Table 2.	Standard	Gibbs	Energy	and	Ethalpy	/ of
Formati	on					

		$\Delta G_{\rm f}^{01}$	$\Delta H_{\rm f}$
Compound name	Composition	(kJ/mol)	(kJ/mol)
Biomass	CH _{1.8} O _{0.5} N _{0.2}	-67	-91
Water	H ₂ O	-237.18	-286
Bicarbonate	HCO_3^-	-586.85	-692
CO_2 (g)	CO ₂	-394.359	-394.1
Ammonium	NH ₄ ⁺	-79.37	-133
Proton	H ⁺ .	-39.87	0
O_2 (g)	02	0	0
Oxalate ²⁻	$C_{2}O_{4}^{2-}$	-674.04	-824
Carbon monoxide	CO	-137.15	-111
Formate	CHO_2^-	-335	-410
Glyoxylate ⁻	$C_2O_3H^-$	-468.6	_
Tartrate ²⁻	$C_4 H_4 O_6^{2-}$	-1,010	_
Malonate ²⁻	$C_{3}H_{2}O_{4}^{2}$	-700	_
Fumarate ²⁻	$C_4 H_2 O_4^2 -$	-604.21	-777
Malate ²⁻	$C_{4}H_{4}O_{5}^{2}$	-845.08	-843
Citrate ³⁻	$C_{6}H_{5}O_{7}^{3}$	-1,168.34	-1,515
Pyruvate ⁻	$C_3H_3O_3^-$	-474.63	-596
Succinate ²⁻	$C_{4}H_{4}O_{4}^{2}$	-690.23	-909
Gluconate ⁻	$C_{6}H_{11}O_{7}^{-}$	-1,154	_
Formaldehyde	CH ₂ O	-130.54	_
Acetate	C ₂ H ₃ O ₂	-369.41	-486
Dihydroxyacetone	$\tilde{C_{3}H_{6}O_{3}}$	-445.18	_
Lactate	$C_{3}H_{5}O_{3}^{-}$	-517.18	-687
Glucose	$C_6H_{12}O_6$	-917.22	-1,264
Mannitol	$C_6 H_{14} O_6$	-942.61	
Glycerol	$C_3H_8O_3$	-488.52	-676
Propionate ⁻	C ₃ H ₅ O ₂₊	-361.08	_
Ethylene glycol	C ₂ H ₆ O ₂	-330.50	_
Acetoine	C₄H _s O _s	-280	_
Butyrate	$C_{4}H_{7}O_{2}^{-}$	-352.63	-535
Propanediol	$C_{3}H_{8}O_{2}$	-327	_
Butanediol	$C_4H_{10}\tilde{O_2}$	-322	_
Methanol	CH₄O	-175.39	-246
Ethanol	C ₂ H ₅ O	-181.75	-288
Propanol	$\tilde{C_3H_8O}$	-175.81	-331
<i>n</i> -Alkane	$C_{15}H_{32}$	+60	-439
Propane	C_3H_8	-24	-104
Ethane	C_2H_6	-32.89	-85
Methane	CH_4	-50.75	-75
H_2 (g)	H_2	0	0
N_2 (g)	N_2	0	0
Nitrite ion	NO_2^-	-37.2	-107
Nitrate ion	NO_3^-	-111.34	-173
Iron II	Fe^{2+}	-78.87	-87
Iron III	Fe ³⁻	-4.6	-4
Hydrogen sulfide (g)	H_2S	-33.56	-20
Sulfide ion	HS^{-}	+12.05	-17
Sulfate ion	SO_4^{2-}	-744.63	-909
Thiosulfate ion	$S_2O_3^{2-}$	-513.2	-608

Note: pH = 7, 1 atm, 1 mol/L, 298 K.

enthalpy, and the Gibbs energy balance). This means also that there must exist mathematical relations between $Y_{\rm DX}$, $Y_{\rm AX}$, $Y_{\rm CX}$, $Y_{\rm QX}$, and $Y_{\rm GX}$ (see Fig. 2b). These relations are addressed in a later section (see equations 9a–9e). It is obvious that this knowledge of the complete growth stoichiometry provides essential engineering information with respect to reactor design on the amount of O_2 that must be transferred (aeration capacity), the amount of carbon di-

oxide that must be removed (ventilation), the amount of heat to be removed (cooling capacity), or the amount of fermentation products (in anaerobic growth). The amounts of the required N source and HCO_3^- (autotrophic growth) also follow from these stoichiometric calculations.

