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THERMAL CONTROL OF TRANSPARENT ELEMENTS ON BOARD ARTIFICIAL SATELLITES

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Thermal Control Of Transparent Elements On Board Of Artificial Satellites
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1. Introduction

Aboard artificial satellites there may be transparent elements (e.g. windows) in conditions effecting thermal exchange with the system behind them. Under these circumstances the optical characteristics of the transparent window affect the behavior of the system by being a contributing factor in the setting of the operating temperature.

The purpose of this paper is to examine this effect in a window-substrate system. The analysis is arranged in such a manner as to express the above effects as changes of the natural optical characteristics (absorbency and emissivity) of the individual surfaces, so as to be able to lay out the thermal balance calculations in a manner that is identical in form with conventional cases.

2. Laying Out The Problem

The model in question is shown in "Figure 1". It is a transparent window (1) flat, undefined, facing a substrate, (2) which is also flat, undefined, and in parallel with the window. The system is illuminated by parallel rays Q arriving at an i angle of incidence with reference to the window's surface.

Let:

$Q' = \frac{dQ}{d\lambda}$	....	be the incident light's spectral power density (in watts/m$^2\mu$)
$r_{1i}(\lambda)$	....	be the window's hemispheric spectral reflectance for the i angle of incidence

$r_1(\lambda)$ .... be the window's hemispheric spectral reflectance for diffused light

$t_{1i}(\lambda)$ .... be the window's spectral transmittency for the i angle of incidence

$t_1(\lambda)$ .... be the window's spectral transmittency for diffused light

$r_{2i}(\lambda)$ .... be the substrate's hemispheric spectral reflectance for the i angle of incidence

$r_2(\lambda)$ .... be the substrate's hemispheric spectral reflectance for diffused light

$\varepsilon'_1(\lambda)$ .... be the window's hemispheric spectral emissivity

$\varepsilon'_2(\lambda)$ .... be the substrate's hemispheric spectral emissivity

$B_1(\lambda)$ .... be the black body's spectral power density at the window's temperature (in watts/$m^2\mu$)

$B_2(\lambda)$ .... be the black body's spectral power density at the substrate's temperature (in watts/$m^2\mu$)

T_1 .... be the window's temperature

T_2 .... be the substrate's temperature

Absorption

$q'_{1r} = \frac{d\,q_{1r}}{d\,\lambda}$ .... be the spectral power density reflected by the system towards the outside (in watts/$m^2\mu$)

$q'_{12} = \frac{d\,q_{12}}{d\,\lambda}$ .... be the spectral power density transmitted and reflected by the window to the substrate (in watts/$m^2\mu$)

$q'_{21} = \frac{d\,q_{21}}{d\,\lambda}$ .... be the spectral power density reflected by the substrate (in watts/$m^2\mu$)

Emission

$q'_{1e} = \frac{d\,q_{1e}}{d\,\lambda}$ .... be the spectral power density emitted by the system towards the outside (in watts/$m^2\mu$)

$q'_{12e} = \frac{d\,q_{12e}}{d\,\lambda}$ .... be the spectral power density emitted and reflected by the window to the substrate (in watts/$m^2\mu$)

$q'_{21e} = \frac{d\,q_{21e}}{d\,\lambda}$ .... be the spectral power density emitted and reflected by the substrate (in watts/$m^2\mu$)

It is assumed that emission and reflection, be they of the window or of the substrate, are diffused.

It is likewise assumed that the window's two faces are in conditions of complete optical equivalence.

3. Absorption

"Figure 1" is a schematic representation of the phenomenon of absorption.

The power reflected in whole by the system, q'_{1r}, is that power directly reflected in 1, plus the aliquot part transmitted by 1 from the power reflected in 2.

