

## Modelvorming van productiesystemen

**Citation for published version (APA):**

Splinter, M. A. M. (1993). *Modelvorming van productiesystemen*. Technische Universiteit Eindhoven.

**Document status and date:**

Gepubliceerd: 01/01/1993

**Document Version:**

Uitgevers PDF, ook bekend als Version of Record

**Please check the document version of this publication:**

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
- The final author version and the galley proof are versions of the publication after peer review.
- The final published version features the final layout of the paper including the volume, issue and page numbers.

[Link to publication](#)

**General rights**

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license above, please follow below link for the End User Agreement:

[www.tue.nl/taverne](http://www.tue.nl/taverne)

**Take down policy**

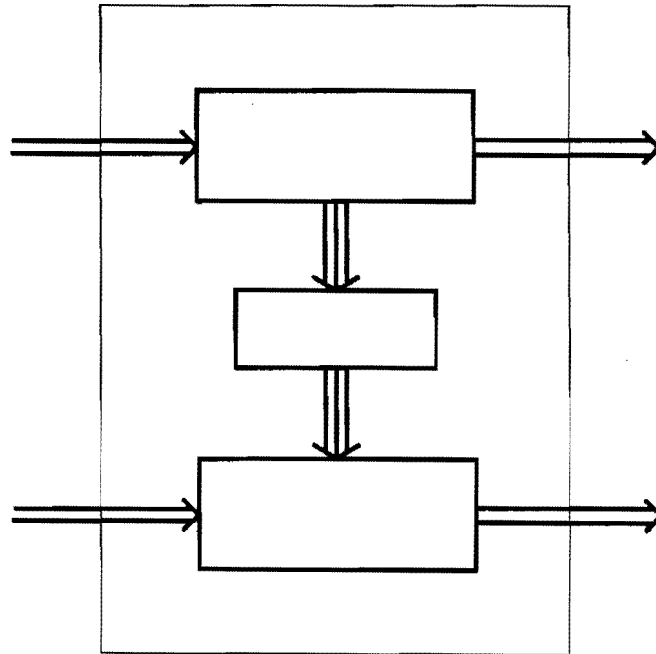
If you believe that this document breaches copyright please contact us at:

[openaccess@tue.nl](mailto:openaccess@tue.nl)

providing details and we will investigate your claim.

# FABRICAGETECHNOLOGIE - Deel C.

## MODELFORMING van PRODUCTIESYSTEMEN



## Inhoudsopgave

INLEIDING	Modelvorming van Productiesystemen
HOOFDSTUK 1	Grondbeginselen van produktiesystemen
	1.1. Het begrip produktie
	1.2. Het energiebegrip
	1.3. Het procesmodel
	1.4. Het systeemmodel
	1.5. Basismodel van een produktiesysteem
	1.6. Produktiefunkties
	1.7. De structuur van produktiesystemen
HOOFDSTUK 2	Heat Exchangers
HOOFDSTUK 3	Fundamentals of Materials Balances
HOOFDSTUK 4	Energy and Energy Balances
HOOFDSTUK 5	Resources, Production, Consumption and Pollution
LITERATUUR	
BIJLAGE 1	Eenheden en Omzettingsfactoren

## INLEIDING

### Modelvorming van Productiesystemen

In dit gedeelte van het college Fabricagetechnologie (FT-C) wordt ingegaan op een drietal manieren van modelvorming van productiesystemen:

1. Een fysisch/technische benadering waarbij het energiebegrip centraal staat en dat leidt tot het opstellen van een procesmodel. Op basis van dit procesmodel kan een massa- en energiebalans worden opgesteld.
2. Een economische benadering op basis van een produktiefunctie.
3. Een milieukundige benadering waarbij de aandacht wordt gelegd op de totale keten van processen die nodig is voor de productie en consumptie van een produkt of dienst.

Bovenstaande benaderingswijzen worden in het dictaat beschreven.

Op het hoorcollege wordt, naast de in het dictaat beschreven stof, vooral ingegaan op de onderlinge verbanden tussen de drie modelbenaderingen en voorbeelden daarvan gegeven.

Een model wordt daarbij gezien als een zodanige beschrijving van een systeem dat er een beter inzicht ontstaat in de problemen die ontstaan ten gevolge van het functioneren van zo'n systeem.

In dit college zal met name vanuit de energie- en milieuproblematiek worden ingegaan op de modelvorming van productiesystemen. Daartoe wordt in het eerste hoofdstuk een basismodel van een productiesysteem ontwikkeld en wordt ingegaan op de produktiefunctie van Georgescu-Roegen.

Daarna volgt een verhandeling over de warmtewisselaar als een elementair, klassiek voorbeeld van een productiesysteem. Alvorens het dictaat af te sluiten met een algemene beschouwing over productie en consumptie, volgen eerst nog inleidingen over de materiaal- en energiebalans van een productiesysteem.

Grondbeginselen van Productiesystemen

1.1. Het begrip produktie.

Gewoonlijk wordt het begrip produktie omschreven in termen als: voortbrenging, vervaardiging of het maken van iets nieuws. Bij een iets verdergaande beschouwing wordt duidelijk dat een dergelijke omschrijving nauwelijks enig inzicht geeft. Toch is zo'n inzicht van belang omdat het hier gaat om een van de meest essentiële karakteristieken van de menselijke beschaving.

Een van de belangrijkste uitgangspunten in het werk van Karl Marx is zijn gelijkstelling van "mens-zijn" met produceren. Hij zegt dat mensen beginnen "sich von der Tieren zu unterscheiden, sobald sie anfangen ihre Lebensmittel zu produzieren".

Tegenwoordig is deze zienswijze verder uitgewerkt door te wijzen op de daaraan voorafgaande ontwikkeling: de produktie en vooral de beheersing van vuur. Norbert Elias heeft er als eerste op gewezen, dat vuurbeheersing alleen gepaard kan gaan met sociale- en zelfbeheersing, en daarmee als een beschavingsproces beschouwd kan worden.

Zo kan dus onderscheid worden gemaakt in de geschiedenis van de mensheid tussen drie revoluties, die alle geconcentreerd zijn rond het centrale begrip produktie.

- Domesticatie van vuur (vuurbeheersing)
- Domesticatie van planten en dieren (landbouwrevolutie)
- Industriële revolutie

Bij een nadere analyse van bovenstaande revoluties wordt duidelijk dat het wezenlijke kenmerk daarvan de produktie van energie is. Naarmate de mensheid dat proces beter ging beheersen nam de ontwikkeling toe. De mens is het enige wezen waarvan gezegd kan worden dat het de produktie van energie en de daarmee samenhangende produktie van goederen en diensten beheerst.

Toen op een gegeven moment ontdekt werd dat het mogelijk was, het wilde paard, schaap en koe te temmen en te fokken, ontstond er een middel van bestaan dat een enorme vooruitgang betekende in de menselijke ontwikkeling. Daarna begon ook het technisch kunnen (technologie) een steeds grotere rol te spelen. De pijl en boog voor de jacht, de bijl en de ploeg voor de landbouw en de verbetering daarvan door de toepassing van ijzer, betekenen allemaal een grote vooruitgang voor de menselijke samenleving. We zien dus een technologische overgang van een samenleving die gebaseerd was op verzamelen en jacht, naar een samenleving gebaseerd op landbouw en veeteelt. En belangrijk, zo niet belangrijker, is de daarmee gepaard gaande sociale verandering van een stammensamenleving naar een burgerlijke samenleving. Ook nu, evenals in alle voorgaande ontwikkelingen, ligt de sleutel bij de energiesituatie.

Door zich te voorzien van een externe energiebron, en daardoor niet langer afhankelijk van de eigen arbeid, kon sociaal-culturele ontwikkeling plaatsvinden. De mens kreeg voor het eerst de tijd zich met andere zaken, dan alleen de voedselvoorziening, bezig te houden. Wanneer het niet mogelijk blijkt, op grote schaal, in de energiebehoefte te blijven voorzien zoals wij dat nu, zeker in het Westen, gewend zijn, dan zal dit vergaande gevolgen hebben voor de verdere sociaal-culturele en economische ontwikkeling.

In de economische geschiedenis nemen we globaal de volgende ontwikkelingen waar in het denken over het produktiebegrif:

- De mercantilisten (17e en 18e eeuw) vonden dat er pas sprake kon zijn van produktie wanneer het de uitvoer van goederen of daarmee samenhangende activiteiten betrof.
- De fysiocraten (Quesnay) onderkenden het belang van de produktie voor de welvaart, met de natuur als enige welvaartsbron. Daardoor zagen zij ook alleen de extraktieve produktie (landbouw, visserij, mijnbouw, jacht, e.d.) als een produktieve activiteit.
- Adam Smith (1723-1790) en David Ricardo (1772-1823) waren de eersten die ook de niet extraktieve produktie als welvaartsbron erkenden. Hun produktietheorie wordt gekenmerkt door het belang van de factor arbeid, voor de waardevermeerdering van het produkt.

Later heeft Karl Marx (1818-1883) die opvatting overgenomen en uitgewerkt in zijn arbeidswaardetheorie.

Tegenwoordig wordt de voor produktie noodzakelijke waardevermeerdering uitgedrukt in het door William Jevons (1831-1882) ontwikkelde nutsbegrif. Het nut is de economische uitdrukking voor de mate waarin een menselijke behoefte wordt bevredigd.

Een zeer afwijkende opvatting ontstond in de Verenigde Staten in de dertiger jaren. Daar was in die tijd, rond mensen als Howard Scott en M. King Hubbert een beweging ontstaan, die de waardevermeerdering voor produktie uitdrukten in de hoeveelheid energie die nodig is voor de produktie. Deze beweging noemde (en noemt!) zich de "Technocracy Movement". Hiervan is later, de bij ons vaak, in een totaal ander verband, gehanteerde term "technocraat" afgeleid.

Samenvattend kan worden gesteld dat door de ontwikkeling van het nutsbegrif, het produktiebegrif een veel ruimere betekenis heeft kregen, zodat daaronder nu ook gebieden vallen zoals de diensten- en transportsector.

In dit college wordt uitgegaan van de definitie van Hollis B. Chenery [1]:

- "Production means anything that happens to an object or set of objects which increases its value"  
Het gaat bij produktie dus om waardevermeerdering.
- "The basic physical condition necessary to effect any of these changes, is that energy must be applied to the material in some form".
- "The application of energy is one element, common to both the economist's and the engineer's concept of production".

Het belangrijkste inzicht van Chenery is, dat hij het produktieproces loskoppelt van de materiaalstroom en het verbindt aan de energiestroom en daarmee samenhangende apparatuur en machines (produktiemiddelen).

Uit het voorgaande blijkt dat dit, technisch georiënteerde, inzicht in het produktiebegrif draait rond de begrippen:

1. produktiefactoren (inputs en outputs)
2. veranderen (transformatie)
3. waarde (vermeerdering)

Het is nu mogelijk door de introductie van het energiebegrip, een eenvoudig, abstract model te ontwikkelen van een productieproces.

## 1.2. Het energiebegrip

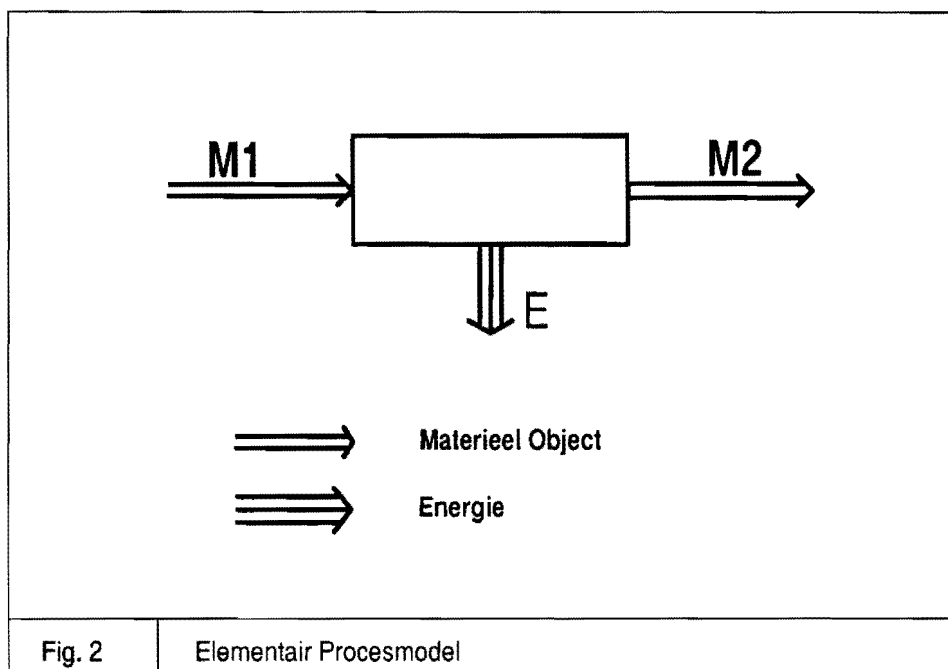
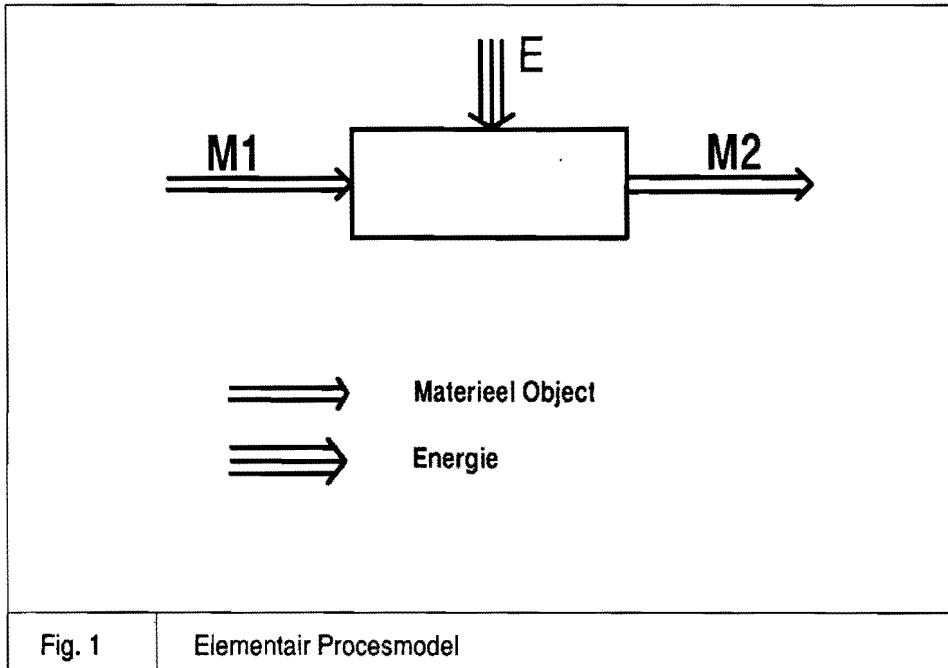
In het dagelijks spraakgebruik wordt het begrip energie gebruikt in twee betekenissen:

- Energie als concept om het plaatsvinden van een verandering te verklaren. Hierbij wordt energie opgevat als een niet-materieel object in de vorm van arbeid en warmte (straling). Deze energievormen treden alleen op als overdrachtsverschijnsel tussen twee of meer systemen met een ongelijk potentiaal (b.v. temperatuur).
- Energie als kenmerkende toestandsgrootte van een drager (massa) of lading (electron). Ieder systeem bevat dus energie en wordt gekenmerkt door de volgende soorten:
  - \* Elektrische energie
  - \* Thermische energie
  - \* Chemische energie
  - \* Mechanische energie
  - \* Nucleaire energie

De hoeveelheid energie is altijd het produkt van een extensiteits- en een intensiteitsparameter. Bij de energiedragers wordt vaak onderscheid gemaakt tussen de primaire (olie, gas, steenkool en manuren) en de secundaire energiedragers (elektriciteit en stoom).

Dat het energiebegrip ook in het dagelijks spraakgebruik, en dus niet alleen bij (bedrijfskundig) ingenieurs, een belangrijke rol speelt komt door het feit dat al onze ervaringen te maken hebben met de overdracht en transformatie van energie. In een ervaringswereld die gekenmerkt wordt door voortdurende verandering (panta rhei) heeft de mens een constante gevonden: energie.

Verder wordt verwezen naar hoofdstuk 4.





### 1.3. Het procesmodel

De essentie van een (technisch) proces is verandering [2] en daarmee het toe- of afvoeren van energie. Zonder energie geen verandering. Bij een produktieproces is de verandering doelgericht: waardevermeerdering.

Door "koppeling" van de definities van energie en produktie, ontstaat een nieuwe definitie van het begrip produktie:

"Het toe- of afvoeren van energie aan een of meer objecten zo dat de waarde daarvan stijgt".

Er bestaan dus twee elementaire produktieprocessen:

- processen met energietoevoer: M-Proces (fig. 1)
- processen met energieafvoer: E-Proces (fig. 2)

Figuur 1 laat het elementaire energietoevoerproces zien waarbij de materiële input M1 wordt getransformeerd tot een meer waardevolle output M2.

Figuur 2 laat het elementaire energie-afvoerproces zien waarbij de materiële input M1 wordt getransformeerd tot een meer waardevolle output M2.

Bij waardedaling spreekt men van een consumptieproces.

Een technische analyse van een produktiesysteem, of dat nu een afzonderlijke installatie is of een heel bedrijf, komt uiteindelijk neer op het weergeven van dat systeem als een samenhangend geheel van elementaire processen.

Voor ieder proces afzonderlijk of een samenstel daarvan, gelden de volgende wetmatigheden:

1. De wet van behoud van massa.

In hoofdstuk 3 van dit dictaat wordt ingegaan op de toepassing van deze wet in een produktiesituatie.

2. De wet van behoud van energie.

In hoofdstuk 4 van dit dictaat wordt ingegaan op de toepassing van deze wet in een produktiesituatie.

3. De tweede hoofdwet van Thermodynamica.

Dit is ook een ervaringswet die uitsluitel geeft over de richting waarin een proces verloopt.

"Het is niet mogelijk met behulp van een kringproces warmte volledig in arbeid om te zetten" (Lord Kelvin).

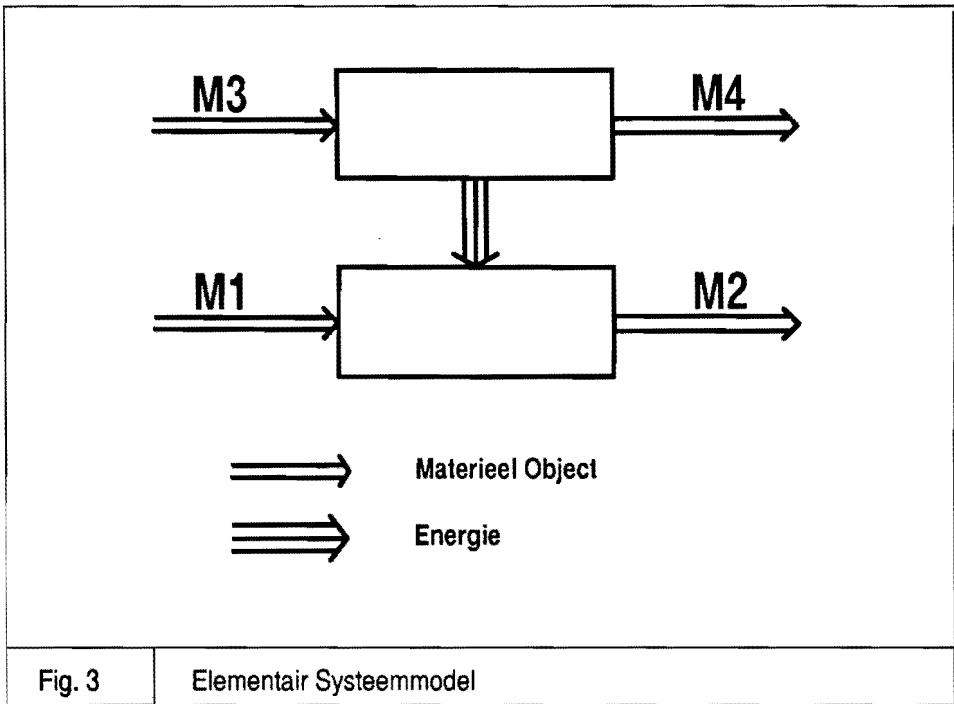


Fig. 3

Elementair Systeemmodel

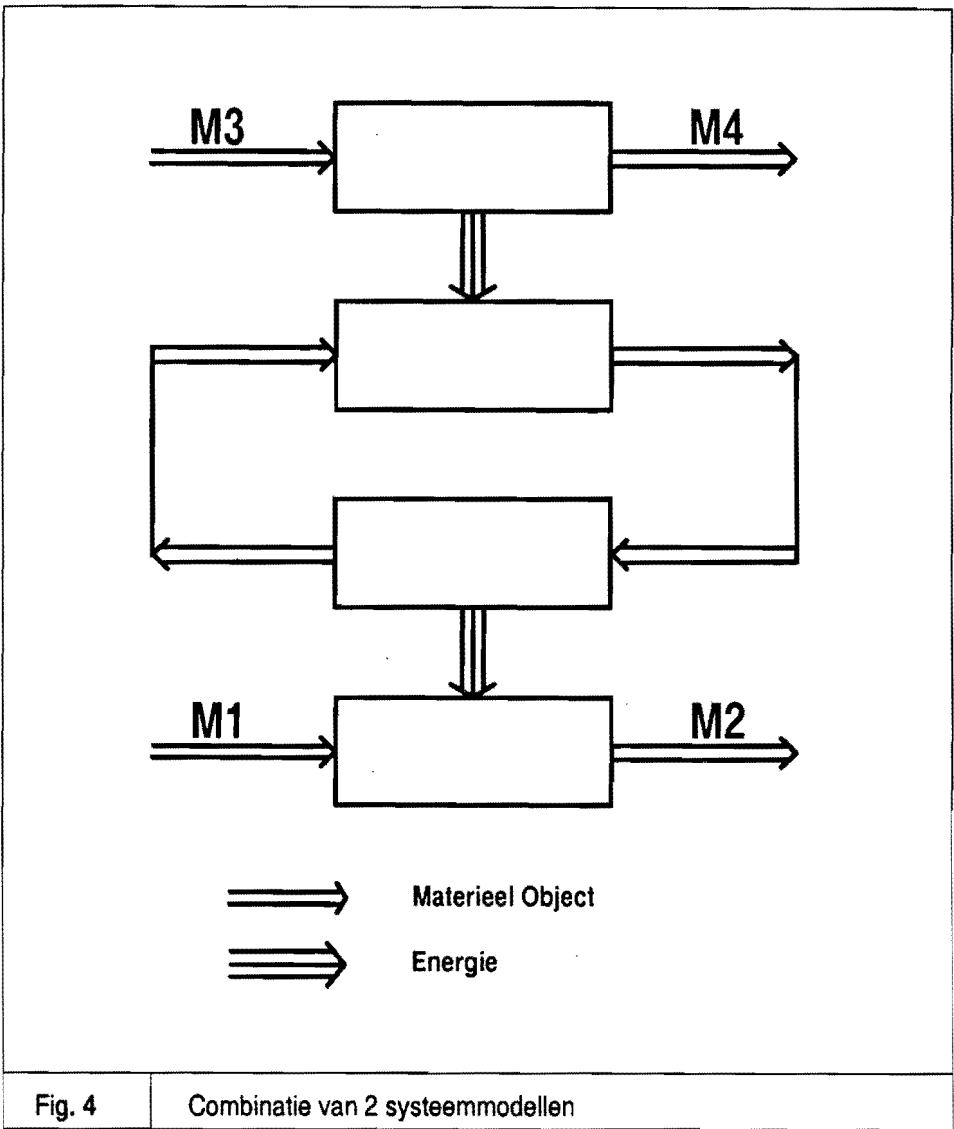


Fig. 4

Combinatie van 2 systeemmodellen

#### 1.4. Het systeemmodel.

Combinatie van de twee elementaire processen geeft het elementaire systeemmodel (fig. 3).

