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**EXPERIMENTAL STUDY  
OF LOW-TEMPERATURE LONG-TIME  
RELAXATION  
IN EPOXY RESIN**

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Экспериментальное изучение низкотемпературной медленной релаксации в эпоксидной смоле

Измерялась мощность тепловыделения  $Q(T_1, T_0, t)$  после быстрого изменения температуры от начального значения  $T_1 (1,1 \text{ K} \leq T_1 \leq 25 \text{ K})$  до конечной величины  $T_0 (1,1 \text{ K} \leq T_0 \leq 4,2 \text{ K})$  для  $0,2 \text{ ч} \leq t \leq 700 \text{ ч}$ . При низких температурах,  $T_1, T_0 < 2 \text{ K}$ , результаты хорошо согласуются с туннельной теорией и соответствующая плотность состояний двухуровневых систем  $\bar{P}_m = 1,0 \cdot 10^{39} / \text{Дж} \cdot \text{г}$ . Для более высоких температур наблюдаются существенные отклонения от туннельной теории.

Работа выполнена в Лаборатории ядерных проблем ОИЯИ.

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Experimental Study of Low-Temperature Long-Time Relaxation in Epoxy Resin

The power  $Q(T_1, T_0, t)$  released after rapid temperature change from initial  $T_1 (1.1 \text{ K} \leq T_1 \leq 25 \text{ K})$  to final  $T_0 (1.1 \text{ K} \leq T_0 \leq 4.2 \text{ K})$  for  $0.2 \text{ h} \leq t \leq 700 \text{ h}$  was measured. At low temperatures,  $T_1, T_0 < 2 \text{ K}$ , the results agree with the tunneling theory well, and the corresponding density of states of two-level systems  $P_m = 1.0 \cdot 10^{39} / \text{Jg}$ . For higher temperatures, essential deviations from the tunneling theory are observed.

The investigation has been performed at the Laboratory of Nuclear Problems, JINR.

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## 1. Introduction

According to the experimental research of recent years /1-6/, long-time heat relaxation is a characteristic feature of amorphous materials: the power release  $Q(T_1, T_0, t)$  observed after rapid temperature change from the initial temperature  $T_1$  to the final (measuring) temperature  $T_0$  falls down very slowly. This heat relaxation - as well as some other features of amorphous solids - may be treated within the phenomenological tunneling model /7,8/.

According to this model, localized two-level systems with quantum tunneling through the barrier between two wells, exist in glasses. Each system may be characterized by the asymmetry energy  $\Delta$ , the barrier energy  $V_B$ , the well separation  $d$ , the tunneling coupling energy  $\Delta_0 = \hbar \omega_0 \exp(-\lambda)$ ,  $\hbar \omega_0$  being the zero-point energy in either well, and the tunneling parameter  $\lambda = d(2m_0 V_B)^{1/2} / \hbar$  ( $m_0$  is the mass of a tunneling particle). The energy splitting between the lowest two states in the two-well system is  $E = (\Delta^2 + \Delta_0^2)^{1/2}$ .

To explain time and temperature heat capacity dependence, observed in glasses, the distribution function  $P(\Delta, \lambda)$  of two-level systems does not need actually to depend on  $\Delta$  and  $\lambda$ : for small  $\Delta$  and  $\lambda$ , contributions of which manifest themselves for  $T \lesssim 1 \text{ K}$  and short measuring time, an assumption of uniform distribution is usually made, namely

$$P(\Delta, \lambda) = \bar{P} = \text{const.} \quad (1)$$

This leads to the time dependent distribution function for the density of states,

$$n_0(t) = (\bar{P}/2) \ln(4t / \tau_{\min}), \quad (2)$$

where  $\tau_{\min}$  is the shortest relaxation time, and to the heat release of the form

$$\dot{Q}(T_1, T_0, t) = (\mathcal{T}^2 k_B^2 / 24) \bar{P} V (T_1^2 - T_0^2) t^{-1}, \quad (3)$$

where  $V$  is the volume of the specimen and  $k_B$  is the Boltzmann number.

Indeed, an accurate  $t^{-1}$  dependence of the heat release was observed in amorphous vitreous silica /1-3/, and in amorphous  $\text{Fe}_{80}\text{B}_{14}\text{Si}_6$

and  $\text{Co}_{69}\text{Fe}_{4.5}\text{Cr}_2\text{Si}_{2.5}\text{B}_{22}$  /5,6/. Heat relaxation proceeds a little slower in organic materials, for instance  $\dot{Q}$  is proportional to  $t^{-0.75}$  in epoxy resin Stycast /3/.