$$q'_{1r} = r_{11} Q' + t_1 q'_{21} \tag{1}$$

The power going from 1 to 2 is the power directly transmitted by 1 plus the aliquot part, reflected in 1, of the power reflected in 2

$$q'_{12} = t_{11} Q' + r_1 q'_{21} \tag{2}$$

The power reflected in 2 is

$$q'_{21} = r_{21} t_{11} Q' + r_2 r_1 q'_{21} \tag{3}$$

Solving (1), (2), and (3), we have:

$$\left\{\begin{aligned} \frac{q'_{21}}{Q'} &= \left(\frac{r_{21} t_{11}}{1-r_2 r_1}\right) = R'_{21} \\ \frac{q'_{12}}{Q'} &= \left[1 + r_1 (r_{21} - r_2)\right] \frac{t_{11}}{1 - r_2 r_1} = \tau'_{11} \\ \frac{q'_{1r}}{Q'} &= \left[r_{11} + r_{21} \frac{t_1 t_{11}}{1 - r_2 r_1}\right] = R'_{11} \end{aligned}\right. \tag{4}$$

R'_1 , R'_2 , τ_1 represent the spectral characteristics of the window/ substrate system.

In terms of absorptivity we have:

$$\begin{aligned} \bar{\alpha}'_{1i} &= 1 - \tau'_{1i} - R'_{1i} + R'_{2i} && = \text{spectral absorptivity of the window for incidence } i \\ \bar{\alpha}'_{2i} &= \tau'_{1i} - R'_{2i} && = \text{spectral absorptivity of the substrate for incidence } i \end{aligned} \qquad (5)$$

With a simple weighted average as regards spectral density Q' we pass from spectral to global characteristics:

$$\begin{cases} \bar{\alpha}_{1i} = \dfrac{1}{Q} \displaystyle\int_0^\infty \alpha'_{1i} \, Q' \, d\lambda \\ \bar{\alpha}_{2i} = \dfrac{1}{Q} \displaystyle\int_0^\infty \bar{\alpha}'_{2i} \, Q' \, d\lambda \end{cases} \qquad (6)$$

The overlining in (5) and (6) indicates that the absorptivity values are "equivalent" in the sense that they differ from those of single materials by the interaction between the two parts of the system.

4. Emission

By a process similar to the one described above for absorption, we have for emission:

$$\begin{cases} q'_{1e} = \varepsilon'_1 B_1 + \dfrac{t_1 \varepsilon'_1 r_2}{1 - r_1 r_2} B_1 + \dfrac{t_1 \varepsilon'_2}{1 - r_1 r_2} B_2 \\ q'_{12e} = \dfrac{\varepsilon'_1}{1 - r_1 r_2} B_1 + \dfrac{r_1 \varepsilon'_2}{1 - r_1 r_2} B_2 \\ q'_{21e} = \dfrac{\varepsilon'_2}{1 - r_1 r_2} B_2 + \dfrac{r_2 \varepsilon'_1}{1 - r_1 r_2} B_1 \end{cases} \qquad (7)$$

By substitution:

$$\begin{cases} E'_{12} = \dfrac{\varepsilon'_1 \; \varepsilon'_2}{1 - r_1 \, r_2} = E'_{21} \\ E'_{11} = E'_{12} + \varepsilon'_1 \left[1 + \dfrac{t_1 \, r_2}{1 - r_1 \, r_2} \right] \\ E'_{22} = E'_{21} + \dfrac{t_1 \; \varepsilon_2}{1 - r_1 \, r_2} \end{cases} \tag{8}$$

$$\begin{cases} \bar{\varepsilon}_{11} = \dfrac{1}{\sigma T_1^4} \displaystyle\int_0^\infty E'_{11} \, B_1 \, d\lambda \\ \bar{\varepsilon}_{12} = \dfrac{1}{\sigma T_2^4} \displaystyle\int_0^\infty E'_{12} \, B_2 \, d\lambda \\ \bar{\varepsilon}_{21} = \dfrac{1}{\sigma T_1^4} \displaystyle\int_0^\infty E'_{21} \, B_1 \, d\lambda \\ \bar{\varepsilon}_{22} = \dfrac{1}{\sigma T_2^4} \displaystyle\int_0^\infty E'_{22} \, B_2 \, d\lambda \end{cases} \tag{9}$$

the heat radiated by the "glass" and the substrate, respectively, is given by these expressions:

$$q_1 = \bar{\varepsilon}_{11} \; \sigma T_1^4 - \bar{\varepsilon}_{12} \; \sigma T_2^4 \quad \text{"emission" of the glass}$$

$$q_2 = \bar{\varepsilon}_{22} \; \sigma T_2^4 - \bar{\varepsilon}_{21} \; \sigma T_1^4 \quad \text{"emission" of the substrate} \tag{10}$$

By using (6) and (10), the equations of the thermal balance of the "glass" and of the substrate may be written in the usual terms of emissivity and absorptivity, with the only difference, as regards opaque systems, of the addition of terms like $\bar{\varepsilon}_{12}$, $\bar{\varepsilon}_{21}$ that we could call terms of "mixed emissivity".

