Solid Waste Engineering

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Exercise No. 1 – what is waste?

- Make groups of 3-4 persons
- Grab a marker and a white board
- Think about the definition of waste
  - Technical sense
  - Economical sense
  - Regulatory sense

Definition of waste – What is waste?

Technical sense

- By-product of civilization
- Leftover after removal/consumption of useful component(s)

Economical sense

- Present value **<** Utilization cost

Image source: www.pixabay.com

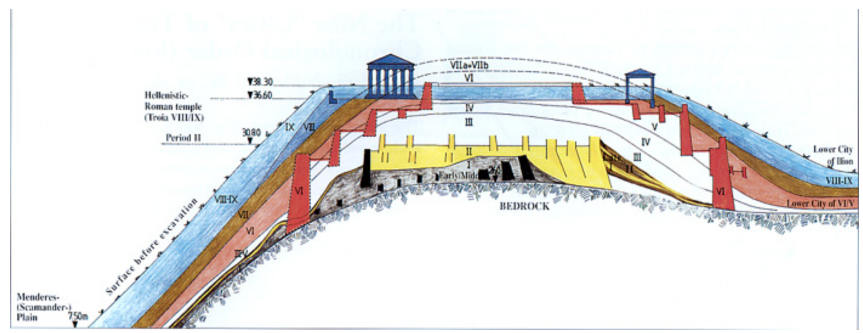
Regulatory sense

- Anything discarded
- Can no longer be used for its original purpose

Waste, now and then…

Edible food packaging for space travel

A cutaway view of ancient Troy shows how the city literally managed to surmount its garbage problem



Solid Waste Engineering

1. Waste classification and characterization
2. Collection / Transport /Recycling
3. Combustion and energy recovery
4. Landfills

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Ways to classify waste

Composition
- Solid waste
- Hazardous waste
- Radioactive waste
- Infectious (medical) waste

Chemistry
- Organic
- Inorganic

Environmental aggressiveness
- Hazardous
- Inert

Source
- Agricultural
- Domestic
- Industrial
- Municipal

Useful characteristics
- Combustible
  - (paper, plastics, etc.)
- Fermentable
  - (food waste)
- Inert
  - (glass, ceramics)
- Fine
  - (soil, ashes, etc.)

Municipal solid waste (MSW)

Refuse = Solid waste generated by households

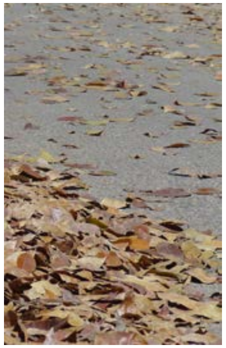
- *Garbage* = food waste
- *Rubbish* = everything else including recyclables
- Household *hazardous* waste
- Yard (or green) waste originating with individual households

Non refuse = not collected with household refuse

- construction and demolition debris
- water and wastewater treatment plant sludge
- leaves and other green collected from streets and parks
- bulky items (large appliances, hulks of old cars, tree limbs)

(MSW)= (refuse) + (C&D waste) + (sludge) + (leaves) + (bulky items)






Exercise No. 2 – Composition of MSW by identifiable items

- Make groups of 3-4 persons
- Grab a marker and a white board
- From the various categories of refuse and non refuse, which specific items would you say occupy more space in a landfill?
- **Hint**: we're talking about identifiable items now, break down *rubbish* into different sub-categories

Composition of MSW by identifiable items

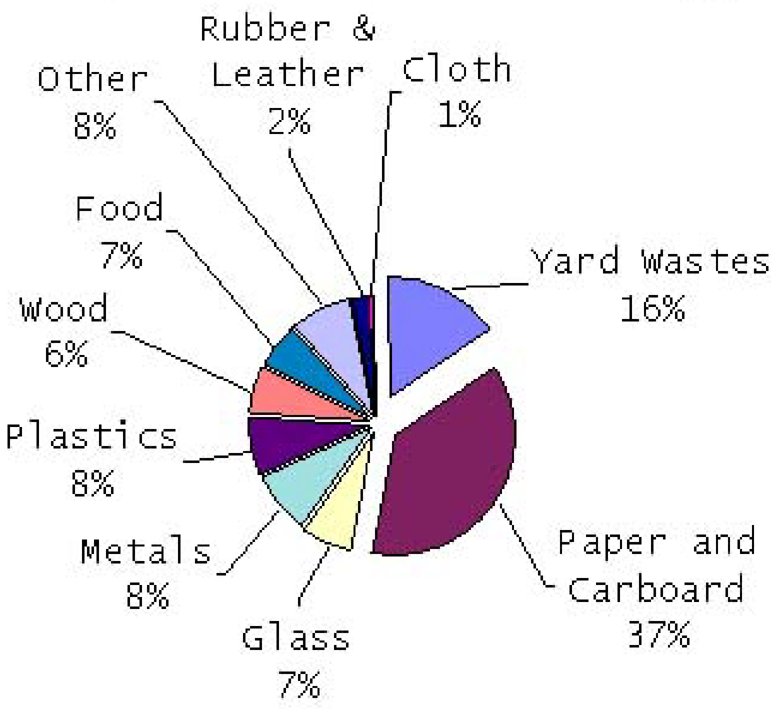
Misconceptions

Waste category	1990 Poll (%)*	Actual volume in landfill (%)
Disposable diapers	**41**	**<2**
Plastic bottles	**29**	**<1**
Large appliances	**24**	**<2**
newspapers	11	13
All papers	**6**	**>40**
Food and yard waste	3	7
Construction debris	**0**	**12**

***** Proportion of respondents identifying a particular item as a major cause of solid waste problems

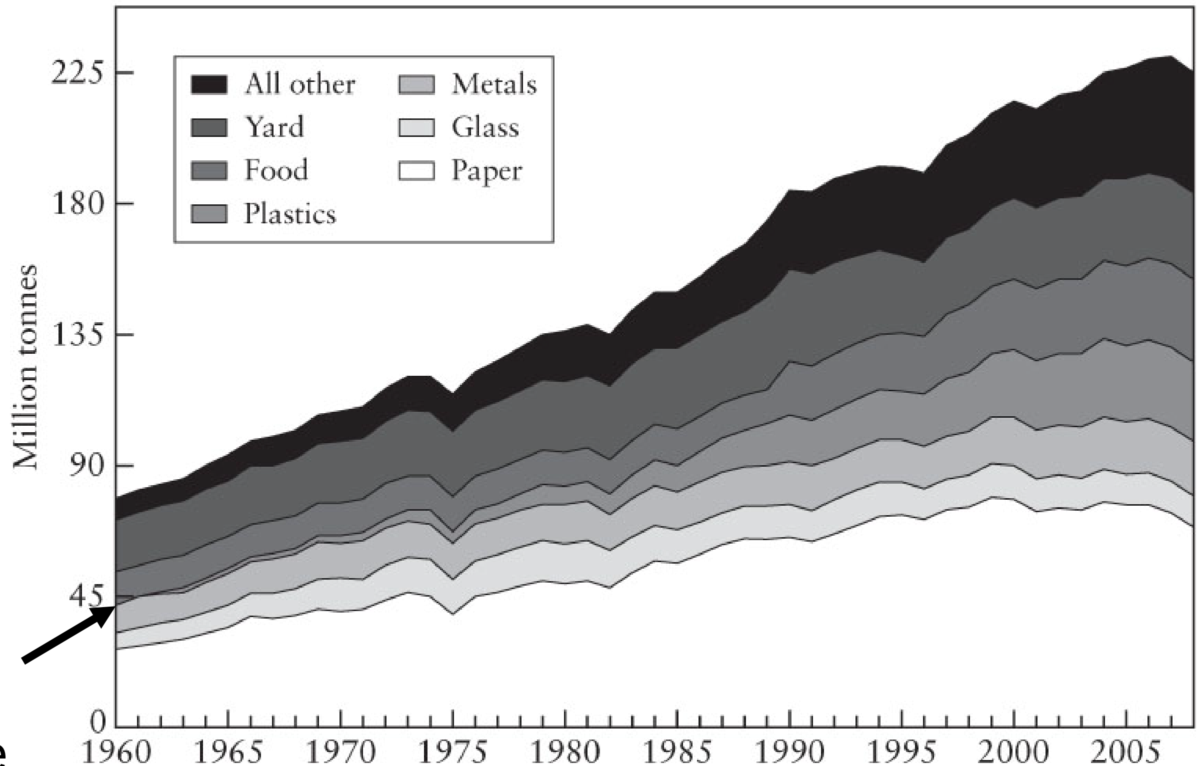
Misconceptions like these can lead to **counterproductive policies and actions.**

Reality



Generation of MSW

Historical trends in MSW generation and composition in the U.S.



*"All Other" includes primarily wood, rubber and leather, and textiles.

Negligible amount of plastic waste in the 1960

Dramatic increase of plastics since the 1960s

Micro-Plastics: Macro-Problem?

Although microbeads from rinse off cosmetics have received a lot of attention lately, the tiny plastics most often being found in our seafood is a different kind of synthetic. We look into marine life in the US and Australia, to find out what plastics escape our household drains and what kind of damage they can do. https://www.youtube.com/watch?v=UpGt5L3GC7o

Exercise No. 3 – MSW characteristics

- Make groups of 3-4 persons
- Grab a marker and a white board
- What should you measure?
- It depends on the planned use for the waste
- List down the possible end uses (or final destination) of MSW and what you would need to monitor as a solid waste engineer

MSW characteristics

What parameters to measure depends on the planned use for the MSW

Planned use	Parameters to measure
Disposal in landfill	Density Hazardous waste Biodegradability (leachate)
Biogas or compost (biochemical transformation)	Organic content Biodegradability
Waste-to-energy (Combustion)	Moisture Heat value
Recycling	Composition by identifiable items

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Have you heard of entropy?

Professor Brian Cox builds sandcastles in the Namib Desert to explain why time travels in one direction. It is a result of a phenomenon called entropy; a law of physics that tells us any system tends towards disorder.
https://www.youtube.com/watch?v=uQSoaiubuA0

Wonders of the Universe - BBC Two

Solid waste collection

Objective: To reduce entropy (increase order) in the system

- Disordered system: scattered MSW components
- Ordered system: all MSW components in a container and transported to a central facility or site

Examples of central facility or site:

- Materials recovery facility
- Disposal site e.g. landfill
- Transfer station

Disorder…

Image source: www.pixabay.com

… to order

Image source: www.pixabay.com

Solid waste collection: a multiphase process

Phase 1:
House-to-can

Phase 2:
Can-to-truck

Phase 3:
Truck from
house-to-house

Phase 4:
Truck routing

Phase 5:
Truck-to-disposal

Images source: www.pixabay.com

Phase 1: House-to-can

Phase 1: House-to-can

Images source: www.pixabay.com

- Regarded as a **personal affair** ⇒ received little attention
- Segregation of MSW viewed as an **inconvenience** by individuals

Three ways to set MSW collection fee		
Fixed tax system	***Volume-based fee system***	***Weight-based fee system***
• Pay a fixed amount regardless of amount of MSW • "Permission" to generate unlimited quantities of waste	• Pay according to volume of waste containers used • Generated interest in compactors	• Pay according to actual weight of MSW • Difficult to implement

Phase 2: Can-to-truck

Images source: www.pixabay.com

Phase 2:
Can-to-truck

Who moves the can to the street?

- If collection crew, then *backyard collection*
- If waste generator, then *curbside collection*

Three ways to operate		
Manual collection	***Semi-automated collection***	***Fully-automated collection***
• Collectors empty cans into truck by hand • Requires a driver with many collectors	• Utilizes can-on-wheels • Collectors move cans close to hydraulic hoists on truck, which empties the can into truck • Requires a driver with a couple of collectors	• Truck equipped with long arms that reach out, grab a can, and empty can into back of truck • Requires only driver

Figure 3-7 Collection with vehicles equipped with “can snatchers.’

Phase 3: Truck from house-to-house

Phase 3: Truck from house-to-house

Images source: www.pixabay.com

Compaction ratio is important

- Higher ratio = More efficient collection

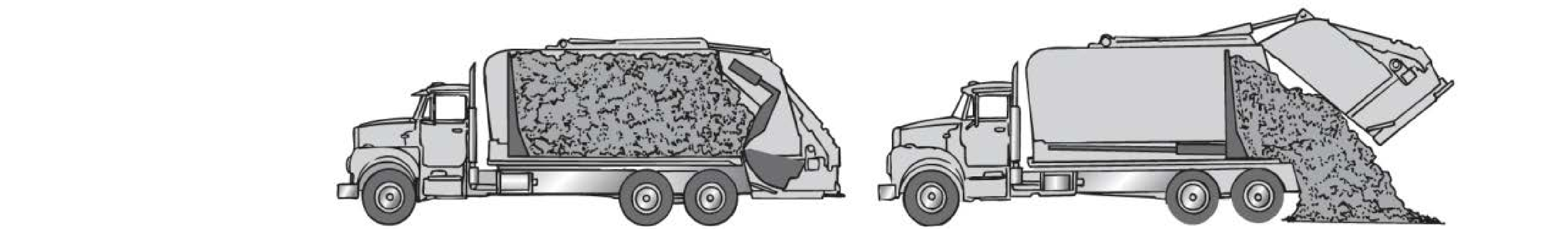
Crew size: Backyard pickup > Curbside pickup

Max capacity of one truck before landfilling is required:

- In theory: 700-1000 customers
- In practice: Only about 200 customers

Phase 3: Truck from house-to-house

Compacting mechanism for a packer truck



Phases 4 and 5: Truck routing and truck-to-disposal

Phase 4: Truck routing

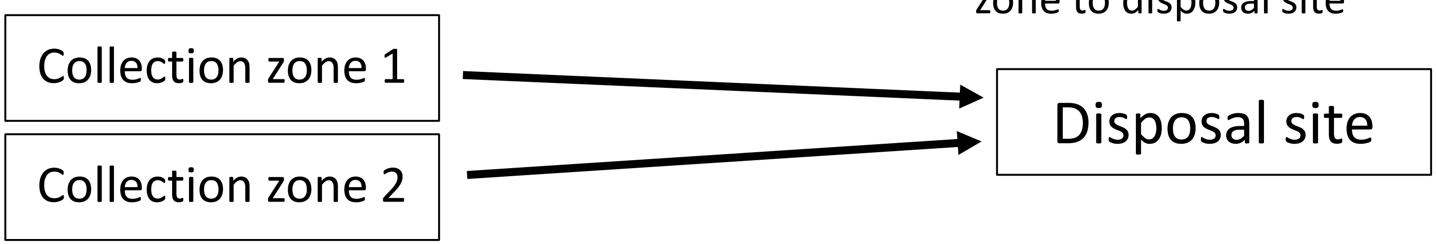
Microrouting

Routing inside an assigned collection zone

Phase 5: Truck-to-disposal

Macrorouting

Routing from collection zone to disposal site



Phase 4: Truck routing

Microrouting

Objective: design routes within collection zone that minimize deadhead (travelling without picking up waste)