MEASUREMENT OF GROWTH STOICHIOMETRY

As shown earlier, the measurement of one stoichiometric coefficient suffices, in general, to calculate all the other stoichiometric coefficients using the conservation relations. This measured stoichiometric coefficient requires the measurement of two conversion rates because, by definition, a stoichiometric coefficient is the ratio of two conversion rates. For example, $Y_{DX} = r_X / - r_D$. The most simple growth system contains eight conversion rates (biomass, N source, H⁺, H₂O, CO₂, electron donor, electron acceptor, heat production) and six conservation equations (C, H, O, N, enthalpy, charge). Measurement of two conversion rates is then sufficient to calculate all other rates and, hence, the complete growth stoichiometry. Currently, the most common measurements are biomass production and substrate (equal to electron donor) consumption. For aerobic growth the on-line measurement of O₂ consumption and CO₂ production by the analysis of O₂ and CO₂ in the off gas in air-sparged fermentors is becoming more and more routine. Especially for autotrophic growth, the online measurement of CO₂ consumption by off-gas analysis gives direct and highly accurate information on microbial growth (because all consumed CO₂ appears as biomass). This method was very successfully applied to study the growth stoichiometry and kinetics of solid pyrite oxidation by Fe²⁺-oxidizing bacteria (12,13) and of Methanobacterium thermoautotrophicum on H_2/CO_2 (14).

Most recently, it was also shown that on-line measurement of heat production during microbial growth can be used to explore growth stoichiometry and kinetics (15-17).

However, such a simple approach of measuring only two conversion rates often makes certain assumptions:

- Each chosen pair of measured conversion rates will allow the complete calculation of all other conversion rates.
- All measurements are reliable within a certain statistical error but without a systematic deviation.
- The assumed description of the growth system is correct, which means that by-products or additional substrates are assumed to be absent.

All these assumptions are subject to critical considerations, which are dealt with extensively in a recent series of publications (18–21). Here, simple examples are provided to illustrate the points of interest. The reader is referred to Refs. 18–21 for a more elaborate introduction, including the full mathematical and statistical aspects.

Noncalculability of Stoichiometry

Suppose that in Example 1a the chosen two conversion rates to be measured are biomass production (r_x) and

