Intro and Terminology

Monday, August 22, 2022 9:51 AM

Units (SI)

Weight = mass (kg) g (9.807 m/sec²)

Units of energy : J ,

Temperature K = T(°C) + 273

Watts = V · A

Watts · sec = J

J = N · m

KPa · m³ = kJ

$\frac{KJ}{kg} = 1000 \frac{m^2}{sec^2}$

Definitions

Energy : the capacity to do work

Work : A force

1st law : Energy is conserved

2nd law : Some energy is "better" than others

System : quantity of matter or a region in space to study

Closed system : fixed mass; can change shape

Open System : mass can cross boundary, does not change shape in ME 251a

Control Surface : boundary of open system

Boundary : surface that separates system from surroundings

Isolated System : Nothing crosses boundary

Properties : characteristics of a system

Intensive properties : Independent of mass

Extensive properties : Dependent on mass

Density (ρ) = $\frac{\text{mass (kg)}}{\text{volume } (m^3)}$

Specific gravity (SG) = $\frac{\rho}{\rho_{water}}$

Specific weight = mg/volume

State : set of properties

Equilibrium state : state doesn't change when system is isolated

Equilibrium

Thermal : T is constant

Mechanical : Pressure is constant

Phase : Mass of each phase is constant

Chemical : Composition is constant

State postulate: state of a simple compressible system is defined by two independent intensive properties

Process: system changes from one equilibrium state to another

Quasi-equilibrium process: always infinitely close to equilibrium

Path: series of equilibrium states through which system passes during process

Cycle: process where final state = initial state

Steady process: all rates at which energy or mass cross the boundary of system are constant

Unsteady process: rates at which energy or mass cross boundary are not constant

Manometers and Barometers

Wednesday, August 24, 2022 9:53 AM

$K = T(°C) + 273.15$

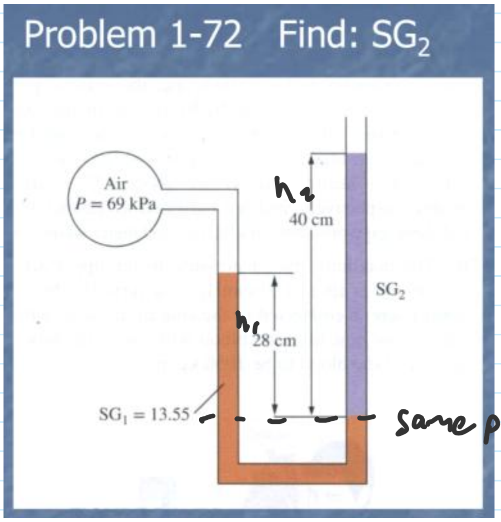
Pressure: Normal force exerted per unit area

$KPa = 1000 \ N/m^2$

$P_{abs} = P_{atm} \pm P_{gage}$

In Fluid, $P = P_{amb} + \rho g h$

Manometer U-tube



Problem 1-72 Find: SG_2

with gravity down

traveling up

$$P_{amb} + \rho_2 g h_2 - \rho_1 g h_1 = P$$

$SG_1 \cdot \rho_w = \rho_1$

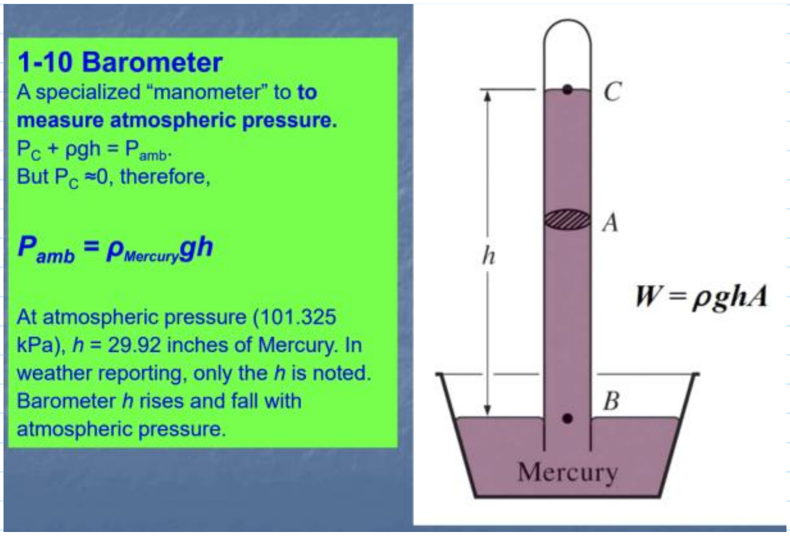
$\rho_w = 1000 \ kg/m^3$

$P_{amb} = 101.3 \ kPa$

$$P_{amb} + SG_2 g h_2 - SG_1 g h_1 = P$$

$$SG_2 = \frac{P + SG_1 g h_1 - P_{amb}}{g h_2}$$

$$SG_2 = \frac{69 + 13.55(9.807)(28) - 101.3}{(9.807)(40)}$$



1-10 Barometer

A specialized “manometer” to **to measure atmospheric pressure.**

$P_C + \rho g h = P_{amb}$.

But $P_C \approx 0$, therefore,

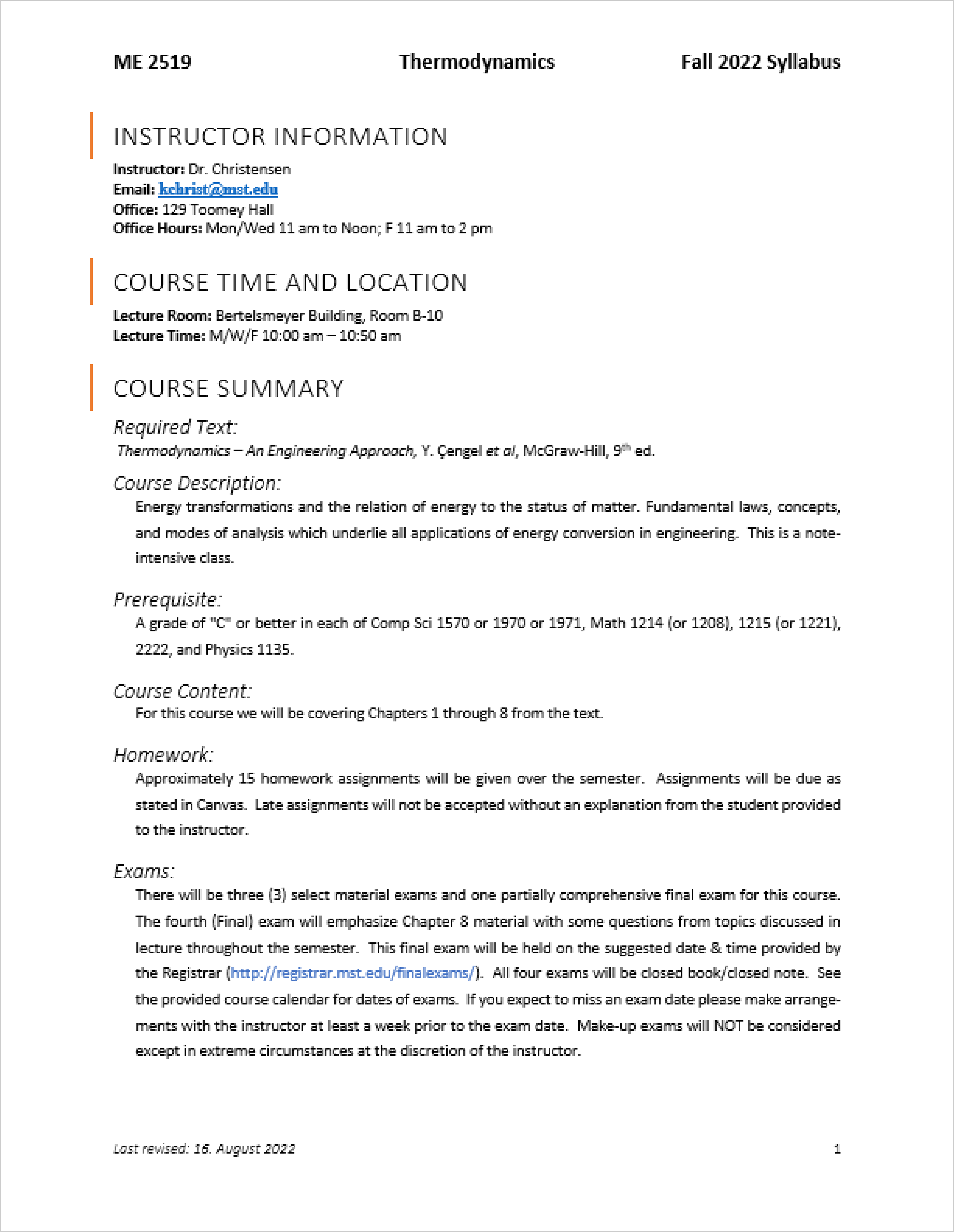
$$P_{amb} = \rho_{Mercury} g h$$

At atmospheric pressure (101.325 kPa), h = 29.92 inches of Mercury. In weather reporting, only the h is noted. Barometer h rises and fall with atmospheric pressure.

Syllabus

Monday, August 22, 2022 10:09 AM

Thermo syllabus



INSTRUCTOR INFORMATION

Instructor: Dr. Christensen
Email: kchrist@mst.edu
Office: 129 Toomey Hall
Office Hours: Mon/Wed 11 am to Noon; F 11 am to 2 pm

COURSE TIME AND LOCATION

Lecture Room: Bertelsmeyer Building, Room B-10
Lecture Time: M/W/F 10:00 am – 10:50 am

COURSE SUMMARY

Required Text:

Thermodynamics – An Engineering Approach, Y. Çengel *et al*, McGraw-Hill, 9th ed.

Course Description:

Energy transformations and the relation of energy to the status of matter. Fundamental laws, concepts, and modes of analysis which underlie all applications of energy conversion in engineering. This is a note-intensive class.

Prerequisite:

A grade of "C" or better in each of Comp Sci 1570 or 1970 or 1971, Math 1214 (or 1208), 1215 (or 1221), 2222, and Physics 1135.

Course Content:

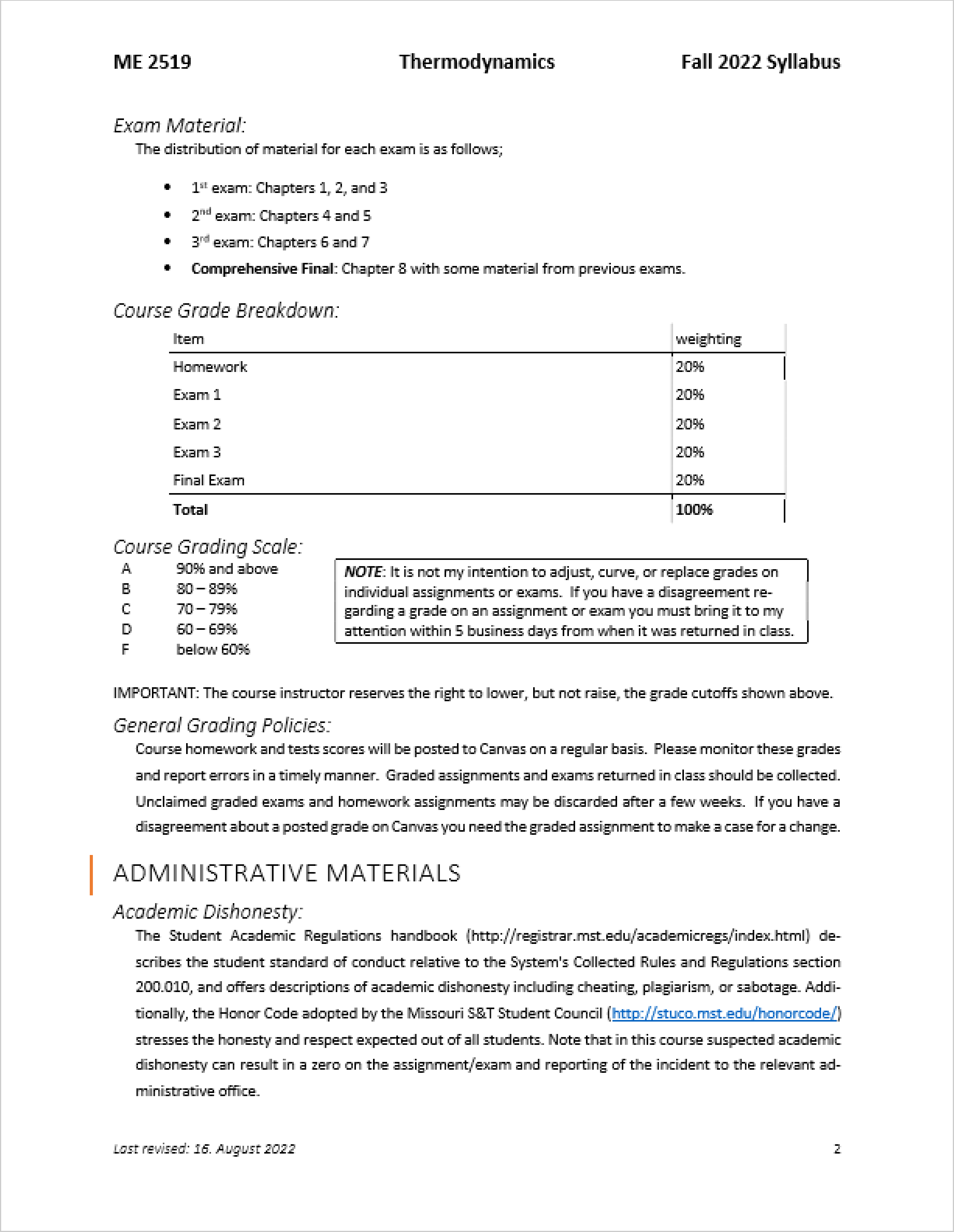
For this course we will be covering Chapters 1 through 8 from the text.

Homework:

Approximately 15 homework assignments will be given over the semester. Assignments will be due as stated in Canvas. Late assignments will not be accepted without an explanation from the student provided to the instructor.

Exams:

There will be three (3) select material exams and one partially comprehensive final exam for this course. The fourth (Final) exam will emphasize Chapter 8 material with some questions from topics discussed in lecture throughout the semester. This final exam will be held on the suggested date & time provided by the Registrar (http://registrar.mst.edu/finalexams/). All four exams will be closed book/closed note. See the provided course calendar for dates of exams. If you expect to miss an exam date please make arrangements with the instructor at least a week prior to the exam date. Make-up exams will NOT be considered except in extreme circumstances at the discretion of the instructor.



Exam Material:

The distribution of material for each exam is as follows;

- 1st exam: Chapters 1, 2, and 3
- 2nd exam: Chapters 4 and 5
- 3rd exam: Chapters 6 and 7
- **Comprehensive Final**: Chapter 8 with some material from previous exams.

Course Grade Breakdown:

Item	weighting
Homework	20%
Exam 1	20%
Exam 2	20%
Exam 3	20%
Final Exam	20%
Total	**100%**

Course Grading Scale:

A	90% and above
B	80 – 89%
C	70 – 79%
D	60 – 69%
F	below 60%

NOTE: It is not my intention to adjust, curve, or replace grades on individual assignments or exams. If you have a disagreement regarding a grade on an assignment or exam you must bring it to my attention within 5 business days from when it was returned in class.

IMPORTANT: The course instructor reserves the right to lower, but not raise, the grade cutoffs shown above.

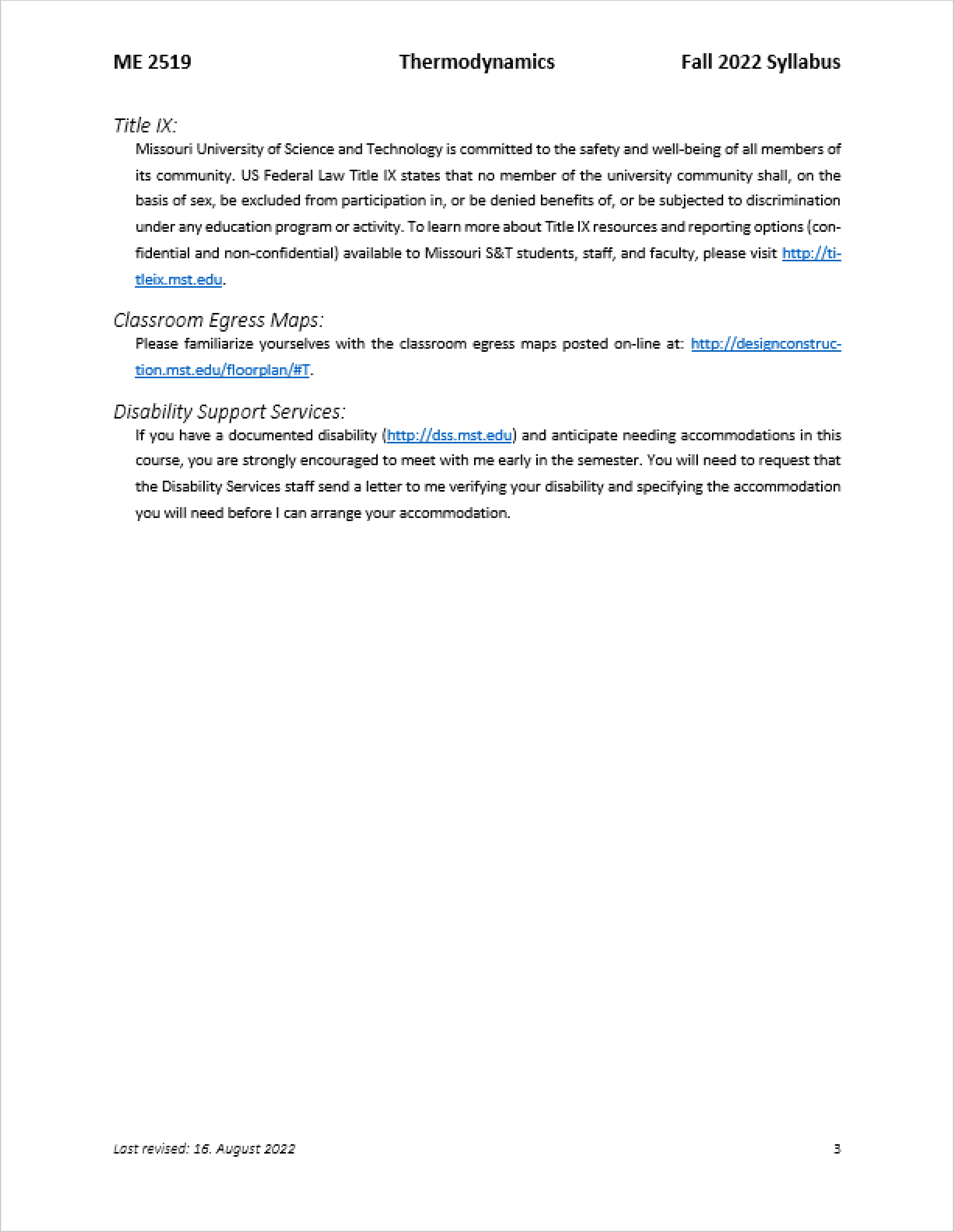
General Grading Policies:

Course homework and tests scores will be posted to Canvas on a regular basis. Please monitor these grades and report errors in a timely manner. Graded assignments and exams returned in class should be collected. Unclaimed graded exams and homework assignments may be discarded after a few weeks. If you have a disagreement about a posted grade on Canvas you need the graded assignment to make a case for a change.

ADMINISTRATIVE MATERIALS

Academic Dishonesty:

The Student Academic Regulations handbook (http://registrar.mst.edu/academicregs/index.html) describes the student standard of conduct relative to the System's Collected Rules and Regulations section 200.010, and offers descriptions of academic dishonesty including cheating, plagiarism, or sabotage. Additionally, the Honor Code adopted by the Missouri S&T Student Council (http://stuco.mst.edu/honorcode/) stresses the honesty and respect expected out of all students. Note that in this course suspected academic dishonesty can result in a zero on the assignment/exam and reporting of the incident to the relevant administrative office.



Title IX:

Missouri University of Science and Technology is committed to the safety and well-being of all members of its community. US Federal Law Title IX states that no member of the university community shall, on the basis of sex, be excluded from participation in, or be denied benefits of, or be subjected to discrimination under any education program or activity. To learn more about Title IX resources and reporting options (confidential and non-confidential) available to Missouri S&T students, staff, and faculty, please visit http://titleix.mst.edu.

Classroom Egress Maps:

Please familiarize yourselves with the classroom egress maps posted on-line at: http://designconstruction.mst.edu/floorplan/#T.

Disability Support Services:

If you have a documented disability (http://dss.mst.edu) and anticipate needing accommodations in this course, you are strongly encouraged to meet with me early in the semester. You will need to request that the Disability Services staff send a letter to me verifying your disability and specifying the accommodation you will need before I can arrange your accommodation.

Homework 1

Sunday, August 28, 2022 3:32 PM

1–47 A vacuum gage connected to a chamber reads 35 kPa at a location where the atmospheric pressure is 92 kPa. Determine the absolute pressure in the chamber.

$$P_{abs} = P_{atm} - P_{guage}$$

$$P_{abs} = 92 \text{ KPa} - 35 \text{ KPa}$$

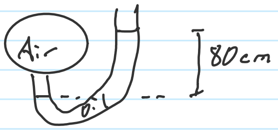
$$P_{abs} = 57 \text{ KPa}$$

1–63 A manometer containing oil ($\rho = 850$ kg/m^3) is attached to a tank filled with air. If the oil-level difference between the two columns is 80 cm and the atmospheric pressure is 98 kPa, determine the absolute pressure of the air in the tank. *Answers:* 105 kPa

$$P_{abs} = P_{atm} + \rho g h$$

$$P_{abs} = 98 \text{ KPa} + \frac{(850 \text{ kg/m}^3)(9.807 \text{ m/s}^2)(.8 \text{ m})}{1000}$$

$$P_{abs} = 104.669 \text{ KPa}$$



1–72 Consider a double-fluid manometer attached to an air pipe shown in Fig. P1–72. If the specific gravity of one fluid is 13.55, determine the specific gravity of the other fluid for the indicated absolute pressure of air. Take the atmospheric pressure to be 100 kPa. *Answer:* 1.59

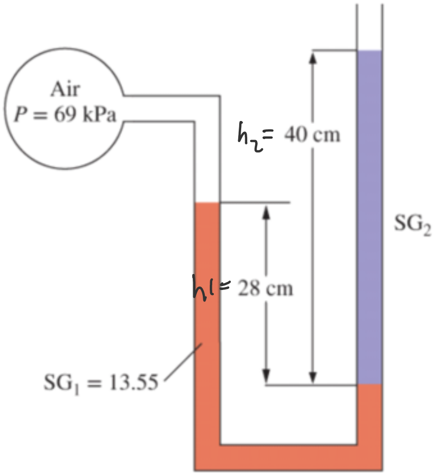


FIGURE P1–72

with gravity down

traveling up

$$P_{amb} + \rho_2 g h_2 - \rho_1 g h_1 = P$$

$$SG_1 \cdot \rho_w = \rho_1 \qquad \rho_w = 1000 \text{ kg/m}^3$$

$$P_{amb} = 100 \text{ KPa}$$

$$P_{amb} + SG_2 g h_2 - SG_1 g h_1 = P$$

$$SG_2 = \frac{P + SG_1 g h_1 - P_{amb}}{g h_2}$$

$$g h_2$$

$$SG_2 = \frac{69\,kPa + 13.55(9.807\,m/s^2)(.28\,m) - 100\,kPa}{(9.807\,m/s^2)(.4\,m)}$$

$$SG_2 = 1.582$$

1–75 Consider the manometer in Fig. 1–73. If the specific weight of fluid B is 20 kN/m³, what is the absolute pressure, in kPa, indicated by the manometer when the local atmospheric pressure is 720 mmHg? h_3

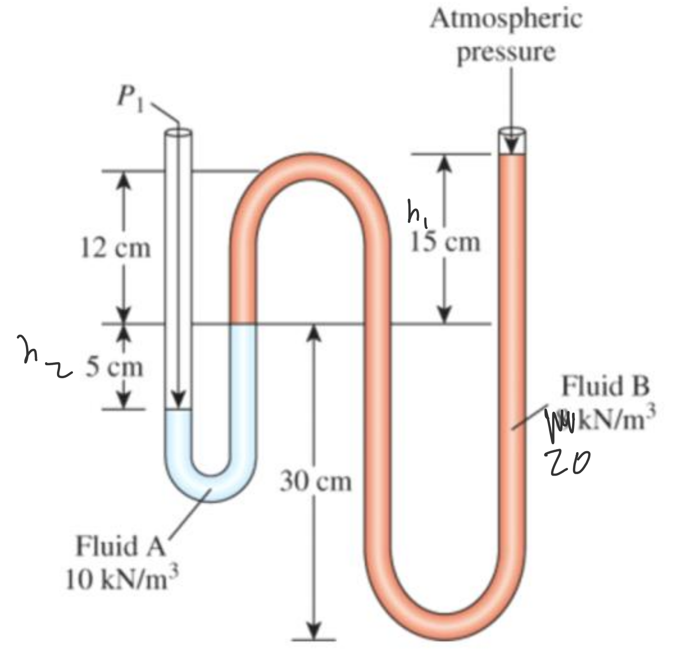


FIGURE P1–73

$$P_1 = P_{atm} + \rho_B g h_1 + \rho_A g h_2 \qquad P_{atm} = \rho_{Hg} g h = SG_{Hg} \cdot \rho_{water} \cdot g \cdot$$

$$P_1 = SG_{Hg} \cdot \rho_{water} \cdot g \cdot h_3 + \rho_B g h_1 + \rho_A g h_2 \qquad Sg_{Hg} = 13.55$$

$$P_1 = SG_{Hg} \cdot \rho_{water} \cdot h_3 g + \rho_B g h_1 + \rho_A g h_2$$

$$P_1 = \frac{13.55(1000\,kg/m^3)(.72\,m)(9.807\,m/s^2)}{1000} + \left((20\,kN/m^3)(.15\,m) + (10\,kN/m^3)(.05\,m)\right)$$

$$P_1 = 99.177\,KPa$$

Energy, Energy Transfer and General Energy Analysis

Monday, August 29, 2022 9:57 AM

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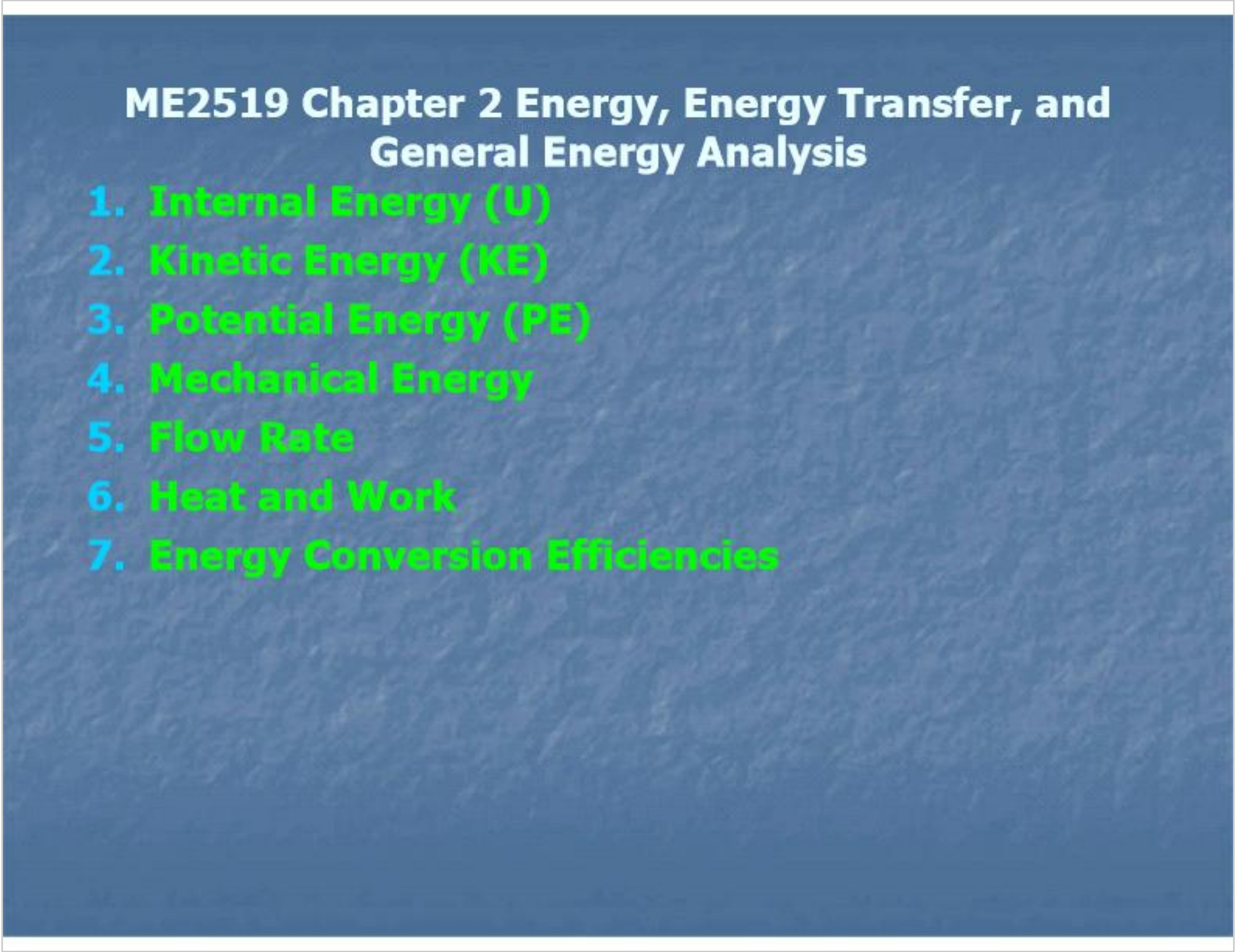
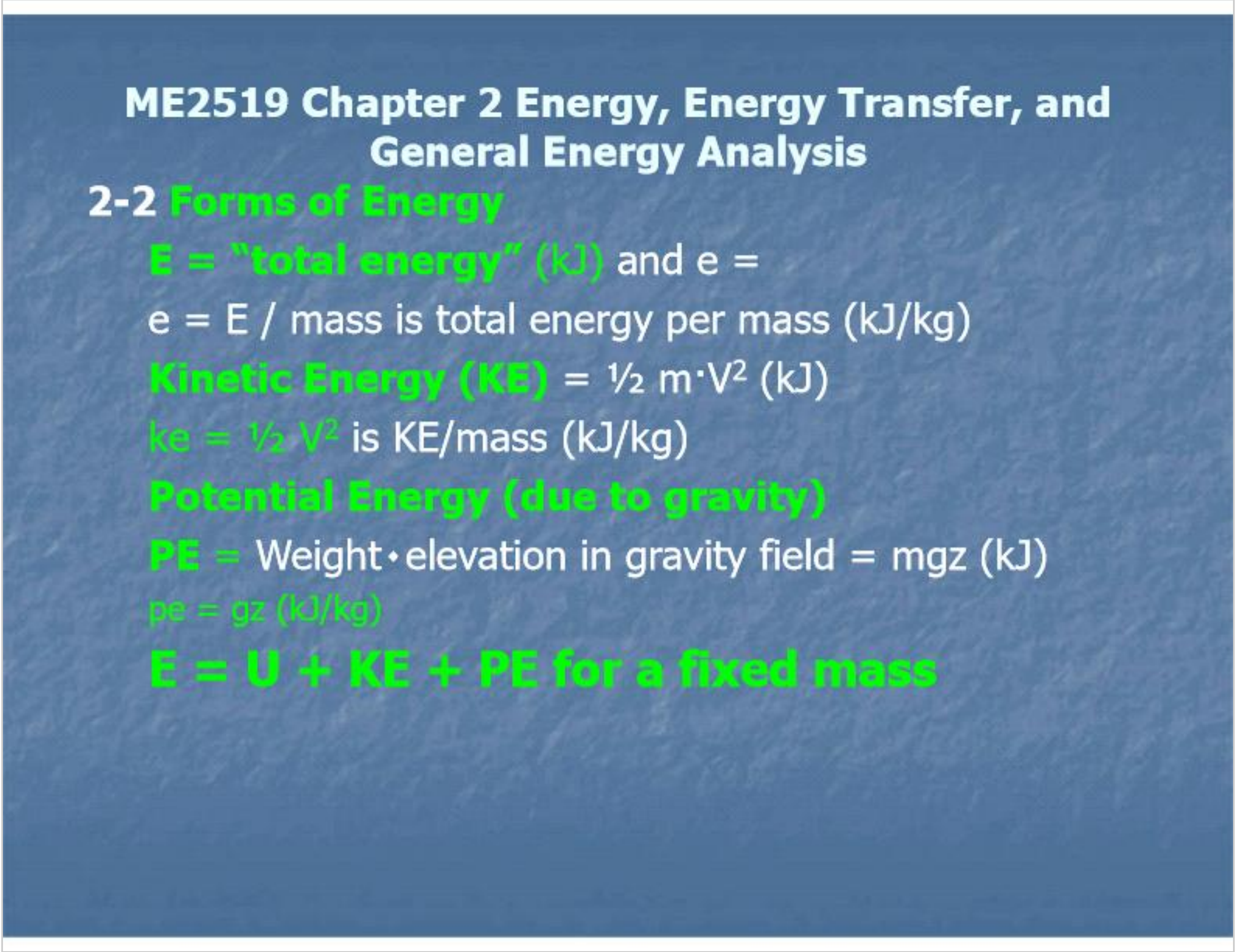


ME2519 Chapter 2 Energy, Energy Transfer, and General Energy Analysis

1. Internal Energy (U)
2. Kinetic Energy (KE)
3. Potential Energy (PE)
4. Mechanical Energy
5. Flow Rate
6. Heat and Work
7. Energy Conversion Efficiencies



ME2519 Chapter 2 Energy, Energy Transfer, and General Energy Analysis

2-2 **Forms of Energy**

E = "total energy" (kJ) and e =

e = E / mass is total energy per mass (kJ/kg)

Kinetic Energy (KE) = ½ $m \cdot V^2$ (kJ)

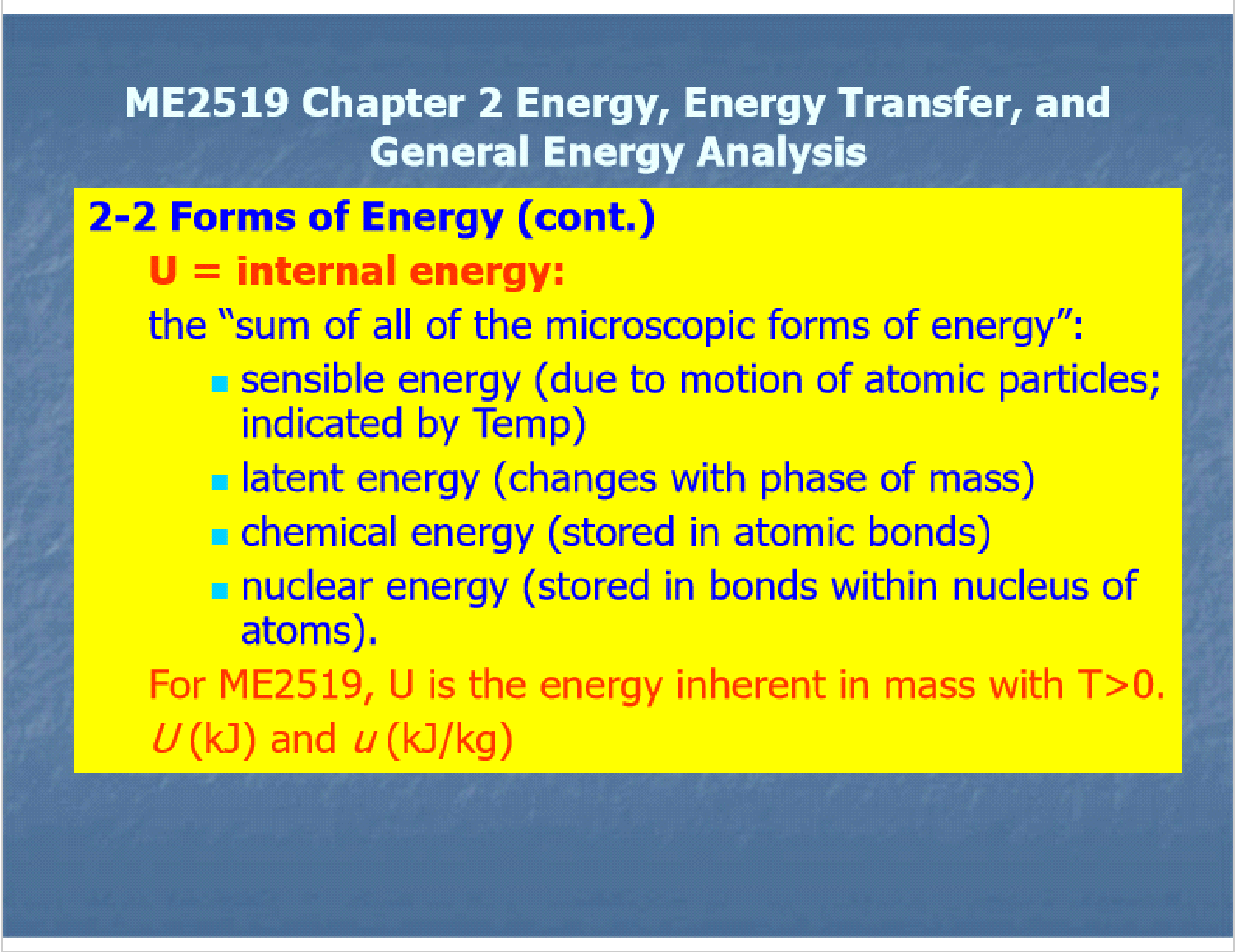
ke = ½ V^2 is KE/mass (kJ/kg)

Potential Energy (due to gravity)

PE = Weight⬩elevation in gravity field = mgz (kJ)

pe = gz (kJ/kg)

E = U + KE + PE for a fixed mass



ME2519 Chapter 2 Energy, Energy Transfer, and General Energy Analysis

2-2 Forms of Energy (cont.)