$T_1$ -dependence of the heat release was measured in vitreous silica /3/ and two metallic glasses /5,6/. The power released is proportional to  $T_1^2 - T_0^2$  for rather low  $T_1$  and  $T_0$  only. One can explain the deviations from (3) observed for higher  $T_1$  assuming more complicated distribution function for the density of states, namely /6/

$$n(E, t) = n_0(t) / (1 + \exp((E - E_f) / k_B T_b)), \quad (4)$$

where  $E_f = k_B T_f$  and  $T_b$  are constants.

With the distribution (4), the heat release is

$$\dot{Q}(T_1, T_0, t) = (\mathcal{F}^2 k_B^2 / 24) \bar{P} V t^{-1} (I_2(T_1/T_f, T_b) T_1^2 - I_2(T_0/T_f, T_b) T_0^2), \quad (5)$$

where

$$I_2(T/T_f, T_b) = 2(T_f/T)^2 \int_0^{T/T_f} (T/T_f) I_1(T/T_f, T_b) d(T/T_f) \quad (6)$$

$$I_1(T/T_f, T_b) = (6/\mathcal{F}^2) \int_0^\infty \frac{x^2 \exp(-x) dx}{(1 + \exp(-x))^2 (1 + \exp((xT/T_f - 1)/(T_b/T_f)))}. \quad (7)$$

The tunneling parameter  $\lambda$  was assumed to be independent of temperature both in (3) and (5). However, the heat relaxation in amorphous metals after "short heating" indicates that  $\lambda$  may depend on  $T$  for  $T \geq 0.1 T_f$  /6/. Such experiments are performed as follows: after complete relaxation at  $T_0$ , the specimen is heated rather rapidly to the "heating" temperature  $T_H$  and after the time interval  $t_H$  is rapidly cooled to  $T_0$  again; then the heat release  $\dot{Q}(T_H, T_0, t_H, t)$  is measured.

With temperature independent  $\lambda$ , the ratio  $r$  of  $\dot{Q}$  for two different  $t_H$  (and the same  $T_0$  and  $T_H$ ) is

$$r = \frac{\dot{Q}(T_H, T_0, t_{H1}, t)}{\dot{Q}(T_H, T_0, t_{H2}, t)} = \frac{1 + t/t_{H2}}{1 + t/t_{H1}} \quad (8)$$

and does not depend on the value of  $T_H$  /6/.

To explain the dependence of  $r$  on  $T_H$  observed in glassy metals /6/, an assumption that

$$\lambda' = \lambda - \alpha T/T_f \quad (9)$$

is made, where  $\alpha$  is constant. This leads to the ratio

$$r = \frac{1 + (t/t_{H2}) \exp(-\alpha T_{H2}/T_f) / \exp(-\alpha T_0/T_f)}{1 + (t/t_{H1}) \exp(-\alpha T_{H1}/T_f) / \exp(-\alpha T_0/T_f)} \quad (10)$$

which is in good agreement with the experimental results for  $t = 1h$ ,  $t_{H2} = 20h$ ,  $t_{H1} = 0.2h$  and  $t_{H1} = 0.5h$  in the region  $0.1 \leq T_H/T_f \leq 1$ , if one takes  $\alpha = 6$ .

Generally, the  $T_0$  dependence of the power release may significantly differ from that of (3) or (5), if  $\lambda$  is temperature dependent.

Until now, measurements with varying  $T_0$  have only been performed for vitreous silica, and only for  $T_0 \ll T_f \approx 13K$  ( $0.05K \leq T_0 \leq 1.08K$ ) /1-3/; the results agree with (3) well.

In this paper we present the results of the heat release measurements in epoxy resin EPILOX T-20-20, hardened with dipropylenetriamine in stoichiometric proportions at room temperature, in a fairly extended region of parameters  $T_1$ ,  $T_H$ ,  $T_0$ ,  $t_H$  and  $t$ .

## 2. Experimental

The specimen (a cylinder 48 mm in diameter, 29 mm high) consisted of 57.54 g of EPILOX T-20-20 and 11.90 g of copper foil (30  $\mu$ m thick) for thermal contact with the thermometer (germanium resistor SI-N1), the heater and the heat switch, connecting the specimen with the body of the calorimeter.

