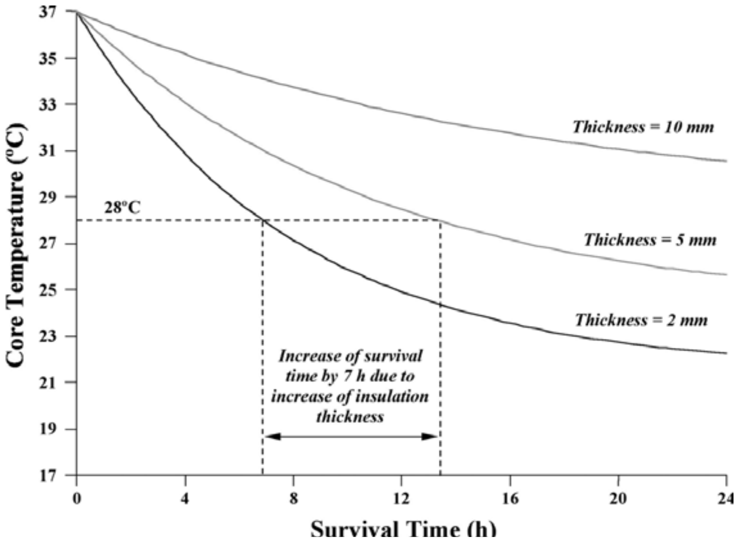

Fig. 2 Variation of the survival time with the suit thickness

3.3. THE PHYSIOGNOMY OF THE SUBJECT

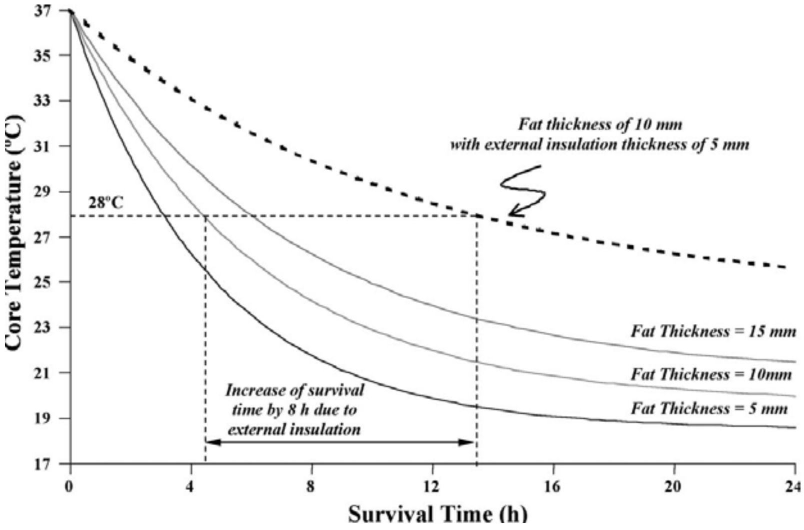

Fig. 3 Variation of the survival time with the fat thickness

The fat thickness beneath the skin was also found to have an influence on the rate of cooling as depicted in Figure 3.

Additionally, Figure 3 also indicates that the survival time required maintaining a core temperature of 28 **°C** in individuals having fat thickness of 10 mm can be increased by about 8 hours by wearing an insulating material (5 mm thick) such as thermal wetsuit.

3.4. THE RATIO S/V FROM THE BODY SURFACE AREA TO THE VOLUME

The body surface area to volume ratio *(S/V)* is also an important factor in determining the probability of survival of an individual stranded at sea. The body S/V ratio is inversely related to size, therefore individuals with small S*/V* ratios are large in size where as those with large S*/V* such as infants and children are generally small size. As a result, children are more vulnerable to hypothermia.

A good correlation was obtained between the core temperature and survival time, insulation thickness, fat thickness and body surface to volume ratio, respectively. In particular, the results indicated that the use of thermal insulation is very important in increasing the survival time. The survival time diversified like the diagram from the Figure 4.