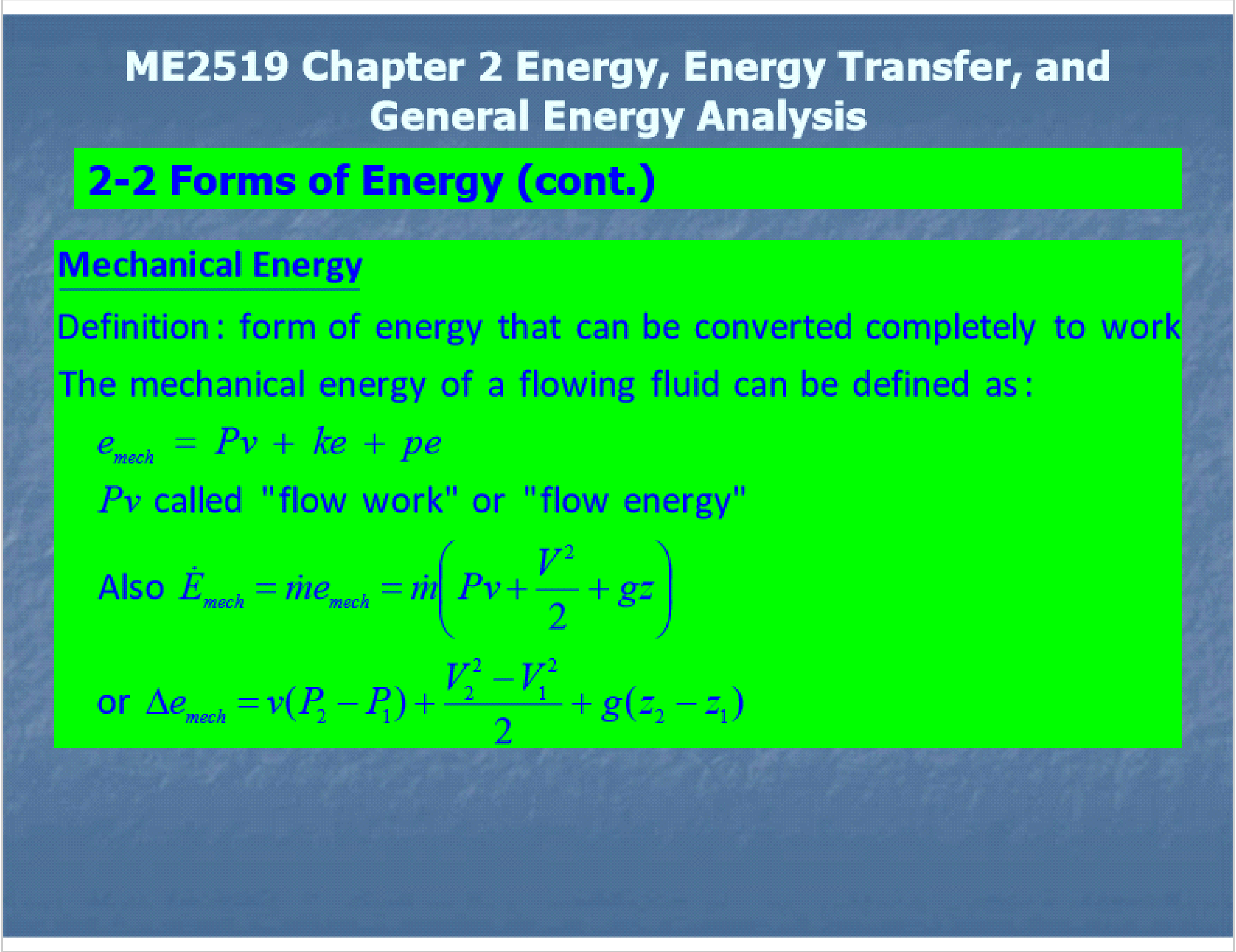
U = internal energy:

the “sum of all of the microscopic forms of energy”:

- sensible energy (due to motion of atomic particles; indicated by Temp)
- latent energy (changes with phase of mass)
- chemical energy (stored in atomic bonds)
- nuclear energy (stored in bonds within nucleus of atoms).

For ME2519, U is the energy inherent in mass with T>0.

U (kJ) and u (kJ/kg)



ME2519 Chapter 2 Energy, Energy Transfer, and General Energy Analysis

2-2 Forms of Energy (cont.)

Mechanical Energy

Definition: form of energy that can be converted completely to work

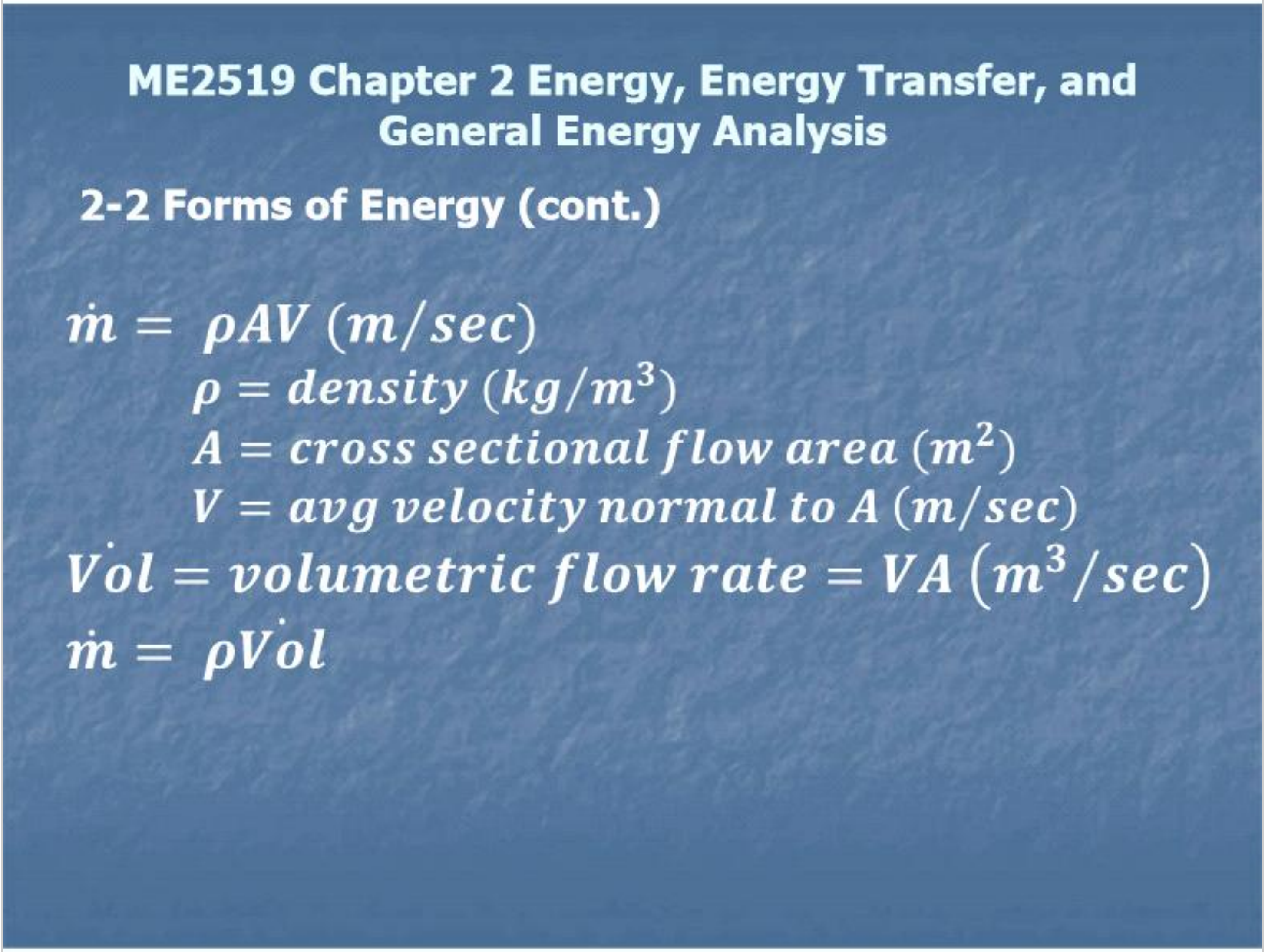
The mechanical energy of a flowing fluid can be defined as:

$$e_{mech} = Pv + ke + pe$$

Pv called "flow work" or "flow energy"

Also $\dot{E}_{mech} = \dot{m}e_{mech} = \dot{m}\left(Pv + \frac{V^2}{2} + gz\right)$

or $\Delta e_{mech} = v(P_2 - P_1) + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1)$



ME2519 Chapter 2 Energy, Energy Transfer, and General Energy Analysis

2-2 Forms of Energy (cont.)

$$\dot{m} = \rho A V \ (m/sec)$$

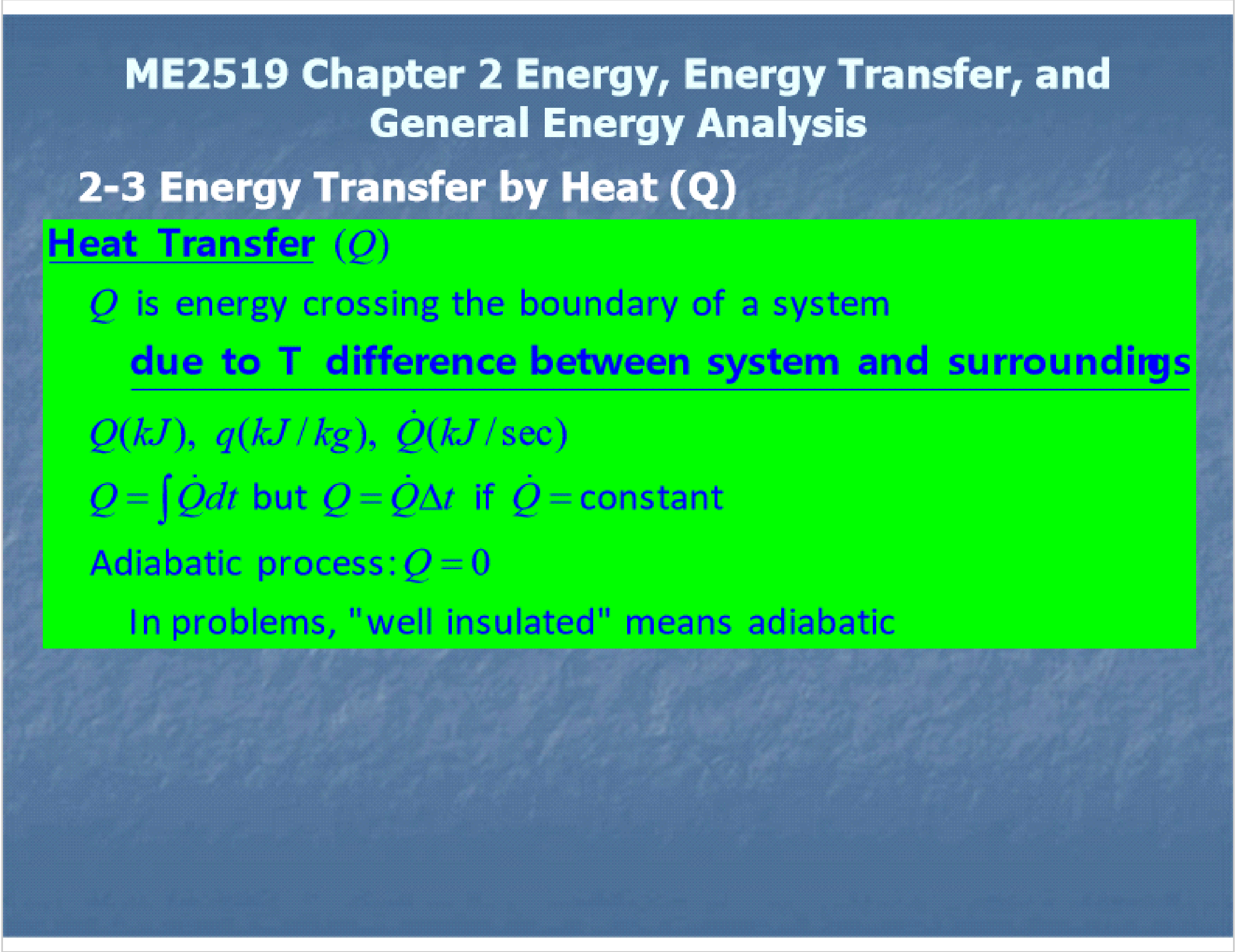
$$\rho = density \ (kg/m^3)$$

$$A = cross\ sectional\ flow\ area \ (m^2)$$

$$V = avg\ velocity\ normal\ to\ A \ (m/sec)$$

$$V\dot{o}l = volumetric\ flow\ rate = VA\ \left(m^3/sec\right)$$

$$\dot{m} = \rho V\dot{o}l$$



ME2519 Chapter 2 Energy, Energy Transfer, and General Energy Analysis

2-3 Energy Transfer by Heat (Q)

Heat Transfer (Q)

Q is energy crossing the boundary of a system

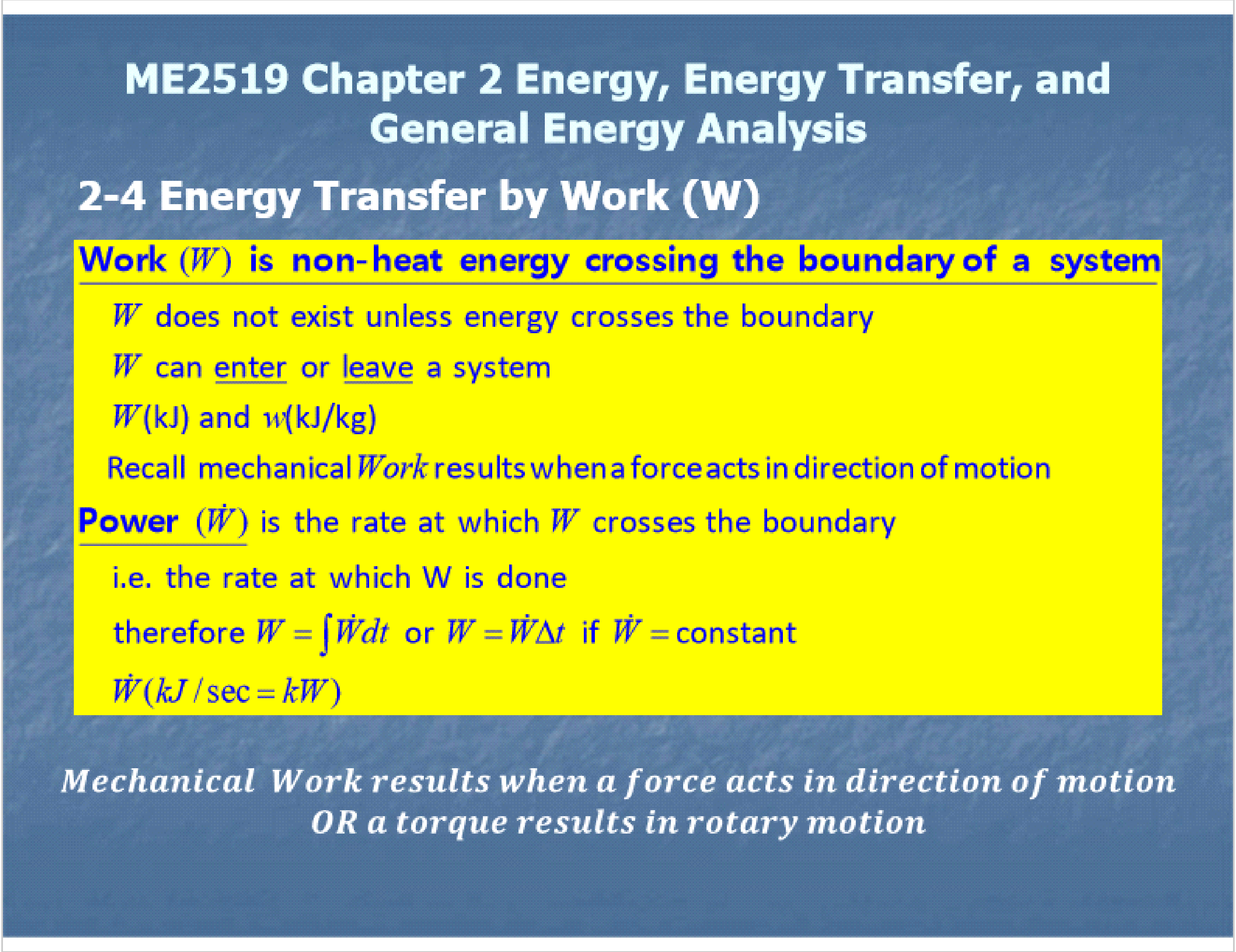
due to T difference between system and surroundings

$Q(kJ),\ q(kJ/kg),\ \dot{Q}(kJ/\sec)$

$Q=\int\dot{Q}dt$ but $Q=\dot{Q}\Delta t$ if $\dot{Q}=$ constant

Adiabatic process: $Q=0$

In problems, "well insulated" means adiabatic



ME2519 Chapter 2 Energy, Energy Transfer, and General Energy Analysis

2-4 Energy Transfer by Work (W)

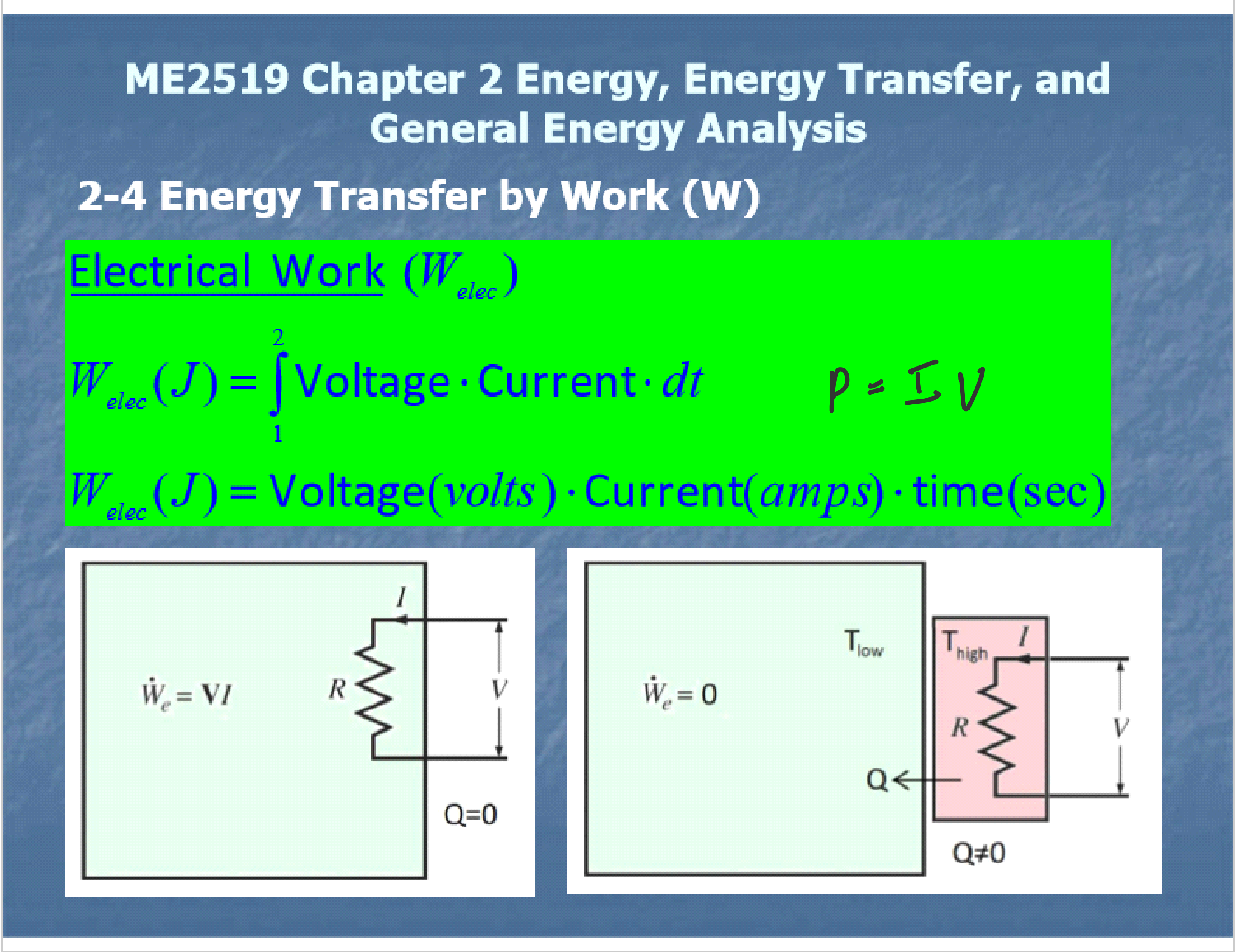
Work (W) is non-heat energy crossing the boundary of a system

- W does not exist unless energy crosses the boundary
- W can enter or leave a system
- W(kJ) and w(kJ/kg)
- Recall mechanical $Work$ results when a force acts in direction of motion

Power $(\dot{W})$ is the rate at which W crosses the boundary

- i.e. the rate at which W is done
- therefore $W = \int \dot{W} dt$ or $W = \dot{W}\Delta t$ if $\dot{W} =$ constant
- $\dot{W}(kJ/\sec = kW)$

Mechanical Work results when a force acts in direction of motion OR a torque results in rotary motion



ME2519 Chapter 2 Energy, Energy Transfer, and General Energy Analysis

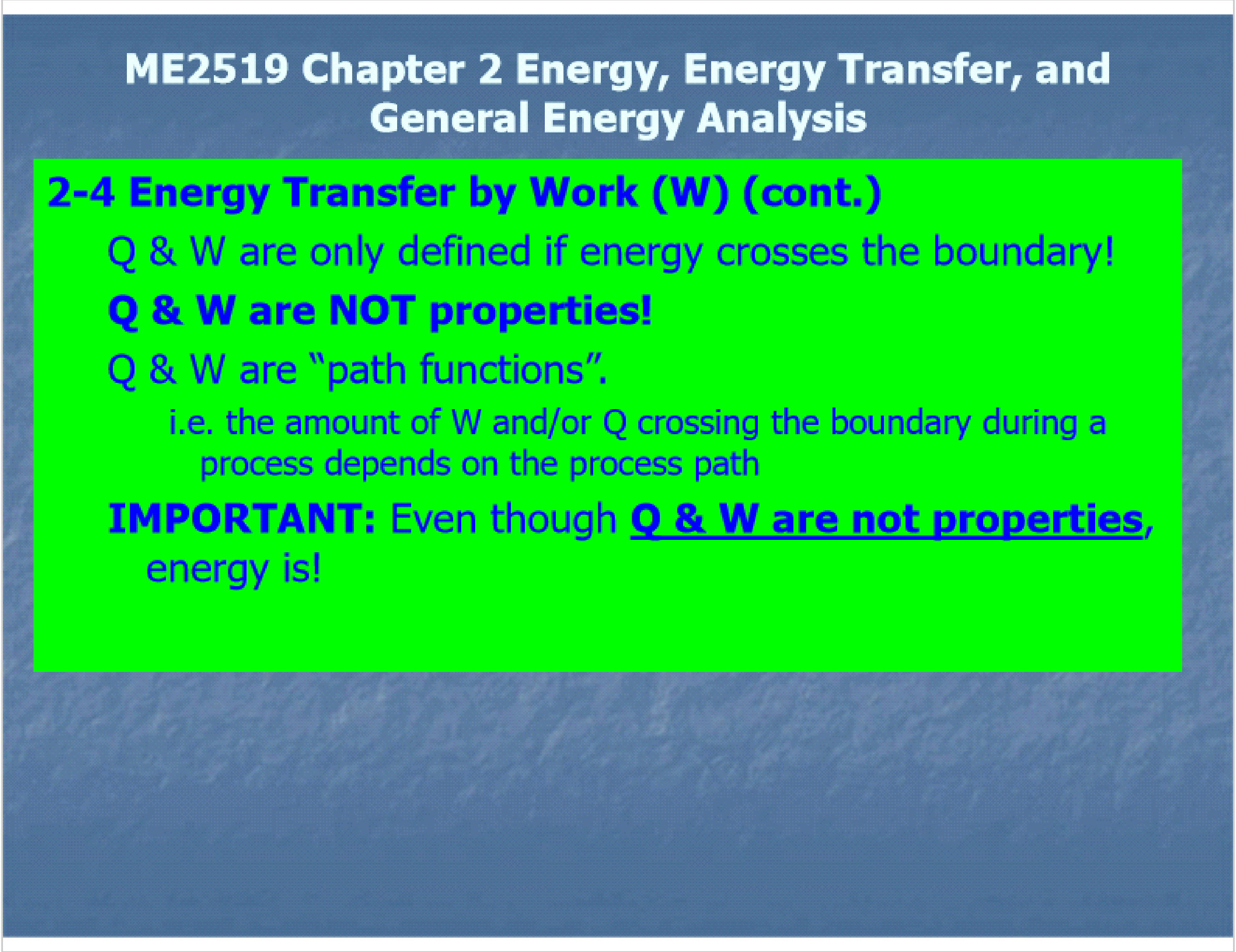
2-4 Energy Transfer by Work (W)

Electrical Work (W_{elec})

$$W_{elec}(J)=\int_1^2 \text{Voltage}\cdot\text{Current}\cdot dt$$

P = IV

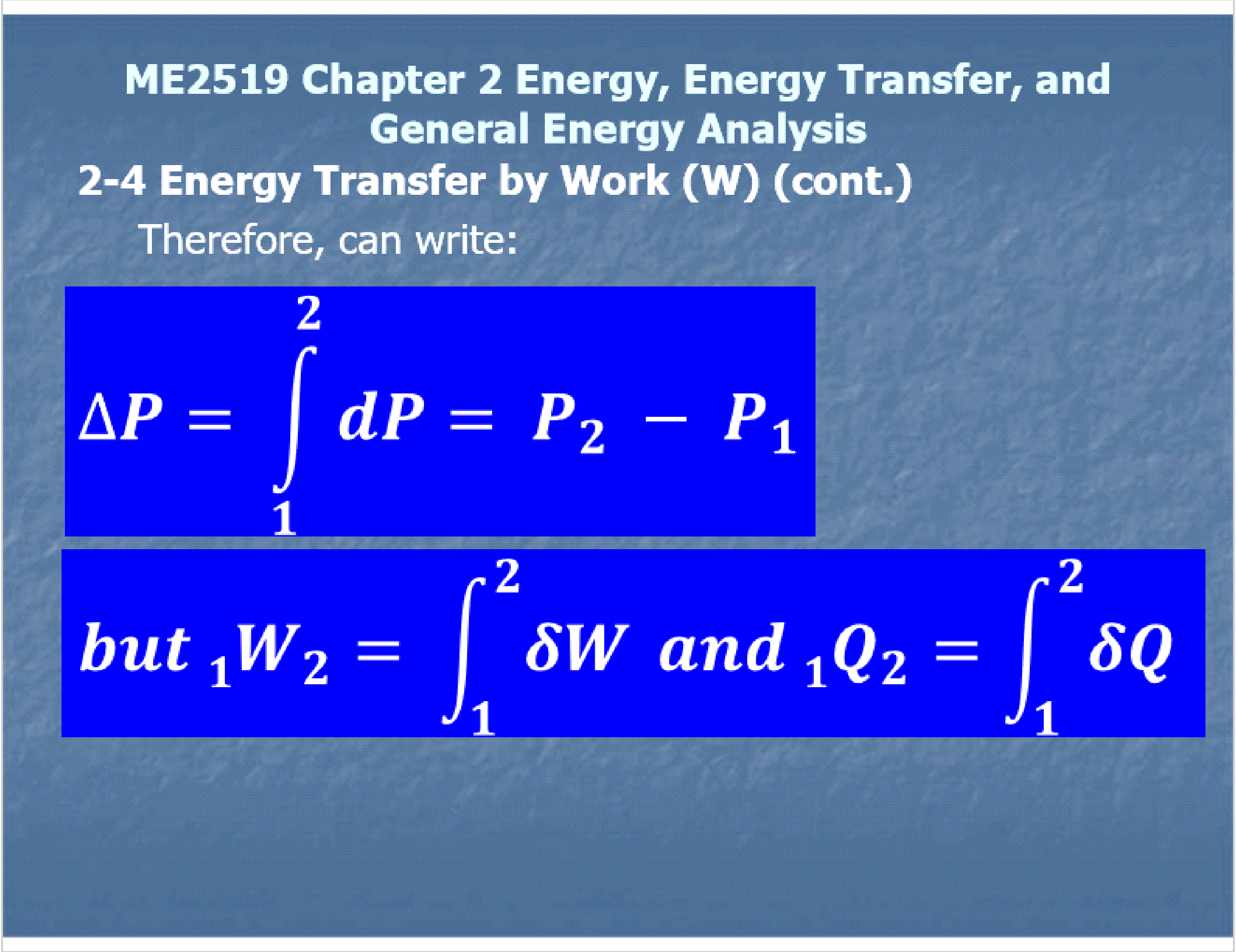
$$W_{elec}(J)=\text{Voltage}(volts)\cdot\text{Current}(amps)\cdot\text{time}(\text{sec})$$



ME2519 Chapter 2 Energy, Energy Transfer, and General Energy Analysis

2-4 Energy Transfer by Work (W) (cont.)

- Q & W are only defined if energy crosses the boundary!
- **Q & W are NOT properties!**
- Q & W are “path functions”.
  - i.e. the amount of W and/or Q crossing the boundary during a process depends on the process path
- **IMPORTANT:** Even though **Q & W are not properties**, energy is!



ME2519 Chapter 2 Energy, Energy Transfer, and General Energy Analysis

2-4 Energy Transfer by Work (W) (cont.)

Therefore, can write:

$$\Delta P = \int_{1}^{2} dP = P_2 - P_1$$

$$but\ {}_1W_2 = \int_1^2 \delta W\ \ and\ {}_1Q_2 = \int_1^2 \delta Q$$

Mechanical Forms of Work

Wednesday, August 31, 2022 10:02 AM

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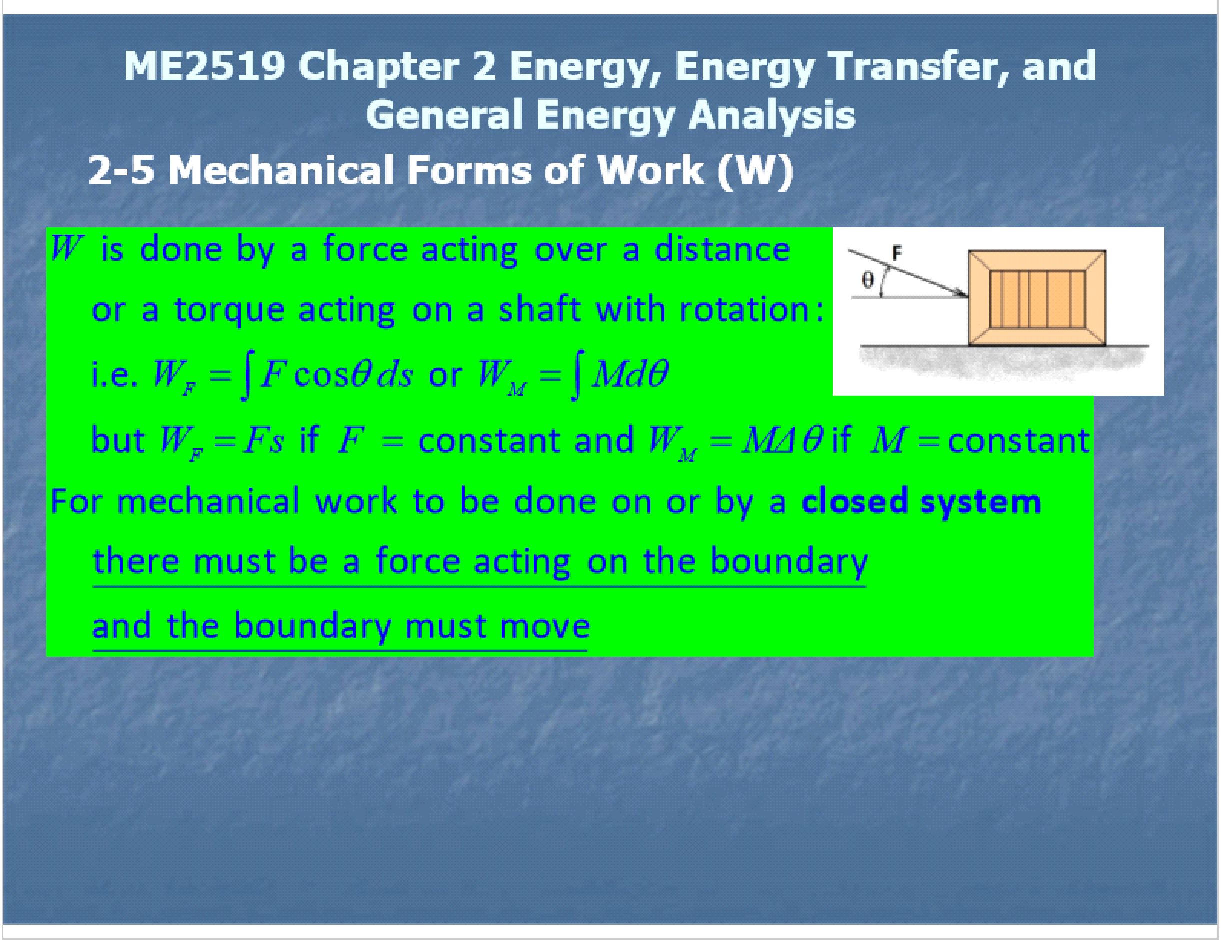
2-5+thru+...



