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Second Law Analysis of the Earth System with a Radiative Model

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Abstract

Solar radiation provides the energy for many processes on Earth including processes that sustain living systems and circulation of the atmosphere and oceans. The Earth does not consume this energy; it is simply converted to outgoing thermal radiation. However, the entropy production rate of Earth causes energy degradation and the exergy destruction rate quantifies this degradation relative to a reference environment. The global entropy production rate also provides an additional constraint for comparison with atmospheric modeling results. In this paper a simplified expression for the global entropy production rate, associated with the absorbed portion of the solar flux, is presented based on a radiative model. The second purpose of this work is to investigate the exergetic analysis of the Earth. It is desirable to consider environment temperatures that are typical temperatures on Earth when comparing the total entropy production rate and irreversibility rate of the planet to those due to processes such as the global energy system; in other words, typical temperatures where these processes occur. However, multiplying the estimated global entropy production rate by an arbitrary environment temperature appears to result in irreversibility rates that violate the second law of thermodynamics. It is shown that the radiative interaction of the Earth with its surroundings can be theoretically modeled and tested in a laboratory environment showing that arbitrary environment temperature specifications should not cause these violations. These apparent violations are resolved through corrections to the energy, entropy and exergy calculations that are due to the specific character of radiative heat transfer. As a result, this analysis also provides an illustrative example of the implications of environment specifications on exergy analysis involving radiative heat transfer.

Key words: irreversible thermodynamics, irreversibility, entropy production, exergy analysis, atmospheric modeling, radiative planetary model

1. Introduction

Solar radiation in many ways sustains the Earth system. For example, solar radiation incident on Earth provides all the energy that sustains the flora and fauna and also keeps the Earth at a suitable temperature for life on a planet that would otherwise be at temperatures near absolute zero. Solar radiation is a direct renewable energy source but is also indirectly responsible for other energy sources such as hydroelectric power (due to the water cycle), wind energy, and even the fossil fuels such as coal and crude oil. The absorption of solar radiation is also responsible for the circulation of the atmosphere and oceans due to non-uniform heating of the atmosphere, land and oceans.

Yet the amount of energy flowing from Earth to space by thermal radiation is essentially equal to the amount of solar energy absorbed by the system, otherwise the mean temperature of Earth would be changing. This is because radiative exchange is essentially the only form of energy interaction between the Earth and its surroundings. The Earth as a thermodynamic system does not consume energy; the low entropy incident solar radiation is simply degraded to a higher entropy stream of thermal radiation leaving the system. Consequently, the entropy production rate, or the rate of exergy destruction (irreversibility), is an important quantity in characterizing the Earth system.

To compare the global irreversibility rate to the irreversibility rates of various sources on Earth, such as atmospheric circulation or the global energy system, it is desirable to determine irreversibility rates relative to a reference environment with temperatures typical on Earth. However, for certain specifications of environment temperature, the calculated irreversibility rates, based on the energy and entropy fluxes of the incident solar radiation and outgoing thermal radiation, appear to violate the second law of thermodynamics.

The global entropy production rate also provides a boundary value or benchmark for atmospheric modeling. A primary motivating force for atmospheric modeling efforts is to predict the effects of rising greenhouse gas effects on the Earth's temperatures and circulation patterns. The interaction of many contributing phenomena, however, makes modeling of the atmosphere a difficult task. For an overview of this subject see, for example, Peixoto and Oort (1992). Recently researchers have made efforts to incorporate the second law of thermodynamics to reduce the large number of predicted possible states made by models based on the principles of energy, momentum (linear and angular), and mass conservation. For further information, see, for example, O'Brien and Stephens (1995), and Stephens and O'Brien (1993).

Even though the Earth is a very complex system, radiative models of the planet provide valuable insight because the thermodynamics of the Earth system is dominated by radiative processes. For example, Wright et al., (2000) finds that the mean temperature of Earth has a tendency of being independent of the amount of solar radiation absorbed while being dependent on effects such as the greenhouse effect.

