Exploitation of solar energy

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The problem of transformng the energy of solar radiation into heat and electricity is reviewed. The main attention is devoted to the possibility of heating up to fairly high temperatures, ~500°C, at which modern heat engines, turbines, etc., ensure efficient transformation of heat into electricity. Schemes are examined which are based on the use of comparatively simple concentrators of solar radiation and selective collectors. It is shown that, in addition to selective coatings, selective gas collectors are of great interest. The possibility of constructing large solar power stations is considered. At the end of the review, approximate estimates are given of the possible cost of a solar power station and the prospects for increasing the competitiveness of solar energy are discussed.

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Limiting working temperature.—Concentrators of solar radiation.—Selective coatings.—Selective gas collectors of radiation.—Projects for solar power stations.

Interest in the exploitation of solar energy is comparatively old. More than once, very optimistic predictions have been made to the effect that solar energy could make an appreciable contribution to the energy requirements of the world. The main hopes were based on the direct transformation of the energy of solar radiation into electricity. These hopes have not however been justified yet. Semiconductor solar cells have been used effectively in space and in a number of other applications. They have a conversion efficiency of ~10%, and there are real hopes of achieving 15–20% (see[1]). However, it has not been possible to obtain energy by means of them on any large scale because of the high cost of the semiconducting materials. The electrical energy of solar batteries costs a hundred times more than the electrical energy of modern fossil-fuel power stations.

Another direction associated with the development of solar devices for heating and air conditioning was also not developed for a number of reasons.

This led to the impression that solar energy is not competitive. Interest in it flagged, and for a number of years the problems of solar energy occupied only individual enthusiasts.[1)]

In recent years however, the attitude to the possibility of wide use of solar energy has begun to change significantly (see, for example,[2–5]). This is due to a number of factors. First, as never before, it has become clear that the energy problem is the principal problem of science and technology, and it has also become clear that the future of this problem is by no means cloudless, above all because of the increasing danger of pollution of the environment (see, for example,[6,7]).

World use of energy at the present time is $\sim 10^{13}$ kilowatt hours per year (the mean power is $\sim 10^{12}$ W), and it is doubling every 15 years. It is hardly realistic to expect a slowing down in the rate of growth of energy requirement, especially if it is borne in mind that the present level is largely determined by the industrially developed countries. Thus, the United States, with 6% of the world's population, uses 35% of the energy. With the existing rates of growth, there will unavoidably be a number of serious problems associated with pollution of the environment by combustion products and radioactive wastes, and also with overheating, or so-called thermal pollution.

In this context, solar energy has undoubted advantages. It is not therefore surprising that more and more strenuous efforts are being made to shift the problem of solar energy from its dead point. The main question which arises concerns the true ratio between the possible cost of energy from solar power stations and from fossil-fuel and atomic power stations today and what this ratio could be in the near future.

With a high degree of probability, the cost of electrical energy extracted from fossil-fuel and atomic power stations will increase. This is because the richest deposits of oil, coal, and uranium will be gradually exhausted and also because current measures to restrict pollution of the environment (including reliable methods for disposing of radioactive wastes and ensuring disaster-free operation of atomic power stations) are very costly.

In the case of solar energy, suggestions have now been put forward that inspire a certain optimism. In particular, it has been established that there is a very real possibility of constructing large thermal solar power stations. According to fairly realistic estimates, the cost of the electrical energy obtained from such power stations must be comparable with the existing cost now.

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1) This does not of course apply to energy sources for space ships, solar furnaces, and other devices with a narrow field of application.

The efficiency with which thermal energy is used depends above all on the working temperature. The failure of the majority of the previously attempted solar thermal devices was largely due to their working temperature's being restricted to values $T \lesssim 100\,°C$. An increase of the temperature to $T \sim 500\,°C$, which now appears fully possible, and moreover with comparatively simple means using already existing technology, appreciably increases the conversion efficiency of the solar energy.

The present paper is a brief review of the proposals currently made for converting solar energy into heat and electricity and the physical principles on which these proposals are based. Particular attention is devoted to the possibility of realizing high-temperature heating by means of methods suitable for creating large thermal installations.

