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1. PREFACE

The purpose of this part of our course on environmental physics is to familiarize you with the basic concepts that facilitate the practical use of solar energy and the design of more sophisticated energy conversion systems.

2. ENERGY UNITS

Let me first review a few basic concepts from the world of energy usage. First, *energy* occurs in various forms. As a result of this, and largely for historical reasons, it is measured in a wide variety of units. The S.I. unit (i.e. commensurate with kilograms, meters and seconds for mass, length and time, respectively) is the *joule*. $1 \text{ J} = 1 \text{ kg m}^2 \text{ s}^{-2}$. The relationships between the joule and a number of other commonly used energy units are shown in **Table 1**

Energy Unit	Joule equivalent
1 electron volt (eV)	$1.60217733 \times 10^{-19}$ J
1 calorie	4.1868 J (exact, by definition)
1 British thermal unit (Btu)	1.055 kJ
1 Therm	105.5 MJ
1 kWh	3.6 MJ (exact)
1 barrel of crude oil (boe)	6.12 GJ
1 cu. ft. of natural gas	1.055 MJ
1 short ton (2000 lb) of coal	26.57 GJ

Table 1: Some energy conversions to S.I. units

The corresponding S.I. unit of *power* (i.e. the rate at which energy "flows", i.e. is generated or consumed) is the *watt*. $1 \text{ W} = 1 \text{ J s}^{-1}$, The relationships between the watt and a number of other commonly used power units are shown in **Table 2**

Power unit	Watt equivalent
1 horse power (hp)	745.7 W
1 Ton of refrigeration	3.517 kW
1 kcal/h	1.163 W (exact, by definition)
1 Btu/h	0.2931 W
1 barrel per day of crude oil	70.8 kW

Table 2: Some power conversions to S.I. units

3. SOLAR ENERGY GENERATION

The sun emits electromagnetic energy at a rate of 3.826×10^{26} J s^{-1} (this is called the *solar luminosity*). The principal mechanism by which the sun produces this radiant energy is by the so-called *fusion* of 4 protons into a helium nucleus. Since the mass difference between 1 helium nucleus and 4 protons is 26.73 MeV (4.283×10^{-12} J), via Einstein's celebrated $E = mc^2$ formula, a solar luminosity of 3.826×10^{26} Js^{-1} corresponds to the "burning" of approximately 10^{38} hydrogen atoms per second. Fortunately, the sun contains very many protons - approximately 10^{57}. That is enough fuel to last for another 10^{19} s, or 317 billion years, which is a long time even on the scale of our 13.7 billion year-old universe!

Many possible fusion reactions can exist for the conversion of 4 protons to a helium nucleus. However, the probability of any given reaction to significantly contribute to the process depends on: (a) the *abundance* of the reacting species; (b) the *reaction probability* at a core temperature of the sun (~ 10^7 K). Coulomb repulsion between nuclei with high Z values would tend to allow only relatively light nuclei to have appreciable reaction probabilities. These include: H, He, C, N, O, Ne, Mg and Si.

In 1938 Hans Bethe identified 2 reaction chains that permit the process 4p -> He with high probability: The so-called *proton-proton chain* (about 99% of the energy output) and the *carbon-nitrogen cycle.* The chief branch of the proton-proton chain is:

Step 1: two protons fuse together and form a deuterium nucleus

$$^{1}H + {}^{1}H \rightarrow {}^{2}D + e^{+} + \nu \quad (\tau \approx 10^{10}\text{ y}) \qquad (1.1)$$

Step 2: a third proton fuses with the deuteron and together they form a helium-3 nucleus

$$^{2}D + {}^{1}H \rightarrow {}^{3}He + \gamma \quad (\tau \approx 10\text{ s}) \qquad (1.2)$$

Step 3: two helium-3 nuclei collide and produce a helium-4 nucleus (a so-called *alpha particle*) and two protons

$$^{3}He + {}^{3}He \rightarrow {}^{4}He + 2\,{}^{1}H \qquad (1.3)$$

There are also a number of other, lower probability, alternatives to reactions (**1.1**) and (**1.3**). These reactions together contribute a total calculated energy of 26.73 MeV for the chain. You will notice that the overall process is limited by the extremely low probability (a so-called *weak interaction*) reaction (**1.1**); i.e. the positron emission must occur while the two protons are in close proximity with one another, which is an extremely rare kind of event. After this has happened the relatively fast (a so-called *electromagnetic interaction*) reaction (**1.2**) can take place. The final (a so-called *strong interaction*) reaction(**1.3**) then proceeds practically instantaneously (i.e. during a characteristic time of about 10^{-24} s).