In the research reported in this paper the objectives are:

1) to investigate the exergy destruction rate (irreversibility rate) of the Earth system,
2) to estimate the entropy production rates on the planet due to the specific processes of reflection of solar radiation and absorption with simultaneous emission by the absorbing material,
3) to present a simplified expression for the global entropy production rate based on analysis results by Wright et al. 2000.

2. Radiative Model

Researchers have analyzed simple blackbody type radiative models to investigate the thermodynamic behavior of the Earth system (for example see Aoki 1982; Stephens and O'Brien 1993 and Weiss 1996). Wright et al., (2000) provided analysis of a graybody model of the planet that more accurately characterizes the radiative behavior of the planet. This model provides improved estimates of the planetary entropy rate and mean planetary temperature because the Earth system only partially absorbs incident solar radiation and emission of thermal radiation is substantially less than that of a blackbody.

In this analysis the Earth system is represented by an isothermal, solid sphere with uniform properties. The approximation of uniform temperature implies the material of the sphere has a very high thermal conductivity. The analysis is at steady state and the 'long wave' emissivity of the sphere is assumed to be independent of the 'short wave' albedo of Earth, where the albedo (a) is an overall measure of the reflectivity of the planet (or one minus the absorptivity). Note that for the Earth the long wave emissivity ε_{LW} is approximately 0.61 while the short wave albedo (a) is approximately 0.30.

By definition of the planetary albedo (a), the energy flow rate absorbed ($\dot{E}_{Abs}$) from the incident solar radiation is

$$\dot{E}_{Abs} = (1-a)\dot{E}_{Inc} \qquad (1)$$

The incident solar radiation, depicted in *Figure 1*, is contained in a small solid angle (Ω_S) given by

$$\Omega_S = 4\pi\left(\frac{\pi R_S^2}{4\pi r^2}\right) = \pi\left(\frac{R_S}{r}\right)^2 \qquad (2)$$

where R_S is the mean radius of the Sun, and r is the mean orbital radius of the Earth or one astronomical unit.

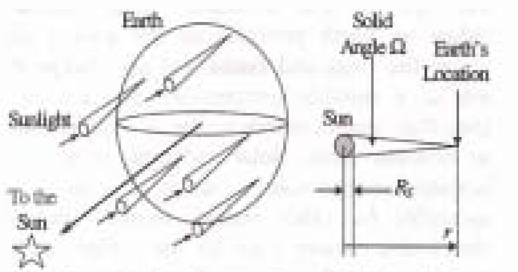

Figure 1. Illustration of SR incident on Earth and the SR solid angle

Consequently, the incident energy flux $\dot{E}_{Inc}$ with solar radiation on a body with cross-sectional area πR^2 can be expressed as

$$\dot{E}_{Inc} = \pi R_E^2 (\Omega_S K_{Inc}) = \pi R_E^2 \sigma T_S^4 \left(\frac{R_S}{r}\right)^2 \quad (3)$$

where R_E is the mean radius of the Earth, T_S is the effective emission temperature of solar radiation, K_{Inc} is the energy radiance of the incident solar radiation (for further details see Wright et al. 2000). The emitted energy flux is emitted over the surface area of the sphere and is given by

$$\dot{E}_{Emi} = 4\pi R^2 \varepsilon_{LW} \sigma T_P^4 \quad (4)$$

where ε_{LW} is the longwave emissivity of the planet, σ is the Stefan-Boltzmann constant, and T_P is the effective temperature of the planet. The mean planetary temperature is determined by equating the absorbed and emitted energy flow rates and is given by

$$T_P = \left(\frac{1-a}{\varepsilon_{LW}}\right)^{\frac{1}{4}} \left(\frac{R_S}{2r}\right)^{\frac{1}{2}} T_S \quad (5)$$

The entropy production rate of the planet is simply the difference between the entropy of incoming solar radiation and outgoing reflected and emitted radiative fluxes:

$$\dot{\Pi} = \dot{S}_{Emi} + \dot{S}_{Ref} - \dot{S}_{Inc} \quad (6)$$

In equation (6) the entropy of the emitted and reflected fluxes are assumed to be independent. Since these fluxes travel in the same direction this implies that the energy spectrums of these fluxes do not overlap significantly as to affect the entropy calculations.

