

practice it is impossible in the initial period of heating or cooling to reveal the finite thickness of the sample which is necessary for successful calculation with Eqs. (6) and (7). On the other hand, the determination of the parameter $\lambda c \gamma$ from the expression

$$\lambda c \gamma = \frac{\gamma_i}{\Psi_i}, \quad (20)$$

which is easily obtained from the relation between Laplace transforms for a semibounded body $[q(s)/T(s)]^2 = s(\lambda c \gamma)$, shows that the calculated values of this parameter in the initial period of heating or cooling are in good agreement with the values assumed in the solution of the forward problem. Thus, the simultaneous calculation of $\lambda c \gamma$ by Eq. (20) and λ and a by (6) and (7) in the present case enables one to judge from the nature of the variation of these parameters both the accuracy of the computational scheme chosen and the legitimacy of using the recommended relations as a whole for the available experimental data.

NOTATION

T, temperature of sample; x, coordinate; δ , thickness of flat plate; λ , thermal conductivity; a , thermal diffusivity; c , specific heat; γ , density; q , heat flux density; t , τ , θ , time.

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PHOTOEMISSION METHOD OF MEASURING TEMPERATURE

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A photoemission method of measuring temperature is presented, and the range of its application is indicated. Expressions are obtained for calculating the systematic error, and a nomogram is given for determining it.

The photoemission method of measuring temperature for a continuous emission spectrum is based on the dependence of the energy distribution of photoelectrons in the photoemission effect on the energy distribution in the spectrum of the radiation source [1, 2]. The temperature of a body is determined from the change in the energy distribution of photoelectrons, i.e., the increase in the number of photoelectrons with the maximum kinetic energy $W_{\max} = eU_{\max}$ with increasing temperature.

By considering Einstein's equation for the photoelectric effect

$$eU_{\max} = h(\nu - \nu_0) \quad (1)$$

or

$$W_{\max} = \hat{f}_1(\nu)$$

together with Planck's equation for blackbody radiation

$$r_0 = \hat{f}_2(\nu, T) \quad (2)$$

it is clear that an implicit relation exists between the maximum kinetic energy of the photoelectrons and the temperature T of the body whose radiation gave rise to the photoelectric effect. It follows from (2) that the frequency ν is a function of the spectral density of the blackbody radiation energy r_0 and the temperature

$$\nu = \varphi(r_0, T) \quad (3)$$

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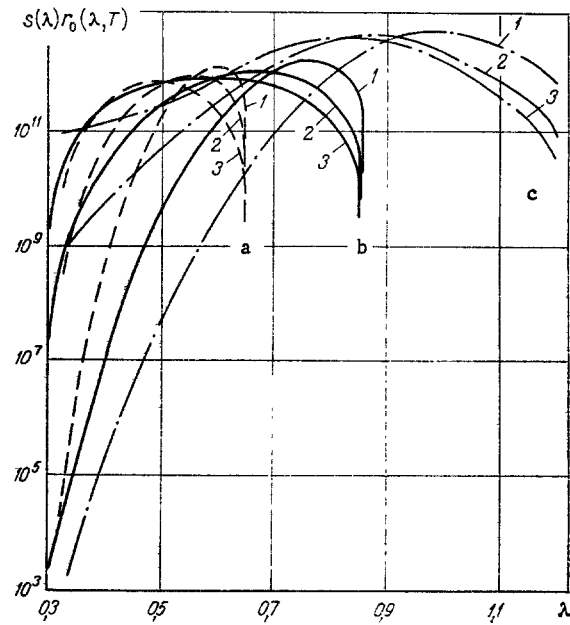


Fig. 1. Spectral distribution of reduced flux densities of blackbody radiation $s(\lambda)r_0(\lambda, T)$ in W/m^{-2} at temperatures of 1) 1000; 2) 2000; 3) 3000°K corresponding to reduced luminous fluxes equal to that at 3000°K. The photocathodes are a) antimony - cesium; b) multialkali; c) silver - oxygen - cesium; λ is in μm .

and consequently

$$W_{\max} = F_1(r_0, T). \quad (4)$$

For $r_0 = \text{const}$ we obtain $W_{\max} = F(T)$ and

$$T = f(U_{\max}). \quad (5)$$

Thus, in this case, the thermometric property is the dependence of the maximum kinetic energy of the photoelectrons on the temperature of the radiating object.