- De input M1 wordt getransformeerd tot de gewenste output M2 (produkt) door directe energie-overdracht van de energiedrager M3, die daardoor getransformeerd wordt tot de output M4 (verwarmen).  
Of:
- De input M3 wordt getransformeerd tot de gewenste output M4 (produkt) door directe energie-overdracht naar M1, die daardoor getransformeerd wordt tot de output M2 (koelen).

De totale energie van dit systeem gaat niet verloren (1e hoofdwet). Er vindt wel degeneratie plaats van energie (2e hoofdwet). Overdracht van energie vindt alleen plaats wanneer er een potentiaal verschil bestaat tussen de in- en uitgaande stromen of toestanden. Zonder een temperatuurverschil tussen de ingaande stroom thermische energie (M3) en de uitgaande stroom (M2) vindt geen energie-overdracht in de vorm van warmte plaats.

#### 1.5. Het basismodel van een produktiesysteem.

Door een combinatie van twee elementaire systeemmodellen (fig. 4) ontstaat het basismodel van een produktiesysteem (fig. 5).

Uit nevenstaande figuur (4) wordt de materiële kringloop duidelijk die karakteristiek is voor ieder fysische systeem dat als intermediair optreedt bij de energie-overdracht van een "bron" met een energetisch hoog potentiaal naar een "put" met een (thermisch) laag potentiaal [3].

In het basismodel van een produktiesysteem (fig. 5) wordt het overdrachtssysteem als een black-box beschouwd met een ingaande en een uitgaande energiestroom. Ieder overdrachtssysteem heeft ook een uitgaande verliesstroom ( $Q_v$ ) naar de omgeving.

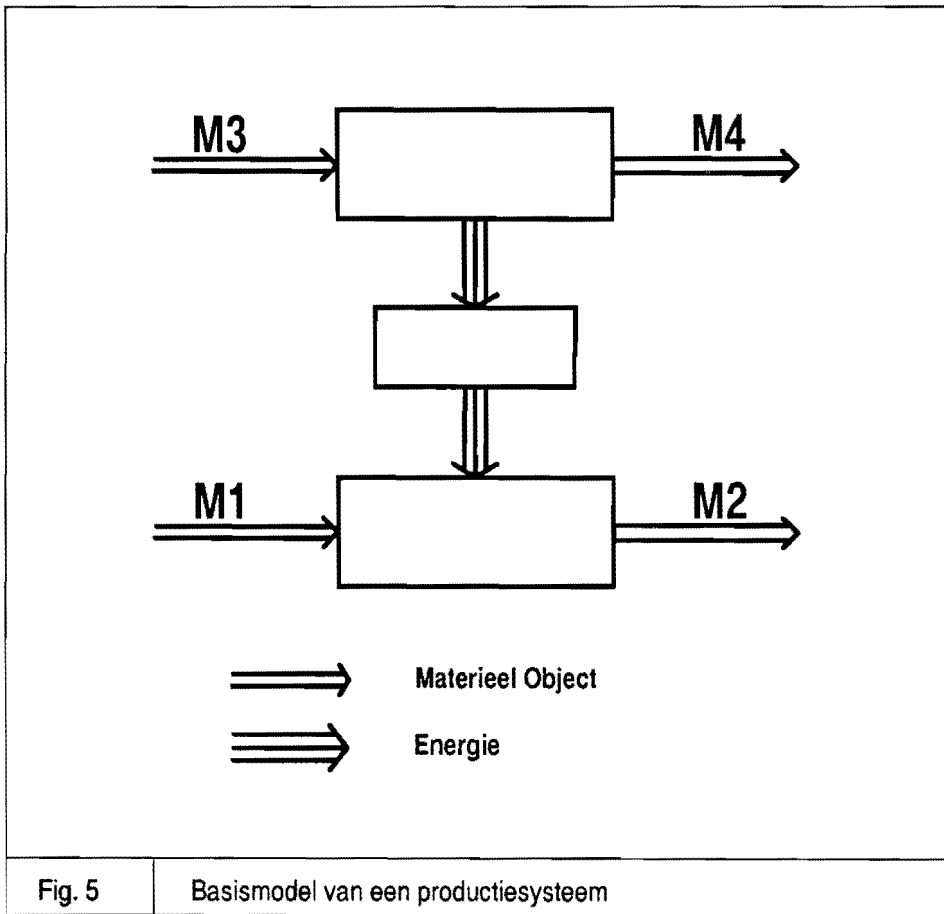


Fig. 5

Basismodel van een productiesysteem

## 1.6. Produktiefunkties

In de ekonomie wordt een produktiesysteem beschreven met behulp van een produktiefunctie, die het verband aangeeft tussen de hoeveelheid produkt en de hoeveelheid benodigde produktiefactoren.

In macro-economische beschouwingen wordt vaak volstaan met de Cobb-Douglas-functie, gebaseerd op twee produktiefactoren: kapitaal en arbeid. De bedrijfskundig ingenieur zal veeleer te maken krijgen met problemen op micro-economische schaal (bedrijven). Een, vanuit een technisch standpunt bekeken, interessante benadering, is die van N. Georgescu-Roegen [2].

Hij maakt onderscheid tussen "fund" en "flow"factoren. Een fund-factor ondergaat geen produktietransformatie, maar werkt in of gebruikt de flow-factoren (levert diensten).

De fund-factoren zijn:

- Kapitaal (K)
- Menselijke arbeid (A)
- Land (L)

De flow-factoren zijn:

- Resources (R); zonlicht, regen, steenkool, aardolie, bauxiet, etc.
- Inputs (I); deze worden geleverd door andere produktiesystemen: materialen en energiedragers.
- Onderhoudsmiddelen (M); smeerolie, poetslappen, verf, etc.
- Afvalmateriaal (W)
- Geproduceerde goederen (Q)

Al deze factoren zijn een functie van de tijd (t) over de tijdsperiode (T) waarover het produktiesysteem wordt beschouwd. Hierbij valt op te merken dat het onderscheid tussen flow- en fund-factoren afhankelijk is van de te beschouwen tijdsperiode (T). Als die maar groot genoeg is zijn ook bijvoorbeeld de kapitaalgoederen (volledig) getransformeerd.

De voorgestelde produktiefunctie ziet er nu als volgt uit:

$$Q(t) = F\{R(t), I(t), M(t), W(t), L(t), K(t), A(t)\}$$

Een van de belangrijkste toepassingen van de economische produktiefunctie is het opstellen van de kostenfunctie. Iedere produktiefactor brengt kosten met zich mee.

In het college wordt deze produktiefunctie gebruikt om een van de belangrijkste menselijke uitvindingen te verduidelijken: de industriële produktie (fabriek). De essentie van het op industriële wijze produceren van goederen en diensten ligt in het feit dat de genoemde produktiefactoren allemaal evenredig zijn met de factor tijd(t).

Dit in tegenstelling tot de agrarische produktie waar de belangrijkste produktiefactor (licht: energie) niet continu ter beschikking is. In de glastuinbouw tracht men zoveel als mogelijk is, met extra verlichting e.d., agrarische produkten industrieel te vervaardigen. Bovenstaande houdt in dat de factor tijd (t) bij industriële produktie, als afzonderlijke produktiefactor kan worden opgenomen. Dor langer te werken wordt ook de hoeveelheid geproduceerde goederen groter.

Georgescu-Roegen vergelijkt een fabriek met een muziekdos, die begint te spelen als je hem opent. Dit geldt voor een fabriek als industrieel produktiesysteem evenzeer; vrijwel ogenblikkelijk na het opstarten "rollen" er produkten uit. Dit is het grote verschil met b.v. het landbouw- of ambachtelijke bedrijf.

Bij industriële produktie, in een fabriek, kunnen alle processen in serie worden geschakeld, waardoor de leegloop van kapitaal en arbeid minimaal kan worden.

#### 1.7. De structuur van produktiesystemen.

In het algemeen kan er een onderscheid worden gemaakt tussen de interne en externe structuur van een systeem.

De interne structuur wordt gedefinieerd als de verzameling relaties tussen de objecten van het systeem.

De externe structuur wordt gedefinieerd als de verzameling relaties van het systeem met zijn (relevante) omgeving.

Wanneer in dit hoofdstuk onderscheid wordt gemaakt tussen het micro-model en het macro-model, dan wordt hiermee het verschil in systeemgrens aangegeven. In het eerste geval worden de grenzen van de produktiesystemen uiteindelijk bepaald door het bedrijf waar de produktie plaatsvindt. In het tweede geval worden de grenzen nationaal of regionaal bepaald, waardoor niet alleen het aggregatieniveau, maar ook de problematiek verandert.

Het micro-model

Deze paragraaf sluit aan bij paragraaf 1.5: het basismodel van een produktiesysteem. Vanuit een technisch oogpunt wordt de structuur van een produktiesysteem vastgelegd door de verzameling relaties tussen de verschillende transformatieprocessen.

In essentie ziet de (technische) structuur van een produktiesysteem eruit als fig. 5.

In de werkelijkheid wordt dit model ingewikkelder vanwege:

- meerdere materiële inputs/outputs per proces
- meerdere energetische inputs/outputs per proces
- meerdere produkten

In de praktijk wordt een dergelijk model te onoverzichtelijk, zodat al vlug overgegaan moet worden op symbolen.

Voorbeelden van toepassingen, uit de duitse industriestandaarden:

DIN 28004, zijn:

- a. Basisschema (fig. 6)
- b. Stroomschema (fig. 7)
- c. Instrumentenschema

ad a.

Bij het basisschema gaat het in de eerste plaats om de ordening van de transformatieprocessen: Dit ordenen houdt in elk geval in:

- het benoemen en aangeven van de processen
- de belangrijkste materiaalstromen
- het benoemen van de inputs en outputs van het produktiesysteem.

Daaraan kunnen worden toegevoegd:

- de materiële inputs en outputs per proces
- de hoeveelheden per materiaalstroom

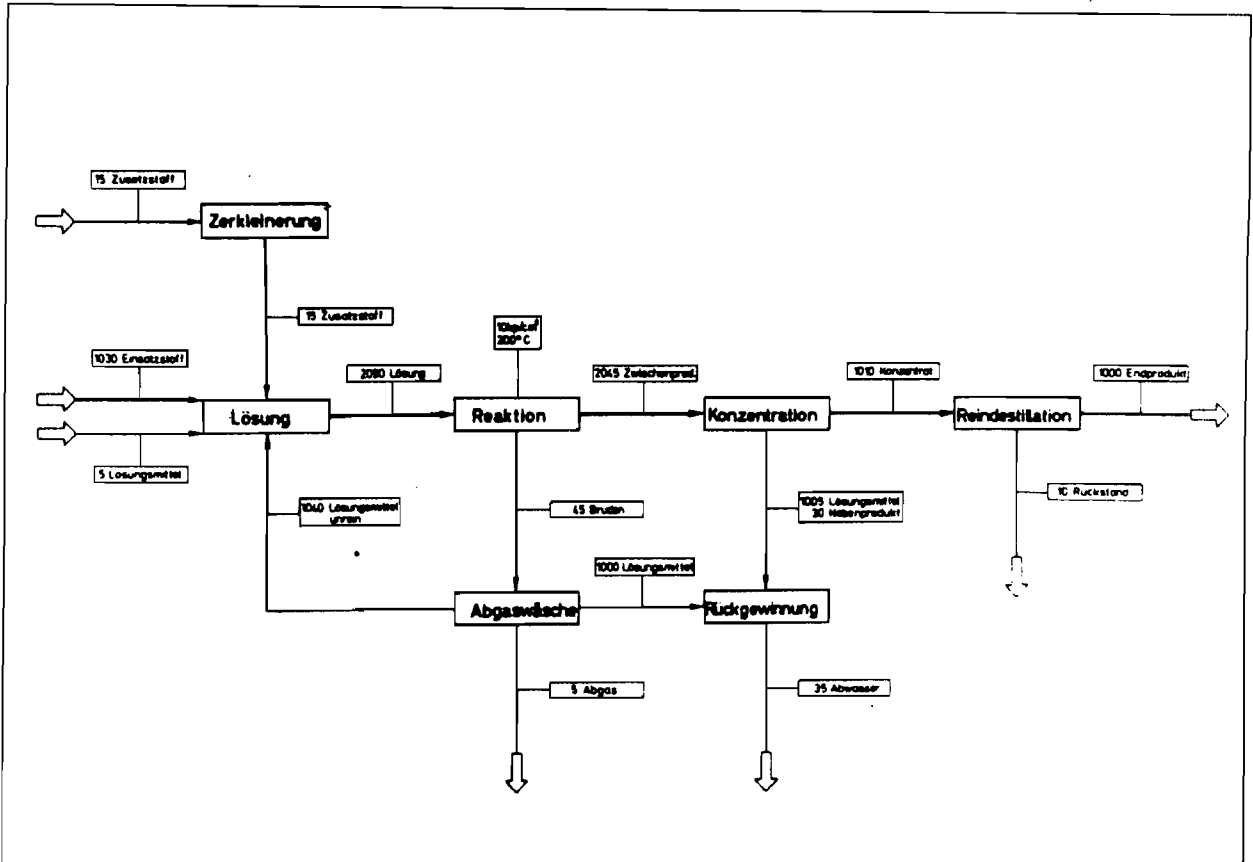


Fig. 6      Voorbeeld van een basischema (procesindustrie)

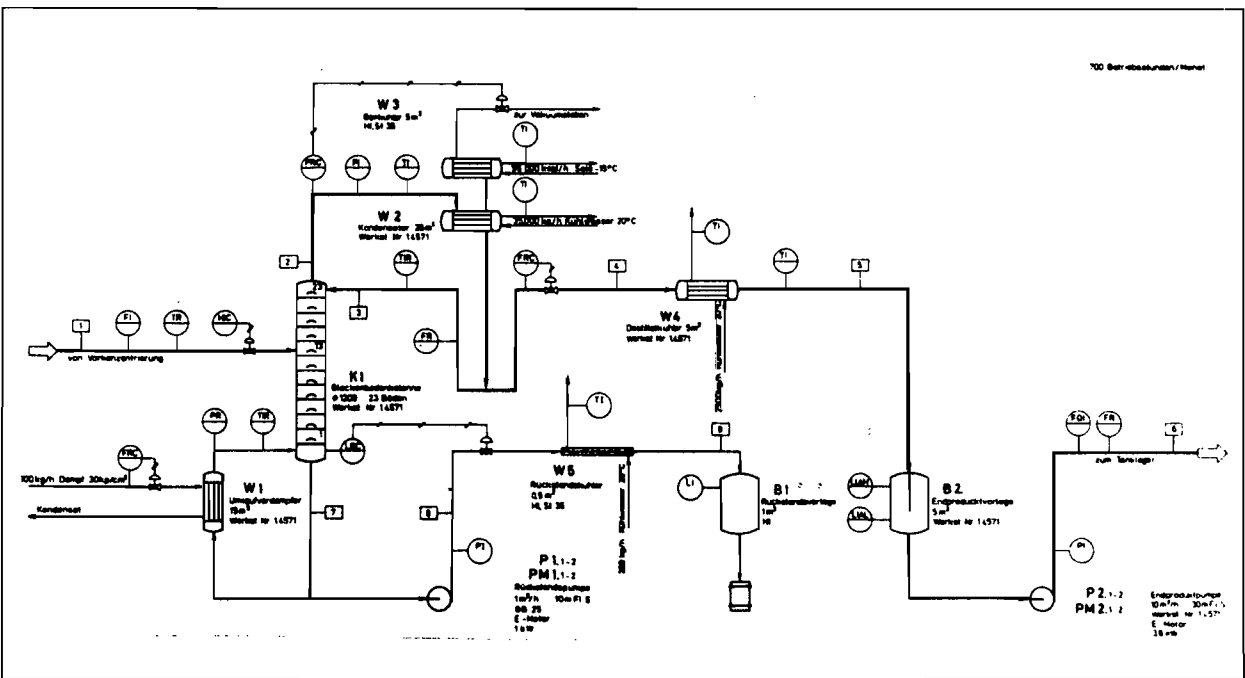


Fig. 7      Voorbeeld van een stroomschema (procesindustrie)

- de benodigde energietoevoer per proces
- de karakteristieke procesgrootheden

Een voorbeeld van zo'n basisschema is fig. 6.

ad b.

Het stroomschema gaat uit van het basisschema, waarvoor het van ieder proces in elk geval aangeeft:

- de benodigde apparatuur of machines
- de benoeming van alle materiaalstromen
- de benoeming van alle toegevoerde energie
- de karakteristieke procescondities

Daaraan kan worden toegevoegd:

- de karakteristieke afmetingen
- de meet- en regeltechnische gegevens.

Een voorbeeld van een stroomschema is fig. 7.

ad c.

Het instrumentenschema bouwt voort op het stroomschema. Het geeft aan waar de benodigde meet- en regelapparatuur moet worden geïnstalleerd. Vooral in de chemische industrie is dit van belang.

Het macro-model.

In het macro-model, waarvan fig. 8 een voorbeeld is, wordt een bepaald produktiesysteem geplaatst in een grotere context.

We zien aan de ene kant de grondstofbronnen en aan de andere kant de afvalputten, waartussen de industriële produktie en consumptie plaatsvindt. De primaire produktie kan worden onderverdeeld in:

1. Extractie  
Hieronder vallen alle produktieprocessen die plaatsvinden bij de grondstoffenbron, zoals de groei en oogst van het gewas en de winning van mineralen.
2. Raffinage  
Hieronder vallen alle produktieprocessen die de grondstoffen doorlopen om de noodzakelijke veranderingen aan te brengen, die nodig zijn voor het verdere gebruik.  
In het geval van bijvoorbeeld groente en fruit is dit het schoonmaken, wanneer het bestemd is voor de directie consumptie. Voor de meeste materialen is het mogelijk bij de raffinage twee stappen te onderscheiden; een aantal mechanische processen, gevolgd door een serie chemische processen.  
Het chemische proces levert dan het materiaal op in zijn meest pure vorm.
3. Combineren.  
Het verschil tussen combineren en fabriceren is, dat het produkt na combineren geschikt is voor een veelheid van toepassingen en gewoonlijk wordt verkocht op basis van gewicht met een gering aantal produktspecificaties.  
De belangrijkste voorbeelden zijn:  
staal; papier; glas; cement; ingevroren voedsel; gas; elektriciteit; olie.
4. Fabricage.  
Een mogelijke indeling die wel in statistieken wordt gebruikt is:
  - vormen: persen, draaien, knippen
  - assembleren: samenstellen, mengen
  - afwerken: poetsen, verven, logen.



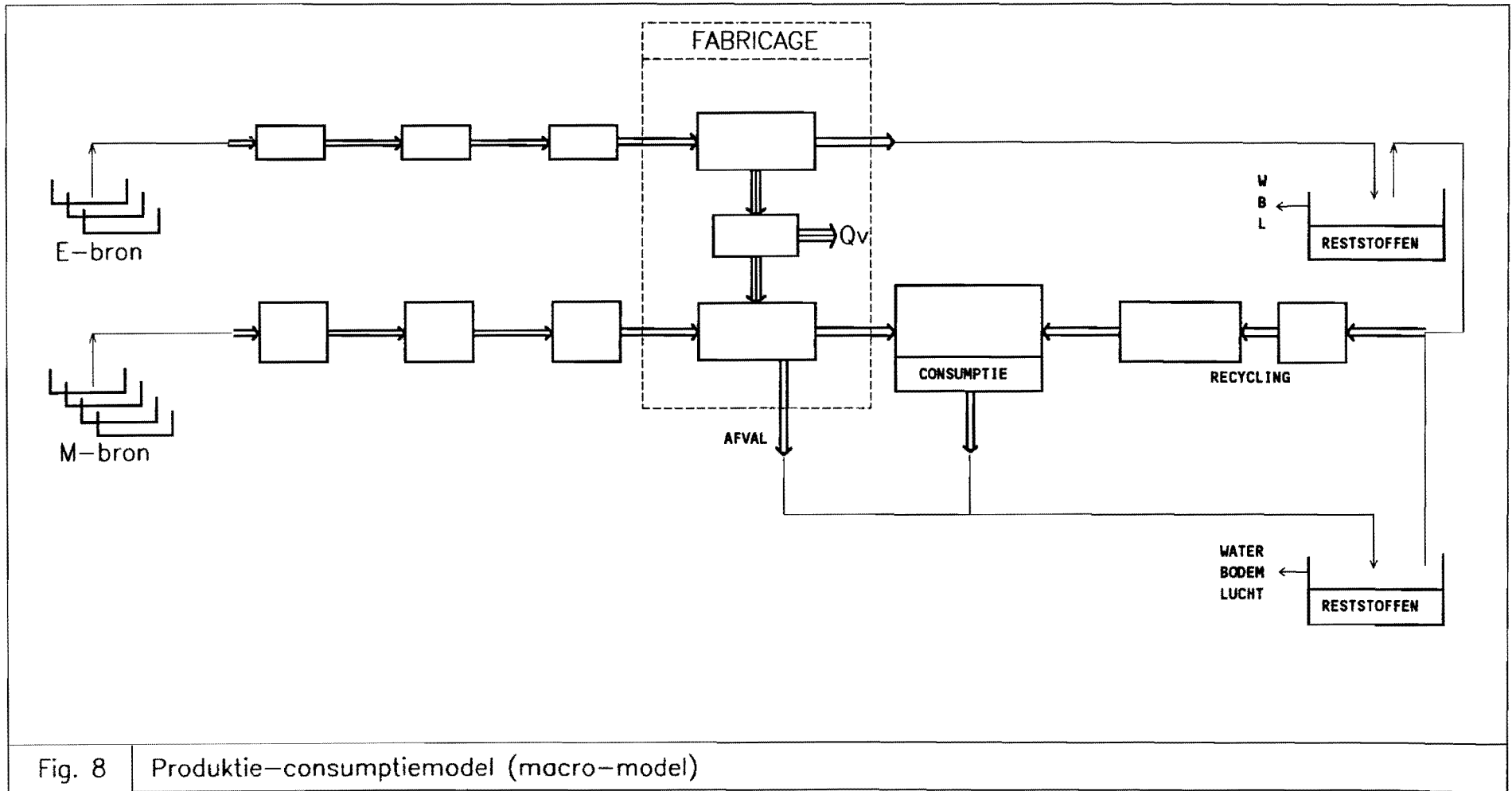


Fig. 8 | Produktie-consumptiemodel (macro-model)

Andere indelingen zijn mogelijk.