Follows heuristic (commensensical) principles

- *Routes*: no overlaps, no fragmentation
- *Starting point*: closest to the truck garage
- *Heavily travelled streets*: avoid during rush hours
- *One-way streets*: lopped from the upper end
- *Dead-end streets*: collect on the right side

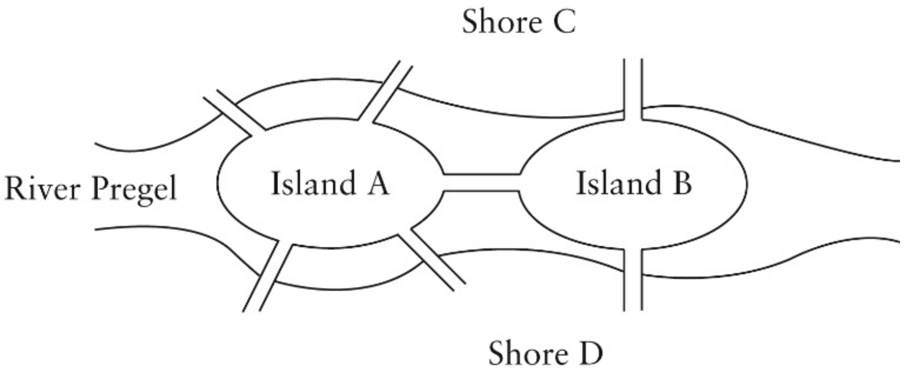
Euler’s tour

Prussia’s King problem: to route a parade across seven bridges of Königsberg **without crossing the same bridge twice**

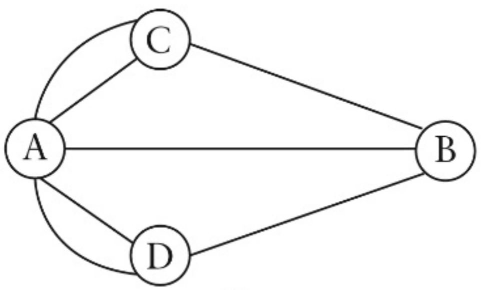
Two conditions for any network (to avoid double traveling on any road)

- All points must be connected
- The number of links to any node must be an even number

Euler’s problem in Königsberg



Network composed of routes (**links**) and locations (**nodes**)



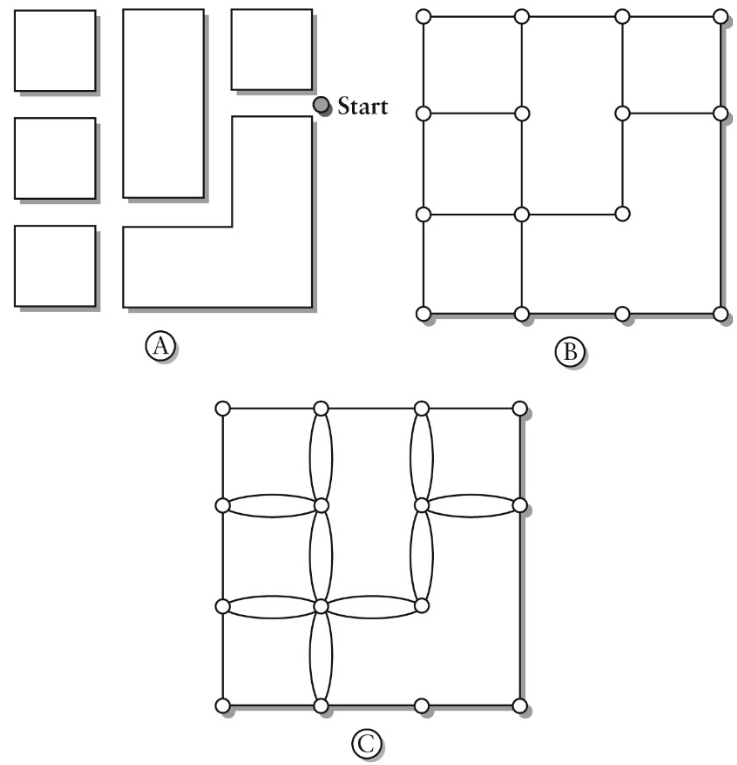
Exercise No. 4 – Euler's tour

Are these possible?

Scenario A: By traveling down each street only once (MSW collected along both sides of street, e.g., residential neighborhood)

Scenario B: Collection only on one side of the street at a time (larger street)

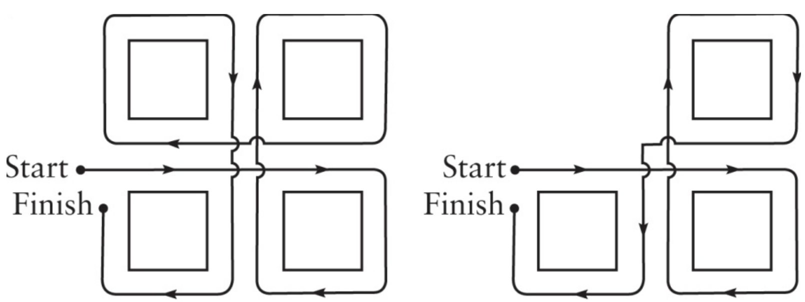
Routing of trucks



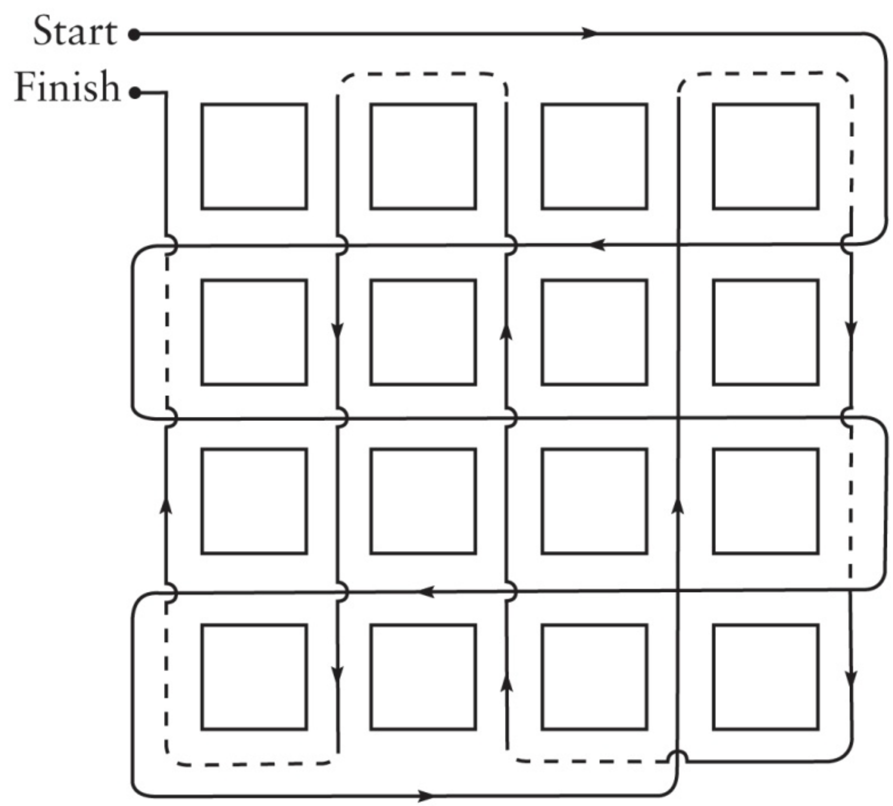
Euler's tour

Larger loops usually result in more efficient collection

Small loop:



Large loop:



Phase 5: Truck-to-disposal

Macrorouting

Objective: determine the most direct route from collection zone to disposal site

small community: finding the most direct road (end of the route to disposal site)

metropolitan areas and regional systems: optimum transport and disposal scheme

Phase 5: Truck-to-disposal

Macrorouting

Objective: determine the most direct route from collection zone to disposal site

small community: finding the most direct road (end of the route to disposal site)

metropolitan areas and regional systems: optimum transport and disposal scheme

There could be a need for a *transfer station* depending on the haul distance to disposal

(a) (b) (c)

Recycling

Entered the mainstream of solid waste management in 1990s

- Could be profitable, regardless of the price of recycled materials
- Requires government leadership and public acceptance that recycling is not free

Options in the design of recycling program

Option 1:
Mixed waste collection and subsequent selection (*dirty MRF*)

Option 2:
Partially selected materials / comingled collection (*clean MRF*)

Placed into one container: paper contamination by residual liquids

Placed into three or more containers (e.g. bottles, paper, cans)

Yard waste: separately collected and transported to the landfill

Profitability of recyclables: Aluminum

By some measures, the most valuable collectable in any municipal recycling program

- 10× more valuable than plastics (PET, HDPE)
- 20× more valuable than glass or newspapers
- 20-40% of the total revenues from recycling

Uses 2-3% of the energy required to make new aluminum from bauxite ore

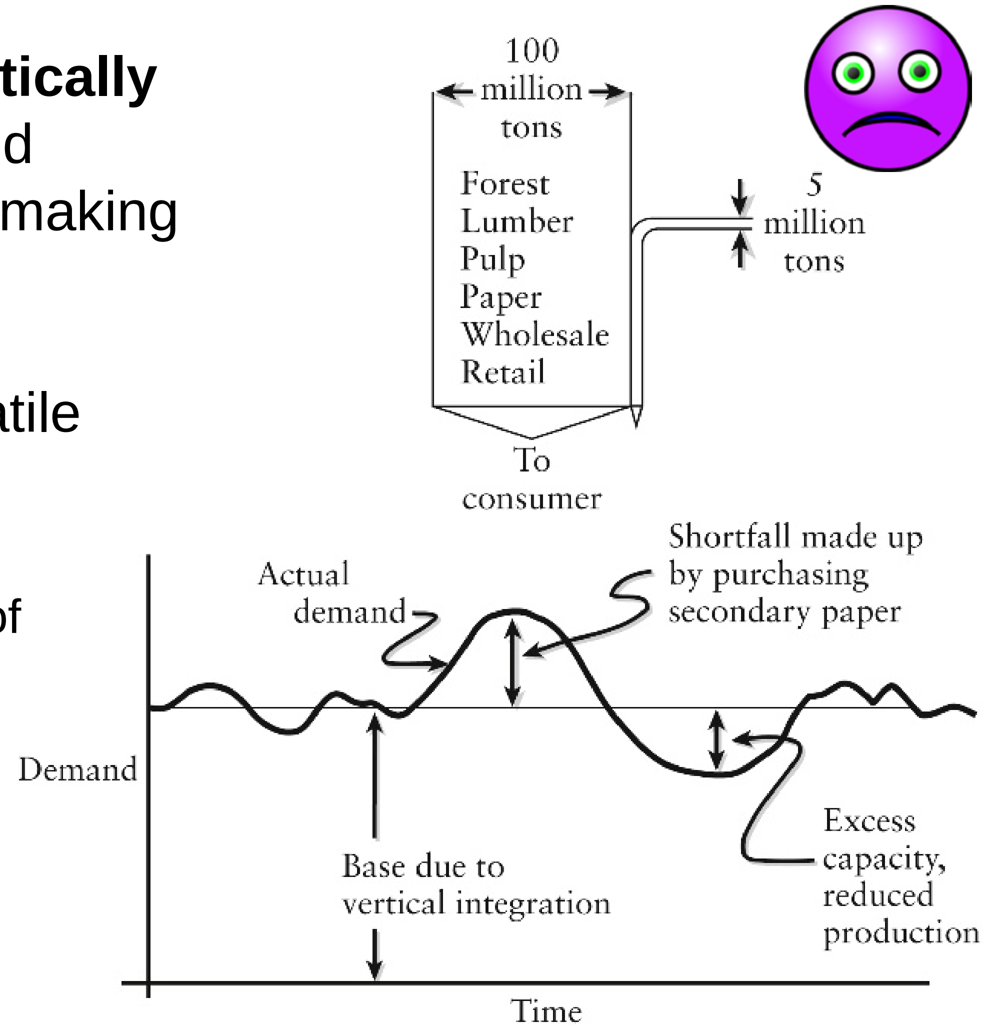
Source	Electricity (kWh/kg)	Fossil fuel (kJ/kg)	Primary energy (kJ/kg)
Bauxite	15	60,000	220,600
Recycled aluminum	0.08	4200	5060
Recycled savings	14.92	55,800	215,540
Percent savings	99%	93%	98%

Profitability of recyclables: Paper

Paper industry companies are **vertically integrated**: the company owns and operates all the steps in the papermaking process

Market for secondary paper is volatile

- Low capacity drives short-term increase in demand for recycled paper, leading to spikes in price of recycled paper
- When paper companies have expanded their capacity, price of recycled paper plummet



Exercise No. 5 – Practice Exam No. 1

- Make groups of 3-4 persons

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MSW characteristics

What parameters to measure depends on the planned use for the MSW

Planned use	**Parameters to measure**
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Waste-to-energy (Combustion)	Moisture Heat value
Recycling	Composition by identifiable items

Measuring heat value: Compositional analysis

Eq. 5: $$\text{Heat value}\left(\frac{\text{kJ}}{\text{kg}}\right) = 113.7\ \text{R} + 52.2\ (\text{G} + \text{P}) - 7.66\ \text{W}$$

Eq. 6: $$\text{Heat value}\left(\frac{\text{kJ}}{\text{kg}}\right) = 2{,}872 + 36.2\ \text{R} + 10.2\ \text{P} + 6.3\ \text{G} - 48\ \text{W}$$

Where

Percent by weight, dry basis

- R = Plastics → Very combustible, high heat value
- P = Paper → Very combustible, high heat value
- G = Food waste → Less combustible, moderate heat value
- W = Water → Non-combustible, negative heat value

Measuring heat value: Bomb calorimetry

A **bomb calorimeter** measures the heat value of a combustible sample.

Step 1: Place combustible sample of known weight inside.

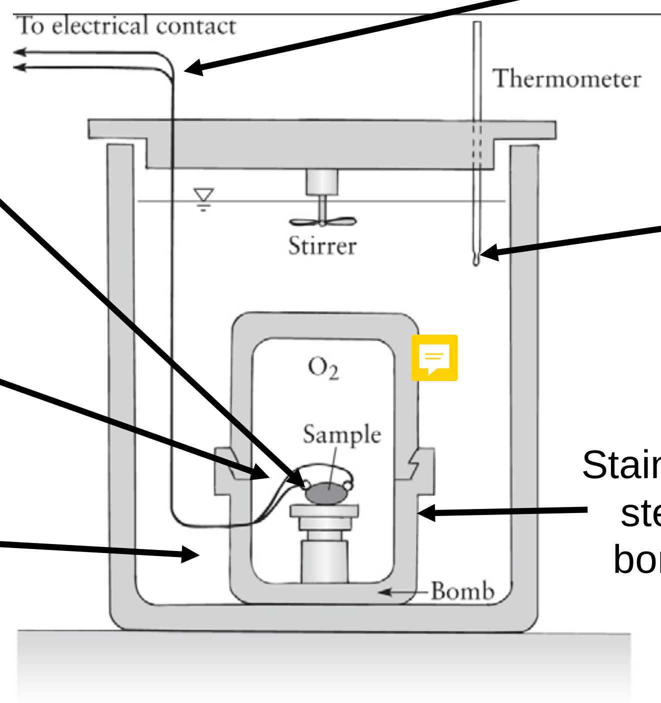
Step 2: Inject high pressure oxygen.

