CRITICAL HEATING TIMES OF EQUIPMENT EXPOSED TO FIRE TEMPERATURES

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ABSTRACT

For emergency shutdown of a NPP it is important to know in case of fire, how long certain critical instruments and machinery would operate after their long term ambient temperature limits have been exceeded. For exploring the problem experimental measurements were carried out for a pressure transmitter and a valve actuator with electric motor. The performance in relation to nominal values was observed by recording relevant times and temperatures. Damages and failures of the equipment were also observed. A simple theoretical model was found applicable in most of the cases. A universal curve was obtained to estimate the critical heating time in hot environments. Experimentally the pressure transmitter was suddenly exposed in a test furnace at different temperatures. In normal operation temperature range the pressure output signal stayed within limits of specifications up to +70 °C. At higher temperatures pressure signal went out of calibration (at 140 °C), and short circuit occurred (at 250 °C) damaging the equipment. In similar experiments of the valve actuator the microswitch failed at 230 °C, and electric motor was damaged at 250 °C.

INTRODUCTION

For fire risk analysis it is important to know how long time an electric instrument works during an emergency situation when exposed to fire in an enclosure. Knowledge of damage thresholds for nuclear qualified electrical cable insulation and instruments are critical to proper modelling of fire growth and fire-induced damage in nuclear power plants. Vendors of those electric instruments supply usually only ambient limits for normal use. In an emergency situation of fire temperatures rise much higher than limits applied in normal situation, but equipment may still work for some time due to delays in various transfer processes. The running time beyond the use limit as temperature, heat release rate or smoke density are exceeded can be investigated by carrying out realistic simulations or experiments. In this study we carried out experiments for two energised electrical instruments: pressure transmitter and valve actuator with electrical motor. We compared temperature development in the instruments calculated by using theoretical models with results yielded from corresponding experiments. A similar experiment and modelling for an energised cable is described.

HEATING OF SIMPLE SHAPED BODIES

The electrical instrument box can be modelled as a thin-wall body with uniform temperature through the wall using well established heat trensfer theory [1-3]. Presuming effective value of the linearized ´convective´ heat transfer coefficient h is temperature independent in the range of ambient fluid temperatures T_a, and taking $\rho_m c$ for the material constant, a closed form linear solution is obtained for the temperature. Presuming further internal heat generation is zero (heating of circuit cards by electric energy can be neglected) for a blunt body temperature T is given by

$$\frac{T - T_o}{T_a - T_o} = 1 - e^{-t/\tau_a} \tag{1}$$

where τ_a is a time constant determined either from experiment or calculated using heat transfer theory from the dimensions of the body. Eq. (1) was shown to represent in the cases studied the most essential temporal behaviour of the critical parts of the intruments [4].

EXPERIMENTS WITH A PRESSURE TRANSMITTER

The pressure transmitter consisting of measuring and electronic units. The transmitter was placed in the centre of a test oven. It was preheated to temperatures of +40, + 70, +140, and 250 °C and kept at this constant temperature by using a PID-regulator. The oven temperatures were selected to correspond: (i) the normal operation temperature, (ii) normal maximum operation temperature, (iii) elevated temperature 20 K beyond the expected damage temperature of 120 °C, and (iv) an elevated temperature 130 K beyond the expected damage temperature in order to obtain permanent transmitter damage. The transmitter was installed to measure a constant water pressure of 1 bar, which was obtained by the hydrostatic pressure of 10 m water column in a tube.

It can be noted that neglecting the initial transient caused by measuring arrangements the instrument retains calibration for +40 °C, and +70 °C tests. For +140 °C test the pressure signal retains calibration until 46.6 min, but does not get damaged during the whole experiment. The signal of +250 °C test went out of calibration limits at 20.4 min. There were a short-circuit in the device in about 40 minutes, when the temperature of the instrument was about +200 °C, and the pressure indicating voltage signal fell down on the level 0.1 ... 0.3 V indicating permanent damage of the transmitter [4].

STRUCTURE AND PROPERTIES OF A VALVE ACTUATOR (ELECTRIC DRIVE) WITH AN ELECTRIC MOTOR

A valve guide - motor -system of 120 W and another of 900 W of Sovjet origin were studied. They were tested under increasing demands until a permanent fatal damage occurred. No technical documents of the systems were available except those stamped on the rating plate of the equipment..