In het schema is ook opgenomen, de produktie en verwerking van energiedragers. In principe is dit hetzelfde schema, met als grootste principiële afwijking dat recycling niet mogelijk is. De onmogelijkheid van recycling van energie is vastgelegd in de tweede hoofdwet van de thermodynamica. Dit betekent dat alle, gebruikte en misbruikte, energie in het milieu terecht komt. Aangezien alle energie uiteindelijk wordt omgezet in thermische energie met omgevingstemperatuur, spreekt men in dit verband van thermische vervuiling. Dit is slechts één aspekt van de vervuiling van het milieu t.g.v. energieproduktie.

Om de diverse gevolgen en alle daarmee samenhangende aspecten van het produceren en consumeren van goederen samen te vatten, spreekt men van de grondstoffen/energieproblematiek.

De ernst van die problematiek wordt vaak aangeduid met de volgende vijf karakteristieke punten:

- De voedselproduktie in de "ontwikkelde" landen bloeit bij de gratie van een aanzienlijke energiesubsidie
- De hoogst ongelijkmatige verdeling van de voornaamste fossiele energiebronnen over de aarde
- De bevolkingsgroei dreigt groter te worden dan de stijging van de daarvoor noodzakelijke energie- en voedselproduktie
- De opname capaciteit is beperkt (milieubelasting)
- Bepaalde technologische omzettingsrendementen naderen het theoretisch maximum.

Het minste dat een ingenieur kan doen om dergelijke "problemen" naar een "oplossing" te helpen, is er zich bewust van te zijn: te beseffen dat hij werkt in een veel groter produktiesysteem.

Hij dient te beseffen dat zijn beslissingen het functioneren van natuurlijke produktiesystemen ernstig in gevaar kan brengen. Veel belangrijker is echter dat hij zich later, bij het nemen van beslissingen, niet louter laat leiden door z.g. economische criteria, maar daarnaast ook aandacht schenkt aan energetische, esthetische, milieutechnische en andere aspecten van zijn beslissingen.

Literatuur:

Incropera, F.P. and De Witt, D.P. (1986). Fundamentals of Heat and Mass Transfer. J. Wiley, New York.

The process of heat exchange between two fluids that are at different temperatures and separated by a solid wall occurs in many engineering applications. The device used to implement this exchange is termed a heat exchanger, and specific applications may be found in space heating and air-conditioning, power production, waste heat recovery, and chemical processing. In this chapter we consider the principles of heat transfer needed to design and/or to evaluate the performance of a heat exchanger.

11.1 HEAT EXCHANGER TYPES

Heat exchangers are typically classified according to *flow arrangement* and *type of construction*. The simplest heat exchanger is one for which the hot and cold fluids move in the same or opposite directions in a *concentric tube* (or *double-pipe*) construction. In the parallel-flow arrangement of Figure 11.1a, the hot and cold fluids enter at the same end, flow in the same direction, and leave at the same end. In the counterflow arrangement of Figure 11.1b, the fluids enter at opposite ends, flow in opposite directions, and leave at opposite ends.

Alternatively, the fluids may move in cross flow (perpendicular to each other), as shown by the *finned* and *unfinned* tubular heat exchangers of Figure 11.2. The two configurations differ according to whether the fluid moving over the tubes is *unmixed* or *mixed*. In Figure 11.2a, the fluid is said to be unmixed because the fins prevent motion in a direction (*y*) that is transverse to the main-flow direction (*x*). In this case the fluid temperature varies with *x* and *y*. In contrast, for the unfinned tube bundle of Figure 11.2b, fluid motion, hence

a  
b  
c

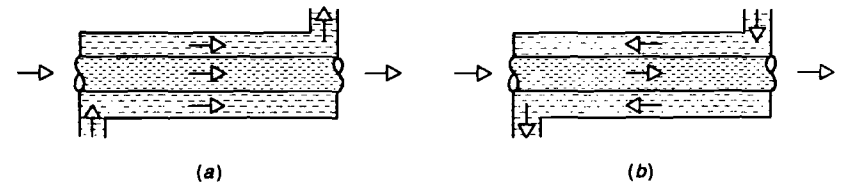


Figure 11.1 Concentric tube heat exchangers. (a) Parallel flow. (b) Counterflow.

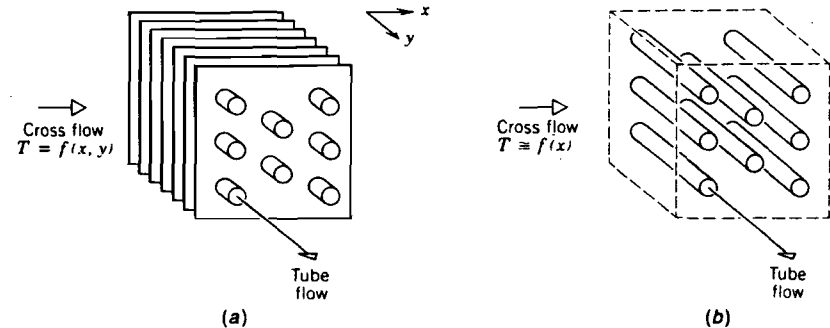


Figure 11.2 Cross-flow heat exchangers. (a) Finned with both fluids unmixed. (b) Unfinned with one fluid mixed and the other unmixed.

11

mixing, in the transverse direction is possible, and temperature variations are primarily in the main-flow direction. Since the tube flow is unmixed, both fluids are unmixed in the finned exchanger, while one fluid is mixed and the other unmixed in the unfinned exchanger. The nature of the mixing condition can significantly influence heat exchanger performance.

Another common configuration is the *shell-and-tube* heat exchanger [1]. Specific forms differ according to the number of shell and tube passes, and the simplest form, which involves single tube and shell passes, is shown in Figure 11.3. Baffles are usually installed to increase the convection coefficient of the shell-side fluid by inducing turbulence and a cross-flow velocity component. Baffled heat exchangers with one shell pass and two tube passes and with two shell passes and four tube passes are shown in Figures 11.4a and 11.4b, respectively.

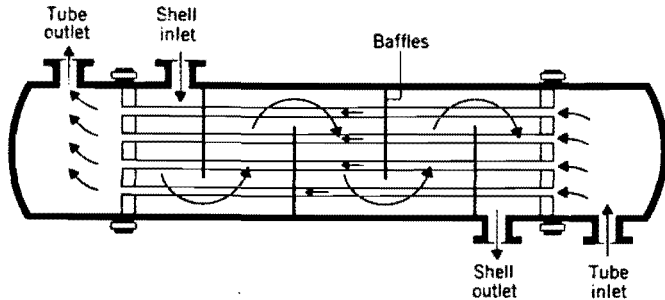


Figure 11.3 Shell-and-tube heat exchanger with one shell pass and one tube pass (cross-counterflow mode of operation).

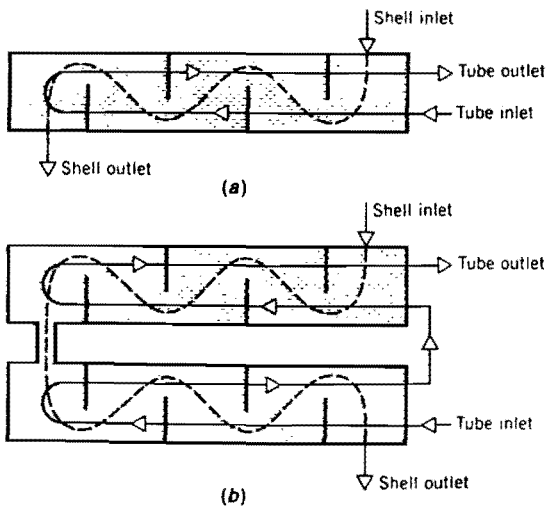


Figure 11.4 Shell-and-tube heat exchangers. (a) One shell pass and two tube passes. (b) Two shell passes and four tube passes.

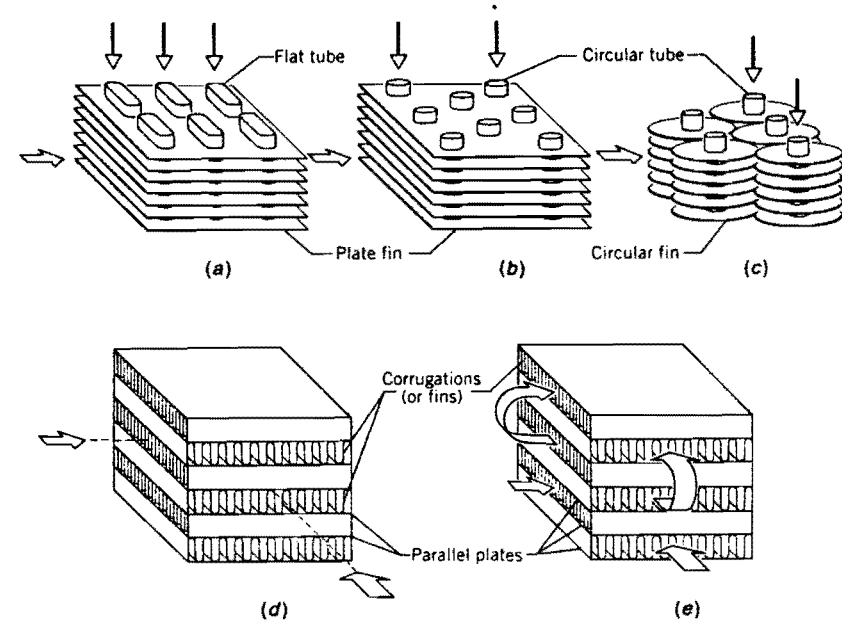


Figure 11.5 Compact heat exchanger cores. (a) Fin-tube (flat tubes, continuous plate fins). (b) Fin-tube (circular tubes, continuous plate fins). (c) Fin-tube (circular tubes, circular fins). (d) Plate-fin (single pass). (e) Plate-fin (multipass).

A special and important class of heat exchangers is used to achieve a very large ( $\geq 700 \text{ m}^2/\text{m}^3$ ) heat transfer surface area per unit volume. Termed *compact heat exchangers*, these devices have dense arrays of finned tubes or plates and are typically used when at least one of the fluids is a gas, and is hence characterized by a small convection coefficient. The tubes may be *flat* or *circular*, as in Figures 11.5a and 11.5b, respectively, and the fins may be *plate* or *circular*, as in Figures 11.5a, b and 11.5c, respectively. Parallel plate heat exchangers may be finned or corrugated and may be used in single-pass (Figure 11.5d) or multipass (Figure 11.5e) modes of operation. Flow passages associated with compact heat exchangers are typically small ( $D_h \leq 5 \text{ mm}$ ), and the flow is usually laminar.

### 11.3 HEAT EXCHANGER ANALYSIS: USE OF THE LOG MEAN TEMPERATURE DIFFERENCE

To design or to predict the performance of a heat exchanger, it is essential to relate the total heat transfer rate to quantities such as the inlet and outlet fluid temperatures, the overall heat transfer coefficient, and the total surface area for heat transfer. Two such relations may readily be obtained by applying overall energy balances to the hot and cold fluids, as shown in Figure 11.6. In particular, if  $q$  is the total rate of heat transfer between the hot and cold fluids and there is negligible heat transfer between the exchanger and its surroundings, as well as negligible potential and kinetic energy changes, application of an energy balance, Equation 1.10a, gives

$$q = \dot{m}_h(i_{h,i} - i_{h,o}) \quad (11.6a)$$

and

$$q = \dot{m}_c(i_{c,o} - i_{c,i}) \quad (11.7a)$$

where  $i$  is the fluid enthalpy. The subscripts  $h$  and  $c$  refer to the hot and cold fluids, whereas  $i$  and  $o$  designate the fluid inlet and outlet conditions. If the fluids

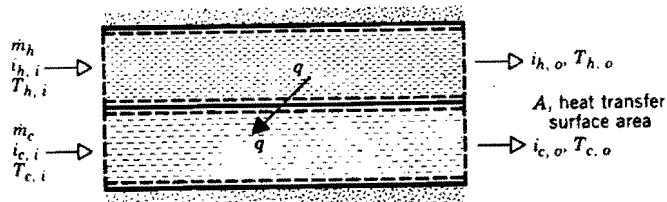


Figure 11.6 Overall energy balances for the hot and cold fluids of a two-fluid heat exchanger.

are not undergoing a phase change and constant specific heats are assumed, these expressions reduce to

$$q = \dot{m}_h c_{p,h} (T_{h,i} - T_{h,o}) \quad (11.6b)$$

and

$$q = \dot{m}_c c_{p,c} (T_{c,o} - T_{c,i}) \quad (11.7b)$$

where the temperatures appearing in the expressions refer to the *mean* fluid temperatures at the designated locations. Note that Equations 11.6 and 11.7 are independent of the flow arrangement and heat exchanger type.

Another useful expression may be obtained by relating the total heat transfer rate  $q$  to the temperature difference  $\Delta T$  between the hot and cold fluids, where

$$\Delta T \equiv T_h - T_c \quad (11.8)$$

Such an expression would be an extension of Newton's law of cooling, with the overall heat transfer coefficient  $U$  used in place of the single convection coefficient  $h$ . However, since  $\Delta T$  varies with position in the heat exchanger, it is necessary to work with a rate equation of the form

$$q = UA\Delta T_m \quad (11.9)$$

where  $\Delta T_m$  is an appropriate *mean* value of the temperature difference. Equation 11.9 may be used with Equations 11.6 and 11.7 to perform a heat exchanger analysis, but before this can be done, the specific form of  $\Delta T_m$  must be established. Consider first the parallel-flow heat exchanger.

#### 11.3.1 The Parallel-Flow Heat Exchanger

The hot and cold fluid temperature distributions associated with a parallel-flow heat exchanger are shown in Figure 11.7. The temperature difference  $\Delta T$  is initially large but decays rapidly with increasing  $x$ , approaching zero asymptotically. It is important to note that, for such an exchanger, the outlet temperature of the cold fluid never exceeds that of the hot fluid. In Figure 11.7 the subscripts 1 and 2 designate opposite ends of the heat exchanger. This convention is used for all types of heat exchangers considered. For parallel flow, it follows that  $T_{h,i} = T_{h,1}$ ,  $T_{h,o} = T_{h,2}$ ,  $T_{c,i} = T_{c,1}$  and  $T_{c,o} = T_{c,2}$ .

The form of  $\Delta T_m$  may be determined by applying an energy balance to differential elements in the hot and cold fluids. Each element is of length  $dx$  and heat transfer surface area  $dA$ , as shown in Figure 11.7. The energy balances and the subsequent analysis are performed subject to the following assumptions.

1. The heat exchanger is insulated from its surroundings, in which case the only heat exchange is between the hot and cold fluids.

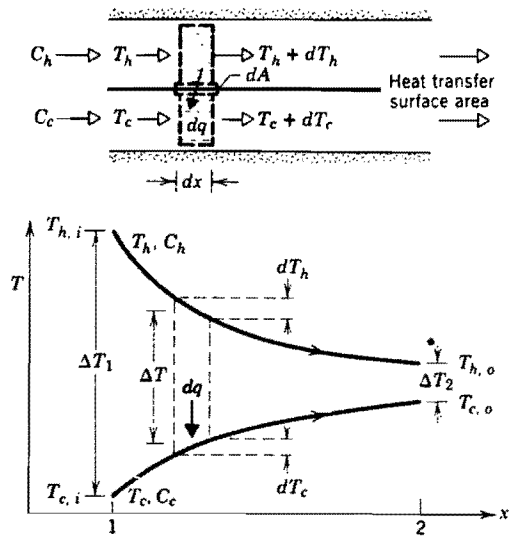


Figure 11.7 Temperature distributions for a parallel-flow heat exchanger.

2. Axial conduction along the tubes is negligible.
3. Potential and kinetic energy changes are negligible.
4. The fluid specific heats are constant.
5. The overall heat transfer coefficient is constant.

The specific heats may of course change as a result of temperature variations, and the overall heat transfer coefficient may change because of variations in fluid properties and flow conditions. However, in many applications such variations are not significant, and it is reasonable to work with average values of  $c_{p,c}$ ,  $c_{p,h}$ , and  $U$  for the heat exchanger.

Applying an energy balance to each of the differential elements of Figure 11.7, it follows that

$$dq = -\dot{m}_h c_{p,h} dT_h \equiv -C_h dT_h \quad (11.10)$$

and

$$dq = \dot{m}_c c_{p,c} dT_c \equiv C_c dT_c \quad (11.11)$$

where  $C_h$  and  $C_c$  are the hot and cold fluid *heat capacity rates*, respectively. These expressions may be integrated across the heat exchanger to obtain the overall energy balances given by Equations 11.6b and 11.7b. The heat transfer across the surface area  $dA$  may also be expressed as

$$dq = U \Delta T dA \quad (11.12)$$

where  $\Delta T = T_h - T_c$  is the *local* temperature difference between the hot and cold fluids.

To determine the integrated form of Equation 11.12, we begin by substituting Equations 11.10 and 11.11 into the differential form of Equation 11.8

$$d(\Delta T) = dT_h - dT_c$$

to obtain

$$d(\Delta T) = -dq \left( \frac{1}{C_h} + \frac{1}{C_c} \right)$$

Substituting for  $dq$  from Equation 11.12 and integrating across the heat exchanger, we obtain

$$\int_1^2 \frac{d(\Delta T)}{\Delta T} = -U \left( \frac{1}{C_h} + \frac{1}{C_c} \right) \int_1^2 dA$$

or

$$\ln \left( \frac{\Delta T_2}{\Delta T_1} \right) = -UA \left( \frac{1}{C_h} + \frac{1}{C_c} \right) \quad (11.13)$$

Substituting for  $C_h$  and  $C_c$  from Equations 11.6b and 11.7b, respectively, it follows that

$$\begin{aligned} \ln \left( \frac{\Delta T_2}{\Delta T_1} \right) &= -UA \left( \frac{T_{h,i} - T_{h,o}}{q} + \frac{T_{c,o} - T_{c,i}}{q} \right) \\ &= -\frac{UA}{q} [(T_{h,i} - T_{c,i}) - (T_{h,o} - T_{c,o})] \end{aligned}$$

Recognizing that, for the parallel-flow heat exchanger of Figure 11.7,  $\Delta T_1 = (T_{h,i} - T_{c,i})$  and  $\Delta T_2 = (T_{h,o} - T_{c,o})$ , we then obtain

$$q = UA \frac{\Delta T_2 - \Delta T_1}{\ln(\Delta T_2/\Delta T_1)}$$

Comparing the above expression with Equation 11.9, we conclude that the appropriate average temperature difference is a *log mean temperature difference*,  $\Delta T_{lm}$ . Accordingly, we may write

$$q = UA \Delta T_{lm} \quad (11.14)$$

where

$$\Delta T_{lm} = \frac{\Delta T_2 - \Delta T_1}{\ln(\Delta T_2/\Delta T_1)} = \frac{\Delta T_1 - \Delta T_2}{\ln(\Delta T_1/\Delta T_2)} \quad (11.15)$$

Remember that, for the *parallel-flow* exchanger,

$$\begin{aligned} \Delta T_1 &\equiv T_{h,1} - T_{c,1} = T_{h,i} - T_{c,i} \\ \Delta T_2 &\equiv T_{h,2} - T_{c,2} = T_{h,o} - T_{c,o} \end{aligned} \quad (11.16)$$

### 11.3.2 The Counterflow Heat Exchanger

The hot and cold fluid temperature distributions associated with a counterflow heat exchanger are shown in Figure 11.8. In contrast to the parallel-flow exchanger, this configuration provides for heat transfer between the hotter portions of the two fluids near the entrance, as well as between the colder portions near the exit. For this reason, the change in the temperature difference,  $\Delta T = T_h - T_c$ , with respect to  $x$  is nowhere as large as it is for the inlet region of the parallel-flow exchanger. Note that the outlet temperature of the cold fluid may now exceed the outlet temperature of the hot fluid.

Equations 11.6b and 11.7b apply to any heat exchanger, and hence may be used for the counterflow arrangement. Moreover, from an analysis like that performed in Section 11.3.1, it may be shown that Equations 11.14 and 11.15 also apply. However, for the *counterflow exchanger* the endpoint temperature differences must now be defined as

$$\begin{cases} \Delta T_1 \equiv T_{h,1} - T_{c,1} = T_{h,i} - T_{c,o} \\ \Delta T_2 \equiv T_{h,2} - T_{c,2} = T_{h,o} - T_{c,i} \end{cases} \quad (11.17)$$

Note that, for the same inlet and outlet temperatures, the log mean temperature difference for counterflow exceeds that for parallel flow,  $\Delta T_{lm,CF} > \Delta T_{lm,PF}$ . Hence the surface area required to effect a prescribed heat transfer rate  $q$  is smaller for the counterflow than for the parallel-flow arrangement, assuming the same value of  $U$ . Also note that  $T_{c,o}$  can exceed  $T_{h,o}$  for counterflow but not for parallel flow.

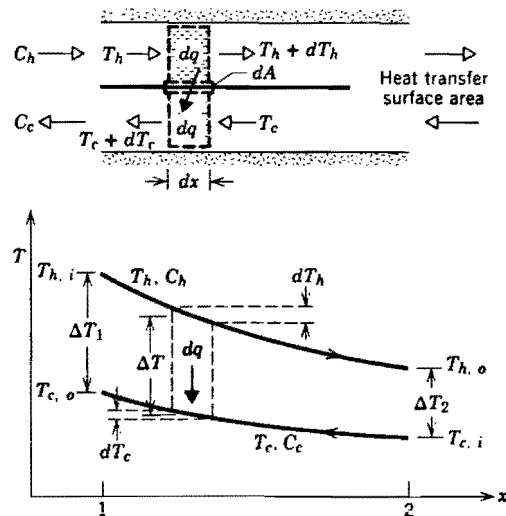


Figure 11.8 Temperature distributions for a counterflow heat exchanger.