LIMITING WORKING TEMPERATURE

The temperature T to which something can be heated by solar radiation is restricted by two processes—thermal emission of the heated object and heat transfer to the surrounding medium. Under equilibrium conditions,

$$S\alpha P_S = S' (\varepsilon\sigma T^4 + h\Delta T), \tag{1}$$

where P_S is the flux of solar radiation, α is the absorptivity, ε is the emissivity, $\sigma = 5.67 \cdot 10^{-5}$ erg $\cdot$ cm^{-2} $\cdot$ sec^{-1} $\cdot$ deg^{-4}, h is the coefficient of heat transfer, ΔT is the difference between the temperature of the body and the surrounding medium, S is the illuminated surface, and S' is the total surface of the body. The coefficient h depends on the size of the body and the state of the atmosphere and may vary in a fairly wide range, $h \approx 2 \cdot 10^3 - 3 \cdot 10^4$ erg $\cdot$ cm^{-2} $\cdot$ sec^{-1} $\cdot$ deg^{-1} (see[8,9]). In the temperature range $T \approx 400-900\,°K$ ($\Delta T \approx 100-600°$) with $\varepsilon \sim 1$ and the maximal value of h, we obtain $\varepsilon\sigma T^4 \approx h\Delta T$. If h has its minimal value, $\varepsilon\sigma T^4 \gg h\Delta T$. Let us omit the second term in (1) and estimate the limiting temperature determined by thermal radiation losses, setting $P_S = 10^6$ erg $\cdot$ cm^{-2} $\cdot$ sec^{-1} (10^3 W/m^2), which corresponds to the flux at noon on the fortieth parallel:

$$T \leqslant \left(\frac{P_S}{\sigma}\right)^{1/4} \left(\frac{\alpha}{\varepsilon} \frac{S}{S'}\right)^{1/4} = 365 \left(\frac{\alpha}{\varepsilon} \frac{S}{S'}\right)^{1/4} (°K). \tag{2}$$

Thus, the maximal temperature of a black body ($\alpha = \varepsilon = 1$) does not even reach $100\,°C$.

The working temperature can be raised in two ways—by using concentrators of solar radiation and by means of the factor α/ε. The second of these possibilities is due to the fact that Eq. (2) contains the ratio of α and ε for different spectral regions. The main part of the solar flux is concentrated in the visible and near infrared regions of the spectrum, $\lambda \sim 0.35-1.2\ \mu$m. The thermal emission at temperatures $T < 1000\,°K$ is in the infrared region $\lambda \gtrsim 2\ \mu$m. Therefore, the optimal conditions are realized in the cases when the heated body absorbs solar radiation efficiently but at the same time has a high transparency or large reflection coefficient in the infrared region $\lambda \sim 2-10\ \mu$m.

It is not difficult to find the maximal temperature which can be obtained under the most favorable circumstances. Suppose that the heated body (for example, a gas) has a single absorption band at a frequency ω in the region of the maximum of the solar spectrum. Then thermal equilibrium between the body and the solar flux (the absorbed energy is equal to the emitted energy) is established at a temperature T which is related to the effective temperature T_S of the Sun by

$$\frac{4\pi}{\exp(\hbar\omega/kT) - 1} = \frac{\Delta O_S}{\exp(\hbar\omega/kT_S) - 1}, \tag{3}$$

where ΔO_S is the solid angle subtended by the Sun. Since $\hbar\omega \approx 2.82 kT_S$ at the maximum of the solar spectrum, $\exp(\hbar\omega/kT) \gg 1$, $\exp(\hbar\omega/kT_S) \gg 1$ and

$$\frac{\hbar\omega}{kT} \approx \frac{\hbar\omega}{kT_S} + \ln\frac{4\pi}{\Delta O_S}. \tag{4}$$

Substituting $T_S \approx 6000\,°K$, $\Delta O_S = 6.8 \cdot 10^{-5}$ sr, $\omega = 2\pi c/\lambda$, $\lambda = 5 \cdot 10^{-5}$ cm, we obtain $T \approx 1500\,°K$.

This example shows that, in principle, very high working temperatures can be obtained despite thermal emission if the spectral characteristics of the body are chosen optimally. The problem is to realize conditions that are most nearly optimal. Possible ways of solving this problem will be considered in the two following sections. First, however, we shall consider what can be achieved by the use of concentrators of solar radiation.