It is worth noting that the photons emitted in reaction (**1.2**) and in the various alternatives to (**1.3**) do not necessarily leave the sun, i.e., they constitute a *negligible part* of the solar energy that reaches the earth. Instead, they, together with the kinetic energy of the massive reaction components, contribute kinetic energy to heating the interior of the sun, which subsequently radiates with its characteristic black body spectrum. It is that radiation which is of interest to us!

The neutrinos, on the other hand, *do* leave the sun but they carry with them only about 2% of the total energy, and are virtually unstoppable. I.e., those neutrinos that reach the earth simply pass through, except for the extremely rare one that occasionally gets absorbed. (Further details of both the proton-proton chain and the carbon-nitrogen cycle - which dominates energy production on certain other types of star - can be found in astrophysics texts such as ref [**1**]).

4. THE SOLAR SPECTRUM

The wavelength spectrum of the radiation leaving the sun is shown in **Fig. 1**. It is approximately that of a *black body* at a temperature of about 5770K - the sun's *effective surface temperature*.

$$BB_\lambda(T) = \frac{15}{\pi^5}\,\frac{1}{\lambda}\left[\frac{hc}{\kappa\lambda T}\right]^4 \frac{1}{\exp(hc/\kappa\lambda T) - 1} \qquad (1.4)$$

By the time the sun’s radiation reaches the earth it has traveled a mean distance of about 1.496 x 10^{11} m (=1 AU) and its intensity has been reduced to S_o = 1360 W m^{-2} - the so-called *solar constant.* [The slight ellipticity of the Earth's orbit is responsible for values of the solar constant differing from each other by 1%, or so, appearing in the solar literature].

When measured at a distance of (1 AU), but above the atmosphere, about 9% of this energy is in the form of ultra-violet radiation ($\lambda \leq 0.40$ µm), approximately 38% is visible ($0.40 \leq \lambda \leq 0.70$ µm) and about 53% lies in the infra-red ($\lambda \geq 0.70$ µm). The shorter wavelength X-rays and gamma rays, and the longer wavelength microwaves and radio waves make negligible contributions to the total solar energy that reaches the earth.

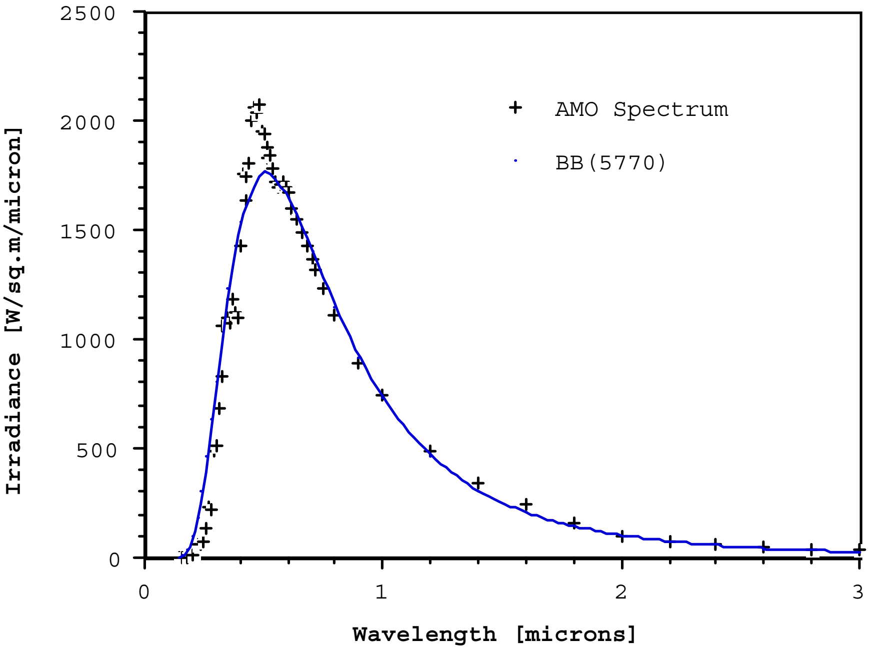

Figure 1: The (AM0) solar spectrum as measured above the earth's atmosphere, compared with the emission spectrum of a black body at a temperature of 5770 K

The maximum irradiance occurs at about 0.45 μm, i.e. in the blue-green part of the visible. However, most of the visible spectrum occurs at longer wavelengths. This, together with the human eye's maximum acuity near 0.55 μm accounts for the sun's characteristic "yellow-white" color. For wavelengths in the blue and ultra-violet parts of the spectrum the sun's output falls *below* that given by the Planck Black Body formula. This is due to various absorption processes that occur within the sun (specifically, the close packing of Fraunhofer absorption lines. These, together with photons sufficient to ionize such metals as Mg and Al, increase the solar opacity at these wavelengths).