Literatuur:

Felder, R.M. and Rousseau, R.W. (1978). Elementary Principles of Chemical Processes. J. Wiley, New York.

# Chapter Five

## FUNDAMENTALS OF MATERIAL BALANCES

There are certain restrictions imposed by nature that must be taken into account when designing a new process or analyzing an existing one. You cannot, for example, specify an input to a reactor of 1000 grams of lead and an output of 2000 grams of lead or gold or anything else; similarly, if you know that 1500 pounds of sulfur are contained in the coal burned each day in a power plant boiler, you do not have to analyze the ash and stack gases to know that 1500 pounds of sulfur per day leave the furnace in one form or another.

The basis for both of these observations is the law of conservation of mass, which states that mass can neither be created nor destroyed. (We will not be concerned in this book with nuclear reactions, for which this law does not hold.) Statements based on the law of conservation of mass such as "total mass of input = total mass of output," or " $(\text{lb}_m \text{ sulfur/day})_{\text{in}} = (\text{lb}_m \text{ sulfur/day})_{\text{out}}$ " are examples of *mass balances* or *material balances*. The design of a new process or analysis of an existing one is not complete until it is established that the inputs and outputs of the entire process and of each individual unit satisfy balance equations applied to each process material.

Part 2 of this book, which begins with this chapter, outlines procedures for writing material balances on individual process units and multiple-unit processes. In this chapter we present methods for organizing known information about process variables, setting up material balance equations, and solving these equations for unknown variables. In Chapters Six and Seven we introduce various physical properties and laws that govern the behavior of process materials, and indicate how these properties and laws are taken into account (as they must be) in formulating material balances.

### 5.1. PROCESS CLASSIFICATION

(Chemical) processes may be classified as *batch*, *continuous* or *semibatch*, and as either *steady state* or *transient*. Before writing a material balance on a process system, you must know which of these categories the process falls into.



- (a) **Batch process.** The feed is charged into the system at the beginning of the process, and the products are removed all at once some time later. No mass crosses the system boundaries between the time the feed is charged and the time the product is removed.

*Example.* Rapidly add reactants to a tank, and remove the products and unconsumed reactants some time later when the system has come to equilibrium.

- (b) **Continuous process.** The inputs and outputs flow continuously throughout the duration of the process.

*Example.* Pump a mixture of liquids into a distillation column at a constant rate, and steadily withdraw vapor and liquid streams from the top and bottom of the column.

- (c) **Semibatch process.** The inputs are nearly instantaneous and the outputs are continuous, or vice versa.

*Examples.* Allow the contents of a pressurized gas container to escape to the atmosphere; slowly blend several liquids in a tank from which nothing is being withdrawn.

If the values of all the variables in a process (i.e., all temperatures, pressures, volumes, flow rates, etc.) do not change with time, except possibly for minor fluctuations about constant mean values, the process is said to be operating at steady state. If any of the process variables changes with time, *transient* or *unsteady-state* operation is said to exist. By their nature, batch and semibatch processes are unsteady-state operations (why?), whereas continuous processes may be either steady state or transient.

Batch processing is commonly used when relatively small quantities of a product are to be produced on any single occasion, while continuous processing is better suited to large production rates. Continuous processes are usually run as close to steady state as possible; unsteady-state (transient) conditions exist during the start-up of a process and following changes—intentional or otherwise—in process operating conditions.

## TEST YOURSELF

Classify the following processes as batch, continuous, or semibatch, and transient or steady state.

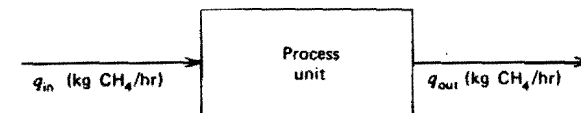
1. A balloon is filled with air at a steady rate of 2 grams per minute.
2. A bottle of milk is taken from the refrigerator and left on the kitchen table.
3. Water in an open flask boils.
4. Carbon monoxide and steam are fed into a tubular reactor at a steady rate, and react to form carbon dioxide and hydrogen. Products and unused reactants are withdrawn at the other end. The reactor contains air when the process is

started up. The temperature of the reactor is constant, and the composition and flow rate of the entering reactant stream are also independent of time. Classify the process (i) initially, (ii) after a long period of time has elapsed.

## 5.2. BALANCES

### 5.2a. The General Balance Equation

Suppose methane is a component of both the input and output streams of a continuous process unit, and that in an effort to determine whether the unit is performing as designed, the mass flow rates of methane in both streams are measured and found to be different.



There are only four possible explanations for the observed difference between the measured flow rates.

1. Methane is leaking from the unit.
2. Methane is either being consumed as a reactant or generated as a product within the unit.
3. Methane is accumulating in the unit—possibly adsorbing on the walls.
4. The measurements are wrong.

If the measurements are correct and there are no leaks, the other possibilities—generation or consumption in a reaction, and accumulation within the process unit—are all that can account for a difference between the input and output flow rates.

A balance (or inventory) on a material in a system (a single process unit, a collection of units, or an entire process) may be written in the following general way:

$$\begin{array}{cccccc} \text{Input} & + & \text{generation} & - & \text{output} & - & \text{consumption} & = & \text{accumulation} \\ \text{(enters} & & \text{(produced} & & \text{(leaves} & & \text{(consumed} & & \text{(buildup} \\ \text{through} & & \text{within} & & \text{through} & & \text{within} & & \text{within} \\ \text{system} & & \text{system)} & & \text{system} & & \text{system)} & & \text{system)} \\ \text{boundaries)} & & & & \text{boundaries)} & & & & \end{array} \quad (5.2-1)$$

This general balance equation may be written for any material that enters or leaves any process system: it can be applied to the total mass of the contents of the system

or to any molecular or atomic species involved in the process. The meaning of each term of the equation is illustrated in the following example.

### EXAMPLE 5.2-1. The General Balance Equation

Each year 50 000 people move into a city, 75 000 people move out, 22 000 are born and 19 000 die. Write a balance on the population of the city.

Solution.

Let  $P$  denote people.

Input + generation – output – consumption = accumulation

$$50\,000 \frac{P}{\text{yr}} + 22\,000 \frac{P}{\text{yr}} - 75\,000 \frac{P}{\text{yr}} - 19\,000 \frac{P}{\text{yr}} = A \left( \frac{P}{\text{yr}} \right)$$

$$\Downarrow$$

$$A = -22\,000 \frac{P}{\text{yr}}$$

(Each year the city's population decreases by 22 000 people.)

Two types of balances may be written:

- Differential balances**, or balances that indicate what is happening in a system at an instant of time. Each term of the balance equation is then a *rate* (rate of input, rate of generation, etc.) and has units of the balanced quantity unit divided by a time unit (people/yr, g SO<sub>2</sub>/s, barrels/day). This is the type of balance usually applied to a continuous process. (See Example 5.2-1.)
- Integral balances**, or balances that describe what happens between two instants of time. Each term of the equation is then an *amount* of the balanced quantity, and has the corresponding unit (people, g SO<sub>2</sub>, barrels). This type of balance is usually applied to a batch process, with the two instants of time being the moment after the input takes place and the moment before the product is withdrawn.

We are concerned in this text primarily with differential balances applied to continuous steady-state systems and integral balances applied to batch systems between their initial and final states. In Chapter Eleven, we consider general balances on unsteady-state systems, and show how integral and differential balances are related—in fact, how each can be derived from the other.

The generation and consumption terms in a balance equation equal zero if the balanced quantity is neither a reactant nor a reaction product. These terms are always zero if the balanced quantity is total mass, since (neglecting nuclear reactions) mass can neither be created nor destroyed.

### 5.2b. Balances on Continuous Steady-State Processes

Suppose hydrogen appears as a component in the input and output streams of a continuous process at steady state. The accumulation term in a balance on hydrogen must equal zero; if it did not, the amount of hydrogen in the process system would necessarily change with time, and the process would then by definition not be at steady state. The same argument holds for every substance involved in the process, so that for continuous steady-state processes the general balance equation, Equation 5.2-1, simplifies to

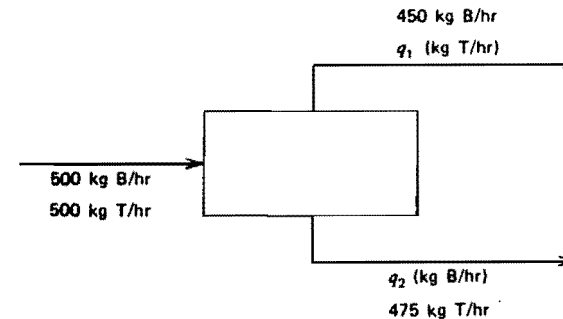
$$\boxed{\text{Input} + \text{generation} = \text{output} + \text{consumption}} \quad (5.2-2)$$

### EXAMPLE 5.2-2. Material Balances on a Continuous Distillation Process

One thousand kilograms per hour of a mixture of benzene and toluene that contains 50% benzene by mass are separated by distillation into two fractions. The mass flow rate of benzene in the top stream is 450 kg B/hr, and that of toluene in the bottom stream is 475 kg T/hr. The operation is at steady state. Write balances on benzene and toluene to calculate the unknown component flow rates in the output streams.

Solution.

The process can be depicted schematically as shown below.



Since the process is at steady state there can be no buildup of anything in the system, so the accumulation term equals zero in all material balances. In addition, since no chemical reactions occur there can be no nonzero generation or

consumption terms. For all balances, Equation 5.2-2 therefore takes the simple form input = output.

$$\text{Benzene balance: } 500 \text{ kg B/hr} = 450 \text{ kg B/hr} + q_2$$

$$\downarrow$$

$$q_2 = 50 \text{ kg B/hr}$$

$$\text{Toluene balance: } 500 \text{ kg T/hr} = q_1 + 475 \text{ kg T/hr}$$

$$\downarrow$$

$$q_1 = 25 \text{ kg T/hr}$$

Check the calculation:

$$\text{Total mass balance: } 1000 \text{ kg/hr} = 450 + q_1 + q_2 + 475 \text{ (all kg/hr)}$$

$$\downarrow q_1 = 25, q_2 = 50$$

$$1000 \text{ kg/hr} = 1000 \text{ kg/hr} \quad \checkmark$$

### 5.2c. Integral Balances on Batch Processes

Ammonia is produced from nitrogen and hydrogen in a batch reactor. At time  $t = 0$  there are  $m_0$  mols of  $\text{NH}_3$  in the reactor, and at a later time  $t_f$  the reaction terminates and the contents of the reactor, which include  $m_f$  mols of ammonia, are withdrawn. Between  $t_0$  and  $t_f$  no ammonia enters or leaves through the reactor boundaries, so the general balance equation (Equation 5.2-1) is simply generation = accumulation. Moreover, the quantity of ammonia that builds up (accumulates) in the reactor between  $t_0$  and  $t_f$  is simply  $m_f - m_0$ , the final amount minus the initial amount.

The same reasoning may be applied to any substance participating in a batch process to obtain the equation

Generation – consumption = accumulation = final output – initial input  
or

$$\boxed{\text{initial input} + \text{generation} = \text{final output} + \text{consumption}} \quad (5.2-3)$$

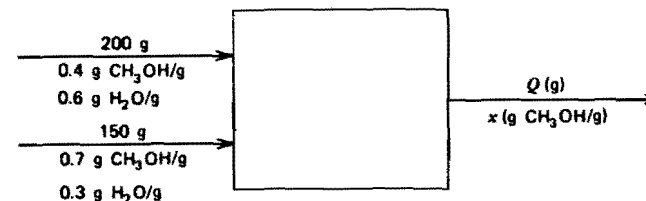
This equation is identical to Equation 5.2-2 for continuous steady-state processes, except that in this case the input and output terms denote the initial and final amounts of the balanced substance rather than flow rates of the balanced substance in continuous feed and product streams.

#### EXAMPLE 5.2-3. Balances on a Batch Mixing Process

Two methanol–water mixtures are contained in separate flasks. The first mixture contains 40 wt% methanol, and the second contains 70 wt% methanol. If

200 g of the first mixture are combined with 150 g of the second, what are the mass and composition of the product?

Solution.



(Observe that the input and output streams shown on the chart denote the initial and final states for this batch process.)

Since no reactions are involved, the generation and consumption terms of Equation 5.2-3 may be omitted so that all balances have the simple form “input = output.”

*Total mass balance*

$$200 \text{ g} + 150 \text{ g} = Q(\text{g})$$

$$\downarrow$$

$$Q = 350 \text{ g}$$

*Methanol balance*

$$\frac{200 \text{ g}}{\text{g}} \left| \frac{0.4 \text{ g CH}_3\text{OH}}{\text{g}} \right| + \frac{150 \text{ g}}{\text{g}} \left| \frac{0.7 \text{ g CH}_3\text{OH}}{\text{g}} \right| = \frac{Q(\text{g})}{\text{g}} \left| \frac{x \text{ g CH}_3\text{OH}}{\text{g}} \right|$$

$$\downarrow Q = 350$$

$$x = 0.529 \text{ g CH}_3\text{OH/g}$$

We now know everything about the product, including the mass fraction of water (what is it?) A water balance serves only to check the calculation.

*Water balance*

Input = output

$$(200)(0.6) + (150)(0.3) = (350)(1 - 0.529) \quad (\text{Verify!})$$

$$\downarrow$$

$$165 \text{ g H}_2\text{O} = 165 \text{ g H}_2\text{O} \quad \checkmark$$

Literatuur:

Felder, R.M. and Rousseau, R.W. (1978). Elementary Principles of Chemical Processes. J. Wiley, New York.

# Chapter Eight

## ENERGY AND ENERGY BALANCES

Energy is expensive. We have not yet learned how to use efficiently the endless supply of "free" energy provided by such sources as the sun, winds, and tides; nuclear power generation is possible, but the need to dispose safely of radioactive wastes from nuclear reactors is a serious unresolved problem; and there are not nearly enough waterfalls and dams to provide sufficient hydroelectric power to meet the world's energy needs. This leaves us with fuel combustion—burning a combustible gas, oil, or solid fuel, and using the heat released as a source of thermal or (indirectly) electrical energy.

Process industries have always recognized that wasting energy leads to reduced profits, but in the past the cost of energy was often an insignificant part of the overall process cost, and gross operational inefficiencies were tolerated. In recent years, however, a dramatic decrease in the availability of natural gas and petroleum has raised the cost of energy severalfold, and has intensified the need to eliminate all unnecessary energy consumption. If a plant uses more energy than its competitors, its product could now be priced out of the marketplace.

As an engineer designing a process, one of your principal jobs would therefore be to account carefully for the energy that flows into and out of each process unit, and to determine the overall energy requirement for the process. You would do this by writing *energy balances* on the process, in much the same way that you would write material balances to account for the mass flows to and from the process and its units. Typical problems that may be solved using energy balances include the following:

1. How much power (energy/time) is required to pump 1250 gal/min of water from a storage vessel to a process unit? (The answer determines the size of the required pump motor.)
2. How much heat is required to convert 2000 lb<sub>m</sub> of water at 30°C to steam at 180°C?

3. A hydrocarbon mixture is distilled, producing a liquid and a vapor stream, each with a known or calculable flow rate and composition. The heat input to the still is provided by condensing saturated steam at a pressure of 15 bars. At what rate must steam be supplied to process 2000 mols/hr of the feed mixture?
4. A highly exothermic chemical reaction  $A \rightarrow B$  takes place in a continuous reactor. If a 75% conversion of A is to be achieved, at what rate must heat be removed from the reactor to keep the contents at a constant temperature?
5. How much coal must be burned each day to produce enough heat to generate the steam to run the turbines to produce enough electricity to meet the daily power requirements of a city of 500 000 people?
6. A chemical process consists of four reactors, 25 pumps, and a number of compressors, distillation columns, mixing tanks, evaporators, filter presses, and other materials handling and separation units. Each individual unit either requires or releases energy in the form of work or heat.
  - (a) How can the process operation be designed to minimize the total energy requirement? (For example, can the energy released by an energy-emitting process unit be used as input to an energy-absorbing process unit?)
  - (b) What is the total energy requirement for the process as it is finally designed, and how much will it cost to provide this energy? (The answer could determine whether or not the process is economically feasible.)

In this chapter we show how energy balances are formulated and applied. Section 8.1 defines the types of energy a process system can possess and the ways in which energy can be transferred to and from a system. Section 8.2 reviews the procedure for calculating the kinetic energy and gravitational potential energy of a process stream. Sections 8.3 and 8.4 derive the general energy balance equation for closed (batch) systems and open (continuous) systems, and various applications of these equations are illustrated in Sections 8.5 to 8.7.

## 8.1. FORMS OF ENERGY: THE FIRST LAW OF THERMODYNAMICS

The total energy of a system has three components:

1. **Kinetic Energy.** Energy due to the motion of the system as a whole relative to some frame of reference (usually the earth's surface).
2. **Potential Energy.** Energy due to the position of the system in a potential field (such as a gravitational or electromagnetic field), or due to the conformation of the system relative to some equilibrium conformation (e.g., due to the extension of a spring).

3. **Internal Energy.** Energy due to the motion of molecules relative to the center of mass of the system, to the rotational and vibrational motion and the electromagnetic interactions of the molecules, and to the motion and interactions of the atomic and subatomic constituents of the molecules.

Suppose a process system is *closed*, meaning that no mass is transferred across its boundaries while the process is taking place. Energy may be transferred between such a system and its surroundings in two ways:

1. As *heat*, or energy which flows as a result of a temperature difference between a system and its surroundings. The direction of flow is always from a higher temperature to a lower one. *Heat is defined as positive when it is transferred to the system from the surroundings.*
2. As *work*, or energy that flows in response to any driving force other than a temperature difference, such as a force, a torque, or a voltage. For example, if a gas in a cylinder expands and moves a piston against a restraining force, the gas does work on the piston (energy is transferred as work from the gas to its surroundings, which include the piston). *In this text, work—like heat—is defined as positive when it is done by the surroundings on the system.*<sup>1</sup>

The terms work and heat refer only to energy that is being transferred: you can speak of the heat or work added to a system or given off by a system, but it is meaningless to speak of the heat or work possessed by or contained within a system.

Energy, like work, has units of force times distance: for example, joules ( $N \cdot m$ ), ergs ( $dyne \cdot cm$ ), and  $ft \cdot lb_f$ . It is also common to use energy units defined in terms of the amount of heat that must be transferred to a specified mass of water in order to raise the temperature of the water by a specified temperature interval at a constant pressure of 1 atm. The most common of these units are tabulated below.

Unit	Symbol	Mass of Water	Temperature Interval
Kilogram-calorie or kilocalorie	kcal	1 kg	15°C to 16°C
Gram-calorie or calorie	cal	1 g	15°C to 16°C
British thermal unit	Btu	1 lb <sub>m</sub>	60°F to 61°F

Conversion between these and other energy units may be performed using the conversion factors in the table on the inside front cover.

<sup>1</sup> The opposite sign convention is also frequently used. The choice is arbitrary, as long as it is used consistently; however, to avoid confusion when reading thermodynamics references, you should be sure which convention has been adopted.

The principle that underlies all energy balance calculations is the law of conservation of energy, which states that energy can neither be created nor destroyed. This law is also called the first law of thermodynamics.

### TEST YOURSELF

1. What forms of energy may a system possess? How may energy be transferred to and from a closed system?
2. Why is it meaningless to speak of the heat possessed by a system?
3. Suppose the initial energy of a system (internal + kinetic + potential) is  $E_i$ , the final energy is  $E_f$ , an amount of energy  $Q$  is transferred from the environment to the system as heat and an amount  $W$  is transferred from the environment to the system as work. According to the first law of thermodynamics, how must  $E_i$ ,  $E_f$ ,  $Q$ , and  $W$  be related?

## 8.2. KINETIC AND POTENTIAL ENERGY

The kinetic energy of an object of mass  $m$  moving with velocity  $v$  relative to the surface of the earth is

$$E_k = \frac{mv^2}{2g_c} \quad (8.2-1)$$

If a fluid enters a system at a mass flow rate  $m$  and uniform velocity  $v$ , then  $E_k$  calculated from Equation 8.2-1 may be thought of as the rate at which kinetic energy is transported into the system by the fluid.

### EXAMPLE 8.2-1. Kinetic Energy Transported by a Flowing Stream

Water flows into a process unit through a 2-cm I.D. pipe at a rate of  $2 \text{ m}^3/\text{hr}$ . Calculate  $E_k$  for this stream in joules/second.

**Solution.**

First calculate the linear velocity (which equals the volumetric flow rate divided by the cross-sectional area of the pipe) and the mass flow rate of the fluid.

$$v = \frac{2 \text{ m}^3}{\text{hr}} \left| \frac{(100)^2 \text{ cm}^2}{\text{m}^2} \right| \left| \frac{1 \text{ hr}}{\pi(1)^2 \text{ cm}^2} \right| \left| \frac{1}{3600 \text{ s}} \right| = 1.77 \text{ m/s}$$

$$m = \frac{2 \text{ m}^3}{\text{hr}} \left| \frac{1000 \text{ kg}}{\text{m}^3} \right| \left| \frac{1 \text{ hr}}{3600 \text{ s}} \right| = 0.556 \text{ kg/s}$$

Then, from Equation 8.2-1,

$$E_k = \frac{0.556 \text{ kg/s}}{2} \left| \frac{(1.77)^2 \text{ m}^2}{\text{s}^2} \right| \left| \frac{1 \text{ N}}{\text{kg}\cdot\text{m/s}^2} \right| = 0.870 \text{ N}\cdot\text{m/s} = \boxed{0.870 \text{ J/s}}$$

The gravitational potential energy of an object of mass  $m$  is

$$E_p = m \frac{g}{g_c} z \quad (8.2-2)$$

where  $z$  is the height of the object above a reference plane at which  $E_p$  is arbitrarily defined to be zero. If  $m$  is the mass flow rate of a flowing stream, then  $E_p$  may be thought of as the rate at which the stream transports potential energy.

### EXAMPLE 8.2-2. Potential Energy Increase of a Flowing Fluid

Crude oil is pumped at a rate of  $15.0 \text{ kg/s}$  from a well  $220 \text{ m}$  deep to a storage tank  $20 \text{ m}$  above ground level. Calculate the attendant rate of increase of potential energy.