ME2519 Chapter 2 Energy, Energy Transfer, and General Energy Analysis

2-5 Mechanical Forms of Work (W)

W is done by a force acting over a distance

or a torque acting on a shaft with rotation:

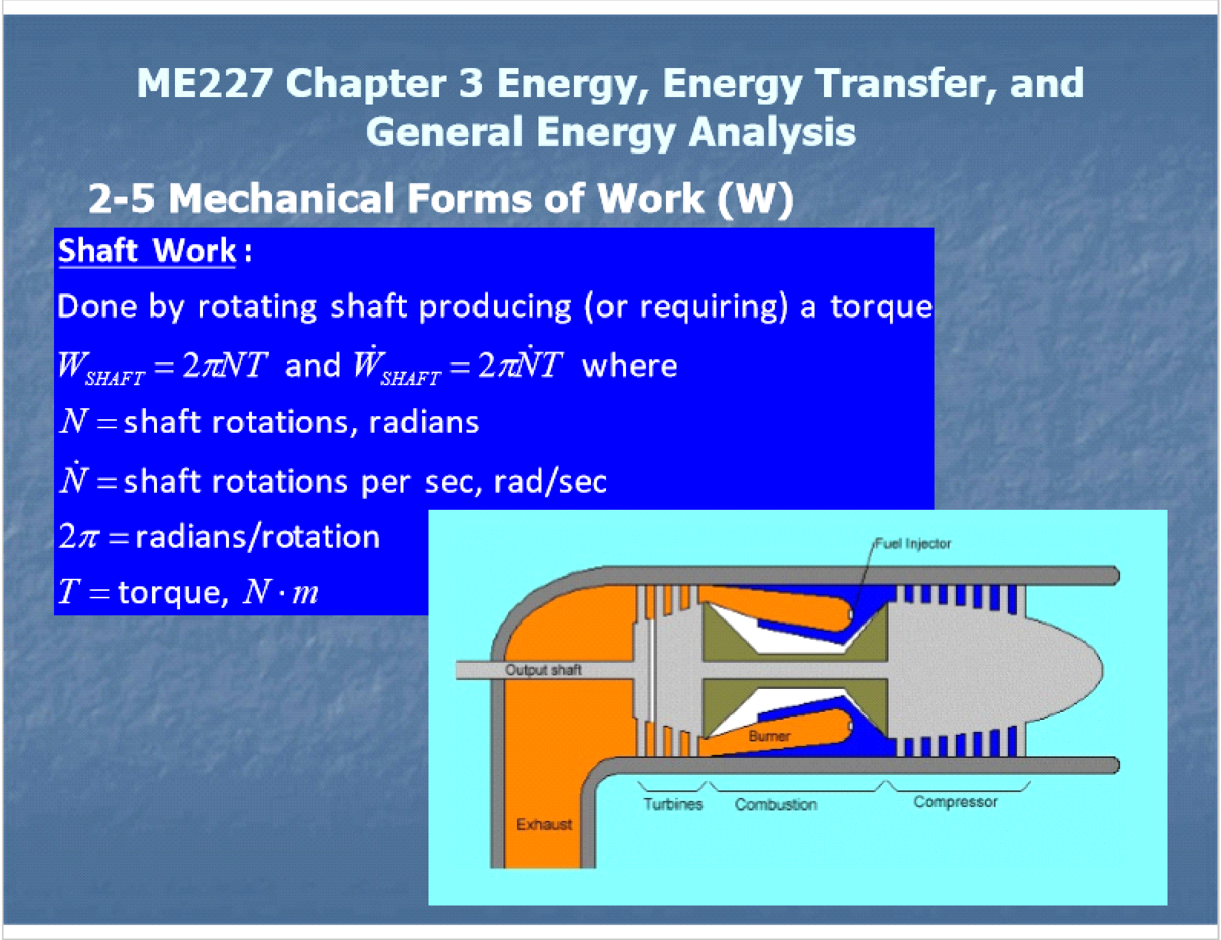
i.e. $W_F = \int F \cos\theta \, ds$ or $W_M = \int M d\theta$

but $W_F = Fs$ if F = constant and $W_M = M\Delta\theta$ if M = constant

For mechanical work to be done on or by a **closed system**

there must be a force acting on the boundary

and the boundary must move



ME227 Chapter 3 Energy, Energy Transfer, and General Energy Analysis

2-5 Mechanical Forms of Work (W)

Shaft Work:

Done by rotating shaft producing (or requiring) a torque

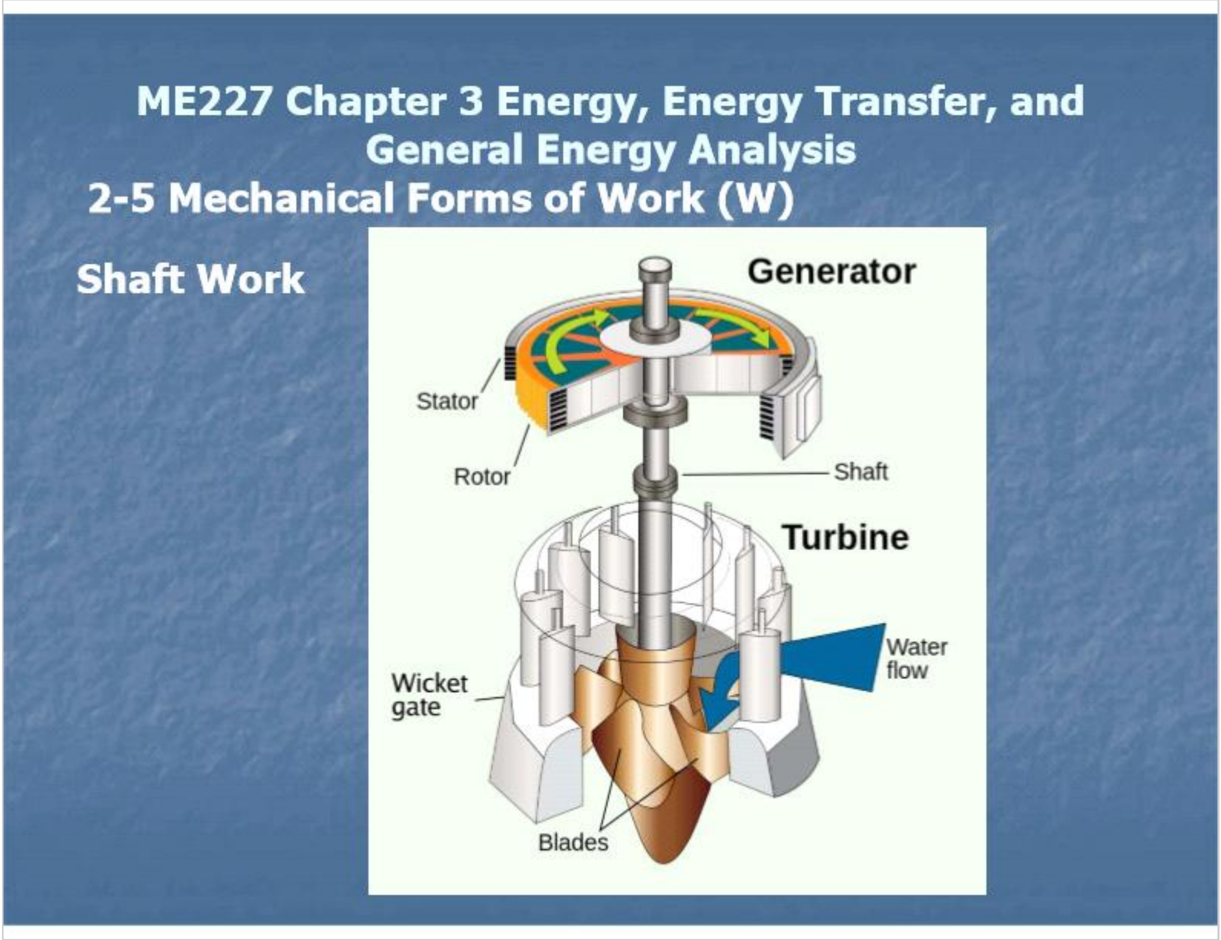
$W_{SHAFT} = 2\pi NT$ and $\dot{W}_{SHAFT} = 2\pi \dot{N} T$ where

$N =$ shaft rotations, radians

$\dot{N} =$ shaft rotations per sec, rad/sec

$2\pi =$ radians/rotation

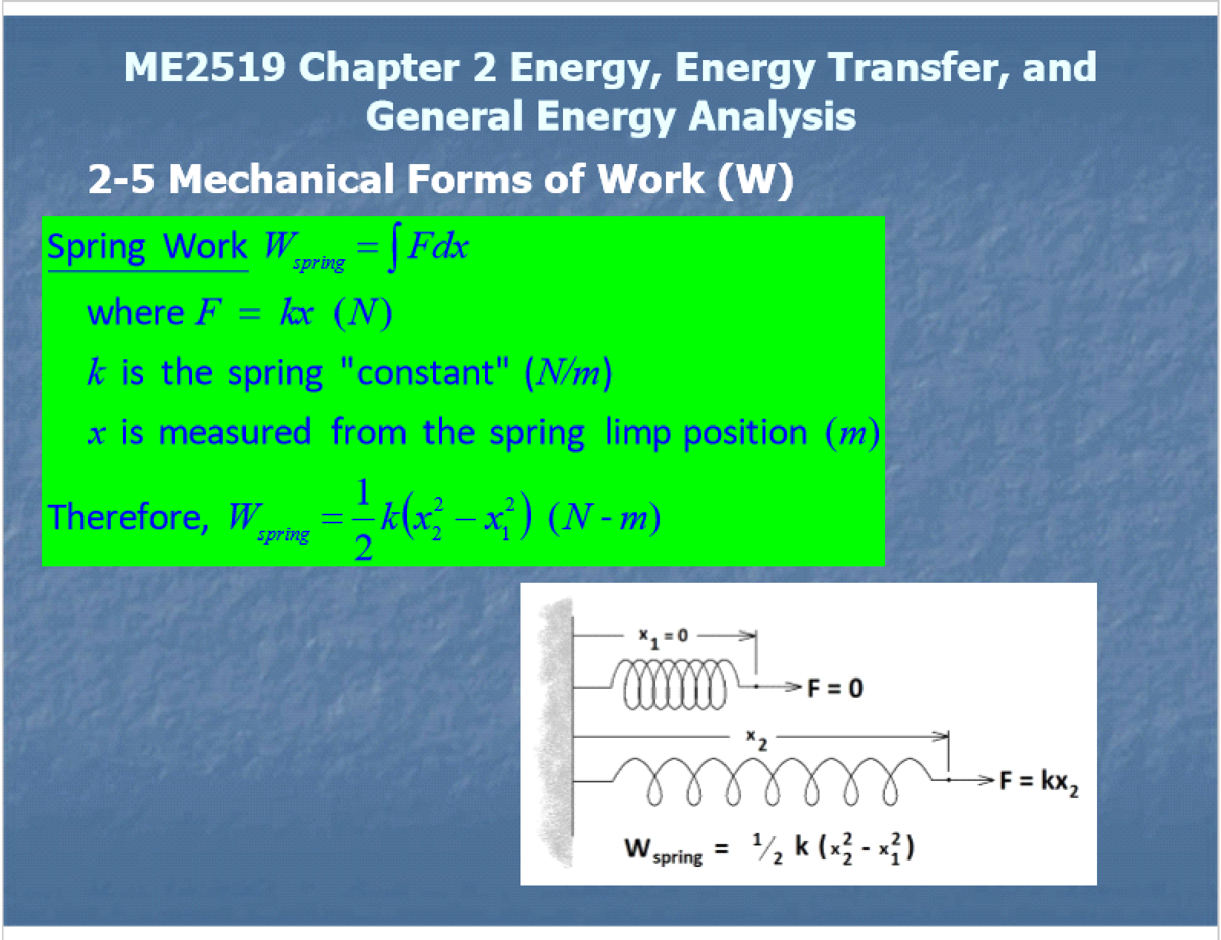
$T =$ torque, $N \cdot m$



ME227 Chapter 3 Energy, Energy Transfer, and General Energy Analysis

2-5 Mechanical Forms of Work (W)

Shaft Work



ME2519 Chapter 2 Energy, Energy Transfer, and General Energy Analysis

2-5 Mechanical Forms of Work (W)

Spring Work $W_{spring} = \int F dx$

where $F = kx$ (N)

k is the spring "constant" (N/m)

x is measured from the spring limp position (m)

Therefore, $W_{spring} = \frac{1}{2}k\left(x_2^2 - x_1^2\right)$ $(N - m)$

ME2519 Chapter 2 Energy, Energy Transfer, and General Energy Analysis

2-5 Mechanical Forms of Work (W) (cont.)

Work required to accelerate a mass $= W_{acc} = \Delta KE$

With $W = \int F dx$ and $F = ma = m\dfrac{dV}{dt}$

$$W_{acc} = \int_1^2 F dx = \int_1^2 m\frac{dV}{dt}dx \text{ but } \frac{dx}{dt} = V$$

$$\text{Therefore } W_{acc} = \int_1^2 mVdV = m\left[\frac{V^2}{2}\right]_1^2$$

or $\underline{W_{acc} = KE_2 - KE_1}$ and $\dot{W}_{acc} = \dfrac{\Delta KE}{\Delta t}$

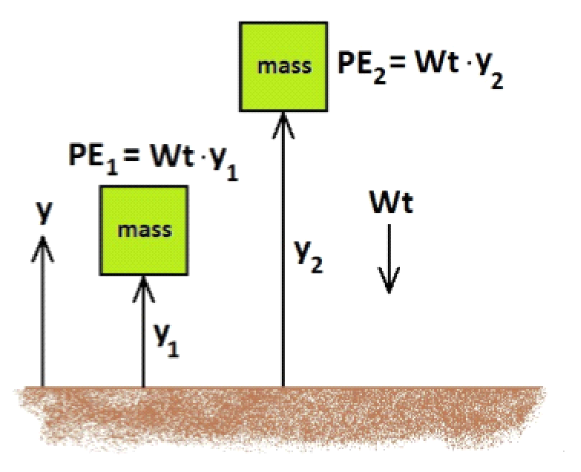
ME2519 Chapter 2 Energy, Energy Transfer, and General Energy Analysis

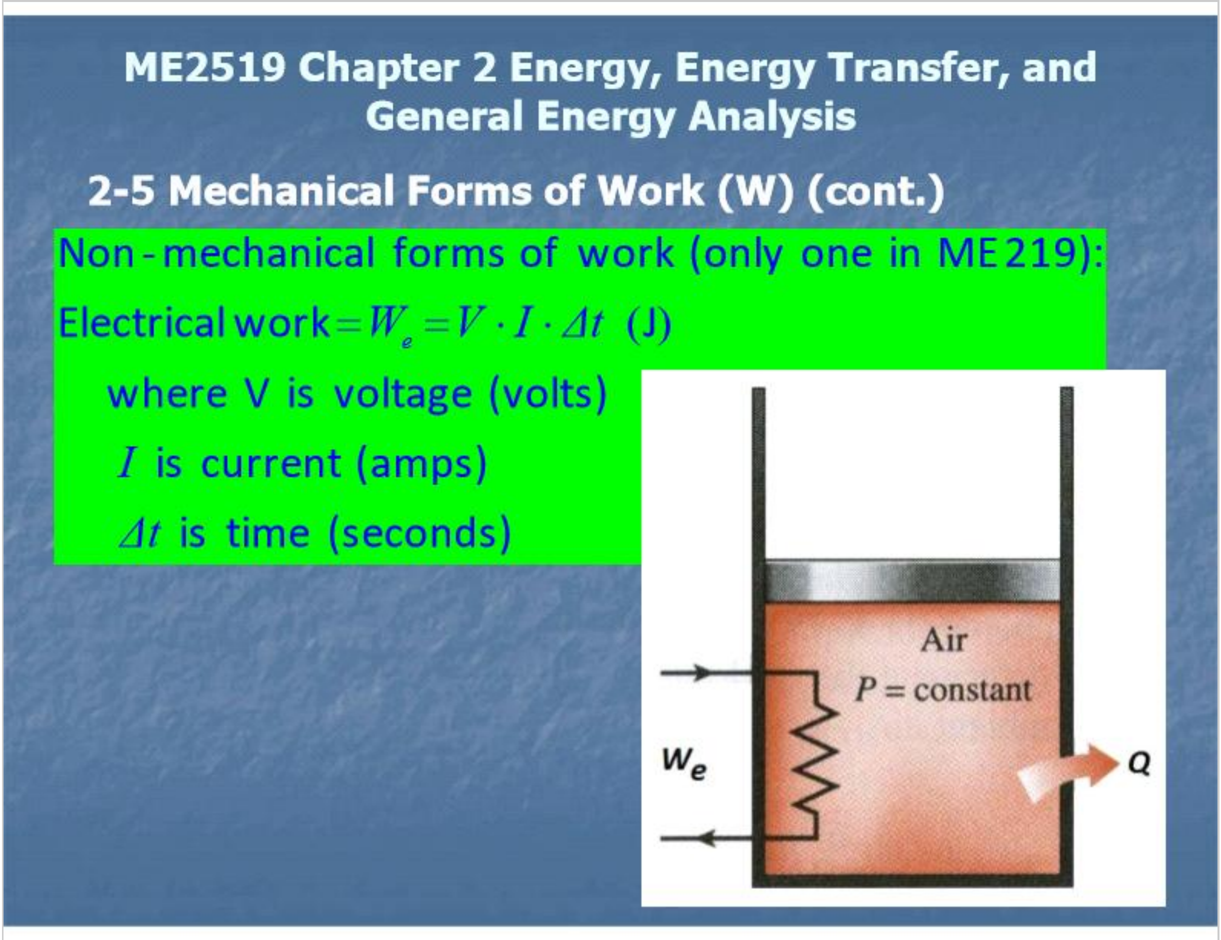
2-5 Mechanical Forms of Work (W) (cont.)

mg

Work required to overcome gravity $= W_{grav} = Wt\Delta y$

where Δy is change in elevation in a gravity field





ME2519 Chapter 2 Energy, Energy Transfer, and General Energy Analysis

2-5 Mechanical Forms of Work (W) (cont.)

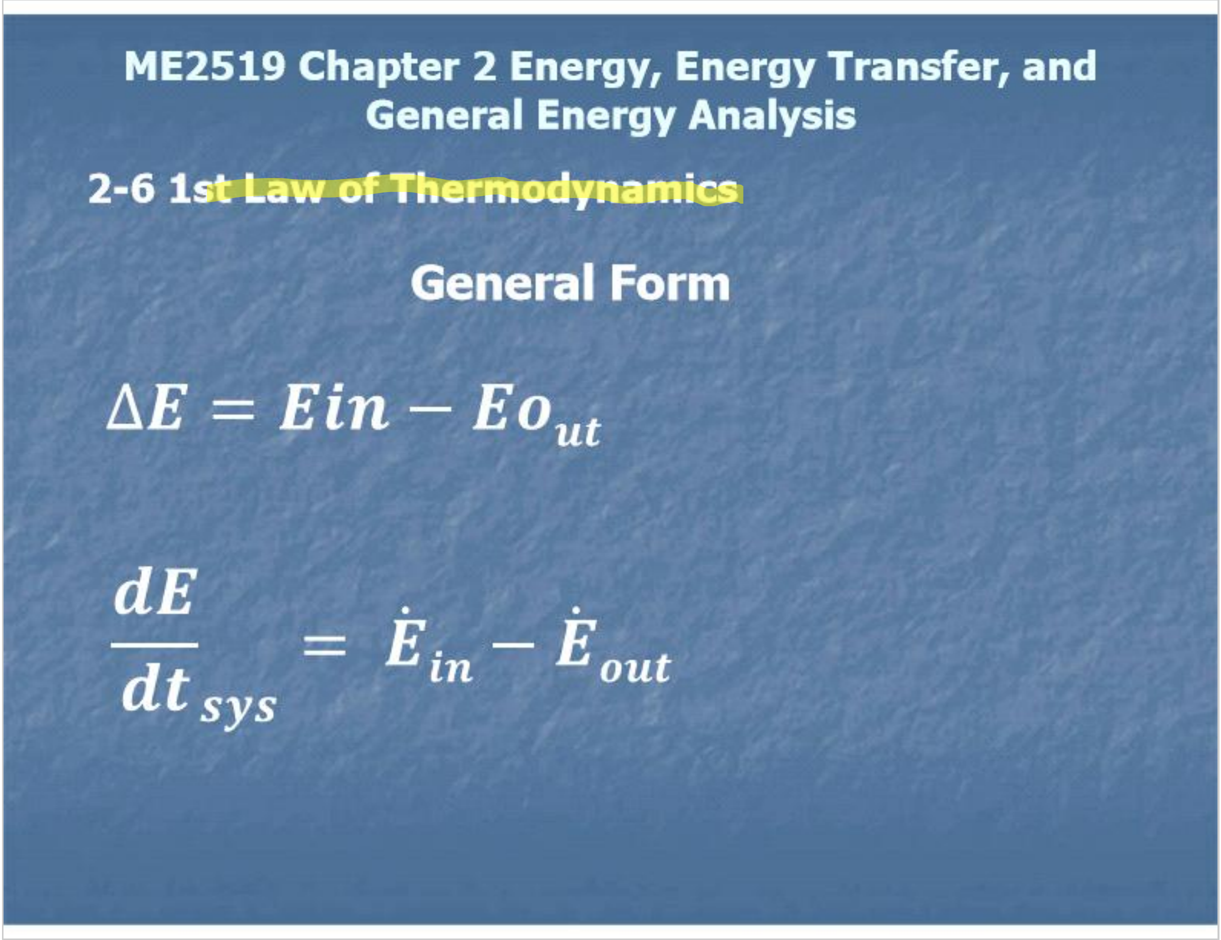
Non-mechanical forms of work (only one in ME219):

Electrical work $= W_e = V \cdot I \cdot \Delta t$ (J)

where V is voltage (volts)

I is current (amps)

Δt is time (seconds)



ME2519 Chapter 2 Energy, Energy Transfer, and General Energy Analysis

2-6 1st Law of Thermodynamics

General Form

$$\Delta E = Ein - Eo_{ut}$$

$$\frac{dE}{dt}_{sys} = \dot{E}_{in} - \dot{E}_{out}$$

Rod / bar

$w_\sigma = \int \sigma_n A dx$

σ_n = Young's moddus

A = cross-sectional area

Film surface tension

$W_{film} = \sigma_s dA$

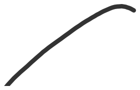
σ_s = surface tension

A = surface area of film

Ex. Car $m = 1500$ kg

motor power = 75 kW

$V_1 = 0$



no sw power

$V_1 = 0$

$V_2 = 1000$ km/hr

level road

find Δt

$$W_{acc} = \dot{W}_{acc}\,\Delta t = m(ke_2 - \cancel{ke_1}^{\,0})$$

$$\uparrow$$

$$\frac{V_2^2}{2}$$

$$\Delta t = \frac{m \quad V_2^2}{\dot{W}_{acc}}$$

Homework 2a

Wednesday, August 31, 2022 5:38 PM

2–15 A water jet that leaves a nozzle at 60 m/s at a flow rate of 120 kg/s is to be used to generate power by striking the buckets located on the perimeter of a wheel. Determine the power generation potential of this water jet.

$\dot{m} = 120 \text{ kg/s} \qquad v = 60 \text{ m/s}$

$\dot{W}_{max} = \dot{m}\, ke \qquad ke = \frac{1}{2} v^2$

$\dot{W}_{max} = \frac{1}{2} v^2 \dot{m}$

$\dot{W}_{max} = \frac{1}{2} (60 \text{ m/s})^2 (120 \text{ kg/s})$

$\dot{W}_{max} = 216{,}000 \text{ W}$

2–17 At a certain location, wind is blowing steadily at 10 m/s. Determine the mechanical energy of air per unit mass and the power generation potential of a wind turbine with 60-m-diameter blades at that location. Take the air density to be 1.25 kg/m^3.

$\dot{m} = \rho A V \qquad A = \pi r^2$

$\dot{m} = \rho \pi r^2 V$

$\dot{m} = (1.25 \text{ kg/m}^3)\, \pi \left(\frac{60}{2} \text{m}\right)^2 (10 \text{ m/s})$

$\dot{m} = 35{,}342.9 \ \frac{\text{kg}}{\text{s}}$

$\dot{W}_{max} = \dot{m}\, ke$

$W_{max} = (35{,}342.9 \ \frac{\text{kg}}{\text{s}})(50 \ \text{m}^2/\text{s}^2) = 1{,}767{,}1000 \text{ w}$

$\boxed{\dot{W}_{max} = 1{,}767.1 \text{ kW}}$

$e_{mech} = \Delta ke = |\cancel{ke_2}^{\,0} - ke_1|$

$e_{mech} = ke_1 = \frac{1}{2} v^2$

$e_{mech} = ke = \frac{1}{2}(10 \ \frac{\text{m}}{\text{s}})^2 = 50 \ \frac{\text{m}^2}{\text{s}^2}$

$\boxed{e_{mech} = 50 \ \frac{\text{m}^2}{\text{s}^2}}$

2–31 How much work, in kJ, can a spring whose spring constant is 3 kN/cm produce after it has been compressed 3 cm from its unloaded length?

$W_{spring} = \int F\,dx \qquad F = kx$

$V_{spring} = \frac{1}{2} k (x_2 - x_1)$

$W_{spring} = \frac{1}{2} (3 \text{ kN/cm}) (3 \text{ cm})^2$

$W_{spring} = 13.5 \text{ kN} \cdot \text{cm}$

$W_{spring} = 0.135 \text{ kN} \cdot \text{m}$

$W_{spring} = 0.135 \text{ kJ}$

2–33 The engine of a 1500-kg automobile has a power rating of 75 kW. Determine the time required to accelerate this car from rest to a speed of 100 km/h at full power on a level road. Is your answer realistic?

$W_{acc} = \dot{W}_{acc} \Delta t = m(ke_2 - \cancel{ke_1}^{\,0})$

$ke = \frac{1}{2} v^2$

$\Delta t = \frac{m v_2^2}{2 \dot{W}_{acc}}$

m = 1500 kg

motor power = 75 kW

$V_1 = 0$

$V_2 = 100 \text{ km/hr}$

$\Delta t = \frac{(1500 \text{ kg})\left(100 \text{ km/h} \ \frac{1 \text{ h}}{3600 \text{ sec}} \ \frac{1 \text{ km}}{1000 \text{ m}}\right)^2}{2 (75 \text{ kW})} \ \frac{1}{1000}$

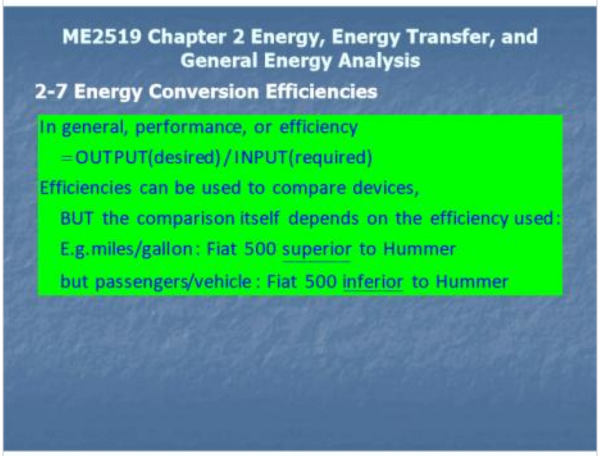
$\Delta t = 7.716 \text{ sec}$

Yes, your averge size car can zero to sixty mph is about 8 sec, which is close to this number.

Energy Conversion Effifiencies

Friday, September 2, 2022 10:02 AM

PDF+Slides
+2-7+thru...



ME2519 Chapter 2 Energy, Energy Transfer, and General Energy Analysis

2-7 Energy Conversion Efficiencies

In general, performance, or efficiency

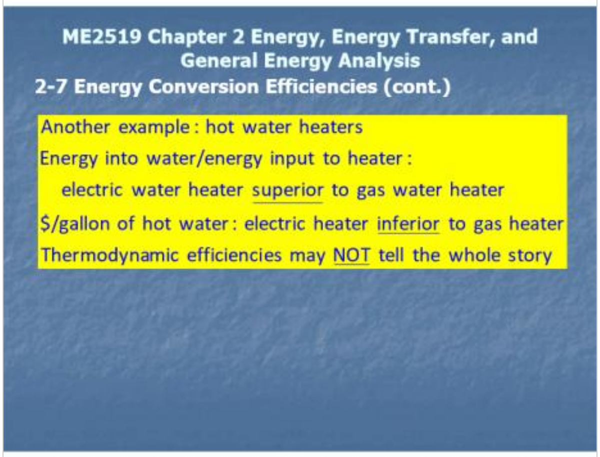
=OUTPUT(desired)/INPUT(required)

Efficiencies can be used to compare devices,

BUT the comparison itself depends on the efficiency used:

E.g. miles/gallon: Fiat 500 superior to Hummer

but passengers/vehicle: Fiat 500 inferior to Hummer



ME2519 Chapter 2 Energy, Energy Transfer, and General Energy Analysis

2-7 Energy Conversion Efficiencies (cont.)

Another example: hot water heaters

Energy into water/energy input to heater:

electric water heater superior to gas water heater

$/gallon of hot water: electric heater inferior to gas heater

Thermodynamic efficiencies may NOT tell the whole story

2-53 Electric grill $.1/KWh ; eff =.73

Power in = 2.4 kW

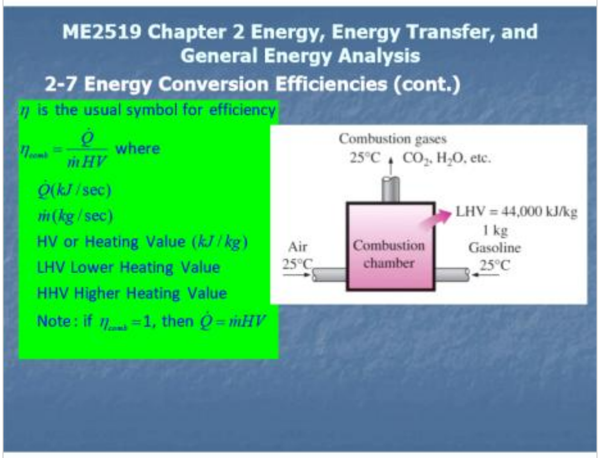
Gas grill $1.2/therm , eff= .38

Elect $n = \frac{\dot{Q}_{out}}{\dot{W}_{in}}$

Gas $n = \frac{\dot{Q}_{out}}{\dot{E}_{in}}$

$\dot{Q}_{out} = n \cdot \dot{W}_{in}$

$\frac{\$}{hr} = \frac{\$}{E_{in}\ (kW\ h)}$ $Q_{out}\ (kW)$



ME2519 Chapter 2 Energy, Energy Transfer, and General Energy Analysis

2-7 Energy Conversion Efficiencies (cont.)

η is the usual symbol for efficiency

$\eta_{comb} = \frac{\dot{Q}}{\dot{m}HV}$ where

$\dot{Q}(kJ/\text{sec})$

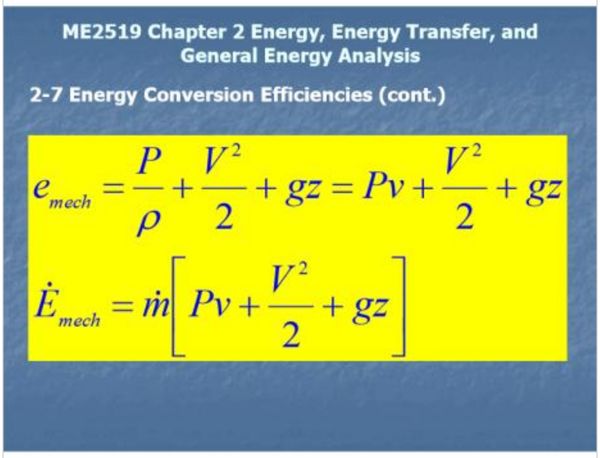
$\dot{m}(kg/\text{sec})$

HV or Heating Value (kJ/kg)

LHV Lower Heating Value

HHV Higher Heating Value

Note: if $\eta_{comb} = 1$, then $\dot{Q} = \dot{m}HV$

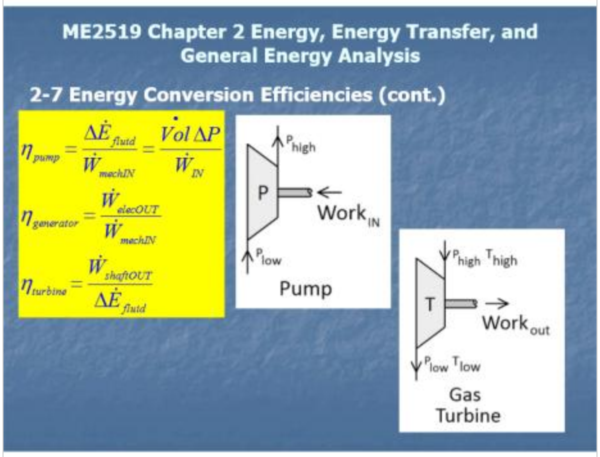


ME2519 Chapter 2 Energy, Energy Transfer, and General Energy Analysis

2-7 Energy Conversion Efficiencies (cont.)

$$e_{mech} = \frac{P}{\rho} + \frac{V^2}{2} + gz = Pv + \frac{V^2}{2} + gz$$

$$\dot{E}_{mech} = \dot{m}\left[Pv + \frac{V^2}{2} + gz\right]$$



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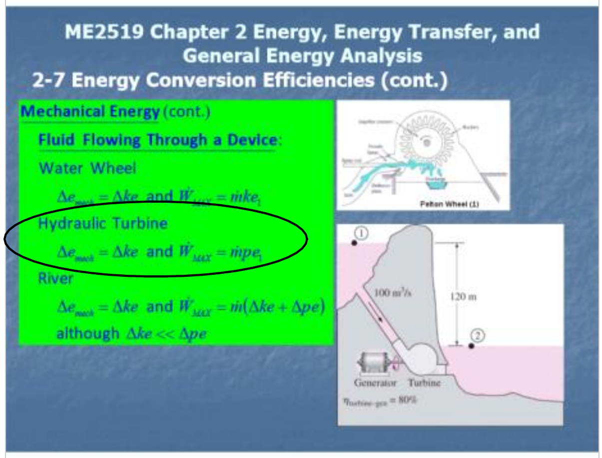
2-7 Energy Conversion Efficiencies (cont.)

$$\eta_{pump} = \frac{\Delta\dot{E}_{fluid}}{\dot{W}_{mechIN}} = \frac{\dot{Vol}\,\Delta P}{\dot{W}_{IN}}$$

$$\eta_{generator} = \frac{\dot{W}_{elecOUT}}{\dot{W}_{mechIN}}$$

$$\eta_{turbine} = \frac{\dot{W}_{shaftOUT}}{\Delta\dot{E}_{fluid}}$$



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2-7 Energy Conversion Efficiencies (cont.)

Mechanical Energy (cont.)

Fluid Flowing Through a Device:

Water Wheel

$\Delta e_{mech} = \Delta ke$ and $\dot{W}_{MAX} = \dot{m}ke_1$

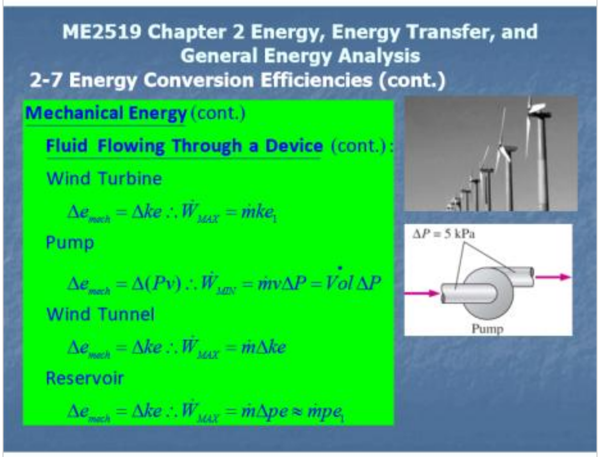
Hydraulic Turbine

$\Delta e_{mech} = \Delta ke$ and $\dot{W}_{MAX} = \dot{m}pe_1$

River

$\Delta e_{mech} = \Delta ke$ and $\dot{W}_{MAX} = \dot{m}(\Delta ke + \Delta pe)$

although $\Delta ke << \Delta pe$



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2-7 Energy Conversion Efficiencies (cont.)

Mechanical Energy (cont.)

Fluid Flowing Through a Device (cont.):

Wind Turbine

$\Delta e_{mech} = \Delta ke \therefore \dot{W}_{MAX} = \dot{m}ke_1$

Pump

$\Delta e_{mech} = \Delta(Pv) \therefore \dot{W}_{MIN} = \dot{m}v\Delta P = \dot{Vol}\,\Delta P$

Wind Tunnel

$\Delta e_{mech} = \Delta ke \therefore \dot{W}_{MAX} = \dot{m}\Delta ke$

Reservoir

$\Delta e_{mech} = \Delta ke \therefore \dot{W}_{MAX} = \dot{m}\Delta pe \approx \dot{m}pe_1$

2.55 pump depth = 200m

$\rho_{brine} = 1050\ kg/m^3$

Vol flow rate = .3 m³/sec

$eff_{pump} = .74$

Find power required by pump

$$\eta = \frac{\dot{Vol}\,\Delta P}{\dot{W}_{in}}$$

$$\rho \dot{Vol} = \dot{m}$$

$$\Delta P = \rho g h$$

$$\dot{W}_{in} = \frac{\dot{Vol}\,\Delta P}{\eta}$$

$$W_{in} = \frac{\dot{Vol}\,\rho g h}{\eta} = \frac{(.3\,m^3/sec)(1050\,kg/m^3)(9.807\,m/s^2)(200m)}{.74\ (1000)}$$

↑ From $\frac{N}{m^2}$ to kPa

ME2519 Chapter 2 Energy, Energy Transfer, and General Energy Analysis

2-7 Energy Conversion Efficiencies (cont.)

Note: There are

Hydraulic (liquid) turbines: $\Delta\dot{E}_{fluid} = \dot{m}pe_1$

Wind turbines: $\Delta\dot{E}_{fluid} = \dot{m}\Delta ke$

Gas turbines: $\Delta\dot{E}_{fluid} = \dot{m}\Delta h$

$pe = mgh$

$\dot{m} = \dot{Vol}\ \rho$

$\rho_{water} = 1000\ \frac{kg}{m^3}$

ME2519 Chapter 2 Energy, Energy Transfer, and General Energy Analysis

2-7 Energy Conversion Efficiencies (cont.)

Problem 2-65
Given: wind turbine
wind velocity = 7 m/sec.
blade diameter = 80 m
overall efficiency = 30%
air density = 1.25 kg/m³.
Find: 1) mechanical energy of air per unit mass (kJ/kg)
2) max power generation (kW)
3) actual power generation (kW)

$\dot{m} = A\rho v$

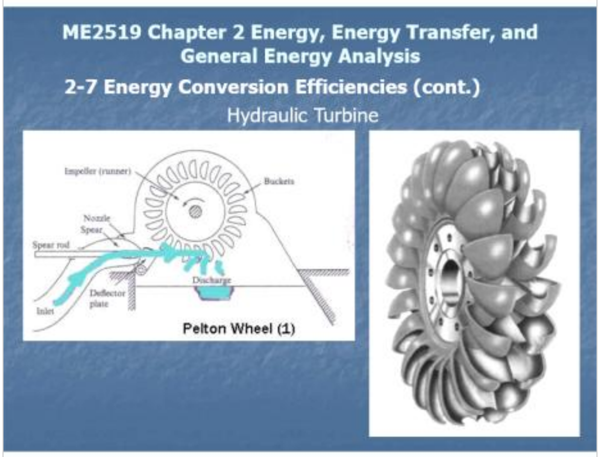
$= \dot{m}\, ke$

$\uparrow$

$\frac{1}{2}v^2$

$② = \pi r^2 \rho v \left(\frac{1}{2}v^2\right) =$

$③ = ② \cdot \eta$



ME2519 Chapter 2 Energy, Energy Transfer, and General Energy Analysis

2-7 Energy Conversion Efficiencies (cont.)

Hydraulic Turbine

Pelton Wheel (1)

ME2519 Chapter 2 Energy, Energy Transfer, and General Energy Analysis

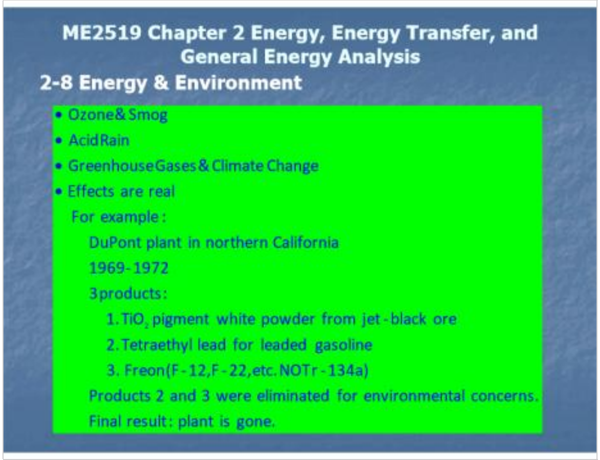
2-7 Energy Conversion Efficiencies (cont.)

Note: η_{motor} is the inverse of $\eta_{generator}$: $\eta_{motor} = \dfrac{\dot{W}_{shaftOUT}}{\dot{W}_{elecIN}}$

similarly

$$\eta_{motor\ driven\ pump} = \eta_{motor}\cdot\eta_{pump} = \frac{\dot{W}_{shaftOUT}}{\dot{W}_{elecIN}}\cdot\frac{\Delta\dot{E}_{fluid}}{\dot{W}_{mechIN}} = \frac{\dot{W}_{shaftOUT}}{\dot{W}_{elecIN}}\cdot\frac{\dot{Vol}\,\Delta P}{\dot{W}_{mechIN}} = \frac{\dot{Vol}\,\Delta P}{\dot{W}_{elecIN}}$$

$$\eta_{turbine\ driven\ generator} = \eta_{turbine}\cdot\eta_{generator} = \frac{\dot{W}_{elecOUT}}{\dot{W}_{shaftIN}}\cdot\frac{\dot{W}_{shaftOUT}}{\Delta\dot{E}_{fluid}} = \frac{\dot{W}_{elecOUT}}{\Delta\dot{E}_{fluid}}$$



ME2519 Chapter 2 Energy, Energy Transfer, and General Energy Analysis

2-8 Energy & Environment

- Ozone & Smog
- Acid Rain
- Greenhouse Gases & Climate Change
- Effects are real

  For example:

    DuPont plant in northern California

    1969-1972

    3 products:

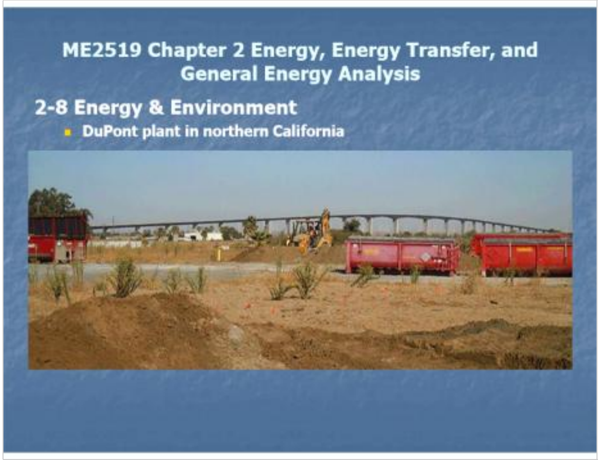
      1. TiO_2 pigment white powder from jet-black ore

      2. Tetraethyl lead for leaded gasoline

      3. Freon (F-12, F-22, etc. NOT r-134a)

    Products 2 and 3 were eliminated for environmental concerns.