CONCENTRATORS OF SOLAR RADIATION

To be specific, let us consider the heating of a cylindrical volume with radius R at the focus of a cylindrical concentrator that intercepts a flux of solar radiation with transverse dimension D. In this case $S' = \pi S$, and the left-hand side of (1) must be multiplied by the concentration factor $\xi = D/2R$. As a result, we obtain

$$T \leqslant \left(\frac{P_S}{\sigma}\right)^{1/4} \left(\frac{\alpha}{\varepsilon} \frac{\xi}{\pi}\right)^{1/4} = 365 \left(\frac{\alpha}{\varepsilon} \frac{\xi}{\pi}\right)^{1/4} (°K). \tag{5}$$

Suppose the concentrator is aligned along a terrestrial parallel, i.e., in the east–west direction, in such a way that its symmetry plane is perpendicular to the axis of rotation of the Earth. In this case, the direction n_S to the Sun makes an angle θ with the symmetry plane of the concentrator, where

$$\sin\theta = \sin\delta\cos\psi = 0.39 \cos\psi;$$

and δ, the angle between the plane of the Earth's equator and the plane of the Earth's orbit, is 23° and the angle ψ is determined by the annual motion of the Earth around the Sun, with $\psi = \pm\pi/2$ at the equinoxes. It can be seen that during the year $\sin\theta$ varies within the range ± 0.39. The corresponding displacement of the focus of the concentrator lies in the range $\pm 0.39f$, where f is the focal distance. If the complete solar flux during the whole of the year is to be intercepted by the heated volume the inequality $R > 0.39f$ must hold. From this one can find the maximal value of ξ permitted for the given concentrator. Similar considerations hold for reflectors of any profile, for example, parabolic, and also for flat Fresnel concentrators. One then finds $\xi = 3-5$.

If the concentrating system is made more complicated and permits a periodic (once every few weeks) adjustment of the symmetry plane of the reflector to mid-day direction n_S, one can achieve $\xi = 10-15$. The use of fixed concentrators ($\xi = 3-5$) and concentrators with seasonal adjustment ($\xi = 10-15$) enables one to obtain the following limiting working temperatures:

$$\xi \approx 5, T \leqslant 400 \left(\frac{\alpha}{\varepsilon}\right)^{1/4} (°\mathrm{K}), \tag{6}$$

$$\xi \approx 15, T \leqslant 540 \left(\frac{\alpha}{\varepsilon}\right)^{1/4} (°\mathrm{K}). \tag{7}$$

Thus, using comparatively simple concentrators of the solar radiation one can raise the temperature of a black body ($\alpha/\varepsilon = 1$) to 400–500 °K (~ 100–200 °C).

Because of the dependence $T \infty \xi^{1/4}$, a further increase in the temperature requires a significant increase of ξ. Thus, for $T \approx 800$ °K, one needs concentrators with $\xi \approx 75$. Concentration factors of this order can be achieved only by means of systems that permit following of the diurnal motion of the Sun with respect to at least one angular coordinate.[2)]

In the literature, systems have also been considered in which a spherical reflector is fixed and the following is achieved by moving the radiation collector (see, for example,[10]). Here, use is made of the circumstance that for any position of the Sun all rays falling on the mirror are intercepted by a cylindrical collector whose axis passes through the center of curvature of the mirror. Tracking can then be achieved by having the collector pivot about the center of curvature of the mirror. The values achieved for ξ are of order 10^2. In experimental investigations of such systems, the area of the spherical segment was raised to ~ 10^4 m^2, and satisfactory results were obtained.

Until recently, concentrating systems using a fixed reflector and moving collector were thought to be suitable only for comparatively small-scale solar thermal devices. Recently, however, the possibilities of using them in large-scale setups have begun to be considered.[10,11]

If nevertheless we consider only the simplest concentrators—fixed and with seasonal adjustment of the symmetry plane—then an increase in the working temperature beyond (6) and (7) can be achieved only through the factor α/ε in (5).

SELECTIVE COATINGS

The "heat trap" principle based on the so-called greenhouse effects is very well known. The heated body is surrounded by a shell which is transparent in the visible part of the spectrum but absorbs in the infrared region (glass or special films). This shell transmits the solar radiation but at the same time partly reduces the thermal emission of the heated body. Not merely one but several shielding layers can be used. In such systems, one can increase the heating efficiency somewhat, both by reducing the losses through thermal emission and by reducing the convective heat transfer. However, the increase in the temperature achieved without the use of concentrators is small (see, for example,[9]).

Another approach is based on the use of selective coatings, which ensure efficient absorption of solar radiation and at the same time small values of the emissivity ε in the infrared region (see, for example,[12–14]). There are several different ways in which the necessary selectivity can be achieved.