The entropy fluxes for emitted and reflected radiation can be expressed in terms of the energy flux and material emission temperature

$$J = I(\varepsilon) \frac{4}{3} \frac{H}{T} \quad (7)$$

where H and J are the energy and entropy irradiance, respectively, and $I(\varepsilon)$ is a coefficient that is unity for blackbody radiation and is greater than one for non-blackbody radiation (Wright et al., 2001). The approximation for the coefficient $I(\varepsilon)$

$$I(\varepsilon) \approx \varepsilon \left\{ \frac{4\pi^4}{45} - (2.336 - 0.260\varepsilon) \ln \varepsilon \right\} \quad (8)$$

has a maximum percent error of 0.33% for emissivities greater than 0.005 (Wright et al., 2001).

The entropy production rate for this model can be expressed as

$$\dot{\Pi} = \pi R^2 \left[\frac{R_S}{r}\right]^{\frac{3}{2}} \left\{ \sqrt{2}(1-a)^{3/4} \varepsilon_{LW}^{1/4} I_1(\varepsilon_{LW}) - \left[1 - a I_2\left(\frac{a R_S^2}{r^2}\right)\right]\left(\frac{R_S}{r}\right)^{\frac{1}{2}} \right\} \frac{4}{3} \sigma T_S^3 \quad (9)$$

Using eq. (1) and eq. (3) for the absorbed energy flux, the global entropy production rate may alternatively be expressed as

$$\dot{\Pi} = \frac{4}{3} \dot{E}_{Abs} \left\{ I_1(\varepsilon_{LW}) T_P^{-1} - T_S^{-1} (1-a)^{-1} \left[1 - a I_2\left(\frac{a R_S^2}{r^2}\right)\right] \right\} \quad (10)$$

and if the longwave emissivity (ε_{LW}) is approximately equal to the shortwave absorptivity (1-a), then the planetary entropy production rate associated with absorbed energy flux becomes

$$\dot{\Pi} = \dot{E}_{Abs} \left\{ \frac{4}{3} I_1(1-a) T_P^{-1} - \frac{4}{3} T_S^{-1} \left[1 - \frac{a}{1-a} I_2\left(\frac{a R_S^2}{r^2}\right)\right] \right\} \quad (11)$$

To determine the global entropy production rate ($\dot{\Pi}_{Abs}$) associated with only the solar radiation that is absorbed by the system, we may omit the entropy flux of the solar radiation that is reflected back to space. Also, for an albedo *a* the planet absorbs (1-*a*)% of the incident energy. However, the entropy flux of the solar radiation that is absorbed is greater than (1-*a*)% of the incident entropy flux. Consequently, the entropy production associated with the absorbed flux may be expressed as

$$\dot{\Pi} = \frac{4}{3} \dot{E}_{Abs} \left\{ I_1(\varepsilon_{LW}) T_P^{-1} - I_1(1-a) T_S^{-1} \right\} \quad (12)$$

and if ε_{LW} is approximately equal to 1-*a* then the planetary entropy production rate associated with absorbed energy flux becomes

$$\dot{\Pi} = \frac{4}{3} I_1(1-a) \left[\frac{1}{T_P} - \frac{1}{T_S}\right] \dot{E}_{Abs} \quad (13)$$

or with $4/3 I_1(\varepsilon) = 1.45$ (Wright et al., 2001) we have

$$\dot{\Pi} = 1.45 \left[\frac{1}{T_P} - \frac{1}{T_S}\right] \dot{E}_{Abs} \quad (14)$$

By substituting data for the Earth ($a = 0.30$, $\varepsilon_{LW} = 0.61$, $R = 6.37 \times 10^6$ m and $r = 1.486 \times 10^{11}$ m) and the Sun ($R_S = 6.923 \times 10^8$ m and $T_S = 5760$ K), the planetary entropy production rate of the Earth associated with the absorbed portion of the solar radiation flux (12) is estimated as 602 TW/K, compared to the total entropy production rate of 641 TW/K (Wright et al., 2000). The difference between these two results is the entropy production rate due to the diffuse reflection of a portion of the incident solar radiation and is approximately 39 TW/K.