The experimental arrangement was the same as in /9/. The specimen with the thermometer and the heater hangs in the calorimeter on 8 Kapron threads (0.13 mm in diameter, 31 mm long).

The resistance drift  $\dot{R}$  of the thermometer was measured as a function of time  $t$  after cooling the specimen from the equilibrium temperature  $T_1$  to  $T_0$ . The corresponding power release was then determined from the directly measured power release  $\dot{Q}_m$ , the heat leak  $\dot{Q}_A$  and the heat background  $\dot{Q}_B$  as

$$\dot{Q}(T_1, T_0, t) = \dot{Q}_m - \dot{Q}_A - \dot{Q}_B, \quad (11)$$

where

$$\dot{Q}_m = \dot{R}C / (\partial R / \partial T) \quad (12)$$

$$\dot{Q}_A = A(T_K - T) \quad (13)$$

$\dot{R}$  is the germanium thermometer resistance drift;  $C$ , the heat capacity of the specimen;  $\partial R / \partial T$ , the sensitivity of the thermo-

meter; and  $A$ , the coupling constant between the specimen (temperature  $T$ ) and the body of the calorimeter (temperature  $T_K$ ); usually,  $T_K \approx T$ . The coupling constant  $A$  with the heat switch off was slightly temperature dependent,  $A = (78 \pm 3) \text{ pW/mK}$  at 1.3K. Time variations of the thermal background power,  $\dot{Q}_B \approx 1150 \text{ pW}$ , approximately equal to 100 pW, determined the accuracy of measurements.

### 3. Results and discussion

Separate measurements of EPILOX T-20-20 heat capacity yielded data consistent with <sup>/10,11/</sup> (see Fig. 1).

The results of two various measurements of the heat release per gram of epoxy resin -  $\dot{q}(292\text{K}, T_0, t) = \dot{Q}(292\text{K}, T_0, t)/m$  ( $m$  is the mass of EPILOX T-20-20) - after cooling from room temperature to  $T_0 = 1.3\text{K}$  and  $T_0 = 1.15\text{K}$  are presented in Fig. 2. Experimental points (dots and open dots) for both  $T_0$  lie on the same curve,  $\dot{q} \sim t^{-0.76}$  for  $t \geq 1.5\text{h}$ . The value of  $\dot{q}$  for  $20\text{h} < t < 200\text{h}$  is very close to the Stycast data <sup>/3/</sup> with and without the filler, i.e. does not significantly depend on the consistence of the epoxy resin.

The heat relaxation observed is thus slower than in glassy metals <sup>/5,6/</sup> or in vitreous silica <sup>/1-3/</sup>, possibly due to the increase of the distribution function  $P(\Delta, \lambda)$  with increasing  $\lambda$ . In EPILOX T-20-20 there is no experimental evidence of changing  $t^{-0.76}$  dependence even after 700 hours - thus the maximal relaxation time  $\tau_{\text{max}} > 1000 \text{ h}$ . As for vitreous silica ( $\tau_{\text{max}} > 200 \text{ h}$ ) <sup>/3/</sup> and amorphous metals ( $\tau_{\text{max}} > 60 \text{ h}$ ) <sup>/5,6/</sup>, it was impossible to determine experimentally the upper limit of the relaxation time spectrum.

The measurements, results of which are shown in Fig. 3, were performed after the main heat release decreased to the

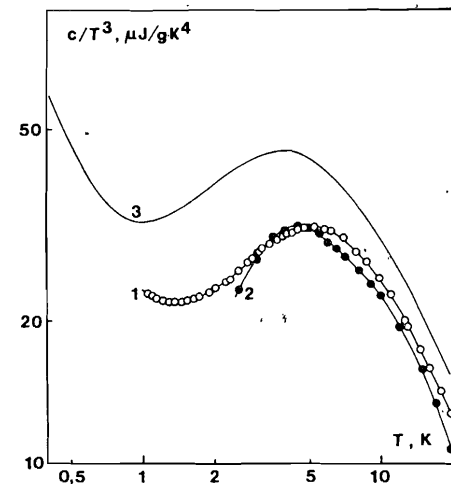
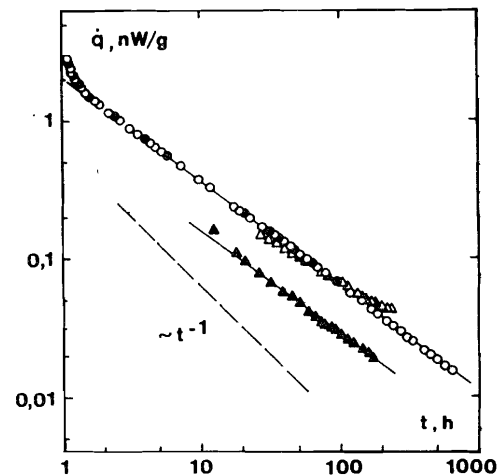


Fig. 1. Specific heat of epoxy resin. 1 - EPILOX T-20-20, this paper; 2 - EPILOX T-20-20, ref. 10; 3 - EPIKOTE 828, ref. 11.