Step 3: Put bomb in adiabatic water bath and connect to electrical source.

does not exchange heat with outside

Step 4: Spark to combust sample.

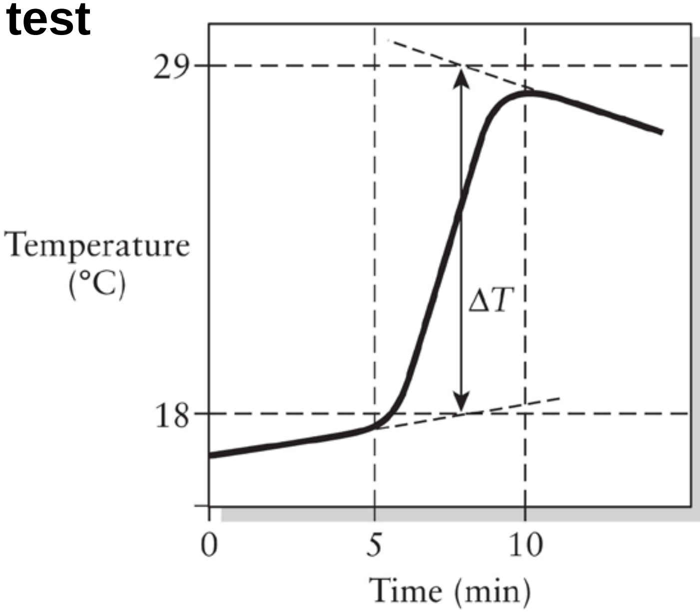
Step 5: Measure increase in temperature of water as a function of time.



Stainless steel bomb

Measuring heat value: Bomb calorimetry

Results of a bomb calorimeter test



- From $t = 0$, heat in the room heats the water.
- At $t = 5$, switch is closed and combustion occurs in the bomb.

Only approximately adiabatic. In reality, the stirrer does work on the calorimeter.

- Increase in temperature up till $t = 10$, from which the water starts to cool.
- Net rise in temperature due to combustion is extrapolated from the initial and final cooling lines.
- Because the calorimeter is an adiabatic system:

Energy content of the material = Energy released as heat

Heat value of fuels

Table 2-7 Heat Value of Fuels

Fuel	Heat Value (kJ/kg)	Composition (wt%) S	H	C	N	O	Ash
Natural gas	54,750	nil	23.5	75.2	1.22	—	nil
Heating oil (no. 2)	45,000	0.3	12.5	87.2	0.02	nil	nil
Coal, anthracite	29,500	0.77	3.7	79.4	0.9	3.0	11.2
Coal, bituminous	26,200	3.22	4.6	40.0	1.0	6.5	9.0
Coal, lignite	19,200	0.4	2.5	32.3	0.4	10.5	4.2
Wood, hardwood	7180*	—	—	—	—	—	—
Wood, softwood	7950*	—	—	—	—	—	—
Shredded refuse[a]	10,846	0.1	—	—	—	—	20.0
RDF[b]	15,962	0.2	—	37.1	0.8	—	22.6
RDF[c]	18,223	0.1	—	45.4	0.3	—	6.0
Unprocessed refuse	10,300	0.1	2.65	25.6	0.64	21.2	20.8
Unprocessed refuse		0.13	4.80	35.6	0.9	29.5	28.9
Paper	24,900	0.1	2.7	20.7	0.13	19.1	2.74

RDF Pellets

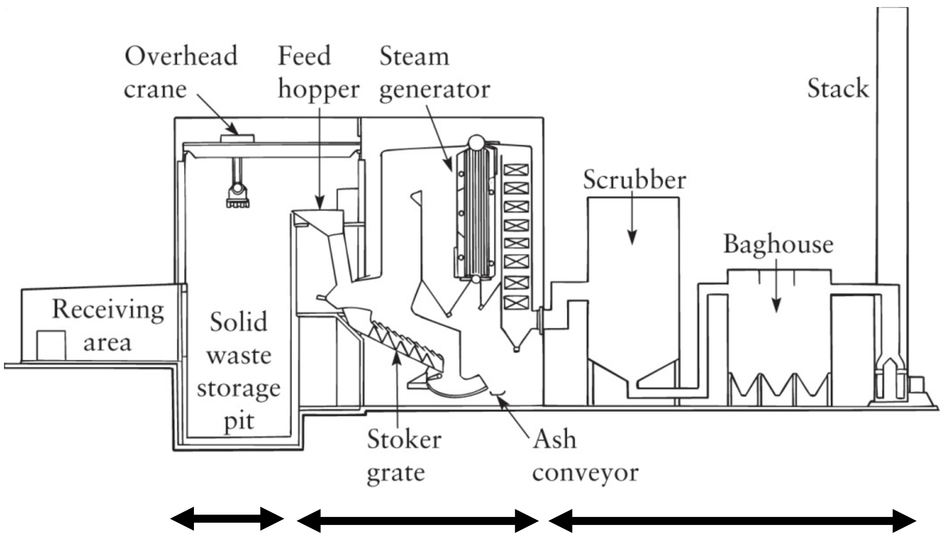
* Lower Heat Value (LHV); all other heat values are Higher Heat Value (HHV)
[a] Shredded, non-air-classified, ferrous removed, not dried; St. Louis RDF facility
[b] Shredded, air-classified, not dried
[c] Same as above, but oversize from a 4.76-mm screen
Source: [18]

Exercise No. 6 – Practice Exam No. 2

- Make groups of 3-4 persons

Waste to Energy

A typical municipal solid waste combustor



Storage | Combustion | Pollution control

Incinerators

- $(CH)x + O_2 \rightarrow CO_2 + H_2O$ + nutrients + heat energy
- Sad record of poor design, inadequate engineering and inept operation.
- Without energy recovery, exhaust gases were very hot.

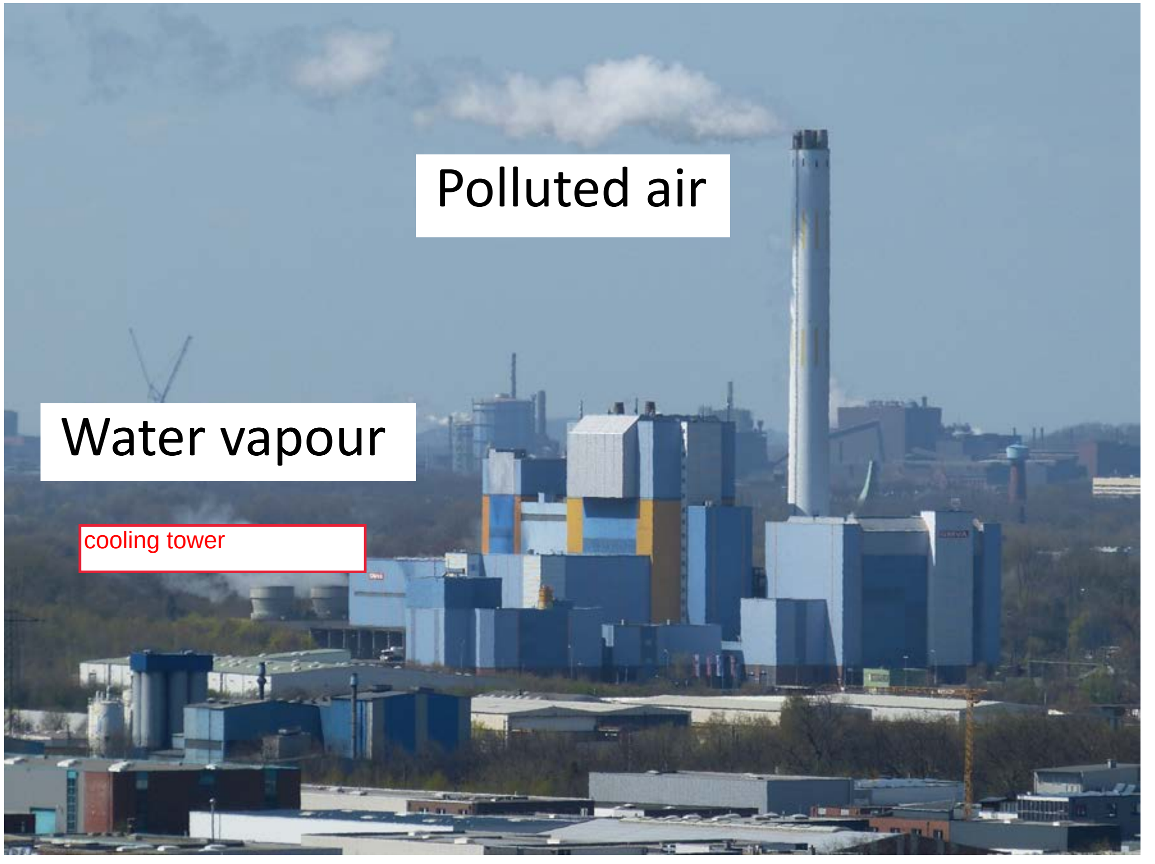


Image source: www.pixabay.com

Modern combustor

- Uses a steam generator
- Temperature is crucial

1090°C

700°C

⇒ Equipment will not stand the heat

⇒ Ideal range

⇒ Some plastics won't burn

Image source: www.pixabay.com

⇒ Good control of temperature through air supply is needed.

⇒ how much work can it do?

Work

- **Work** is energy transferred by a **force**, described by the product of force and the displacement of an object caused by that force.

$$\boxed{\mathbf{W = F \times d}}$$

Where:

- W = Work (in Nm or J)
- F = Force (in N)
- d = Distance moved in the direction of the force (in m)

- 1 Nm = 1 joule (unit of energy)

- Why are we interested in work?

So that we can calculate how much electricity a steam generator can produce!

Work done by an expanding gas

$$\mathbf{W = Fd} \quad \text{and} \quad \mathbf{F = pA}$$

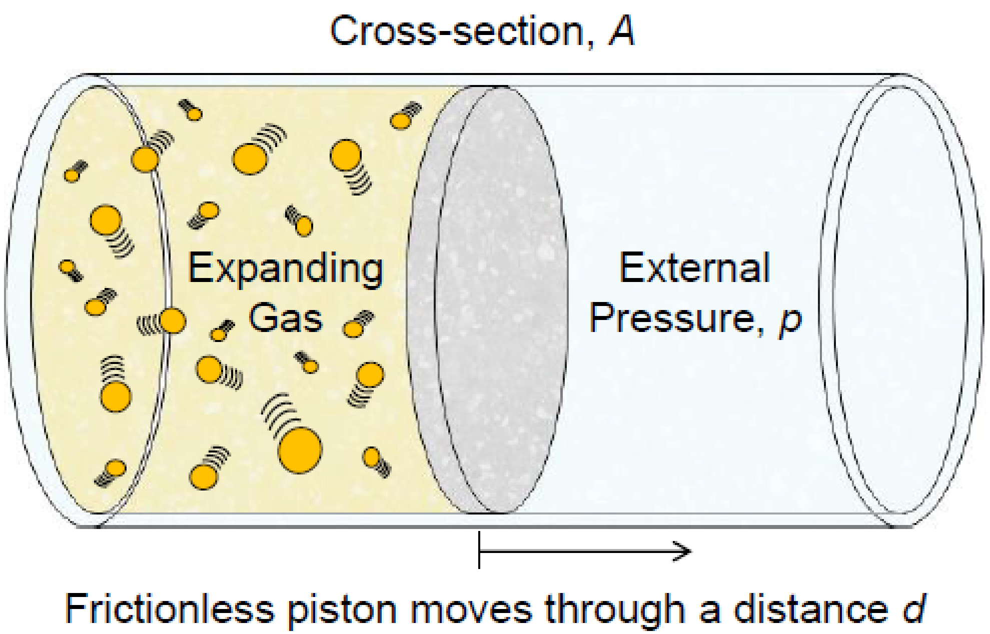
$$\therefore \mathbf{w = pAd}$$

If $\mathbf{A}$ is area (m^2) and $\mathbf{d}$ is distance (m), then $\mathbf{Ad = V}$ (m^3).

$$\therefore \mathbf{w = p\Delta V}$$

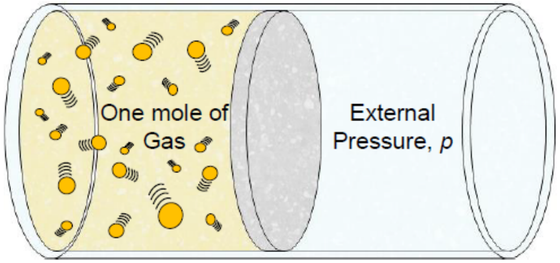
Where:

- p = Pressure (in Pa)
- V = Volume (in m^3)



Example

- Consider 1 mol of an ideal gas at 298 K
  - $p = nRT/V$
  - p = (1 mol × 8.314 J/K/ mol × 298 K) / V
  - p = (2478 J) / V
  - Initially, V= 1 m^3 → p = 2478 Pa
  - What happens to p when the gas expand gradually from 1 m^3 to 3, 5, 7, 9 and 11 m^3 ?
  - Answer:



V (m^3)	1	3	5	7	9	11
p (Pa)	2478	826	496	354	275	225

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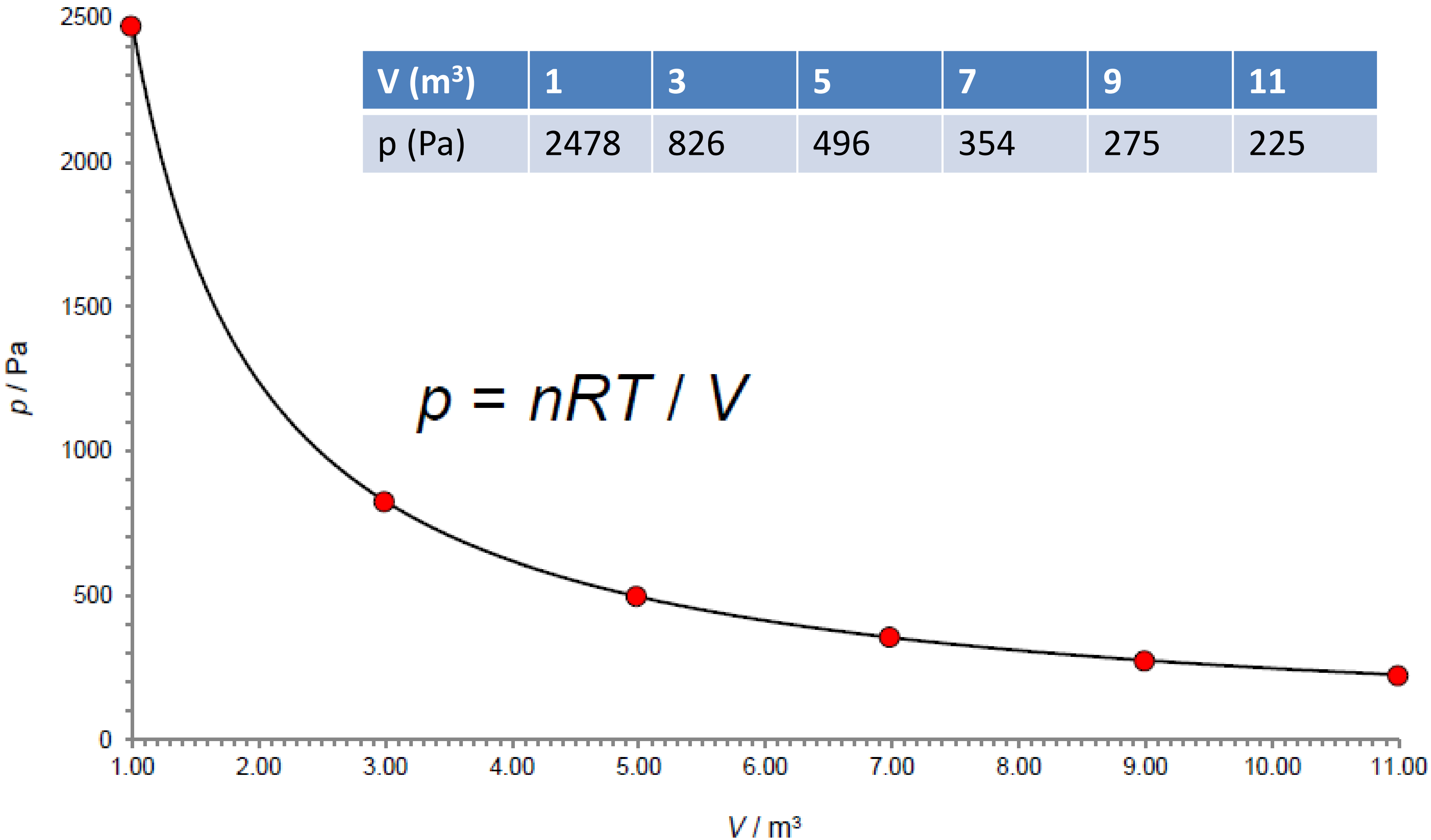
p (Pa)	2478	826	496	354	275	225

$$p = nRT / V$$



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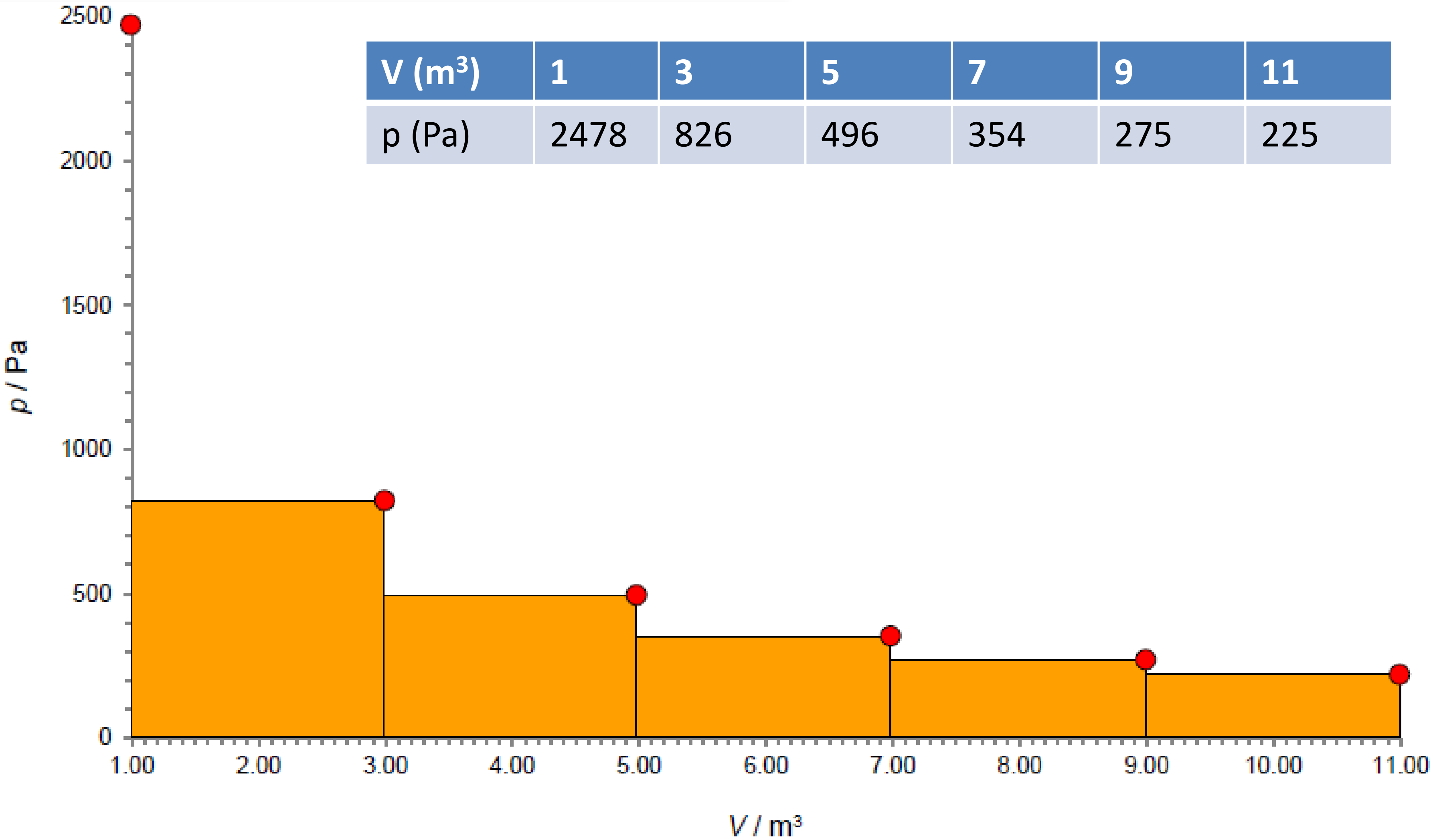
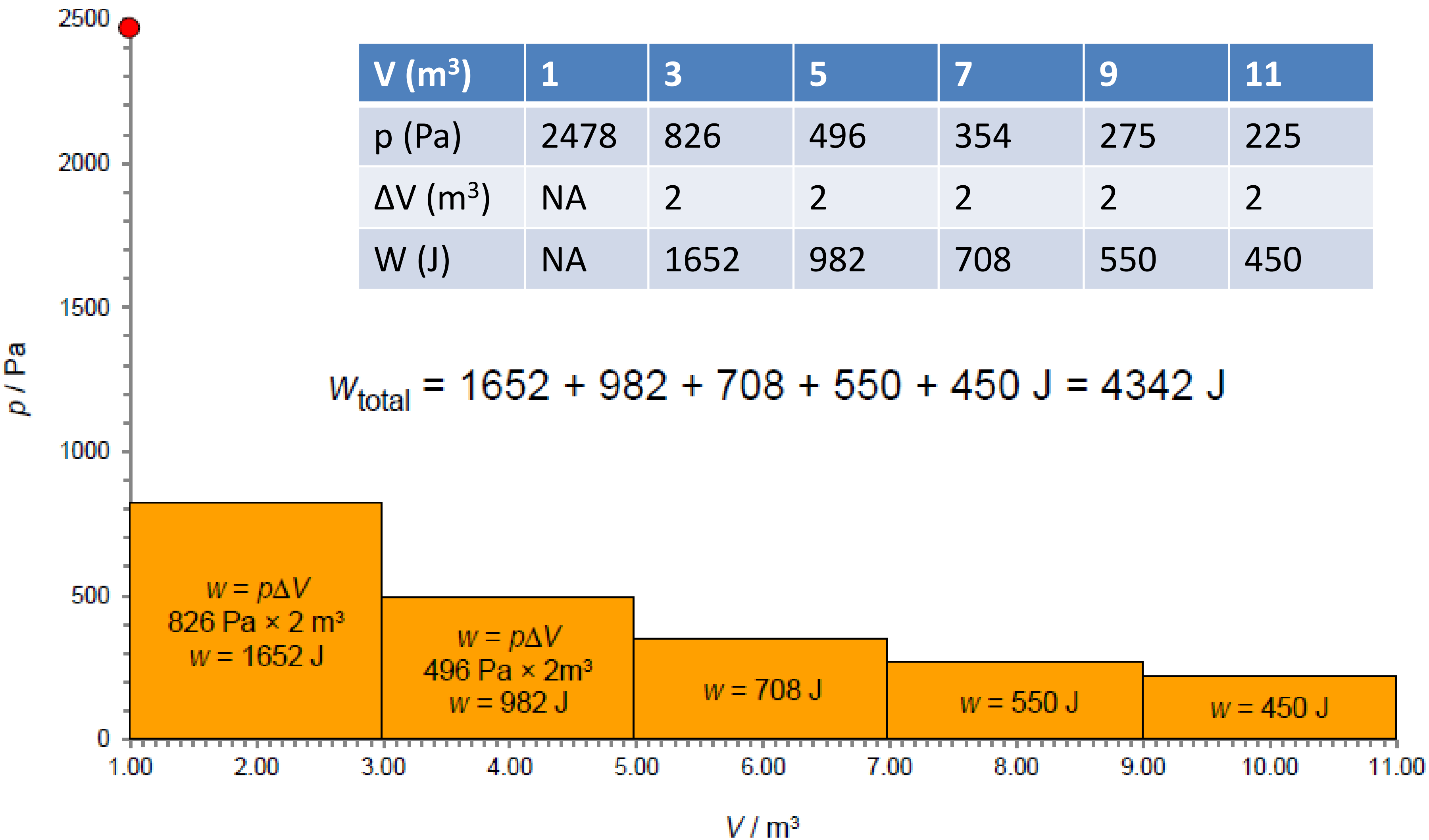
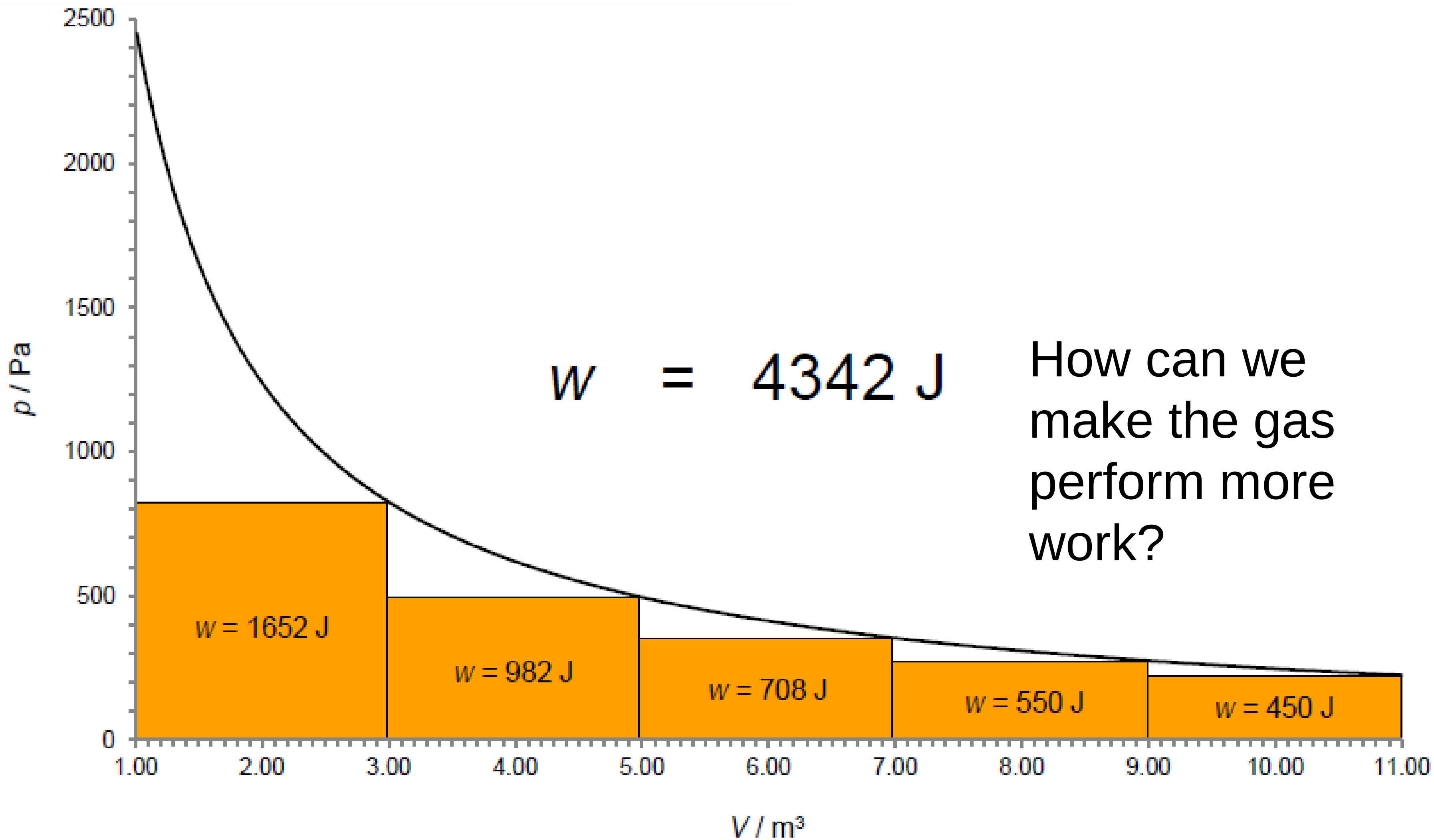