    Final result: plant is gone.



ME2519 Chapter 2 Energy, Energy Transfer, and General Energy Analysis

2-8 Energy & Environment

- DuPont plant in northern California

Homework 2b

Saturday, September 3, 2022 10:28 AM

2–55 Consider a 2.4-kW hooded electric open burner in an area where the unit costs of electricity and natural gas are $0.10/kWh and $1.20/therm (1 therm = 105,500 kJ), respectively. The efficiency of open burners can be taken to be 73 percent for electric burners and 38 percent for gas burners. Determine the rate of energy consumption and the unit cost of utilized energy for both electric and gas burners.

Electric

$\frac{\$}{hr} = \frac{\$}{E_{in}\,(kW\,h)}\; Q_{out}\,(kW)$

$\frac{\$.1}{kWh}\;\; 2\;4\,kW = \frac{\$.24}{hr}$

$\eta = \frac{Q_{out}}{W_{in}}$

$Q_{out} = \eta\, W_{in} = .73\,(2.4\,kW) = 1.752\ kW$

Gas

$\eta = \frac{Q_{out}}{W_{in}}$

$W_{in} = \frac{Q_{out}}{\eta} = \frac{1.752\ kW}{.38} = 4.61\ kW$

$\frac{\$}{kWh} = \frac{\$1.2}{therm}\;\frac{1\ therm}{105{,}500\ KJ}\;\frac{1\ KJ}{sec}\;\frac{3600\ sec}{1\ hr} = .0409\ \frac{\$}{kWh}$

$\frac{\$}{h} = \frac{\$}{E_{in}\,(kWh)}\;Q_{out} = .0409\ \frac{\$}{kWh}\;\; 4.61\,kW = .189\ \frac{\$}{hr}$

2–64 A geothermal pump is used to pump brine whose density is 1050 kg/m^3 at a rate of 0.3 m^3/s from a depth of 200 m. For a pump efficiency of 74 percent, determine the required power input to the pump. Disregard frictional losses in the pipes, and assume the geothermal water at 200 m depth to be exposed to the atmosphere.

$\eta = \frac{Vol\,\Delta P}{W_{in}}$ $\quad \rho\, Vol = \dot m$ $\quad \Delta P = \rho h g$

$W_{in} = \frac{Vol\,\Delta P}{\eta}$

$W_{in} = \frac{Vol\,\rho g h}{\eta} = \frac{(.3\,\cancel{m^3}/sec)(1050\ kg/\cancel{m^3})(9.807\,m/s^2)(200\,m)}{.74} = 834920\ \frac{kg\cdot m^2}{s^3} = 834.92\ KW$

2–65 At a certain location, wind is blowing steadily at 7 m/s. Determine the mechanical energy of air per unit mass and the power generation potential of a wind turbine with 80-m-diameter blades at that location. Also determine the actual electric power generation assuming an overall efficiency of 30 percent. Take the air density to be 1.25 kg/m^3.

$\Delta e_{mech} = \dot m\; ke$

$\dot m = \rho A V = 1.25\ kg/m^3\ \pi\left(\frac{80m}{2}\right)^2\ 7\ m/s = 43{,}9823\ \frac{kg}{s}$

$ke = \frac{1}{2}v^2 = \frac{1}{2}(7m/s)^2\ \frac{1\ kJ\ s^2}{1000\ kg\ m^2} = .245\ \frac{kJ}{kg}$

$\Delta e_{mech} = \dot m\; ke = 43{,}982.3\ \frac{kg}{s}\left(.245\ \frac{kJ}{kg}\right) = 1078\ \frac{kJ}{s} = 1078\ kW$

$e_{mech\ out} = e_{mech\ in}\cdot\eta = 1078\ kW\cdot .3 = 323.3\ kW$

2–71 A hydraulic turbine has 85 m of elevation difference available at a flow rate of 0.25 m^3/s, and its overall turbine–generator efficiency is 91 percent. Determine the electric power output of this turbine.

$\dot W_{max} = \dot m\, pe = \rho_w\, Vol\ gh = 1000\ \frac{kg}{\cancel{m^3}}\left(.25\ \frac{\cancel{m^3}}{s}\right)\left(9.807\ \frac{m}{s^2}\right)(85m) = 208{,}399\ \frac{kg}{s^3}m^2$

$208{,}399\ \frac{kg}{s^3}m^2 = 208.4\ \frac{kJ}{s} = 208.4\ kW$

$\dot W_{tot} = \dot W_{max}\cdot\eta = 208.4\ kW\,(.91) = 189.6\ kW$

Properties of a Pure Substance

Monday, September 12, 2022 9:58 AM

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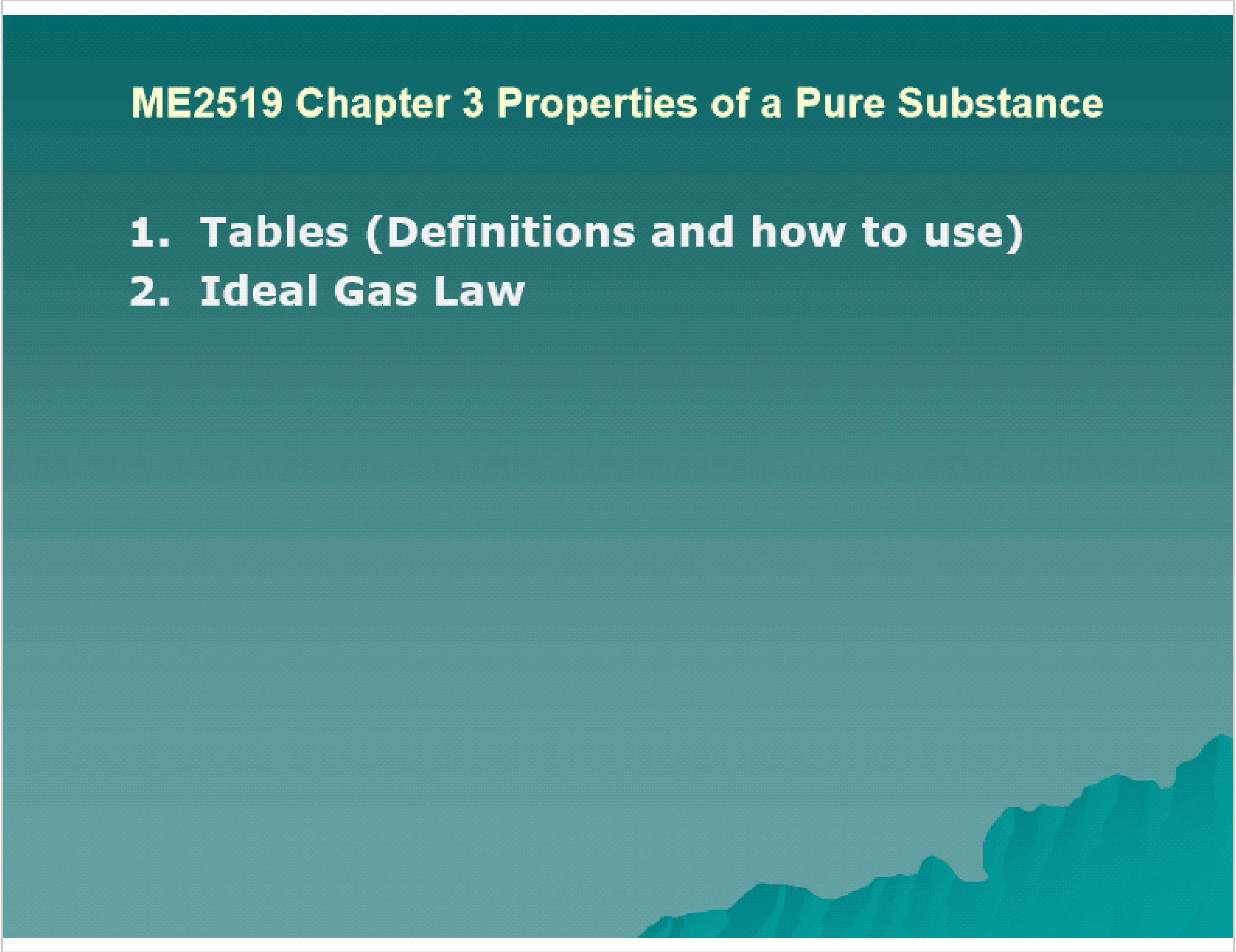
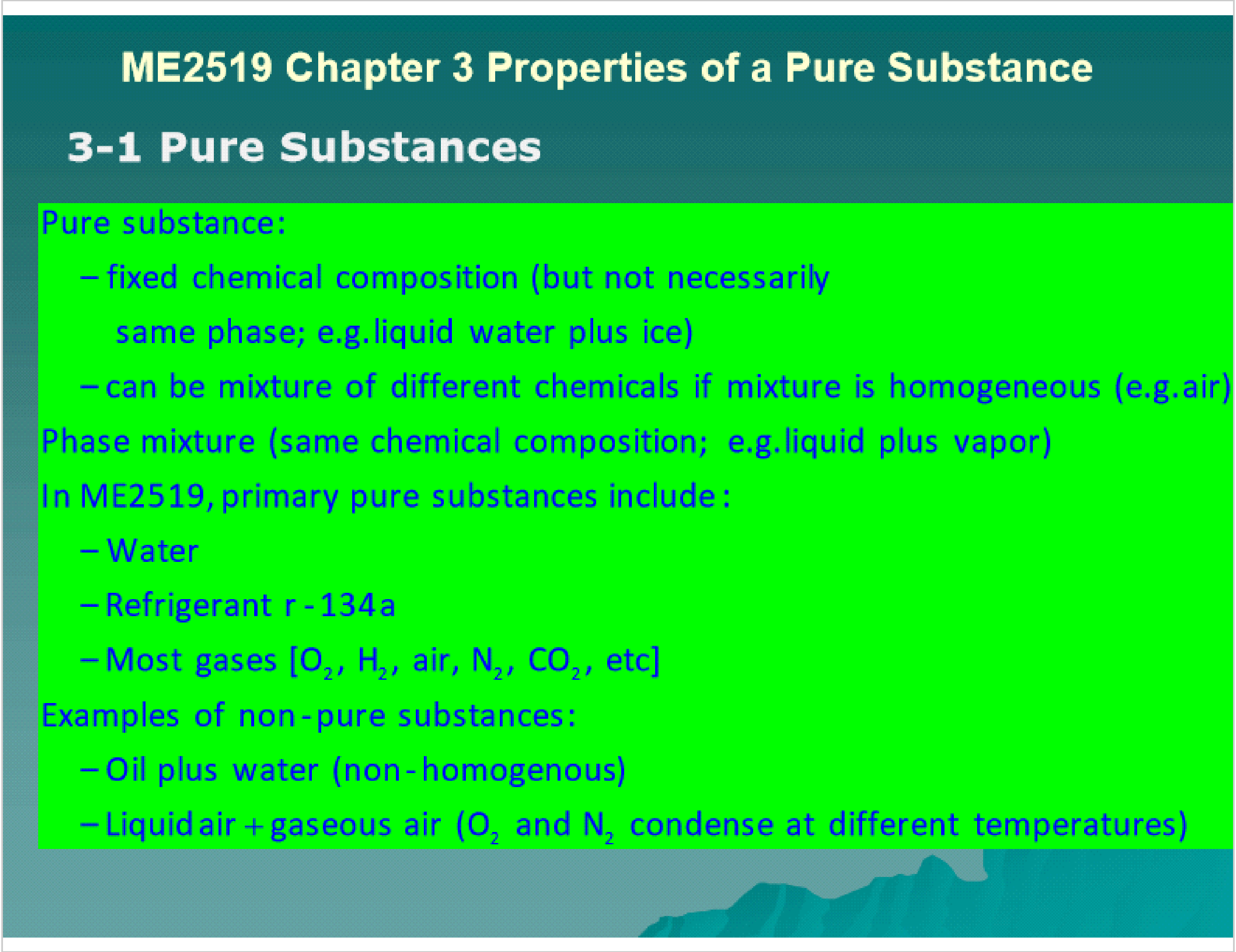


ME2519 Chapter 3 Properties of a Pure Substance

1. Tables (Definitions and how to use)
2. Ideal Gas Law



ME2519 Chapter 3 Properties of a Pure Substance

3-1 Pure Substances

Pure substance:

- fixed chemical composition (but not necessarily same phase; e.g.liquid water plus ice)
- can be mixture of different chemicals if mixture is homogeneous (e.g.air)

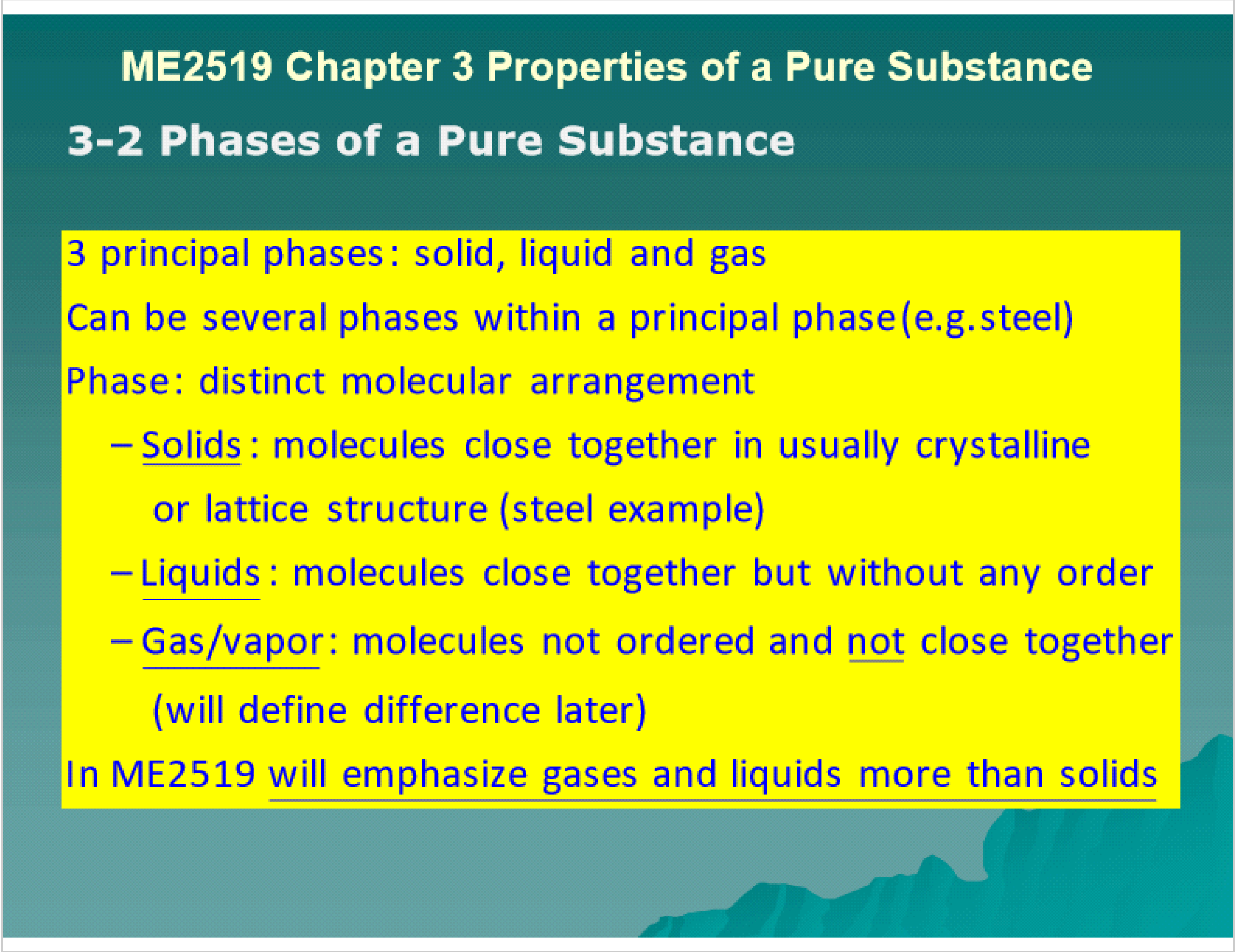
Phase mixture (same chemical composition; e.g.liquid plus vapor)

In ME2519, primary pure substances include:

- Water
- Refrigerant r-134a
- Most gases [O_2, H_2, air, N_2, CO_2, etc]

Examples of non-pure substances:

- Oil plus water (non-homogenous)
- Liquid air + gaseous air (O_2 and N_2 condense at different temperatures)



ME2519 Chapter 3 Properties of a Pure Substance

3-2 Phases of a Pure Substance

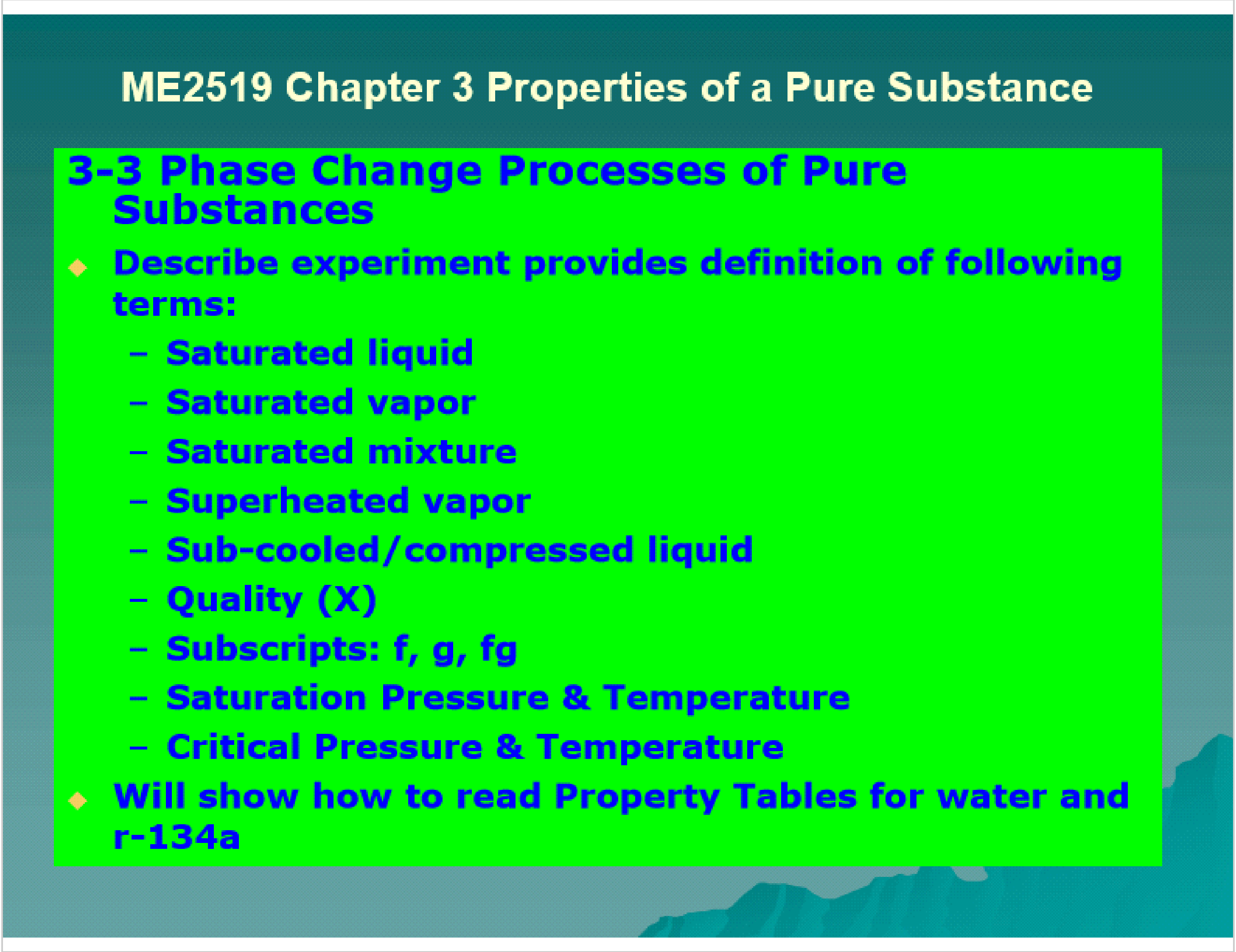
3 principal phases: solid, liquid and gas

Can be several phases within a principal phase (e.g. steel)

Phase: distinct molecular arrangement

- Solids: molecules close together in usually crystalline or lattice structure (steel example)
- Liquids: molecules close together but without any order
- Gas/vapor: molecules not ordered and not close together (will define difference later)

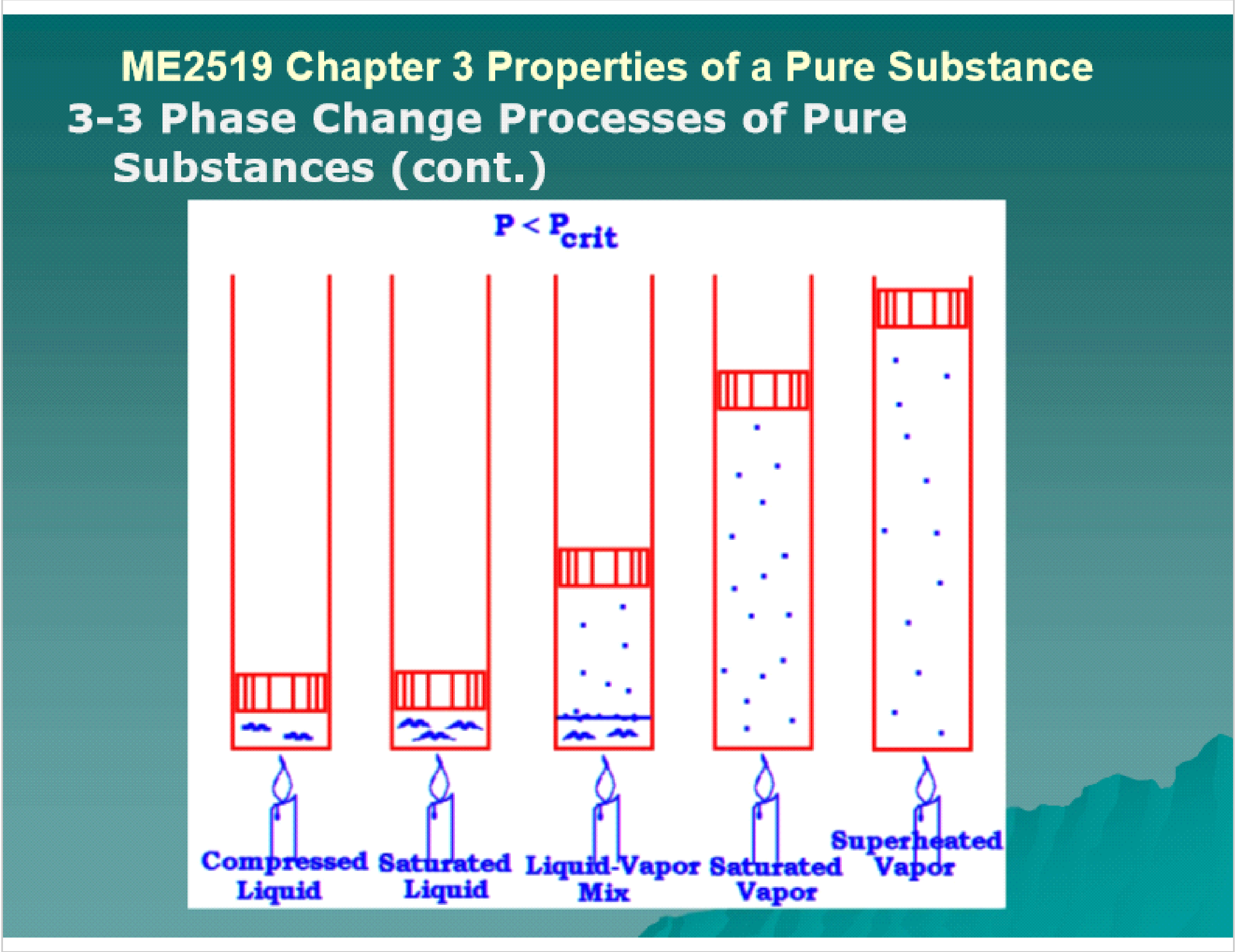
In ME2519 will emphasize gases and liquids more than solids



ME2519 Chapter 3 Properties of a Pure Substance

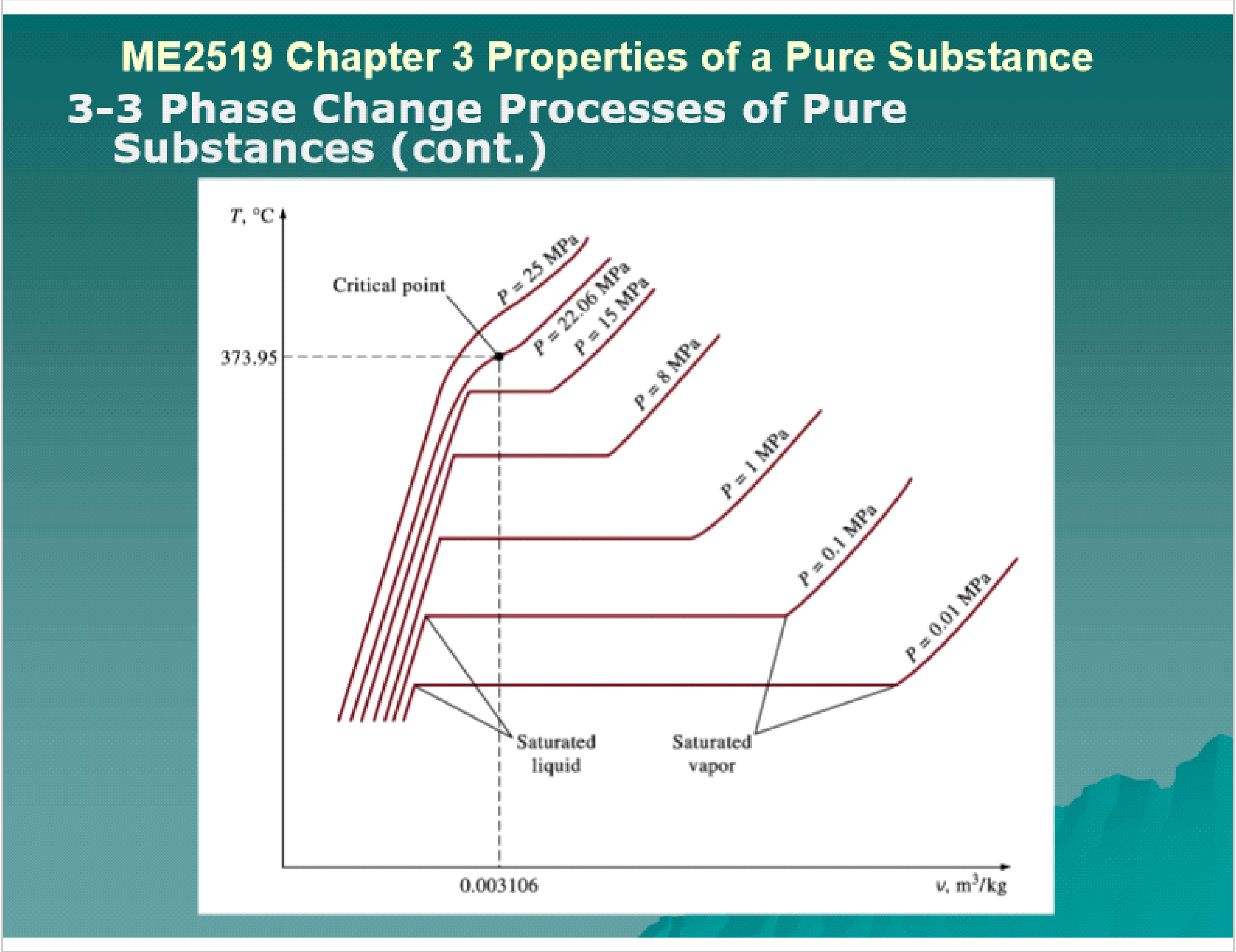
3-3 Phase Change Processes of Pure Substances

- Describe experiment provides definition of following terms:
  - Saturated liquid
  - Saturated vapor
  - Saturated mixture
  - Superheated vapor
  - Sub-cooled/compressed liquid
  - Quality (X)
  - Subscripts: f, g, fg
  - Saturation Pressure & Temperature
  - Critical Pressure & Temperature
- Will show how to read Property Tables for water and r-134a



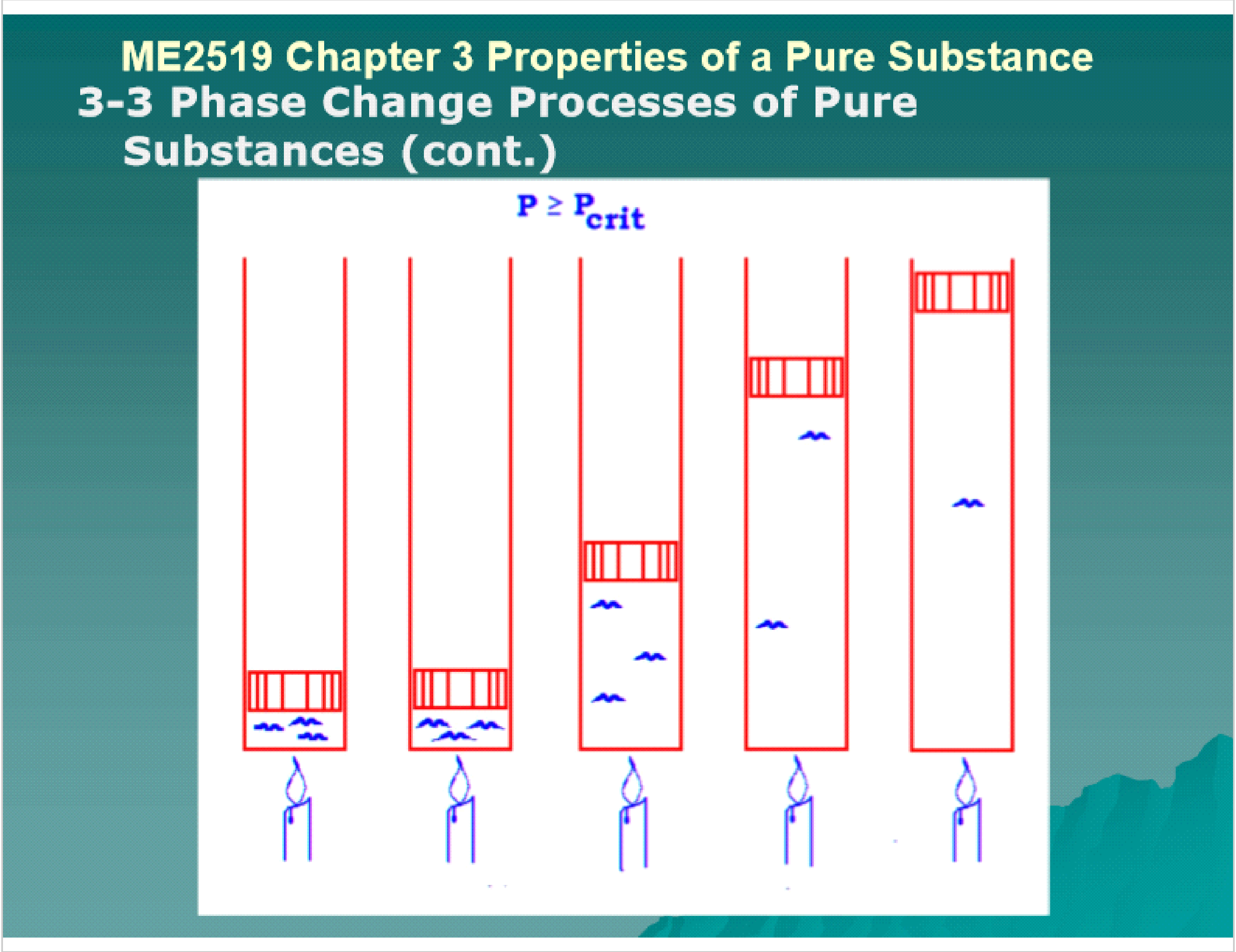
ME2519 Chapter 3 Properties of a Pure Substance

3-3 Phase Change Processes of Pure Substances (cont.)



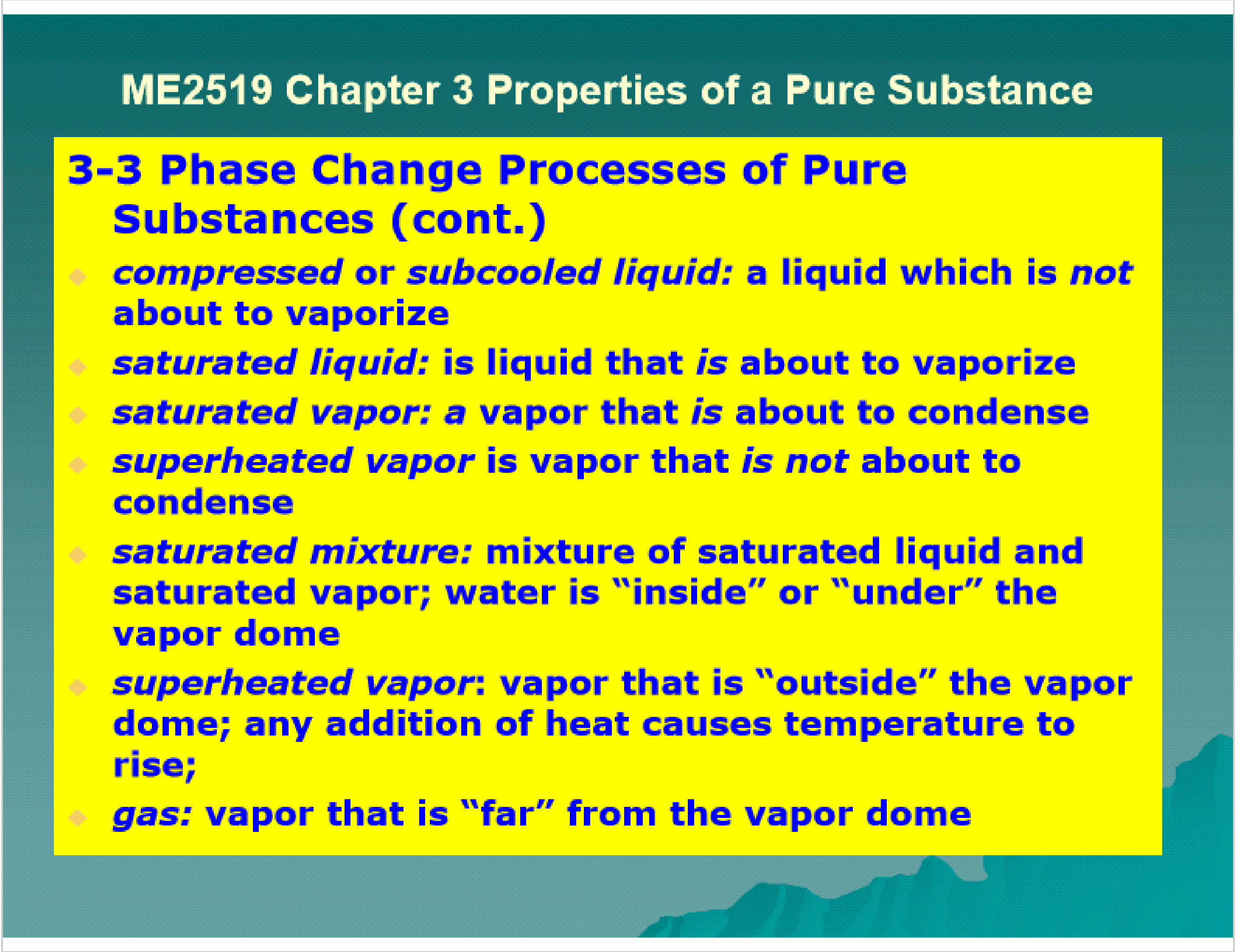
ME2519 Chapter 3 Properties of a Pure Substance

3-3 Phase Change Processes of Pure Substances (cont.)