**Solution.**

$$\Delta z = z_{\text{final}} - z_{\text{initial}} = +240 \text{ m}$$

$$\begin{aligned} \Delta E_p &= m \frac{g}{g_c} \Delta z \\ &= \frac{15.0 \text{ kg}}{\text{s}} \left| \frac{9.81 \text{ N}}{\text{kg}} \right| \left| \frac{240 \text{ m}}{\text{m}} \right| = 35\,300 \text{ N}\cdot\text{m/s} = \boxed{35\,300 \text{ J/s}} \end{aligned}$$

A pump would have to deliver at least this much power to raise the oil at the given rate.

### TEST YOURSELF

A gas flows through a long pipe of constant diameter. The outlet of the pipe is higher than the inlet, and the pressure of the gas at the outlet is less than the inlet pressure. The gas temperature is constant throughout the pipe and the system is at steady state.

1. How do the mass flow rates at the inlet and outlet compare? The densities? The volumetric flow rates?
2. Is the change in potential energy of the gas from inlet to outlet positive, negative, or zero? What about the change in kinetic energy?

## 8.3. ENERGY BALANCES ON CLOSED SYSTEMS

A system is referred to as *open* or *closed* according to whether or not mass crosses the system boundary during the period of time covered by the energy balance. A batch process system is, by definition, closed, and semibatch and continuous systems are open.

An integral energy balance equation may be derived for a closed system between two instants of time. Since energy can neither be created nor destroyed,

the generation and consumption terms of the general balance equation (5.2-1) drop out, leaving

$$\text{Accumulation} = \text{input} - \text{output} \quad (8.3-1)$$

In deriving the integral mass balance equation for a closed system in Section 5.2c we eliminated the input and output terms, since by definition no mass crosses the boundaries of a closed system. It is possible, however, for energy to be transferred across the boundaries as heat or work, so that the right-hand side of Equation 8.3-1 may not be automatically eliminated. As with mass balances, however, the accumulation terms equals the final value of the balanced quantity (in this case, the system energy) minus the initial value of this quantity. Equation 8.3-1 may therefore be written

$$\begin{array}{l} \text{final} \\ \text{system} \\ \text{energy} \end{array} - \begin{array}{l} \text{initial} \\ \text{system} \\ \text{energy} \end{array} = \begin{array}{l} \text{net energy transferred} \\ \text{to the system} \\ \text{(in-out)} \end{array} \quad (8.3-2)$$

Now

$$\begin{aligned} \text{Initial system energy} &= U_i + E_{ki} + E_{pi} \\ \text{Final system energy} &= U_f + E_{kf} + E_{pf} \\ \text{Energy transferred} &= Q + W \end{aligned}$$

where the subscripts  $i$  and  $f$  refer to the initial and final states of the system and  $U$ ,  $E_k$ ,  $E_p$ ,  $W$ , and  $Q$  represent internal energy, kinetic energy, potential energy, work done on the system by its surroundings, and heat transferred to the system from its surroundings. Equation 8.3-2 then becomes

$$(U_f - U_i) + (E_{kf} - E_{ki}) + (E_{pf} - E_{pi}) = Q + W \quad (8.3-3)$$

or, if the symbol  $\Delta$  is used to signify (final-initial),

$$\Delta U + \Delta E_k + \Delta E_p = Q + W \quad (8.3-4)$$

Equation 8.3-4 is the basic form of the first law of thermodynamics for a closed system. When applying this equation to a given process, you should be aware of the following points.

1. The internal energy of a system depends almost entirely on the chemical composition, state of aggregation, and temperature of the system materials:  $U$  is independent of pressure for ideal gases and is nearly independent of pressure for liquids and solids. Therefore, if no changes in temperature, phase, or chemical composition occur in a process, and if the process materials are all either solids, liquids, or ideal gases, then  $\Delta U \approx 0$ .

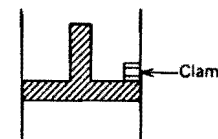
2. If a system and its surroundings are at the same temperature (or if the system is perfectly insulated), then  $Q = 0$ . The system is then termed *adiabatic*.
3. Work done on or by a closed system is accomplished by movement of the system boundary against a resisting force, or by the generation of an electrical or radiation current that passes beyond the system boundary. (Examples of the first type of work are the motion of a piston or the rotation of a shaft which projects through the system boundary.) If there are no moving parts or generated currents in a closed system, then  $W = 0$ .
4. If potential energy changes other than those due to change in height are involved in a process (e.g., movement against an elastic restraining force or an electric or magnetic field), terms to account for them must be included in the  $\Delta E_p$  term of Equation 8.3-4.

### TEST YOURSELF

1. What do the terms closed system and open system mean? What is an adiabatic system?
2. If 250 J are added to a system as heat, what is the value of  $Q$  in the energy balance equation? If 250 J of work are done by the system on its surroundings, what is the value of  $W$ ?
3. If a closed system has an internal energy of 100 kcal at the beginning of a process and 50 kcal at the end, what is  $\Delta U$ ?
4. Under what circumstances might  $U$  be considered independent of pressure for a pure substance?

### EXAMPLE 8.3-1. Energy Balance on a Closed System

A gas is contained in a cylinder fitted with a movable piston.



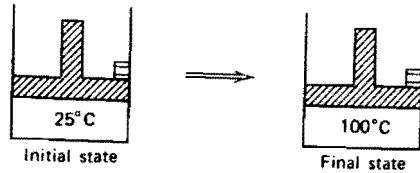
The initial gas temperature is 25°C.

The cylinder is placed in boiling water with the piston held in a fixed position. Heat in the amount of 2 kcal is absorbed by the gas, which equilibrates at 100°C (and a higher pressure). The piston is then released, and the gas does 100 J of work in moving the piston to its new equilibrium position. The final gas temperature is 100°C.

Write the energy balance equation for each of the two stages of this process, and in each case solve for the unknown energy term in the equation. In solving this

problem, consider the gas in the cylinder to be the system, neglect the change in potential energy of the gas as the piston moves vertically, and assume the gas behaves ideally. Express all energies in joules.

Solution.  
(a)



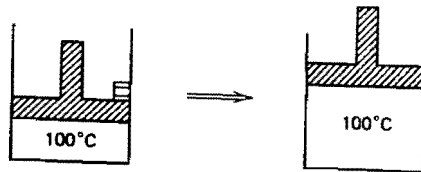
$$\Delta U + \Delta E_k + \Delta E_p = Q + W \text{ (Equation 8.3-4)}$$

$$\begin{aligned} \Delta E_k &= 0 \text{ (the system is stationary)} \\ \Delta E_p &= 0 \text{ (no vertical displacement)} \\ W &= 0 \text{ (no moving boundaries)} \end{aligned}$$

$$\Delta U = Q$$

$$\Delta U = \frac{2 \text{ kcal}}{\text{kcal}} \times \frac{10^3 \text{ cal}}{\text{kcal}} \times \frac{1 \text{ J}}{0.23901 \text{ cal}} = 8368 \text{ J} = \Delta U$$

The gas thus gains 8368 J of internal energy in going from 25 to 100°C.



(b)  $\Delta U + \Delta E_k + \Delta E_p = Q + W$

$$\begin{aligned} \Delta E_k &= 0 \text{ (the system is stationary at the initial and final states)} \\ \Delta E_p &= 0 \text{ (assumed negligible by hypothesis)} \\ \Delta U &= 0 \text{ (} U \text{ depends only on } T \text{ for an ideal gas, and } T \text{ does not change)} \end{aligned}$$

$$0 = Q + W$$

$$W = -100 \text{ J (why is it negative?)}$$

$$Q = 100 \text{ J}$$

Thus an additional 100 J of heat are absorbed by the gas as it expands and re-equilibrates at 100°C.

### 8.4. ENERGY BALANCES ON OPEN SYSTEMS AT STEADY STATE

An open process system by definition has mass crossing its boundaries as the process occurs. Work must be done on such a system to force mass in, and work is done on the surroundings by mass that emerges; both work terms must be included in the energy balance equation.

In Section 8.4a we outline the calculation of the work required to move fluid through a continuous process system, and in Section 8.4b we review the concepts of intensive and extensive variables introduced in Chapter Seven, and introduce the concept of specific properties of a substance. Section 8.4c uses the results of the two preceding sections to derive the energy balance equation for an open system at steady state.

#### 8.4a. Flow Work and Shaft Work

The net work  $W$  done on an open system by its surroundings may be written as

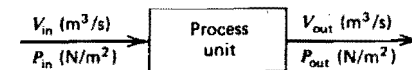
$$W = W_s + W_f \tag{8.4-1}$$

where

$W_s$  = shaft work, or work done on the process fluid by a moving part within the system (e.g. a pump rotor)

$W_f$  = flow work, or work done on the fluid at the system inlet minus work done by the fluid at the system outlet

To derive an expression for  $W_f$ , we consider the system shown below.



Fluid at a pressure  $P_{in}(\text{N/m}^2)$  enters a pipe at a volumetric flow rate  $V_{in}(\text{m}^3/\text{s})$  and exits at a pressure  $P_{out}(\text{N/m}^2)$  and volumetric flow rate  $V_{out}(\text{m}^3/\text{s})$ . The fluid that enters the system has work done on it by the fluid just behind it at a rate

$$W_{in}(\text{N} \cdot \text{m/s}) = P_{in}(\text{N/m}^2) V_{in}(\text{m}^3/\text{s}) \tag{8.4-2}$$

while the fluid leaving the system performs work on the surroundings at a rate

$$W_{out} = P_{out} V_{out} \tag{8.4-3}$$

The net rate at which work is done on the system at the inlet and outlet is, therefore,

$$W_f = P_{in} V_{in} - P_{out} V_{out} \tag{8.4-4}$$



If several input and output streams enter and leave the system, the  $PV$  products for each must be summed up to determine  $W_f$ .

### TEST YOURSELF

An incompressible liquid flows through a straight horizontal pipe. Friction of the fluid within the pipe causes a small amount of heat to be generated; to compensate for this, flow work must be done on the fluid to move it through the system (so that  $W_f$  is greater than zero).

1. How are  $V_{in}$  and  $V_{out}$  related, where  $V$  is the volumetric flow rate of the liquid? (Remember, the fluid is incompressible.)
2. How must the pressures  $P_{in}$  and  $P_{out}$  be related? ( $P_{in} > P_{out}$ ,  $P_{in} = P_{out}$  or  $P_{in} < P_{out}$ ?)

### 8.4b. Specific Properties: Enthalpy

As we observed in Section 7.2, the properties of a process material are either extensive (proportional to the quantity of the material) or intensive (independent of the quantity). Mass, number of moles, and volume (or mass flow rate, molar flow rate, and volumetric flow rate for a continuous stream), kinetic energy, potential energy, and internal energy (or the rates of transport of these quantities by a continuous stream) are extensive properties, while temperature, pressure, and density are intensive.

A *specific property* is an intensive quantity obtained by dividing an extensive stream property by the total amount (or flow rate) of the stream material. Thus, if the volume of a fluid is  $200 \text{ cm}^3$  and the mass of the fluid is  $200 \text{ g}$ , the *specific volume* of the fluid is  $1 \text{ cm}^3/\text{g}$ . Similarly, if the mass flow rate of a stream is  $100 \text{ lb}_m/\text{min}$  and the volumetric flow rate is  $150 \text{ ft}^3/\text{min}$ , the specific volume of the stream material is  $(150/100) = 1.5 \text{ ft}^3/\text{lb}_m$ ; if the rate at which kinetic energy is transported by this stream is  $300 \text{ J}/\text{min}$ , then the *specific kinetic energy* of the stream material is  $(300 \text{ J}/\text{min})/(100 \text{ lb}_m/\text{min}) = 3 \text{ J}/\text{lb}_m$ . We will use the symbol  $\hat{H}$  to denote a specific property:  $\hat{V}$  will denote specific volume,  $\hat{U}$  specific internal energy, and so on.

If the temperature and pressure of a process material are such that the specific internal energy of the material is  $\hat{U}(\text{J}/\text{kg})$ , then a mass  $m(\text{kg})$  of this material has a total internal energy

$$U(\text{J}) = m(\text{kg})\hat{U}(\text{J}/\text{kg}) \quad (8.4-5)$$

Similarly, a continuous stream of this material with a mass flow rate  $m(\text{kg}/\text{s})$  transports internal energy at a rate

$$\dot{U}(\text{J}/\text{s}) = m(\text{kg}/\text{s})\hat{U}(\text{J}/\text{kg}) \quad (8.4-6)$$

A property that occurs in the energy balance equation for open systems (Section 8.4c) is the *specific enthalpy*, defined as

$$\hat{H} = \hat{U} + P\hat{V} \quad (8.4-7)$$

where  $P$  is total pressure and  $\hat{U}$  and  $\hat{V}$  are specific internal energy and volume. The gas constants tabulated on the inside back cover provide a convenient source for the conversion factors needed to evaluate  $\hat{H}$  from Equation 8.4-7, as the following example shows.

#### EXAMPLE 8.4-1. Calculation of Enthalpy

The specific internal energy of helium at  $300 \text{ K}$  and  $1 \text{ atm}$  is  $3800 \text{ J}/\text{mol}$ , and the specific molar volume at the same temperature and pressure is  $24.63 \text{ liters}/\text{mol}$ . Calculate the specific enthalpy of helium at this temperature and pressure, and the rate at which enthalpy is transported by a stream of helium at  $300 \text{ K}$  and  $1 \text{ atm}$  whose molar flow rate is  $250 \text{ kg-moles}/\text{hr}$ .

Solution.

$$\hat{H} = \hat{U} + P\hat{V} = 3800 \text{ J}/\text{mol} + (1 \text{ atm})(24.63 \text{ liters}/\text{mol})$$

To convert the second term to joules we need the factor ( $\text{J}/\text{liter} \cdot \text{atm}$ ). From the gas constant table on the inside back cover,

$$0.08206 \text{ liter} \cdot \text{atm}/\text{mol} \cdot \text{K} = 8.314 \text{ J}/\text{mol} \cdot \text{K}$$

Dividing the right-hand side by the left-hand side yields the desired factor

$$\frac{8.314 \text{ J}/\text{mol} \cdot \text{K}}{0.08206 \text{ liter} \cdot \text{atm}/\text{mol} \cdot \text{K}} = 101.3 \text{ J}/\text{liter} \cdot \text{atm}$$

Therefore,

$$\hat{H} = 3800 \text{ J}/\text{mol} + \frac{24.63 \text{ liter} \cdot \text{atm}}{\text{mol}} \left| \frac{101.3 \text{ J}}{\text{liter} \cdot \text{atm}} \right| = \boxed{6295 \text{ J}/\text{mol}}$$

If  $n = 250 \text{ kg-moles}/\text{hr}$

$$H = n\hat{H} = \frac{250 \text{ kg-moles}}{\text{hr}} \left| \frac{10^3 \text{ mols}}{\text{kg-mole}} \right| \left| \frac{6295 \text{ J}}{\text{mol}} \right| = \boxed{1.57 \times 10^9 \text{ J}/\text{hr}}$$

### TEST YOURSELF

The specific internal energy of a fluid is  $200 \text{ cal}/\text{g}$ .

1. What is the internal energy of  $30 \text{ g}$  of this fluid?

- If the fluid leaves a system at a flow rate of 5 g/min, at what rate does it transport internal energy out of the system?
- What would you need to know to calculate the specific enthalpy of this fluid?

### 8.4c. The Steady-State Open System Energy Balance

The first law of thermodynamics for an open system at steady state has the form

$$\text{input} = \text{output} \quad (8.4-8)$$

(Why do the accumulation, generation, and consumption terms of the general balance equation vanish?) "Input" here signifies the total rate of transport of kinetic, potential, and internal energy by all process input streams plus the rates at which energy is transferred as heat and work, and "output" is the total rate of energy transport by the output streams.

If  $E_j$  denotes the total rate of energy transport by the  $j$ th input or output stream of a process, and  $Q$  and  $W$  are again defined as the rates of flow of heat and work into the process, then Equation 8.4-8 may be written

$$Q + W + \sum_{\text{input streams}} E_j = \sum_{\text{output streams}} E_j \quad (8.4-9)$$

$$\sum_{\text{output streams}} E_j - \sum_{\text{input streams}} E_j = Q + W$$

If  $m_j$ ,  $E_{kj}$ ,  $E_{pj}$ , and  $U_j$  are the mass flow rate, kinetic energy, potential energy, and internal energy of the  $j$ th process stream, then the rate at which energy is transported into or out of the system by this stream is

$$E_j = U_j + E_{kj} + E_{pj}$$

$$\begin{aligned} & \begin{array}{l} U_j = m_j \hat{U}_j \\ E_{kj} = m_j v_j^2 / 2g_c \\ E_{pj} = m_j (g/g_c) z_j \end{array} \\ & \Downarrow \\ E_j &= m_j \left( \hat{U}_j + \frac{v_j^2}{2g_c} + \frac{g}{g_c} z_j \right) \end{aligned} \quad (8.4-10)$$

where  $v_j$  is the velocity of the  $j$ th stream and  $z_j$  is the height of this stream relative to a reference plane at which  $E_p = 0$ .

The total work  $W$  done on the system by its surroundings equals the shaft work  $W_f$  plus the flow work  $W_f$ . If  $V_j$  is the volumetric flow rate of the  $j$ th stream, and  $P_j$

is the pressure of this stream, then, as was shown in Section 8.4a,

$$W_f = \sum_{\text{input streams}} P_j V_j - \sum_{\text{output streams}} P_j V_j$$

$$\Downarrow \quad v_j = m_j \hat{V}_j$$

$$W = W_s + \sum_{\text{input streams}} m_j P_j \hat{V}_j - \sum_{\text{output streams}} m_j P_j \hat{V}_j \quad (8.4-11)$$

Substituting the expression for  $E_j$  of Equation 8.4-10 and that for  $W$  of Equation 8.4-11 into Equation 8.4-9 and bringing the  $PV$  terms to the left-hand side yields

$$\sum_{\text{output streams}} m_j \left[ \hat{U}_j + (P_j \hat{V}_j) + \frac{v_j^2}{2g_c} + \frac{g}{g_c} z_j \right] - \sum_{\text{input streams}} m_j \left[ \hat{U}_j + (P_j \hat{V}_j) + \frac{v_j^2}{2g_c} + \frac{g}{g_c} z_j \right] = Q + W_s \quad (8.4-12)$$

Equation 8.4-12 could be used for all steady-state open system energy balance problems. As a rule, however, the term  $\hat{U}_j + P_j \hat{V}_j$  is combined and written as  $\hat{H}_j$ , the variable previously defined as the specific enthalpy. In terms of this variable, Equation 8.4-12 becomes

$$\sum_{\text{output streams}} m_j \left( \hat{H}_j + \frac{v_j^2}{2g_c} + \frac{g}{g_c} z_j \right) - \sum_{\text{input streams}} m_j \left( \hat{H}_j + \frac{v_j^2}{2g_c} + \frac{g}{g_c} z_j \right) = Q + W_s \quad (8.4-13)$$

Finally, let us use the symbol  $\Delta$  to denote total output minus total input, so that

$$\sum_{\text{output streams}} m_j \hat{H}_j - \sum_{\text{input streams}} m_j \hat{H}_j = \Delta H \quad (8.4-14a)$$

$$\sum_{\text{output streams}} m_j v_j^2 / 2g_c - \sum_{\text{input streams}} m_j v_j^2 / 2g_c = \Delta E_k \quad (8.4-14b)$$

$$\sum_{\text{output streams}} m_j z_j (g/g_c) - \sum_{\text{input streams}} m_j z_j (g/g_c) = \Delta E_p \quad (8.4-14c)$$

In terms of these quantities, Equation 8.4-13 becomes

$$\Delta H + \Delta E_k + \Delta E_p = Q + W_s \quad (8.4-15)$$

We will use Equation 8.4-15 as the starting point for most energy balance calculations on open systems at steady state.

Notice that if a specific variable has the same value for all input and output streams, the corresponding term of Equation 8.4-15 drops out. For example, if  $\hat{H}$  is the same for all streams, then from (8.4-14a)

$$\Delta H = \hat{H} \left[ \sum_{\text{output streams}} m_j - \sum_{\text{input streams}} m_j \right] \quad (8.4-16)$$

But from a total mass balance the quantity in brackets (which is simply total mass in minus total mass out) equals zero, and hence  $\Delta H = 0$ , as claimed.

TEST YOURSELF

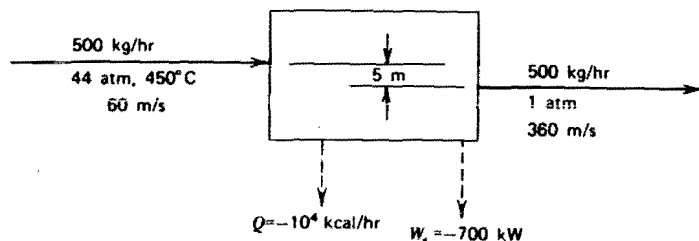
How would you simplify Equation 8.4-15 in each of the following cases?

- (a) There are no moving parts in the system.
- (b) The system and its surroundings are at the same temperature.
- (c) The linear velocities of all streams are the same.
- (d) All streams enter and leave the process at a single height.

EXAMPLE 8.4-2. Energy Balance on a Turbine

Five hundred kilograms per hour of steam drive a turbine. The steam enters the turbine at 44 atm and 450°C at a linear velocity of 60 m/s, and leaves at a point 5 m below the turbine inlet at atmospheric pressure and a velocity of 360 m/s. The turbine delivers shaft work at a rate of 700 kW, and the heat loss from the turbine is estimated to be 10<sup>4</sup> kcal/hr. Calculate the specific enthalpy change associated with the process.

Solution.