First, there are a number of materials that absorb or transmit well the solar radiation and have high reflection coefficients r in the infrared. In accordance with Kirchhoff's law, the emissivity of such materials is low, $\varepsilon = 1 - r$. For example, hafnium carbide, HfC, in the region 4–10 μm has reflection coefficient $r = 0.8$–0.9 but in the visible region $r \approx 0.25$. The reflection in the visible region can be reduced by depositing a film of a transparent dielectric on the surface of HfC. By means of such materials, one can obtain values $\alpha/\varepsilon \approx 4-5$.

To increase the selectivity, one can use more complicated multilayer coatings; for example, three-layer sandwiches—dielectric–semiconductor–metal.[14–16] The absorption takes place in the metal. The first two layers are transparent for the solar radiation. Their purpose is to reduce the thermal emission through the high reflection coefficient of the semiconductor in the infrared.

Finally, one can also use multilayer interference coatings similar to those used to make lenses nonreflecting.

If selective coverings with small ε are used, the relative importance of heat exchange with the surrounding medium (the second term on the right-hand side of (1)) increases considerably. The limiting working temperatures permitted by thermal emission losses can be achieved only under the condition that the thermal losses are lower than the emission losses. The thermal losses can be reduced to the necessary level by enclosing the heated body in a transparent evacuated container.

In laboratory investigations, using complicated multilayer coatings, the ratio α/ε can be raised to 7–10 (see[14]).

Using simultaneously concentration of solar energy and selective coatings, one can in principle obtain a working temperature which is adequate for many applications. For example, if $\alpha/\varepsilon \approx 8$ and $\xi = 4$ (fixed concentrator), then $T \approx 650$ °K. If $\alpha/\varepsilon = 8$ and $\xi = 13$ (concentrator with seasonal adjustment), then $T \approx 870$ °K.

It should however be pointed out that the selective coatings currently used are as a rule insufficiently thermally resistant and they are at the same time rather

2) Complicated focusing systems that enable one to follow the motion of the Sun with respect to both angular coordinates are used in solar furnaces. In them, $\xi \approx 10^4$ is achieved.

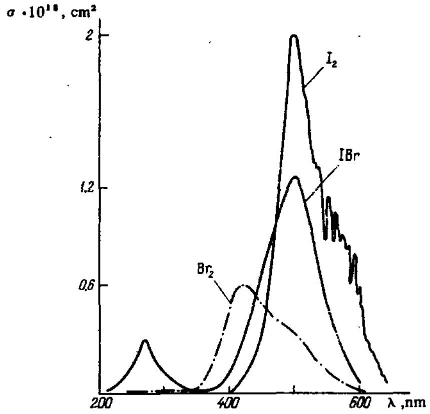

FIG. 1. Absorption spectra of Br_2, I_2, and IBr vapor.

expensive.[14] Therefore, in the next section we shall consider a different possible way of achieving the necessary value of the parameter α/ε based on the use of selective gas collectors of solar radiation. Such collectors were proposed independently by the author[17] and Palmer.[18]

SELECTIVE GAS COLLECTORS OF RADIATION

In the first section it was shown that in the case of a gas that is transparent in the infrared but has an absorption band in the region of the maximum of the solar spectrum, the losses on thermal emission are maximally suppressed. They only begin to be serious at temperatures of order 1000 °K and above. Gases of symmetric diatomic molecules of the type X_2 have a high transparency in the infrared. Such molecules do not have dipole moments and therefore have neither vibrational or rotational absorption spectra. At the same time, in the region of the maximum of the solar spectrum some of them have strong electron absorption bands. Examples are the molecules of bromine (Br_2) and iodine (I_2). The absorption spectra of Br_2 and I_2 are shown in Fig. 1. The absorption peak of Br_2 is situated in the region $\lambda = 0.42$ μm, the effective absorption cross section is $\sigma_{max} = 6 \cdot 10^{-19}$ cm² ($T = 293$ °K), and $\sigma_{max} = 4 \cdot 10^{-19}$ cm² ($T = 900$ °K). For I_2, respectively, $\lambda = 0.52$ μm and σ_{max} is about three times larger than for Br_2. One can heat Br_2 and I_2 vapor to a temperature $T \approx 1000$ °K. Thermal dissociation begins only when $T > 1100$ °K.