Degree of reduction per C-mole for inorganic compounds in \mathcal{AC}^0 \mathcal{AC}^0 \mathcal{AL}^0 binnass/N11' - N source + 4.2 + 33.840 - 26.1 Binnass/N2 - N source + 5.8 + 14.820 - 44.2 Binnass/N2 - N source + 5.8 + 14.820 - 44.2 Binnass/N2 - N source + 4.8 + 25.248 - 26.1 Ocalate 1 + 25.252 - 00 Oralate + 1 + 25.22 - 00 Formate + 2 + 48.289 Tartrate + 2.67 + 28.976 - Funarate + 3 + 33.354 - 22.20 Ofmate + 3.3 + 34.129 - 23.60 Succinate + 3.67 + 39.166 - Funarate + 3 + 32.282 - - Gluconate + 3.67 + 39.168 - - - Funarate + 4 + 45.322 - - - Cliconate + 3.67 + 39.168 -		γ		
for organic compounds in progranic compounds in (L/k-mol) (L/k-mol) (L/k-mol) biomass/N ₂ - N source + 4.2 + 33.840 - 26.11 Biomass/N ₂ - N source + 5.8 + 14.820 - 44.2 Biomass/N ₂ - N source + 4.8 + 32.948 - 26.12 Biomass/N ₂ - N source + 4.8 + 32.948 - 26.3 No core for growth 0 0 0 0 Colate + 1 + 52.522 - 20 - 20 Formate + 2 + 33.186 - 15.50 - 15.50 Glowylate + 2 + 33.531 - 32.22 - 23.22 Funarate + 2.67 - 28.975 Funarate + 3.3 + 33.642 - 64.65 Christe + 3 - 33.254 - 32.29 -33.69 Christe + 3 - 33.261 - 32.29 -33.69 Christe + 3 - 33.234 - 38.69 - 28.29 Christe + 3.67 - 28.205 0 -<		Degree of reduction per C-mole		
$\begin{tabular}{ c c c c } \hline between between$		for organic and per mole for		
Image in the points in the point of the point		inorganic compounds in	4001	1 LI ⁰
$\begin{array}{c c c c c } (2) Findly (c) Fi$		aloctrons/(C) molo	(k L/a mal)	(k I/o mol)
$\begin{array}{cccccccccccccccccccccccccccccccccccc$		electrons/(C)-mole	(KJ/E-11101)	(KJ/C-11101)
Biomass/No, - N source + 5.8 + 14.82042.2 N source for growth 0 0 0 0 Oxalatc + 1 + 22,252 - 20 formate + 2 + 39.186 - 15.50 Clyoxylate + 2 + 48.299 - Tartrate + 2.5 + 39.577 - Malonate + 2.67 + 28.976 - Fumarate + 3 + 33.642 - 31.60 Malate + 3 + 33.642 - 31.60 Malate + 3 + 33.54 + 22.82 Orbital + 4 + 4 + 26.86136.50 Orbital + 4 + 4 + 45.86131.50 Orbital + 4 + 4 + 45.86132.50 Dromate + 4 + 4 + 45.86131.50 Orbital + 4 + 4 + 45.86131.50 Orbital + 4 + 46.7 + 45.9393.8.60 Orbital + 4.83 + 38.777 - Orbital + 4.67 + 78.93933.80 Propanella + 5 + 42.825 - Dromate + 5.33 + 33.177 - Acetoin + 5 + 42.825 - Dromatedia + 5.50 + 31.374 - Nethanol + 6 + 30.032 - 23 Dropanella + 5.50 + 31.374 - Dropanella + 6.13 + 26.668 - Propanel Orbital + 6 + 30.032 - 23 Dropanella + 6 + 30.032 - 23 Dropan	biomass/NH ₄ ⁺ $-$ N source	+4.2	+33.840	-26.1
Biomass/N ₂ – N source + 4.8 + 42.948 -26.3 Nource for growth 0 0 0 0 Nexate for growth 1 + 52.522 -20 Formate + 2 + 48.259 - Tartrate + 2.5 + 39.577 - Tartrate + 2.67 + 28.976 - Fumarate + 3 + 33.354 -32.20 Malate + 3 + 33.354 -32.20 Chrate + 3 + 33.354 -22.360 Succinate + 3.67 + 38.01 -33.50 Succinate + 3.67 + 39.106 - - - - - - Gluconate + 4.4 + 45.368 -0.10 Cactate + 4 + 37.88 -28.50 Glucose + 4 + 33.33 + 38.177 - Cactate + 4 + 33.33 + 38.177 - Chromate + 5.33 + 37.292 - 4.30	$Biomass/NO_3 - N$ source	+5.8	+ 14.820	-44.2
N source for growth 0 0 0 Oxalate +1 +2522 -20 Oxalate +2 +39.186 -15.50 Glyoxylate +2 +48.29 Turtrate +2.67 +89.577 - Malonate +2.67 +89.578 Fumorate +3.3 +33.562 -31.60 Malate +3 +33.534 22.00 Ormate +3.33 +41.29 -23.60 Succinate +3.67 +99.106 - Cluconate +3.67 +99.106 - Cluconate +3.67 +99.106 - Cluconate +3.67 +99.106 - Cluconate +4 +45.526 0.10 Cluconate +4.7 +88.601 -33.30 Clactate +4 +45.33 +87.17 - Cluconate +4.67 +7.89.99 -38.30 Cluconate +5.33 +37.292	$Biomass/N_2 - N$ source	+4.8	+32.948	-26.3
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	N source for growth	0	0	0