Fig. 2. Power released after cooling from 292K to  $T_0$ .  $\dot{q}$  - power released in 1g of epoxy resin;  $t$  - time after cooling to  $T_0$ ; ● - EPILOX T-20-20,  $T_0 = 1.3\text{K}$ ; ○ - EPILOX T-20-20,  $T_0 = 1.15\text{K}$ ; ▲ - Stycast 1266,  $T_0 \approx 0.05\text{K}$  <sup>/3/</sup>; △ - Stycast 2850 with filler,  $T_0 \approx 0.05\text{K}$  <sup>/3/</sup>; solid line:  $\dot{q} \sim t^{-0.76}$ ; broken line:  $\dot{q} \sim t^{-1}$ .



value of 34 pW/g. Then the specimen was successively heated to various  $T_1$  ( $1.78\text{K} \leq T_1 \leq 22.2\text{K}$ ) and kept for  $t_H = 20 \text{ h}$  at that temperature; after another cooling to 1.1K, the time dependence of  $\dot{q}(T_1, 1.3\text{K}, t)$  was measured again. The

proportionality to  $t^{-0.76}$  is observed in all cases, at least for  $t > 1\text{h}$ .

Dependence of power  $\dot{q}(T_1, T_0, 1\text{h})$  ( $T_0 = 1.15\text{K}$  or  $1.3\text{K}$ ), released one hour after cooling, on  $T_1^2 - T_0^2$  is plotted in Fig. 4. The proportionality  $\dot{q} \sim T_1^2 - T_0^2$  according to (3) only holds for low  $T_1$  ( $T_1 \leq 2\text{K}$ ). Here the distribution parameter  $\bar{P}_m = \bar{P}/\rho$  ( $\rho$  is the density of EPILOX T-20-20) can be determined,  $\bar{P}_m = (1.0 \pm 0.1) \cdot 10^{39} \text{ J/g}$ . This value is not far from  $\bar{P}_m = 3 \cdot 10^{39} \text{ J/g}$  for PMMA <sup>/4/</sup>, and is

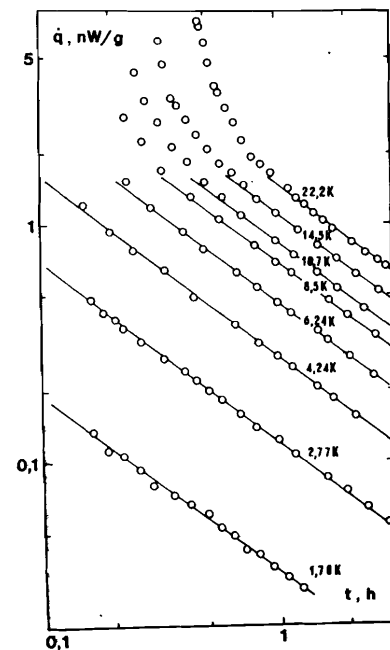


Fig. 3. Power released after cooling from different  $T_1$  to 1.3K.  $\dot{q}$  - power released in 1g of EPILOX T-20-20;  $t$  - time after cooling to 1.3K. Straight lines:  $\dot{q} \sim t^{-0.76}$ . Values of  $T_1$  are indicated inside the figure.