Besides symmetric diatomic molecules, some other diatomic and triatomic molecules have the necessary properties. For example, the molecule IBr has two electron absorption bands in the regions $\lambda \sim 0.5$ μm and $\lambda \sim 0.27$ μm (see Fig. 1). The circumstance that this molecule is not symmetric and has an infrared absorption spectrum does not lead to difficulties. The fundamental vibration frequency of IBr at $\nu = 288$ cm⁻¹ corresponds to the wavelength $\lambda = 37$ μm. In the region 1–10 μm there are only high overtones. In addition, the molecule IBr has a weak dipole. In what follows, to be specific, we shall consider a vapor of the type Br_2, I_2, IBr, and also mixtures of these with one another and noble gases, nitrogen (N_2), etc. The absorption spectra shown in Fig. 1 indicate that in this case one can take $\alpha = 0.4$ if the concentrations are appropriately chosen.

As we showed in the section devoted to the limiting working temperature, the thermal emission of the selected gas can be ignored in the temperature range $T \lesssim 1000$ °K. Therefore, the working temperature is restricted solely by the heat flux q_T to the walls of the volume. To be specific, we shall assume that the heated volume is a cylinder of radius R. In this case.

$$q_T = \varkappa \, \mathrm{Nu} \frac{\Delta T}{R}, \quad \Delta T = T - T_0, \tag{8}$$

where $\varkappa$ is the coefficient of thermal conductivity, **Nu** is the Nusselt number, which characterizes the increase in heat conduction due to convection, T is the maximal temperature within the volume, and T_0 is the wall temperature of the volume. For Br_2, $\varkappa = 10^3$ erg · cm⁻¹ · sec⁻¹ · deg⁻¹ ($T \sim 500$ °C). The Nusselt number **Nu** can be estimated from[8]

$$\mathrm{Nu} \simeq 0.2\mathrm{Gr}^{1/4}, \quad \mathrm{Gr} = \frac{gR^3\beta\,\Delta T}{\nu^2}, \tag{9}$$

where **Gr** is the Grashof number, g is the acceleration due to gravity, β is the coefficient of thermal expansion, and ν is the kinetic viscosity. For gases, $\beta = 3.7 \cdot 1s^{-3}$ deg⁻¹ to a good accuracy. The kinetic viscosity of gases is inversely proportional to the pressure p. For Br_2, $\nu \approx 0.1 N_0/N$ cm²/sec, where N is the concentration of the molecules and N_0 is the concentration at atmospheric pressure.

As can be seen from (9), $\mathrm{Gr} \propto p^2$, and $\mathrm{Nu} \propto \sqrt{p}$, and therefore low pressures are advantageous for reducing convective heat transfer. Because of the large absorption cross sections of Br_2, I_2, and IBr vapor, solar radiation can be efficiently absorbed at pressures much less than atmospheric pressure. To ensure the adopted value $\alpha \approx 0.4$, one needs a concentration of molecules at which $N\sigma_{max} 2R \approx 5$. Since $\sigma_{max} \approx 5 \cdot 10^{-19}$ cm², we obtain $N \gtrsim 10^{19}/2R$. The concentration N can be increased by using a dipoleless buffer gas.[3)] From (8) and (9)

$$\Delta T \simeq 55\xi^{4/5} R^{1/5} \left(\frac{N_0}{N}\right)^{2/5}. \tag{10}$$

At atmospheric pressure $N \approx N_0$ under conditions of developed convection (for $R \approx 10$–20 cm, $\mathrm{Gr} \sim 10^8$–10^9)

$$\Delta T \simeq 55\xi^{4/5} R^{1/5}. \tag{11}$$

For $N \approx 10^{-19} (2R)^{-1}$, when the role of convection is appreciably reduced (for $R \approx 10$–20 cm, $\mathrm{Gr} \sim 10^5$)

$$\Delta T \simeq 85\,\xi^{4/5} R^{3/5}. \tag{12}$$

It can be seen from (12) that if the pressure is reduced, even without concentration of the solar energy ($\xi = 1$),

[3)]The product $\varkappa\mathrm{Nu} \propto \nu^{-1/2}\varkappa$ varies from gas to gas much less than $\varkappa$ and ν separately. For N_2 and Br_2, the ratio $\nu^{-1/2}\varkappa$ is 2.2. For Ar and Br it is 1.5.

one can obtain $\Delta T \approx 500\,^\circ\mathrm{C}$ ($R \approx 20$ cm). If radiation concentrators are used, high-temperature heating is possible even at pressures as high as the atmospheric. For example, for $N = N_0$, $R = 20$, and $\xi = 13$, $\Delta T \approx 700\,^\circ\mathrm{C}$.