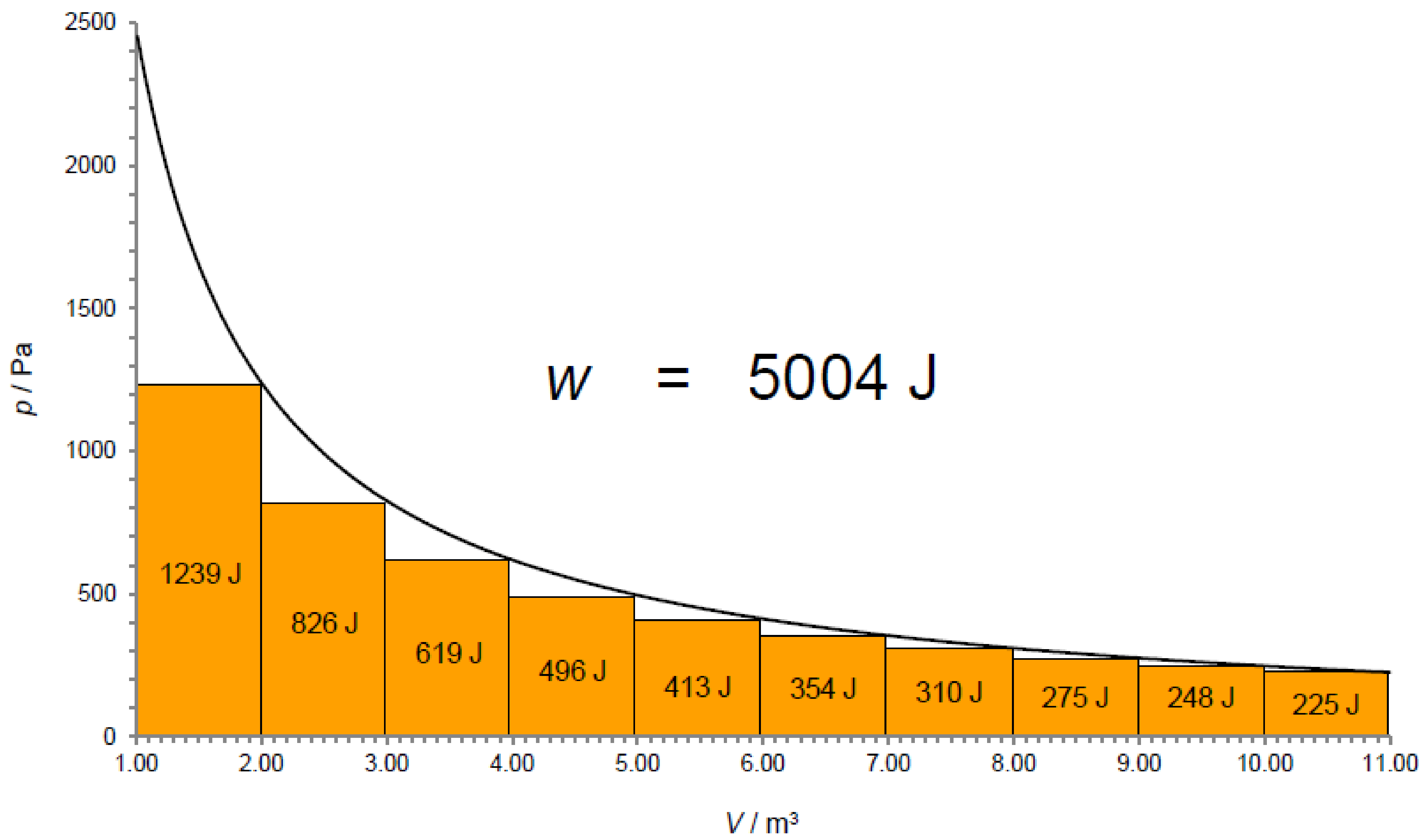
V (m^3)	1	3	5	7	9	11
p (Pa)	2478	826	496	354	275	225
ΔV (m^3)	NA	2	2	2	2	2
W (J)	NA	1652	982	708	550	450

$$W_{total} = 1652 + 982 + 708 + 550 + 450 \text{ J} = 4342 \text{ J}$$

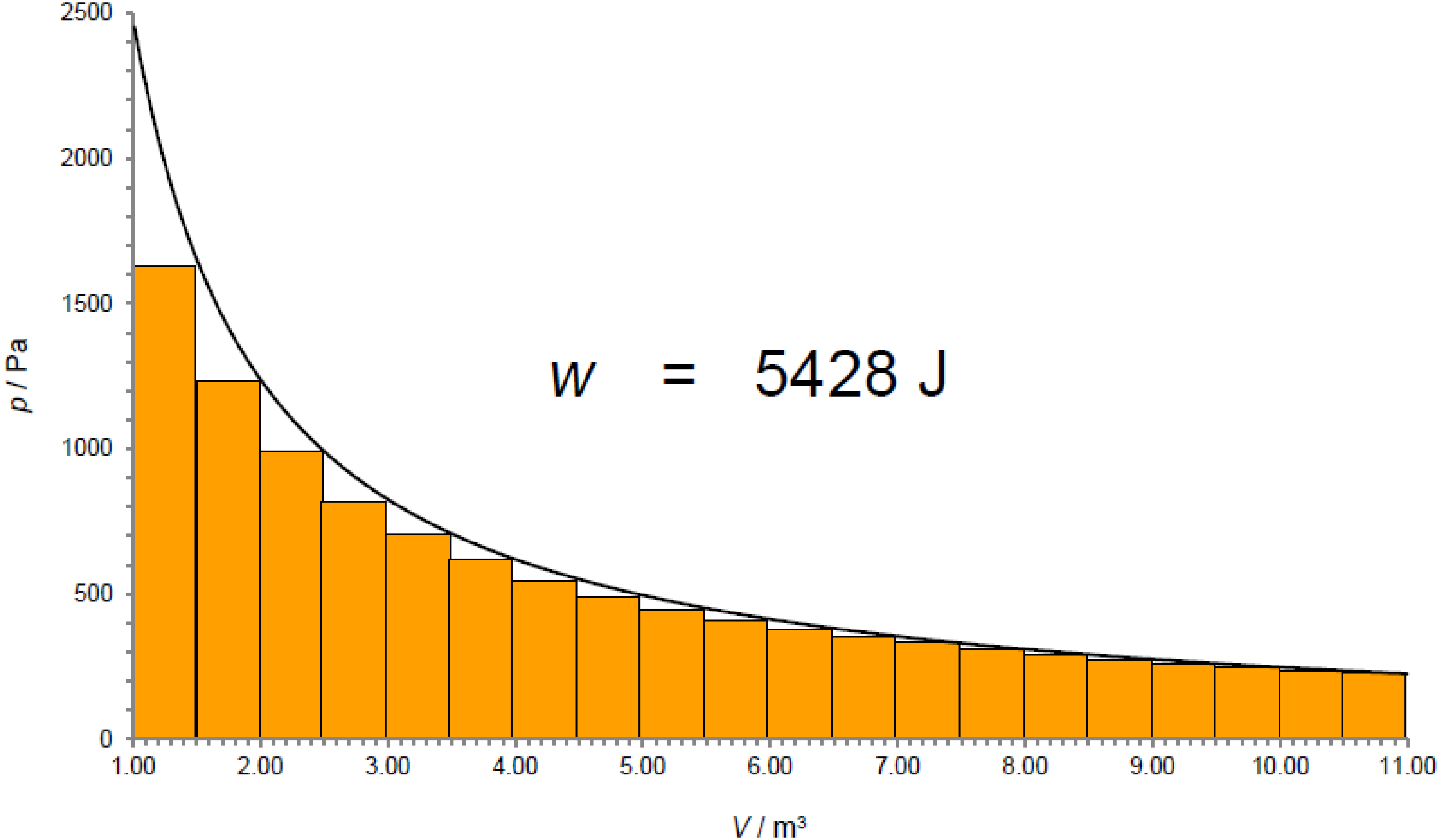




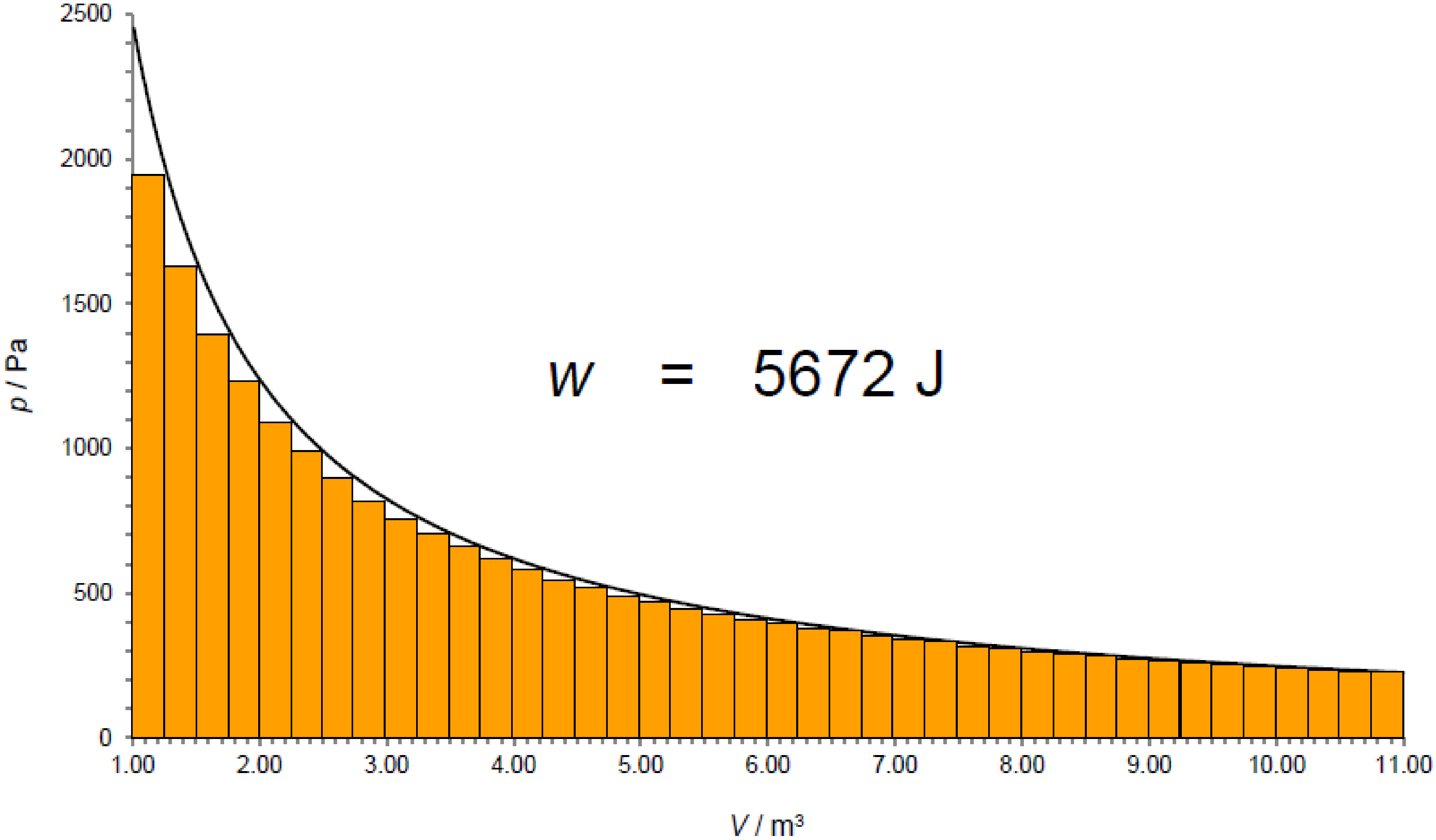
How can we make the gas perform more work?



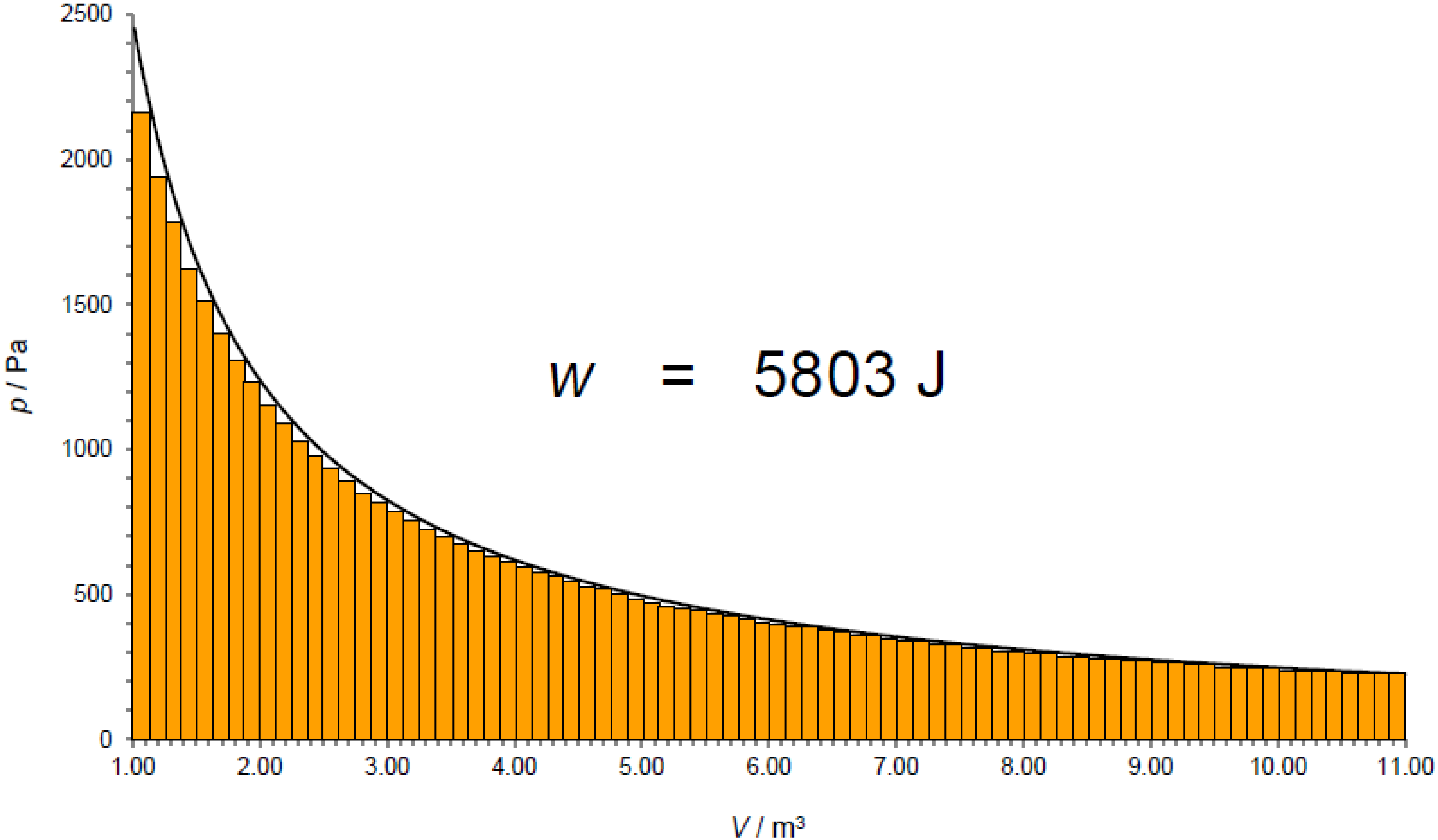
w = 5004 J
p / Pa
2500
2000
1500
1000
500
0
1239 J
826 J
619 J
496 J
413 J
354 J
310 J
275 J
248 J
225 J
1.00
2.00
3.00
4.00
5.00
6.00
7.00
8.00
9.00
10.00
11.00
V / m³