5. Radiation Balance Of The "Glass"

When the following hypotheses can be admitted:

i) exclusively radiation-type thermal coupling between window and substrate;

ii) negligible thermal inertia effects of the "glass"

then we can formally eliminate the consideration of the problem of the "glass" in the system's thermal balance.

Observe that hypothesis i) is widely verified in many practical cases, while ii) holds strictly in balance temperature calculations and in many cases it is acceptable also in transients.

Within the allowed hypotheses the equation of the problem of the "glass" is written:

$$\bar{\alpha}_{11} Q = \bar{\varepsilon}_{11} \sigma T_1^4 - \bar{\varepsilon}_{12} \sigma T_2^4$$

whence:

$$T_1^4 = \frac{\bar{\varepsilon}_{12}}{\bar{\varepsilon}_{11}} T_2^4 + \frac{\bar{\alpha}_{11}}{\bar{\varepsilon}_{11}} \frac{Q}{\sigma} \qquad (11)$$

Substituting this in the second equation of (10) we get

$$q_2 = \left[\bar{\varepsilon}_{22} - \bar{\varepsilon}_{21} \frac{\bar{\varepsilon}_{12}}{\bar{\varepsilon}_{11}}\right] \sigma T_2^4 - \bar{\varepsilon}_{21} \frac{\bar{\alpha}_{11}}{\bar{\varepsilon}_{11}} Q$$

Thus the equation of problem 2 will be written as:

$$\bar{\alpha}_{21} Q = \left[\bar{\varepsilon}_{22} - \bar{\varepsilon}_{21} \frac{\bar{\varepsilon}_{12}}{\bar{\varepsilon}_{11}}\right] \sigma T_2^4 - \bar{\varepsilon}_{21} \frac{\bar{\alpha}_{11}}{\bar{\varepsilon}_{11}} Q + \dots \qquad (12)$$

(The dots represent the omitted terms which are of no importance as regards this discussion).

Therefore we reduce the equation to the conventional form

$$\bar{\bar{\alpha}}_{21} Q = \bar{\bar{\varepsilon}}_2 \ \sigma T^4 + \ldots\ldots \qquad (12')$$

having put:

$$\bar{\bar{\alpha}}_{21} = \bar{\alpha}_{21} + \left(\frac{\bar{\varepsilon}_{21}}{\bar{\varepsilon}_{11}}\right) \bar{\alpha}_{11}$$ (equivalent absorptivity of the substrate for incidence i)

$$\bar{\bar{\varepsilon}}_2 = \bar{\varepsilon}_{22} - \frac{\bar{\varepsilon}_{21}\,\bar{\varepsilon}_{12}}{\bar{\varepsilon}_{11}}$$ (equivalent absorptivity of the substrate)

The double overlining indicates that we are dealing with "equivalent" characteristics in the particular case of radiation-type balance of the "glass".

6. Applicatory Example

Let us consider a system such as the one in "Figure 1" exposed to normal insolation (i.e. solar radiation = sunshine) and having the following ideal characteristics:

<u>Substrate:</u> Grey in the whole spectrum $\begin{cases} r_2 = 0{,}2 \\ \alpha_2 = \varepsilon_2 = 0{,}8 \end{cases}$

Emissivity of the glass $\bar{\bar{\varepsilon}}_2 = 0{,}8$

<u>Window:</u> Grey in the visible range (solar spectrum) $\begin{cases} r_1 = 0{,}1 \\ t_1 = 0{,}8 \\ \alpha_1 = \varepsilon_1 = 0{,}1 \end{cases}$

Grey in the infrared range (black body at ~300°K) $\begin{cases} r_1' = 0{,}1 \\ t_1' = t_r \\ \varepsilon_1' = 0{,}9 - t_r \end{cases}$