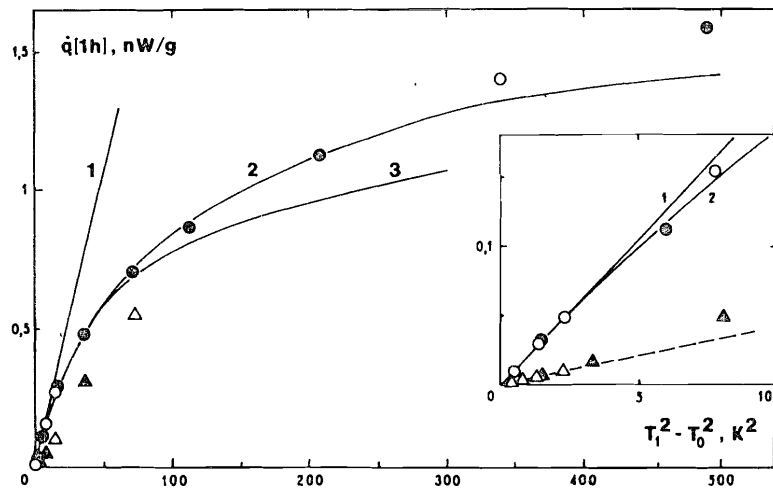


Fig. 4. Temperature dependence of the heat release.  $\dot{q}(1h)$  - power released in 1g of EPILOX T-20-20 1 hour after cooling from  $T_1$  to  $T_0$ ;  
 $\bullet$  -  $T_0 = 1.3K$ , heating time  $t_H = 20h$ ;  $\circ$  -  $T_0 = 1.15K$ ,  $t_H = 20h$ ,  
 $\blacktriangle$  -  $T_0 = 1.3K$ ,  $t_H = 0.2h$ ,  $\triangle$  -  $T_0 = 1.15K$ ,  $t_H = 0.2h$ .  
 Curve 1: equation (3) with  $\bar{P}_m = 1.0 \cdot 10^{39}/Jg$ ; curve 2: equation (5) with  $\bar{P}_m = 1.0 \cdot 10^{39}/Jg$ ,  $T_f = 16.5K$ ,  $T_b/T_f = 0.2$ ; curve 3: equation (5) with  $\bar{P}_m = 1.0 \cdot 10^{39}/Jg$ ,  $T_f = 15K$ ,  $T_b = 0$ .

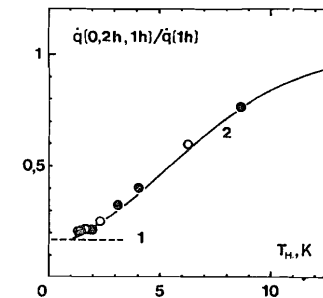
essentially larger than vitreous silica and glassy metals  $\bar{P}_m$ 's ( $4.5 \cdot 10^{37}/Jg^{1/3}$  and  $(1.2 + 2.3) \cdot 10^{37}/Jg^{1/6}$  respectively). With  $\bar{P}_m = 1.0 \cdot 10^{39}/Jg$  and  $T_f = 16.5K$ ,  $T_b/T_f = 0.2$ , the distribution function (4) yields values in good agreement with the experiment even for higher  $T_1$  (see curve 2 in Fig. 4). The value of  $T_f$  is slightly higher than that for vitreous silica ( $13K^{1/3,6/}$ ) and lower in comparison with amorphous metals (20K for  $Fe_{80}B_{14}Si_6$  and 24K for  $Co_{69}Fe_{4.5}Cr_{2.5}Si_{2.5}B_{22}$ ); in all these materials  $T_f$  is much smaller than the glass temperature  $T_g$  ( $T_g = 353K$  for EPILOX T-20-20  $^{12/}$ ).

The experimental results of the power released 1 hour after cooling, when the heating time  $t_H$  at  $T_H$  was short, are shown in Fig. 4 (triangles), too. The ratio of this power for  $t_{H1} = 0.2h$  and  $t_{H2} = 20h$ ,

$$\dot{q}(0.2h, 1h)/\dot{q}(1h) = \dot{q}(T_H, T_0, 0.2h, 1h)/\dot{q}(T_H, T_0, 20h, 1h)$$

as a function of  $T_H$  ( $T_0 = 1.3K$  and  $1.15K$ ) is shown in Fig. 5. Unlike

Fig. 5. Ratio of power released 1h after cooling from  $T_H$  with short heating time ( $t_{H1} = 0.2h$ ) to that after cooling from equilibrium  $T_H = T_1$  ( $t_{H2} = 20h$ ).  
 $\bullet$  -  $T_0 = 1.3K$ ,  $\circ$  -  $T_0 = 1.15K$ ;  
 curve 1: equation (8);  
 curve 2: equation (10),  $T_f = 16.5K$ ,  
 $\lambda = 6$ .