3. Exergetic (Second Law) Analysis

The first law of thermodynamics states that energy is neither created nor destroyed[1]. The Earth as a thermodynamic system does not consume energy; the low entropy incident solar radiation is simply degraded to a higher entropy stream of thermal radiation leaving the system. Consequently, the entropy production rate, or the rate of exergy destruction (irreversibility), is an important quantity in characterizing the Earth system.

The entropy content of incoming and outgoing radiative fluxes is used to calculate the exergy content or thermodynamic value of the radiative energy flux in a given environment. Note that the entropy content alone does not determine the value of the energy flux (exergy content) that is also dependent on the environment specification. Likewise, the entropy production rate is used to calculate the exergy destruction rate that occurs in a system. The Gouy-Stodola theorem states that the exergy destruction rate or irreversibility of a system is given by the product of the entropy production rate and the environment temperature

$$\dot{I} = T_0 \, \dot{\Pi} \qquad (15)$$

The entropy production rate, as well as the irreversibility rate, are proportional to the albedo or the absorbed energy flow rate. On the other hand, for a fixed albedo or absorbed energy flow rate, the planetary entropy production rate (Wright et al., 2000) is only weakly dependent on longwave emissivity[2]. However, even when there is little variation in the entropy production rate, the irreversibility rate (15) is strongly dependent on the specification of the environment temperature.

In general, the environment is defined as a region with uniform properties that is beyond the immediate surroundings and whose intensive properties (such as temperature and pressure) are not affected by the system (for example, see Cengel and Boles 2002 or Bejan 1997).

The surroundings of the Earth system are not homogenous and do not have uniform properties. However, the surroundings of the Earth system appear as a very low temperature region (near 3 to 4 K) as far as thermal interactions are concerned. With an environment temperature of say 4 K, the irreversibility rate of the Earth system is (4 K)*(641 TW/K) ≈ 2600 TW; a quantity that is orders of magnitude lower than the incident energy flow rate of solar radiation, estimated as 173,000 TW. This means that the exergy content of thermal radiation leaving the Earth is very high (nearly unity) relative to an environment with such a low temperature.

If instead we wish to specify an environment temperature typical of temperatures on Earth, the calculated irreversibility rate is much higher. This serves the purpose of determining exergy content and irreversibility rates with respect to the environment on the surface of the Earth or in the atmosphere where the processes of absorption and emission occur. However, in this case the distinction between the system and environment becomes unclear and the irreversibility rate for the planet takes the questionable form of

$$\dot{I}_{Earth} = T_{Earth} \, \dot{\Pi}_{Earth} \qquad (16)$$

where the entropy production rate of the system is multiplied by the system's temperature. For the radiative model the irreversibility rate using (16) is (278 K)*(641 TW/K) ≈ 178,000 TW. This value of irreversibility is greater than the incident energy flux (≈ 173,000 TW), clearly indicating the application of equation (16) may be somehow erroneous.

3.1. Exergetic analysis with an elevated environment temperature

The difficulties in applying equation (16) become even more pronounced if we consider arbitrary values for the environment temperature. This is acceptable because the temperature in equation (16) need not be interpreted as the Earth's temperature. The relation (16) should result in appropriate values of the irreversibility

[1] Energy is conserved even in nuclear processes because of the equivalency of energy and matter according to Einstein's relation ($E = mc^2$).

[2] For this radiative model the greenhouse effect may be represented by a difference between longwave emissivity and global albedo. When the albedo is considered fixed, this has little effect on the global entropy production rate. However, the greenhouse effect will significantly affect the estimated mean global temperature, and indirectly the albedo of the actual Earth, thereby affecting the irreversibility rate calculation through both the temperature and entropy production rate. As a result, the relationship between the dynamic behavior of the greenhouse effect and the global irreversibility rate is not straightforward to determine and is not considered in the present paper. Also, dynamic effects such as daily variations due to rotation of the Earth, seasonal variations and the effects of cloud formation are not considered in the present paper.

rate, relative to the incident or absorbed energy flow rates, for arbitrary specifications of environment temperature.

