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Definition of Emergy

Sholto Maud has asked me to give a definition of the emergy unit. I would like to do a little more and define emergy itself as well as emergy efficiency. Further, I will give some examples as they apply to special cases.

Definition (Availability). A*vailability* (or *available energy*) is energy [*enthalpy*, H, or *internal energy*, U] corrected for *entropy*, S. Rigorous definitions of the *Gibbs availability function* [$H - T_oS$], the *Helmholtz availability function* [$U - T_oS$], and entropy are given in Appendix I, Fundamentals of Thermodynamics, where the symbols and technical terms employed in this paragraph are explained. [T_o is the temperature of the environment, usually taken to be the temperature of the coldest body of water or the atmosphere into which the waste heat of a heat engine can be discharged. For Earth, 300 K will do. The effect of entropy on the availability function of sunlight is to reduce it by the ratio of the temperature of Earth to the temperature of the Sun – a factor of about 19/20. Since the enthalpy of a proton is 4/3 times the energy, the Gibbs availability of sunlight is about 76/60 times the energy.]

Odum's original definition of emergy. Odum defined *emergy*, measured in emjoules, to be the Gibbs availability of the sunlight, measured in joules, required to produce, by an optimal process, (1) fuels; (2) other energy sources such as wind or fresh water in mountain lakes; (3) natural resources such as grass and trees, (4) *manufactured objects*, (5) human resources; (6) information; and (7) any other *objects of economic interest that can be associated with an identifiable quantity of sunlight*. This is a sunlight-based emergy. It leads to large numbers for the emergies of primary fuels that are known only approximately; therefore, we shall modify the definition slightly to give common industrial energy products emergies that are known precisely and that are close to 1.0 in magnitude.

Definition (Standard Electricity). In this paper, single-phase, 60 Hz, 110-volt alternating current delivered to the user's meter is taken to be *standard electricity*.

Definition (Emergy Unit). My arbitrary – but well-defined – choice for one unit of emergy (1 MU) is 1.0 kilowatt-hours of standard electricity. Although electrical current carries a small amount of entropy manifest in difference currents, for all practical purposes, that is, for engineering purposes, electricity is pure work. The availability of electricity is equal to its energy; and, with this choice of emergy unit, the emergy of electrical current is numerically equal to its energy in kilowatt-hours. The transformity of sunlight, wind, biomass, and other energy products will be less than – but close to – 1.0.

Definition (Transformity). The *transformity* of a primary fuel is the number of kilowatt-hours of standard electricity one can obtain from 1 kWhr of the primary fuel by an efficient process, the tradition of reporting the availability of fuels in BTUs per pound or kilocalories per gram mole notwithstanding. Any unit of energy can be converted to kilowatt-hours. This is an electricity-based transformity, the units of which are emergy units per kilowatt-hour.

Definition (Emergy). The embodied energy or emergy of a primary fuel is the Gibbs availability of the fuel in kilowatt-hours multiplied by the electricity-based transformity. The emergy of anything else is the sum of all the emergy that went into producing it by an efficient process minus the emergies of any by-products formed. The emergy of an activity is the average rate of expenditure of emergy times the time. These definitions are easily extended to include the dependence of emergy on location and time. The concept of *nemergy* or negative emergy can be introduced to aid in the discussion of environmental damage.

Definition (Emergy efficiency). *Emergy efficiency* of a manufacturing process is emergy *out* divided by emergy *in*. This efficiency is 1.0 for an optimal process because the emergy of the output is *defined* to be the emergy of the inputs. For a less than optimal process, the emergy efficiency is the emergy of the inputs to an optimal process over the emergy of the inputs to the process under investigation. Emergy efficiency lies between zero and one. A useful definition of emergy efficiency for the production or extraction of a fuel might be the emergy of the fuel plus the emergy of any byproducts divided by the emergy of all the inputs including the emergy supplied by nature. Clearly, the energy supplied by nature is not considered part of the energy-invested term, otherwise an EROI greater than would 1.0 could not be obtained. Thus this efficiency is necessary to completely evaluate the process under investigation.

The transformity of any fuel can be determined by using it to generate standard electricity by an efficient process. The most efficient process might be a fuel cell. Therefore, the emergy of any fuel is the Gibbs availability of the fuel multiplied by the electricity-based transformity.