(8) (broken line 1 in Fig. 5), this ratio increases with  $T_H$ . As in amorphous metals, (10) with  $\lambda = 6$  (putting  $T_f = 16.5K$ ) holds well for EPILOX T-20-20, when  $t_H = 0.2h$ ,  $t = 1h$  (curve 2 in Fig. 5). Such coincidence may be in principle due to the existence of a universal dependence of the low-temperature heat release on  $T_H/T_f$  and  $T_0/T_f$ . Varying  $T_H$ ,  $t_H$  and  $t$  more significantly, we have found out:

For low values of heating temperature  $T_H < 2K$ , deviations from (10) were not seen for  $0.2 \leq t_H/t \leq 4$  (see Fig. 6). For higher  $T_H$  and sufficiently larger  $t_H/t$ , more two-level systems are excited, than is implied in (9), (10) (Fig. 7). Trying to explain such behaviour within the tunneling model, we have to assume such a deformation of the distribution function  $P(\Delta, \lambda)$  at higher  $T_0$  or/and  $T_H$  that variations of large  $\lambda$  are greater than those of small  $\lambda$  (short relaxation time):  $\lambda$  in (9), (10) is greater for greater values of  $\lambda$ . This yields a maximum of the function  $P(\Delta, \lambda)$  at certain  $\lambda = \lambda_{max}$ , which drifts to lower  $\lambda$ , when temperature increases. This deformation of the tunneling-level spectrum allows us to explain another experimental fact: measuring alternatively the heat release

after cooling from various equilibrium  $T_1$  to fixed  $T_0 \approx 1.15K$ , and heat ab-

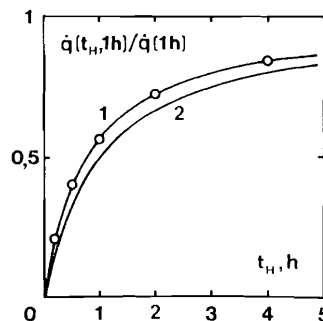


Fig. 6. Dependence of the heat released on the heating time.  
 $\dot{q}(t_H, 1h)$  - power released 1h after cooling from  $T_H = 1.92K$  to  $T_0 = 1.15K$  with the heating time  $t_H$ ;  $\dot{q}(1h)$  - power released 1h after cooling from equilibrium  $T_H = T_1 = 1.92K$  ( $t_H = 20h$ ) to  $T_0 = 1.15K$ ; curve 1: equation (10),  $T_f = 16.5K$ ,  $\lambda = 6$ ; curve 2: equation (8).

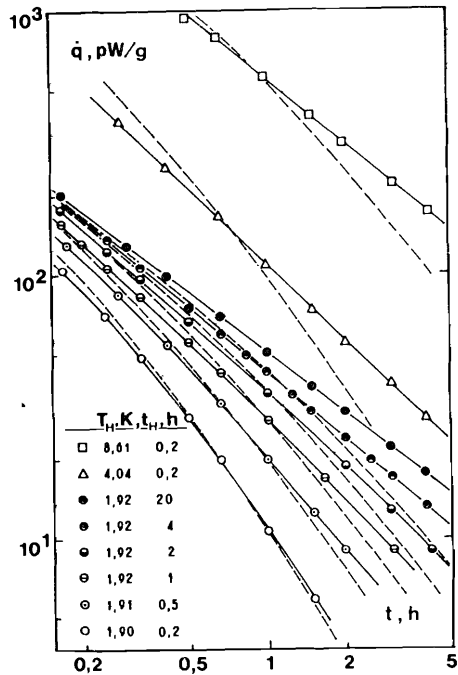


Fig. 7. Time dependence of power released after cooling from  $T_H$  ( $1.9K \leq T_H \leq 8.61K$ ) to  $T_0 = 1.15K$  with various  $t_H$  ( $0.2h \leq t_H \leq 20h$ ).  $t$  - time; solid curves - experiment; broken curves - equation (10) with  $T_f = 16.5K$  and  $\alpha = 6$ .

sorption after heating from equilibrium  $T_0$  to  $T_1$  (Fig. 8), we see that for sufficiently large  $T_1$ , absolute values of release and corresponding absorption significantly differ in contradiction to (3) and (5). Because of maximum appearing at higher temperature, the observed heat absorption is greater than corresponding heat release, which is measured at the lower of both temperatures  $T_0, T_1$ .

Thus, when temperature increases the number of states with long relaxation time decreases and the

Fig. 8. Heat release after cooling ( $T_0 < T_1$ ) and heat absorption after heating ( $T_0 > T_1$ ) for various  $T_1$  and  $T_0$ .  $\dot{q}$  - absolute value of power released or absorbed in 1g of EPILOX T-20-20;  $t$  - time; full dots - release, open dots - absorption.