It appears that: $\begin{cases} \tau_1 = 0{,}653 \\ R_1 = 0{,}185 \\ R_2 = 0{,}131 \end{cases}$ and thus: $\bar{\alpha}_1 = 0{,}293 \quad \bar{\alpha}_2 = 0{,}522$

and yet: $\bar{\varepsilon}_{22} = 0{,}7344 \qquad \bar{\varepsilon}_{11} = (0{,}9 - t_r)(1{,}816 + 0{,}204\ t_r)$

$\bar{\varepsilon}_{12} = \bar{\varepsilon}_{21} = 0{,}7344 - 0{,}816\ t_r$

hence:

$$\begin{cases} \bar{\bar{\alpha}}_2 = 0{,}522 + \dfrac{0{,}239}{1{,}816 + 0{,}204\ t_r} \\ \bar{\bar{\varepsilon}}_2 = 0{,}7344 - \dfrac{0{,}600 - 0{,}667\ t_r}{1{,}816 + 0{,}204\ t_r} \end{cases}$$

Figure 2 shows the course of $\bar{\bar{\alpha}}_2$, $\bar{\bar{\varepsilon}}_2$ and $\bar{\bar{\gamma}}_2 = \bar{\bar{\alpha}}_2/\bar{\bar{\varepsilon}}_2$ as a function of the transparency of the "glass" in the infrared range, t_r .

The balance temperature of the substrate and of the "glass" for an amount of insolation of $Q = 1{,}400$ watts/m^2 are shown in Figure 3.

It can be seen that the substrate's temperature tends to rise as the transparency of the "glass" decreases in the infrared range; it is the well-known glass-house (hot house) effect. By contrast, the temperature of the glass rises as the infrared transparency increases, and that is a consequence of the drop of the "glass's" own emissivity.

In practical cases the infrared transparency is always very low.