$\begin{array}{llllllllllllllllllllllllllllllllllll$	HCO ₃	0	0	0
Formate+2+38-15.50Glogoyate+2+48.229-Tartrate+2.5+39.577-Fumarate+2.67+28.976-Fumarate+3+33.662-31.60Clarate+3+33.534-32.20Clarate+3+32.282-33.90Succinate+3.63+43.129-23.60Gluconate+3.67+38.106-Formaldelyde+4+45.326-0.10Acetate+4+45.326-0.10Acetate+4+3.47-32.59Gluconate+4.67+3.744-22.57Glucose+4+3.488.77-Glucose+4.67+3.745-24.30Glucose+4.67+3.625-24.30Charler glycol+5.5+37.000-33.30Ethylen glycol+5.53+27.000-33.30Ethylen glycol+5.53+27.000-33.30Ethyland+6+30.632-28.90Propaneto+6.66+33.33-28.90Propaneto+5.33+28.144-30.90Mathanol+6+30.632-28.90Propaneto+6.66+30.632-28.90Propaneto+6.66+25.948-31.90CO+2+4.477-1.55Sol+2.1337-28.90-0Sol+3.33+28.90-0Sol+2.9384-31.90-0Co+2+4.477-1.55 <tr< td=""><td>Oxalate</td><td>+1</td><td>+52.522</td><td>-20</td></tr<>	Oxalate	+1	+52.522	-20
Clyosylate+ 2+ 42+ 4282-Malonate+ 2.67+ 28.976-Fumarate+ 3+ 33.662- 31.60Malate+ 3+ 33.354- 32.20Chrate+ 3+ 33.354- 32.20Chrate+ 3+ 32.82- 33.90Succinate+ 3.60+ 28.405- 38.50Gluconate+ 3.67+ 39.106-Formaldehyde+ 4+ 45.326-0.10Acetate+ 4+ 45.326-0.10Cluose+ 4+ 45.326-28.50Cluose+ 4+ 39.744- 25.75Mamitol+ 4.33+ 38.777-Clyocrol+ 4.67+ 28.939- 33.80Ethylene glycol+ 5.5+ 37.625- 24.30Propinate+ 4.67+ 28.939- 33.80Ethylene glycol+ 5.5+ 37.625- 24.50Propinate+ 4.67+ 28.939- 33.80Ethylene glycol+ 5.53+ 32.625- 31.50Retoin+ 5.53+ 27.000- 33.30Propanediol+ 5.53+ 28.90- 33.50Propanediol+ 5.53+ 28.625- 31.50CO+ 2+ 4.477- 28.90Propanediol+ 5.53+ 28.625- 31.50CO+ 2+ 4.677- 28.90- 28.90Propanediol+ 6.613+ 28.625- 31.50CO+ 2+ 4.677- 28.90- 28.90CO- 7+ 28.625- 31.50<	Formate	+2	+39.186	-15.50
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	Glyoxylate	+2	+48.229	_
Malonate $+ 2.67$ $+ 2.876$ $-$ Fumarate $-$ Fumarate $- 3.3362$ $- 31.60$ Malate $+ 3$ $+ 33.362$ $- 31.60$ Citrate $+ 3$ $+ 32.282$ $- 33.90$ Pyruvate $+ 3.33$ $+ 34.129$ $- 23.60$ Succinate $+ 3.67$ $+ 39.106$ $-$ Formaldohyde $+ 4$ $+ 45.326$ $- 0.10$ Acetate $+ 4$ $+ 45.326$ $- 0.10$ Acetate $+ 4$ $+ 39.714$ $- 28.90$ Glucose $+ 4$ $+ 39.714$ $- 28.90$ Glucose $+ 4$ $+ 39.744$ $- 28.90$ Glucose $+ 4.67$ $+ 37.625$ $- 24.30$ Propionate $+ 4.67$ $+ 37.625$ $- 24.30$ Enlylone glycol $+ 5.5$ $+ 22.625$ $-$ Butyrate $+ 5.5$ $+ 32.625$ $-$ Butyrate $+ 5.5$ $+ 32.625$ $-$ Butyrate $+ 5.33$ $+ 38.718$ $- 30.90$ Propaneliol $+ 5.33$ $+ 38.718$ $- 30.90$ Butanedio $+ 6.66$ $+ 36.032$ $- 23.30$ Propaneliol $+ 6.66$ $+ 29.144$ $- 32.50$ Aceton $+ 6.66$ $+ 29.144$ $- 32.80$ Propaneliol $+ 6.66$ $+ 29.144$ $- 32.80$ Propaneliol $+ 6.66$ $+ 29.148$ $- 31.90$ CO $+ 2$ $+ 37.77$ $- 27.5$ Propanel $+ 6.66$ $+ 29.148$ $- 31.30$ CO $+ 2$ $+ 37.77$ $- 27.5$ Na ¹ Co	Tartrate	+2.5	+39.577	_
Fumarate+ 3+ 33 + 33 662- 31.60Malate+ 3+ 33.362- 32.20Cltrate+ 3+ 32.22- 33.80Pyruvate+ 3.33+ 42.222- 33.80Succinate+ 3.33+ 84.129- 22.60Succinate+ 3.87+ 39.106-Formaldehyde+ 4+ 45.326- 0.10Acetate+ 4+ 45.326- 0.10Acetate+ 4+ 31.488- 28.80Gluconate+ 4.47+ 39.744- 22.575Mannitol+ 4.67+ 37.625- 24.30Glycorol+ 4.67+ 37.625- 24.30Propionate+ 4.67+ 37.625- 24.30Propionate+ 5.53+ 37.292Acetoin+ 5+ 37.292Acetoin+ 5+ 37.292Acetoin+ 5.53+ 37.00- 33.80Butyrate+ 5+ 37.292Acetoin+ 5.53+ 37.202Acetoin+ 5.53+ 37.202Butyrate+ 5+ 37.292Butyrate+ 5+ 37.292Butyrate+ 5+ 37.292Acetoin+ 5.53+ 37.202Butyrate+ 5+ 37.292Butyrate+ 5+ 37.292Butyrate+ 5.33+ 28.755Butyrate+ 5.33+ 28.756Butyrate+ 5.33+ 28.718	Malonate	+2.67	+28.976	_