Balance Equations. Sholto Maud suggested working out energy, availability, and emergy balance equations for simple extraction and conversion processes. Writing balance equations for extraction and Type 1 conversion helped me to understand what must be included in the definition of emergy and what may not be included without encountering inconsistencies. Many other people can improve their understandings by studying the balance equations discussed at http://www.dematerialism.net/Mark-II-Balance.html.

Extraction. An example of extraction is the production of petroleum from the well to the refinery. Extraction is discussed in http://www.dematerialism.net/Mark-II-EROI.html.

Type 1 Conversion. The first type of conversion is the production of primary energy from energy supplied by Nature for which we do not compensate Nature. This is a sustainable process provided the energy from Nature (natural energy) comes from a source that is continuously renewed by the Moon or by the Sun shining on the Earth. The input to such a process includes other types of energy, material goods, transportation, labor, taxes, etc. The output includes the principal product, one or more by-products, waste heat, and pollution. Normally, pollution is not considered; however, the concept of nemergy (negative emergy) should be employed to account for pollution of every type even, for example, the extent to which animals are deprived of habitat by the mere existence of the energy production facility. Examples of Type 1 conversion are the production of electricity by windpower and solar power. The emergy balance equation for a Type 1 process will be discussed next:

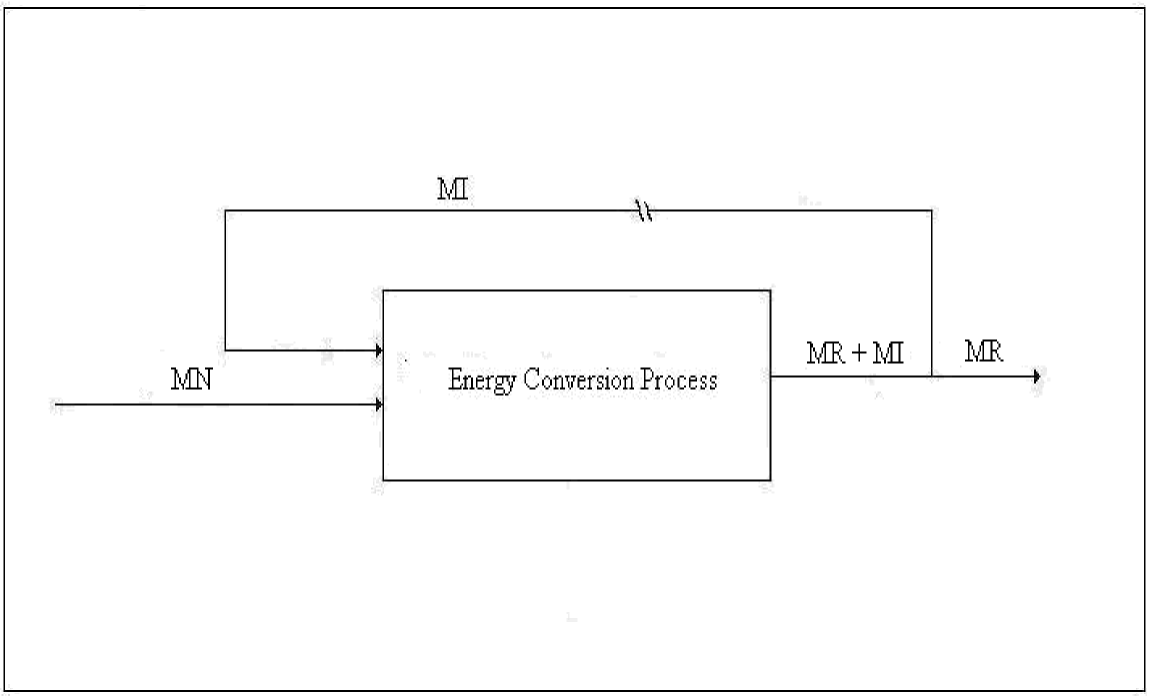

Figure 1. Emergy Balance for Type 1 Conversion

Let us define some symbols to be used in connection with Figure 1:

Table of symbols used in this discussion	
ER	Gibbs availability of fuel produced by process
λ_R	electricity-based transformity of fuel produced
MR	emergy of fuel produced by process = $\lambda_R \cdot$ ER
MI	the algebraic sum of all of the emergy inputs (except for MN) minus the by-products
EI	Gibbs availability of stream MI
μ	ratio of EN per unit mass to ER per unit mass
EN	Gibbs availability of energy from Nature = $\mu \cdot$ (ER + EI)
λ_N	the electricity-based transformity of the energy supplied by Nature
MN	emergy of energy from Nature = $\lambda_N \cdot$ EN
β	Energy returned over energy invested (EROI) = ER/EI = MR/MI
EP	the Gibbs availability of primary energy in Type 2 conversions
λ_P	the transformity of the primary energy source in Type 2 conversions
MP	the emergy of the primary energy supply in Type 2 conversions

Each of the input emergies, except the emergy supplied by Nature, is to be transformed into a product-equivalent emergy. Then, the emergy invested, MI, is imagined to have been produced by the same process that produced the fuel. In this way, it will be apparent immediately if the process consumes more emergy than it produces. All indirect energy expenses should be included in the MI term, in which case EROI is a good measure of the effectiveness of the process. (See http://www.dematerialism.net/Mark-II-EROI.html.) [An example of an indirect cost is the *pro-rata* share of the commuting costs of the tax consultant (A) that should be charged to the worker (B) who maintains a windpower installation because the man (C) who serves B lunch had his taxes done by A.]
Then, since

$$\mathrm{MN} = \lambda_N \cdot \mathrm{EN}, \quad \mathrm{EN} = \mu \cdot (\mathrm{ER} + \mathrm{EI}), \quad \mathrm{MR} = \lambda_R \cdot \mathrm{ER}, \quad \text{and} \quad \mathrm{EI} = \frac{1}{\beta} \cdot \mathrm{ER},$$

$$\lambda_N \cdot \mu \cdot \left(\mathrm{ER} + \frac{1}{\beta} \cdot \mathrm{ER} \right) = \lambda_R \cdot \mathrm{ER};$$

and,

$$\lambda_N = \frac{1}{\mu} \cdot \left(\frac{\beta}{\beta + 1} \right) \cdot \lambda_R . \qquad \text{Eq.1}$$

In the first approach, the transformity of the product is determined by the generation of standard electricity with a well-known efficient process and the transformity of the energy from Nature, whether it be from the tides, from biomass, from wind, from sunlight itself, or from some other natural source, is determined from the emergy balance. Normally, this transformity is well established. Therefore, two separate cases obtain:

Case 1. If λ_N, the value we compute, is greater than λ_{N*}, the accepted value of the transformity of the natural energy, then we should report that our process is part of a more efficient route to standard electricity, and λ_N should be considered for a new value of the transformity of the energy supplied by Nature.

Case 2. If λ_N is less than λ_{N*}, then our process is less efficient than the process that established the larger value and we must report an efficiency, η, for our process because we could have generated more emergy with the same quantity of natural energy if we had used the standard process. The reader should remember that the energy from Nature is "free", but the area of the solar collector or the size of the windmill is not.

$$\eta = \frac{MR}{MN} = \frac{\lambda_R \cdot ER}{\lambda_{N*} \cdot EN} = \frac{\lambda_N \cdot EN}{\lambda_{N*} \cdot EN} = \frac{\lambda_N}{\lambda_{N*}}. \qquad \text{Eq. 2}$$

In the second approach, the well-established value of the transformity of the energy supplied by Nature is accepted and the transformity of the product is computed from it. Call it $\lambda_{R'}$. If $\lambda_{R'}$ is less than λ_R, the true value, we should revert to Case 1 and recalculate the transformity of the natural energy. If $\lambda_{R'}$ is greater than λ_R, then the efficiency is λ_R over $\lambda_{R'}$. This is in agreement with Equation 2 above.

Let us imagine the process in the configuration illustrated by Figure 2.