From Equation 8.4-15

$$\Delta H = Q + W_s - \Delta E_k - \Delta E_p$$

Normally heat, work, and kinetic and potential energy terms are determined in different units. To evaluate  $\Delta H$ , we will convert each term to kW(kJ/s), using conversion factors given on the inside front cover, first noting that  $m = (500/3600) = 0.139 \text{ kg/s}$ .

$$\begin{aligned} \Delta E_k &= \frac{m}{2g_c} (v_2^2 - v_1^2) \\ &= \frac{0.139 \text{ kg/s}}{2} \left| \frac{1 \text{ N}}{1 \text{ kg} \cdot \text{m/s}^2} \right| \frac{(360^2 - 60^2) \text{m}^2}{\text{s}^2} \left| \frac{1 \text{ W}}{1 \text{ N} \cdot \text{m/s}} \right| \frac{1 \text{ kW}}{10^3 \text{ W}} \\ &= 8.75 \text{ kW} \end{aligned}$$

$$\begin{aligned} \Delta E_p &= \frac{mg}{g_c} (z_2 - z_1) \\ &= \frac{0.139 \text{ kg/s}}{1} \left| \frac{9.81 \text{ N}}{\text{kg}} \right| (-5) \text{m} \left| \frac{1 \text{ kW}}{10^3 \text{ N} \cdot \text{m/s}} \right| = -6.81 \times 10^{-3} \text{ kW} \end{aligned}$$

$$Q = \frac{-10^4 \text{ kcal}}{\text{hr}} \left| \frac{\text{J}}{0.239 \times 10^{-3} \text{ kcal}} \right| \frac{1 \text{ hr}}{3600 \text{ s}} \left| \frac{1 \text{ kW}}{10^3 \text{ J/s}} \right| = -11.6 \text{ kW}$$

$$\begin{aligned} W_s &= -700 \text{ kW} \\ \Downarrow \\ \Delta H &= Q + W_s - \Delta E_k - \Delta E_p = -720 \text{ kW} \end{aligned}$$

But

$$\begin{aligned} \Delta H &= m(\hat{H}_2 - \hat{H}_1) \\ \Downarrow \\ \hat{H}_2 - \hat{H}_1 &= \Delta H/m \\ &= \frac{-720 \text{ kJ/s}}{0.139 \text{ kg/s}} = \boxed{-5180 \text{ kJ/kg}} \end{aligned}$$

hr

Literatuur:

Mills, E.S. and Graves, Ph.E. (1986). The Economics of Environmental Quality. W.W. Norton & Company, New York.

## Chapter 1

# *Resources, Production, Consumption, and Pollution*

Like other sciences, economics started by gradual separation from people's broad speculative thought about themselves, society, and the world around them. Each new intellectual discipline—physics, psychology, sociology, economics—emerged slowly during many decades. Identification of a birthday for economics is thus arbitrary, but the publication of Adam Smith's *Wealth of Nations* in 1776 is as good a date as any.

It is no exaggeration to say that economics originated in the deep concern among eighteenth-century thinkers about the relationship between people's living standards and their physical environment. Much early speculation among economists was about the most basic aspects of the relationship, that between food production and growth of the population to be fed. The physiocrats, who preceded Smith, could hardly recognize commodities other than food as genuine wealth and output. Smith greatly broadened the concepts of wealth and output to include other goods produced to satisfy people's needs and wants. Gradually, services—such as haircuts, teaching, and legal advice—came to be recognized as part of society's total production. Marxists have never recognized services to be socially valuable output ~~and to this day Communist countries do not include them in their measures of national output~~. The physiocrats, and classical

economists such as Smith, Thomas Malthus, David Ricardo, and Karl Marx, spent most of their lives studying whether and, if so, how people could produce enough goods with the labor and materials available to rise above a subsistence living standard.

Today it would be said that the classical economists were concerned mostly with resource, in contrast with environmental, economics. In part, the reason is that resource problems were more pressing than environmental problems during the eighteenth and nineteenth centuries. In part, the reason is also that environmental economics requires tools of analysis that were unavailable to the classical economists. The neoclassical economists, writing during a period centered on the turn of the twentieth century, placed great emphasis on developing tools of analysis. Much of the modern theory of the firm, the consumer, and market equilibrium was developed by neoclassical writers such as Alfred Marshall, Knut Wicksell, Léon Walras, and A. C. Pigou. Marshall and Pigou, in particular, developed the concepts of external economies and diseconomies, which are crucial in understanding environmental problems.

After World War II, tools of economic theory and statistical methods, and data concerning resources and the environment, have improved steadily. In addition, society rapidly became conscious of environmental problems in the 1960s and of shortages of fuels and resources in the 1970s. The result has been rapid growth in research by natural scientists, engineers, and economists on resource and environmental problems. Although serious inadequacies remain in the analysis and the data, environmental economics can now be treated in a unified and comprehensive way that was impossible as recently as the 1960s.

If one reviews the two-hundred-year history of economic thought about the relationship between people's living standards and their environment, one is impressed that progress in understanding has been painfully slow, but that it has been definite and quite steady.

### Resource and Environmental Economics

Economic activity consists of the application of energy to materials to transform them from their natural forms into forms in which they are useful to people. Behind this simple statement lies all the complexity of modern industrial society. Every commodity that you use—the house you live in, the food you eat, and the book you are

reading—is made by applying energy to materials extracted from the earth's crust, surface, atmosphere, or waters. Although it is less obvious, the same is true of the economic activities usually classified as services. A doctor providing patient care uses the hospital building, fuel to heat or cool it, and complex equipment as inputs to provide the service. In addition, the food he eats provides his energy used in providing his services. (Food is classified as a final or consumption good instead of an input in the national income accounts, but it is clearly necessary to enable people to produce services.)

All these materials have been extracted from the environment and processed with the use of energy. The natural forms of materials are their forms before people process them. Some are metals, fossil fuels, and other elements and compounds in the ground; some are living organisms on the earth's surface or in its waters; and some are gases in the atmosphere. When the energy used to transform materials is human or animal energy, food is the fuel. Only since the Industrial Revolution have human and animal work ceased to be society's major energy sources. Some energy is obtained by directly harnessing natural forces, such as hydroelectric power, tidal power, solar energy, and geothermal energy. A small but growing amount of energy is generated by atomic fission world-wide, although cancellations have been exceeding new applications for nuclear power plants in the United States since the Three Mile Island accident. In the United States, more than 90 percent of the energy generated comes from combustion of fossil fuels—petroleum, coal, and natural gas.

Materials are transformed by many complex mechanical, biological, and chemical processes to make useful products. Metals are mined with large amounts of unwanted materials. The materials are separated, refined, combined with other materials, and fabricated into useful products. Food is extracted in the agricultural and fisheries industries and then processed in factories, stores, and homes before consumption. Petroleum is pumped from the ground and then refined and processed into fuel, chemicals, plastics, and many other products.

As technology progresses and living standards rise, materials are subjected to more and more complex processing between their extraction from the environment and their consumption by people. The manufacture of a steam shovel requires much more, and much more complex, processing than the manufacture of enough hand shovels to move the same amount of earth. In fact, the period since

the Industrial Revolution can be characterized by the discovery of new materials, increasingly complex products and fabrication methods, and new sources of energy and ways to use it. The result has been that common people, at least in industrialized countries, have achieved living standards far above the subsistence level for the first time in history. Industrialization has in the past resulted in dramatic increases in materials and fuels extracted from the environment, although this trend may not continue in the future.

Unfortunately, no comprehensive historical data exist on materials extracted from the environment. We do know that currently materials extraction is on a truly massive scale, with many *billions* of tons of materials being extracted annually in recent years in the United States. To put the matter in more meaningful human terms, this is roughly 130 pounds per day per person! The presumption is strong that total materials extraction has grown somewhat less rapidly than total national output in the course of American history. One reason is that services, which presumably require less materials extraction per dollar of output than do commodities, have been an increasing share of total output as income and output have risen. Another reason is that commodity output per unit of materials extraction grows as technology improves and processing becomes more efficient.

It is also known that extractive industries have become a much smaller part of the American economy since the beginning of rapid industrialization in the early nineteenth century. Harold Barnett and Chandler Morse show that value added, or income earned, in extractive industries—agriculture, fisheries, lumbering, and mining—fell from 44 percent of gross national product (GNP) in 1870 to 10 percent in 1954. This dramatic decrease resulted in part from the reasons given in the last paragraph for gradual increases in output per unit of materials extraction and in part from large decreases in the prices of materials relative to prices of other inputs. Thus, for at least a century and possibly continuing at the present time materials have become increasingly plentiful despite rapid growth in worldwide demand.<sup>1</sup>

The basic reason for the long-term decline in the relative price of materials was that technology continually found ways of using plentiful and previously unused materials. Oil was not valuable until

1. See among the references Johnson, Bell, and Bennett, who support Barnett and Morse, but also Slade, who presents evidence of a recent turnabout.

technology enabled people to refine it and to make fuels and many other products from it. Likewise, plutonium was not a valuable fuel until science and technology enabled people to generate electricity from atomic fission.

The first half of the 1970s was a period of shortages and rapidly rising prices for certain materials, while the early 1980s experience appears to indicate a return to earlier declines in real prices of many materials. Some people suggest (for example Margaret Slade in the *Journal of Environmental Economics and Management*) that the period of increasingly plentiful materials has ended and that growth of demand has caught up with the ability of technology and of extractive industries to increase supply. That is far from certain, but it is wise to be aware that declining relative prices of materials may not continue indefinitely. We shall return to this topic in Chapter 13.

There have also been dramatic increases in energy use in the American economy. Data are much better on energy use than on use of total materials, lending confidence to the observations that follow. Danielsen, in *The Evolution of OPEC*, a book with a much broader scope than is suggested by its title, compiled and analyzed this (and other) information: From 1960 to 1973, the pre-embargo period, the Gross Domestic Product of the United States grew at an annual rate of 4.0 percent, while both total primary energy used and oil consumption grew at a 4.3 percent annual rate. In the post-embargo period of 1973–78, the GDP growth rate was only 1.7 percent, total primary energy used grew at 1.2 percent, and oil usage grew at 2.4 percent. The United States in 1980 used 39 percent of the free world's primary energy consumption and 27 percent of the world total.<sup>2</sup> In spite of early 1980s gluts of oil, energy use should be expected to grow somewhat more slowly than total output because of the shift to services in total output and because of gradual increases in efficiency of energy conversion. Services typically require less energy per unit of output than commodities. And each form of energy conversion—thermal electric generation, transportation, space heating, and others—is subject to gradual improvements in efficiency as technology progresses. It is likely that the increases in fuel costs during

2. The data of the text were taken from tables presented in Albert L. Danielsen's *The Evolution of OPEC*, 1982. Another useful reference for those interested in energy issues is James M. Griffin and Henry B. Steele's *Energy Economics and Policy*, 1980. Annual data may be obtained, additionally, from recent *Statistical Abstracts of the United States* and from various *Economic Reports of the President*.

the 1970s will result in further reductions in energy use per unit of total output. Except for direct harnessing of natural forces, such as hydroelectric generation, all energy consumption requires extraction of fuels from the environment. In fact, about half of all materials extraction consists of fuels in the United States.

An obvious question to ask, and the subject of environmental economics presented in this book, is what happens to the materials extracted from the environment for use in the economic system? Many details of the answer are complex and poorly understood. But the basic fact is that economic activity neither creates nor destroys matter; it merely transforms it. Economic activity cannot violate the laws of conservation of matter and energy. All materials extracted from the environment and inserted into the economic system continue to exist in some form. This notion has led to a concept called the materials balance, which is simply a set of accounts that show the source, use, and disposition of all materials extracted. In its simplest form it says: All the materials in the economic system at the beginning of a year plus those extracted during the year must equal those in the system at the end of the year plus those returned to the environment during the year. Put slightly differently, the increase in the stock of materials in the economic system during a year must equal the excess of withdrawals from over discharges to the environment during the year. The increase in the stock of materials in the system is another expression for capital accumulation, and includes increases in fixed capital, business inventories, and goods in the hands of consumers. The terms *withdrawals* and *extractions* are synonymous, as are *returns* and *discharges*.

The materials balance is an identity that plays exactly the role in resource and environmental economics that the identity between sources and dispositions of income plays in national income analysis. Both are simple and intuitively persuasive ideas once explained, but both lead to important insights and both help to avoid mistakes frequently made by those who do not understand them. Equally important, both have limitations. Complete economic theories consist not only of identities but also of relationships that represent technology and the behavior of people in the system to be analyzed. Production functions are examples of technological relationships and demand and supply functions are examples of behavioral relationships. Identities are not substitutes for carefully specified technological and behavioral relations. Much of this chapter is about the

materials balance. Subsequent chapters are mostly about behavioral and technological relationships.

Resource economics is about the extraction and use of natural resources. Environmental economics is about the return of materials to the environment and about alternatives to their return, such as reuse. The materials balance provides the link between the two subjects. It is unfortunate that we do not have a complete set of materials accounts for any year in the United States. A beginning has been made by Allen Kneese and a team at Resources for the Future, a Washington research institution at which much good work on environmental economics has been carried out.

It is important to understand that the materials balance, like all identities, holds because its terms are defined so that it must hold. The environment must be defined to include all places from which materials are obtained and all places to which they are discharged by people. The economic system must be defined to include all activities that use materials to contribute to people's living standards. For the most part, one's intuitive notion of the environment is appropriate for the materials balance—the crust of the earth, its land and water surfaces, and its surrounding atmosphere. In fact, most withdrawals are of materials on or just under the earth's land surface. Relatively small amounts are extracted from water and the atmosphere. Also, most materials are discharged on or just under the land surface. But more is discharged than is withdrawn from water and air, and discharges to those media give rise to most environmental problems. Note that the definition of the environment does not distinguish among private, government, and no ownership, although that distinction is important in understanding most environmental problems.

For the most part, one's intuitive notion of what constitutes the economic system and economic activity is also clear. Economic activity includes extraction of materials, production and consumption of goods and services, and the disposal of materials when they are not wanted in the economic system. By no means all economic activity, and by no means all polluting discharges, take place in the profit-seeking sector. Much economic activity is in the private nonprofit and government sectors.

Like all social-science concepts that cover a great variety of human activities, including the concepts of income and wealth, the terms in the materials balance are fuzzy at the edges of the subject. Strip

mining digs up enormous quantities of earth to get at the coal underneath. Once the coal is removed, the earth is put back more or less in place, and without being processed in any way. The earth so removed is an extraction in that it is removed in an important economic activity which causes a serious environmental problem. But there is no way of knowing the volume of such extractions. The same analysis applies to the top of a hill that is cut away in building a road and to material taken from the middle of a river and deposited at the edge in dredging a ship channel. Large amounts of materials are extracted in the sense of merely being moved around in the course of economic activity, although no one knows exactly how much. What about human respiration? Inspiration withdraws the mixture of gases in the atmosphere, and expiration discharges a different mixture containing more carbon dioxide and less oxygen. Respiration certainly contributes to people's well-being, and it alters the atmospheric environment; but it is quantitatively unimportant.

The basic notion behind the materials balance is that the distinction between the economic system and the environment is important. People and their activities are as much a part of nature as are animals and plants. The point of the materials balance is not to make an artificial distinction between people and nature. Instead, the point is that people and their activity can have important and controllable effects on the environment. Understanding the distinction between the economic system and the environment is the first step in learning to make rational decisions affecting both.

The materials balance says that except for capital accumulation, all materials withdrawn from the environment are returned. Two additional notions are needed to complete the panoramic view of resource and environmental economics.

First, people's welfare or utility is affected not only by the goods and services they consume, but also by the quality of the environment in which they live. Breathing badly polluted air or drinking badly polluted water can make people ill and in extreme cases, kill them. Less dramatically, the enjoyment of a day at the beach depends on the quality of the water and on the quantity of litter on the sand. There are many dimensions to environmental quality, and they will be explored in subsequent chapters. But it would be uninteresting were it not that people's welfare is affected not only by goods and services consumption, but also by environmental pollution caused by economic activity.

Second, every discharge to the environment alters its quality in some way. Discharges intended mainly to dispose of unwanted materials cheaply almost always impair the environment's quality, sometimes very seriously indeed. There are many less damaging ways to return materials to the environment, but virtually all require energy and other valuable resources. The relationships between discharges and environmental quality are complex and will also be explored in subsequent chapters. The main point is that emissions are not of interest *per se*, but rather become of interest because of their impact on environmental quality.

### Uses of the Materials Balance

The first use of the materials balance is to state carefully how the familiar economic notions of production and consumption fit into a materials framework. In the usual microeconomics textbook, resources first appear in conjunction with input-supply equations and they disappear as the products in which they are incorporated are consumed. There is nothing wrong with this picture. But it needs to be embellished and clarified for the important purposes of this book, which are to analyze where the materials come from and go to.

It was said in the last section that production and consumption do not create or destroy matter, but that they change its form. Iron ore in the ground cannot satisfy human needs and wants. For that purpose, it must be removed from the ground, processed, and fabricated, along with many additional materials, into cars, buildings, and other products. Production consists of conversion of materials from their natural forms into forms in which they satisfy human needs and wants.

Consumption is the reverse process. It consists of use of products, thereby converting materials from forms that satisfy human needs and wants to forms that cannot do so. Food is a nondurable commodity and is changed from useful to nonuseful form in a single act of consumption. An aluminum frying pan is a durable good and can be used to cook food for many years. But eventually a hole burns through it or the handle comes off and it is no longer useful. It has been gradually consumed. But the same amount of aluminum exists in the world before it is removed from the ground, while it is in the form of frying pans and after it has become unusable and been discarded. No consumption activity changes the total amount of mat-



ter. Of course, the amount of consumption, or utility, obtained from a product may depend on how it is made or used. If a TV set is poorly made or abused in use, it will be consumed after a few uses and will therefore yield little consumption or utility. A well-cared-for work of art may last hundreds of years, but it too deteriorates eventually. It is possible to economize on the materials needed to satisfy a given need or want by making and using products carefully, but it does not change the fact that neither creation nor destruction of matter occurs in production or consumption.

The foregoing implies that the notion of resource exhaustion is somewhat fanciful. All of human activity has not exhausted one ounce of the stock of aluminum, iron, or copper in the world. The same amounts of these elements are in and on the earth as were there a million years ago. Although economic activity does not affect the total amounts of materials, it does affect their availability. Some uses of materials make them more easily available for further use and some make them less easily available. It depends on the extent to which processing and consumption concentrate or disperse the materials. And that in turn depends on how materials are processed, what is made of them, how products are used, and what happens to them after they have been consumed. Resource exhaustion and availability are determined by the detailed performance of the economic system and not merely by the rate of extraction. The current performance of the economic system makes it easy to reuse some materials and hard to reuse others. But *ways will be found to reuse most materials if it is expensive either to extract materials from the environment or to return materials to the environment.*

The term *resource exhaustion* may be used to mean that materials are processed and discharged to the environment in ways that make it difficult to reuse or re-extract them. Modern products are complex and combine many materials in physical and chemical ways that may make it difficult or impossible to separate the materials.

Alternatively, the term *resource depletion* may be used to mean that all of a material that can be easily extracted is already incorporated in products in the economic system. All the world's copper or aluminum might someday be contained in wires, frying pans, and other products in use. Then the only source of the material would be its reuse from existing products. In that case, the material would be exhausted in the sense that there was no more to be extracted from the environment. A less extreme form of the same situation would

occur if such a large fraction of some material were in products that the cost of obtaining it from used products were less than the cost of further extraction from the environment. Then there would be no extraction and it might be useful to say that the material was exhausted, at least in an economic sense. Although there is probably no material whose entire supply now comes from used products, there are many materials whose supply is partly from reuse. Increasing percentages of expensive metals such as copper are in this latter category.

Fuels are somewhat different. Fuels are not incorporated in products. Instead, energy is extracted from them by combustion. This energy is eventually dissipated into outer space in the form of heat, along with a much larger volume of heat that is radiated by the earth after having been absorbed from the sun. Once that heat leaves contained areas such as pipes and buildings, it is mostly irretrievable. Thus fuels are exhaustible in an almost literal sense in which other materials are not. Of course, the source of all energy stored in fossil fuels, the sun, is itself exhaustible in that it contains only a finite amount of energy that will eventually be dissipated. As with all environmental questions, the important issues are quantitative: How much and how soon? These questions will be discussed in a later chapter.

2 Another use of the materials balance is to clarify the notion of replenishable resources. Fresh water, wood, and food are sometimes classified as replenishable resources, in contrast with metals and other resources that are referred to as exhaustible. The term is useful provided it is properly interpreted. It does not mean that the creation of replenishable resources violates the laws of conservation of matter and energy. Instead, it means that there are natural processes that do just what economic activity does: apply energy to materials to change their form. Trees grow because energy from the sun is used to extract materials from the earth's crust and to combine them in the form of trees; there is a continuing supply of fresh water because the sun provides energy to evaporate water from oceans and to deposit it as fresh water on land masses. Gathering and hunting societies depend on the natural production of food. Agricultural societies organize the process of food production as part of economic activity. Thus natural processes replenish certain resources without man's intervention. People can and do intervene to alter and augment natural processes. People began to cultivate crops only a relatively few

thousand years ago. Forests have been increasingly cultivated the same way in recent years. People are just beginning to produce fresh water by desalting salt or brackish water.

3 The final use to be made of the materials balance in this chapter is to classify methods of improving environmental quality. The basic message of this book is that a wealthy society like ours has a wide range of options as to the kinds, amounts, and locations of pollution it wishes to accept. And it is important to understand at the start that some pollution will be preferred to none since all but the most trivial improvements in environmental quality involve costs that must be borne by all or part of society. Some environmental protection and improvement measures are cheap and bestow large benefits. Others are expensive and entail dubious benefits. Sorting these issues out is the nuts and bolts of environmental economics. The materials balance can help with the first steps along the way.

The materials balance says that discharges equal the excess of withdrawals over capital accumulation. Thus, by definition, the only ways to reduce discharges are to withdraw less or to accumulate more. Increasing the rate of capital accumulation can be dismissed out of hand as a way of solving environmental problems. Capital should be accumulated to the extent justified by its contribution to the production of goods and services. To accumulate otherwise unwanted capital as a means of material disposal would rightly be regarded as itself a form of pollution.<sup>3</sup> It would be better not to withdraw the materials in the first place. In this book, it will be assumed that capital accumulation is not a viable means of environmental protection. That does not preclude the possibility that other environmental protection measures might affect the rate of capital accumulation or the kind of capital that is accumulated.

Thus the only practical way to reduce discharges, one of several approaches leading to improved environmental quality, is to reduce material withdrawals from the environment. One way to reduce withdrawals is simply to produce less output, that is, to lower living standards. The dismantling of industrial society and the return to a simpler economy which withdraws less material from the environ-

3. Radioactive wastes from atomic electric plants are an exception to this statement. There appears to be no safe way to return them to the environment. Practice in the United States has therefore been to store them in concrete drums. This must be interpreted as capital accumulation to avoid polluting discharges.

ment has indeed been suggested by some writers. It is a drastic solution and is a counsel of despair in that it explicitly abandons the goal of improving living standards by goods and services production, which is what economics has been about for two centuries and what most human effort has been about since people appeared on earth. Furthermore, although total returns are proportional to total withdrawals, the common dimensions of pollution are not proportional to living standards. Most poor countries have much less good quality environments than do rich countries. For example, many have badly polluted public water supplies. Nevertheless, intentional reduction of production would be justifiable if the alternative were to so damage the environment that human life was impossible or possible only at a lower level of welfare than would result from reduced production of goods and services. Fortunately, it is likely that such drastic cures are unnecessary. As with capital accumulation, other environmental protection measures than direct reduction of output may have the indirect effect that goods and services production is reduced. Productive resources are scarce and devoting more to environmental protection leaves less to devote to goods and services production. For example, if a large part of the construction industry is employed building sewage-treatment plants, it is necessary to restrict construction of houses, offices, factories, and roads. Likewise, if we produce chemicals to treat wastes, we must restrict production of chemicals for other purposes.