To illustrate the effect of arbitrary environment temperature specifications consider the process depicted in *Figure 2*. A radiation source produces radiation identical to extraterrestrial solar radiation contained in the same small solid angle (Ω_s) subtended by the Sun.

The sphere is identical to the graybody model of the Earth system except for scaling. This setup could hypothetically be carried out in a laboratory where the environment temperature could have an arbitrary value. The energy, entropy and exergy flow rates per unit surface area are the same as for the graybody model of the Earth system. Consequently, we arrive at the same questionable results where the calculated irreversibility rate is greater than the incident and absorbed energy flow rates.

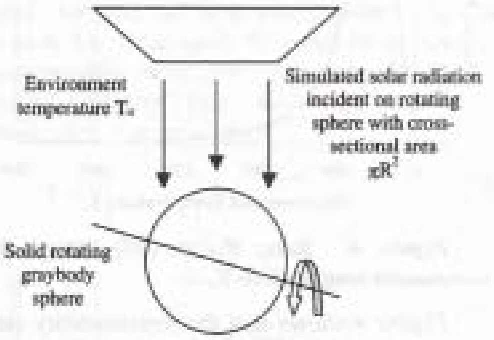

Figure 2. Simulated solar radiation incident on solid rotating sphere in an environment with an arbitrary temperature T_o

The difficulties that arise in determining the irreversibility rate and in applying (16) are due to neglecting fluxes that must be incorporated in the analysis. If we consider, case I, an environment at temperature T_o in direct radiative contact with the system then we must consider the radiation emitted from the environment and incident on the system. The radiation emitted from the environment has a non-zero energy and entropy flux but zero exergy flux.

For this case the energy flux of the absorbed solar radiation plus the energy flux incident from the environment must equal the emitted energy flux at steady state. Assuming the radiation incident from the environment has a blackbody character, as would be expected from a system in equilibrium with uniform properties regardless of its radiative character, the absorbed energy flux is given by

$$\dot{E}_{\substack{Abs\\Env}} = 4\pi R^2 \alpha_{LW} \sigma T_o^4 \tag{17}$$

where α_{LW} is the absorptivity of the sphere for incoming longwave radiation emitted from the environment. Using the graybody assumption we have

$$\alpha_{LW} = \varepsilon_{LW} = 1 - a \tag{18}$$

and based on an energy balance for the system at steady state, the temperature is given by

$$T_P^4 = T_o^4 + \frac{1}{4}\frac{\Omega_S}{\pi} T_S^4 \tag{19}$$

The entropy production rate associated with the absorbed solar energy flux is

$$\dot{\Pi} = \left[\frac{4}{3} I_1(1-a)\right]\left[\frac{T_P^3}{T_P^4 - T_o^4} - \frac{1}{T_S} - \frac{4\pi T_o^3}{\Omega_S T_S^4}\right]\dot{E}_{Abs} \tag{20}$$

and the irreversibility rate is

$$\dot{I} = T_o\left[\frac{4}{3} I_1(1-a)\right]\left[\frac{T_P^3}{T_P^4 - T_o^4} - \frac{1}{T_S} - \frac{4\pi T_o^3}{\Omega_S T_S^4}\right]\dot{E}_{Abs} \tag{21}$$

For a = 0.30 the ratio (R_{IE}) of the irreversibility rate to the absorbed energy flow rate from the incident solar radiation is

$$R_{IE} = \frac{\dot{I}}{\dot{E}_{Abs}} = (1.45) T_o \left[\frac{T_P^3}{T_P^4 - T_o^4} - \frac{1}{T_S} - \frac{4\pi T_o^3}{\Omega_S T_S^4}\right] \tag{22}$$

taking $4/3 I_1(\varepsilon) = 1.45$ (Wright et al., 2001). *Figure 3* shows that the ratio of the irreversibility rate to the absorbed energy flow rate from solar radiation is always positive and less than unity.

So for case I, where the system is in direct radiative contact with the surrounding environment at T_o, the incident energy and entropy flux from the environment must be included in the calculation of the entropy production rate and irreversibility rate; thus resolving the unacceptable result that the irreversibility rate is greater than the absorbed solar energy flow rate.