A very important feature of this gas collector of solar radiation is the circumstance that the transparent shell remains comparatively cold during the heating process. The temperature T_0 of the shell can be estimated by equating the heat flux q_T from the gas to the losses due to emission and heat transfer to the surrounding medium [cf. (11)]. Since the emissivity of the shell, in contrast to the gas's, is $\varepsilon_0 = 1$, its heating is restricted by the emission losses. It is easy to show that for $\alpha = 0.4$ the temperature T_0, even for $\xi = 15$, does not exceed the temperature of the surrounding medium by more than $100\,^\circ\mathrm{C}$. Therefore, in estimates of the temperature T in (10)–(12) one can take $T_0 \approx 300$–$400\,^\circ\mathrm{K}$.

PROJECTS FOR SOLAR POWER STATIONS

In the literature devoted to solar energy, very varied projects for large scale solar power stations have been discussed. Some of them, although based on already known scientific and technological advances, are clearly intended for the distant future. An example is the possibility considered by Glaser for constructing in space on a synchronous orbit a gigantic semiconductor battery. The energy is to be transmitted to the Earth in the microwave range (see[3]). The number of projects that are perfectly realistic now have such low efficiencies of conversion of solar energy into electricity that they could hardly be successful. Among projects of this type, we must include the construction of hydroelectric power stations based on the evaporation of water. Other possibilities have been considered, including the construction of dams enclosing bays. The lowering of the water level in the bay compared with the sea by evaporation produces a constant source of hydroelectric energy. It is however easy to see that the efficiency of such systems is very low. Suppose that the difference in the water levels H is ~10–100 m. The evaporation of 1 g water requires $\sim 600\ \mathrm{cal} = 25 \cdot 10^9$ erg, whereas the potential energy is $gH = 10^6$–10^7 erg. Taking into account the losses accompanying conversion into electricity, the efficiency is $\sim 2 \cdot 10^{-5}$–$2 \cdot 10^{-4}$. Allowance for the circumstance that evaporation takes place not only through the radiation falling on the area of the bay itself but also due to the flux of heat from adjacent regions does not significantly alter this estimate.

The most realistic and competitive at the current time would be solar thermal power stations. In them one would use existing heat engines, turbines, etc, so that solar thermal power stations would differ from ordinary fossil-fuel power stations essentially in only the method of heating the working medium (high-pressure gas, superheated water vapor, etc). In what follows we shall therefore discuss only methods of heating by solar radiation.

Different heating schemes are considered. In the so-called variant with tower collector, the heated volume is placed above the power station at a height of 100–300 m, and the solar flux is directed onto it by means of reflectors arranged around it and covering a large area of several square kilometers. The reflectors needed for such systems are rather complicated. In particular, they necessitate following of the diurnal motion of the Sun.

Much more attractive are those heating schemes in which comparatively simple concentrators are used in conjunction with selective collectors. One of the schemes of this type was proposed in[14]. The main element in the collector is a long line, a concentrator which focuses solar radiation onto a pipe with a selective coating. As the heat carrier moves along the pipe, it is heated from its initial temperature T_i to the final working temperature T_f. In order to collect radiation from a large area but at the same time reduce to a minimum the heat losses in the passive sections of the pipes joining the radiation collectors to the heat machine, it is necessary to have a sufficient length L of the collector. The value of L is determined by the speed v at which the carrier is pumped through the pipe and the heating time τ. The maximally allowed value of v can be estimated by requiring that the power W' expended on the pumping should not exceed 10^{-2} of the power of the thermal flux W at the end of the pipe.

Let Δp be the pressure difference. Then

$$W' = \pi R^2 v\, \Delta p, \quad \Delta p = \rho \frac{v^2}{2} \frac{L}{2R} f, \tag{13}$$

where ρ is the density of the heat carrier, and f is a dimensionless coefficient which depends on the quality of the walls of the pipe. Taking the typical value $f = 0.3$, we obtain

$$W' = 0.02\, \rho R v^3 L. \tag{14}$$

For W and τ, we have

$$W = c_p \rho \pi R^2 T_f v, \tag{15}$$

where c_p is the specific heat, and

$$\tau \sim \frac{c_p \rho \pi R^2 (T_f - T_i)}{\xi \cdot 2RP_S} \simeq \frac{c_p \rho R (T_f - T_i)}{\xi P_S}. \tag{16}$$