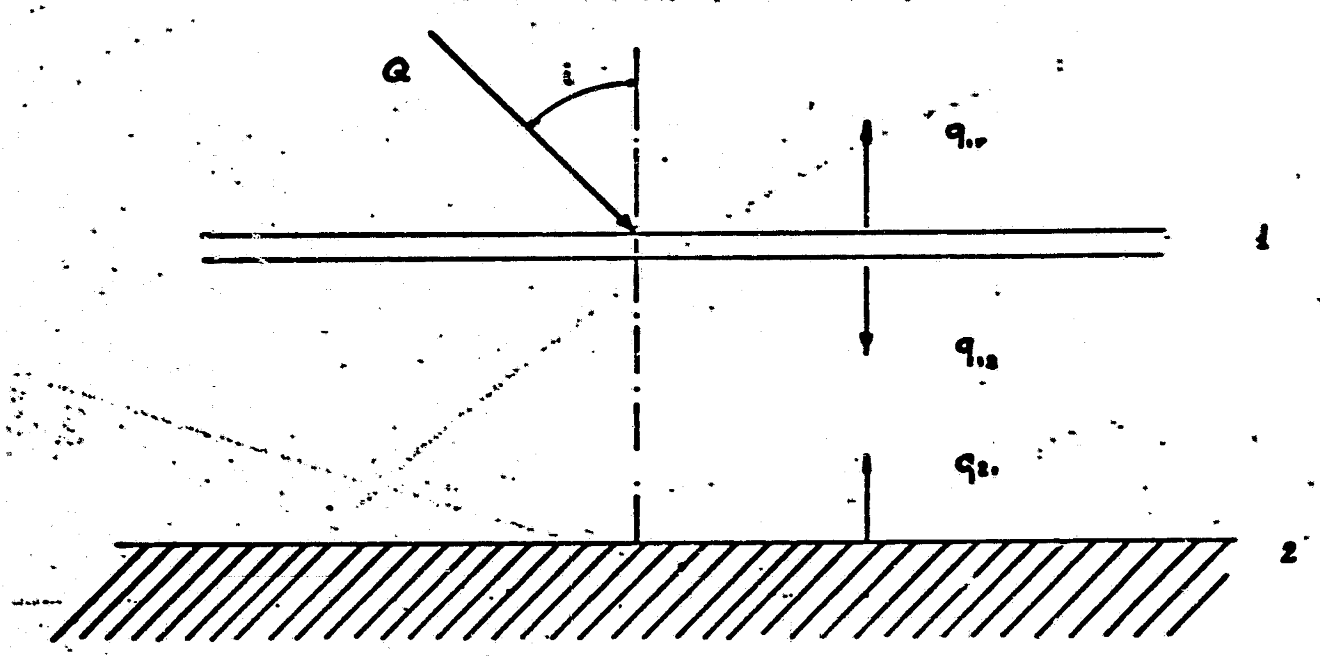

Figure 1

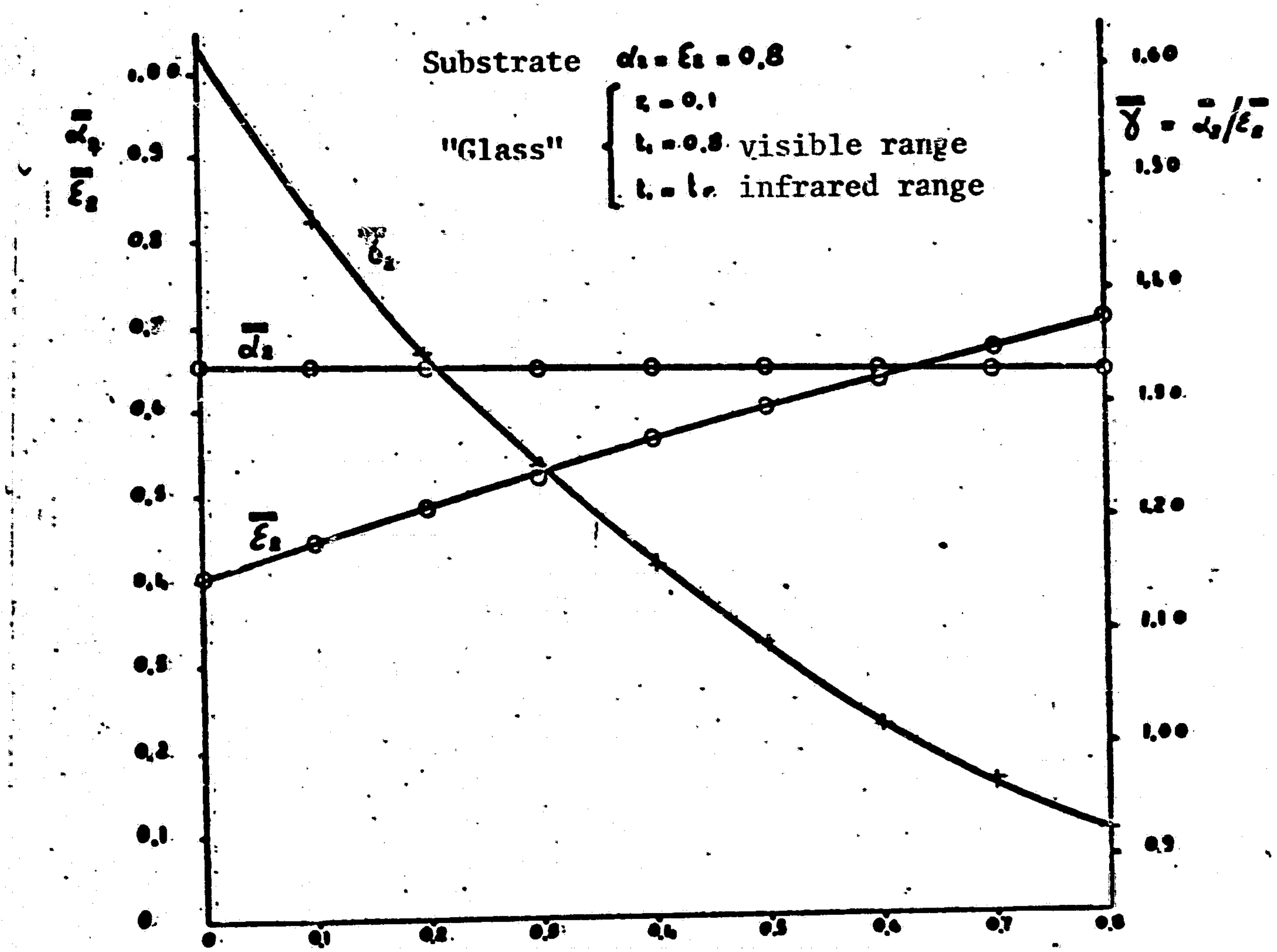

Figure 2. Optical characteristics of the substrate as a function of the "glass's" infrared transparency.