On the other hand, we may consider case II where the immediate surroundings are a vacuum near absolute zero (simulating deep space). This can be accomplished with the system depicted in *Figure 2* using a concentric spherical shell surrounding the system and maintained at a temperature near absolute zero. The environment is still at an arbitrary temperature T_o and is located outside of the immediate surroundings that are maintained at a temperature near absolute zero.

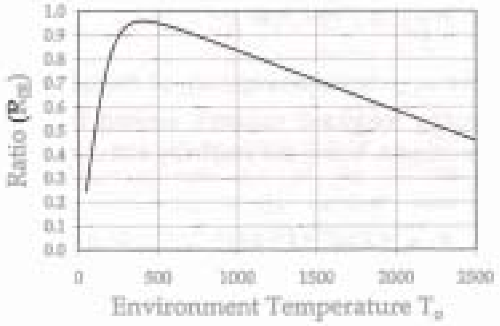

Figure 3. Ratio R_{IX} in (22) versus the environment temperature T_o

In this case there is no energy or entropy flux incident on the system except for the simulated solar radiation. However, with a non-zero environment temperature the absence of incident radiation represents a non-zero exergy flux (Wright et al, 2002) and is given by

$$\dot{\Xi}_{\substack{from\\Surr}} = (4\pi R^2)\frac{\sigma}{3}T_o^4 \tag{23}$$

The concentric shell maintained near absolute zero has a very high exergy content, and exergy actually flows from this shell to the system at a rate given by (23), as discussed near the end of section 3. The total incoming exergy flux is the sum of the exergy flux of incident solar radiation plus the exergy flux from the coencentric shell surrounding the system. The irreversibility rate, assuming $\varepsilon_{LW} = (1\text{-}a)$, is

$$\dot{I} = T_o\left[\frac{4}{3}I_1(1-a)\right]\left[\frac{1}{T_P}-\frac{1}{T_S}\right]\dot{E}_{Abs} \tag{24}$$

The exergy flux of the incident solar radiation, assuming a blackbody spectrum, is approximately

$$\dot{\Xi}_{\substack{Inc\\SR}} = (0.931)\dot{E}_{\substack{Inc\\SR}} = (0.931)\pi R_E^2(\frac{\sigma}{\pi}T_S^4)\Omega_S \tag{25}$$

which has the numeric value of 160,800 TW. The 0.931 factor represents the exergy content, or ratio of exergy to energy flux, of blackbody radiation.

A portion of the incident exergy flux is absorbed and can be approximated as

$$\dot{\Xi}_{\substack{Abs\\SR}} = (0.931)(1-a)\dot{E}_{\substack{Inc\\SR}} \tag{26}$$

and has the numeric value of 112,600 TW. The irreversibility rate must be less than or equal to the combined exergy influx with absorbed solar radiation (26) and the radiation incident from the environment (23). Thus, the ratio (R_{IX}) of the irreversibility rate (24) to the total exergy influx, (23) and (24);

$$R_{IX} = \frac{\dot{I}}{\dot{\Xi}_{\substack{from\\Surr}} + \dot{\Xi}_{\substack{Abs\\SR}}} = \frac{T_o\left[\frac{4}{3}I_1(1-a)\right]\left[\frac{1}{T_P}-\frac{1}{T_S}\right](1-a)\dot{E}_{\substack{Inc\\SR}}}{(4\pi R^2)\frac{\sigma}{3}T_o^4 + (0.931)(1-a)\dot{E}_{\substack{Inc\\SR}}} \tag{27}$$

must be positive and less than unity. With a = 0.30, and upon using (3) and (5), this expression for the ratio R_{IX} reduces to

$$R_{IX} = \frac{(1.015)\left[\left(\frac{4\pi}{\Omega_S}\right)^{\frac{1}{4}} - 1\right]T_o T_S^3}{\frac{4}{3}\frac{\pi}{\Omega_S}T_o^4 + (0.652)T_S^4} \tag{28}$$

Figure 4 illustrates the variation of the ratio R_{IX} with the environment temperature.