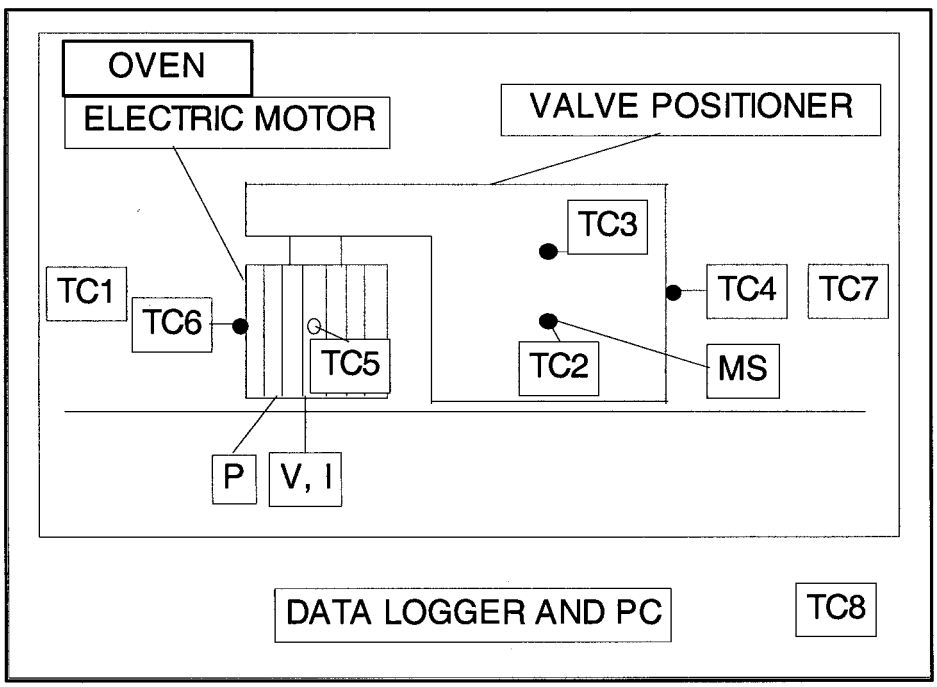

Figure 1. Experimental arrangements. TC: thermocouples, P: power, V: voltage, I: current and MS: micro switch.

The valve guide - motor (Fig. 1) consisted of an asyncronous electric motor, and the valve guide proper with an optional manual steering wheel. Nominal electrical values of the motor from the rating plate were: power 120 W, current 0.44 A, voltage 380 V, and rotating velocity 1380 rpm (23 r/s). The

measured mass of the electric motor was 4.03 kg. Nominal values of the valve guide, type AA were: torque 100 Nm, mass 23 kg, rotation velocity 24 rpm (0.4 r/s), regulation limit from 10 to 45 r (25 ... 60 Nm). The weighed mass of the electric motor and valve guide -system was 24.57 kg. The difference between the nominal and measured mass may be that the latter included oils and dust.

The other valve guide -motor consisted of an electric induction motor, and a valve guide with a manual steering wheel. Nominal electric values were: power 900 W, current 4.8...2.8 A, voltage 220/380 V and rotating velocity 1340 rpm (22.3 r/s). The measured mass of the motor was 15.7 kg. values of the valve guide were: torque 250 Nm, nominal mass 62 kg, velocity of rotation 25 rpm (0.42 r/s), regulation limit from 1 to 6 r. The weighed mass of the electric motor and valve guide system was 59.51 kg. again the difference between nominal and measured masses may be that the latter included oils and dust.

The electric motor (120 W, Ø100 mm x 170 mm) is fastened with screws on the valve guide apparatus. The sensitive parts of the motor are insulation papers and lacquers. The interior of the valve guide consists of two chambers, the upper chamber containing mechanical gearing, and the lower chamber electric components: cables, switches and pointers, which are potentially the most sensitive components. The structure and sensitive components of the 900 W device are essentially the same but bigger in size. The major question of this study was, what are the maximum allowed temperatures of those sensitive components?