The condition $r_0 = \text{const}$ is achieved by maintaining a constant intensity of illumination E (W/cm^2) of the photocathode, since the constancy of the spectral interval $\Delta\lambda$ is ensured by the practically constant value of the dispersion of the electron flux D ($mV/\text{\AA}$) in the cutoff region of the photocurrent. Since the sensitivity of the photocathode is not constant over its surface, the position and area of the bright spot on the photocathode must also be kept constant.

It should be noted, however, that Eq. (5) is not necessarily unique, since it is determined by the properties of the photocathode material in the specific range of energies of the incident light quanta. Strictly speaking, Eq. (1) is applicable for metals at 0°K. For compound photocathodes ν_0 is not the same for all wavelengths since the photoelectric effect at various photon energies can proceed either from the fundamental region (the photoelectric effect proper) or from levels in the forbidden zone, in which case the relation between U_{\max} and $h\nu - h\nu_0$ is no longer unique. For example, solid-state detectors show a pronounced dependence of the work function on wavelength in the ultraviolet region. Of course, if the mechanism of the photoelectric effect changes with changing frequency of the light, the method of measuring temperature under consideration is not applicable.

The Einstein equation establishes a relation between the kinetic energy of a photoelectron, on the one hand, and the energy of the absorbed quantum and the initial energy of the electron in the solid, measured from the vacuum level, on the other hand. This relation is valid not only for the electrons with the maximum kinetic energy, but also for photoelectrons produced in direct transitions, both in metals and in semiconductors, and escaping into vacuum without loss of energy. For example, for antimony - cesium and multialkali photocathodes this statement is confirmed in the visible region of the spectrum by the fact that close to the maximum energy the shape of the photoelectron energy distribution does not vary with changing frequency of the light, and the

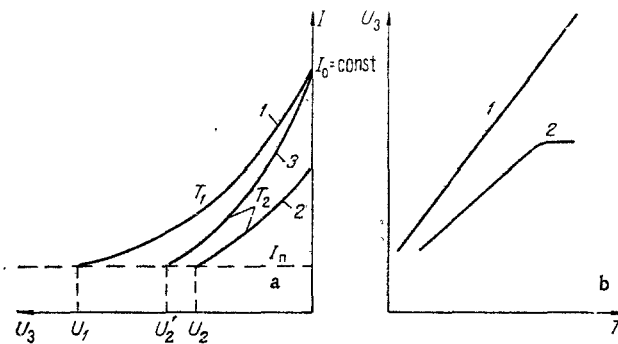


Fig. 2. a) Current — voltage characteristics for temperatures of a heated body $T_1 > T_2$ and constant values of the total (1, 2; $P = \text{const}$) and reduced (1, 3; $I_0 = \text{const}$) luminous fluxes; b) stopping potential as a function of the temperature of the radiation source [1, $P = \text{const}$ (W); 2, $I_0 = \text{const}$ (A)].

distribution curves are only displaced on the energy scale by the amount of the change in energy of the quantum. In this case the temperature of a heated body can be determined not only from the maximum energy of the photoelectrons, but also over a rather broad region close to the maximum energies, where the energy distribution of the photoelectrons remains of the same type and the shape of the current — voltage characteristics close to the cutoff voltage of the photocurrent is unchanged [2]. Otherwise, if the current — voltage characteristics intersect, photoelectrons with energies close to the maximum cannot be used to measure temperature.

A change in the shape of the current — voltage characteristics can result, in particular, from the nonmonotonic dependence of the density of electron states on energy in the conduction band. In a number of cases the characteristic curves of the energy distribution of photoelectrons have several peaks which may be related to the complex structure of the energy bands or to various processes of dissipating the energy of the photoelectrons [3]. For example, the presence of two peaks in the energy distribution of photoelectrons from a silver — oxygen — cesium (Ag — O — Cs) photocathode for quantum energies above 2.7 eV ($0.46 \mu\text{m}$) can be accounted for by the emission of electrons from the highest occupied levels of the impurity band or the conduction band, and also by surface photoemission as a result of the photoionization of cesium atoms adsorbed on the surface or electrons of surface states of the host crystal [4]. From the current — voltage characteristics and the initial energy distribution of the photoelectrons from a semitransparent Ag — O — Cs photocathode it can be seen that with an increase in frequency a group of electrons appears whose energy increases proportionally to the frequency, and whose number decreases as the energy of the quanta increases.