ME2519 Chapter 3 Properties of a Pure Substance

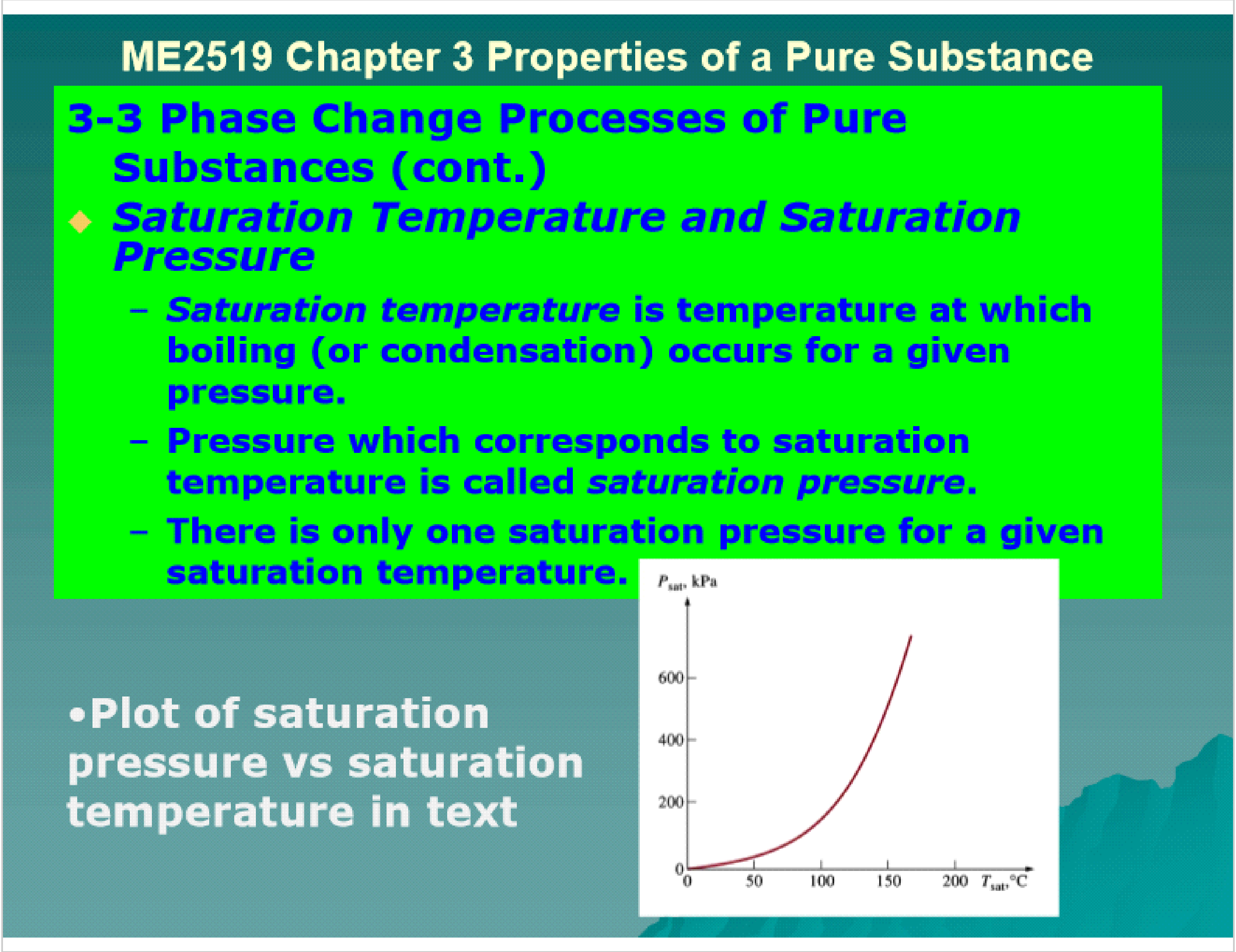
3-3 Phase Change Processes of Pure Substances (cont.)



ME2519 Chapter 3 Properties of a Pure Substance

3-3 Phase Change Processes of Pure Substances (cont.)

- ***compressed*** **or** ***subcooled liquid:*** **a liquid which is** ***not*** **about to vaporize**
- ***saturated liquid:*** **is liquid that** ***is*** **about to vaporize**
- ***saturated vapor: a*** **vapor that** ***is*** **about to condense**
- ***superheated vapor*** **is vapor that** ***is not*** **about to condense**
- ***saturated mixture:*** **mixture of saturated liquid and saturated vapor; water is “inside” or “under” the vapor dome**
- ***superheated vapor*****: vapor that is “outside” the vapor dome; any addition of heat causes temperature to rise;**
- ***gas:*** **vapor that is “far” from the vapor dome**

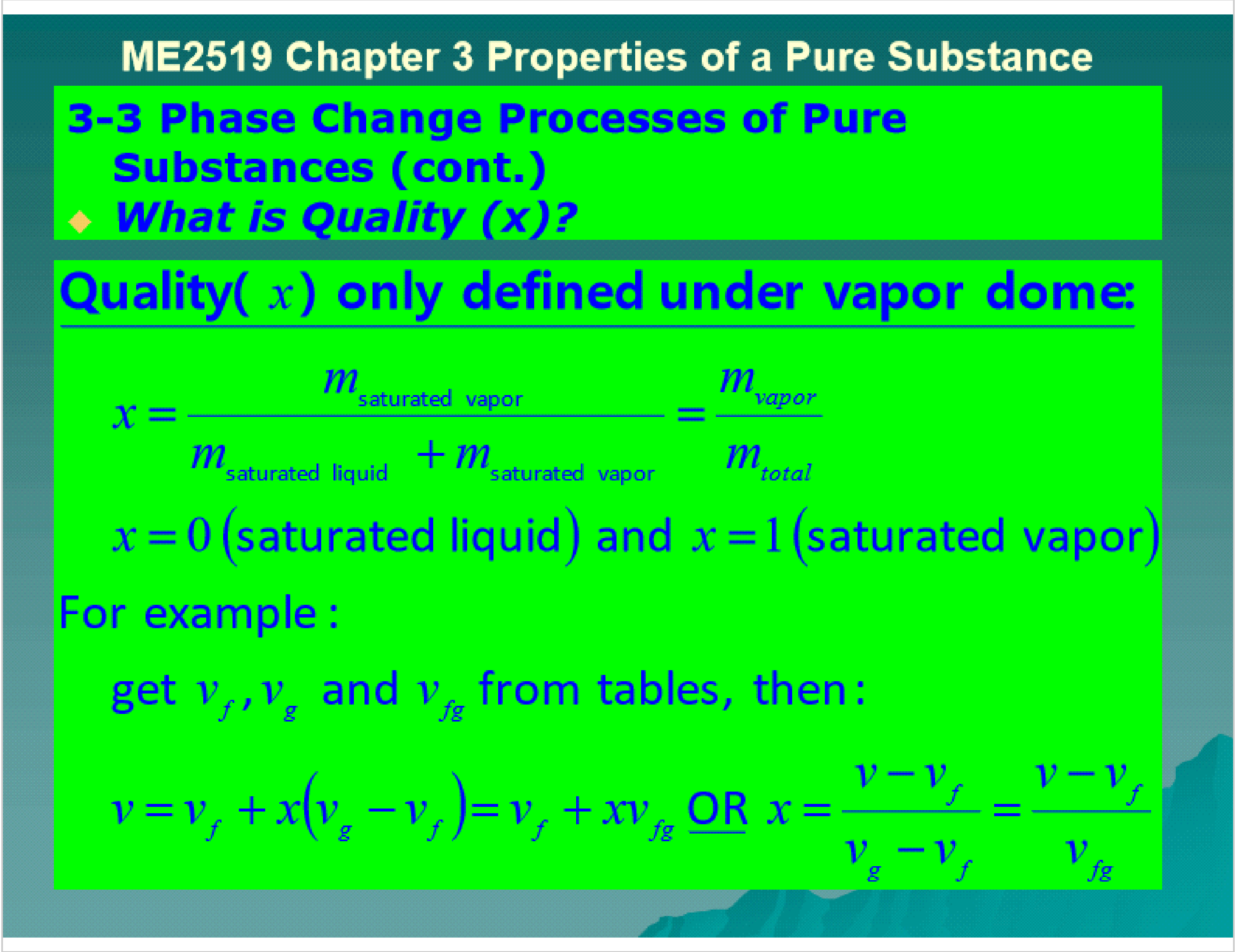


ME2519 Chapter 3 Properties of a Pure Substance

3-3 Phase Change Processes of Pure Substances (cont.)

- ***Saturation Temperature and Saturation Pressure***
  - *Saturation temperature* is temperature at which boiling (or condensation) occurs for a given pressure.
  - Pressure which corresponds to saturation temperature is called *saturation pressure*.
  - There is only one saturation pressure for a given saturation temperature.

•Plot of saturation pressure vs saturation temperature in text



ME2519 Chapter 3 Properties of a Pure Substance

3-3 Phase Change Processes of Pure Substances (cont.)

- ***What is Quality (x)?***

Quality(x) only defined under vapor dome:

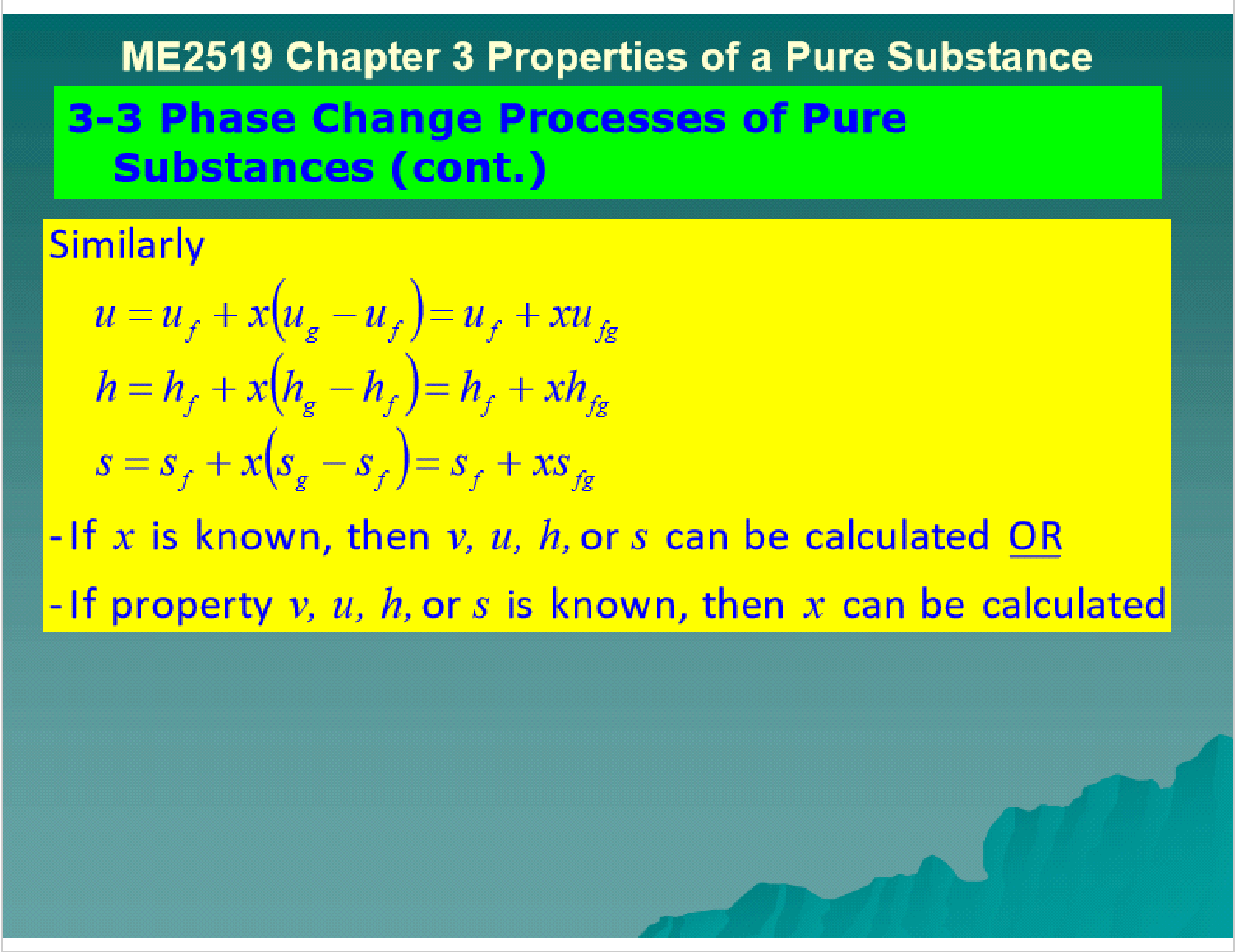
$$x = \frac{m_{\text{saturated vapor}}}{m_{\text{saturated liquid}} + m_{\text{saturated vapor}}} = \frac{m_{vapor}}{m_{total}}$$

$$x = 0 \left(\text{saturated liquid}\right) \text{ and } x = 1 \left(\text{saturated vapor}\right)$$

For example :

get v_f, v_g and v_{fg} from tables, then :

$$v = v_f + x\left(v_g - v_f\right) = v_f + x v_{fg} \; \underline{\text{OR}} \; x = \frac{v - v_f}{v_g - v_f} = \frac{v - v_f}{v_{fg}}$$



ME2519 Chapter 3 Properties of a Pure Substance

3-3 Phase Change Processes of Pure Substances (cont.)

Similarly

$$u = u_f + x\left(u_g - u_f\right) = u_f + xu_{fg}$$

$$h = h_f + x\left(h_g - h_f\right) = h_f + xh_{fg}$$

$$s = s_f + x\left(s_g - s_f\right) = s_f + xs_{fg}$$

-If x is known, then $v,\ u,\ h,$ or s can be calculated OR

-If property $v,\ u,\ h,$ or s is known, then x can be calculated

Property Diagrams

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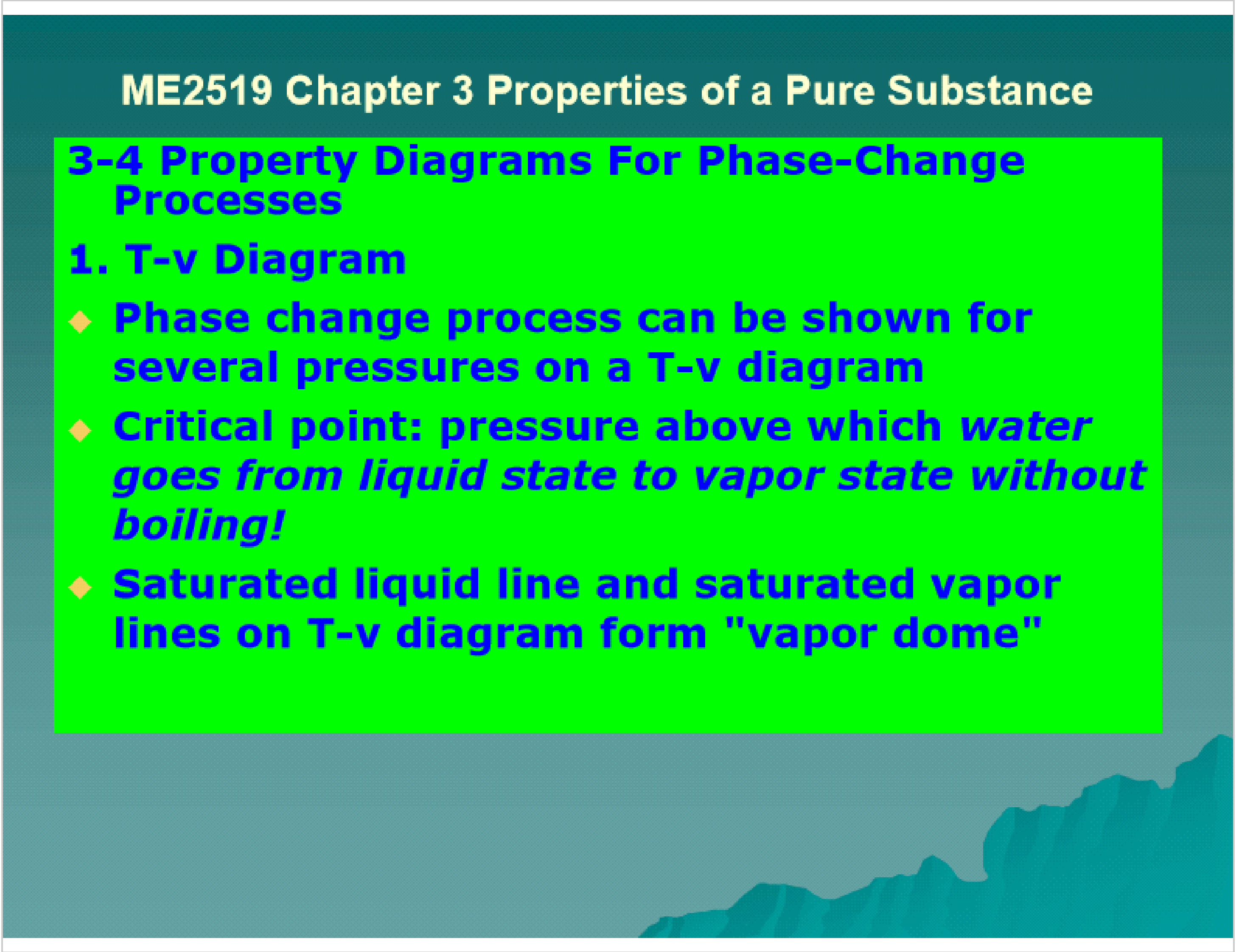

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3-4 Property Diagrams For Phase-Change Processes

1. T-v Diagram

- **Phase change process can be shown for several pressures on a T-v diagram**
- **Critical point: pressure above which *water goes from liquid state to vapor state without boiling!***
- **Saturated liquid line and saturated vapor lines on T-v diagram form "vapor dome"**

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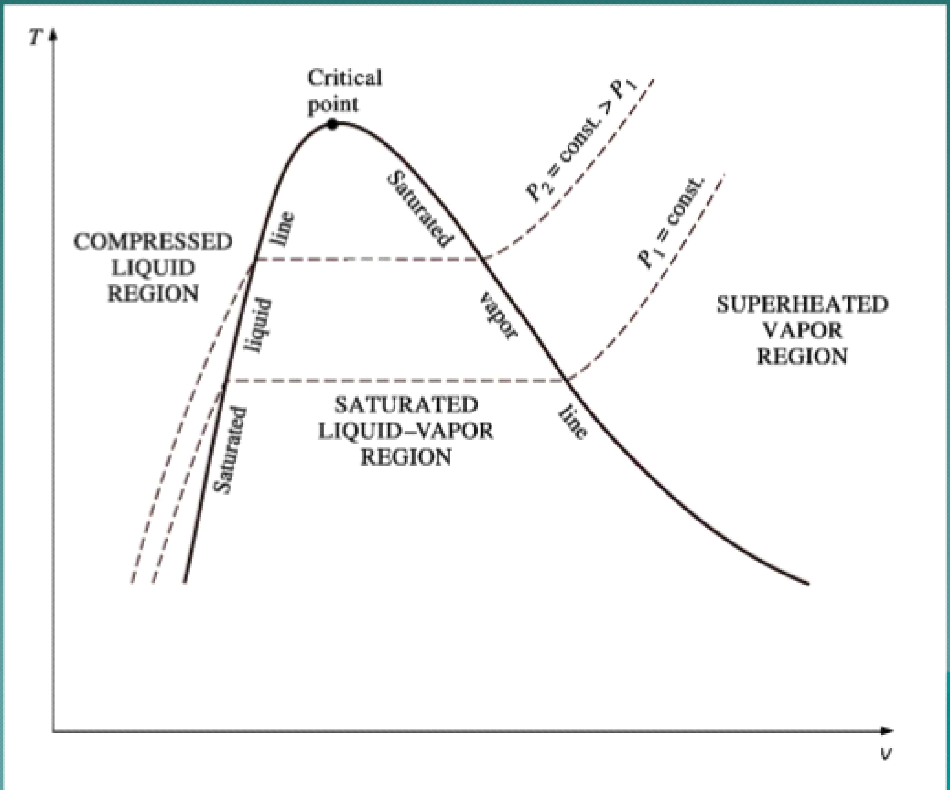
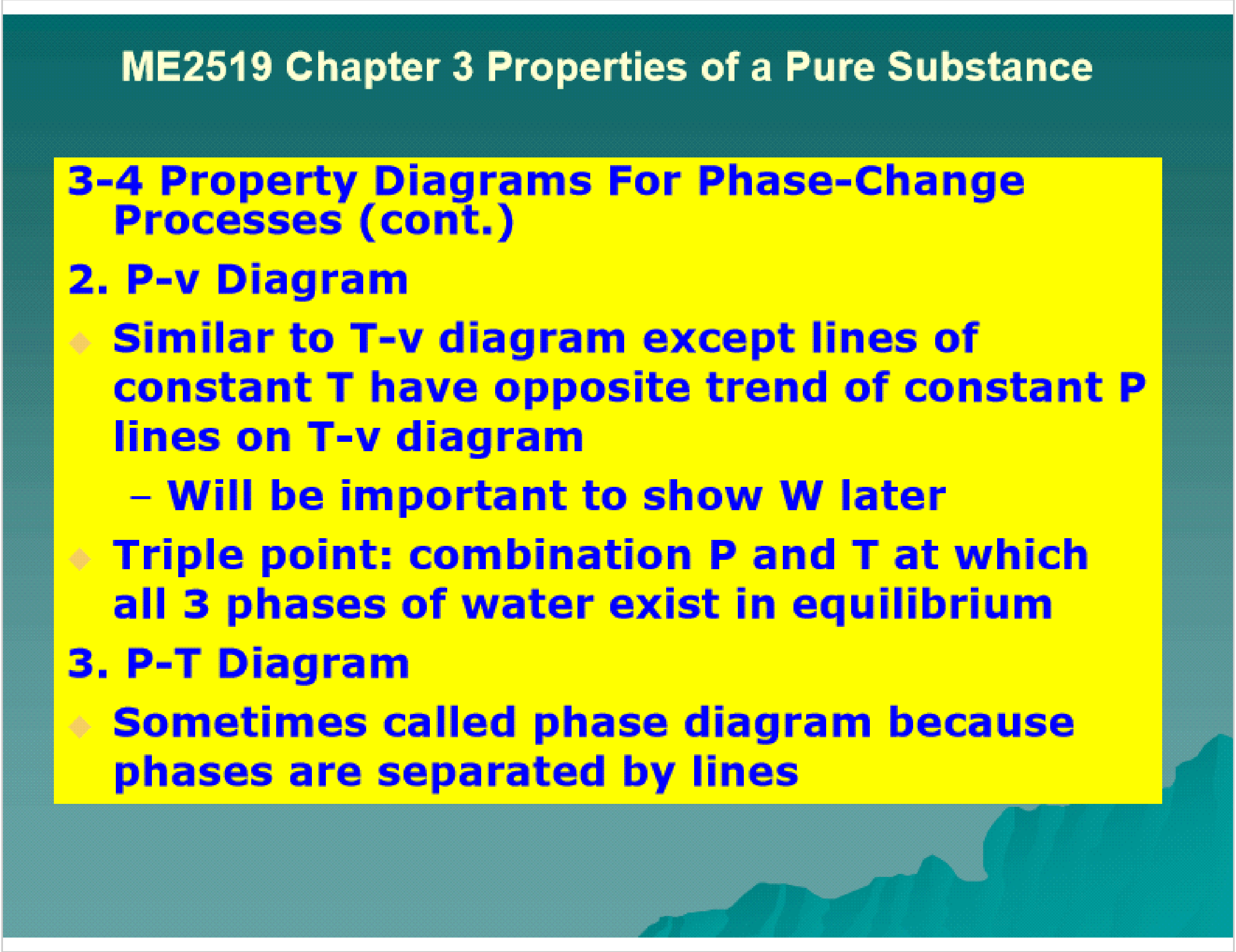
3-4 Property Diagrams For Phase-Change Processes (cont.)

1. T-v Diagram





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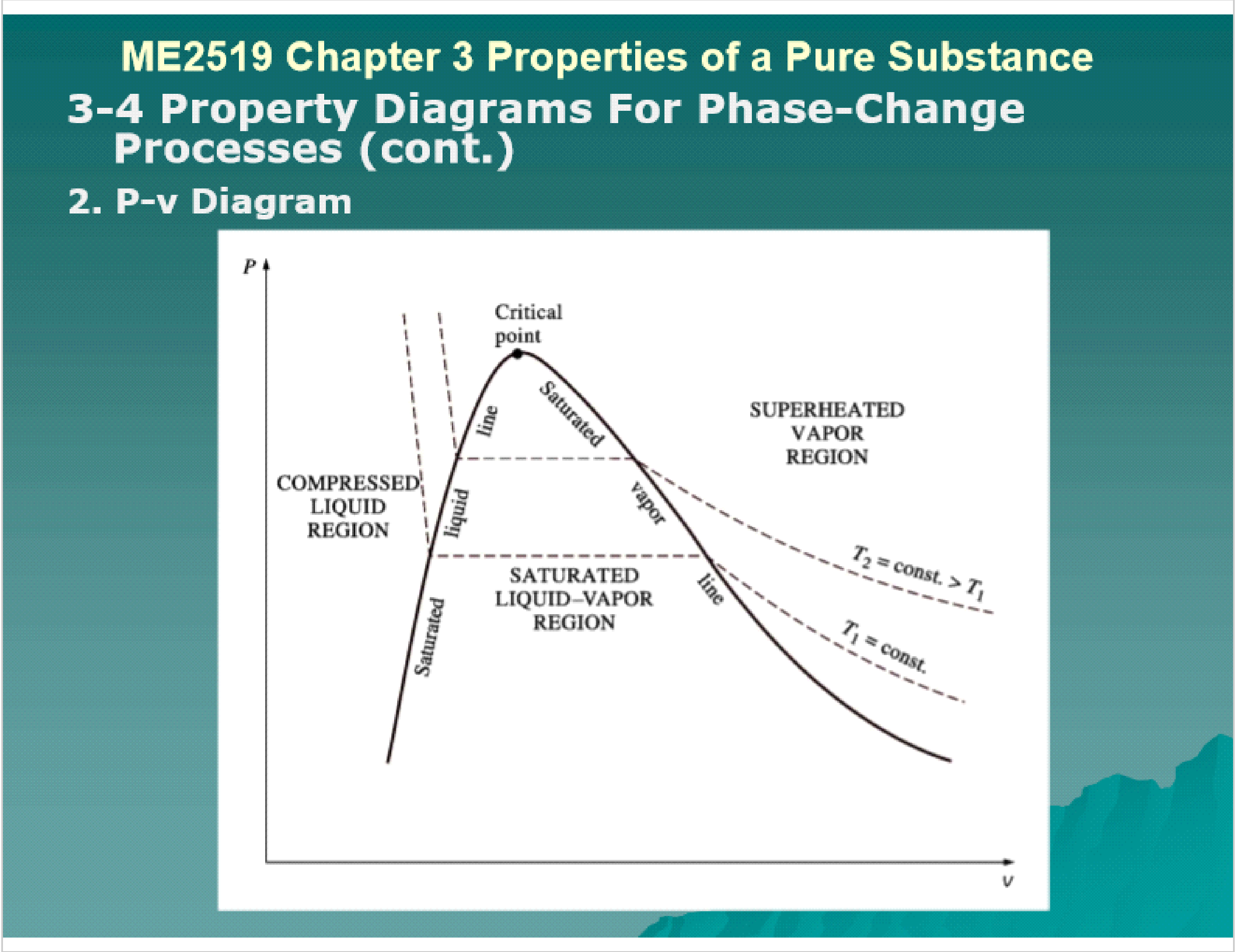
3-4 Property Diagrams For Phase-Change Processes (cont.)

2. P-v Diagram

- Similar to T-v diagram except lines of constant T have opposite trend of constant P lines on T-v diagram
  - Will be important to show W later
- Triple point: combination P and T at which all 3 phases of water exist in equilibrium

3. P-T Diagram

- Sometimes called phase diagram because phases are separated by lines



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3-4 Property Diagrams For Phase-Change Processes (cont.)

2. P-v Diagram

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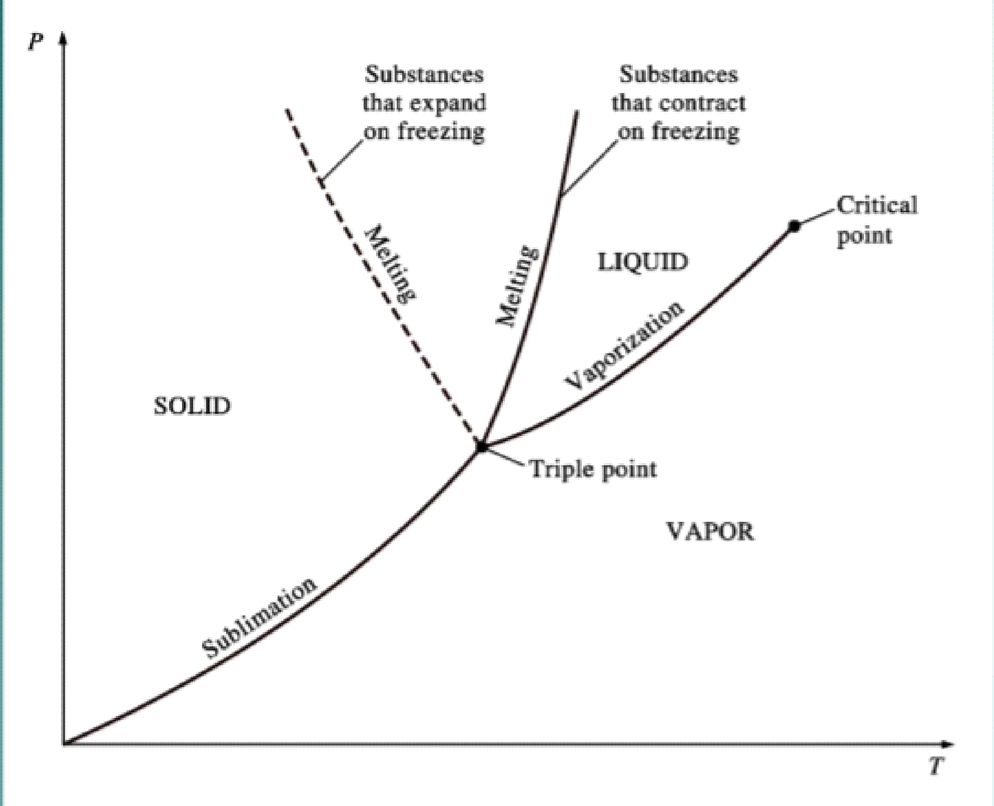
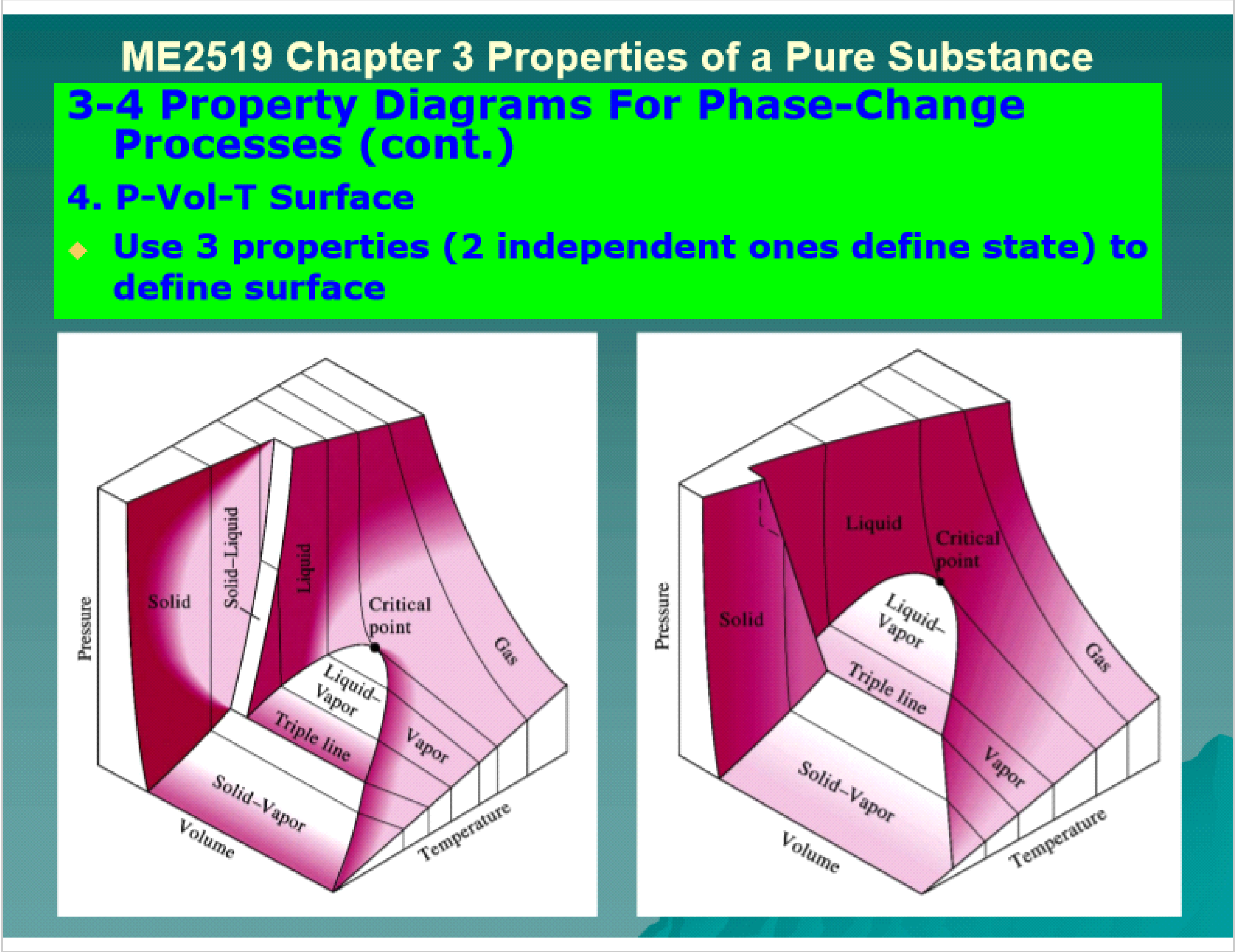
3-4 Property Diagrams For Phase-Change Processes (cont.)

3. P-T Diagram





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3-4 Property Diagrams For Phase-Change Processes (cont.)

4. P-Vol-T Surface

- Use 3 properties (2 independent ones define state) to define surface

Property Tables

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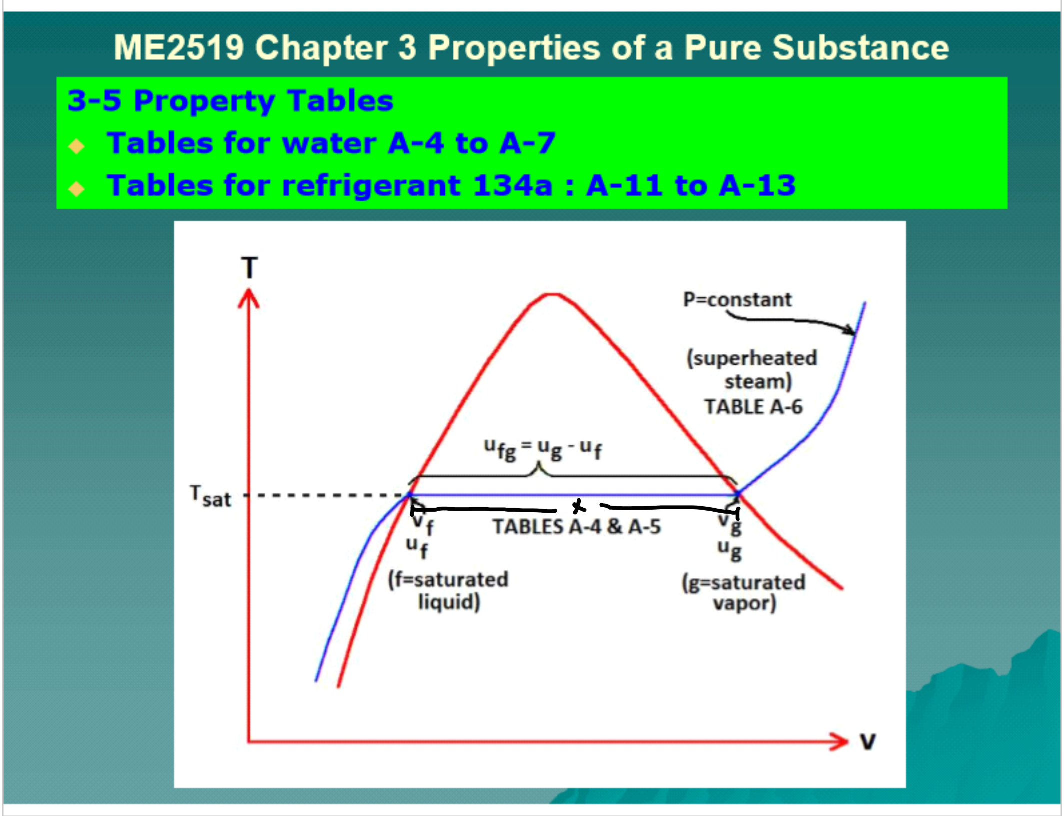

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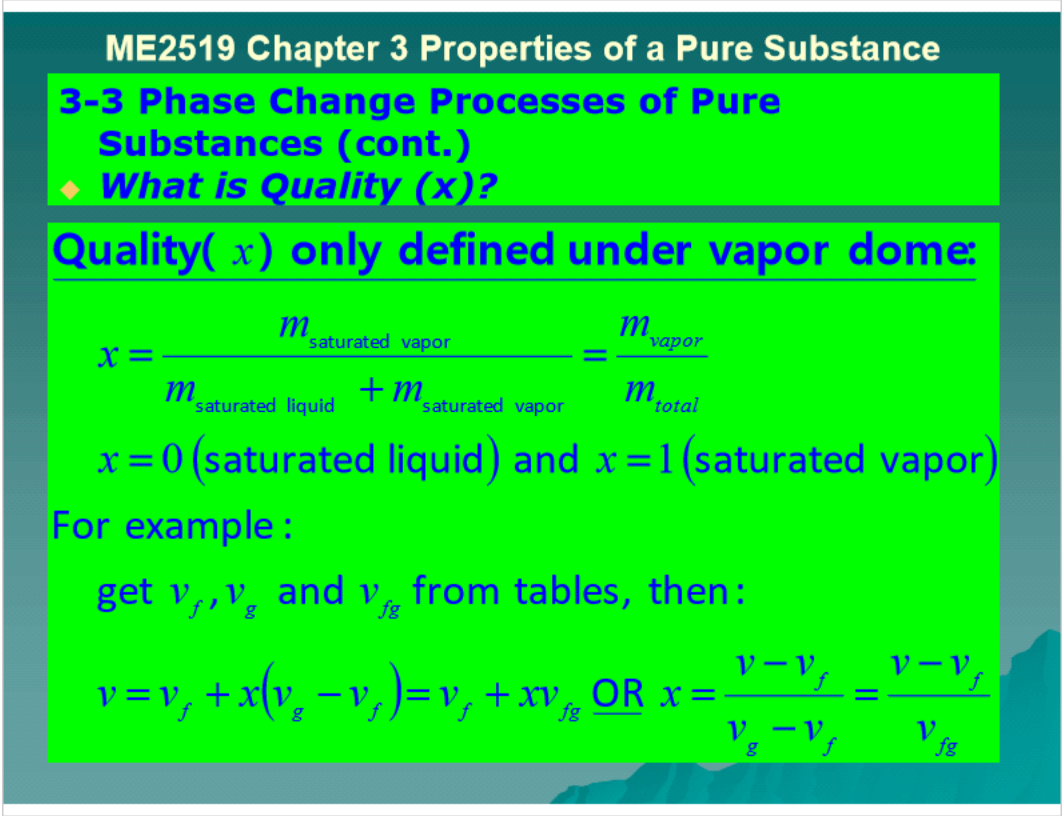
3-5 Property Tables

- **Tables for water A-4 to A-7**
- **Tables for refrigerant 134a : A-11 to A-13**

$$x = \frac{M_{vapor}}{M_{vapor} + M_{liquid}}$$

x=0 = saturated liquid

x=1 = saturated vapor



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3-3 Phase Change Processes of Pure Substances (cont.)