Bearing in mind that $L = v\tau$, and taking $W'/W \leqslant 10^{-2}$, $(T_f - T_i) \sim T_f$, we obtain

$$v^3 \leqslant 1.5 \frac{\xi P_S}{\rho}. \tag{17}$$

Suppose that the pressure of the gas heat carrier, for example, air, is $p \simeq 10$ atm. For $T \sim 500\,^\circ\mathrm{C}$ and $p = 10$ atm, we have $\rho \approx 5 \cdot 10^{-3}\ \mathrm{g/cm^3}$, $c_p \approx 10^7\ \mathrm{erg \cdot g^{-1} \cdot deg^{-1}}$. Substituting these values into (13)–(17) and assuming $\xi \sim 10$, $R \sim 10$–30 cm, we obtain

$$v \leqslant 10^3\ \mathrm{cm/sec}, \quad \tau \sim 100\ \mathrm{sec}, \quad \frac{\Delta p}{p} \leqslant 0.03. \tag{18}$$

Thus, v can vary in a wide range, which allows us to take large values of $L = v\tau$, right up to kilometers.

If $R \sim 10$–30 cm and $\xi \sim 10$, then $D = 2R\xi \sim 200$–600 cm. Concentrators with a transverse dimension of a few meters and concentration factor $\xi \sim 10$ are comparatively cheap. Simple technology (see, for example, [19]) can be used for their construction. Therefore, a concentrator–collector combination with a selective coating is very advantageous. It enables one to achieve the necessary working temperatures and simultaneously reduce appreciably the area of the selective collector.[4)]

For the parameters of the gas heat carrier chosen above for estimates and $v = 10^3$ cm/sec and $R = 30$ cm, the total thermal flux at the end of one collector is in accordance with (15) $W \approx 15$ MW.

In[14] the use of selective coatings with $\alpha/\varepsilon \sim 10$ and concentrators with $\xi \sim 10$ is advocated. The maximal working temperature which can then be achieved is, in accordance with (5), $T_{max} \simeq 900$ °K. This permits one to choose a certain optimal temperature $T_f < T_{max}$ at which one can guarantee fairly high coefficients of conversion η_t of thermal radiation into heat, of heat into electricity, η_e, and total efficiency $\eta = \eta_t \eta_e$. Estimates show that $\eta_t \simeq 0.5$ and even 0.7 is perfectly realistic for $T_f \simeq 770$ °K (~500 °C). Since $\eta_e \sim 0.3$–0.35 for modern heat engines at these temperatures, we obtain $\eta \sim 0.15$–0.2.

Thus, the total area required for a power station of this type with a mean 24-hour power of 10^9 W must be ~15 km^2.

In[18] it is shown that the use of gas selective collectors of solar radiation in a similar arrangement leads to approximately the same results. It is true that the required area is about twice the above value since in this case only a fraction $\alpha \simeq 0.4$ of the solar flux P_S is used. In compensation, the radiation collectors are simpler and cheaper.

It should be noted that the particular gas selective collector considered in[18] is probably not optimal. One should mix an absorbing component of the type Br_2 directly to the high-pressure working gas such as argon. Moreover, one is making no use at all of the possibility considered above of completely eliminating convective heat transport in the collector. The possibility cannot be excluded that the use of a two-step scheme—heating of a low-pressure gas with subsequent transfer of the heat to a high-pressure working gas in a heat exchanger—would be more advantageous. In addition, the fraction $(1-\alpha)P_S$ of the solar flux that is not observed in the collector and escapes through the transparent shell could be used for a preliminary heating of the gas, which would somewhat increase the value of η_t.

CONCLUDING REMARKS

Thus, there is a very real possibility of constructing large scale solar thermal power stations that guarantee a working temperature sufficient for many applications, including the transformation of solar radiation into electricity with an efficiency of 10–20%. From an area of ~ 1 km^2 one can take an electrical power ~ 10^8 cm during about eight hours of the day.

How promising are these results? Do they give ground for optimism? It is not so easy to answer this question. If one compares a solar thermal power station with currently existing power stations (fossil-fuel, atomic, hydroelectric), many positive and negative factors must be taken into account. The positive factors are obvious: inexhaustible energy source, absence of pollution (including thermal) of the environment. The negative factors are the large area, the dependence on meteorological conditions, the specific conditions of exploitation resulting from operation during the day only or the need to store heat. Ultimately, everything however reduces to the two decisive factors—cost and area.