Malate+3+33+33-32.20Cltrate+3+33+34.129-23.60Cltrate+3.33+34.129-23.60Succinate+3.50+28.405-38.50Gluconate+3.67+39.106-Formaldehyde+4+45.326-0.10Acetate+4+26.801-33.50Lactate+4+31.488-28.90Glucose+4+33.744-25.75Mannitol+4.33+38.777-Glycerol+4.677+26.939-33.80Ethylene glycol+5+37.292-Acetoin+5+32.625-Butyrate+5+32.625-Ropopanetiol+5.53+33.177-Acetoin+5.50+31.374-Acetoin+66+30.353-28.90Butanediol+5.50+31.374-Arbane+66+25.948-31.90Buthanol+66+25.948-31.90Ethanol+7+25.694-Propanetic+8+22.925-31.50CO+2+47.477-1.5Methane+8+22.936-31.40Methane+8+22.936-31.40Methane+8+22.935-31.40Methane+7+25.946-SQ3"+2+47.477-1.5Mane+7+25.946-NoT000OQ00<	Fumarate	+3	+33.662	-31.60
Citrate+3+32.282-33.90Pyruvate+3.33+34.129-23.60Succinate+3.50+28.405-36.30Gluconate+3.67+39.106-Formaldehyde+4+45.326-0.10Acetate+4+43.326-0.28.90Lactate+4+31.488-28.80Lactate+4+33.744-25.75Mannitol+4.33+38.777-Ciycerol+4.67+37.625-24.30Propionate+4.67+37.625-24.30Propionate+5.5+37.292-Acetoin+5+37.292-Acetoin+5.5+32.625-Butyrate+5+37.625-Proponatiol+5.33+33.177-Acetoin+5.53+31.374-Methanol+6+30.353-28.90Propanediol+6.13+26.694-Propaned+6.66+25.948-31.90Propane+6.66+25.948-31.90CO+2+47.477-1.5SQ ² -0000SQ ² 000SQ ² -+2+38.70-05SQ ² -+2+47.477-1.5Sylo+4.81+25.544-21.50Nop-000SQ ² -+2+47.477-1.5Sylo+4.81+25.544-21.50Nop-0 <td>Malate</td> <td>+3</td> <td>+33354</td> <td>-32.20</td>	Malate	+3	+33354	-32.20
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	Citrate	+ 3	+32.282	- 33 90
$\begin{array}{cccc} 1 & 1 & 2 & 1 & 2 & 1 & 2 & 1 & 2 & 1 & 2 & 2$	Pyriyate	+ 3 33	+34.129	- 23 60
Jatulate $+ 3.67$ $+ 25.400$ $- 40.50$ Formaldehyde $+ 4$ $+ 25.75$ Formaldehyde $+ 4$ $+ 45.326$ $- 0.10$ Acetate $+ 4$ $+ 25.801$ $- 33.50$ Lactate $+ 4$ $+ 31.488$ $- 28.90$ Glucose $+ 4$ $+ 39.744$ $- 25.75$ Mannitol $+ 4.33$ $+ 38.777$ $-$ Glycerol $+ 4.67$ $+ 26.939$ $- 33.80$ Ethylene glycol $+ 5$ $+ 37.625$ $- 24.30$ Ethylene glycol $+ 5$ $+ 37.292$ $-$ Acetoin $+ 5$ $+ 37.292$ $-$ Butyrate $+ 5$ $+ 27.000$ $- 33.30$ Propanediol $+ 5.33$ $+ 28.718$ $- 30.90$ Butanediol $+ 5.50$ $+ 31.374$ $-$ Methanol $+ 6$ $+ 30.353$ $- 28.90$ Propanediol $+ 6.13$ $+ 26.694$ $-$ Propane $+ 6.666$ $+ 25.948$ $- 31.40$ Methane $+ 7$ $+ 25.404$ $- 31.40$ Methane $+ 7$ $+ 25.404$ $- 31.40$ Methane $+ 8$ $+ 22.925$ $- 31.60$ CO $+ 2$ $+ 30.870$ 0So ² ₁ 0 0 0 So ² ₂ $+ 2$ $+ 30.870$ $-$ Sylas $+ 6.13$ $+ 26.944$ $- 75.540$ CO $+ 2$ $+ 30.870$ $-$ CO $+ 2$ $+ 30.870$ $-$ So ² ₁ 0 0 0 0 So ² ₂	Succinate	+ 3.55	+ 34.123	- 23.00
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	Chaopata	+ 3.50	+ 20,100	- 30.30
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	Giuconale	+ 3.07	+ 39.106	
Acting+4+20.801 -33.30 Catcate+4+31.488 -228.00 Glucose+4+39.744 -225.75 Mannitol+4.33+38.777Glycerol+4.67+37.625 -24.30 Propionate+4.67+37.625-24.30Propionate+4.67+37.625-24.30Propionate+5.5+37.292Acetoin+5+37.292Acetoin+5+37.292Acetoin+5+37.292Acetoin+5+37.292Acetoin+5+37.292Acetoin+5+37.292Acetoin+5+37.292Butyrate+5+37.292Butyrate+5+37.292Store+5+37.292Methanol+6+30.353-28.90Propanediol+5.33+28.718-30.90Butanediol+5.50+31.374Propane+6+29.144-32.50 <i>n</i> Akane+6+30.353-28.90 <i>n</i> Propane+6.66+25.9481 <i>n</i> Propane+6.66+25.948-31.90CO+2+47.477-1.5H ₂ +2+39.8700SO ² -+2+39.870O000SO ² +2+47.477-1.55H ₂ +2+39.870 <t< td=""><td>Formaldenyde</td><td>+4</td><td>+ 45.326</td><td>-0.10</td></t<>	Formaldenyde	+4	+ 45.326	-0.10