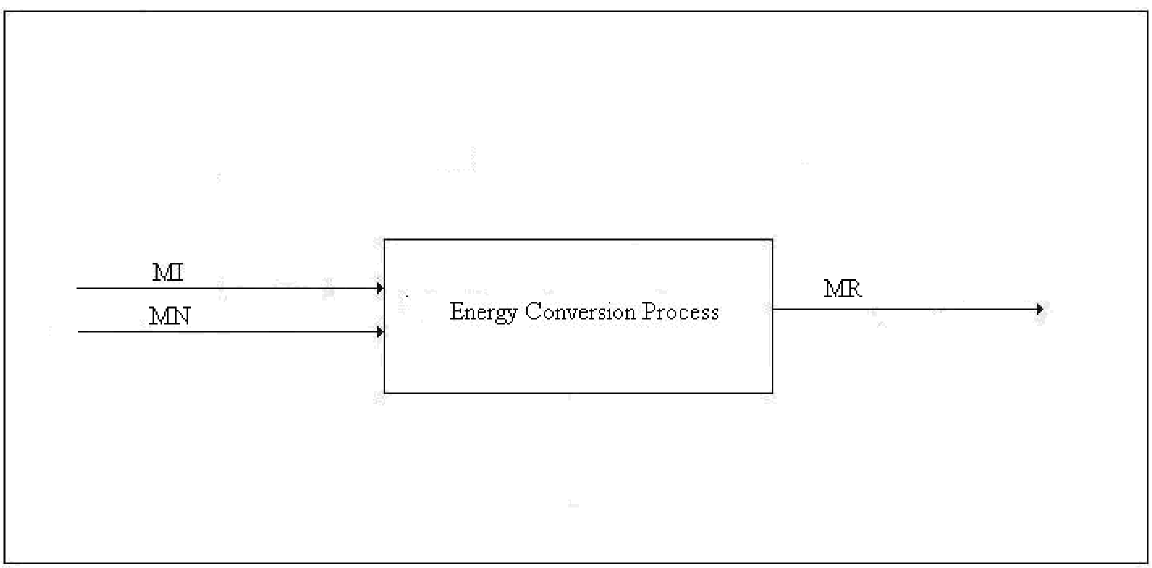

Figure 2. Alternative Diagram for Type 1 Conversion

If the algebraic sum of the emergy inputs to a process *minus the emergy supplied by Nature* exceeds the emergy of the product, that is, if MI > MR, then the process is wasting energy resources. This is the case for some alternative energy projects that seek venture capital, government subsidies, donations, or unwary buyers. If they were not subsidized by fossil fuel, they would not work.

Type 2 Conversion. The second type of conversion is the production of secondary energy from primary energy. The production of hydrogen from methane or from electrolysis of water is an example of Type 2 conversion. Figure 2 is the same as Figure 1 except that MP, the primary energy, is substituted for MN:

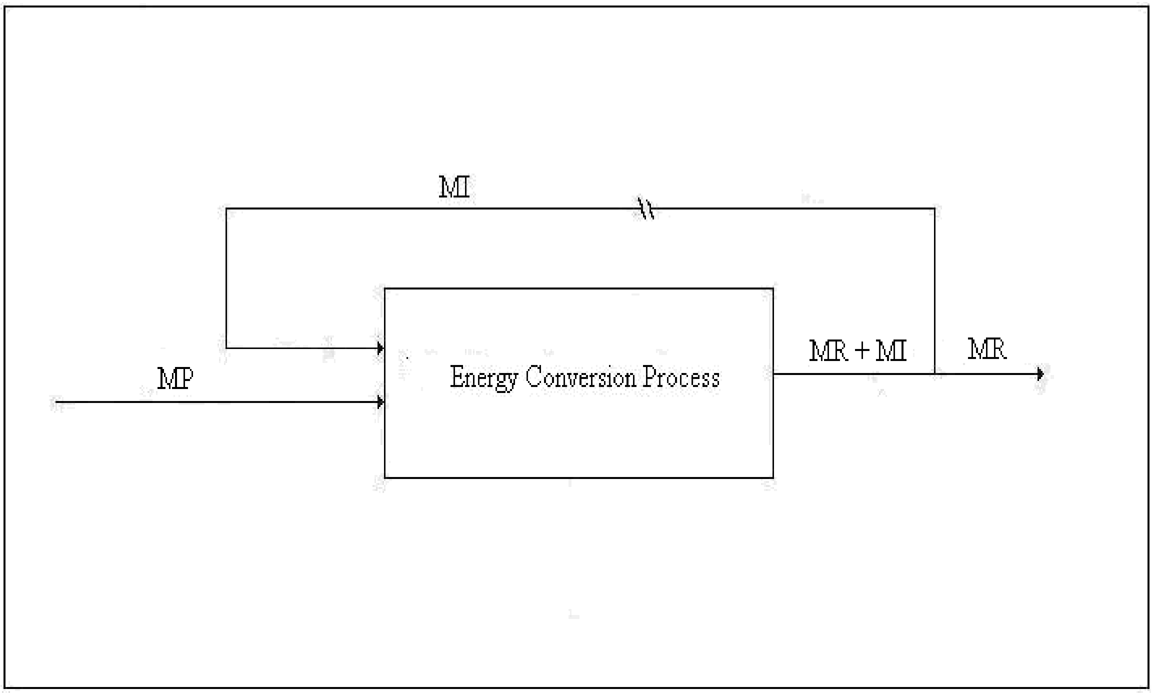

Figure 3. Emergy Balance for Type 2 Conversion

In the first approach, the transformity of the product is determined by the generation of standard electricity by a well-known efficient process and the transformity of the primary energy is computed from the emergy balance equation just as we did in the case of a Type 1 conversion, *mutatis mutandis*:

$$\lambda_P = \frac{1}{\mu} \cdot \left(\frac{\beta}{\beta + 1} \right) \cdot \lambda_R .$$

Case 1. If λ_P, the value we compute, is greater than λ_{P*}, the accepted value of the transformity of the primary energy, then we should report that our process is part of a more efficient route to standard electricity, and λ_P should be considered for a new value of the transformity of the primary energy.

Case 2. If λ_P is less than λ_{P*}, then our process is less efficient than the process that established the larger value and we must report an efficiency, η, for our process because we could have generated more emergy with the same quantity of primary energy if we had used the standard process.

$$\eta = \frac{MR}{MN} = \frac{\lambda_R \cdot ER}{\lambda_{P*} \cdot EN} = \frac{\lambda_P \cdot EN}{\lambda_{P*} \cdot EN} = \frac{\lambda_P}{\lambda_{P*}}. \qquad \text{Eq. 3}$$

In the second approach, the well-established value of the transformity of the primary energy is accepted and the transformity of the product is computed from it. Call it $\lambda_{R'}$. If $\lambda_{R'}$ is less than λ_R, the true value, we should revert to Case 1 and recalculate the transformity of the natural energy. If $\lambda_{R'}$ is greater than λ_R, then the efficiency is λ_R over $\lambda_{R'}$. This is in agreement with Equation 3 above. These results are worth deriving in a different way:

If a fuel the emergy of which is known is produced by the process under investigation and the sum of all of the emergy costs – both direct and indirect – that go into the process (computed with the true transformity λ_{P*}) minus the emergies of any useful by-products is greater than the algebraic sum of the emergy inputs for the process that determined the known emergy of the energy product, the process under investigation is sub-optimal and the efficiency, η, is

$$\eta = \frac{MP^*}{MP} = \frac{\lambda_R}{\lambda_{P*}} \cdot \frac{1}{\mu} \cdot \left(\frac{\beta}{\beta + 1} \right);$$

and, the transformity of the product we would compute from

$$\lambda_{R'} = \mu \cdot \left(\frac{\beta + 1}{\beta} \right) \cdot \lambda_{P*}$$

is higher than the true value λ_R. The only justification for the process is that we cannot do without the product and there is no other way to get it, which is *not* the case when electricity is used to produce hot water (discussed below) since hot water can be produced with less emergy by burning fuel under normal circumstances. Nevertheless, the process may be needed in extraordinary circumstances where the burning of fuel is prohibited, e. g., in a space capsule.

If the algebraic sum of the emergy inputs for the process under investigation is less than that of the older process, the transformity of the primary energy should be recalculated. It may not be expedient to discontinue production by the older process immediately because of compelling reasons not to shut down the older facilities – not the least of which is the time delay before new facilities can be built. The emergy efficiency of the older process is now less than 1.0.

Type 3 Conversion. The third type of conversion is the manufacture of non-energy goods. The manufacturing process has inputs of energy, material goods, transportation, labor, taxes, etc., and outputs that include a principal product, one or more by-products, and waste heat. This is best illustrated with a diagram such as Figure 4.