- ***What is Quality (x)?***

Quality(x) only defined under vapor dome:

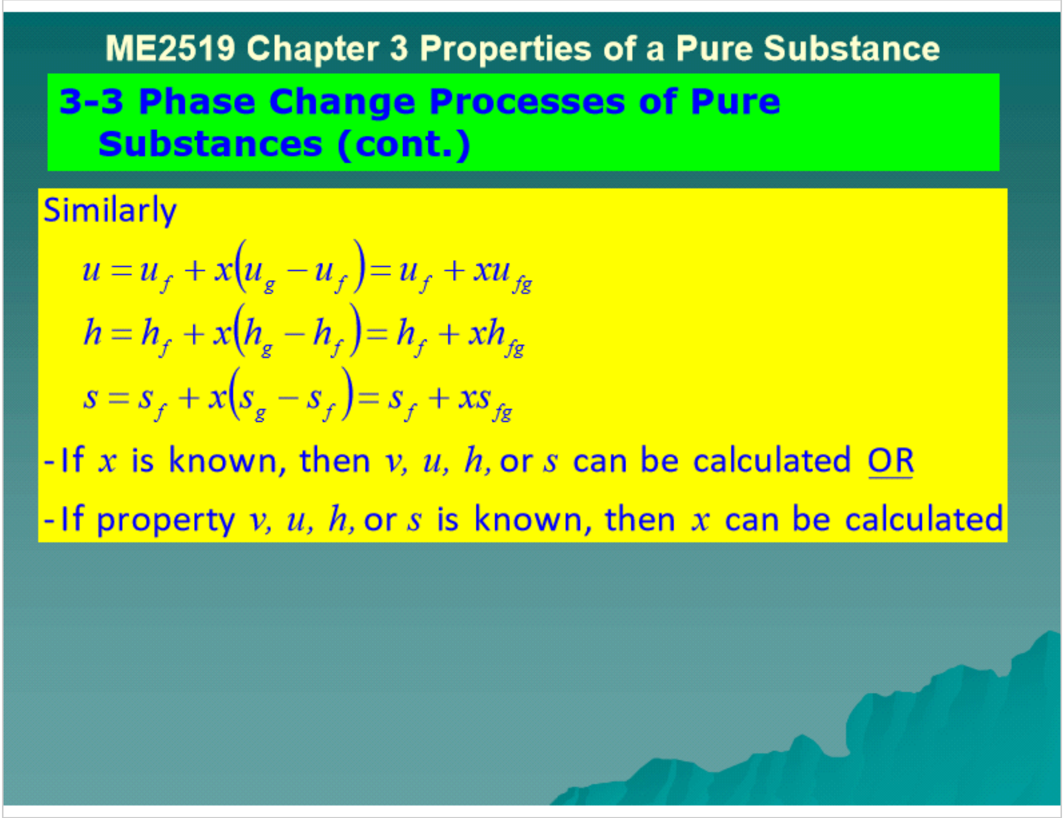
$$x = \frac{m_{\text{saturated vapor}}}{m_{\text{saturated liquid}} + m_{\text{saturated vapor}}} = \frac{m_{vapor}}{m_{total}}$$

$x = 0$ (saturated liquid) and $x = 1$ (saturated vapor)

For example :

get v_f, v_g and v_{fg} from tables, then :

$$v = v_f + x(v_g - v_f) = v_f + xv_{fg} \text{ OR } x = \frac{v - v_f}{v_g - v_f} = \frac{v - v_f}{v_{fg}}$$



ME2519 Chapter 3 Properties of a Pure Substance

3-3 Phase Change Processes of Pure Substances (cont.)

Similarly

$$u = u_f + x(u_g - u_f) = u_f + xu_{fg}$$
$$h = h_f + x(h_g - h_f) = h_f + xh_{fg}$$
$$s = s_f + x(s_g - s_f) = s_f + xs_{fg}$$

-If x is known, then v, u, h, or s can be calculated OR

-If property v, u, h, or s is known, then x can be calculated

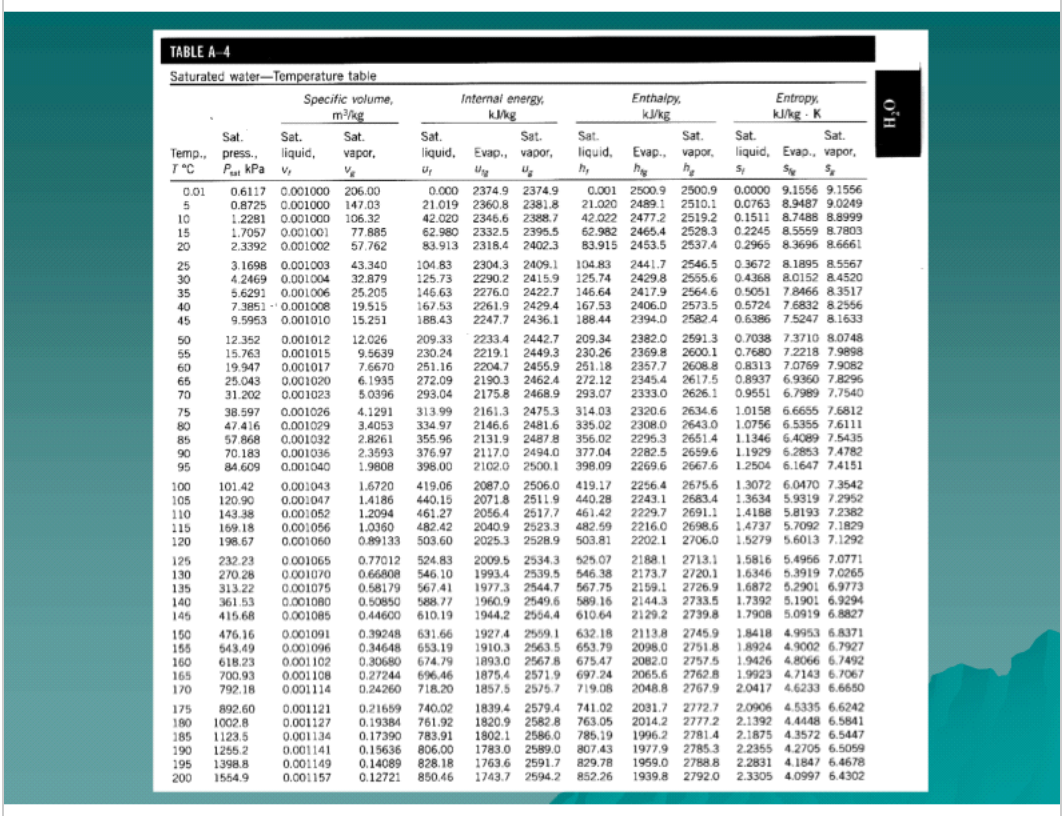


TABLE A–4

Saturated water—Temperature table

H_2O

		Specific volume, m^3/kg		Internal energy, kJ/kg			Enthalpy, kJ/kg			Entropy, kJ/kg · K		
Temp., T °C	Sat. press., P_{sat} kPa	Sat. liquid, v_f	Sat. vapor, v_g	Sat. liquid, u_f	Evap., u_{fg}	Sat. vapor, u_g	Sat. liquid, h_f	Evap., h_{fg}	Sat. vapor, h_g	Sat. liquid, s_f	Evap., s_{fg}	Sat. vapor, s_g
0.01	0.6117	0.001000	206.00	0.000	2374.9	2374.9	0.001	2500.9	2500.9	0.0000	9.1556	9.1556
5	0.8725	0.001000	147.03	21.019	2360.8	2381.8	21.020	2489.1	2510.1	0.0763	8.9487	9.0249
10	1.2281	0.001000	106.32	42.020	2346.6	2388.7	42.022	2477.2	2519.2	0.1511	8.7488	8.8999
15	1.7057	0.001001	77.885	62.980	2332.5	2395.5	62.982	2465.4	2528.3	0.2245	8.5559	8.7803
20	2.3392	0.001002	57.762	83.913	2318.4	2402.3	83.915	2453.5	2537.4	0.2965	8.3696	8.6661
25	3.1698	0.001003	43.340	104.83	2304.3	2409.1	104.83	2441.7	2546.5	0.3672	8.1895	8.5567
30	4.2469	0.001004	32.879	125.73	2290.2	2415.9	125.74	2429.8	2555.6	0.4368	8.0152	8.4520
35	5.6291	0.001006	25.205	146.63	2276.0	2422.7	146.64	2417.9	2564.6	0.5051	7.8466	8.3517
40	7.3851	0.001008	19.515	167.53	2261.9	2429.4	167.53	2406.0	2573.5	0.5724	7.6832	8.2556
45	9.5953	0.001010	15.251	188.43	2247.7	2436.1	188.44	2394.0	2582.4	0.6386	7.5247	8.1633
50	12.352	0.001012	12.026	209.33	2233.4	2442.7	209.34	2382.0	2591.3	0.7038	7.3710	8.0748
55	15.763	0.001015	9.5639	230.24	2219.1	2449.3	230.26	2369.8	2600.1	0.7680	7.2218	7.9898
60	19.947	0.001017	7.6670	251.16	2204.7	2455.9	251.18	2357.7	2608.8	0.8313	7.0769	7.9082
65	25.043	0.001020	6.1935	272.09	2190.3	2462.4	272.12	2345.4	2617.5	0.8937	6.9360	7.8296
70	31.202	0.001023	5.0396	293.04	2175.8	2468.9	293.07	2333.0	2626.1	0.9551	6.7989	7.7540
75	38.597	0.001026	4.1291	313.99	2161.3	2475.3	314.03	2320.6	2634.6	1.0158	6.6655	7.6812
80	47.416	0.001029	3.4053	334.97	2146.6	2481.6	335.02	2308.0	2643.0	1.0756	6.5355	7.6111
85	57.868	0.001032	2.8261	355.96	2131.9	2487.8	356.02	2295.3	2651.4	1.1346	6.4089	7.5435
90	70.183	0.001036	2.3593	376.97	2117.0	2494.0	377.04	2282.5	2659.6	1.1929	6.2853	7.4782
95	84.609	0.001040	1.9808	398.00	2102.0	2500.1	398.09	2269.6	2667.6	1.2504	6.1647	7.4151
100	101.42	0.001043	1.6720	419.06	2087.0	2506.0	419.17	2256.4	2675.6	1.3072	6.0470	7.3542
105	120.90	0.001047	1.4186	440.15	2071.8	2511.9	440.28	2243.1	2683.4	1.3634	5.9319	7.2952
110	143.38	0.001052	1.2094	461.27	2056.4	2517.7	461.42	2229.7	2691.1	1.4188	5.8193	7.2382
115	169.18	0.001056	1.0360	482.42	2040.9	2523.3	482.59	2216.0	2698.6	1.4737	5.7092	7.1829
120	198.67	0.001060	0.89133	503.60	2025.3	2528.9	503.81	2202.1	2706.0	1.5279	5.6013	7.1292
125	232.23	0.001065	0.77012	524.83	2009.5	2534.3	525.07	2188.1	2713.1	1.5816	5.4956	7.0771
130	270.28	0.001070	0.66808	546.10	1993.4	2539.5	546.38	2173.7	2720.1	1.6346	5.3919	7.0265
135	313.22	0.001075	0.58179	567.41	1977.3	2544.7	567.75	2159.1	2726.9	1.6872	5.2901	6.9773
140	361.53	0.001080	0.50850	588.77	1960.9	2549.6	589.16	2144.3	2733.5	1.7392	5.1901	6.9294
145	415.68	0.001085	0.44600	610.19	1944.2	2554.4	610.64	2129.2	2739.8	1.7908	5.0919	6.8827
150	476.16	0.001091	0.39248	631.66	1927.4	2559.1	632.18	2113.8	2745.9	1.8418	4.9953	6.8371
155	543.49	0.001096	0.34648	653.19	1910.3	2563.5	653.79	2098.0	2751.8	1.8924	4.9002	6.7927
160	618.23	0.001102	0.30680	674.79	1893.0	2567.8	675.47	2082.0	2757.5	1.9426	4.8066	6.7492
165	700.93	0.001108	0.27244	696.46	1875.4	2571.9	697.24	2065.6	2762.8	1.9923	4.7143	6.7067
170	792.18	0.001114	0.24260	718.20	1857.5	2575.7	719.08	2048.8	2767.9	2.0417	4.6233	6.6650
175	892.60	0.001121	0.21659	740.02	1839.4	2579.4	741.02	2031.7	2772.7	2.0906	4.5335	6.6242
180	1002.8	0.001127	0.19384	761.92	1820.9	2582.8	763.05	2014.2	2777.2	2.1392	4.4448	6.5841
185	1123.5	0.001134	0.17390	783.91	1802.1	2586.0	785.19	1996.2	2781.4	2.1875	4.3572	6.5447
190	1255.2	0.001141	0.15636	806.00	1783.0	2589.0	807.43	1977.9	2785.3	2.2355	4.2705	6.5059
195	1398.8	0.001149	0.14089	828.18	1763.6	2591.7	829.78	1959.0	2788.8	2.2831	4.1847	6.4678
200	1554.9	0.001157	0.12721	850.46	1743.7	2594.2	852.26	1939.8	2792.0	2.3305	4.0997	6.4302

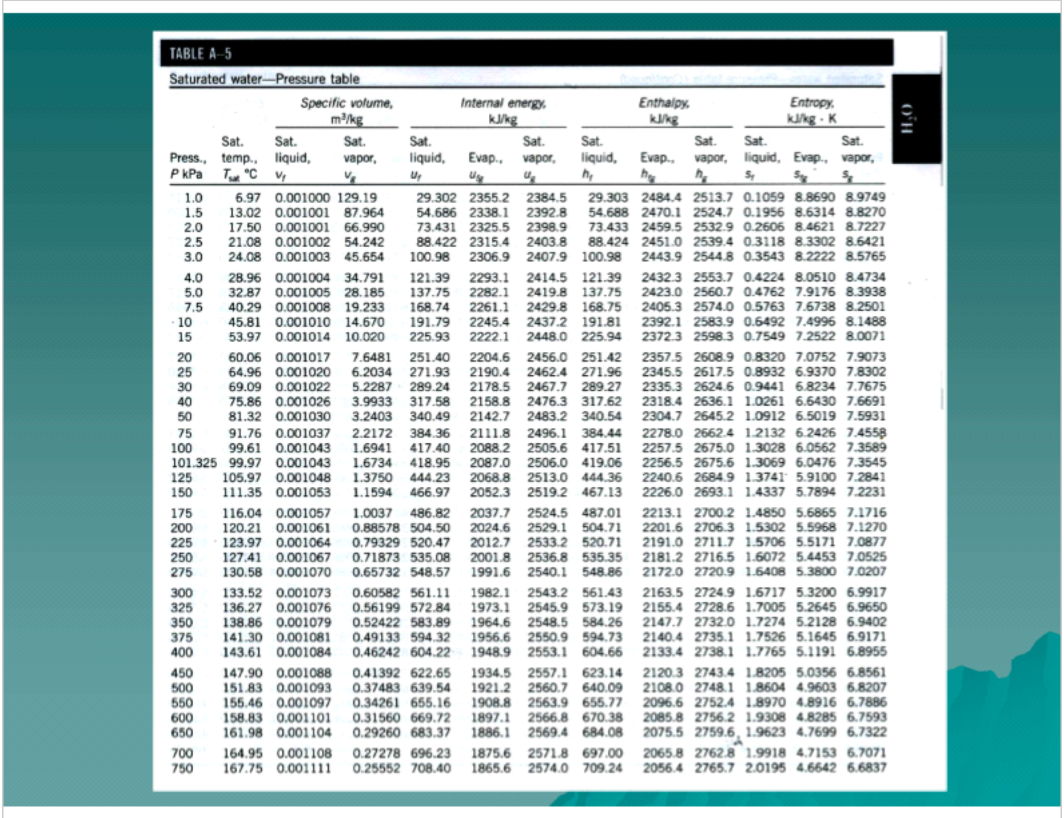


TABLE A–5

Saturated water—Pressure table

H_2O

		Specific volume, m^3/kg		Internal energy, kJ/kg			Enthalpy, kJ/kg			Entropy, kJ/kg · K		
Press., P kPa	Sat. temp., T_{sat} °C	Sat. liquid, v_f	Sat. vapor, v_g	Sat. liquid, u_f	Evap., u_{fg}	Sat. vapor, u_g	Sat. liquid, h_f	Evap., h_{fg}	Sat. vapor, h_g	Sat. liquid, s_f	Evap., s_{fg}	Sat. vapor, s_g
1.0	6.97	0.001000	129.19	29.302	2355.2	2384.5	29.303	2484.4	2513.7	0.1059	8.8690	8.9749
1.5	13.02	0.001001	87.964	54.686	2338.1	2392.8	54.688	2470.1	2524.7	0.1956	8.6314	8.8270
2.0	17.50	0.001001	66.990	73.431	2325.5	2398.9	73.433	2459.5	2532.9	0.2606	8.4621	8.7227
2.5	21.08	0.001002	54.242	88.422	2315.4	2403.8	88.424	2451.0	2539.4	0.3118	8.3302	8.6421
3.0	24.08	0.001003	45.654	100.98	2306.9	2407.9	100.98	2443.9	2544.8	0.3543	8.2222	8.5765
4.0	28.96	0.001004	34.791	121.39	2293.1	2414.5	121.39	2432.3	2553.7	0.4224	8.0510	8.4734
5.0	32.87	0.001005	28.185	137.75	2282.1	2419.8	137.75	2423.0	2560.7	0.4762	7.9176	8.3938
7.5	40.29	0.001008	19.233	168.74	2261.1	2429.8	168.75	2405.3	2574.0	0.5763	7.6738	8.2501
10	45.81	0.001010	14.670	191.79	2245.4	2437.2	191.81	2392.1	2583.9	0.6492	7.4996	8.1488
15	53.97	0.001014	10.020	225.93	2222.1	2448.0	225.94	2372.3	2598.3	0.7549	7.2522	8.0071
20	60.06	0.001017	7.6481	251.40	2204.6	2456.0	251.42	2357.5	2608.9	0.8320	7.0752	7.9073
25	64.96	0.001020	6.2034	271.93	2190.4	2462.4	271.96	2345.5	2617.5	0.8932	6.9370	7.8302
30	69.09	0.001022	5.2287	289.24	2178.5	2467.7	289.27	2335.3	2624.6	0.9441	6.8234	7.7675
40	75.86	0.001026	3.9933	317.58	2158.8	2476.3	317.62	2318.4	2636.1	1.0261	6.6430	7.6691
50	81.32	0.001030	3.2403	340.49	2142.7	2483.2	340.54	2304.7	2645.2	1.0912	6.5019	7.5931
75	91.76	0.001037	2.2172	384.36	2111.8	2496.1	384.44	2278.0	2662.4	1.2132	6.2426	7.4558
100	99.61	0.001043	1.6941	417.40	2088.2	2505.6	417.51	2257.5	2675.0	1.3028	6.0562	7.3589
101.325	99.97	0.001043	1.6734	418.95	2087.0	2506.0	419.06	2256.5	2675.6	1.3069	6.0476	7.3545
125	105.97	0.001048	1.3750	444.23	2068.8	2513.0	444.36	2240.6	2684.9	1.3741	5.9100	7.2841
150	111.35	0.001053	1.1594	466.97	2052.3	2519.2	467.13	2226.0	2693.1	1.4337	5.7894	7.2231
175	116.04	0.001057	1.0037	486.82	2037.7	2524.5	487.01	2213.1	2700.2	1.4850	5.6865	7.1716
200	120.21	0.001061	0.88578	504.50	2024.6	2529.1	504.71	2201.6	2706.3	1.5302	5.5968	7.1270
225	123.97	0.001064	0.79329	520.47	2012.7	2533.2	520.71	2191.0	2711.7	1.5706	5.5171	7.0877
250	127.41	0.001067	0.71873	535.08	2001.8	2536.8	535.35	2181.2	2716.5	1.6072	5.4453	7.0525
275	130.58	0.001070	0.65732	548.57	1991.6	2540.1	548.86	2172.0	2720.9	1.6408	5.3800	7.0207
300	133.52	0.001073	0.60582	561.11	1982.1	2543.2	561.43	2163.5	2724.9	1.6717	5.3200	6.9917
325	136.27	0.001076	0.56199	572.84	1973.1	2545.9	573.19	2155.4	2728.6	1.7005	5.2645	6.9650
350	138.86	0.001079	0.52422	583.89	1964.6	2548.5	584.26	2147.7	2732.0	1.7274	5.2128	6.9402
375	141.30	0.001081	0.49133	594.32	1956.6	2550.9	594.73	2140.4	2735.1	1.7526	5.1645	6.9171
400	143.61	0.001084	0.46242	604.22	1948.9	2553.1	604.66	2133.4	2738.1	1.7765	5.1191	6.8955
450	147.90	0.001088	0.41392	622.65	1934.5	2557.1	623.14	2120.3	2743.4	1.8205	5.0356	6.8561
500	151.83	0.001093	0.37483	639.54	1921.2	2560.7	640.09	2108.0	2748.1	1.8604	4.9603	6.8207
550	155.46	0.001097	0.34261	655.16	1908.8	2563.9	655.77	2096.6	2752.4	1.8970	4.8916	6.7886
600	158.83	0.001101	0.31560	669.72	1897.1	2566.8	670.38	2085.8	2756.2	1.9308	4.8285	6.7593
650	161.98	0.001104	0.29260	683.37	1886.1	2569.4	684.08	2075.5	2759.6	1.9623	4.7699	6.7322
700	164.95	0.001108	0.27278	696.23	1875.6	2571.8	697.00	2065.8	2762.8	1.9918	4.7153	6.7071
750	167.75	0.001111	0.25552	708.40	1865.6	2574.0	709.24	2056.4	2765.7	2.0195	4.6642	6.6837

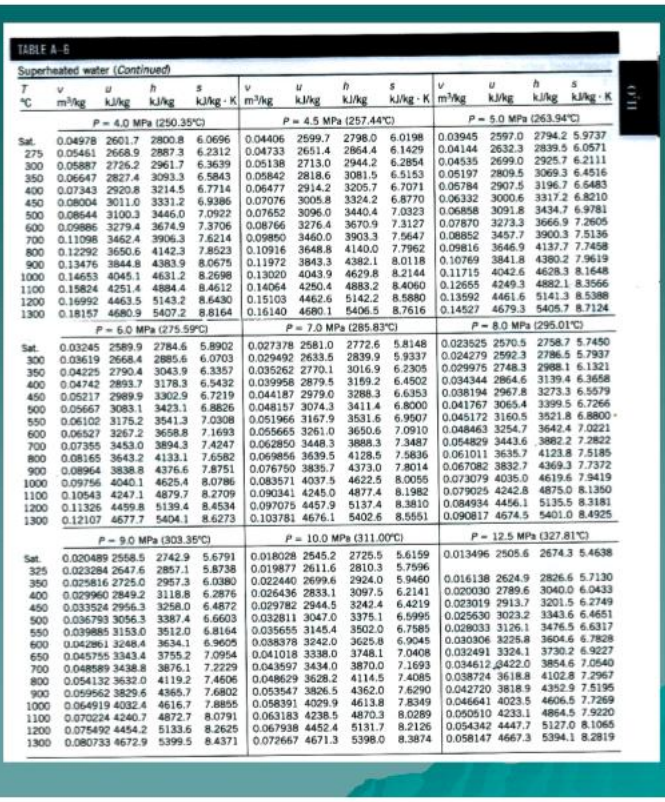


TABLE A–6

Superheated water (*Continued*)

T °C	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg · K	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg · K	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg · K
	P = 4.0 MPa (250.35°C)				*P* = 4.5 MPa (257.44°C)				*P* = 5.0 MPa (263.94°C)			
Sat.	0.04978	2601.7	2800.8	6.0696	0.04406	2599.7	2798.0	6.0198	0.03945	2597.0	2794.2	5.9737
275	0.05461	2668.9	2887.3	6.2312	0.04733	2651.4	2864.4	6.1429	0.04144	2632.3	2839.5	6.0571
300	0.05887	2726.2	2961.7	6.3639	0.05138	2713.0	2944.2	6.2854	0.04535	2699.0	2925.7	6.2111
350	0.06647	2827.4	3093.3	6.5843	0.05842	2818.6	3081.5	6.5153	0.05197	2809.5	3069.3	6.4516
400	0.07343	2920.8	3214.5	6.7714	0.06477	2914.2	3205.7	6.7071	0.05784	2907.5	3196.7	6.6483
450	0.08004	3011.0	3331.2	6.9386	0.07076	3005.8	3324.2	6.8770	0.06332	3000.6	3317.2	6.8210
500	0.08644	3100.3	3446.0	7.0922	0.07652	3096.0	3440.4	7.0323	0.06858	3091.8	3434.7	6.9781
600	0.09886	3279.4	3674.9	7.3706	0.08766	3276.4	3670.9	7.3127	0.07870	3273.3	3666.9	7.2605
700	0.11098	3462.4	3906.3	7.6214	0.09850	3460.0	3903.3	7.5647	0.08852	3457.7	3900.3	7.5136
800	0.12292	3650.6	4142.3	7.8523	0.10916	3648.8	4140.0	7.7962	0.09816	3646.9	4137.7	7.7458
900	0.13476	3844.8	4383.9	8.0675	0.11972	3843.3	4382.1	8.0118	0.10769	3841.8	4380.2	7.9619
1000	0.14653	4045.1	4631.2	8.2698	0.13020	4043.9	4629.8	8.2144	0.11715	4042.6	4628.3	8.1648
1100	0.15824	4251.4	4884.4	8.4612	0.14064	4250.4	4883.2	8.4060	0.12655	4249.3	4882.1	8.3566
1200	0.16992	4463.5	5143.2	8.6430	0.15103	4462.6	5142.2	8.5880	0.13592	4461.6	5141.3	8.5388
1300	0.18157	4680.9	5407.2	8.8164	0.16140	4680.1	5406.5	8.7616	0.14527	4679.3	5405.7	8.7124
	P = 6.0 MPa (275.59°C)				*P* = 7.0 MPa (285.83°C)				*P* = 8.0 MPa (295.01°C)			
Sat.	0.03245	2589.9	2784.6	5.8902	0.027378	2581.0	2772.6	5.8148	0.023525	2570.5	2758.7	5.7450
300	0.03619	2668.4	2885.6	6.0703	0.029492	2633.5	2839.9	5.9337	0.024279	2592.3	2786.5	5.7937
350	0.04225	2790.4	3043.9	6.3357	0.035262	2770.1	3016.9	6.2305	0.029975	2748.3	2988.1	6.1321
400	0.04742	2893.7	3178.3	6.5432	0.039958	2879.5	3159.2	6.4502	0.034344	2864.6	3139.4	6.3658
450	0.05217	2989.9	3302.9	6.7219	0.044187	2979.0	3288.3	6.6353	0.038194	2967.8	3273.3	6.5579
500	0.05667	3083.1	3423.1	6.8826	0.048157	3074.3	3411.4	6.8000	0.041767	3065.4	3399.5	6.7266
550	0.06102	3175.2	3541.3	7.0308	0.051966	3167.9	3531.6	6.9507	0.045172	3160.5	3521.8	6.8800
600	0.06527	3267.2	3658.8	7.1693	0.055665	3261.0	3650.6	7.0910	0.048463	3254.7	3642.4	7.0221
700	0.07355	3453.0	3894.3	7.4247	0.062850	3448.3	3888.3	7.3487	0.054829	3443.6	3882.2	7.2822
800	0.08165	3643.2	4133.1	7.6582	0.069856	3639.5	4128.5	7.5836	0.061011	3635.7	4123.8	7.5185
900	0.08964	3838.8	4376.6	7.8751	0.076750	3835.7	4373.0	7.8014	0.067082	3832.7	4369.3	7.7372
1000	0.09756	4040.1	4625.4	8.0786	0.083571	4037.5	4622.5	8.0055	0.073079	4035.0	4619.6	7.9419
1100	0.10543	4247.1	4879.7	8.2709	0.090341	4245.0	4877.4	8.1982	0.079025	4242.8	4875.0	8.1350
1200	0.11326	4459.8	5139.4	8.4534	0.097075	4457.9	5137.4	8.3810	0.084934	4456.1	5135.5	8.3181
1300	0.12107	4677.7	5404.1	8.6273	0.103781	4676.1	5402.6	8.5551	0.090817	4674.5	5401.0	8.4925
	P = 9.0 MPa (303.35°C)				*P* = 10.0 MPa (311.00°C)				*P* = 12.5 MPa (327.81°C)			
Sat.	0.020489	2558.5	2742.9	5.6791	0.018028	2545.2	2725.5	5.6159	0.013496	2505.6	2674.3	5.4638
325	0.023284	2647.6	2857.1	5.8738	0.019877	2611.6	2810.3	5.7596				
350	0.025816	2725.0	2957.3	6.0380	0.022440	2699.6	2924.0	5.9460	0.016138	2624.9	2826.6	5.7130
400	0.029960	2849.2	3118.8	6.2876	0.026436	2833.1	3097.5	6.2141	0.020030	2789.6	3040.0	6.0433
450	0.033524	2956.3	3258.0	6.4872	0.029782	2944.5	3242.4	6.4219	0.023019	2913.7	3201.5	6.2749
500	0.036793	3056.3	3387.4	6.6603	0.032811	3047.0	3375.1	6.5995	0.025630	3023.2	3343.6	6.4651
550	0.039885	3153.0	3512.0	6.8164	0.035655	3145.4	3502.0	6.7585	0.028033	3126.1	3476.5	6.6317
600	0.042861	3248.4	3634.1	6.9605	0.038378	3242.0	3625.8	6.9045	0.030306	3225.8	3604.6	6.7828
650	0.045755	3343.4	3755.2	7.0954	0.041018	3338.0	3748.1	7.0408	0.032491	3324.1	3730.2	6.9227
700	0.048589	3438.8	3876.1	7.2229	0.043597	3434.0	3870.0	7.1693	0.034612	3422.0	3854.6	7.0540
800	0.054132	3632.0	4119.2	7.4606	0.048629	3628.2	4114.5	7.4085	0.038724	3618.8	4102.8	7.2967
900	0.059562	3829.6	4365.7	7.6802	0.053547	3826.5	4362.0	7.6290	0.042720	3818.9	4352.9	7.5195
1000	0.064919	4032.4	4616.7	7.8855	0.058391	4029.9	4613.8	7.8349	0.046641	4023.5	4606.5	7.7269
1100	0.070224	4240.7	4872.7	8.0791	0.063183	4238.5	4870.3	8.0289	0.050510	4233.1	4864.5	7.9220
1200	0.075492	4454.2	5133.6	8.2625	0.067938	4452.4	5131.7	8.2126	0.054342	4447.7	5127.0	8.1065
1300	0.080733	4672.9	5399.5	8.4371	0.072667	4671.3	5398.0	8.3874	0.058147	4667.3	5394.1	8.2819

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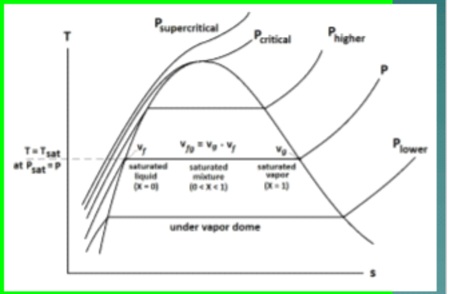
3-5 Property Tables (cont.)

- **How to know if water (or r-134a) is compressed/subcooled, under the vapor dome (saturated mixture), or superheated?**
- **Given T & v:**
  - **At $T_{sat} = T$,**
    - **If $v < v_f$, then subcooled**
    - **If $v_f \le v \le v_g$ then sat mixture (i.e. under vapor dome)**
    - **If $v > v_g$ then superheated**
- **Given P & v:**
  - **At $P_{sat} = P$,**
    - **If $v < v_f$, then subcooled**
    - **If $v_f \le v \le v_g$ then sat mixture**
    - **If $v > v_g$ then superheated**

ME2519 Chapter 3 Properties of a Pure Substance

3-5 Property Tables (cont.)

- How to know if water (or r-134a) is compressed/subcooled, under the vapor dome (saturated mixture), or superheated?
- Given P & T:
  - At $P_{sat} = P$,
    - If $T \leq T_{sat}$ then subcooled
    - If $T = T_{sat}$, then sat mixture
    - If $T \geq T_{sat}$ then superheated
  - Or at $T_{sat} = T$,
    - If $P \geq P_{sat}$ then subcooled
    - If $P = P_{sat}$, then sat mixture
    - If $P \leq P_{sat}$ then superheated



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3-5 Property Tables (cont.)

- Two additional properties (besides v and u):
  - Enthalpy (h) - A Combination Property
    - $h = u + Pv$ (kJ/kg) OR $H = U + PVol$ (kJ/kg)
  - Entropy (s) in tables is also a property (Chapter 7) (kJ/kg-K)
- h and s are determined from tables just like v and u

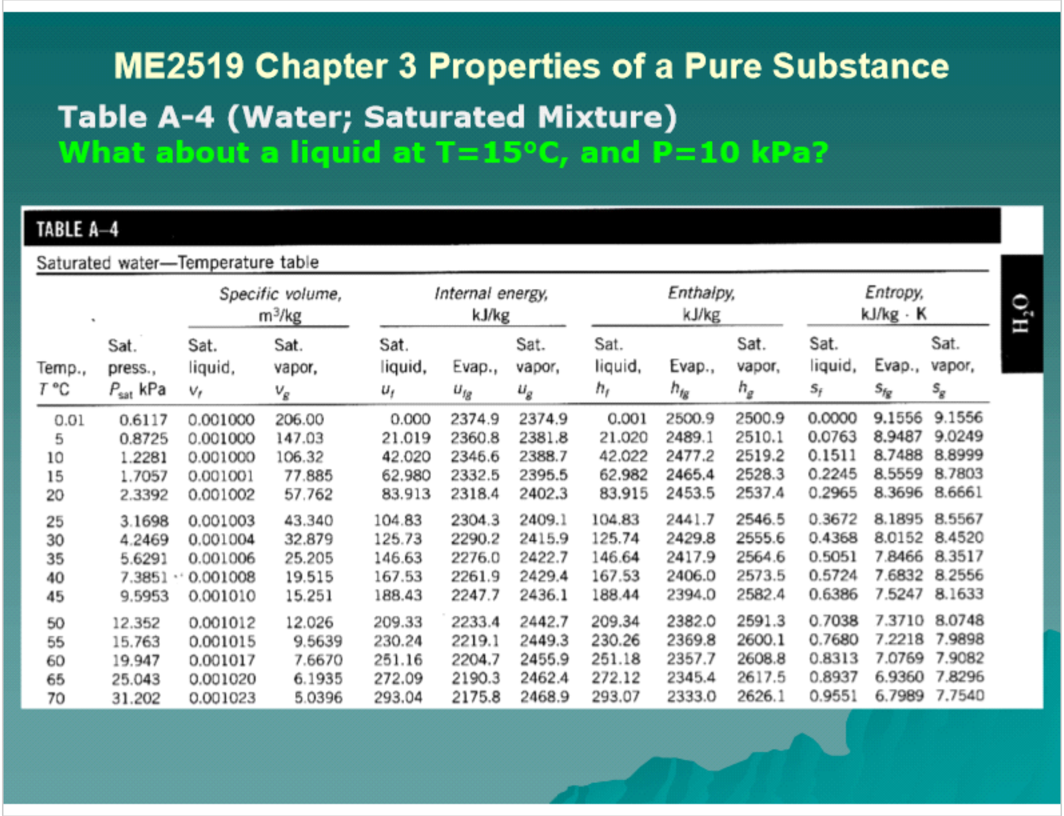

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Table A-4 (Water; Saturated Mixture)

What about a liquid at T=15°C, and P=10 kPa?