It is interesting to compare the amounts of solar energy that actually reach the earth's surface in various wavelength ranges of interest, with the corresponding amounts of energy that arrive at the top of the atmosphere (**Table 3**). The ranges of interest are the three ultraviolet bands: UV-C ($\lambda <$ 290 nm), which is attenuated by oxygen molecules in the stratosphere; UV-B (290 nm $< \lambda <$ 320 nm), which is attenuated by the stratospheric ozone layer; UV-A (320 nm $< \lambda <$ 400 nm), Visible (400 nm $< \lambda <$ 700 nm) and Infrared ($\lambda >$ 700 nm), all of which are attenuated by various molecular absorption bands, mainly ozone, water vapor and carbon dioxide. Of particular importance are O_2, H_2O and CO_2, which produce characteristic absorption dips in the IR. These minima are the result of almost total absorption at wavelengths in the vicinity of 1.38 μm (H_2O), 1.86 μm (CO_2) and 2.54 μm (CO_2). It is these absorption bands that play a critical role, via the *atmospheric greenhouse effect*, in regulating the earth's temperature.

Wavelength band [nm]	Radiation type	(AM0) Intensity above atmosphere [W m^{-2}]	(AM1.5) Intensity at sea level [W m^{-2}]	Attenuation [%]
$\lambda < 290$	UV-C	11.0	0	100
$290 < \lambda < 320$	UV-B	19.1	1.3	93.2
$320 < \lambda < 400$	UV-A	88.5	44.9	49.3
$400 < \lambda < 700$	Visible	518.9	427.9	17.5
$\lambda > 700$	IR	722.4	525.9	27.2
All wavelengths	E-M	1360	1000	26.5

Table 3: Attenuation by the earth's atmosphere of solar radiation in various wavelength ranges

5. THE SUN AS TERRESTRIAL FUEL

The solar constant represents the solar intensity intercepted by a disk with diameter equal to that of the Earth. When this energy is smeared over the *surface* of the Earth's sphere it is reduced by a factor of precisely 4, and passage through the atmosphere reduces it by a further factor of approximately 2. Thus the mean solar intensity at ground level is a mere 170 W m^{-2}. When *integrated over one year* the resulting 5.4 GJ m^{-2} is approximately the energy that can be extracted from one barrel of oil, as may be seen from **Table 1**. Naturally some parts of the Earth receive more than this annual average - up to about 40% more - but solar energy is still seen to be a most *dilute source of energy* compared to the non-renewable forms. The possibility of it replacing fossil fuel will accordingly depend on the development of low cost and high efficiency methods of conversion, transmission and storage.

6. WHAT CAN SOLAR ENERGY BE USED FOR?

At the lowest level of sophistication comes *heating*. Water can be heated and so too can living spaces, by using the direct rays of the sun. However, if this is to be done efficiently it is best to employ the laws of physics.

For example, one might want hot water at nighttime, when sunshine is not available. This means that some kind of well-insulated storage tank must be provided. One might also want hot water on days when there is little or no sunshine. This requires special considerations, involving the optical, absorption and emission properties of the material surfaces that collect the solar energy.

Another seemingly simple example involves the heating of buildings. However, very often, buildings need to be heated in winter but not in summer. If a building is designed so that the sun's rays render it comfortably warm in winter, there is a danger that it will become uncomfortably hot in summer. So here too, the laws of physics will play an important role - particularly as regards the thermal response times associated with the passage of heat through walls, roofs, etc.

At a higher level of sophistication, the energy we collect from the sun can be used to drive heat pumps in order to provide cooling and refrigeration. It can also be converted to electrical energy in a variety of ways, and then used for any purpose for which electricity is normally employed.

Naturally, the more sophisticated the solar energy conversion system will be, the greater will be the expense that is involved. So, in addition to the laws of physics, it is important to understand some basic ideas about economics.

This, in broad outline, is the scope of the solar energy part of this Environmental Physics course. Since this will be the first time that I (personally) have taught such a course to non-physics students, I do not know how much of the above list I shall be able to cover. However, my hope is that you will fully understand however much we shall manage to get through. Although this will not make solar scientists out of you, it will enable you to understand the possible ways in which solar energy could be of use to you and the societies in which you live. By having such an understanding you will be better able to appreciate the difference between a truly feasible project and one in which some confidence trickster seeks to take your money and run.

REFERENCE

[**1**] **Foukal, P.V**.: Solar Astrophysics (Wiley, New York etc, 1990)