Rated nominal continuous maximum operation temperature for insulation classes B and F are 130 °C and 155 °C, respectively. Motors are designed for maximum operation temperature of 110 °C and 130 °C, respectivelly. Coils breake approximately at 250 °C, and soft soldering of wires melts at about 180 °C. Therefore, after short preliminary study motor insulation was taken as the most sensitive part of the system. Other sensitive parts were the electrical components in the lower chamber of the valve guide. This information was used for designinig the experiments, especially for placing the measurement gauges. Heat transfer calculations as shown in [4] were carried out based on the nominal values and measured dimensions of the equipment to estimate the heating of the instruments during the tests.

EXPERIMENTS WITH THE VALVE ACTUATOR AND ELECTRIC MOTOR

The oven temperatures during tests were chosen on similar principles as for the pressure transmitter mentioned above: a common upper limit of normal operation temperature (40 °C) in plants, maximum operation temperature (110 ...130 °C) of electric motor, and a temperature, where coils are likely to become damaged (250 °C). The electric performance of the equipment was studied before, during and after the heating experiment. The motor was started for a while before placing into the oven, a few times while heating, and finally after removal from the oven. Mechanical performance was monitored from the operation of a microswitch in the position transmitter. If it worked not in a certain temperature it was taken the to be failure temperature.

Two K-type thermocouples were mounted on the electric motor (TC5, TC6 in Figure 1). Similarly, two thermocouples (TC3, TC4) were fixed on the outer surface of the valve actuator box, and one (TC2) inside the lower chamber of the valve actuator at the vicinity of cables and switches. A thermocouple (TC1) measured the air temperature in the oven away from the unit, and another (TC7) the temperature of the wall. Ambient temperature in the test hall (TC8) was also measured. The thermocouples were shielded. Painting was removed from the body of the electric motor and the valve actuator at the area where thermocouples were fixed in order to prevent thermal gradients. Measurements were recorded by a PC-controlled data acquisition system.

For performance measurements the electric motor was switched on 380 V mains for a short moment before, during and after heating. Current in the motor was measured by using an AC/DC clamp meter Lutron DM-6052, and a Fluke clamp current probe AC/DC Y8100. Electric power of the electric motor was measured by using the SOAR model 2720 digital watt/watt-hour measuring instrument. Results were recorded manually. Function of a microswitch in the position transmitter was monitored continuously using a simple electrical circuitry.

In the oven an experiment was continued until thermal equilibrium was reached (temperature difference < 5 K). The system was allowed to cool down to initial temperature before the next experiment was started.

EXPERIMENTAL RESULTS

It took typically 2 ... 3 hour for the valve actuator and electric motor to reach thermal equilibrium. In Fig. 2 temperature of the valve actuator body (TC2 - TC4), and oven air (TC1) is plotted as a function of time. It is clearly seen that temperature inside the electrical box in the vicinity of cables and microswitches (TC2) is lower than on the surface of the valve actuator (TC3 - TC4). The valve actuator and electric motor -system were massive heat absorbers with a significant heat capacitance. When the device was placed in the oven the controlling system was outpowered by the disturbance and failed to keep air temperature constant. It decreased for a period of at least 40 minutes significantly below the set temperature (TC1 in Fig. 2). This caused a significant problem in modelling the heating of the system, because constant ambient was no more valid. In the 40 °C experiment we could use only time range from 50 to 100 minutes, where oven temperature was again reached its desired constant value.

Another unavoidable problem arose from heat generation of the electric motor during test runs, which caused additional steps in the temperature curves of the oven air (TC1 in Fig. 2 at 39 min). Neither one of these phenomena does not prevent using the model deviced here. There are enough good data (TC2 - TC4 from 50 to 100 min in Fig. 2) to determine the time constant. The step in curve TC1 allows determining the heat capacity of the motor around 39 min. This information is easily used for estimating heating times during emergency use.