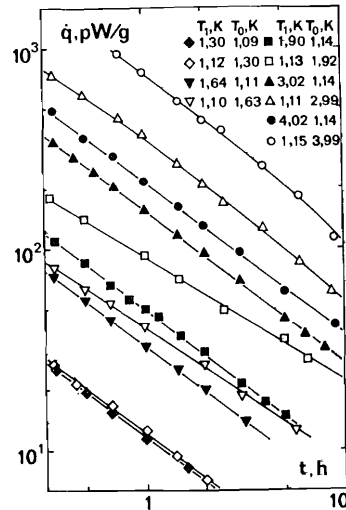
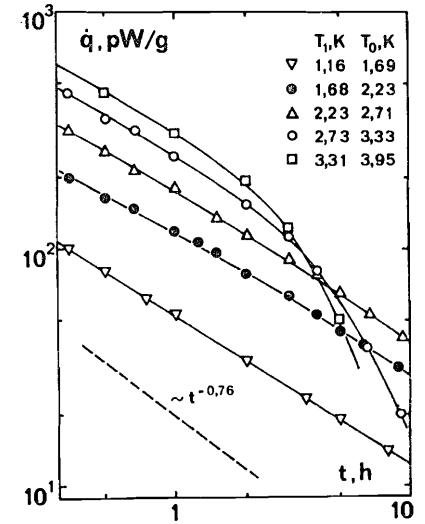


Fig. 9. Heat absorption after subsequent small steps between 1.16K and 3.96K.  $\dot{q}$  - power released in 1g of EPILOX T-20-20;  $t$  - time; solid curves - experiment; broken line  $q \sim t^{-0.76}$ .



number of short-relaxation-time states increases. Higher density of the latter states will after all imply lowering the thermal conductivity. The observed plateau of the thermal conductivity for vitreous silica <sup>/13/</sup> and epoxy resin <sup>/10,11/</sup> between  $0.3T_f$  and  $T_f$  seems to be reasonable from this point of view.

The results of absorption measurements after small steps between  $T_1$  and  $T_0$ ,  $T_0 - T_1 \ll T_0, T_1$  - probably, more convenient for theoretical analysis - are presented in Fig. 9. Variations of mean temperature  $T = (T_1 + T_0)/2$  essentially affect the time dependence of the absorption. In the first approximation at time  $t_0$ , the largest part of  $\dot{q}(t_0)$  is due to transitions with relaxation-time value  $\tau_0$  (and corresponding  $\lambda_0$ ) in the vicinity of  $t_0$ . The time dependence of the heat release varies according to the difference between  $\lambda_0$  and  $\lambda_{max}$ : decrease-

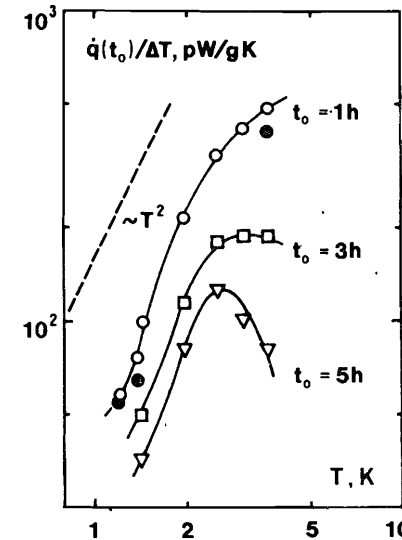


Fig. 10. Temperature dependence of the heat release (absorption) at fixed time  $t_0$  after cooling (heating).  $\dot{q}(t_0)/\Delta T$  - power absorbed (released)  $t_0$  hours after transition from  $T_1$  to  $T_0$  divided by  $\Delta T = |T_1 - T_0|$ ;  $T = (T_1 + T_0)/2$ ; open dots - absorption, full dots - release; solid curves - experiment; broken line -  $\dot{q}(t_0) \sim T^2 \Delta T$ .

ing distance between  $\lambda_0$  and  $\lambda_{\max}$  implies increasing the heat release. According to this simple model, the curve  $t_0 = 5h$  (fixed  $t_0$  - fixed  $\lambda_0$ ) in Fig. 10 illustrates, how for  $T > 1.2K$  with increasing  $T$  the corresponding  $\lambda_{\max}$  approaches  $\lambda_0$  from the right, the difference  $\lambda_0 - \lambda_{\max}$  being zero around  $2.7K$ , and negative for  $T > 2.7K$  with the absolute value increasing with  $T$ . Fig. 10 is rearranged Fig. 9, showing clearly the temperature dependence of  $\dot{q}(t_0)/\Delta T$  ( $\Delta T = |T_1 - T_0|$ ). In the region below the maximum  $\dot{q}(t_0)/\Delta T$  is approximately proportional to  $T^2$ .