Lactate+4+31.488-28.90Glucose+4+39.744-25.75Mannitol+4.33+38.777Glycerol+4.67+37.625-24.30Propionate+4.67+26.939-33.80Ethylene glycol+5+37.292Acetoin+5+37.292Butyrate+5+37.292Butyrate+5+37.292Butyrate+5+27.000-33.30Propanediol+5.33+33.177Acetone+5.33+28.718-30.90Butanediol+6+30.353-28.90Propanol+6+30.353-28.90Propanol+6+29.144-32.50Propanol+6.666+25.948-31.90Ethanol+6+25.948-31.90Ethane+7+25.404-31.40CO+2+47.477-1.5H2+2.925-31.500CO+2+39.8700S02^-+2+47.477-1.5H2+2.0850S02^-+2+5.264-27.5S02^-+2+30.754-124.55NOTS02^-+2+47.477-1.5H2+30.805-43.900S02^-+2+47.477-1.6N020000N02^-0000N0200 </td <td>Acetate</td> <td>+4</td> <td>+ 26.801</td> <td>- 33.50</td>	Acetate	+4	+ 26.801	- 33.50
Glucose+4+39,/44-23,73Mannitol+4.33+38,777-Glycerol+4.67+37,625-24.30Propinente+4.67+20.939-33.80Propinente+5+37,292-Acetoin+5+32,625-Butyrate+5+27,000-33.30Propanediol+5.33+33.177-Acetone+5.33+28,718-30.90Butanediol+6+36.032-23Ethanol+6+30.353-28.90Propanediol+6+29.144-32.50 <i>Propanel</i> +6.66+29.144-32.50 <i>Propanel</i> +6.66+25.948-31.40Methane+7+25.404-31.40Methane+8+22.925-31.50CO+2+47.477-1.5Methane+8+22.925-31.50CO+2+39.8700S0 $_7^{-1}$ 000S0 $_7^{-1}$ +2+39.8700S0 $_7^{-1}$ +2+39.8700S0 $_7^{-1}$ +2+39.8700S0 $_7^{-1}$ 000NO $_7$ +2-41.650-108.5NO $_7$ +2-41.650-108.5NO $_7$ +2-41.650-108.5NO $_7$ +2-41.650-108.5NO $_7$ +2-41.650-108.5NO $_7$ +2-41.650-108.5NO $_7$ +4-75.7540 <td>Lactate</td> <td>+4</td> <td>+31.488</td> <td>- 28.90</td>	Lactate	+4	+31.488	- 28.90
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	Glucose	+4	+39.744	-25.75
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	Mannitol	+4.33	+38.777	
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	Glycerol	+4.67	+37.625	-24.30
Ethylene glycol +5 +37.292 - Acetoin +5 +32.625 Butyrate +5 +27.000 -33.30 Propanediol +5.33 +33.177 Acetome +5.33 +28.718 -30.90 Butanediol +5.50 +31.374 Methanol +6 +30.353 -28.90 Propanol +6 +29.144 -32.50 <i>p</i> -Rakane +6.13 +26.694 Propanol +6 +25.948 -31.90 Ethanol +7 +25.404 -31.40 Methane +7 +25.404 -1.51 Propane +6.66 +22.925 -31.50 CO +2 +47.477 -1.5 H_2 +2 +30.870 0 SQ ² - 0 0 0 0 SQ ² - - 1.50 -55.2 -55.2 SQ ² - +8 +20.850 -43.9 NO ₃ 0 0 0 0 <t< td=""><td>Propionate</td><td>+4.67</td><td>+26.939</td><td>-33.80</td></t<>	Propionate	+4.67	+26.939	-33.80
Acetoin $+5$ $+22.625$ $-$ Butyrate $+5$ $+27.000$ -33.30 Propanediol $+5.33$ $+28.718$ -30.90 Butanediol $+5.33$ $+28.718$ -30.90 Butanediol $+5.50$ $+31.374$ $-$ Methanol $+6$ $+38.032$ -23 Ethanol $+6$ $+30.353$ -28.90 Propanel $+6.13$ $+26.694$ $-$ Propanel $+6.66$ $+25.948$ -31.90 Ethane $+7$ $+25.404$ -31.40 Methane $+8$ $+22.925$ -31.50 CO $+2$ $+47.477$ -1.5 H_2 $+2.925$ -31.50 CO $+2$ $+39.870$ 0 S0 3^{-7} $+2$ $+39.870$ 0 S0 3^{-7} $+2$ $+30.296$ $-$ S0 3^{-7} $+2$ $+50.296$ $-$ S0 3^{-7} $+2$ $+50.296$ $-$ S0 3^{-7} $+8$ $+20.850$ -43.9 NO 3^{-7} $+2$ -41.650 -108.5 NO 3^{-7} $+8$ $+20.850$ -43.9 NO 3^{-7} $+2$ -41.650 -108.5 NO 3^{-7} $+2$ -41.650 -108.5 NO 3^{-7} $+8$ -57.540 -124.55 NH 4^{-7} $+10$ -72.194 -136.4 Fe ³⁺ 0 0 0 0 N 2 $+10$ -74.270 -46.8 H $2O$ 0 0 0 0 O	Ethylene glycol	+5	+37.292	—
Butyrate $+5$ $+27.000$ -33.30 Propanediol $+5.33$ $+33.177$ $-$ Acetone $+5.33$ $+28.718$ -30.90 Butanediol $+5.50$ $+31.374$ $-$ Methanol $+6$ $+36.032$ -23 Ethanol $+6$ $+30.353$ -28.90 Propanel $+6$ $+29.144$ -32.50 n -Alkane $+6.13$ $+26.694$ $-$ Propanel $+6.666$ $+25.948$ -31.90 Ethane $+7$ $+25.404$ -31.40 Methane $+8$ $+22.925$ -31.50 CO $+2$ $+47.477$ -1.5 CO $+2$ $+39.870$ 0SO $_4^{}$ 000SO $_4^{}$ 000SO $_4^{}$ -8 $+22.925$ -31.50 CO $+2$ $+47.477$ -1.5 Main -7 $+25.404$ -31.40 Methane $+8$ $+20.926$ -7 So $_4^{}$ 000SO $_4^{}$ 0 00SO $_4^{}$ -7 -74.576 -74.576 Nor -8 $+20.850$ -43.9 Nor 0 0 0 0 Nor -74.650 -108.5 -108.5 No(g) $+8$ -57.540 -124.55 No(g) $+8$ -57.540 -124.55 Na -74.270 -46.8 $+74.270$ -46.8 Na -57.90 -74.270 $-$	Acetoin	+5	+32.625	_