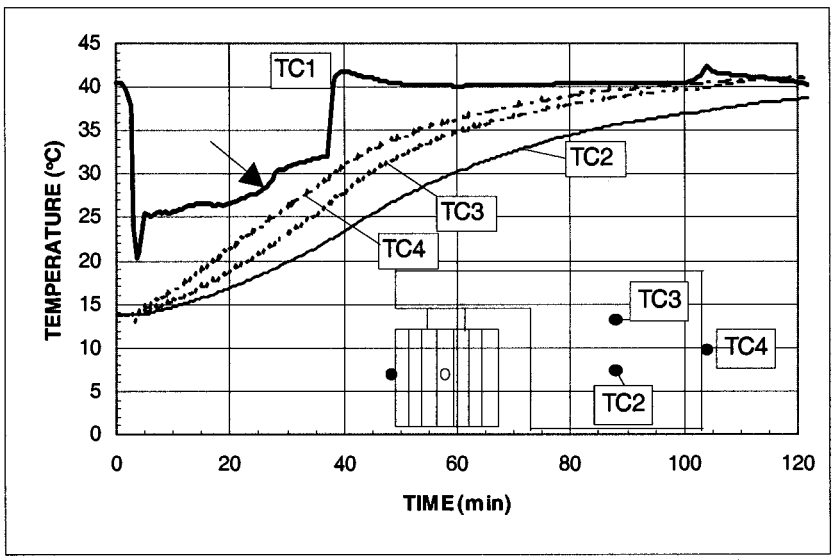

Figure 2. Measured temperatures in the electrical box (TC2) and on the box (TC3 - TC4) as well as air temperature (TC1) in the oven (+40 °C).

In Fig. 3 relative temperature of the body of the motor is plotted as function of time. The temperature development on the electric motor is the same at its two measuring points. It was found that temperature distribution in the oven is slightly uneven. Temperature difference between the and right sides could be up to 10 K. It was caused by a faulty heating resistor in the oven. Even this does not invalidate our results.

Due to problems with constant air temperature in the oven during heating, we carried out cooling experiments after the heating experiments of 140 °C and 250 °C. After tests the valve actuator and electric motor -system was quickly taken from the oven for cooling in constant ambient in the test hall. Temperature development of the system was measured during cooling period until to test hall temperature 10...20 °C in about 10 hours. This allowed determining the time constant of the system in case of cooling. For linear thermal theory time constants shoud be the same for both heating and cooling provided there are no internal sources of heat.

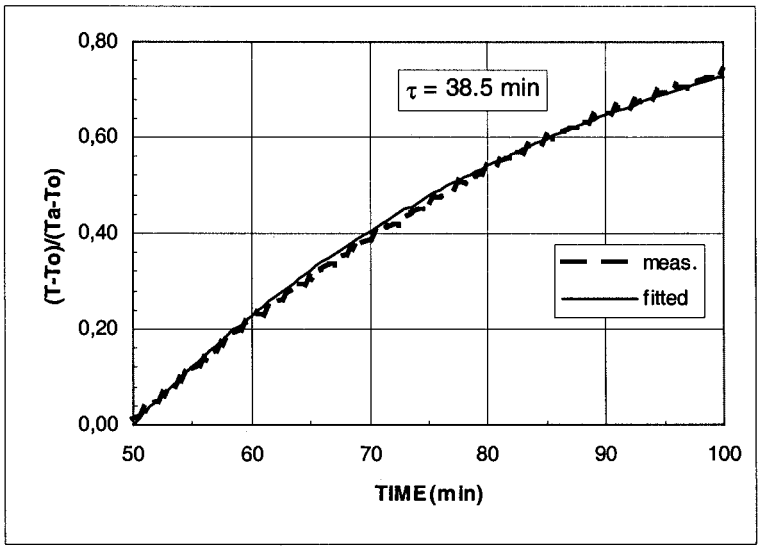

Figure 3. Fitting of the model to the experimental data on the range of 50 ... 100 min in case of electric motor at 40 °C heating experiment.

COMPARISON WITH THEORETICAL PREDICTIONS

Measured temperatures were compared with theoretical predictions in blind and open way. Blind predictions were made based on determination of the effective value of h on physical dimensions of the heated object, and using the theory described in [4]. Data shown in [4] indicate qualitative and even quantitative agreement. For the instrument case the error between blind and open fits is from 10 % to 50% at maximum. For open fits very good agreement was obtained using Eq. (1) as shown by an example in Fig. 3. In Table 1 comparison is made between values of time constants obtained from blind and open fits of the pressure transmitter measuring (τ_b) and electronic (τ_a) units. It is noticed blind fit is good to a factor of 2, which is fairly well for risk analysis purposes.