2500
2000
1500
1000
500
0
p / Pa
w = 5428 J
1.00
2.00
3.00
4.00
5.00
6.00
7.00
8.00
9.00
10.00
11.00
V / m³



2500
2000
1500
1000
500
0
p / Pa
w = 5672 J
1.00
2.00
3.00
4.00
5.00
6.00
7.00
8.00
9.00
10.00
11.00
V / m³



w = 5803 J
p / Pa
V / m³
2500
2000
1500
1000
500
0
1.00
2.00
3.00
4.00
5.00
6.00
7.00
8.00
9.00
10.00
11.00

What is the maximum work theoretically achievable?

$$w = pdV$$

But, $pV = nRT \rightarrow p = \frac{nRT}{V}$

So, $w = \frac{nRT}{V} dV$

Now consider an expansion from V_i to V_f

$$w = nRT \int_{Vi}^{Vf} \frac{dV}{V}$$

w_{on} for reversible isothermal expansion

$$\int \frac{dx}{x} = \ln x + c$$

$$w = nRT \int_{Vi}^{Vf} \frac{dV}{V}$$

$$\int_a^b f(x)\,dx = F(b) - F(a).$$

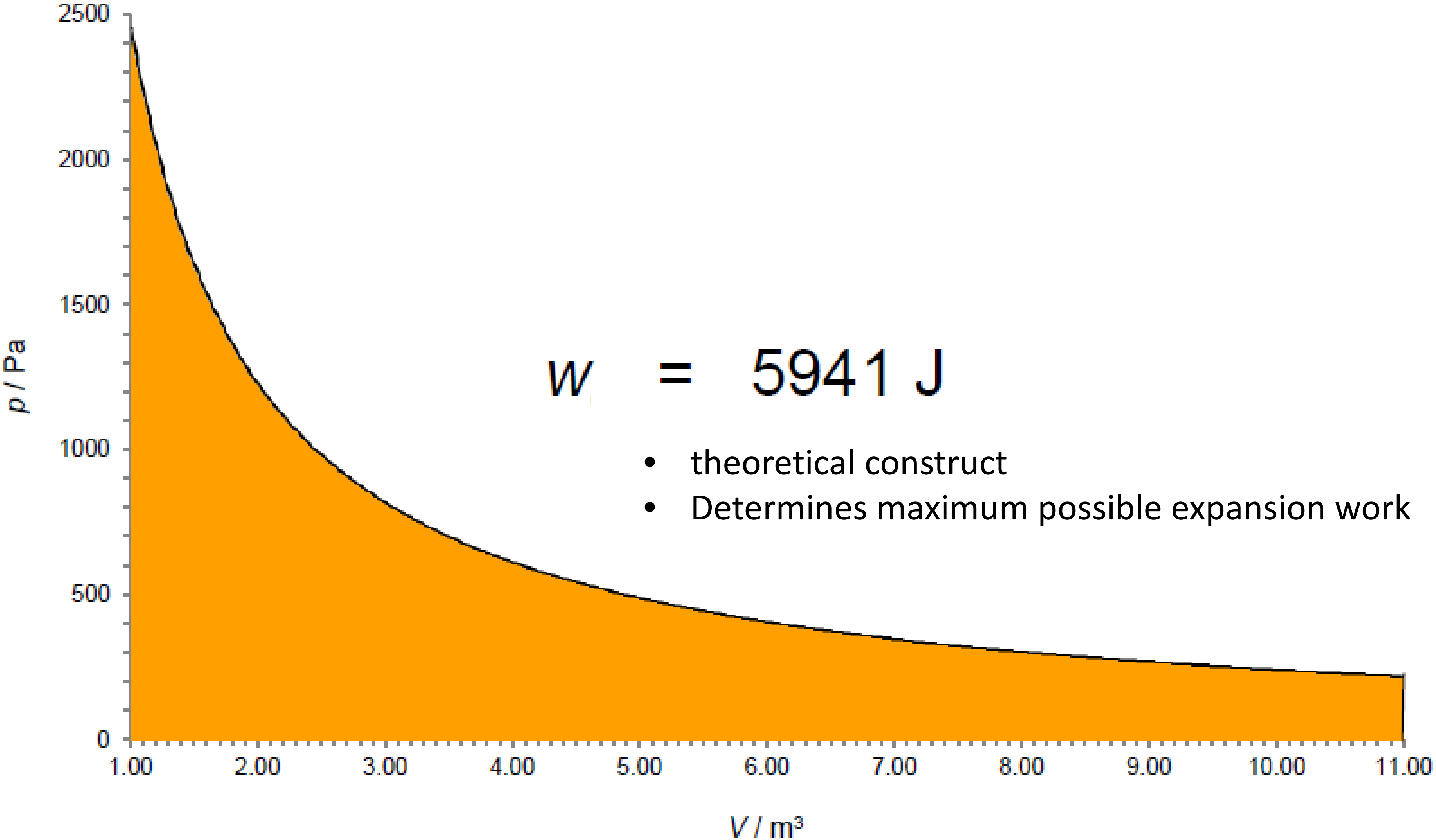
$$w = nRT(lnV_f - lnV_i)$$

$$\boxed{w = nRT ln \frac{V_f}{V_i}}$$

$$\ln A - \ln B = \ln \frac{A}{B}$$

w = 1 mol× 8.314 J/K/mol × 298 K × ln(11/1)

w = 5941 J

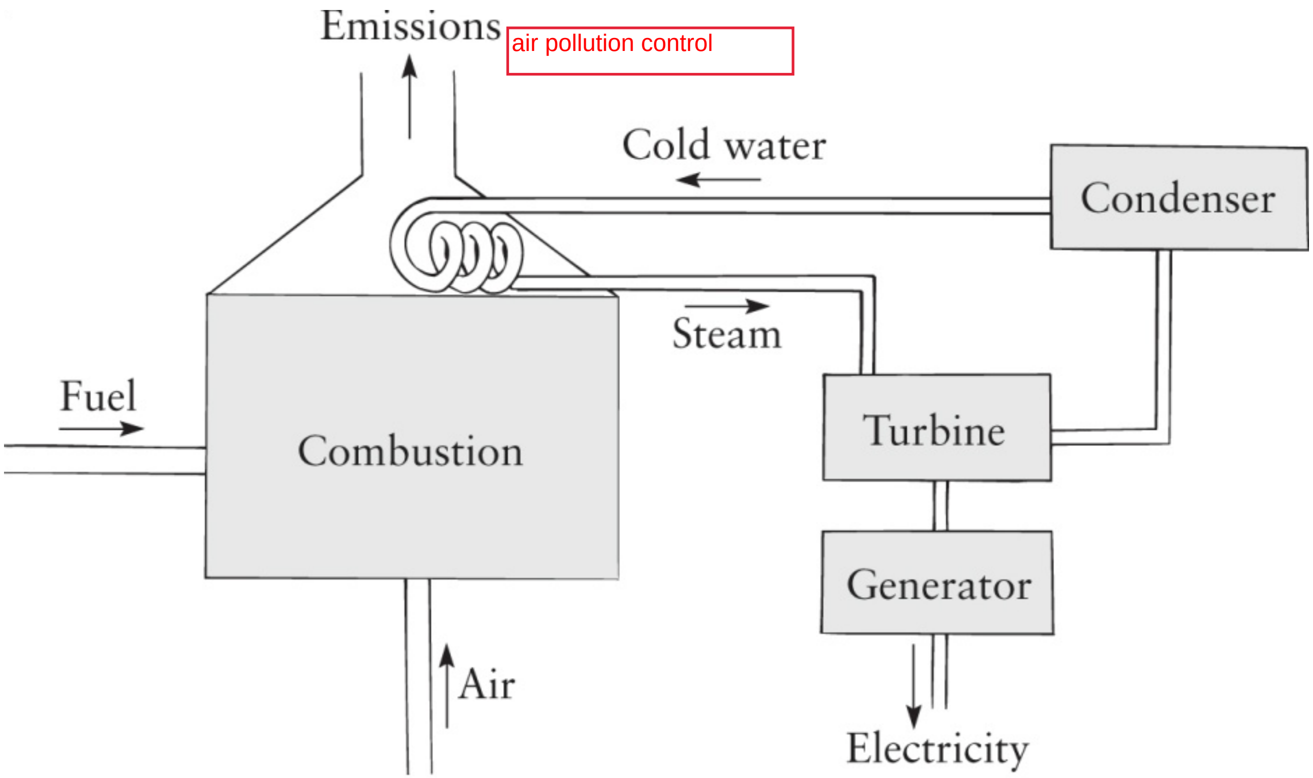


$$w = 5941 \text{ J}$$

- theoretical construct
- Determines maximum possible expansion work

Producing electricity from a steam generator

Operation of a fossil-fuel power plant



Efficiency of WTE plants

- All power plants have losses in energy due to hot stack gases, evaporation, friction, etc. The best plants so far have been hovering around *40%* efficiency
- The typical electrical efficiency of the newer generation WTE plants using mass burn technology is around 23%. Efficiencies are relatively low compared to fossil fuel power plants because of the lower calorific value of the waste and limitations on stream temperatures to avoid excessive corrosion caused by high temperature and acidic gases from MSW combustion

<u>Rule of thumb</u>: *for every 3 units of energy entering the average thermal power plant, approximately 1 unit is converted to electricity and 2 units are rejected to the environment as waste heat*, divided between stack gases (≈10%) and cooling water (≈57%)

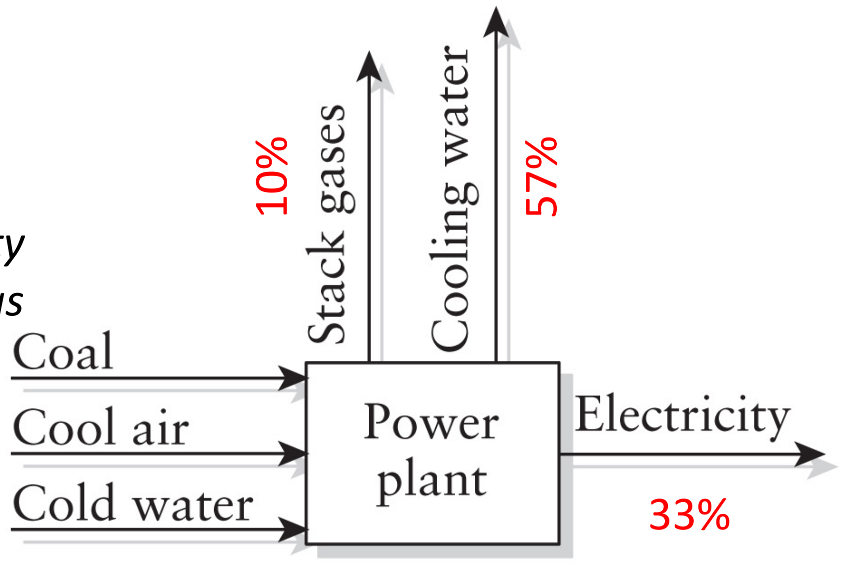


Figure 7.8 The power plant as a black box.

Undesirable effects of thermal technologies

- Waste heat
  - Usual limit at 1 °C
  - Large shallow pond or cooling tower
- Ash
  - 25% in mass and 5% in volume
  - 90% bottom ash and 10% fly ash
- Air pollutant
  - Sulfur oxides → acid rain
  - Thermal NOx (N from air 25%) and fuel NOx (N from fuel 75%) → Photochemical smog
  - Dioxin and Heavy metals → bioconcentration
  - CO_2 → global warming

https://www.youtube.com/watch?feature=player_embedded&v=p6Jabn5rhtk

Pollution control

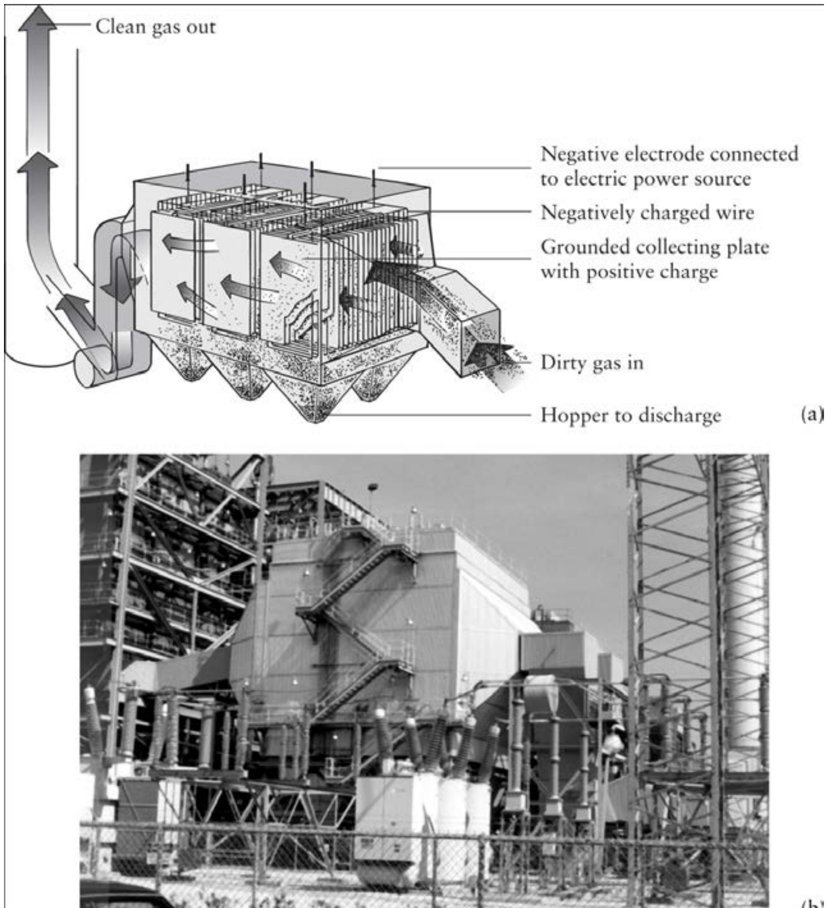


Figure 7-24 Electrostatic precipitator. (Courtesy P. Aarne Vesilind)

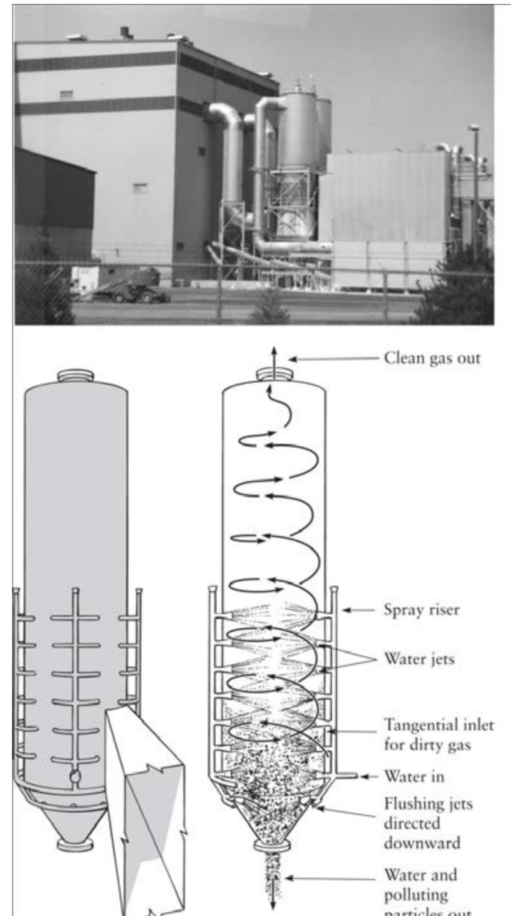


Figure 7-23 Scrubbers used for air pollution control. (Courtesy P. Aarne Vesilind)

Combustors produce a toxic ash

What?