The intersection of the current — voltage characteristics which occurs in this case permits the use of an Ag — O — Cs photocathode to measure temperature only by means of the maximum velocities of the photoelectrons. This photocathode can be used to measure temperature in the range of photoelectron energies close to the maximum only for photon energies of 1.0–2.7 eV, where there is still no intersection of the current — voltage characteristics. Practically, this means that the temperature of an object must not exceed about 600°C , when there are not enough photons with energies above 2.7 eV in the spectrum of the heated body to produce a detectable photocurrent. This is true for "normal" Ag — O — Cs photocathodes, both thick and semitransparent, i.e., those for which $\lambda_{\text{max}} = 0.6\text{--}0.8 \mu\text{m}$, $\lambda_0 \geq 1 \mu\text{m}$, and where the current — voltage characteristics intersect in the short-wave part of the working range. For an Ag — O — Cs photocathode strongly contaminated with oxygen so that the long wavelength maximum disappears, there is no intersection of the stopping curves for shortwaves. However, there is no point in using such a photocathode to measure temperature since it has $\lambda_0 = 0.8 \mu\text{m}$ and the sensitivity is 5–10 $\mu\text{A/lm}$, which is 25–50 times smaller than for a multialkali cathode having the same long wavelength threshold of the photoelectric effect.

Consequently, before proceeding to measure the temperature it is necessary to take the current — voltage characteristics of the stopping of the photocurrent of the particular photoelectric pyrometer (PEP) for monochromatic fluxes of light of constant intensity and to make certain that the photocathode material is appropriate for measuring temperature in the range of photon energies in question.

In the photoemission method of measuring temperature r_0 can be kept constant by flattening the luminous flux with nonselective radiation detectors such as thermocouples, bolometers, etc. But since their readings

TABLE 1. "Photoemission" Temperature of Tungsten Calculated for Three Types of Photocathodes and Compared with True and Color Temperatures

Photoemission method T_p , °K	True temperature T , °K		
	1000	2000	3000
	color temperature T , °K		
	1006	2033	3094
Photocathode:			
antimony-cesium	1007	2020	3042
multialkali	1015	2036	3062
Ag-O-Cs	1018	2060	—

can be graduated directly in degrees, and their sensitivity is considerably lower than that of a PEP, there is no point in first flattening the total luminous fluxes P in measuring temperature by the photoemission method.

In flattening the reduced luminous fluxes $\Phi = \int_{\lambda_{\min}}^{\lambda_0} s(\lambda)r_0(\lambda, T)d\lambda$, where $s(\lambda)$ is the relative spectral sensitivity of the photocathode, and λ_{\min} and λ_0 are the limits of the range of its spectral sensitivity, there is a displacement of the maximum of the curve $\Phi = f(\lambda)$ into the short wavelength region with increasing temperature (Fig. 1) just as in the nonselective flattening of luminous fluxes, and consequently in the flattening of luminous fluxes by the equality of photocurrents ($I_0 = \text{const}$ for $U_S = 0$) there is also a temperature dependence of the cutoff potential of the photocurrent (Fig. 2). At a high temperature the sensitivity falls off because of the limitation of the radiation by the entrance window of the PEP (curve 2 of Fig. 2b).

The temperature T_p measured by the photoemission method is determined from the identity of the relative distributions of spectral energy density of the radiation from a blackbody (standard) and the object. The identity of the relative spectral distributions is established by the equality of the energy fluxes of the standard and the given body in two parts of the spectrum: in the whole sensitive region of the photocathode from λ_0 to λ_{\min} (as in partial radiation pyrometers) and, as in brightness pyrometers, in a narrow range of wavelengths of the order of 5-10 Å in the region of the shortest wavelength radiation λ_S whose level exceeds the threshold of sensitivity of the PEP. The width of the interval close to λ_S is determined by the sensitivity of the PEP to the stopping of the photocurrent, and its position in the spectrum is not constant but depends on the temperature of the object. The temperature measured in this way is clearly the color temperature, but it differs from the color temperature measured with optically monochromatizing elements in that it is produced not by the monochromatization of the luminous flux of the object but of the PEP electron flux correlated with it.