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	Butyrate	+5	+27.000	-33.30
$\begin{array}{llllllllllllllllllllllllllllllllllll$	Propanediol	+5.33	+33.177	—
Butanediol $+5.50$ $+31.374$ $-$ Methanol $+6$ $+36.032$ -23 Ethanol $+6$ $+30.353$ -28.90 Propanol $+6$ $+29.144$ -32.50 n -Alkane $+6.13$ $+26.694$ $-$ Propane $+6.666$ $+25.948$ -31.90 Ethane $+7$ $+25.404$ -31.40 Methane $+8$ $+22.925$ -31.50 CO $+2$ $+47.477$ -1.5 H_2 $+22$ $+47.477$ -1.5 V_2 $+22$ $+39.870$ 0 SO $_4^2^ 0$ 0 0 SO $_4^2^ 0$ 0 0 SO $_4^2^ +2$ $+50.296$ $-$ SV $_5^2^ +8$ $+23.584$ -27.5 HS^- $+8$ $+23.584$ -27.5 HS^- $+8$ $+20.850$ -43.9 NO $_5^ +2$ -41.650 -108.5 NO(g) $+3$ -96.701 $-$ Nu (g) $+3$ -57.540 -124.55 NH $_4^+$ $+8$ -35.109 -101.9 Nu $_2$ $+10$ -72.194 -136.4 Fe ³⁺ 0 0 0 Nu $_2$ $+10$ -74.270 -46.8 H $_2O$ 0 0 0 <	Acetone	+5.33	+28.718	-30.90
$\begin{array}{llllllllllllllllllllllllllllllllllll$	Butanediol	+5.50	+31.374	_
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	Methanol	+6	+36.032	-23
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	Ethanol	+6	+30.353	-28.90
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	Propanol	+6	+29.144	-32.50
$\begin{array}{llllllllllllllllllllllllllllllllllll$	<i>n</i> -Alkane	+6.13	+26.694	_
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	Propane	+6.66	+25.948	-31.90
Methane $+ 8$ $+ 22.925$ $- 31.50$ CO $+ 2$ $+ 47.477$ $- 1.5$ H_2 $+ 2$ $+ 39.870$ 0 $SO_4^2^ 0$ 0 0 $SO_4^2^ + 22$ $+ 50.296$ $ S^0$ $+ 6$ $+ 19.146$ $- 55.2$ $S_2O_3^2^ + 8$ $+ 23.584$ $- 27.5$ $HS^ + 8$ $+ 20.850$ $- 43.9$ $NO_3^ 0$ 0 0 $NO_2^ + 2$ $- 41.650$ $- 108.5$ $NO(g)$ $+ 3$ $- 96.701$ $ N_2O(g)$ $+ 8$ $- 57.540$ $- 124.55$ NH_4^+ $+ 8$ $- 35.109$ $- 101.9$ N_2 $+ 10$ $- 72.194$ $- 136.4$ N_2 $+ 10$ 0 0 Pe^{2+} $+ 1$ $- 74.270$ $- 46.8$ H_2O 0 0 0 0 O_2 -4 $- 78.719$ $- 143$	Ethane	+7	+25.404	-31.40
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	Methane	+8	+22.925	-31.50
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	СО	+2	+47.477	-1.5
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	Ha	+2	+39.870	0
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	SO ² -	0	0	ů 0
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	SO_4^2	+2	+ 50 296	_
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	S ⁰	+ 6	+19146	- 55 2
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	$S_{-}\Omega^{2-}$	+ 8	+23584	_ 27 5
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	HS-	+ 8	+ 20 850	_/3 9
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	NO ⁻	0	0	40.0
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	NO ⁻		41 650	109.5
$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	NO_2	+2		-108.5
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	NO(g)	+3	- 90.701	104 55
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	$N_2 O(g)$	+8	- 57.540	- 124.33
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	NT4	+ð	- 35.109	- 101.9
res000 Fe^{2+} +1 -74.270 -46.8 H_2O 000 O_2 -4 -78.719 -143	IN2	+10	- /2.194	- 136.4
Fe^{-T} +1-74.270-46.8 H_2O 000 O_2 -4-78.719-143	Fe	U	0	0
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	Fe ² ⁺	+1	-74.270	-46.8
O_2 -4 -78.719 -143	H ₂ O	0	0	0
	U ₂	-4	-78.719	-143