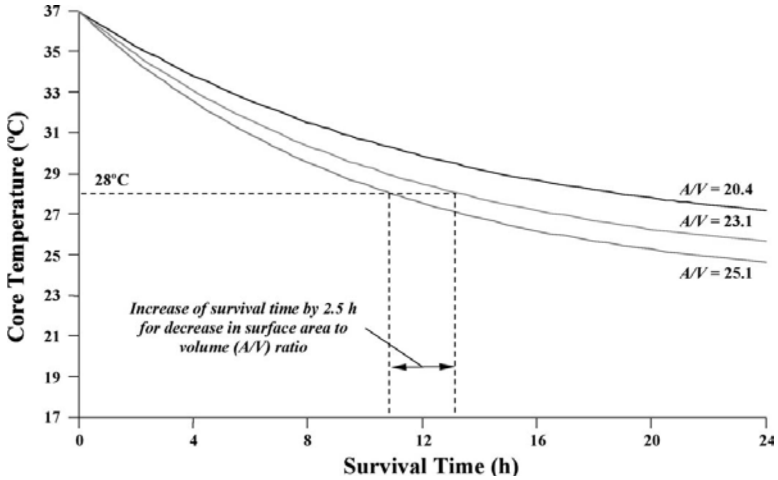

Fig. 4 Variation of the survival time with the ratio S/V

4. EXPERIMENTAL DETERMINATIONS

4.1. THE LOGISTIC LIMITS

The measurements were made in simulated surrounding, at Hyperbaric Laboratory of the Divers Centrum, with the following limits:

- The Simulator disposes by a single immersed thermal sensor attached at the analyzer rack and a mobile sensor, with a digital display limited at pressure and with a linkage cable by 3m longer.
- The water temperature from the simulator can't be much varied, it depends on the ambient temperature from the laboratory, and therefore the tests were made in diversified days, with varied surrounding temperatures.

4.2. DIVING CONDITIONS

To obtain viable results were made diving at the following descents: 15m, stopping at 9m and 30m stopping at 21m.

The subjects dived in different days, with varied water temperatures.

For each diving, the diving's dates were noted into a table like this:

Table1- Diving dates

Size	*Noted*	*U.m.*	*Value*
Depth	h	m	
Water temperature	t_a	^0C	
The water thermal conductivity	λ_a	W/mK	0,6
The water kinematics viscosity at T_a	v_a	m^2/s	
The water density	ρ_a	kg/m^3	1000
The water heat transfer coefficient	c_a	$j/kg\ K$	4182
The water compressibility coefficient	β_a	K^{-1}	$207*10^{-6}$
The gravity acceleration	g	m/s^2	9,8

$$\gamma_a = \frac{1{,}78 \bullet 10^{-6}}{1 + 0{,}0337 \bullet t_a + 0{,}00022 \bullet t_a^2} \quad [m^2/s]$$ (5), Poiseuille formula

Three subjects, having diverse physiognomic characteristics record into a table like this, participated to experiment:

Table2- Divers dates

Size	***Noted***	***U.m.***	***Subjects***		
			subject 1	***subject 2***	***subject 3***
Corporal mass	***m***	***kg***	***80***	***100***	***78***
Height	***L***	***m***	***1,80***	***1,74***	***1,78***
Corporal surface	S_c	m^2	***2,05***	***2,15***	***2***
Thorax circumference	***l***	***m***	***1***	***1,10***	***1***
Specific ratio	S_c/V_c	m^{-1}	***20,6***	***18,47***	***20,32***
Age	***a***	***years***	***29***	***27***	***31***
The skin heat transfer coefficient	c_p	W/m^2K	***0,32***	***0,25***	***0,32***

Each diver was equipped by range with two types of neoprene wet suits, of thickness 5 and 7mm.

4.3. RECORDING OF THE MEASUREMENTS

The diver and his retainer descended an intermediary diving stop. For 15m depth the diving stop was made at 9m. For 30m depth the diving stop was made at 21m.

On surface the two operators recorded the measured temperatures at the moment **τ** = 0, from 2 in 2 minutes, until the moment **τ** = 16 min too, from the both sensors.

The sensor 1 was putted between the wet suit and the diver's body, on his arm, for the external temperature of the body. The sensor 2 was putted on the ear lobe, for the internal temperature.

It kept the pressuring until 15m, respectively 30m. The surface operators recorded the measured temperatures at the moment **τ** = 18, from 2 in 2 minutes, until the moment **τ** = 32 min too, from the both sensors.