A second way to reduce withdrawals and discharges is to increase the reuse or recycling of materials, that is, to retain and reuse materials within the economic system once the consumption value of the products they are contained in is gone. A given rate of goods and services production can be maintained while reducing both withdrawals and discharges by reusing materials. For example, trees are felled to manufacture newspapers and petroleum is pumped from the ground to be used as a fuel in thermal electric generation. Newspapers are mostly returned to the environment by placing them in dumps and landfills. A day or two after publication, a newspaper's consumption value is gone although its physical condition is virtually unchanged by consumption. Petroleum is returned to the environment partly by wastes generated in refining, but mostly by discharge of gases and heat to the air during combustion. The production and consumption of newspapers and electricity could be maintained, while reducing the withdrawal and discharge of petroleum, if used news-

papers were used as fuel in thermal electric plants. The amount of newspaper produced and returned to the environment would be unchanged, but less petroleum would be needed. Of course, the time, place, and form of the return of newspapers would be altered by burning them in a thermal electric plant instead of burying them in a landfill, but the amount of newspaper returned would be unchanged. None of this proves that burning newspapers in thermal electric plants is advantageous, only that it is possible. Indeed, it is possible to burn most organic wastes in power plants, although whether this is advantageous is an economic question, discussed later in the book.

As a second example, glass bottles can be collected, cleaned, and reused for their original purposes, thus reducing by equal amounts the materials withdrawn to make glass and the discharge of glass to the environment. Reuse of bottles would leave unchanged the number of bottles available to be used as containers. Glass is made from inexpensive and widely available substances that are innocuous in the environment in their natural state. As is common, processing these materials to make glass transforms them into a form in which they become annoying and dangerous if not returned to the environment with care. As always, whether recycling is or is not desirable is an economic issue, and such issues are seldom immediately clear. Moreover, recycling may be undesirable at one time and desirable at another: for example, rising fossil-fuel prices might raise the cost of producing new aluminum cans relative to the cost of recycling, which is much less energy intensive. Many materials are reused in the normal course of production and consumption. Many more could be reused, all at some cost. Despite the enthusiasm for recycling in recent years, the evidence is that the amount of materials reuse still depends mostly on what it has always depended on: relative costs of new and used materials and the technology of materials reuse.

*A third way to reduce withdrawals and discharges is to increase the technical efficiency with which materials are used*, thereby increasing production of commodities per unit of materials withdrawn from the environment. A pervasive element of technological progress for a century or more has been a gradual improvement in the efficiency of materials use. Technological progress increases the efficiency of materials use by subjecting them to more and more careful processing and by finding uses for previously discarded materials. In the early years of the century, much of the content of crude oil was returned to the environment after fuel was refined out. Now a wide

range of other products—plastics, chemicals, medicines, and many others—is made from materials previously discarded. A different example is that better layout of patterns on fabrics and metals reduces the waste when the material is cut. As a third example, better combustion has increased the amount of usable energy obtained per pound of fuel burned for many purposes. Most improvements in materials use come about as a by-product of the search for better products and cheaper means of production. The reasons that technological change is successfully pursued in one direction instead of another are poorly understood, and little is known about the likelihood of success in trying to turn technological change more in the direction of increased efficiency in materials use. But materials use does respond to economic incentives. When fuel becomes expensive, buildings are insulated and fuel-efficient vehicles are demanded and produced. When a metal becomes expensive, industries spend money to avoid its waste and to find less costly substitutes.

Efficiency in materials use includes efficiency in construction, maintenance, and use of capital goods and consumer durables. Materials withdrawals and returns can be reduced by making capital goods that are more durable, by better maintenance of capital goods, and by more care in their use. The services yielded by structures and machinery depend very much on how they are built, maintained, and used. Although there is widespread belief that products are less well made and durable than formerly, there is almost no evidence to support the claim. Also, it is possible to invest excessive materials and other inputs in making products durable. The important question is whether competition among firms results in optimally durable products. Diversity is likely to characterize the optimal durability since uses will vary (as for example the paper plate—certainly the extreme case of “planned obsolescence”) and tastes or incomes will vary (e.g., the Mercedes versus the Chevrolet).

Technology also creates environmental problems. Persistent pesticides, such as DDT, or atomic energy are products of modern technological progress whose environmental effects are of great concern. These effects were not anticipated during development of the products, but some writers tend to assume that most new technology is likely to do more harm than good. This is a badly distorted view. Technological advance has generally favored the environment. That is, homes are heated largely by electricity or natural gas now, rather than with coal. horses (while rustic in small numbers) would

be much more polluting than cars as the sole means of transportation in New York City, and so on. Moreover, technological progress has been extremely important in raising living standards during the last century or two. It will continue to be important and will be crucial in finding alternatives to dwindling supplies of some materials.

Thus several options are available to society to alter the amounts of materials it withdraws from and returns to the environment. But the one option that is not available is a policy of no returns or no discharges. It is impossible to reuse all materials and economically infeasible to reuse large amounts. A zero-discharge economy would be a zero-withdrawal economy; a zero-withdrawal economy would be a zero-production economy and a zero-production economy would be a zero-people economy. A zero-discharge economy is a figment of dreamers' imaginations.

### Other Environmental Protection Measures

Fortunately, reducing the total volume of discharges is by no means the only way to reduce pollution and other means are often more desirable. Pollution is damage to the environment that impairs its usefulness to people. Environmental damage depends not only, or even mainly, on the volume of discharges, but also on the kinds of discharges and the locations of discharges. Thus pollution depends on the details of resource allocation in the economy; and much of this book is concerned with exploration of these issues.

Almost all material withdrawals from the environment are from the crust and land surface of the earth, including almost all metals, fuels, and food. Only small amounts are from its waters and its atmosphere. In principle, large amounts of materials could be returned to the land after use in more or less their form before withdrawal, although it would be extremely expensive in some instances. Such returns would hardly be classified as polluting. In fact, large amounts of materials are returned to the air and water environments, and they cause most of the pollution problems of great concern. Thus one way to reduce pollution, although not total discharges, is to abate discharges to the air and water environments and to increase amounts of materials returned to the land. For example, sewage consists of organic material most of which was extracted from the earth's crust before its consumption generated sewage. Most cities collect the sewage in pipes and some discharge it raw to the nearest water body.

In that case the organic material withdrawn from the land is discharged to the water environment. Most American cities treat sewage in a treatment plant, in which case most of the organic material is converted into a solid waste called sludge. With further processing, sludge can be returned to the land and used as high-quality fertilizer. Then most of the organic material is returned to the land and is nonpolluting. Of course, the fact that the sewage is treated does not guarantee that it is nonpolluting. New York City treats most, but not all, of its sewage, and then dumps the sludge in the water just a few miles farther out than it dumps its untreated sewage.

Thus the most important way to abate pollution is to reduce residual discharges to the air and water environments and instead to discharge materials to the land. But that is not the entire story. In the first place, it is neither possible nor economical to eliminate all discharges to air and water. The air and water environments, as well as the land, can absorb limited amounts of most discharges without impairment of their quality. Even when abused by excessive discharges, the environment usually regenerates itself, although sometimes only slowly. Discharge of limited amounts of wastes is a legitimate use of the absorptive capacity of each environmental medium. The damage done by discharges to the environment depends greatly—a point we will emphasize again and again throughout the book—on the time, form, and place of such discharges. The damage depends to a much smaller extent on the sheer volume or tonnage of discharges. A large part of this book is about the ways society should ration discharges to air and water. In the second place, discharges to the land can also entail severe environmental damage. One need only look at the town dump, an abandoned strip mine, or a slag heap to appreciate the possibility of such damage. But it is of a lesser order of magnitude than air and water pollution.

It is common to refer to air, water, and land as sinks into which materials are discharged. The notion of a sink suggests a long residence time of the material in the place identified. But there are important connections between environmental sinks. Ashes discharged to the air eventually fall onto land or water. Soil disturbed in strip mining may wash into streams. Heat discharged to water passes to the atmosphere as water evaporates. Frequently materials do the most damage in the medium to which they are discharged. But it is important to ask about movements of pollutants among

environmental media. For example, if the ocean is the ultimate sink for airborne fuels and fuel by-products, then the magnitude of damages to ocean life from oil-tanker spills, drilling accidents, and other marine discharges would be dwarfed in comparison.

There is a basic difference between land on the one hand and air and water on the other which accounts for their different positions in environmental problems. It is technically relatively easy to define property rights in land. The result is that most land is privately owned and traded on markets. Individual owners benefit when the land is productive and attractive and suffer when it is abused and ugly. Thus private owners limit the amounts, kinds, and forms of materials they discharge or permit to be discharged on their land. Air and water are in large part fugitive substances whose movements are difficult to control and predict. It is difficult to establish property rights in air and water and they are part of what is usually referred to as the public domain. This means that everyone can use them more or less freely. It is extremely cheap to dispose of unwanted materials by washing them into the nearest stream or sending them up the chimney. It is much more expensive to collect and transport residuals to open land that they can be deposited on or under, especially from urban centers where most materials are used. Wastes discharged to air and water are widely dispersed by natural forces. The harmful effects of each discharge are therefore felt by many people, albeit only slightly. Everyone thus finds it easy to discharge materials to the air and water environments, and everyone suffers. The importance of property rights and public goods to an understanding of environmental quality will be further clarified in the next chapter.

Location of discharges, both in the time and in the spatial dimensions, has already been indicated to be of critical importance to proper environmental policy. The damages resulting from any given quantity of emissions to the air or water can be orders of magnitude larger or smaller depending on where and when they are discharged. Considering air, emissions in downtown areas of major cities where densities of fifteen thousand people per square mile are not uncommon will be, roughly, a thousand times more damaging than those same emissions in a rural area with fifteen people per square mile. Emissions during periods of stagnant meteorological conditions (air inversions) are, similarly, much more damaging than those same emissions at other times.

In the case of water, an urban lake might have far more recreational, fishing, and other users than a rural lake, hence emissions into the former are (other things equal) much more damaging and undesirable. During the late summer, stream flow is normally low and water temperatures high—emissions at this time are much more damaging to stream biota than at other times of the year. As will be seen, these considerations—where and when emissions occur—are largely ignored or mishandled in current environmental policy, at great disservice to mankind.

### Pollutants: Categories, Sources, Trends

For each environmental medium there are many different types of pollutants, with each having diverse sources. Some of these pollutants are of increasing concern while others are becoming of less concern with the passage of time. This section briefly introduces some environmental jargon, but it is useful jargon and will additionally give more of a “real-world” feel to the study of environmental economics. Additional detail, by environmental media categories, is presented in later chapters.

Air Air pollution was synonymous, up until about 1950, with “smoke”—what would now be referred to as Total Suspended Particulates (TSP). This pollutant, along with various sulfur oxides ( $\text{SO}_2$ ,  $\text{SO}_3$ , and  $\text{SO}_4$ ), comes predominantly from fossil-fuel combustion and industrial processes. Particulates (diverse in chemical structure) and sulfur oxides (especially the non- $\text{SO}_2$  forms) were the pollutants implicated in the health damages resulting from air inversions in the 1940s, 1950s, and 1960s in Donora (Pennsylvania), London, New York, and elsewhere. Among the commonly monitored pollutants, TSP and  $\text{SO}_x$  continue to be of principal concern from the perspective of human health.

Fortunately, during the 1970s air quality improved with respect to these pollutants. In part, that improvement was due to environmental controls enacted during this period, but part was due to voluntary conversions from coal, which is messy and bulky, to alternative energy sources for residential heating. As these alternative fuels rose in price in the 1970s due to OPEC oil price increases, this long-standing trend may be reversed, eliminating much of the past decade's environmental progress. Already one is seeing greatly increased use

of wood-burning stoves—among the most environmentally damaging residential-heating alternatives—in many parts of the United States. Even lovely resort areas, such as Aspen, Colorado, are currently experiencing severe local pollution problems, and it is estimated that a substantial portion of the winter pollution haze in Denver and parts of the Northeast is due to stoves and fireplaces.

In terms of tonnage of emissions, the transportation sector, primarily the automobile, is now the largest polluting sector. Carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NO<sub>x</sub>), and lead are the principal pollutants emitted by the automobile. Additionally, ozone (O<sub>3</sub>) is formed, in complicated photochemical reactions in the atmosphere, from HC and NO<sub>x</sub>, which operate as so-called precursors. Lead and carbon monoxide have very serious health consequences in high concentrations, although such concentrations are unlikely to occur under ordinary circumstances in ambient air. Ozone and NO<sub>x</sub> have very weak health impacts, while HC appears to have no short-run health effects at concentrations near those actually observed in urban atmospheres. However, acute health effects may not be as important as health problems associated with chronic, long-term exposures. Hydrocarbons, HC, are actually composed of at least 200 different chemical compounds, several of which might be carcinogenic (cancer-causing), and lead is so impervious to degradation that even low-level exposures can accumulate in the environment in adverse ways. The lack of information about such long-term effects makes environmental analysis live and exciting. But it greatly complicates rational environmental decision-making.

Trends in atmospheric concentrations of transportation-related pollutants are mixed. On the positive side, add-on control devices (for example, exhaust gas recirculation systems, catalytic converters) have reduced emissions substantially of hydrocarbons, HC, and carbon monoxide, CO. However, the more complete burning associated with the higher temperatures and better oxygen supplies of such emission systems, while converting HC and CO to relatively harmless water and carbon dioxide, tends to also create more nitrogen oxides, NO<sub>x</sub>, from the normally inert and harmless nitrogen gas which comprises four-fifths of the atmosphere. Hence, CO and HC emissions have been declining, while NO<sub>x</sub> has increased. Atmospheric lead concentrations appear to be falling in very recent years, due mainly to the larger number of catalytic-converter-equipped cars, which require lead-free gasoline.

Overall, most dimensions of air quality affected by automobile emissions appear to be improving somewhat. However, the larger number of vehicles in the rapidly growing sunbelt cities has caused photochemical-smog (mostly ozone) problems to worsen in some areas. Continued general improvement is expected as the automobile population ages, with newer cleaner vehicles replacing their older more polluting counterparts. Partially offsetting this expectation is the fact that substantial percentages (2 to 13 percent according to one estimate<sup>4</sup>) of catalytic-converter-equipped cars are being fueled by leaded gas; such cars are as much as 100 times dirtier than they would have otherwise been.

The measures of the preceding air contaminants, and standards applicable to them, are increasingly given in terms of micrograms per cubic meter ( $\mu\text{g}/\text{m}^3$ ) of air. Other measures sometimes used are parts per million (ppm), parts per hundred million (pphm) or, rarely, parts per billion (ppb). Larger numbers indicate lower quality of air from the perspective of the specific measured pollutant.

Overall, and in spite of delays and confrontation between states and the federal government, the 1970–1980 decade was one of progress in air quality. During the 1940–1970 period, air pollution emissions grew 40 percent, while in the more recent decade particulate emissions are down 50 percent, leading to a 20 percent improvement in ambient particulate levels. Similar progress has been noted for sulfur dioxide, SO<sub>2</sub>, and carbon monoxide, CO. This progress has not come cheaply: 90 percent of the 68 percent increase between 1971 and 1978 in the real capital costs of providing coal-fired electricity was for pollution control. P. R. Portney estimates, in 1978 dollars, that the real cost of efforts to improve air quality between 1978 and 1987 will be about \$280 billion (\$111 billion for mobile source control, \$83 billion for industrial control, \$66 billion for utility control, and \$20 billion for governmental sources of pollution).

Water Interest in water pollution predates interest in air pollution both historically in the United States and in the context of

4. This figure, and a great many others throughout the book in discussions about air quality, come from articles in the *Journal of the Air Pollution Control Association* (in this case, *JAPCA*, November 1980, p. 1232). To avoid numerous lengthy citations, we shall merely note here that much of the information presented here comes from various monthly issues of this journal dating from the early 1980s.

developing countries today. However, the study of water quality shares two difficulties with the study of air quality. First, how to define "quality" is not easy since water quality, like air quality, has many dimensions. Second, the hydrological mechanism that converts effluent discharges along a stream into in-stream water quality is, like the meteorological mechanism converting emissions into air quality, poorly understood. Yet the hydrological mechanism is vital to the conduct of rational water quality policy: *benefits* of clean-up relate to water quality changes resulting from a policy action, while *costs* of clean-up relate to discharges. Hence to compare benefits with costs of a policy response (we will see in the following chapter why this comparison is desirable), we must be able to convert changes in discharges to changes in water quality.

The most common measures of water quality relate to the presence of either dissolved oxygen (DO) or deoxygenating wastes, for example, biochemical oxygen demand (BOD). This water-quality parameter—oxygen—has an important bearing on the quality and diversity of stream life, with rainbow trout, for example, being unable to survive in water that can support carp quite nicely.

Other less frequently monitored measures of water quality are microbiological content (total coliform, fecal coliform), acidity or alkalinity (pH, total alkalinity), and presence of solids (total hardness, total dissolved solids, "conductivity," suspended solids, "turbidity"). Conductivity measures how easily electricity passes through water and turbidity is a measure of the clarity of the water. Water that "looks clean" may, like air, be highly polluted—for example, the water is much clearer in acid-rain-polluted lakes than in lakes with a normal pH.

Specific sources of water pollution will be discussed in detail in a later chapter, but some observations may usefully be made now. First, in terms of bulk, the largest single "point-source" polluter category is governmentally owned wastewater treatment plants. Second, point sources (easily identified sources discharging piped or channeled effluent which may be, or not be, toxic) have generally become sufficiently highly controlled that *non*-point sources, such as runoff from agriculture, construction, and urban land uses, would in many cases violate existing water-quality standards *even if* point sources had zero discharges. The policy implication is that other approaches (water-absorbent parking lots, earth barriers to retain runoff, and so on) should at least be examined as an alternative to

additional, very costly point-source controls. Finally, as with the automobile in the case of air, trade-offs in attempts to control pollution emerge in unanticipated ways: using hypochlorides to kill fecal coliform in sewage also destroys nitrogen-oxidizing organisms in a stream, reducing its natural waste-assimilative capacity.

Trends in water quality are mixed, as was the case with air. DO levels appear to be increasing generally, on the positive side, but nutrient levels have also been growing, with resulting undesirable algae blooms in stagnant water bodies. As with air, positive or negative trends have a strong spatial component, with some rivers or lakes improving (for example, the Great Lakes, Hudson River, Thames River, among others) while continuing deterioration characterizes rivers and lakes in other locations.

The measures of water quality are, as was true with air, of many types and somewhat confusing. Not only are ppm, pphm, or ppb used as with air, but also milliliters per liter (ml/l), milligrams per liter (mg/l), and, for dissolved oxygen, percent of saturation.

---

Other Environmental-Quality Dimensions Thermal pollution, while not of great significance for air, is a major water pollutant and is associated almost exclusively with energy production. Water is used as a coolant (as in the large cooling towers one sees in the air case) and returned to a stream or lake. The heat rise can harm some species directly or can affect the aquatic system indirectly since warmer water contains less DO.

Similarly noise pollution, while not important for water (as far as we know), is a major air pollutant, one that despite being non-chemical is frequently cited in urban surveys as the most irritating neighborhood disamenity.

---

Pollution of the land, while much less of an environmental problem than air or water pollution, is of considerable concern in that large numbers of people may be damaged by aesthetically loathsome urban blight, dumps, strip mines, and the like. Emissions to the land are growing, as we know they must if overall material use increases: improvements in overall air or water quality must involve increases in materials discharged to land. As noted earlier, *daily* discharges into all environmental media must approximately equal daily materials extraction, the latter being the weight of the entire U.S. population.

Only one hazardous material (lead, emitted into the atmosphere

by vehicles) has been mentioned thus far. This is not because hazardous materials are environmentally unimportant. Quite the opposite is the case. Hazardous materials such as PCB, arsenic, lead, asbestos, mercury, beryllium, sulfuric acid, vinyl chloride, fluoride, hydrogen sulfide, reduced sulfur, and radioactive substances, while exceedingly small in bulk when compared to pollutants already discussed, are very damaging and also poorly understood. Moreover, the number and variety of such pollutants are increasing, as is the amount discharged of each.

Damages from hazardous substances take the form of cancer, mutation, brain damage, and sterility, to name only a few impacts. It can confidently be predicted that, to the extent that future environmental policy is rational, hazardous substances will receive far greater attention and control resources than they have in the past. Recent political concerns also suggest that this change in relative emphasis is likely to occur.

The bare bones of the environmental problem have now been laid out. Enough has been said to indicate that pollution of the air, water, and land is a problem of resource allocation. Why do we have these resource-allocation problems? What policy responses to these problems will lead to their solution in the most desirable way? Understanding the answers to these questions is to clothe the bare bones of the environment with solid economic analysis. Chapters 2, 3, and 4 show how the economic theory of resource allocation can be used to shed light on the causes and solutions of pollution problems.

#### REFERENCES AND FURTHER READING

- Barnett, Harold, and Morse, Chandler. *Scarcity and Growth: The Economics of Natural Resource Availability*. Baltimore: Johns Hopkins University Press, for Resources for the Future, Inc., 1963.
- Baumol, William, and Oates, Wallace. *Economics, Environmental Policy and the Quality of Life*. Englewood Cliffs, N.J.: Prentice-Hall, 1979.
- Council on Environmental Quality. *Environmental Quality*. Washington, D.C.: U.S. Government Printing Office, published annually.
- Danielsen, Albert L. *The Evolution of OPEC*. New York: Harcourt Brace Jovanovich, 1982.
- Enthoven, Alain C., and Freeman, A. Myrick, eds. *Pollution, Resources and the Environment*. New York: Norton, 1973.
- Griffin, James M., and Steele, Henry B. *Energy Economics and Policy*. New York: Academic Press, 1980.
- Johnson, Manuel H.; Bell, Frederick W.; and Bennett, James T. "Natural Resource Scarcity: Empirical Evidence and Public Policy." *Journal of Environmental Economics and Management* 7, no. 3 (September 1980): 256-71.
- Journal of the Air Pollution Control Association*, A Monthly Journal Devoted to Air Quality Management.
- Kneese, Allen; Ayres, Robert; and d'Arge, Ralph. *Economics and the Environment*. Baltimore: Johns Hopkins University Press, for Resources for the Future, Inc., 1970.
- Meier, Richard. *Science and Economic Development*. Cambridge, Mass.: MIT Press, 1966.
- Schumpeter, Joseph. *A History of Economic Analysis*. New York: Oxford University Press, 1954.
- Slade, Margaret E. "Trends in Natural-Resource Commodity Prices: An Analysis of the Time Domain." *Journal of Environmental Economics and Management* 9, no. 2 (June 1982): 122-37.
- Tolley, George S.; Blomquist, G. C.; and Yaron, D. *Environmental Policy: Water Quality*. Cambridge, Mass.: Ballinger, 1983.
- Tolley, George S.; Graves, Philip E.; and Cohen, Alan S. *Environmental Policy: Air Quality*. Cambridge, Mass.: Ballinger, 1982.
- Tolley, George S.; Graves, Phillip E.; and Blomquist, Glenn C. *Environmental Policy: Elements of Environmental Analysis*. Cambridge, Mass.: Ballinger, 1981.