- The better the air pollution control, the more toxic the ash
- Problem with heavy metals: close to being hazardous waste
- Final destination?

A modern incinerator – For every 4 tons of waste burned, > 1 ton of ash is produced

Table 7-13 Total Metal in Combined Ash

Metal	Ash by Weight, mg/kg
Aluminum	17,800
Calcium	33,600
Sodium	3,800
Iron	20,400
Lead	3,100
Cadmium	35
Zinc	4,100
Manganese	500
Mercury	Less than 3

Source: Modified from [22]

Solid Waste Engineering

1. Waste classification and characterization
2. Collection / Transport /Recycling
3. Combustion and energy recovery
4. Landfills

Landfills

- Engineered method for land disposal of solids or hazardous wastes in a manner that protects the environment
- Biological + chemical + physical processes → leachate + biogas
- In Europe, restrictions about putting biodegradable waste into landfills → most waste is incinerated or composted before landfilling → containment of waste
- Another approach in the US is to operate a landfill as a bioreactor → process optimization and control (addition of sludge, wastewater, nutrients) → treatment of waste

Planning a landfill

- The nightmare of the solid waste engineer
- Need to think 30 years into the future → difficult to anticipate the situation beyond that

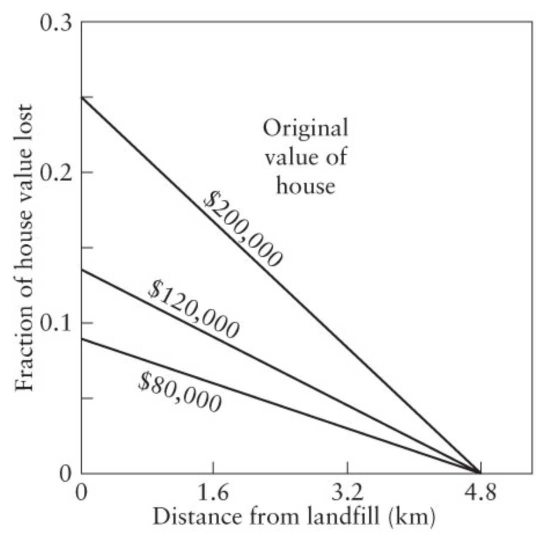
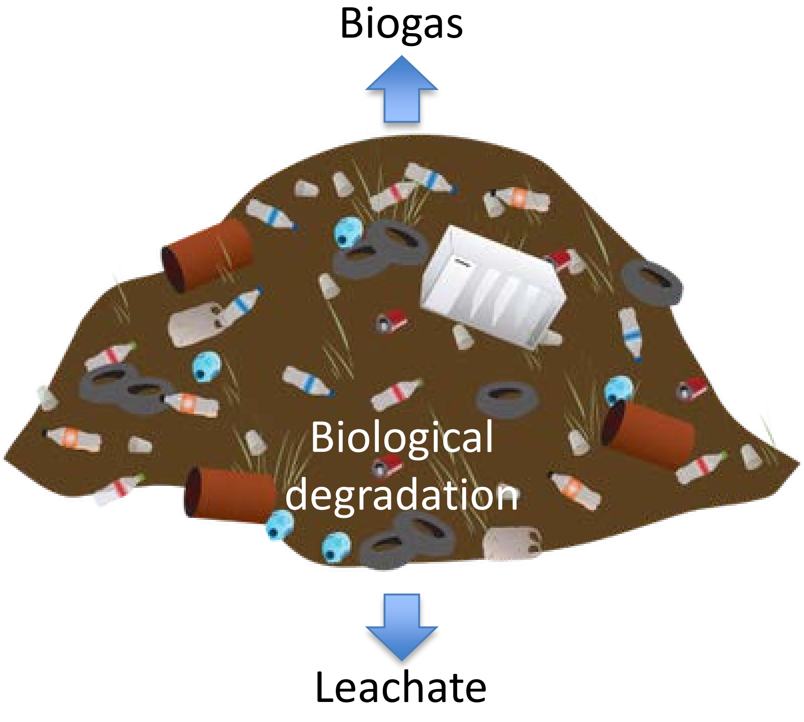


Figure 4-1 Effect on property values of siting a new landfill at a distance of three miles. Source: Vesilind, P. A., and E. I. Pas. 1998. "Discussion of A. C. Nelson, J. Genereux, and M. M. Genereux, A Price Effect of Landfills on Different House Value Strata." Journal of Urban Planning and Development, ASCE, 123, n. 3: 59–68. With permission from ASCE.

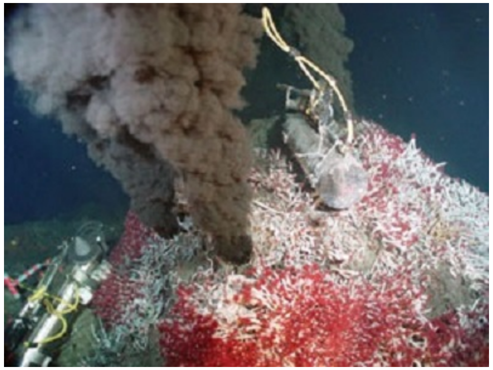
Loss in value
No compensation

Landfill processes

- 75% organic matter in refuse
- Rain → leachate
- Flooded landfill → Anaerobic digestion → biogas

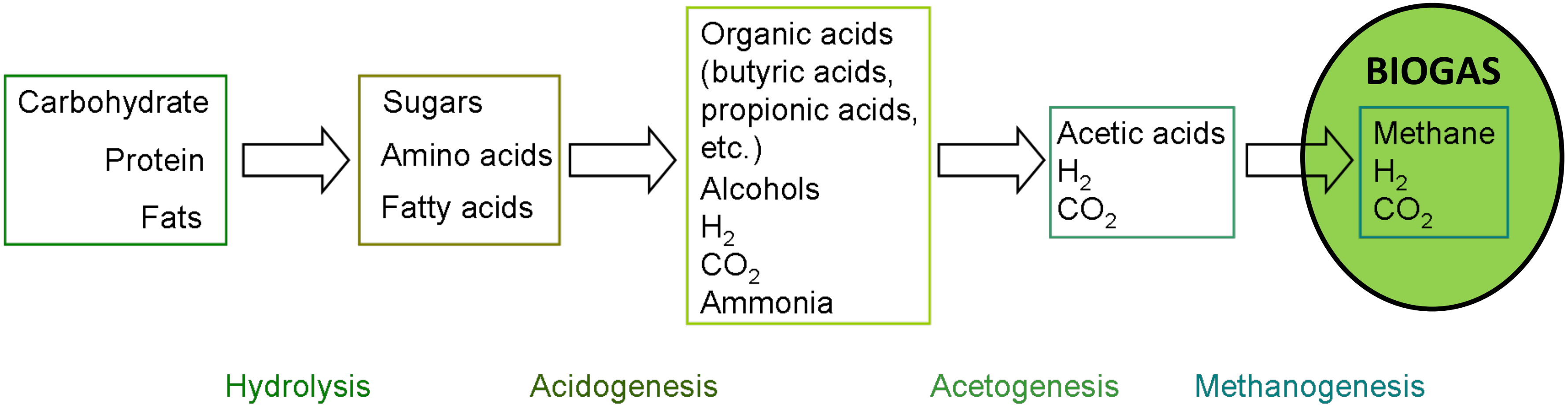


Biogas



Produced by *methanogenic Archaea*

- A taxonomic subgroup of *Archaea* with over 50 species
- Produce methane as metabolic product in *anaerobic conditions*
- Common in wetlands and in the guts of animals and humans, typically found near hot springs and thermal vents (generally *extremophiles*)
- Usually, methanogens cannot function under aerobic conditions (*oxygen intolerant*)



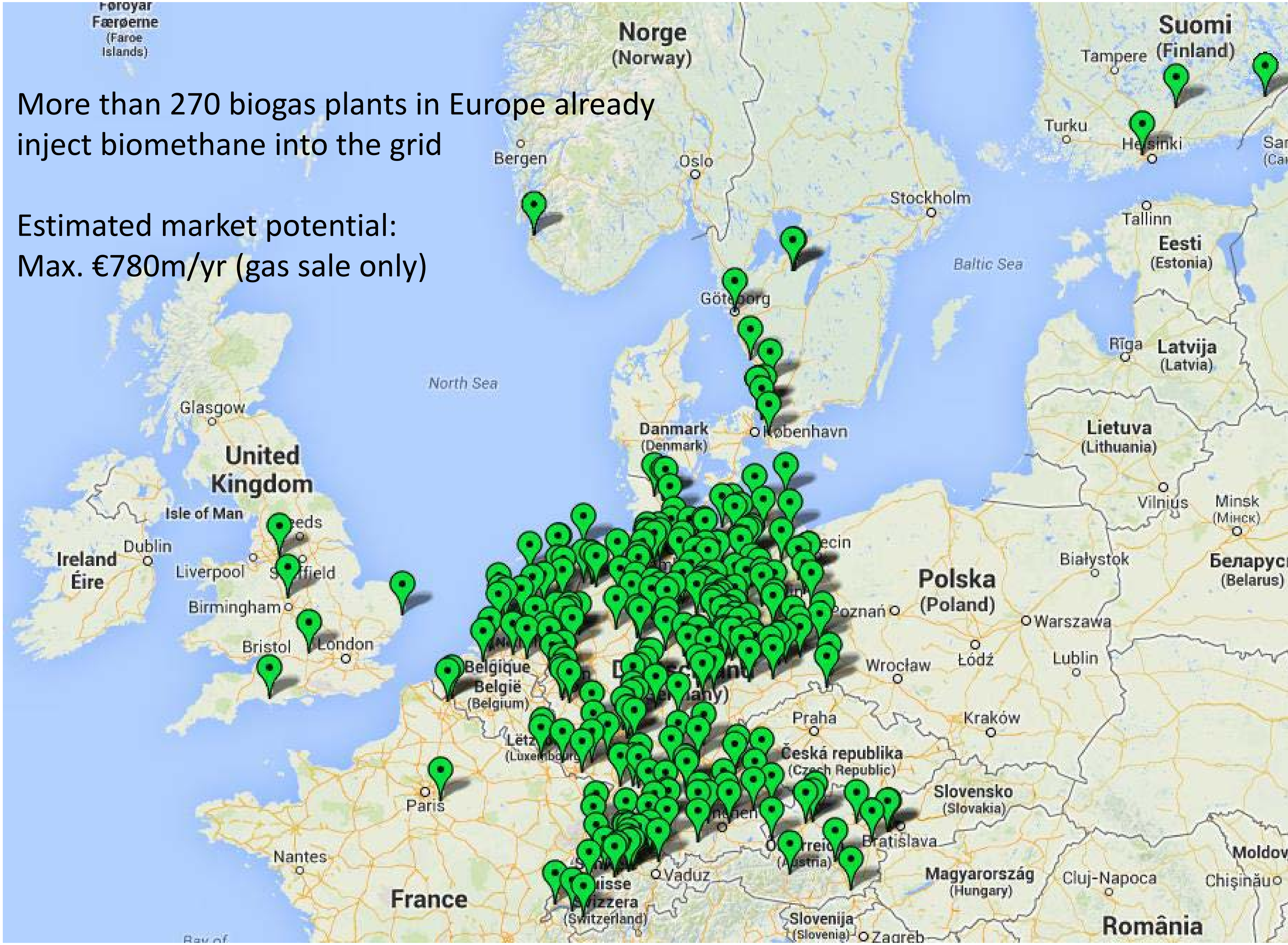
Applications and challenges

- Applications
  - Agricultural wastes
  - Food wastes
  - Municipal wastes
  - Wastewater in tropical countries (ideal T > 30 °C)

- Challenges
  - Biogas is a low energy fuel ≈ 50% CO_2
  - Requires large scale to be viable
  - Public acceptance
  - Sensitive to heavy metals
  and pesticides

More than 270 biogas plants in Europe already inject biomethane into the grid

Estimated market potential:
Max. €780m/yr (gas sale only)



Methane extraction from landfills

- Excellent fuel but transport is expensive
- Needs upgrading to remove water, CO_2, other contaminants, before going into a pipeline (adsorption)
- Large landfill needed for economy of scale
- biogas is a fuel if recovered…
- … But a GHG if wasted

Figure 4-21 Gas extraction well in place. (Courtesy William A. Worrell)

Leachate production

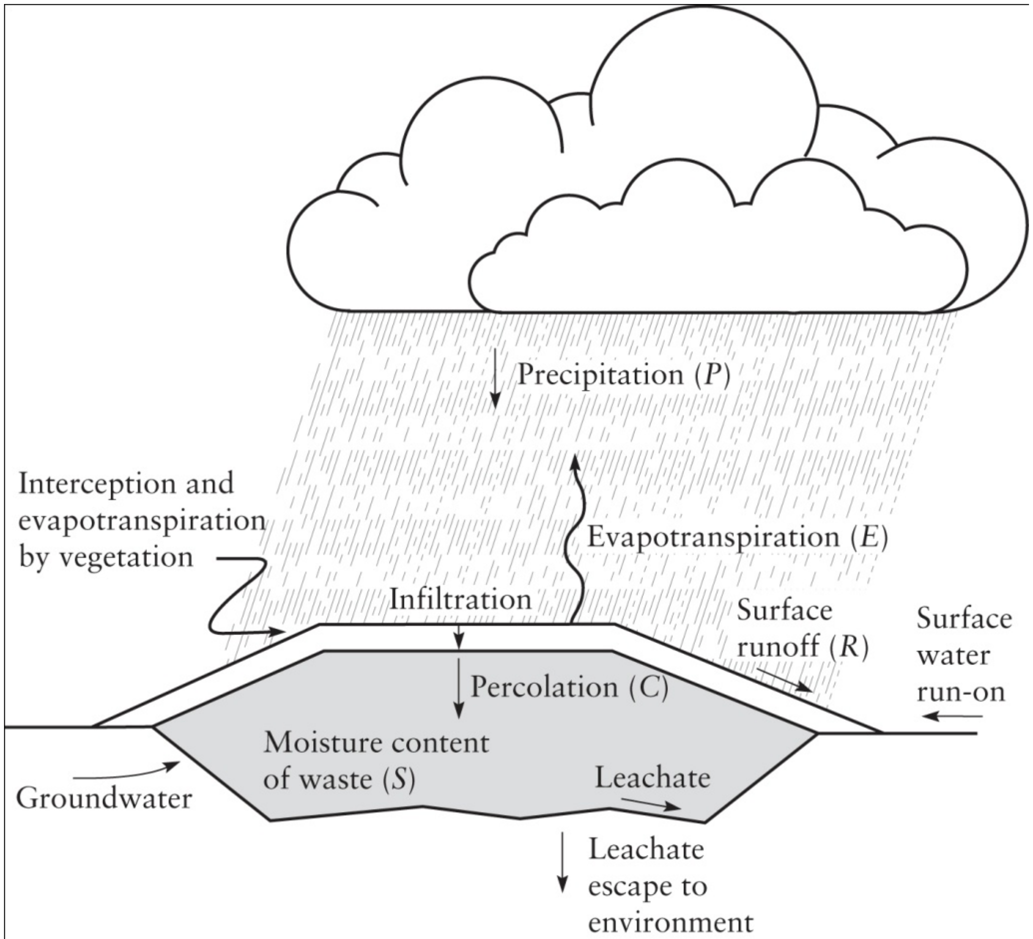


Figure 4-4 Schematic of components of water balance within a landfill.