Simple exponential temporal behaviour of temperature transients was observed experimentally in all tested equipment within a metal case. Despite some experimental shortcomings time constants for heating could be determined. The heating model combined with heat transfer calculation for simple geometric bodies allow quick estimation of heating time constants for an arbitrary equipment. Only the mass, rough information of material, as well as physical dimensions are needed. Critical heating time is then obtained immediatelly from the time constant for arbitrary ambient temperature from the universal curve.

Table 1. Time constants at different ambient temperatures obtained fron blind and open fits of the measuring (τ_b) and electronic (τ_a) units of a pressure transmitter.

Test	Blind fit (min)		Open fit (min)	
	τ_b	τ_a	τ_b	τ_a
+40 °C	163	43	70	30
+70 °C	140	37	70	31
+140 °C	102	28	110	48
+250 °C	71	20	45	25

GENERALIZED UNIVERSAL CURVE

For equipment contained within metal boxes a very simple general estimate of the critical heating time could be obtained by generalizing the results from the present experiments. In case of fire a sudden change of ambient temperature ΔT_a occurs. The critical temperature ΔT_{cr} above normal ambient temperature is the maximum temperature, where the instrument still functions. The time t_{cr} when this temperature is reached is called the critical time span. This time solved from Eq. (1) becomes

$$\frac{t_{cr}}{\tau} = -ln(1 - \frac{\Delta T_{cr}}{\Delta T_a}) \quad (2)$$

where τ is the heating time constant of the instrument box. The value of τ can be determined experimentally using similar experiments carried out here. However the universality of this result becomes valuable, because a rough value of τ, accurate enough for risk analysis purposes, can be calculated from the mass and physical dimensions of the instrument. In Table 2 failure data are presented from all experiments carried out in this work. In Fig. 4 these are plotted with estimated error bars on double logarithmic plane using different symbols. Curve of Eq. 2 is plotted as full line. The experimental observations fall in this line within experimental errors.

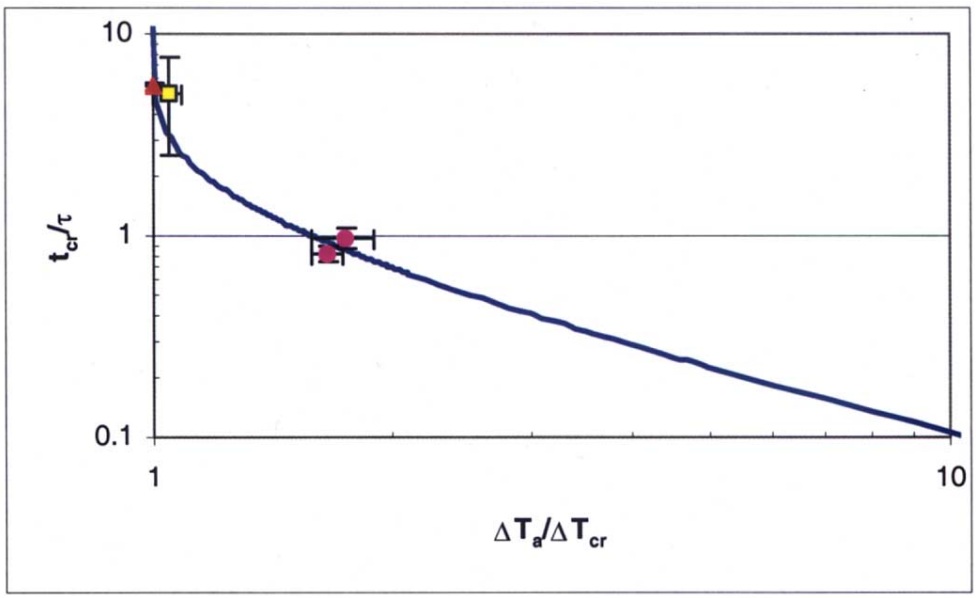

Figure 4. Universal dependence of non-dimensional critical heating time on non-dimensional ambient temperature change relative to the critical temperature change plotted on linear logarithmic scales. Experimental points with error bars shown: pressure transmitter (circles), valve actuator (square), and electric motor (triangle).

Table 2. Critical temperature changes and times for the tested instruments.

Device	**ΔT_a (K)**	**ΔT_{cr} (K)**	**t_{cr} (min)**
Pressure transmitter	120	69	46.6
Pressure transmitter	230	139	20.4
Valve actuator	230	225	174
Electric motor	230	236	181

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