Another evidence of the deformation of the distribution function  $P(\lambda)$  while measuring temperature increases can be seen in Fig. 11: after 3.83h (16h) of measurement at 1.15K, when  $\dot{q} \sim t^{-0.76}$  and  $\dot{q}(3.83h) = 0.5$  nW/g ( $\dot{q}(16h) = 0.27$  nW/g), measuring temperature was elevated to 4.2K;  $\dot{q}$  increased to 1.2 nW/g (0.4 nW/g), but the relaxation proceeded faster,  $\dot{q} \sim t^{-1.4}$ . It is probably due to still higher density of states with maximum at  $\lambda$  lower than  $\lambda_0$ .

Summing it up, it seems impossible to explain the dependence of the heat release  $\dot{q}$  on the measuring temperature  $T_0$  and  $T_H$  in the temperature range over  $0.1T_f$  within the standard tunneling theory.

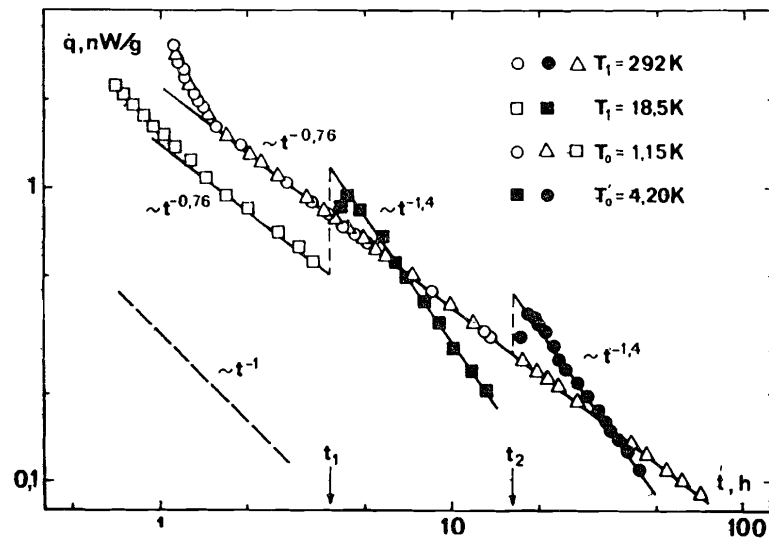


Fig. 11. Dependence of the heat release on measuring temperature.  $\dot{q}$  - power released in 1g of EPILOX T-20-20;  $t$  - time; at  $t_1, t_2$ , measuring temperature  $T_0$  was rapidly elevated from 1.15K to 4.2K.

#### 4. Conclusions

1. For sufficiently low temperatures,  $T_0, T_1 \leq 2K$ , experimental heat release in EPILOX T-20-20 agrees with the standard tunneling theory well. It enables us to determine the density of states of two-level systems. Its value is fairly close to that in PMMA, and essentially higher than in vitreous silica and metal glasses.

2. Temperature dependence of the heat release for  $T_1 > 2K$  and  $T_0 \leq 1.3K$  can be understood within the modified version of the tunneling theory, assuming the existence of a maximum energy  $E_f = k_B T_f$  in the distribution function. Corresponding  $T_f = 16.5K$  is not far from those for vitreous silica and amorphous metals, but much smaller than the glass temperature  $T_g$ .

3. At last, it is necessary to take into account temperature dependence of the tunneling parameter  $\lambda$  for explaining experimental results on heat release and heat absorption for different  $T_0$  and  $T_H$ ,  $T_0, T_H > 1.3K$ . Since dependence of  $\dot{Q}(T_H, T_0, t_H, t)/\dot{Q}(T_H, T_0, t)$  on  $T_H/T_f$  seems to be the same for both epoxy resin and two amorphous metals, an idea arises about a universal temperature dependence of the tunneling parameter  $\lambda$ , which is controlled by the characteristic temperature  $T_f$ .

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