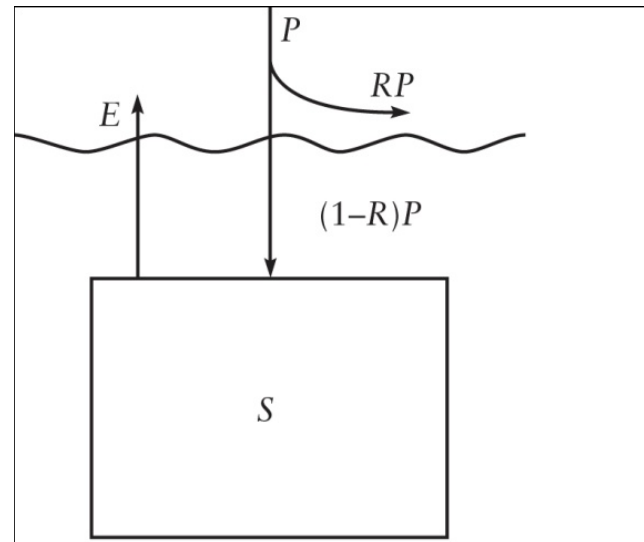
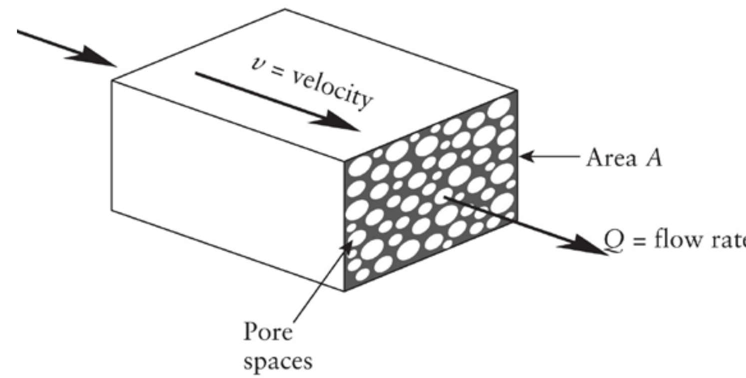


Figure 4-6 Mass balance of moisture in a landfill.

Determined by water balance:
percolation > evapotranspiration

Leachate quality

- Composition depends on composition of MSW, precipitation rates, compaction, cover design, waste age, interactions of leachate with environment, landfill design and operation
- Concerns about surface water and groundwater contamination
  - Gasoline and fuel oils
  - Chlorinated solvents (detergents)
  - Pesticides
  - Lead and Cadmium: batteries, light bulbs, electronic appliances
  - Combination of physical-chemical and biological processes



Flow from a porous medium such as soil.

Landfill design

- Liners
- Leachate collection, treatment and disposal
- Landfill gas collection and use

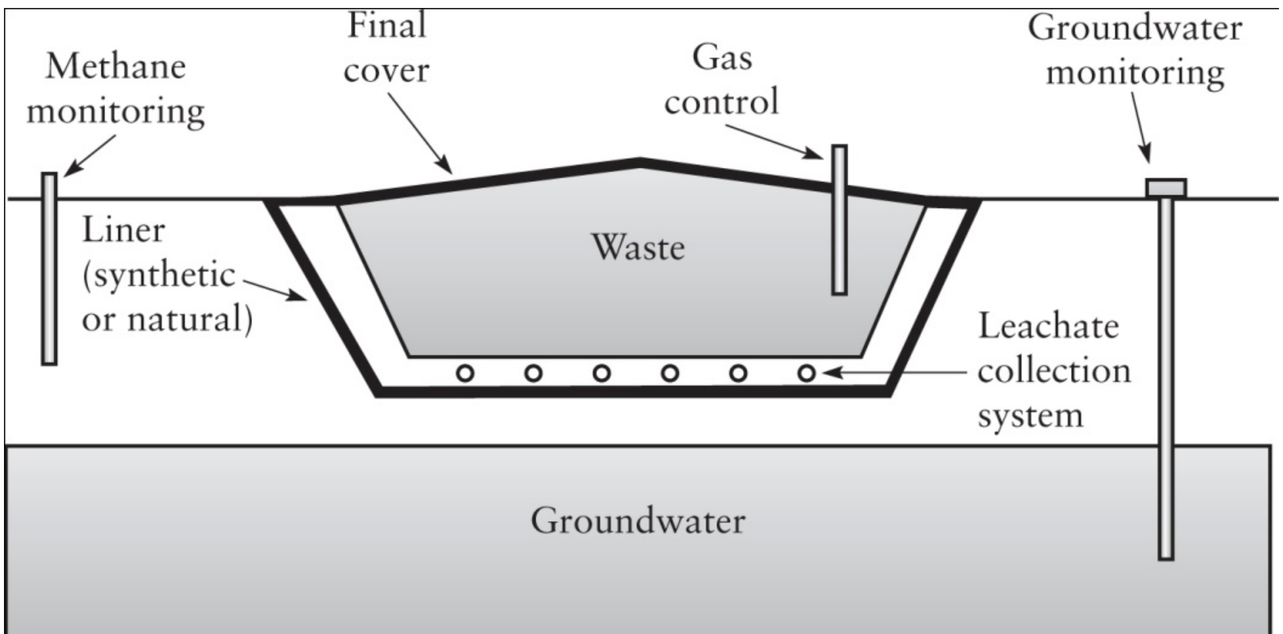
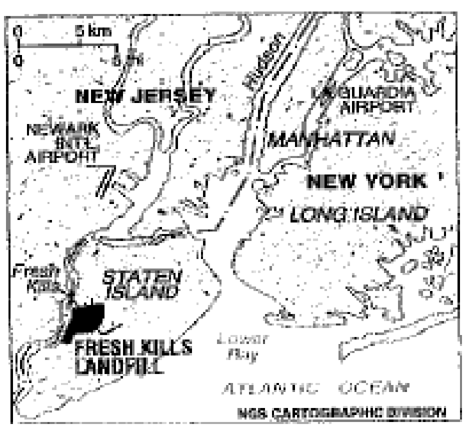


Figure 4-8 Design components in a Subtitle D landfill.

Final use should be considered as early as planning stage

- Golf course
- Natural area/open space
- Recreation parks
- Parking lots
- Building construction

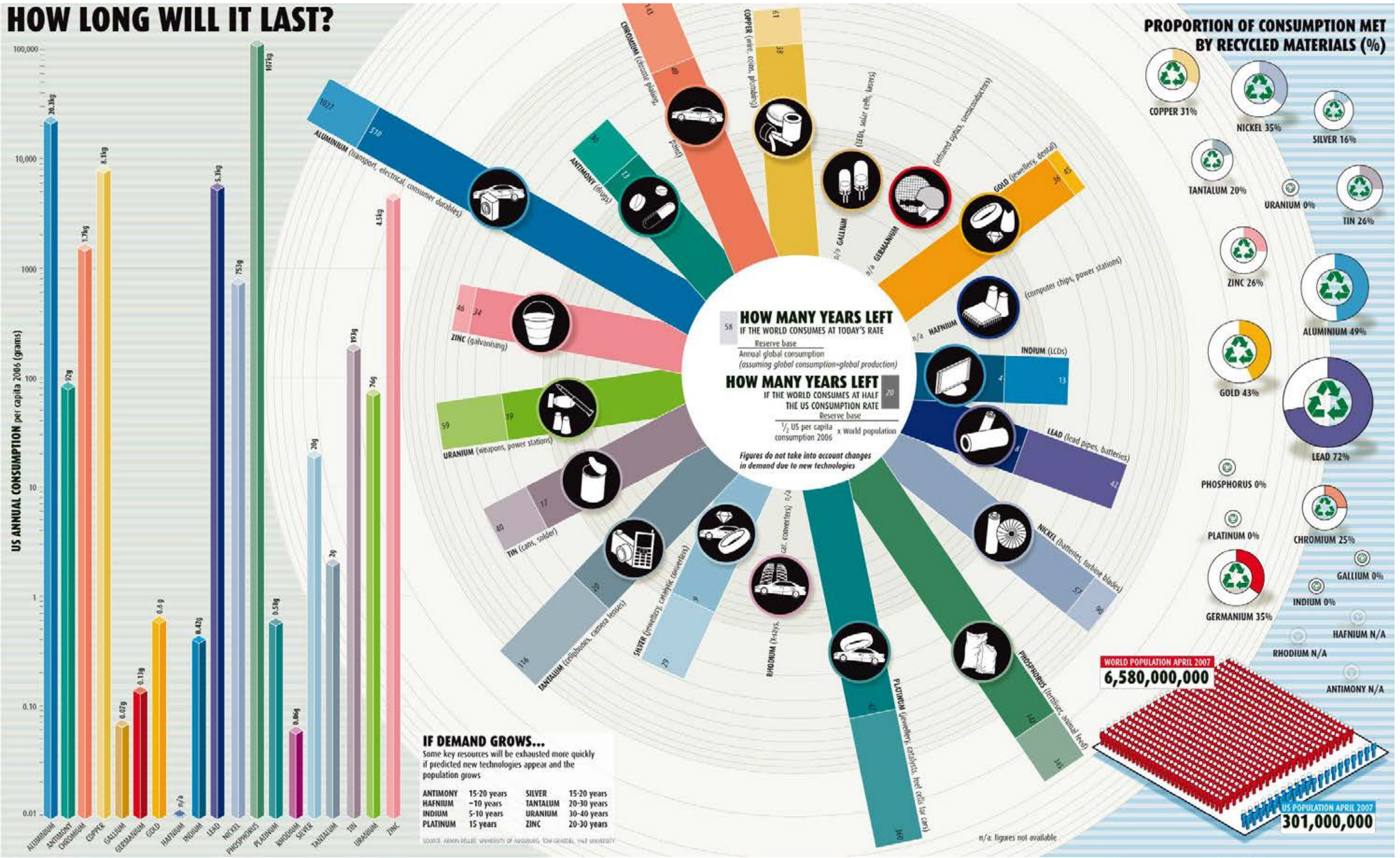
Figure 4-22 An unfortunate motel built on a settling landfill. (Courtesy P. Aarne Vesilind)



https://www.youtube.com/watch?feature=player_embedded&v=YxPJYiZNFGg

Landfill mining?

- If significant biodegradation has taken place
- Metal recovery
- Dirt and cover can be reused for present landfills
- But gas escape to atmosphere, contaminated runoffs
- Typically little value (dirty material) except for production of new space to extend the life of an existing landfill



HOW LONG WILL IT LAST?
US ANNUAL CONSUMPTION per capita 2006 (grams)
100,000
10,000
1000
100
10
1
0.10
0.01
ALUMINIUM 20.3kg
ANTIMONY 92g
CHROMIUM 1.7kg
COPPER 8.1kg
GALLIUM 0.07g
GERMANIUM 0.13g
GOLD 0.6g
HAFNIUM n/a
INDIUM 0.42g
LEAD 5.3kg
NICKEL 753g
PHOSPHORUS 107kg
PLATINUM 0.58g
RHODIUM 0.06g
SILVER 20g
TANTALUM 2g
TIN 193g
URANIUM 76g
ZINC 4.5kg
HOW MANY YEARS LEFT
IF THE WORLD CONSUMES AT TODAY'S RATE
Reserve base
Annual global consumption
(assuming global consumption=global production)
HOW MANY YEARS LEFT
IF THE WORLD CONSUMES AT HALF THE US CONSUMPTION RATE
Reserve base
1/2 US per capita consumption 2006 x World population
Figures do not take into account changes in demand due to new technologies
ALUMINIUM (transport, electrical, consumer durables) 1027 510
ANTIMONY (drugs) 30 13
CHROMIUM (chrome plating) 143 40
COPPER (wire, coins, plumbing) 61 38
GALLIUM (LEDs, solar cells, lasers) n/a
GERMANIUM (infrared optics, semiconductors) n/a
GOLD (jewellery, dental) 36 45
HAFNIUM (computer chips, power stations) n/a
INDIUM (LCDs) 4 13
LEAD (lead pipes, batteries) 8 42
NICKEL (batteries, turbine blades) 57 90
PHOSPHORUS (fertiliser, animal feed) 142 345
PLATINUM (jewellery, catalysts, fuel cells for cars) 42 360
RHODIUM (X-rays, cat. converters) n/a
SILVER (jewellery, catalytic converters) 9 29
TANTALUM (cellphones, camera lenses) 20 116
TIN (cans, solder) 17 40
URANIUM (weapons, power stations) 19 59
ZINC (galvanising) 34 46
IF DEMAND GROWS...
Some key resources will be exhausted more quickly if predicted new technologies appear and the population grows
ANTIMONY 15-20 years
HAFNIUM ~10 years
INDIUM 5-10 years
PLATINUM 15 years
SILVER 15-20 years
TANTALUM 20-30 years
URANIUM 30-40 years
ZINC 20-30 years
SOURCE: ARMIN RELLER, UNIVERSITY OF AUGSBURG; TOM GRAEDEL, YALE UNIVERSITY
n/a: figures not available
PROPORTION OF CONSUMPTION MET BY RECYCLED MATERIALS (%)
COPPER 31%
NICKEL 35%
SILVER 16%
TANTALUM 20%
URANIUM 0%
TIN 26%
ZINC 26%
ALUMINIUM 49%
GOLD 43%
LEAD 72%
PHOSPHORUS 0%
PLATINUM 0%
CHROMIUM 25%
GALLIUM 0%
GERMANIUM 35%
INDIUM 0%
HAFNIUM N/A
RHODIUM N/A
ANTIMONY N/A
WORLD POPULATION APRIL 2007
6,580,000,000
US POPULATION APRIL 2007
301,000,000

Moving toward a sustainable society

- Is zero waste achievable?
- Who are the stakeholders?
- Can we add a 4th R?