## Literatuur.

- [1] Chenery, H.B. (1953). In W. Leontief (Ed.), Studies in the Structure of the American Economy. Oxford University Press, New York. Chapter 8. Process and Production Functions from Engineering Data. p.299-300.
- [2] Georgescu-Roegen, N. (1971). The Entropy Law and the Economic Process. Harvard University Press, Cambridge U.S.A.
- [3] Morowitz, H.J. (1966) Physical Background of Cycles in Biological Systems. J. Theoretical Biology, 13, 60-62.

## Aanbevolen literatuur:

- Hitomi, K. (1979). Manufacturing Systems Engineering. Taylor & Francis Ltd., London.  
De nadruk ligt bij dit werk op de relaties tussen produktietechnologie en produktmanagement. Het accent ligt op de mechanische technologie, waarbij ook geavanceerde komputer gestuurde systemen worden besproken.
- Manufacturing Systems (CIRP Journal).  
Dit tijdschrift geeft een goed overzicht van de technische ontwikkelingen binnen produktiesystemen.
- Vauck, W.R.A. (1969). Grundoperationen Chemischer Verfahrenstechnik. Verlag Theodor Steinkopf, Dresden.  
Een technisch handboek voor de chemische technologie.
- Dolezalek, C.M. (1982). Planung von Fabrikanlagen. Springer-Verlag, Berlin.  
Een algemeen ytechnisch-bedrijfskundig handboek over de inrichting van produktiesystemen in de mechanische technologie.
- Hyvälinen, L. (1970). Mathematical Modelling for Industrial Processes. Springer-Verlag, Berlin.  
Diepgaande algemene analysemethode voor industriële processen, met de nadruk op optimaliseringstechnieken.
- Alting, L. (1982). Manufacturing Engineering Processes. Marcel Dekker, Inc. Basel.  
Vanuit een werktuigbouwkundige ontwerp-optiek geschreven boek over produktieprocessen. Van harte aanbevolen voor de meer technisch georiënteerde student.

## Technische handboeken

- Beltz, W. en Küttner, K. (1981). Taschenbuch für den Maschinenbau/Dubbel. Springer-Verlag, Berlin. Het meest erkende en volledige technische handboek. Het accent ligt op de werktuigbouwkunbde.
- Perry, R.H. (1973). Chemical Engineers' Handbook. McGrawhill, New York.  
Het handboek voor de chemische technologie. Het accent ligt op de technische uitvoering van chemische processen.
- Recknagel, H. (1981). Taschenbuch für Heizung und Klimatechnik. R. Oldenbourg, München.

## 2. Voorvoegsels bij het SI

In Tabel 5 worden de namen en symbolen opgesomd van voorvoegsels waarmee decimale veelvoudten en factoren van SI-eenheden kunnen worden gevormd, zoals aangenomen door de Algemene Conferentie inzake Maten en Gewichten (CGPM).

Tabel 5. SI-voorvoegsels

Factor	Voorvoegsel	Symbool	Factor	Voorvoegsel	Symbool
$10^{12}$	tera	T	$10^{-1}$	deci	d
$10^9$	giga	G	$10^{-2}$	centi	c
$10^6$	mega	M	$10^{-3}$	milli	m
$10^3$	kilo	k	$10^{-6}$	micro	$\mu$
$10^2$	hecto	h	$10^{-9}$	nano	n
$10^1$	deca	da	$10^{-12}$	pico	p
			$10^{-15}$	femto	f
			$10^{-18}$	atto	a

## 3. Eenheden die worden gebruikt met het Internationale Stelsel

Eenheden die niet tot het Internationale Stelsel behoren, maar die toch belangrijk zijn en algemeen worden gebruikt, worden gegeven in Tabel 6. De combinatie van deze eenheden met SI-eenheden dient echter slechts te worden toegestaan in een beperkt aantal gevallen; met name de aanduiding kilowattuur (kWh) (thans slechts in gebruik als eenheid van elektrische energie) dient uiteindelijk te worden afgeschaft.

Tabel 6. Eenheden die worden gebruikt met het Internationale Stelsel

Naam	Symbool	Waarde in SI-eenheden
minuut	min	1 min = 60 s
uur	h	1 h = 60 min = 3.600 s
dag	d	1 d = 24 h = 86.400 s
liter	l	1 l = 1 dm <sup>3</sup> = 10 <sup>-3</sup> m <sup>3</sup>
ton	t	1 t = 10 <sup>3</sup> kg
graad	°	1° = ( $\pi/180$ ) rad
minuut	'	1' = (1/60)° = ( $\pi/10.800$ ) rad
seconde	"	1" = (1/60)' = ( $\pi/648.000$ ) rad

Er bestaan enkele andere eenheden, buiten het SI, die op gespecialiseerde gebieden hun nut hebben, maar waarvan de in SI-eenheden uitgedrukte waarden door proeven moeten worden verkregen en derhalve niet exact bekend zijn (Tabel 7).

Tabel 7. Eenheden die worden gebruikt met het Internationale Stelsel en waarvan de waarden in SI-eenheden door proeven zijn verkregen

Naam	Symbool	Benaderde waarde in SI-eenheden
electronvolt	eV	1 eV = 1,60219 x 10 <sup>-19</sup> J
geünificeerde atomaire massa-eenheid	u	1 u = 1,66053 x 10 <sup>-27</sup> kg
astronomische eenheid	AU	1 AU = 149.600 x 10 <sup>6</sup> m
parsec	pc	1 pc = 206.265 AU = 30.857 x 10 <sup>12</sup> m

Gezien de bestaande praktijk, worden de in Tabel 8 opgesomde eenheden tijdelijk aanvaard voor gebruik bij de eenheden van het Internationale Stelsel.

Tabel 8. Eenheden die nog beperkte tijd mogen worden gebruikt naast het Internationale Stelsel

Naam	Symbool	Waarde in SI-eenheden
zeemijl	—	1 zeemijl = 1.852 m
knoop	—	1 zeemijl per uur = (1.852/3.600) m/s
ångström	Å	1 Å = 0,1 nm = 10 <sup>-10</sup> m
are	a	1 a = 1 dam <sup>2</sup> = 10 <sup>2</sup> m <sup>2</sup>
hectare	ha	1 ha = 0,01 km <sup>2</sup> = 10 <sup>4</sup> m <sup>2</sup>
barn	b	1 b = 100 fm <sup>2</sup> = 10 <sup>-28</sup> m <sup>2</sup>
bar	bar	1 bar = 0,1 MPa = 10 <sup>5</sup> Pa
standaardatmosfeer	atm	1 atm = 101.325 Pa
gal	Gal	1 Gal = 1 cm/s <sup>2</sup> = 10 <sup>-2</sup> m/s <sup>2</sup>
curie	Ci	1 Ci = 3,7 x 10 <sup>10</sup> s <sup>-1</sup>
röntgen	R	1 R = 2,58 x 10 <sup>-4</sup> C/kg
rad	rad	1 rad = 10 <sup>-2</sup> J/kg

Alle andere eenheden buiten het Internationale Stelsel dienen te worden vermeden en in plaats daarvan moeten de passende SI-eenheden worden gebruikt. Ten behoeve van de lezer geeft Tabel 9 een aantal van dergelijke eenheden met de corresponderende waarden in SI-eenheden en omgekeerd.

## 4. Energie-inhoud van brandstoffen

Bij besprekingen over brandstoffen worden vaak eenheden gebruikt die — in beperkte mate — nuttig kunnen zijn voor onderlinge vergelijking; daarbij wordt dan een hoeveelheid ruwe olie uitgedrukt in tonnen steenkoolequivalent of een hoeveelheid aardgas in vaten ruwe olie. Maar helaas wordt het vergelijken en verwijzen vaak bemoeilijkt door het feit dat door verschillende bronnen en schrijvers soms uiteenlopende waarden voor de energie-inhoud van een brandstof zijn aangenomen.

In deze publikatie zijn twee stel waarden gebruikt, onderscheidenlijk voor internationale en nationale doeleinden, opdat gemakkelijk kan worden verwezen naar de oorspronkelijke literatuur en andere bronnen. Een stel waarden (Tabel 10), dat wordt gebruikt door M. King Hubbert, verwijst uitsluitend naar mondiale hulpbronnen en het wereldenergieverbruik, terwijl het andere het stelsel is dat wordt gebruikt door het Nederlandse Centraal Bureau voor de Statistiek (CBS) en dat geldt voor de situatie in Nederland (Tabel 11).

Tabel 10. Energiegehalte van brandstoffen volgens M. King Hubbert (uitsluitend toegepast in Hoofdstuk 1)

1 ton steenkool	≈	7.350 kWh = 26,5 x 10 <sup>9</sup> J
1 vat ruwe olie	≈	1.625 kWh = 5,85 x 10 <sup>9</sup> J
1 ton ruwe olie	≈	11.860 kWh = 42,7 x 10 <sup>9</sup> J
1 m <sup>3</sup> aardgas	≈	10,4 kWh = 37,5 x 10 <sup>6</sup> J

Tabel 11. Energiegehalte van brandstoffen volgens het Nederlandse CBS (toegepast voor Nederlandse gegevens)

1 kg steenkool	≈	7.000 kcal = 8,14 kWh = 29,3 x 10 <sup>6</sup> J
1 kg ruwe olie	≈	10.000 kcal = 11,63 kWh = 41,9 x 10 <sup>6</sup> J
1 m <sup>3</sup> aardgas	≈	8.400 kcal = 9,77 kWh = 35,2 x 10 <sup>6</sup> J

Uit ruwe olie worden verscheidene brandstoffen voor speciale doeleinden vervaardigd, waarvan de calorische waarde wordt vermeld in Tabel 12. Deze tabel is speciaal van toepassing op de situatie in Nederland.

# Eenheden en omzettingfactoren

## 1. SI-eenheden

In deze hele studie is gebruik gemaakt van de eenheden van het Internationale Eenhedenstelsel (SI). SI-eenheden zijn verdeeld in drie categorieën:

- grondeenheden;
- afgeleide eenheden;
- aanvullende eenheden.

### Grondeenheden

De grondeenheden worden algemeen beschouwd als dimensionaal onafhankelijk. Zij worden opgesomd in Tabel 1.

Tabel 1. SI-grondeenheden

Grootheid	Naam	Symbool
lengte	meter	m
massa	kilogram	kg
tijd	seconde	s
elektrische stroomsterkte	ampère	A
thermodynamische temperatuur <sup>1)</sup>	kelvin	K
hoeveelheid substantie	mol <sup>2)</sup>	mol
lichtsterkte	candela	cd

<sup>1)</sup> De Celsius-temperatuur wordt uitgedrukt in graden Celsius (symbool °C).

<sup>2)</sup> Een mol is de hoeveelheid substantie van een stelsel, die evenveel elementaire eenheden bevat als er atomen zijn in 0,012 kilogram koolstof 12. Er zij op gewezen dat massa en hoeveelheid substantie geheel verschillende grootheden zijn.

### Afgeleide eenheden

Afgeleide eenheden worden uitgedrukt in grondeenheden. Verscheidene afgeleide eenheden hebben een speciale naam en symbool gekregen, die zelf weer kan worden

gebruikt om andere afgeleide eenheden eenvoudiger uit te drukken dan in grondeenheden.

Afgeleide eenheden kunnen daarom onder drie hoofden worden gerangschikt:

- afgeleide eenheden uitgedrukt in grondeenheden;
- afgeleide eenheden met een speciale naam,
- afgeleide eenheden uitgedrukt met behulp van speciale namen.

Voorbeelden van elke categorie worden gegeven in de Tabellen 2, 3 en 4.

Tabel 2. Voorbeelden van van het SI afgeleide eenheden, uitgedrukt in grondeenheden

Grootheid	Naam	SI-eenheid	Symbool
oppervlakte	vierkante meter		m <sup>2</sup>
volume	kubieke meter		m <sup>3</sup>
snelheid	meter per seconde		m/s
versnelling	meter/seconde in het kwadraat		m/s <sup>2</sup>
dichtheid, massa-dichtheid	kilogram per kubieke meter		kg/m <sup>3</sup>
stroombichtheid	ampère per vierkante meter		A/m <sup>2</sup>
magnetische veldsterkte	ampère per meter		A/m
soortelijk volume	kubieke meter per kilogram		m <sup>3</sup> /kg

### Aanvullende eenheden

Als aanvullende SI-eenheden komen er tot nu toe slechts twee, zuiver meetkundige, eenheden voor, de eenheden van een vlakke hoek (radiaal), en van een ruimtehoek (sterdiaal).

Tabel 3. Voorbeelden van afgeleide SI-eenheden met een speciale naam

Grootheid	SI-eenheid			
	Naam	Symbool	Weergave in andere eenheden	Weergave in grondeenheden
frequentie	hertz	Hz	—	s <sup>-1</sup>
kracht	newton	N	—	m.kg.s <sup>-2</sup>
druk, spanning	pascal	Pa	N/m <sup>2</sup>	m <sup>-1</sup> .kg.s <sup>-2</sup>
energie, arbeid, hoeveelheid warmte	joule	J	N.m	m <sup>2</sup> .kg.s <sup>-2</sup>
vermogen, stralingsvermogen	watt	W	J/s	m <sup>2</sup> .kg.s <sup>-3</sup>
elektrisch potentiaalverschil, elektromotorische kracht	volt	V	W/A	m <sup>2</sup> .kg.s <sup>-3</sup> .A <sup>-1</sup>
elektrische weerstand	ohm	Ω	V/A	m <sup>2</sup> .kg.s <sup>-3</sup> .A <sup>-2</sup>
magnetische flux	weber	Wb	V.s	m <sup>2</sup> .kg.s <sup>-2</sup> .A <sup>-1</sup>
magnetische inductie	tesla	T	Wb/m <sup>2</sup>	kg.s <sup>-2</sup> .A <sup>-1</sup>
hoeveelheid elektriciteit, elektrische lading	coulomb	C	—	s.A

Tabel 4. Voorbeelden van afgeleide SI-eenheden, weergegeven met behulp van speciale namen

Grootheid	Naam	SI-eenheid	Symbool	Weergave in basiseenheden
oppervlaktespanning	newton per meter		N/m	kg.s <sup>-2</sup>
dichtheid van de warmte-overdracht, stralingsdichtheid	watt per vierkante meter		W/m <sup>2</sup>	kg.s <sup>-3</sup>
entropie, warmtecapaciteit	joule per kelvin		J/K	m <sup>2</sup> .kg.s <sup>-2</sup> .K <sup>-1</sup>
soortelijke energie	joule per kilogram		J/kg	m <sup>2</sup> .s <sup>-2</sup>
warmtegeleiding	watt per meter kelvin		W/(m.K)	m.kg.s <sup>-3</sup> .K <sup>-1</sup>
energiedichtheid	joule per kubieke meter		J/m <sup>3</sup>	m <sup>-1</sup> .kg.s <sup>-2</sup>
elektrische veldsterkte	volt per meter		V/m	m.kg.s <sup>-3</sup> .A <sup>-1</sup>
molaire energie	joule per mol		J/mol	m <sup>2</sup> .kg.s <sup>-2</sup> .mol <sup>-1</sup>

Tabel 9. Een aantal eenheden dat niet meer dient te worden gebruikt en hun waarde, uitgedrukt in SI-eenheden en omgekeerd

SI-eenheid A	Naam van eenheid B	1A = ↓ .B	1B = ↓ .A
<b>Lengte</b>			
meter m	ångström (Å)	$10^{10}$	$10^{-10}$
	micron (μ)	$10^6$	$10^{-6}$
	mil	$39,37 \times 10^3$	$2,54 \times 10^{-5}$
	inch	39,37	$2,54 \times 10^{-2}$
	voet	3,28	0,3048
	yard	1,094	0,9144
	zeemijl (zee, luchtstroming)	$0,5396 \times 10^{-3}$	1,853
	Engelse mijl (land)	$0,6215 \times 10^{-3}$	1,609
<b>Oppervlakte</b>			
vierkante meter m <sup>2</sup>	vierkante inch	$1,55 \times 10^3$	$6,452 \times 10^{-4}$
	vierkante voet	10,764	0,0929
	vierkante yard	1,196	0,8361
	acre	$0,2471 \times 10^{-3}$	$4,05 \times 10^3$
	hectare	$10^{-4}$	$10^4$
	vierkante mijl (land)	$0,3861 \times 10^{-6}$	$2,59 \times 10^6$
<b>Inhoud</b>			
kubieke meter m <sup>3</sup>	kubieke inch	$61,02 \times 10^3$	$16,39 \times 10^{-6}$
	liter	$10^3$	$10^{-3}$
	Am. gallon	264,2	$3,785 \times 10^{-3}$
	imperial gallon	220	$4,546 \times 10^{-3}$
	kubieke voet	35	$28,32 \times 10^{-3}$
	barrel	6,289	0,159
	kubieke yard	1,308	0,7646
	<b>Massa</b>		
kilogram kg	ounce	35,27	$28,35 \times 10^{-3}$
	pound	2,21	$453,59 \times 10^{-3}$
	Amerikaanse (short) ton	$1,102 \times 10^{-3}$	$0,9072 \times 10^3$
	metrieke ton	$10^{-3}$	$10^3$
	Engelse (long) ton	$0,984 \times 10^{-3}$	$1,016 \times 10^3$
<b>Kracht</b>			
newton N (m.kg.s. <sup>-2</sup> )	dyne	$10^5$	$10^{-5}$
	poundal	7,232	0,1383
	poundweight (lb)	0,2248	4,4483
	kilogramkracht (kgf)	0,102	9,8067
	<b>Druk, spanning</b>		
pascal Pa (N/m <sup>2</sup> ) (m.kg.s. <sup>-2</sup> )	mm H <sub>2</sub> O	0,102	9,8067
	pond per vierkante voet	0,0209	47,88
	torr	$7,5 \times 10^{-3}$	133,3224
	pond per vierkante inch	$0,145 \times 10^{-3}$	$6,8941 \times 10^3$
	standaardatmosfeer	$0,9869 \times 10^{-5}$	$1,01325 \times 10^5$
<b>Energie, arbeid, hoeveelheid warmte</b>			
joule J (N.m) (m <sup>2</sup> .kg.s. <sup>-2</sup> )	erg	$10^7$	$10^{-7}$
	voetpond	739	$13,54 \times 10^{-4}$
	calorie	0,2388	4,1868
	kilogram (kracht)meter (mkgf)	0,102	9,8067
	BTU	$0,9478 \times 10^{-3}$	$1,055 \times 10^3$
	kilowattuur	$0,278 \times 10^{-6}$	$3,6 \times 10^6$
<b>Vermogen, stralingsvermogen</b>			
watt W (J/s) (m <sup>2</sup> .kg.s. <sup>-3</sup> )	erg per seconde	$10^7$	$10^{-7}$
	calorie per seconde	0,2388	4,1868
	paardekracht (pk,cv,PS)	$1,36 \times 10^{-3}$	736
	Engelse paardekracht	$1,34 \times 10^{-3}$	746
	BTU per seconde	$0,9478 \times 10^{-3}$	1,055
<b>Temperatuur</b>			
<p>Naaft de thermodynamische temperatuur (symbool T), die wordt uitgedrukt in graden kelvin, wordt tevens gebruik gemaakt van de temperatuur in graden Celsius (symbool t), omschreven door de vergelijking <math>t = T - T_0</math>, waarin <math>T_0</math> wordt gedefinieerd als 273,15 K. De Celsius-temperatuur wordt uitgedrukt in graden Celsius (symbool °C). De eenheid 'graad Celsius' is gelijk aan de eenheid 'kelvin'.</p>			
<p>Temperatuur in graden Celsius °C                  Temperatuur in graden Fahrenheit °F } <math>T^{\circ}C = 5/9 (t^{\circ}F - 32)</math> en <math>t^{\circ}F = 1,8t^{\circ}C + 32</math></p>			

De rechterkolom toont de in de Hoofdstukken 2 (sectie III.4.4), 6 en 7 (sectie II.1) en in enkele andere gevallen gebruikte waarden.

Tabel 12. Calorische waarden van vloeibare brandstoffen

Brandstof	10 <sup>6</sup> J per kilo hoog (bruto)	10 <sup>6</sup> J per kilo laag <sup>1</sup> ) (netto)	10 <sup>6</sup> J per kilo zoals gebruikt in deze studie
LPG	48,7 - 49,7	45,5 - 46,4	45,9
benzine	47,1 - 49,2	44,0 - 46,0	48,0
kerosine (vliegtuigbrandstof)	46,0 - 46,7	43,0 - 43,7	45,9
gasolie (licht)	45,5 - 46,6	42,5 - 43,5	44,5
gasolie (zwaar)	44,9 - 45,8	42,0 - 42,8	44,5
stookolie	43,3 - 44,6	40,5 - 41,7	44,4

<sup>1</sup>) Exclusief de verdampingswarmte van het water dat tijdens de verbranding vrijkomt.

Op sommige punten in deze publikatie kan het nuttig zijn de massadichtheid van vloeibare en gasvormige koolwaterstof-brandstoffen te kennen. Deze staan vermeld in Tabel 13.

Tabel 13. Massadichtheid (kg/m<sup>3</sup>) van bepaalde vloeibare en gasvormige brandstoffen

ruwe olie	850 - 950
benzine	730 - 760
kerosine (vliegtuigbrandstof)	790 - 830
gasolie (licht)	810 - 850
gasolie (zwaar)	840 - 870
stookolie	900 - 1.000
aardgas (veld in Groningen)	0,79

## 5. Omzetting van brandstoffen in elektriciteit

Waar geen melding wordt gemaakt van een bijzonder omzettingsrendement, wordt stilzwijgend aangenomen dat de waarde hiervan 1/3 bedraagt. Dit verhoudingsgetal is gekozen ten einde de berekeningen te vereenvoudigen, aangezien het een goede benadering is van het huidige gemiddelde omzettingsrendement<sup>1</sup>) in Nederland, waar vrijwel alle elektriciteit wordt opgewekt op basis van fossiele brandstoffen en waar geen waterkrachtstations en getijdencentrales zijn.

<sup>1</sup>) In 1972 bedroeg dit rendement 33,7% (CBS).