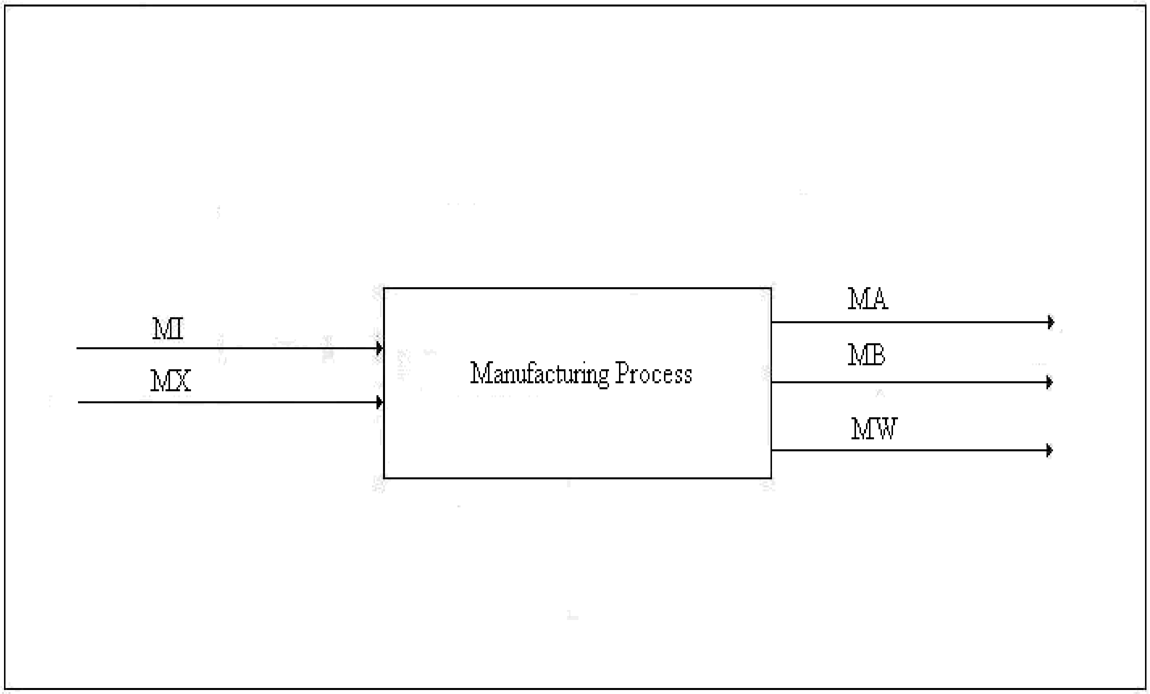

Figure 4. Emergy Balance for Manufacturing Process

Table of symbols for Figure 4	
MI	emergy of direct energy supplies
MX	emergy of inputs of material, transportation, labor, taxes, etc.
MA	emergy of principal product
MB	emergy of by-product
MW	emergy of waste heat stream

The emergy, MW, of the waste heat stream is its availability times the number of kilowatts of standard electricity that can be generated efficiently by one kilowatt-hour of waste heat. The emergy of the sum total of all direct energy inputs to the process is determined in the usual way. The emergy of the sum total of all non-energy inputs must be available from past studies or must be determined during the analysis. It may include contributions from pollution etc. in which case negative emergy in the output is added to the input. Unlike the case of energy production, the transformities of the inputs cannot be influenced by the

process. The emergy of the principal product and the by-product must equal the emergy of the inputs minus the emergy of the waste heat. In the case of a principal product as the sole output, the determination is trivial. However, when one or more by-products are present, the emergies of the by-products and the principal project must be apportioned in a canonical manner that should be determined by the analyst on a case-by-case basis.
If the emergy of a by-product is known in some other way, it may be appropriate to use the known value. In a case where the emergies must be distributed equitably, the relation between market price, either instantaneous or averaged over time, and energy or emergy may be useful. See "The Relation of Energy to Money". Thus, the emergy is apportioned according to market value. This is a singular intrusion of money into the physical realm of emergy analysis and may not be advisable. In a non-market economy, some combination of energy, labor, capital expenditures, product mass or heat of fusion (even) might be of use. In any case, the sum of the emergies of the products must close the emergy balance.
The consumer may find it expedient to compare the emergy of any given product with the emergy of a comparable product to minimize his impact upon the environment.
Note. The EROI defined in this essay is sometimes denoted EROI-1 because it is one less than the usual EROI which equals (MR + MI)/MI. The reader should realize that the terms Type 1, Type 2, and Type 3 Conversion have no currency outside of this paper.

Houston, Texas
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