It was measured initial medium temperature t_{mi} (C^0) and final medium temperature t_{mf} (C^0) from the surface.

The values were recorded into a table like this:

Table 3- Measurements Table

Time	τ_i	***[min]***	***0***	***2***	***4***	***6***	***8***	***10***	***12***	***14***	***16***	***.***	***.***	***.***	***.***	***32***
Temp. Sensor1	t_{1i}	$[C^0]$														
Temp. sensor2	t_{2i}	$[C^0]$														

5. THE DIAGRAMS BY VARIATION IN TIME OF THE THERMAL FLUX DENSITY

$$\dot{q}\left[W/m^2\right] - \tau[\min]$$

It was traced diagrams, pursuing the two coordinates from a table:

Table 4- Measured thermal flux density

Time	**τ**	**[min]**	**0**	**2**	**4**	**6**	**8**	**10**	**12**	**14**	**16**	**.**	**.**	**.**	**.**	**32**
Thermal flux density	$\dot{q}_i$	**[W/m^2]**														

It compared three types of diving to pursue the influence of certain factors on the thermal flux density and implied on the survival time.

5.1. DIVING WITH THE SAME SUBJECT, SAME DEEP, DIFFERENT THICKNESS ON THE SUIT

Observations

- after 16 min, it exists tendency to uniform grow up of the thermal flux density;
- the thickness of the neoprene with 2mm greater, leads to a diminution of the thermal flux density with 40 -50W/m^2 in stabilized operating.