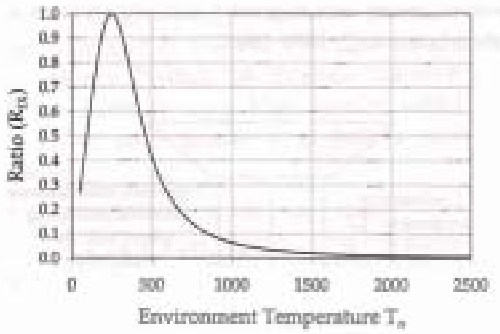

Figure 4. Ratio R_{IX} in (28) versus the environment temperature T_o

Figure 4 shows that the irreversibility rate is always positive and less than the total incoming exergy, the exergy influx with the absorbed solar radiation and the influx from the surroundings near absolute zero. Thus, in section 3 it appeared that the irreversibility rate was greater than the incident energy flux because the exergy flux from the surroundings near absolute zero was neglected. Although there is zero energy and entropy flux from the surroundings there is a non-zero positive exergy flux.

In the environment with non-zero temperature, blackbody radiation will exist in any evacuated or gaseous regions. A cavity devoid of radiation represents dis-equilibrium with the environment and consequently non-zero exergy. This is analogous to the mechanical exergy of an evacuated cavity in an environment with a non-zero pressure.

For a material near absolute zero, such as the surroundings of this system, the exergy content (ratio of exergy to energy) is very high. For example, the ratio of the exergy to energy (R_{XII}) of a simple incompressible substance with constant specific heats is

$$R_{XE} = 1 - \frac{T_o}{T}\left(1 + \ln\frac{T}{T_o}\right) \quad (29)$$

Figure 5 illustrates qualitatively that as the temperature approaches absolute zero (T/T_o approaches zero), the exergy to energy ratio approaches infinity.

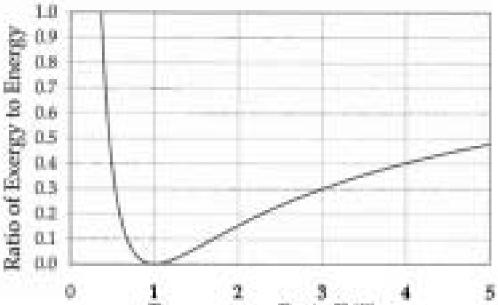

Figure 5. The exergy to energy ratio R_{XE} (29) for a material system vs. the ratio T/T_o

The exergy of a material system near absolute zero decreases rapidly even when only small amounts of heat are transferred to the system. Consider again the example of a simple compressible substance discussed above. The exergy transfer rate associated with heat conduction is expressed as

$$\dot{\Xi} = \dot{Q}\left(1 - \frac{T_o}{T}\right) \quad (30)$$

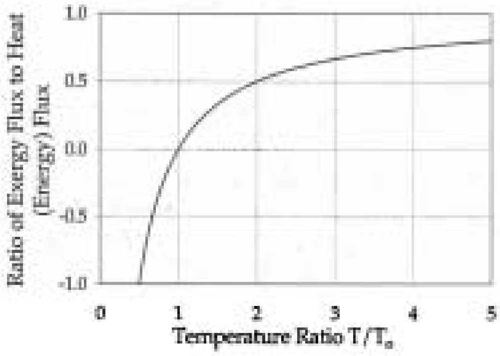

Figure 6. The ratio of exergy flux to heat flux versus the temperature ratio T/T_o

Figure 6 depicts qualitatively the ratio of the exergy flux (30) to the energy flux versus the temperature T of the system to which heat is being transferred. At very low system temperatures (T), the exergy flux has a large magnitude and is in the opposite direction of the heat flux. Thus, exergy is transferred out of the system as the system near absolute zero is heated.

In this radiative analysis there is negligible incident radiation on the system because the surroundings are maintained at a temperature near absolute zero. Consequently, the exergy flux steadily received by the system, analogous to the material system, originates from the surrounding material maintained near absolute zero.

Thus, whether the system is in radiative contact with its environment or not, the energy, entropy and exergy fluxes incident from the surroundings must be considered even when there is no incident radiation. Since the environment temperature is always non-zero, the absence of incident radiation represents a non-zero exergy flux.