To be specific, let us consider a power station with a 24-hour average power ~10^9 W. As we have shown, such a power station requires an area ~ 15–30 km^2. Although large, this does not seem excessive. In particular, it does not exceed the area of modern hydroelectric power stations for rivers in plains (the area of the water reservoir and the earth in the dams). In addition, solar power stations could be situated in arid or desert regions. In order to meet entirely the present energy requirements of the Soviet Union one would need an area ~5000 km^2, i.e., a square with side 70 km, which is less than 1% of the area taken up ty the production of food stuffs.[5)]

Thus, an area 15–30 km^2 for a 10^9 W power station is perfectly reasonable. The only question concerns the complexity and cost of radiation collectors that permit one to "collect" solar energy from such an area. Among the arguments advanced against solar energy one frequently encounters references to the specific and unusual conditions of exploitation. For example, the periodic cleaning and decontamination of the concentrators and collectors is mentioned. It is obvious that everything again reduces to the cost. The cost of periodic cleaning can be regarded as analogous to, for example, the cost of maintaining a guard in the case of an atomic power station. Therefore, the only decisive factor is the cost of producing the energy, i.e., the cost of the solar power station and its exploitation. This applies equally to large scale power stations or any other solar thermal installations.

From the point of view of economics, the currently most attractive variants of solar thermal installations are those using selective collectors and comparatively simple concentrators (without diurnal following of the Sun's motion). We have pointed out above that simple and cheap technology can be used in the construction of these concentrators. This is particularly true of Fresnel concentrators.

Preliminary estimates of economic factors always contain an arbitrary element. Nevertheless, it can be

4) The use of concentrators in the case of direct conversion into electricity is also of undoubted interest. If one could produce semiconducting cells that are more thermally resistant than the existing ones, the use of concentrators would considerably reduce the necessary number of semiconductors.

5) Note also that this is less than the area occupied by coal mines, oil fields, and oil pipelines.

seen from the estimates made in[14,18] that the cost of electrical energy from solar thermal power stations is perfectly reasonable.

At the present cost of electricial energy, acceptable capital expenditure on the construction of a power station is usually estimated at $200 per kW (see[14,18]). What would be the cost of a selective collector together with the concentrator? Gas selective collectors are very simple. The total amount of absorbing components such as Br_2 is small. If the concentration factor is $\xi \sim 10$, one requires several tens of grams of Br_2 per kW or several tens of tons for 10^9 W. Therefore, their cost is largely determined by the cost of the glass pipe and its support. If $R \sim 20$ cm and $\xi \sim 10$, the length of the pipe element corresponding to a power of 2 kW is ~ 8 m. According to the estimates made in[18], the cost of a fairly complicated gas collector designed to heat high-pressure gas and equipped with heat insulation of the nonilluminated part of the surface is ~ 200 dollars per 1 kW. For the optimal choice of the collector, its cost can hardly exceed several tens of dollars per kilowatt. Detectors with selective coatings would apparently be several times more expensive.[14] In this case, though, the required area is reduced by a factor 1.5–2. The cost of the concentrators should also not exceed 100–200 dollars per kW (see, for example,[18]).

It is possible that these estimates are too large since they do not take into account fully the possibility of cheaper technology under conditions of mass production. But in any case it can be seen that solar thermal power stations may be perfectly competitive even in the near future. Final conclusions can however be drawn only after the construction of large-scale experimental installations and evaluation of the experience gained from their use.

Another question is whether there is a sufficiently acute need for solar energy and whether its advantages, such as the absence of pollution (including thermal) of the environment, outweigh the disadvantages due to the specific conditions of exploitation of solar power stations. It is possible that these inconveniences and difficulties are strongly overestimated under the influence of prejudice, tradition, etc. In this connection, it is apposite to quote the following passage taken from[20], which very nicely characterizes the situation.

"Just imagine that solar energy is everywhere in use, providing energy at a cost slightly above current prices. Imagine further that I was proposing the 'radical' idea of sending geological survey terms to the Middle Eastern deserts to search for oil and, having found it, to erect derricks, extract it and transport it either by pipeline or by especially constructed ships to the other side of the world where it would be refined and delivered to end-use point by truck. I am sure that, in these cases, there would be many people who would prove 'conclusively' that this would be economically infeasible."

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