TABLE A–4

Saturated water—Temperature table

		Specific volume, m³/kg		Internal energy, kJ/kg			Enthalpy, kJ/kg			Entropy, kJ/kg · K		
Temp., T °C	Sat. press., P_{sat} kPa	Sat. liquid, v_f	Sat. vapor, v_g	Sat. liquid, u_f	Evap., u_{fg}	Sat. vapor, u_g	Sat. liquid, h_f	Evap., h_{fg}	Sat. vapor, h_g	Sat. liquid, s_f	Evap., s_{fg}	Sat. vapor, s_g
0.01	0.6117	0.001000	206.00	0.000	2374.9	2374.9	0.001	2500.9	2500.9	0.0000	9.1556	9.1556
5	0.8725	0.001000	147.03	21.019	2360.8	2381.8	21.020	2489.1	2510.1	0.0763	8.9487	9.0249
10	1.2281	0.001000	106.32	42.020	2346.6	2388.7	42.022	2477.2	2519.2	0.1511	8.7488	8.8999
15	1.7057	0.001001	77.885	62.980	2332.5	2395.5	62.982	2465.4	2528.3	0.2245	8.5559	8.7803
20	2.3392	0.001002	57.762	83.913	2318.4	2402.3	83.915	2453.5	2537.4	0.2965	8.3696	8.6661
25	3.1698	0.001003	43.340	104.83	2304.3	2409.1	104.83	2441.7	2546.5	0.3672	8.1895	8.5567
30	4.2469	0.001004	32.879	125.73	2290.2	2415.9	125.74	2429.8	2555.6	0.4368	8.0152	8.4520
35	5.6291	0.001006	25.205	146.63	2276.0	2422.7	146.64	2417.9	2564.6	0.5051	7.8466	8.3517
40	7.3851	0.001008	19.515	167.53	2261.9	2429.4	167.53	2406.0	2573.5	0.5724	7.6832	8.2556
45	9.5953	0.001010	15.251	188.43	2247.7	2436.1	188.44	2394.0	2582.4	0.6386	7.5247	8.1633
50	12.352	0.001012	12.026	209.33	2233.4	2442.7	209.34	2382.0	2591.3	0.7038	7.3710	8.0748
55	15.763	0.001015	9.5639	230.24	2219.1	2449.3	230.26	2369.8	2600.1	0.7680	7.2218	7.9898
60	19.947	0.001017	7.6670	251.16	2204.7	2455.9	251.18	2357.7	2608.8	0.8313	7.0769	7.9082
65	25.043	0.001020	6.1935	272.09	2190.3	2462.4	272.12	2345.4	2617.5	0.8937	6.9360	7.8296
70	31.202	0.001023	5.0396	293.04	2175.8	2468.9	293.07	2333.0	2626.1	0.9551	6.7989	7.7540

H_2O

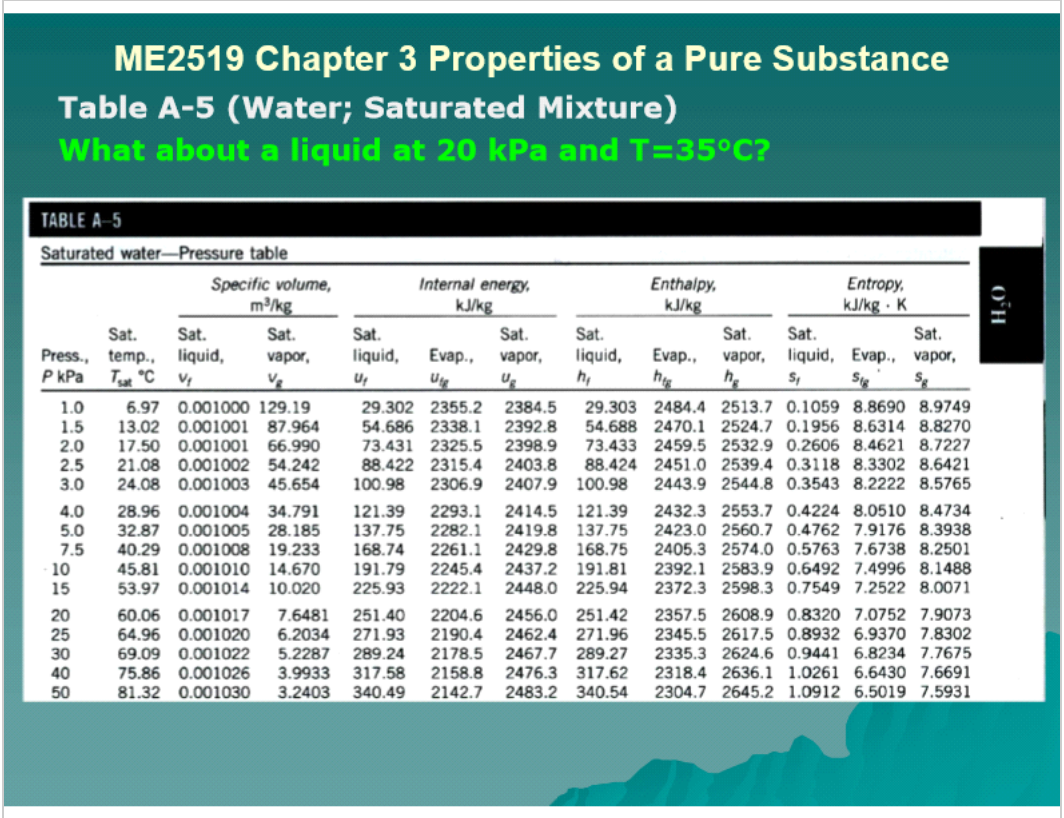

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Table A-5 (Water; Saturated Mixture)

What about a liquid at 20 kPa and T=35°C?

TABLE A–5

Saturated water—Pressure table

		Specific volume, m³/kg		Internal energy, kJ/kg			Enthalpy, kJ/kg			Entropy, kJ/kg · K		
Press., P kPa	Sat. temp., T_{sat} °C	Sat. liquid, v_f	Sat. vapor, v_g	Sat. liquid, u_f	Evap., u_{fg}	Sat. vapor, u_g	Sat. liquid, h_f	Evap., h_{fg}	Sat. vapor, h_g	Sat. liquid, s_f	Evap., s_{fg}	Sat. vapor, s_g
1.0	6.97	0.001000	129.19	29.302	2355.2	2384.5	29.303	2484.4	2513.7	0.1059	8.8690	8.9749
1.5	13.02	0.001001	87.964	54.686	2338.1	2392.8	54.688	2470.1	2524.7	0.1956	8.6314	8.8270
2.0	17.50	0.001001	66.990	73.431	2325.5	2398.9	73.433	2459.5	2532.9	0.2606	8.4621	8.7227
2.5	21.08	0.001002	54.242	88.422	2315.4	2403.8	88.424	2451.0	2539.4	0.3118	8.3302	8.6421
3.0	24.08	0.001003	45.654	100.98	2306.9	2407.9	100.98	2443.9	2544.8	0.3543	8.2222	8.5765
4.0	28.96	0.001004	34.791	121.39	2293.1	2414.5	121.39	2432.3	2553.7	0.4224	8.0510	8.4734
5.0	32.87	0.001005	28.185	137.75	2282.1	2419.8	137.75	2423.0	2560.7	0.4762	7.9176	8.3938
7.5	40.29	0.001008	19.233	168.74	2261.1	2429.8	168.75	2405.3	2574.0	0.5763	7.6738	8.2501
10	45.81	0.001010	14.670	191.79	2245.4	2437.2	191.81	2392.1	2583.9	0.6492	7.4996	8.1488
15	53.97	0.001014	10.020	225.93	2222.1	2448.0	225.94	2372.3	2598.3	0.7549	7.2522	8.0071
20	60.06	0.001017	7.6481	251.40	2204.6	2456.0	251.42	2357.5	2608.9	0.8320	7.0752	7.9073
25	64.96	0.001020	6.2034	271.93	2190.4	2462.4	271.96	2345.5	2617.5	0.8932	6.9370	7.8302
30	69.09	0.001022	5.2287	289.24	2178.5	2467.7	289.27	2335.3	2624.6	0.9441	6.8234	7.7675
40	75.86	0.001026	3.9933	317.58	2158.8	2476.3	317.62	2318.4	2636.1	1.0261	6.6430	7.6691
50	81.32	0.001030	3.2403	340.49	2142.7	2483.2	340.54	2304.7	2645.2	1.0912	6.5019	7.5931

H_2O

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3-5 Property Tables (cont.)

- **How to get properties for subcooled/compressed liquids**
- **Basic problem: Can't match the given P *AND* T.**
  - **If you match P, then T is too low (subcooled liquid).**
  - **If you match T, then P is too high (compressed liquid).**
- **Which point do you select?**
  - **Answer: Because T is a bigger driver of v, u, h and s, pick T = Tsat, and use the saturated liquid properties (i.e. v_f, u_f, h_f, and s_f)**
- **Don't use Table A-7 (compressed water table)**

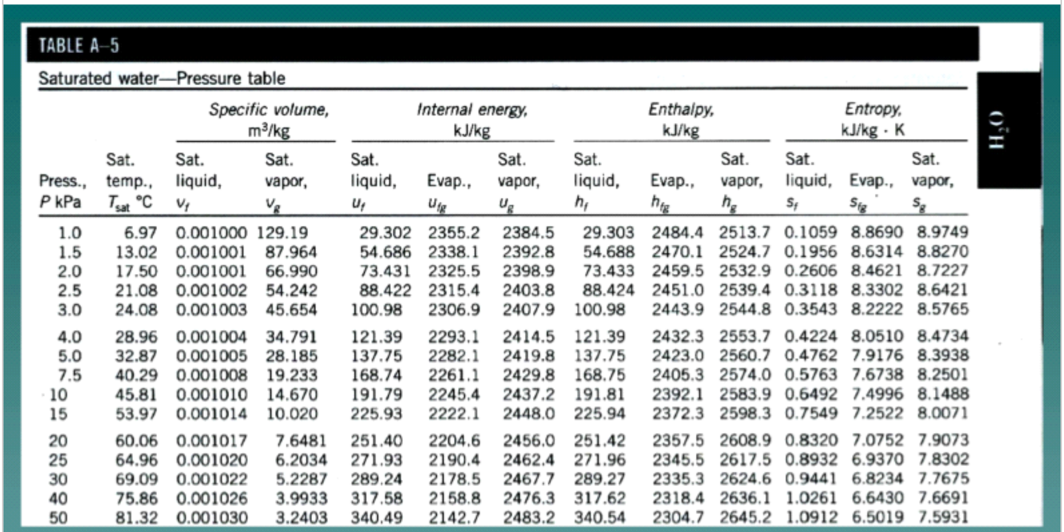

TABLE A–5

Saturated water—Pressure table

		Specific volume, m³/kg		Internal energy, kJ/kg			Enthalpy, kJ/kg			Entropy, kJ/kg · K		
Press., P kPa	Sat. temp., T_{sat} °C	Sat. liquid, v_f	Sat. vapor, v_g	Sat. liquid, u_f	Evap., u_{fg}	Sat. vapor, u_g	Sat. liquid, h_f	Evap., h_{fg}	Sat. vapor, h_g	Sat. liquid, s_f	Evap., s_{fg}	Sat. vapor, s_g
1.0	6.97	0.001000	129.19	29.302	2355.2	2384.5	29.303	2484.4	2513.7	0.1059	8.8690	8.9749
1.5	13.02	0.001001	87.964	54.686	2338.1	2392.8	54.688	2470.1	2524.7	0.1956	8.6314	8.8270
2.0	17.50	0.001001	66.990	73.431	2325.5	2398.9	73.433	2459.5	2532.9	0.2606	8.4621	8.7227
2.5	21.08	0.001002	54.242	88.422	2315.4	2403.8	88.424	2451.0	2539.4	0.3118	8.3302	8.6421
3.0	24.08	0.001003	45.654	100.98	2306.9	2407.9	100.98	2443.9	2544.8	0.3543	8.2222	8.5765
4.0	28.96	0.001004	34.791	121.39	2293.1	2414.5	121.39	2432.3	2553.7	0.4224	8.0510	8.4734
5.0	32.87	0.001005	28.185	137.75	2282.1	2419.8	137.75	2423.0	2560.7	0.4762	7.9176	8.3938
7.5	40.29	0.001008	19.233	168.74	2261.1	2429.8	168.75	2405.3	2574.0	0.5763	7.6738	8.2501
10	45.81	0.001010	14.670	191.79	2245.4	2437.2	191.81	2392.1	2583.9	0.6492	7.4996	8.1488
15	53.97	0.001014	10.020	225.93	2222.1	2448.0	225.94	2372.3	2598.3	0.7549	7.2522	8.0071
20	60.06	0.001017	7.6481	251.40	2204.6	2456.0	251.42	2357.5	2608.9	0.8320	7.0752	7.9073
25	64.96	0.001020	6.2034	271.93	2190.4	2462.4	271.96	2345.5	2617.5	0.8932	6.9370	7.8302
30	69.09	0.001022	5.2287	289.24	2178.5	2467.7	289.27	2335.3	2624.6	0.9441	6.8234	7.7675
40	75.86	0.001026	3.9933	317.58	2158.8	2476.3	317.62	2318.4	2636.1	1.0261	6.6430	7.6691
50	81.32	0.001030	3.2403	340.49	2142.7	2483.2	340.54	2304.7	2645.2	1.0912	6.5019	7.5931

H_2O

Case 1: P=4 kPa and T = 20°C means?
Case 2: P=20 kPa and T = 95°C means?
Case 3: P=7.5 kPa and u=1800 kJ/kg means?
Case 4: P=7.5 kPa and u=2600 kJ/kg means?
Case 5: P=25 kPa and s=.6500 kJ/kg-K means?

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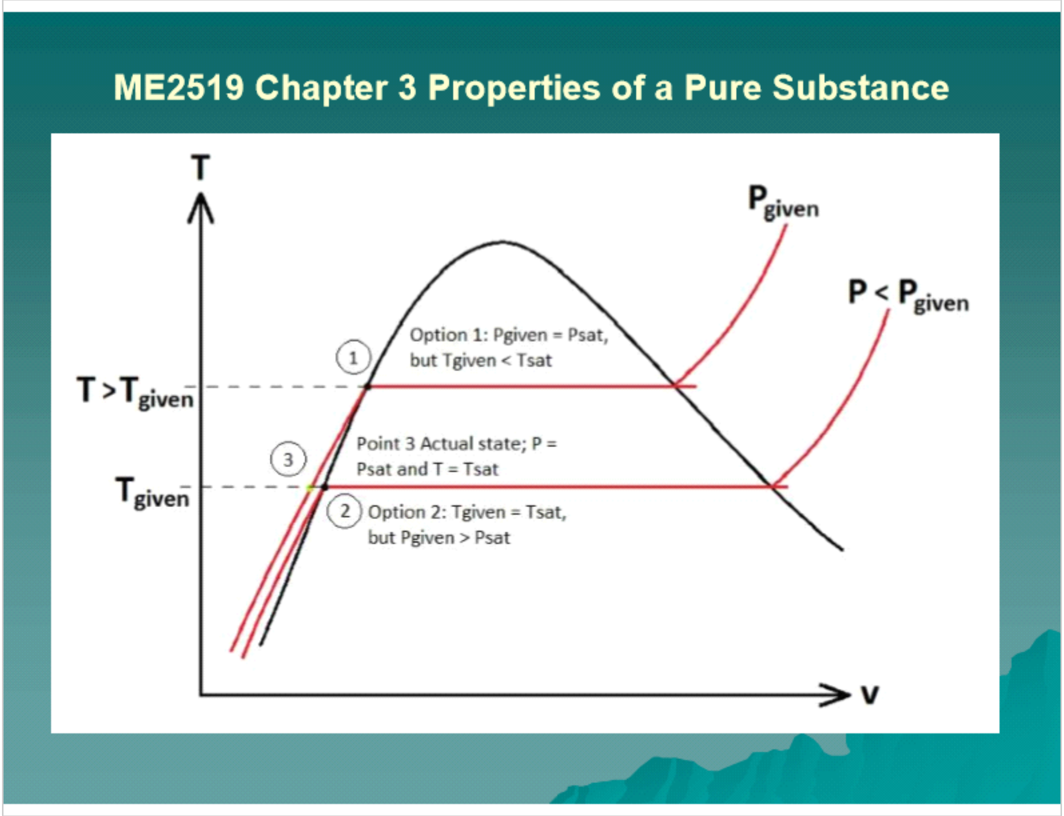


Option 1: Pgiven = Psat, but Tgiven < Tsat

Point 3 Actual state; P = Psat and T = Tsat

Option 2: Tgiven = Tsat, but Pgiven > Psat

HW 3a

Tuesday, September 20, 2022 9:49 AM

3–22 Complete this table for H_2O:

T, °C	P, kPa	v, m³/kg	Phase description
140	361.53	0.035	Saturated mixture
155.46	550	.001097	Saturated liquid
125	750	.001065	Compressed liquid
300	1.8 MPa	0.140	Superheated vapor

$v_f < v < v_g$ A-4

A-5

$P > P_{sat}$ Compressed liquid A-4

A-6

3–27 Complete this table for refrigerant-134a:

T, °C	P, kPa	u, kJ/kg	Phase description
20	571.60	95	Saturated mixture
–12	185.40	34.25	Saturated liquid
86.2	400	300	Superheated vapor
8	600	60.43	Supercooled liquid

$u_f < u < u_g$ A-11

$80 + \frac{300-294.58}{303.54-294.58}(90-80)$ A-11

$u > u_g$ A-13

$P > P_{sat}$ A-11

3–43 100 kg of R-134a at 200 kPa are contained in a piston–cylinder device whose volume is 12.322 m³. The piston is now moved until the volume is one-half its original size. This is done such that the pressure of the R-134a does not change. Determine the final temperature and the change in the total internal energy of the R-134a.

$V_1 = Vol / m = 12.322/100$ $m = 100$ kg

$v_1 = .12322$ m³/kg $P_1 = 200$ kPa

$T_1 = 40$ A-13 $Vol \cdot 12.322$ m³

$v_2 = \frac{1}{2}v_1 = .06161$ $\frac{1}{2}v_1 = v_2$

$T_2 = -10.9$°C A-12 $P_2 = P_1$

$u_f = 38.26$

$$x_2 = \frac{v_2 - v_f}{v_g - v_f} = \frac{.06161 - .0007532}{0.09951 - .0007532} = .6135$$

$$u_2 = u_f + x_2(u_g - u_f) = 38.26 + .6135(224.51 - 38.26) = 152.5 \text{ kJ/kg}$$

$$\Delta U = m(u_2 - u_1) = 100 \text{ kg}(152.5 - 263.09) \text{ kJ/kg} = -11059 \text{ kJ}$$

3–57 10 kg of R-134a fill a 0.7-m³ weighted piston–cylinder device at a pressure of 200 kPa. The container is now heated until the temperature is 30°C. Determine the initial temperature and final volume of the R-134a.

$m = 10$ kg

$v_1 = Vol/m = .7 \text{ m}^3 / 10 \text{ kg} =$

$Vol = .7 \text{ m}^3$

$v_1 = .07 \text{ m}^3/\text{kg}$

$P_1 = 200$

$T_1 = -10.09\ °C$ A-12

$T_2 = 30°C$

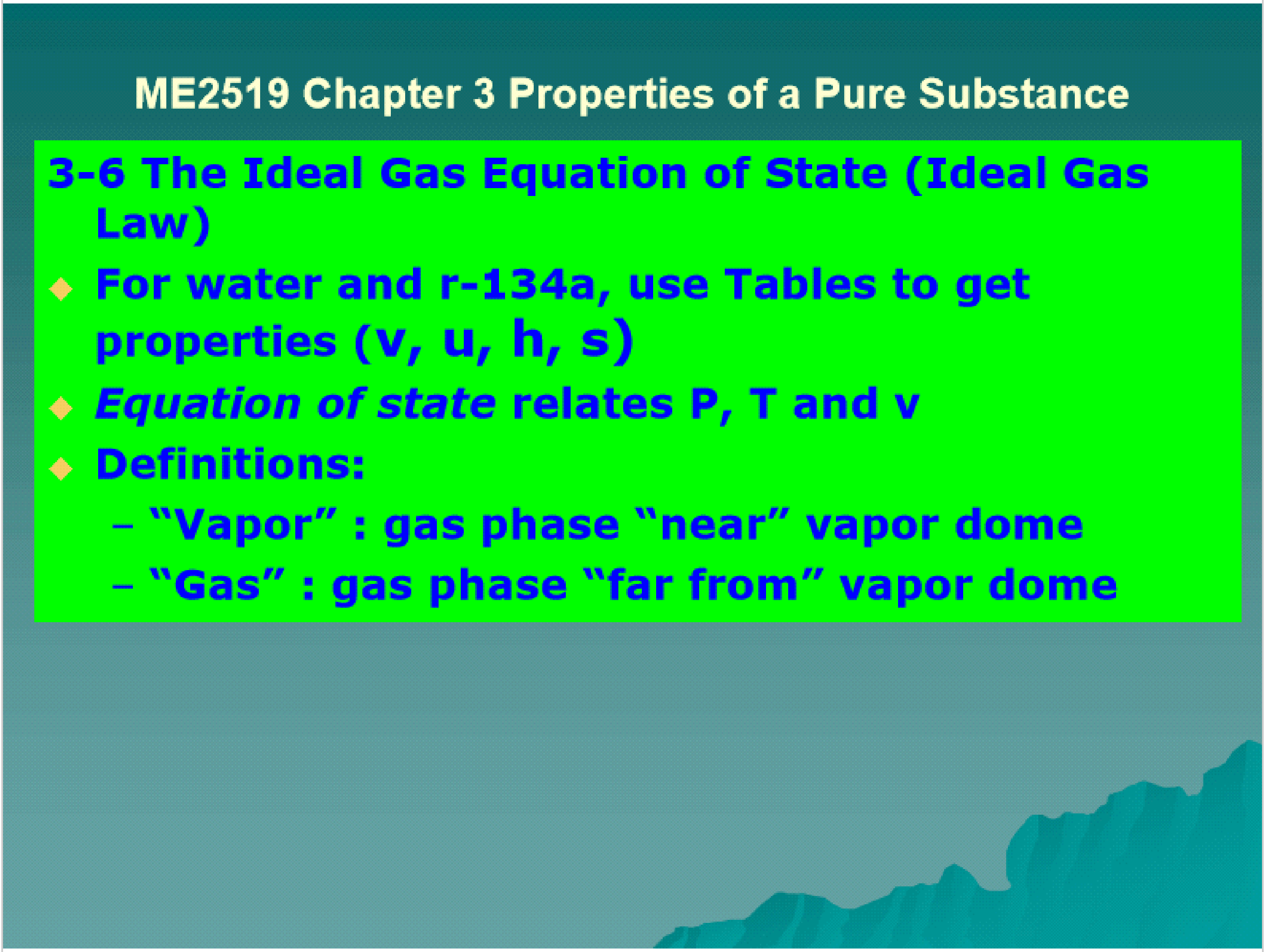
$v_2 = .11874 \text{ m}^3/\text{kg}$ A-13

$Vol_2 = v_2 \cdot m = 10 \text{ kg} \cdot .11874 \text{ m}^3/\text{kg} = 1.1874 \text{ m}^3$

Ideal Gas Equations

Monday, September 19, 2022 10:01 AM

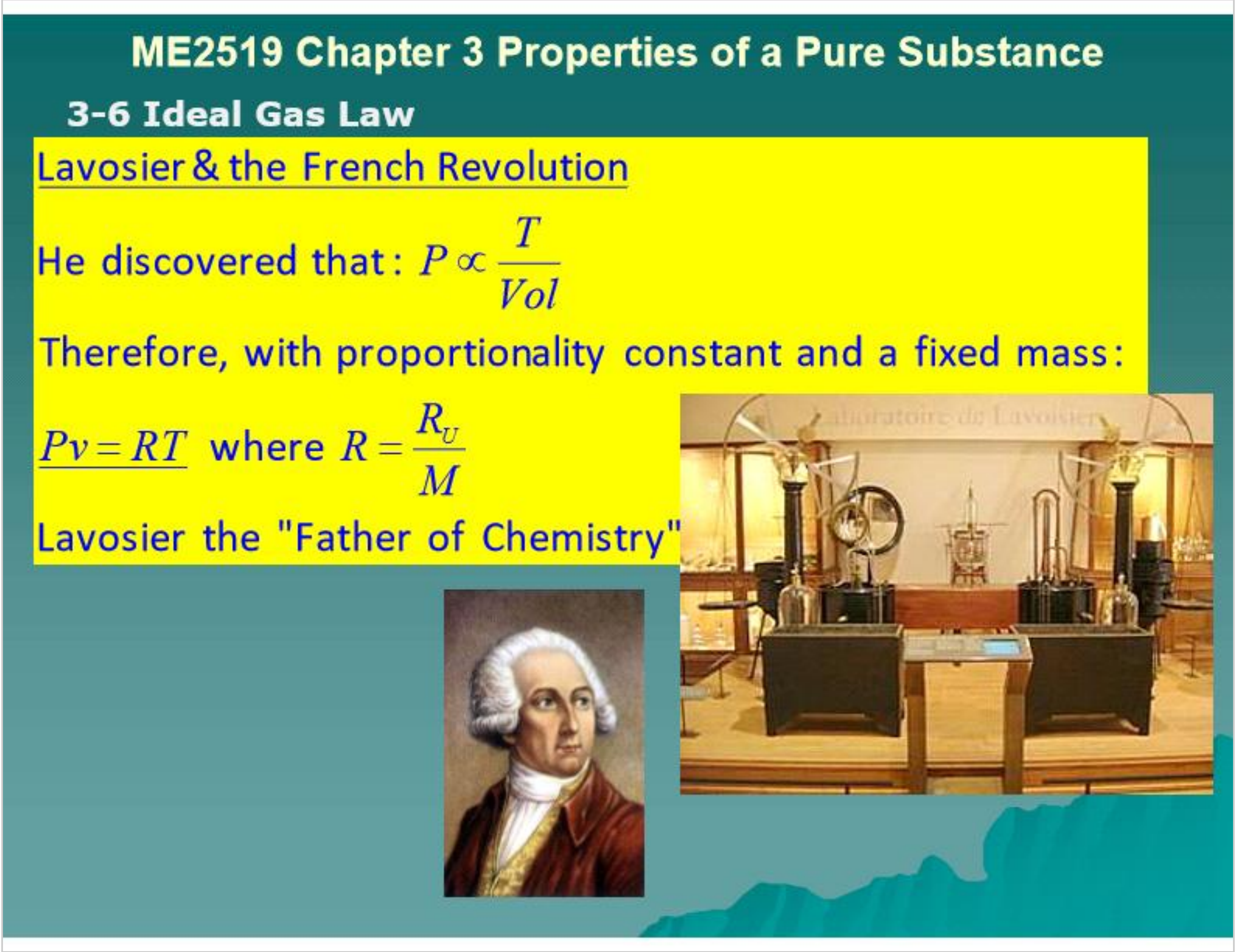
PDF+Slides +3-6+thru...



ME2519 Chapter 3 Properties of a Pure Substance

3-6 The Ideal Gas Equation of State (Ideal Gas Law)

- For water and r-134a, use Tables to get properties (v, u, h, s)
- *Equation of state* relates P, T and v
- Definitions:
  - "Vapor" : gas phase "near" vapor dome
  - "Gas" : gas phase "far from" vapor dome



ME2519 Chapter 3 Properties of a Pure Substance

3-6 Ideal Gas Law

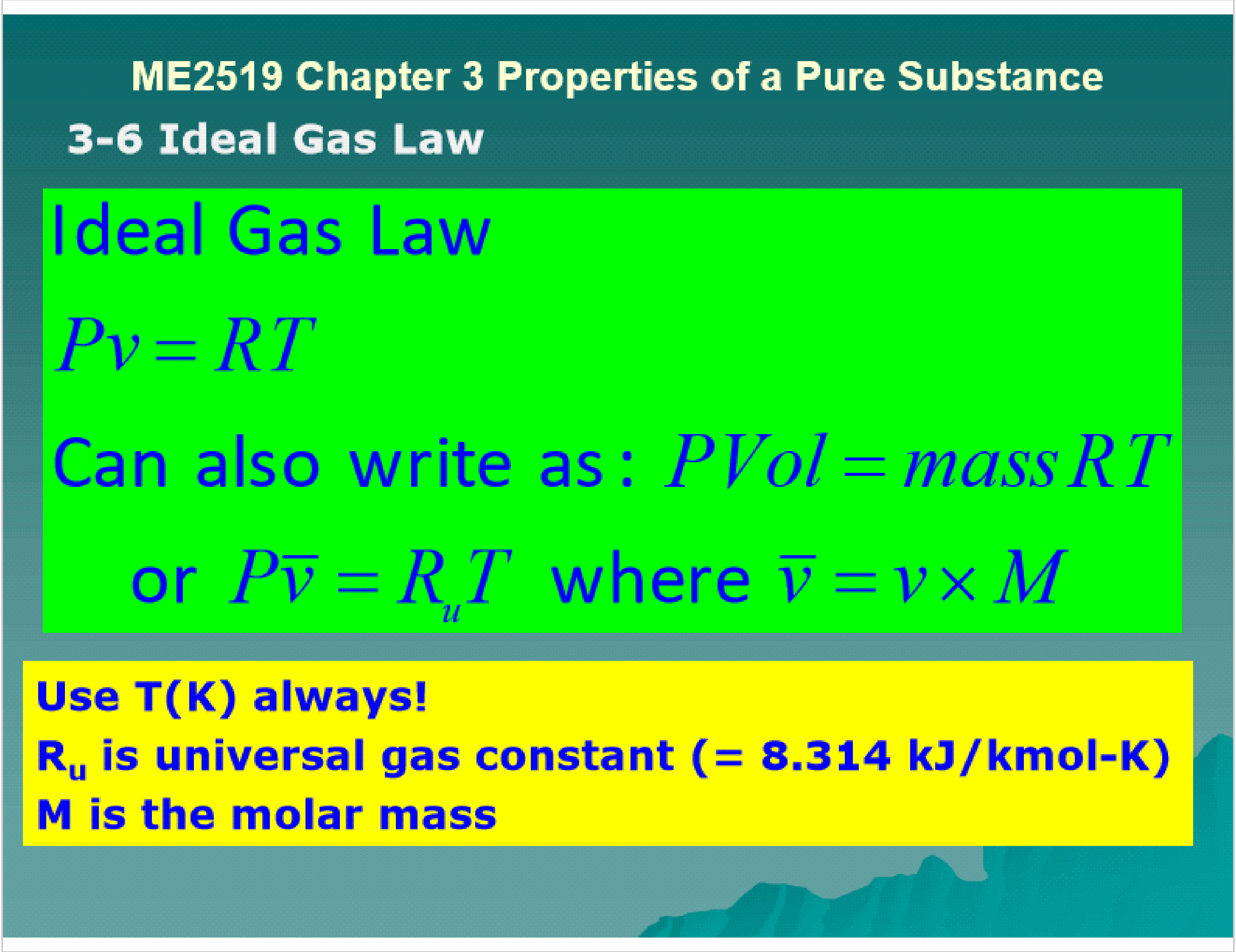
Lavosier & the French Revolution

He discovered that: $P \propto \frac{T}{Vol}$

Therefore, with proportionality constant and a fixed mass:

$\underline{Pv = RT}$ where $R = \frac{R_U}{M}$

Lavosier the "Father of Chemistry"



ME2519 Chapter 3 Properties of a Pure Substance

3-6 Ideal Gas Law

Ideal Gas Law

$$Pv = RT$$

Can also write as: $PVol = mass\,RT$

or $P\bar{v} = R_u T$ where $\bar{v} = v \times M$

Use T(K) always!

R_u is universal gas constant (= 8.314 kJ/kmol-K)

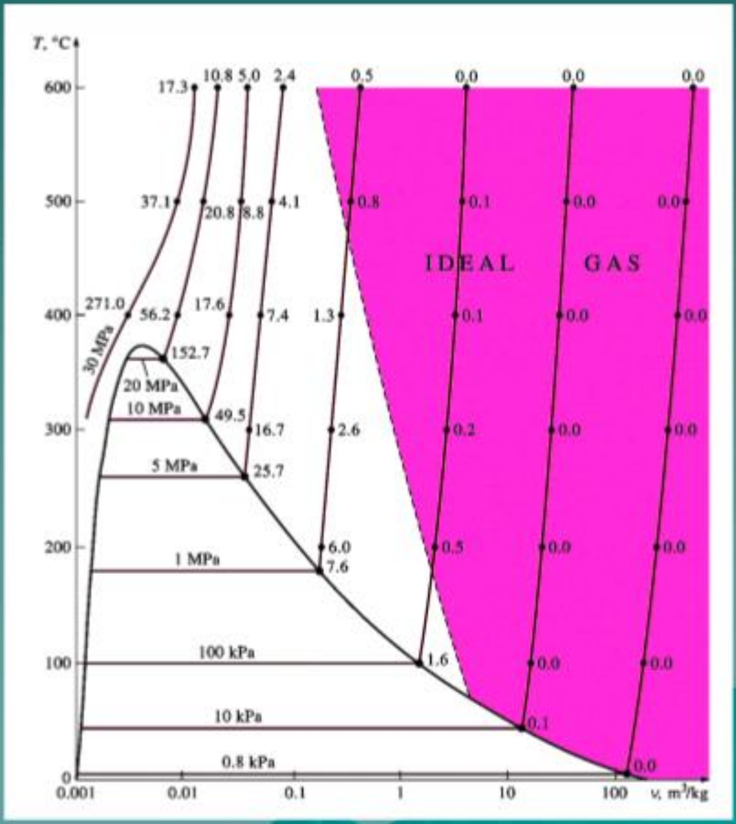
M is the molar mass

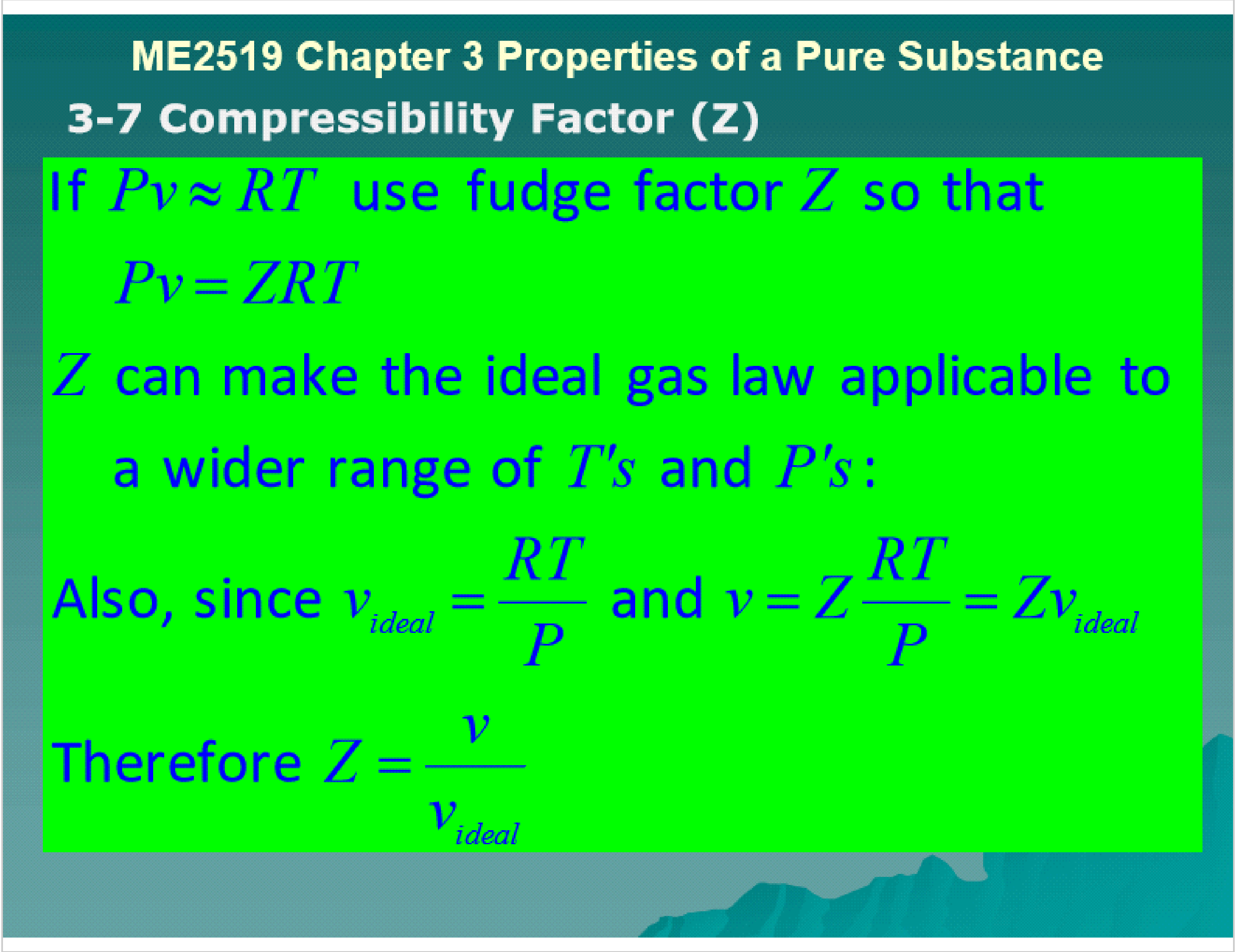
ME2519 Chapter 3 Properties of a Pure Substance

3-6 Ideal Gas Law

- **Is Steam an Ideal Gas?**

- **Only away from the vapor dome (see figure)**





ME2519 Chapter 3 Properties of a Pure Substance

3-7 Compressibility Factor (Z)

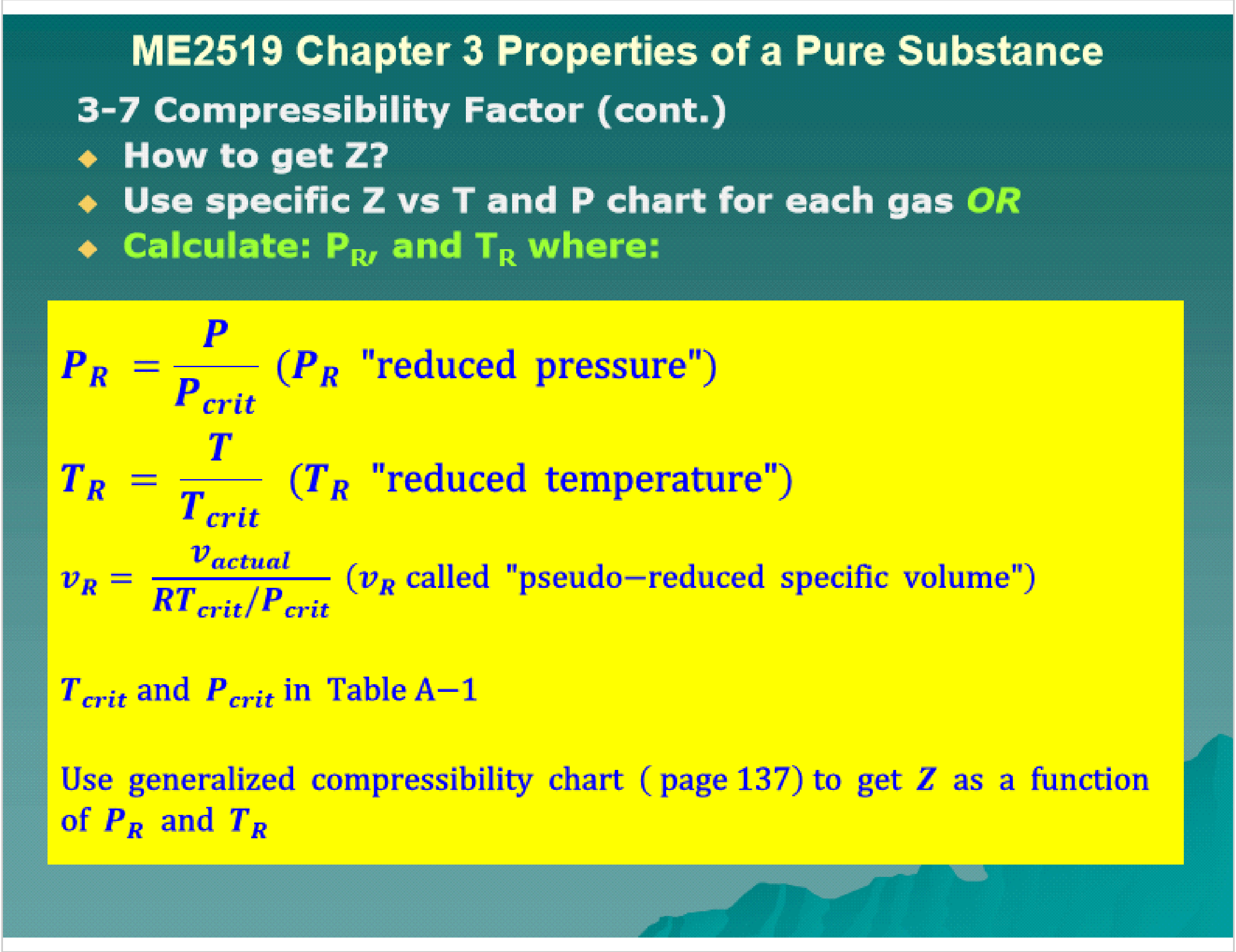
If $Pv \approx RT$ use fudge factor Z so that

$$Pv = ZRT$$

Z can make the ideal gas law applicable to a wider range of $T's$ and $P's$:

Also, since $v_{ideal} = \frac{RT}{P}$ and $v = Z\frac{RT}{P} = Zv_{ideal}$

Therefore $Z = \frac{v}{v_{ideal}}$



ME2519 Chapter 3 Properties of a Pure Substance

3-7 Compressibility Factor (cont.)