The systematic error $\Delta T = T_p - T$ of the photoemission method for measuring the color temperature is determined by the spectral characteristic of the sensitivity of the photocathode $s(\lambda)$, and depends on the emissivity of the object $\epsilon(\lambda, T)$, where T is the true temperature of the body.

To derive the relation between the "photoemission" temperature T_p , measured by the stopping of the photocurrent, and the true temperature T , we define the "stopping" wavelength λ_S as the shortest wavelength whose content in the nonmonochromatic radiant flux of a heated body for a chosen value of the initial current I_0 is sufficient to produce the minimum measurable photocurrent close to the potential for complete stopping of the photocurrent. This wavelength is analogous to the threshold wavelength or "red threshold" λ_0 , but is measured in the shortwavelength part of the spectrum, and in contrast with λ_0 , is not a characteristic of the material, but depends on the temperature of the object and the initial current I_0 .

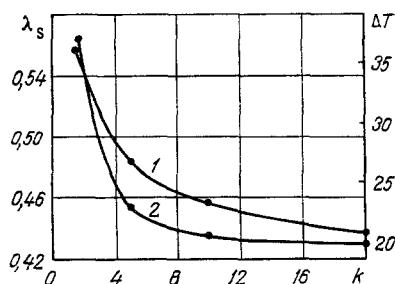


Fig. 3. 1) λ_S in μm , and 2) systematic error ΔT as functions of the ratio of currents k at $T = 2000^\circ\text{K}$.

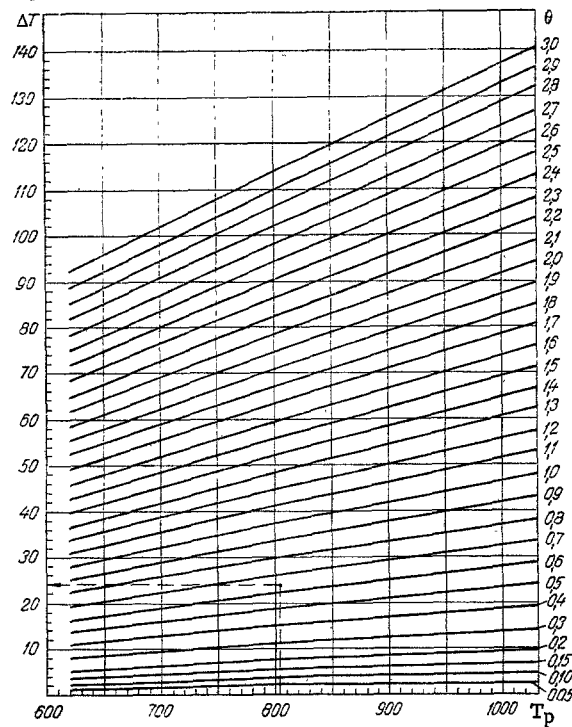


Fig. 4. Nomogram for determining the systematic error. For example, at a measured temperature $T_p = 805^\circ\text{C}$ and $\theta = 0.65$ the systematic error $\Delta T = 24^\circ\text{C}$ and the true temperature $T = 805 - 24 = 781^\circ\text{C}$.

In order to find the systematic error and to determine its dependence on the temperature of the body $\Delta T = f(T)$, it is necessary first to find the relation between λ_s and T_p :

$$\lambda_s = f(T_p) \quad (6)$$

and then to determine

$$T_p = f(T) \quad \text{for } \lambda_s = \text{const.} \quad (7)$$

Since the emissivity of many materials is nearly temperature independent over a wide range of temperatures (e.g., it varies by 5% from 1600-3000°K for tungsten), we assume ϵ does not depend on the temperature. Substituting T and the corresponding values of λ_s from (6) into (7), we obtain the temperature T_p for each value of the true temperature and determine the systematic error ΔT .