Table 3. Calculated γ , ΔG_{e}^{01} , and ΔH_{e}^{0} Values for Chemical Compounds under Standard Conditions

Note: pH = 7, 1 mol/L, 1 atm, 298 K.

ENERGY AND LIFE

Table 2.2	Typical values	for daily energy	expenditure in humans
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		/ monol/ emperiance in numaris		
Activity	Time (min)	Energy cost (kJ min ⁻¹)	Total energy expenditure (kJ)	
lying	540	5.0	2700	
sitting	600	5.9	3540	
standing	150	8.0	1200	
walking	150	13.4	2010	
TOTAL	1400	-	9450	

The values were recalculated from measurements derived by indirect calorimetry of students by Haslam and Banner (1991, *Biochem. Soc. Trans.* **19**, 433S). A value of around 10 000 kJ is usually taken to be the daily energy requirement for humans, of which 6000 kJ will be the contribution by the basal metabolic rate. The calorific equivalent of the daily energy requirement will be 2400 kcal. (Note that the latter units are kilocalories not calories. How many times have you seen a diet in the press recommending daily requirements in calories, with a small 'c'? The dieter would soon starve to death.)

and can be up to a third higher in growing young children. The basal metabolic rate is also higher, by around 10%, than the sleeping metabolic rate because of the additional energy expenditure of wakefulness.

2.2.1 Energy expenditure and size

Many attempts have been made to relate the basal metabolic rate to body size. For aerobic organisms the relationship seems to be proportional to body mass raised to the power 0.75:

basal metabolic rate = $a \cdot M^{0.75}$

The constant of proportionality a varies with phylum and even class, although little change is seen in the value of the exponent. For example, the basal metabolic rates for mammals are higher than for cold-blooded vertebrates such as reptiles when compared at the same body mass, but the slopes of the lines relating metabolic rate with mass are similar (see Figure 2.1). Even the metabolic rates for trees and microorganisms fall on lines with similar slopes but with different values of a. The results suggest some common mechanism to explain the rate-mass relationship.

The separate contributions of different metabolic reactions to steady-state heat production are not yet known. Brand (1990) has proposed that mitochondrial activity is important to the basal metabolic rate in aerobic organisms. He has related the total mitochondrial inner membrane area to the



basal metabolic rate over a wide range of body masses in both warm and cold blooded animals. Mitochondria conserve the energy of oxidation of metabolites such as pyruvate by the creation of a gradient of protons across the inner mitochondrial membrane. The gradient can then be used to catalyse the movement of other ions across the membrane and also for the synthesis of ATP (see Chapter 7). The free energy stored in the gradient can be lost if the protons simply leak back across the inner membrane. Brand suggests that a significant contribution to heat production by mitochondria is the leak of protons across the mitochondrial inner membrane. In fact, the total number of liver mitochondria in mammals has been shown to be proportional to $M^{0.72}$. As might be expected from this argument, anaerobic organisms have a relationship more directly proportional to body mass.

The ability to store food (for example carbohydrate or triglyceride) is generally proportional to the mass, M, of an organism. Since energy expenditure relates to $M^{0.75}$, problems of size can arise. A large animal such as a camel has plenty of body size to store food for its energy needs. As size decreases, the difference between the two mass functions, food storage and energy expenditure, converges (Figure 2.2). A mouse has relatively smaller energy stores to meet