Arbitrary specifications of the environment temperature are permissible when calculating the irreversibility rate of the system. The particular choice of environment temperature will depend on the purpose of the analysis. An environment temperature similar to the temperatures on Earth is desirable when comparing the global irreversibility rate to the irreversibility rates of processes on Earth such as the irreversibility rate associated with the global energy system.

4. Conclusions

The planetary entropy production rate associated with the absorbed of solar radiation can be approximated by a concise relation involving the absorbed energy flow rate, the effective emission temperature of the Sun, the effective planetary temperature, and the planetary albedo.

The estimated planetary entropy production rate associated with the absorbed solar flux is 602 TW/K, and that due to diffuse reflection of solar radiation is 39 TW/K, for a total global entropy production rate of 641 TW/K. The entropy production rate of 602 TW/K is the appropriate value for comparison with atmospheric modeling in which the calculations of entropy production due to the reflection of solar radiation wish to be omitted.

The theoretical model presented in this paper used to simulate the radiative interaction of the Earth with its surroundings illustrates that arbitrary environment temperature specifications do not cause a violation of the second law. The apparent violations are resolved through corrections to the energy, entropy, and exergy calculations that are due to the specific character of radiative heat transfer. As a result, this analysis provides an illustrative example of the implications of environment specifications on exergy analysis involving radiative heat transfer. When the immediate surroundings are near absolute zero (simulating deep space), there is no incident energy or entropy flux from the surroundings but there is a non-zero exergy flux when the environment temperature is non-zero.

TABLE I. NOMENCLATURE ASSOCIATED WITH THE ENERGY, ENTROPY AND EXERGY OF RADIATION

	Energy	Exergy	Units	Entropy	
	Symbol	Symbol		Symbol	Units
Internal	U	Ξ*	J	S	J/K
Specific	u	ξ	J/m^3	s	J/m^{3}K
Flow Rate	$\dot{E}$	$\dot{\Xi}$	W	$\dot{S}$	W/K
Irradiance (Flux)	H	M	W/m^2	J	W/Km^2
Radiance	K	N	W/m^{2}sr	L	W/Km^{2}sr

* Ξ and ξ are the Greek letters corresponding to the English/Latin X and x, respectively.

* The specific energy and entropy for TR are per unit volume rather than per unit mass as they are for material related quantities.

For an arbitrary environment temperature the global irreversibility rate associated with the absorbed solar energy satisfies the second law because it is always less than the total influx of exergy, the exergy influx with solar radiation and the exergy influx from the surroundings.

When the environment is in direct radiative contact with the system, the energy and entropy flux incident from the environment must be considered in the energy balance equation and the entropy production rate calculation. With this correction the irreversibility rate does not violate the second law because it is always less than the exergy influx from the absorbed solar radiation.

Nomenclature

A	Planetary albedo
c	Speed of light = $(2.9979)10^8$ m/s
I_1, I_2	Entropy functions
$\dot{I}$	Irreversibility (exergy destruction rate)
r	Mean radius of planetary orbit (m)
R	Radius of the planet (m)
T	Material emission temperature (K)
α	Absorptivity
ε	Emissivity
π	Physical constant, 3.14159…
$\dot{\Pi}$	Entropy production rate (W/K)
σ	Stefan-Boltzmann constant = $(5.67)10^{-8}$ W/m^{2}K^4
Ω	Solid angle (sr)

Subscripts

Abs	Absorbed
Abs Env	Absorbed from environment
Abs SR	Absorbed solar radiation
BR	Blackbody radiation
E	Earth
Emi	Emitted
IE	Ratio of irreversibility to the absorbed energy flow from solar radiation
Inc	Incident
Inc SR	Incident solar radiation
IX	Ratio of irreversibility to exergy inflow
LW	Long-wave
O	Environment conditions
P	Planet
Ref	Reflected
S	Sun

Abbreviations

BB	Blackbody
BR	Blackbody radiation
GR	Graybody radiation
SR	Solar radiation
TR	Thermal radiation
TW	Terawatt = 10^{12} Watts

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