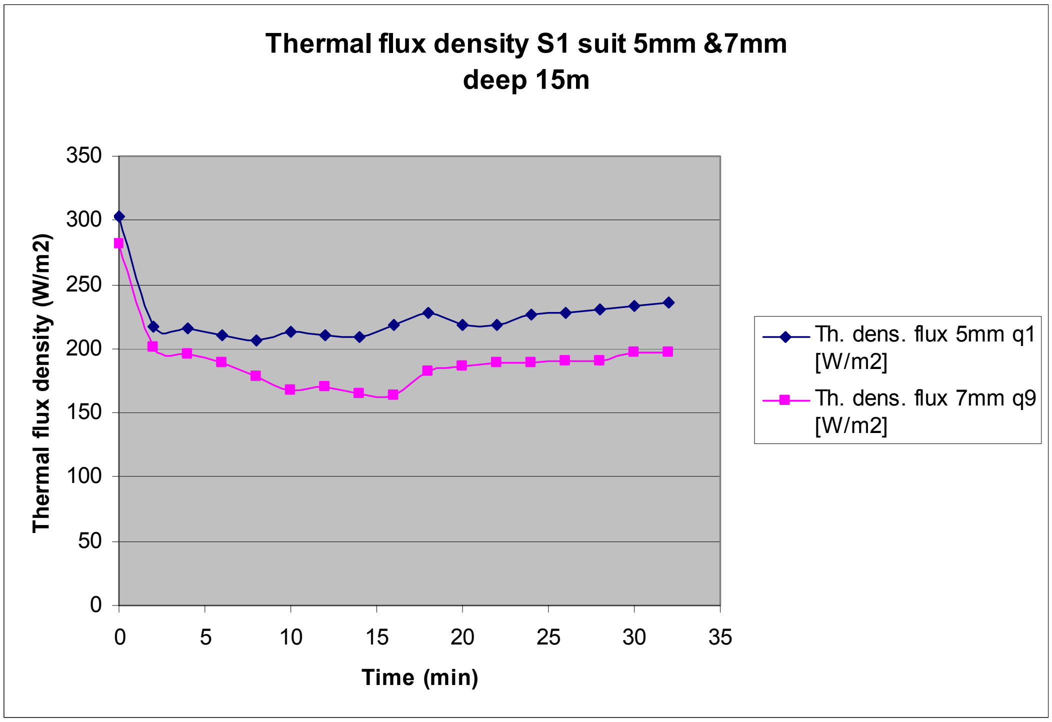

Fig.5

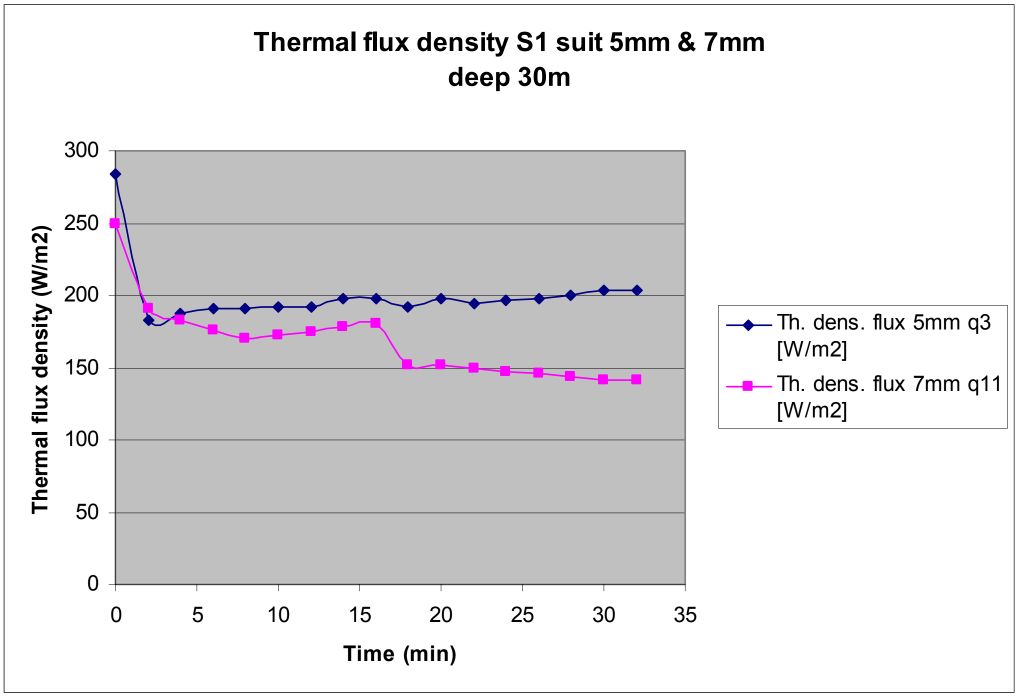

Fig.6

5.2. DIVING WITH DIFFERENT SUBJECTS (DIFFERENT RATIO S/V), SAME DEEP, SAME THICKNESS ON THE SUIT

In this situation, the ratio from the corporal surface aria and the volume S/V is very important. Like the 2.4 point from this paper, this ratio is direct proportional to the heat loss. The value of this ratio is different at the persons with diverse physiognomies (the thin subject has the ratio S/V greater than the fat subject). We analyzed two situations.

5.2.1. SUBJECTS WITH DIVERSIFIED RATIO S/V

S_1/V_1= 20,6; S_2/V_2= 18,47

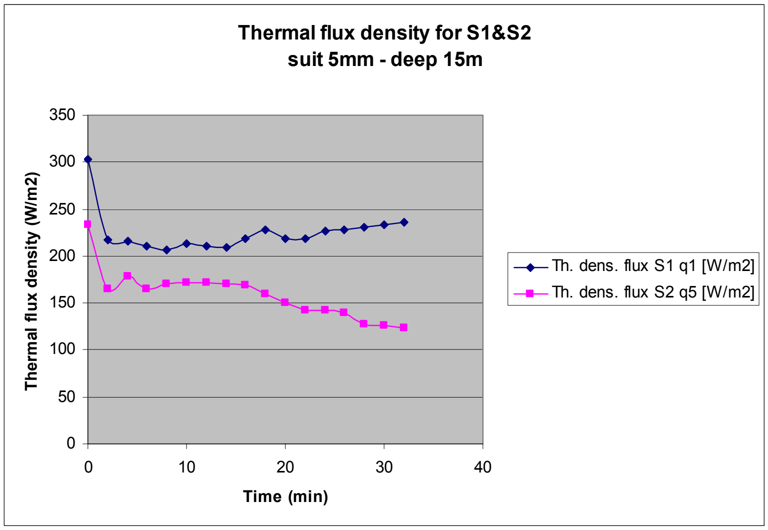

Fig.7

Observations

- after 10 min appears the tendency to uniform grow up of the thermal flux density for the subject S_1 with a great ratio S/V;
- after 10 min appears the tendency to uniform come down of the thermal flux density for the subject S_2 with a small ratio S/V;
- It can presume the tendency to uniform grow up of the thermal flux density appears after a long time, at the subject with S/V smaller.