In the absence of a stopping potential the photocurrent produced by the radiation of a blackbody at temperature T_p and proportional to the luminous flux Φ is

$$I_0 = \int_{\lambda_{\min}}^{\lambda_0} s(\lambda) r_0(\lambda, T_p) d\lambda. \quad (8)$$

At this same blackbody temperature and for a potential $U_s = U_{\max}$ at which the current produced by the radiation of wavelength λ_s is stopped, the current through the PEP has its threshold value

$$I_t = \int_{\lambda_{\min}}^{\lambda_s} s(\lambda) r_0(\lambda, T_p) d\lambda. \quad (9)$$

The ratio

$$\frac{I_0}{I_t} = \frac{\int_{\lambda_{\min}}^{\lambda_0} s(\lambda) r_0(\lambda, T_p) d\lambda}{\int_{\lambda_{\min}}^{\lambda_s} s(\lambda) r_0(\lambda, T_p) d\lambda} = k \quad (10)$$

is the relation $\lambda_S = f(T_p)$. Assigning a series of values of the temperature, we obtain for each of them a corresponding value of λ_S for a given constant value of the ratio k .

To obtain from this same photocathode a current I_0 from an actual body, the body must have the temperature T for an emissivity $\varepsilon(\lambda, T)$. Equating the currents from the actual and blackbody sources we obtain

$$I_0 = \int_{\lambda_{\min}}^{\lambda_0} s(\lambda) r_0(\lambda, T_p) d\lambda = \int_{\lambda_{\min}}^{\lambda_0} s(\lambda) \varepsilon(\lambda, T) r_0(\lambda, T) d\lambda, \quad (11)$$

where T_p is the blackbody photoemission temperature and T is the true temperature of the actual body. In a similar way, for the complete stopping of the photocurrent we write

$$I_t = \int_{\lambda_{\min}}^{\lambda_S} s(\lambda) r_0(\lambda, T_p) d\lambda = \int_{\lambda_{\min}}^{\lambda_S} s(\lambda) \varepsilon(\lambda, T) r_0(\lambda, T) d\lambda. \quad (12)$$

Dividing (11) by (12) we obtain

$$\frac{\int_{\lambda_{\min}}^{\lambda_0} s(\lambda) r_0(\lambda, T_p) d\lambda}{\int_{\lambda_{\min}}^{\lambda_S} s(\lambda) r_0(\lambda, T_p) d\lambda} = \frac{\int_{\lambda_{\min}}^{\lambda_0} s(\lambda) \varepsilon(\lambda, T) r_0(\lambda, T) d\lambda}{\int_{\lambda_{\min}}^{\lambda_S} s(\lambda) \varepsilon(\lambda, T) r_0(\lambda, T) d\lambda}. \quad (13)$$

The left-hand side of this equation is equal to k . Taking as the upper limit of the integral in the denominator on the right-hand side any value of the wavelength from the range of values of $\lambda_S = f(T_p)$ obtained, we choose a value of the temperature T in the neighborhood of T_p so that the ratio on the right-hand side of Eq. (13) is also equal to k . The difference $T_p - T$ will be the systematic error of the method for the given value of T_p .

Table 1 lists the temperatures T_p of tungsten calculated for three types of photocathodes, and presents for comparison the color temperatures measured by the usual method of the red — blue ratio [5].

The systematic error increases for an increase in the range of sensitivity of the photocathode. In addition, it depends on the value of k — the ratio of the initial current I_0 to the threshold current I_t , which results from the dependence of the wavelength λ_S on k . For $k \geq 10$ the systematic error is practically constant (Fig. 3).

Figure 4 is a nomogram for determining the systematic error ΔT in using a PEP with a multi-alkali photocathode. The parameter $\theta = \alpha/l$ is determined from the spectral characteristic of the emissivity $\varepsilon(\lambda)$ as the ratio of the parameter α , determining the slope of the characteristic $\varepsilon(\lambda)$, to the value of the emissivity in the middle of the spectral range $\varepsilon(0.65) = l$. The parameter α is defined as $\alpha = [\varepsilon(\lambda_{\min}) - \varepsilon(\lambda_0)] / (\lambda_0 - \lambda_{\min})$ for a linear approximation of the function $\varepsilon(\lambda)$. The systematic error ΔT and the true temperature $T = T_p - \Delta T$ are determined from θ for the measured temperature T_p .