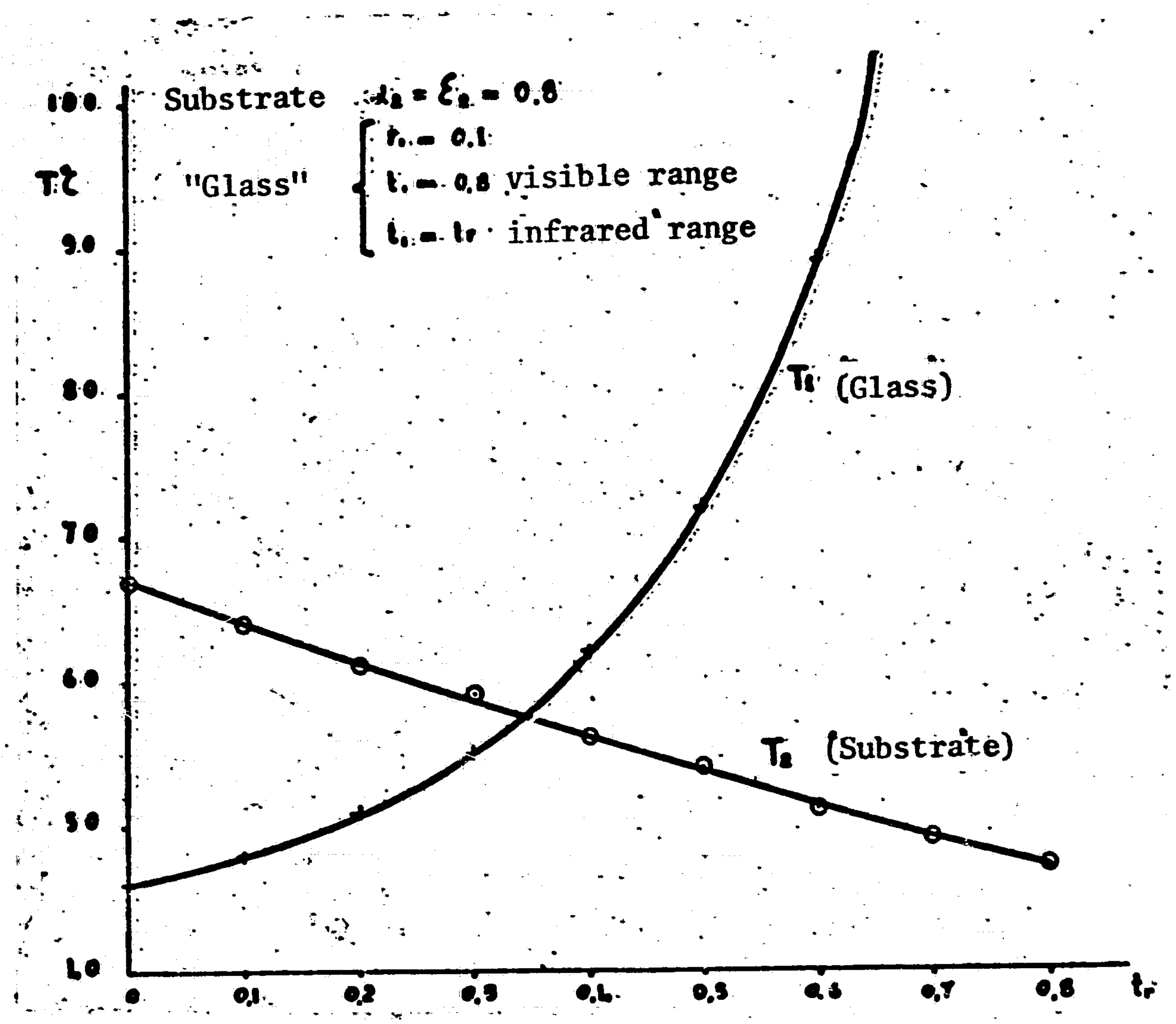

Figure 3. Temperature of the "glass" and of the substrate as a function of the "glass's" infrared transparency.