5.2.2. SUBJECTS WITH PROXIMA VALUE OF THE RATIO S/V

S_1/V_1= 20,6; S_3/V_3= 20,32

Observations

- after 16 min appears the tendency to uniform grow up of the thermal flux density for the both subjects;
- after the next 16 min appears the tendency to uniform come down of the thermal flux density for the subject S_3 with a smaller ratio S/V

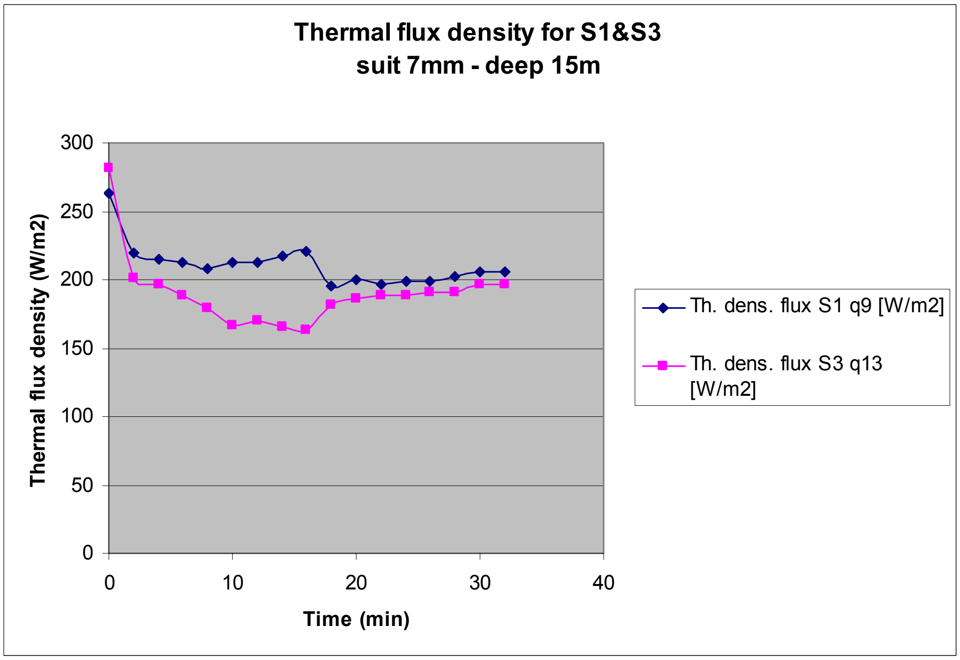

Fig.8

6. CONCLUSIONS

The harvested temperatures with the sensor 2 from the ear are approaching by the heart temperature, but not exactly enough. The heart temperatures are appreciatively 1^0C greater than the skin temperatures.

For the calculations were used the skin temperatures t_{1i}, measured by the sensor 1, on the arm, under the suit.

The obtained dates were processed and introduced in the measurement tables.

We calculated the $\dot{q}i$ values of the thermal flux density, at the moment τ_i and we assigned the diagrams $\dot{q}\left[W/_{m^2}\right] - \tau[\min]$ for every diving and for every subject.

During 10 min proximal, the operating is transitory; afterwards it observes the stabilization of measured thermal flux density.

The thermal flux density which is experimentally measuring represents the quantity which exceeds the metabolic flux density (the human body heat loss).

Like the diagrams show, the values of the thermal flux density were stabilized after 16 minutes, at 150 - $250W/m^2$, a constant proximate value.

Because the experiments were made in the simulator of the Hyperbaric Laboratory, the water temperature wasn't varied very much, the values diversified between 20 – 21 ^{0}C. In real conditions, into the see water, the heat losses will be greater.

The values obtained for the thermal flux density will be helpful for the diving planning. It can appreciate the loss of the heat by the time and implicit the thickness and the type of the recommending suit, by knowing the surrounding conditions (water temperature, depth) and the diving time.

The results of the experimental research will be introduce in a final dates base, to assure the thermal comfort of the divers, using appropriate diving suits.

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Annex 1- DUNN Diagram