It is easy to construct a device for measuring temperature by the method described above. The photoemission method of measuring temperature permits the construction of a quick-response pyrometer having a large aperture and a small systematic error. The use of such a pyrometer is most promising for measuring rapidly varying temperatures of microscopic objects or for scanning a heated surface with a resolving power of the order of tens of microns. Our photoemission scanning pyrometer ensures a measurement of temperatures in the 600–1300°C range with a spatial resolution of 40 μm and an instrumental error of 0.2 to 0.05% depending on the construction of the photoelectronic device used.

NOTATION

W_{\max} , maximum kinetic energy of a photoelectron; e , charge of electron; U_{\max} , potential difference between photocathode and anode to stop the current in the external circuit; h , Planck's constant; ν , frequency; ν_0 , threshold frequency; $r_0(\lambda, T)$, spectral distribution of blackbody radiation density; T , true temperature; T_p , temperature measured by photoemission method; E , intensity of illumination; λ_{\min} , λ_0 , short and long wavelength limits of range of spectral sensitivity of photocathode; Φ , luminous flux; U_S , voltage producing stopping field in interelectrode gap; I_0 , photocurrent at $U_S = 0$; $s(\lambda)$, relative spectral sensitivity of photocathode; $\Delta T = T_p - T > 0$, systematic error of photoemission method of measuring temperature; λ_S , shortest wavelength in emission spectrum of a heated body for which the radiation energy density is sufficient to produce the minimum measurable photocurrent for $|U_S| \leq |U_{\max}|$; $\varepsilon(\lambda, T)$, emissivity; I_t , photocurrent for $U_S = U_{\max}$; $k = r_0/I_t$, coefficient; α , parameter determining selectivity of emissivity of object in spectral sensitivity range of

photocathode; l , emissivity in middle of spectral sensitivity range of photocathode; $\theta = \alpha/l$, parameter characterizing deviation of emissivity of object from that of a blackbody.

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OPTIMAL GAS DISCHARGE THROUGH CRYOGENIC FLOW INLETS IN REFRIGERATOR COOLING OF SUPERCONDUCTING MAGNETIC SYSTEMS

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UDC 536.483

A relationship connecting the discharge of the gas-cooling cryogenic flow inlets to the discharge of the gas returning in the reverse flow is obtained, for which the cold-productivity of the refrigerator, which is required, is a minimum.

Cryostating the turns of superconducting magnets (SM) with large working volumes is accomplished, as a rule, by using helium refrigeration apparatus. In the majority of cases, the quantity of liquid helium needed, which is delivered to the SM cryostat, is produced in the refrigerator and the refrigerator cold-productivity is later used to maintain a given level of liquid helium by compensating for the heat influxes into the low-temperature zone.

Part of the cold gas in the refrigerator cooling of SM is ordinarily supplied to cool the flow inlets (this gas flow is heated to the temperature of the environment and is not directed into the reverse flow of the refrigerator).

A diagram of the lower part of the refrigerator including the Joule — Thomson heat exchanger 1, throttle 2, and the SM cryostat 3, is shown in Fig. 1. The flow inlet channel being cooled 4 is also shown.

The liquefiable part M_l of the gas flow M_1 passing through the throttle compensates for the decrease in the liquid helium in the cryostat, while the unliquefied helium goes together with the saturated vapor being formed because of the total heat influx ΣQ to the cryostat, into the refrigerator reverse flow M_2 and into cooling the flow inlets M_3 . The total heat influx is comprised of the cryostat background Q_{bgd} (the heat influx to the cryostat from different heat sources), the heat influx over the flow inlets being cooled $Q_{cld}(M_3)$, and the additional heat influx Q_{add} , which can be considered as the refrigerator power reserve; i.e.,

$$\Sigma Q = Q_{bgd} + Q_{cld}(M_3) + Q_{add} \quad (1)$$

The maximum refrigerator power required in order to cool the SM is defined by the relationship

$$Q_r = \Sigma Q + Q_3 \frac{l_f}{l_r} - Q_3 \quad (2)$$

where $Q_3 = M_3 r$ is the cold used to cool the flow inlets and the term $Q_3 (l_f/l_r)$ in (2) is the refrigerator cold-productivity ensuring a supply of liquid helium in the amount M_3 .

Using the notation $\gamma = r[(l_f/l_r) - 1]$, we have

$$Q_r = \Sigma Q + \gamma M_3 \quad (3)$$

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