- How to get Z?
- Use specific Z vs T and P chart for each gas *OR*
- Calculate: P_R, and T_R where:

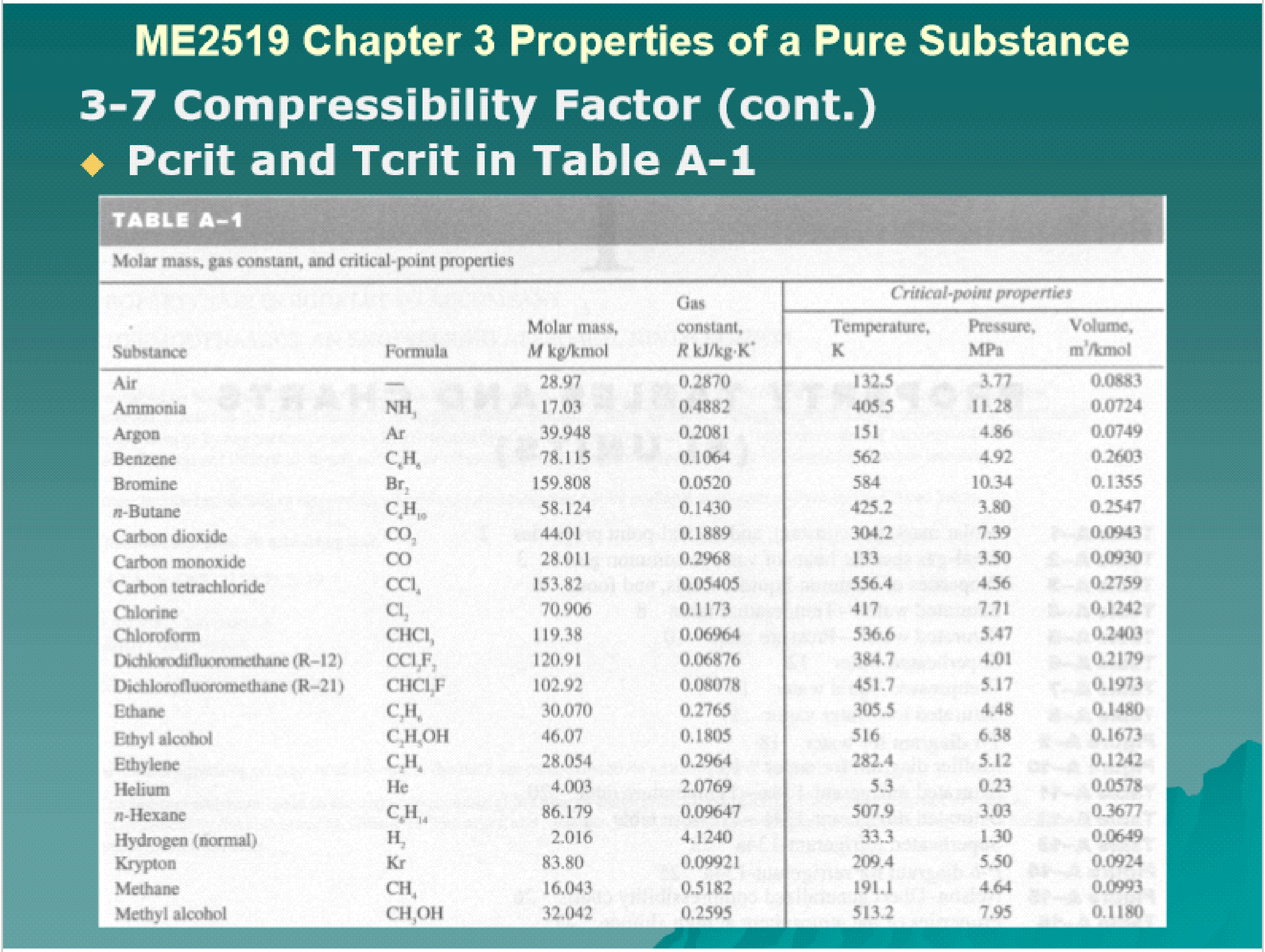
$$P_R = \frac{P}{P_{crit}} \quad (P_R \text{ "reduced pressure"})$$

$$T_R = \frac{T}{T_{crit}} \quad (T_R \text{ "reduced temperature"})$$

$$v_R = \frac{v_{actual}}{RT_{crit}/P_{crit}} \quad (v_R \text{ called "pseudo-reduced specific volume"})$$

T_{crit} and P_{crit} in Table A−1

Use generalized compressibility chart (page 137) to get Z as a function of P_R and T_R



ME2519 Chapter 3 Properties of a Pure Substance

3-7 Compressibility Factor (cont.)

- Pcrit and Tcrit in Table A-1

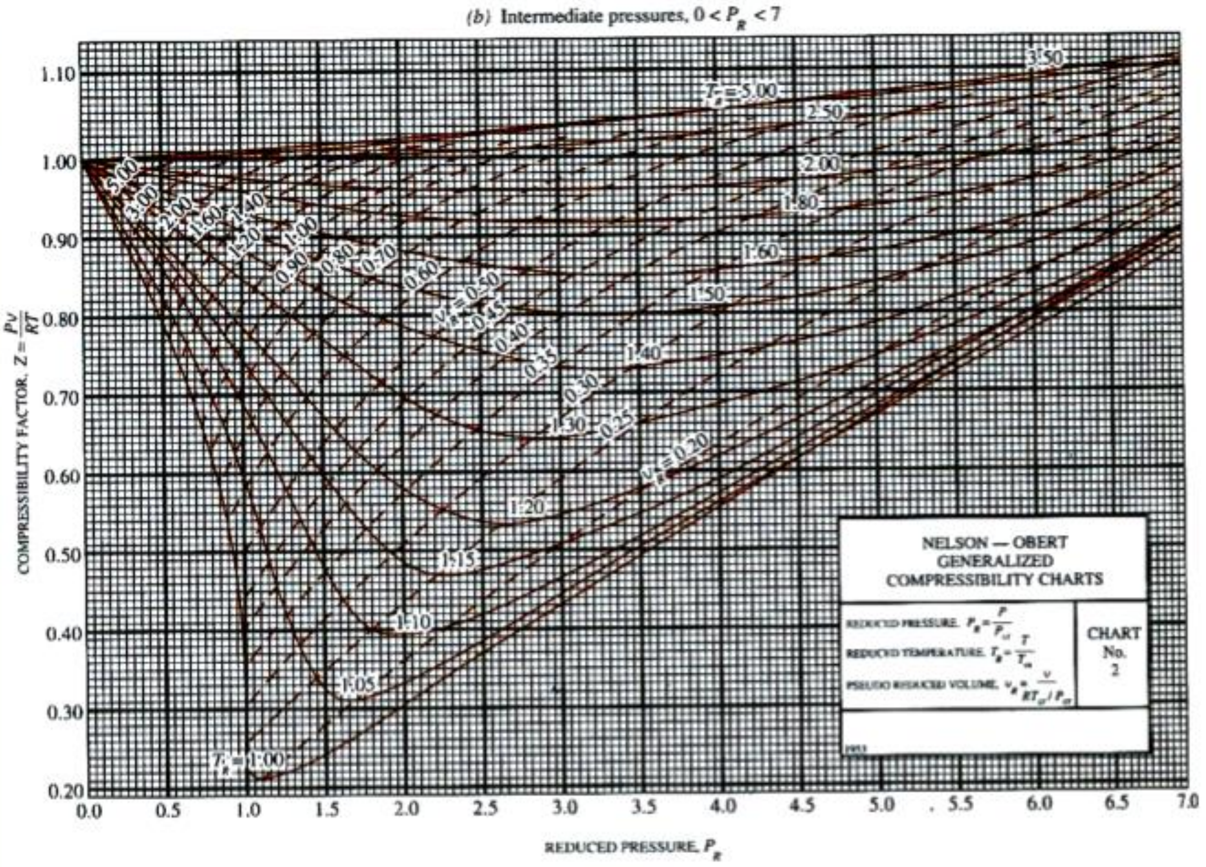
TABLE A–1

Molar mass, gas constant, and critical-point properties

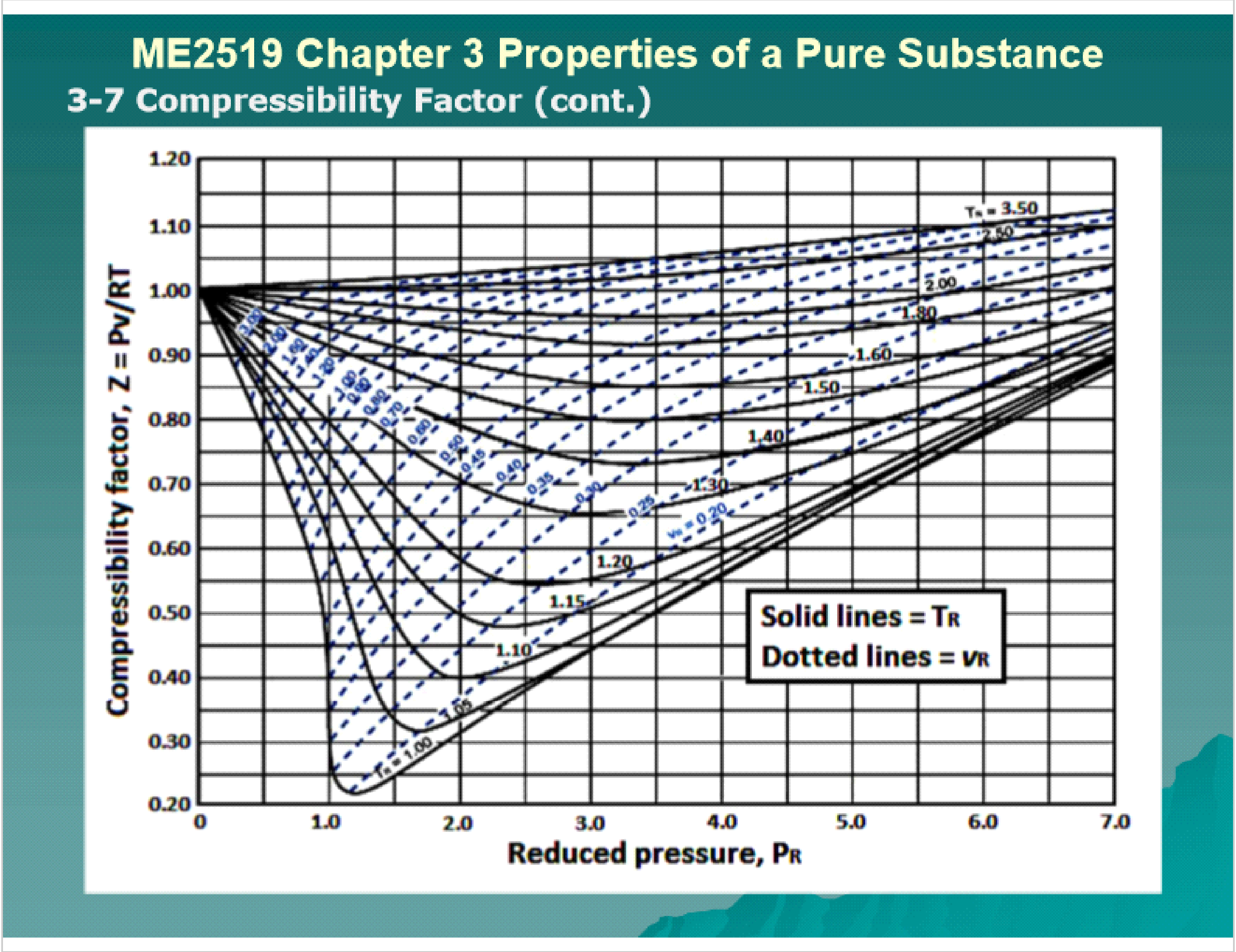
Substance	Formula	Molar mass, M kg/kmol	Gas constant, R kJ/kg·K*	*Critical-point properties* Temperature, K	Pressure, MPa	Volume, m^3/kmol
Air	—	28.97	0.2870	132.5	3.77	0.0883
Ammonia	NH_3	17.03	0.4882	405.5	11.28	0.0724
Argon	Ar	39.948	0.2081	151	4.86	0.0749
Benzene	C_6H_6	78.115	0.1064	562	4.92	0.2603
Bromine	Br_2	159.808	0.0520	584	10.34	0.1355
n-Butane	C_4H_{10}	58.124	0.1430	425.2	3.80	0.2547
Carbon dioxide	CO_2	44.01	0.1889	304.2	7.39	0.0943
Carbon monoxide	CO	28.011	0.2968	133	3.50	0.0930
Carbon tetrachloride	CCl_4	153.82	0.05405	556.4	4.56	0.2759
Chlorine	Cl_2	70.906	0.1173	417	7.71	0.1242
Chloroform	$CHCl_3$	119.38	0.06964	536.6	5.47	0.2403
Dichlorodifluoromethane (R–12)	CCl_2F_2	120.91	0.06876	384.7	4.01	0.2179
Dichlorofluoromethane (R–21)	$CHCl_2F$	102.92	0.08078	451.7	5.17	0.1973
Ethane	C_2H_6	30.070	0.2765	305.5	4.48	0.1480
Ethyl alcohol	C_2H_5OH	46.07	0.1805	516	6.38	0.1673
Ethylene	C_2H_4	28.054	0.2964	282.4	5.12	0.1242
Helium	He	4.003	2.0769	5.3	0.23	0.0578
n-Hexane	C_6H_{14}	86.179	0.09647	507.9	3.03	0.3677
Hydrogen (normal)	H_2	2.016	4.1240	33.3	1.30	0.0649
Krypton	Kr	83.80	0.09921	209.4	5.50	0.0924
Methane	CH_4	16.043	0.5182	191.1	4.64	0.0993
Methyl alcohol	CH_3OH	32.042	0.2595	513.2	7.95	0.1180

ME2519 Chapter 3 Properties of a Pure Substance

3-7 Compressibility Factor (cont.) (Figure A-15)



(b) Intermediate pressures, $0 < P_R < 7$



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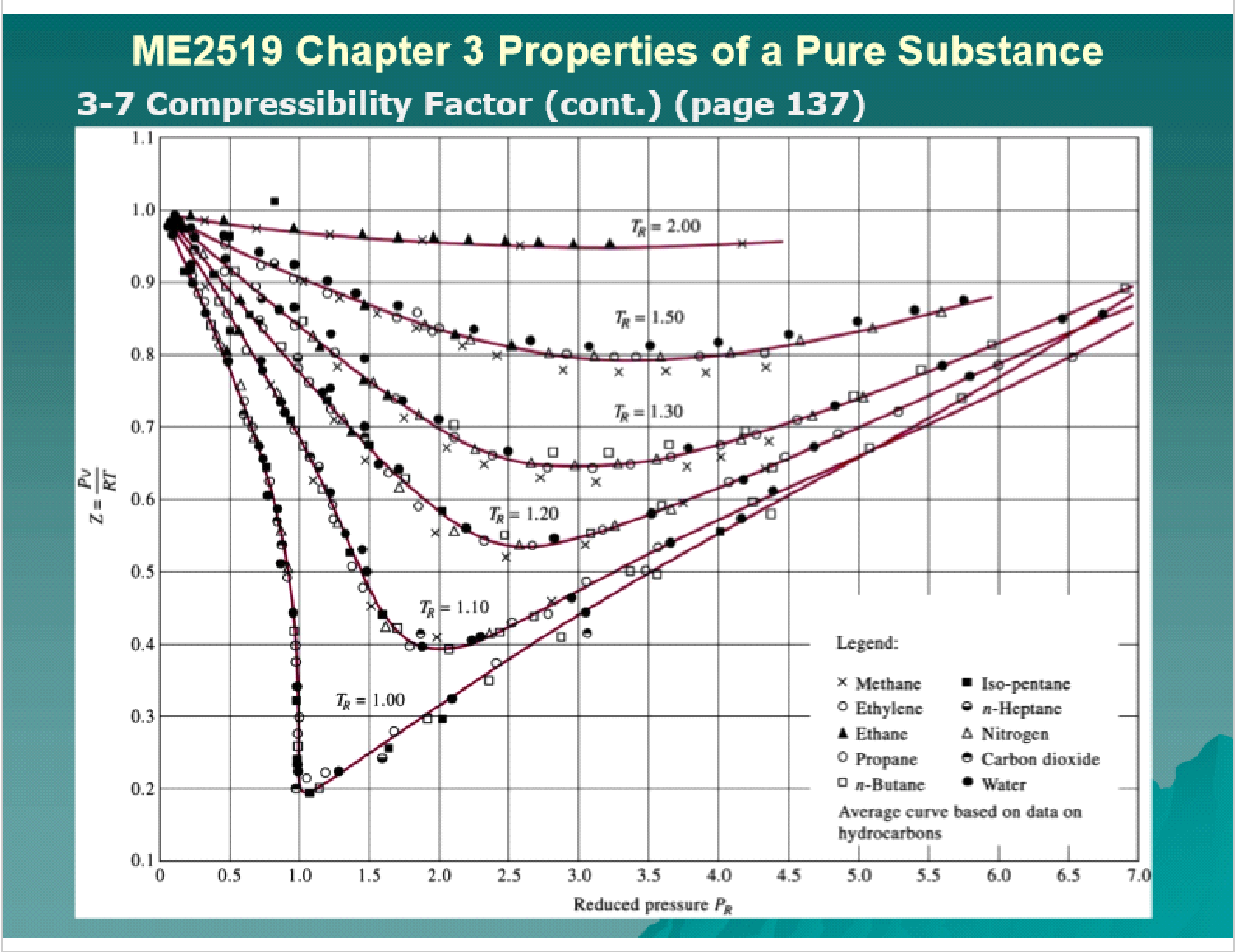
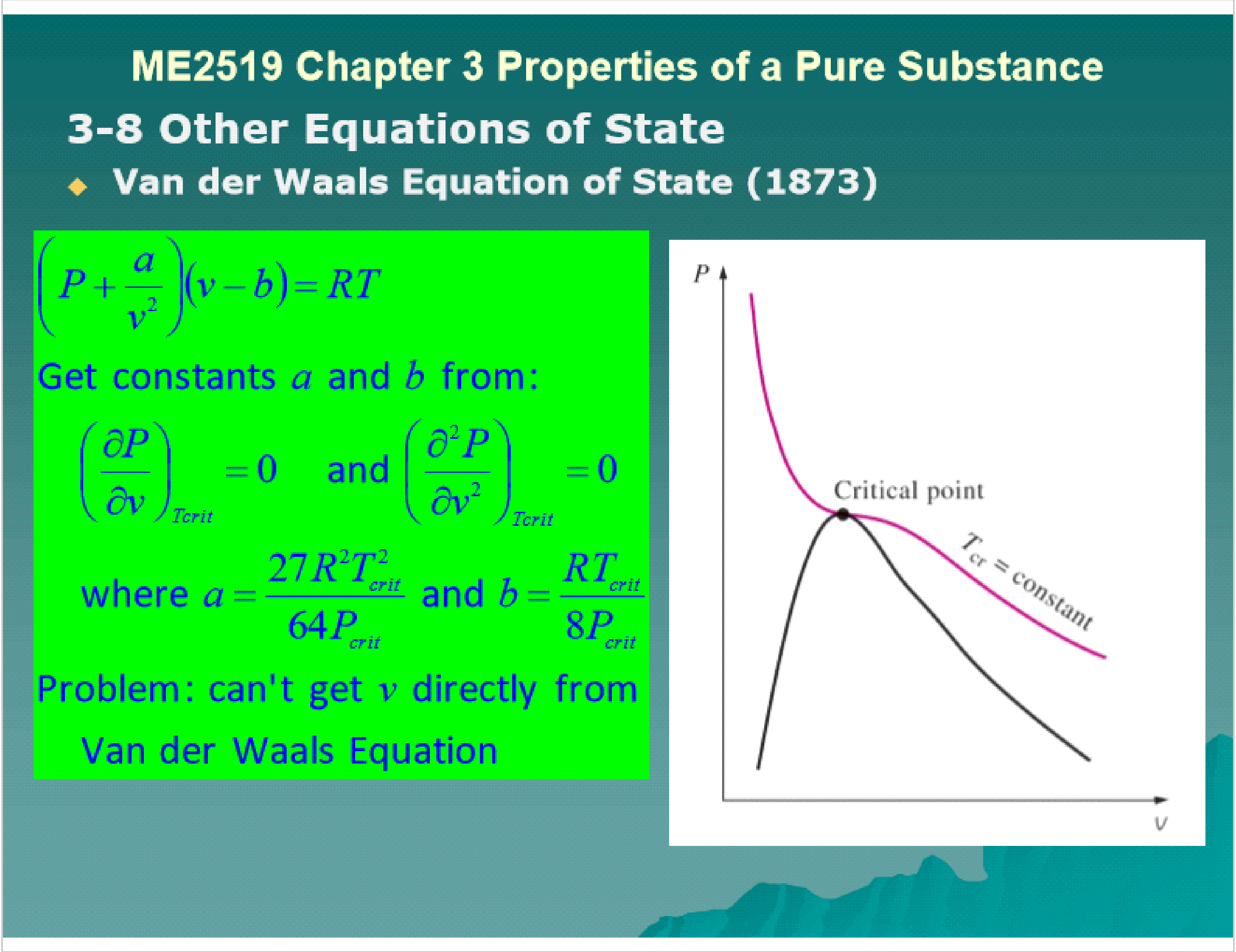
3-7 Compressibility Factor (cont.)



ME2519 Chapter 3 Properties of a Pure Substance

3-7 Compressibility Factor (cont.) (page 137)



ME2519 Chapter 3 Properties of a Pure Substance

3-8 Other Equations of State

- Van der Waals Equation of State (1873)

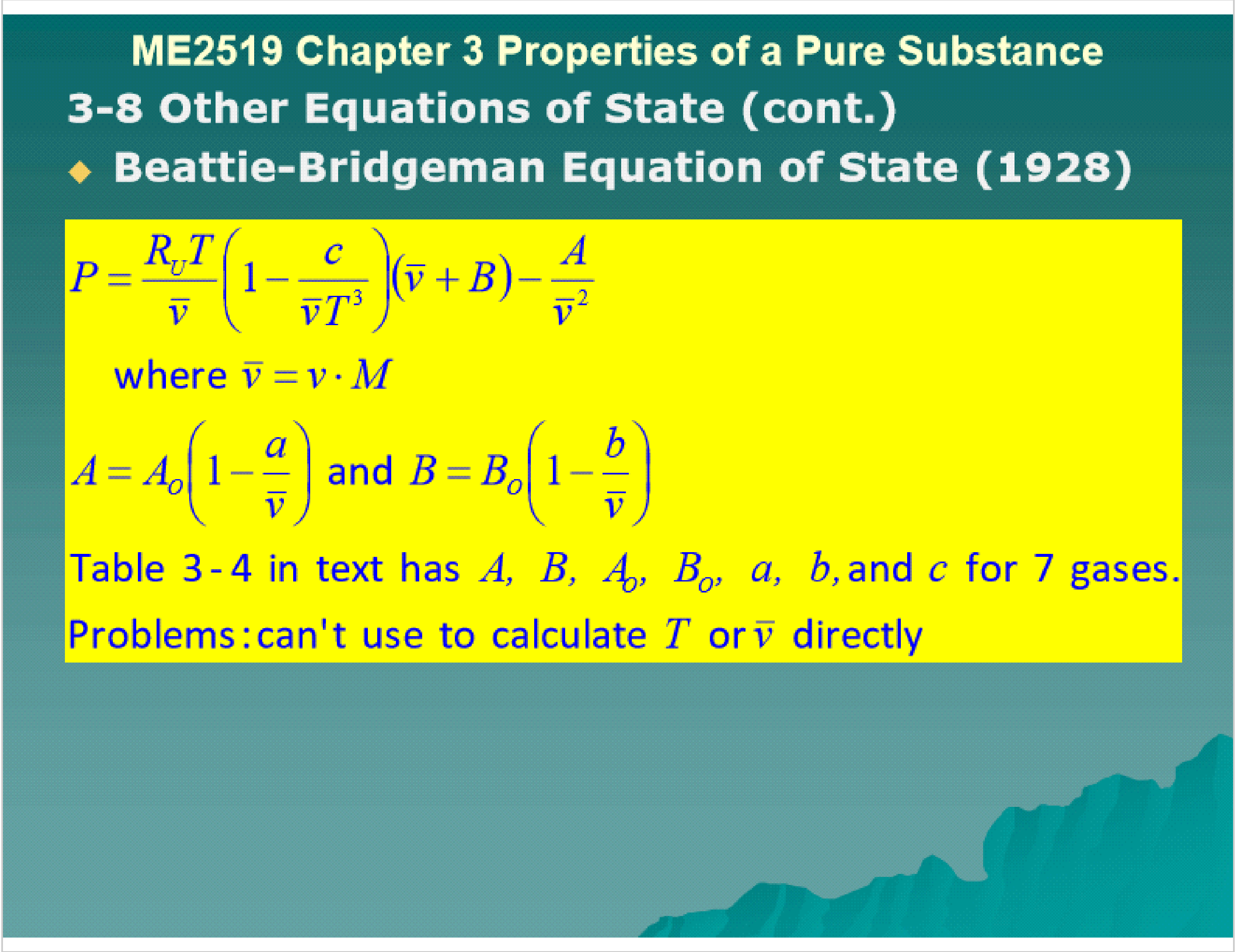
$$\left(P+\frac{a}{v^2}\right)(v-b)=RT$$

Get constants a and b from:

$$\left(\frac{\partial P}{\partial v}\right)_{Tcrit}=0 \quad \text{and} \quad \left(\frac{\partial^2 P}{\partial v^2}\right)_{Tcrit}=0$$

$$\text{where } a=\frac{27R^2T_{crit}^2}{64P_{crit}} \text{ and } b=\frac{RT_{crit}}{8P_{crit}}$$

Problem: can't get v directly from Van der Waals Equation



ME2519 Chapter 3 Properties of a Pure Substance

3-8 Other Equations of State (cont.)

- **Beattie-Bridgeman Equation of State (1928)**

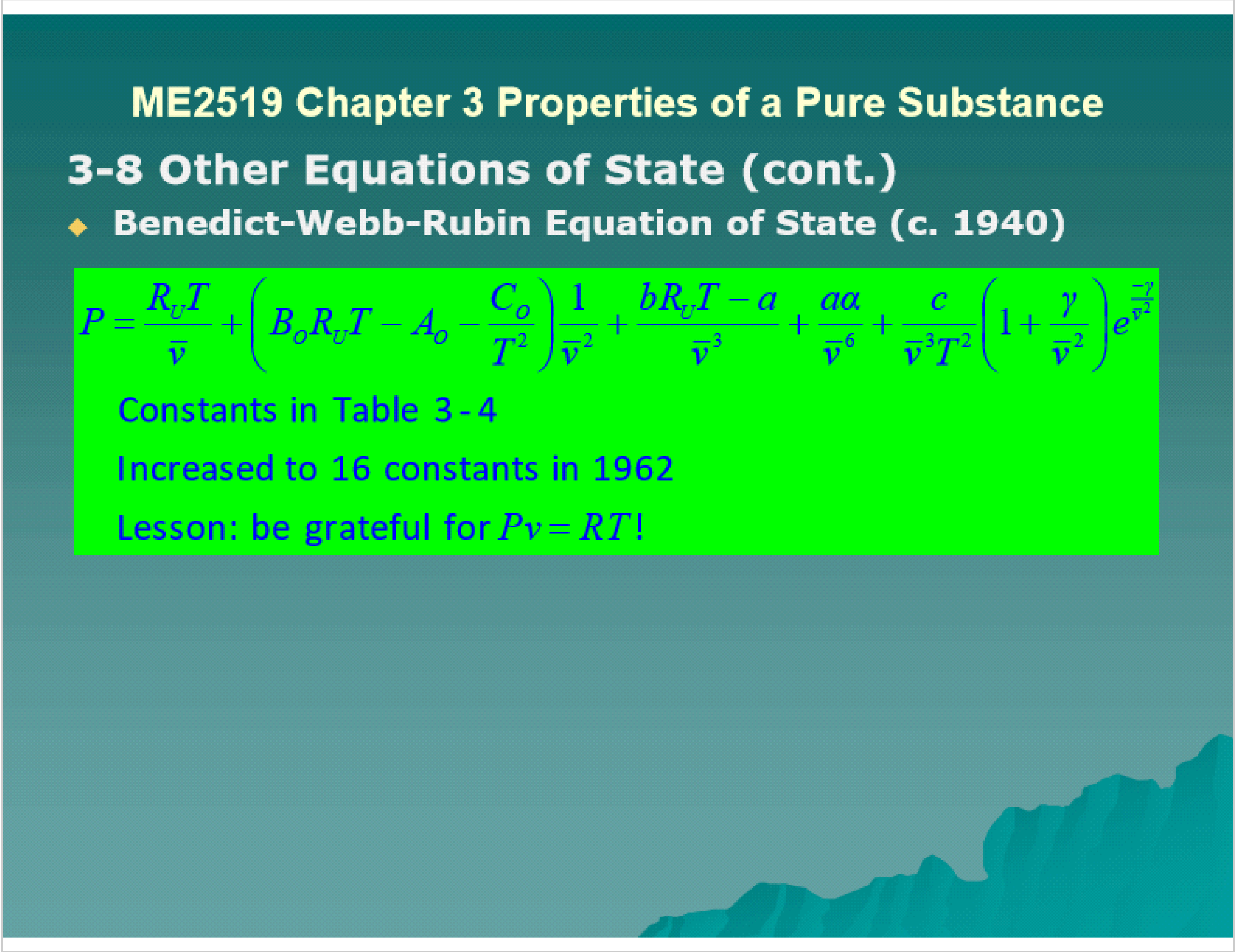
$$P = \frac{R_U T}{\bar{v}}\left(1 - \frac{c}{\bar{v} T^3}\right)\left(\bar{v} + B\right) - \frac{A}{\bar{v}^2}$$

where $\bar{v} = v \cdot M$

$A = A_o\left(1 - \frac{a}{\bar{v}}\right)$ and $B = B_o\left(1 - \frac{b}{\bar{v}}\right)$

Table 3-4 in text has $A,\ B,\ A_o,\ B_o,\ a,\ b,$ and c for 7 gases.

Problems: can't use to calculate T or $\bar{v}$ directly



ME2519 Chapter 3 Properties of a Pure Substance

3-8 Other Equations of State (cont.)

- Benedict-Webb-Rubin Equation of State (c. 1940)

$$P = \frac{R_U T}{\bar{v}} + \left(B_o R_U T - A_o - \frac{C_o}{T^2} \right) \frac{1}{\bar{v}^2} + \frac{bR_U T - a}{\bar{v}^3} + \frac{a\alpha}{\bar{v}^6} + \frac{c}{\bar{v}^3 T^2} \left(1 + \frac{\gamma}{\bar{v}^2} \right) e^{\frac{-\gamma}{\bar{v}^2}}$$

Constants in Table 3-4

Increased to 16 constants in 1962

Lesson: be grateful for $Pv = RT$!

ME2519 Chapter 3 Properties of a Pure Substance

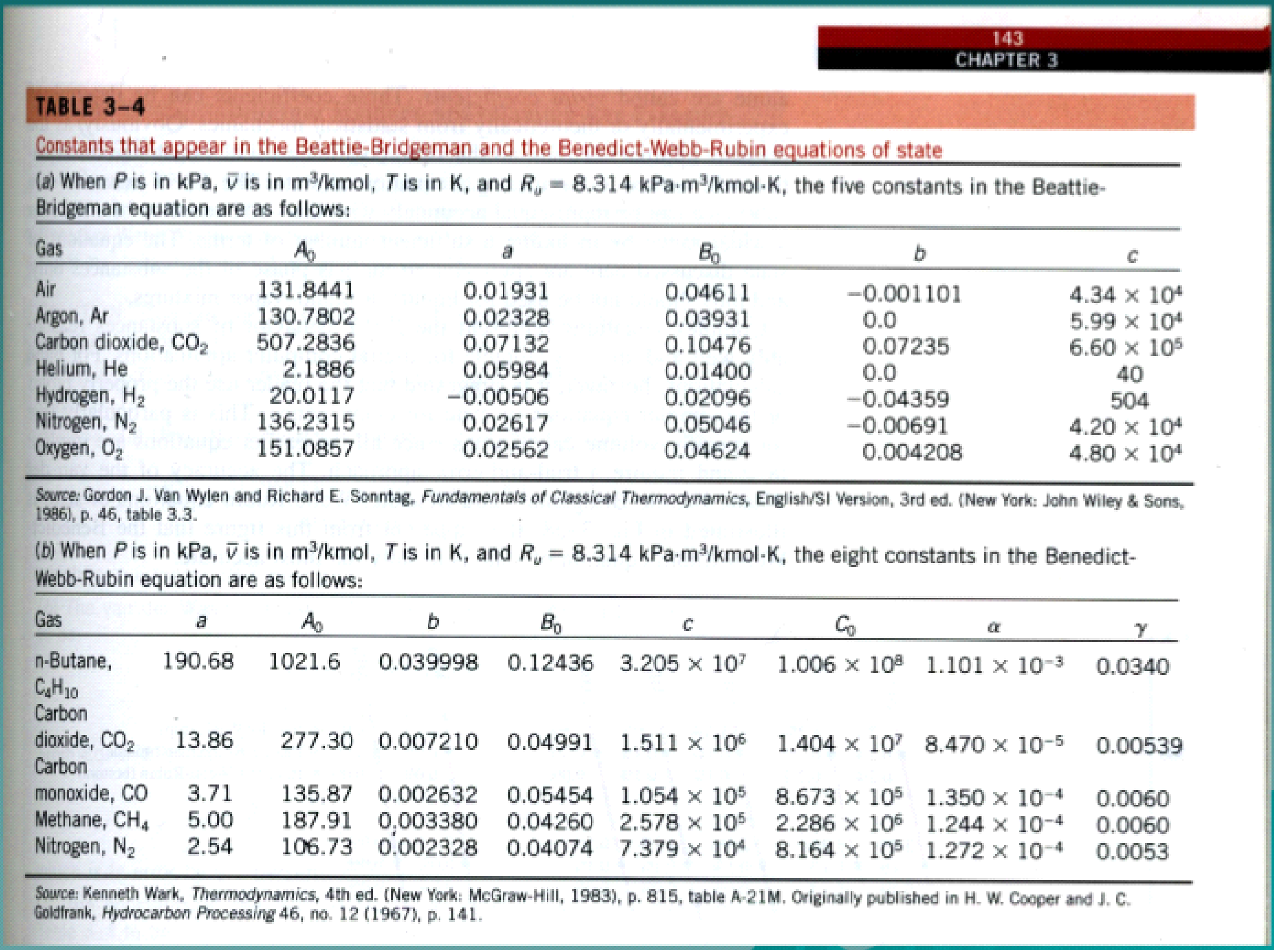


TABLE 3–4

Constants that appear in the Beattie-Bridgeman and the Benedict-Webb-Rubin equations of state

(*a*) When *P* is in kPa, $\bar{v}$ is in m³/kmol, *T* is in K, and R_u = 8.314 kPa·m³/kmol·K, the five constants in the Beattie-Bridgeman equation are as follows:

Gas	A_0	a	B_0	b	c
Air	131.8441	0.01931	0.04611	−0.001101	4.34×10^4
Argon, Ar	130.7802	0.02328	0.03931	0.0	5.99×10^4
Carbon dioxide, CO_2	507.2836	0.07132	0.10476	0.07235	6.60×10^5
Helium, He	2.1886	0.05984	0.01400	0.0	40
Hydrogen, H_2	20.0117	−0.00506	0.02096	−0.04359	504
Nitrogen, N_2	136.2315	0.02617	0.05046	−0.00691	4.20×10^4
Oxygen, O_2	151.0857	0.02562	0.04624	0.004208	4.80×10^4

Source: Gordon J. Van Wylen and Richard E. Sonntag, *Fundamentals of Classical Thermodynamics*, English/SI Version, 3rd ed. (New York: John Wiley & Sons, 1986), p. 46, table 3.3.

(*b*) When *P* is in kPa, $\bar{v}$ is in m³/kmol, *T* is in K, and R_u = 8.314 kPa·m³/kmol·K, the eight constants in the Benedict-Webb-Rubin equation are as follows:

Gas	a	A_0	b	B_0	c	C_0	α	γ
n-Butane, C_4H_{10}	190.68	1021.6	0.039998	0.12436	3.205×10^7	1.006×10^8	1.101×10^{-3}	0.0340
Carbon dioxide, CO_2	13.86	277.30	0.007210	0.04991	1.511×10^6	1.404×10^7	8.470×10^{-5}	0.00539
Carbon monoxide, CO	3.71	135.87	0.002632	0.05454	1.054×10^5	8.673×10^5	1.350×10^{-4}	0.0060
Methane, CH_4	5.00	187.91	0.003380	0.04260	2.578×10^5	2.286×10^6	1.244×10^{-4}	0.0060
Nitrogen, N_2	2.54	106.73	0.002328	0.04074	7.379×10^4	8.164×10^5	1.272×10^{-4}	0.0053

Source: Kenneth Wark, *Thermodynamics*, 4th ed. (New York: McGraw-Hill, 1983), p. 815, table A-21M. Originally published in H. W. Cooper and J. C. Goldfrank, *Hydrocarbon Processing* 46, no. 12 (1967), p. 141.

ME2519 Chapter 3 Properties of a Pure Substance

3-8 Other Equations of State (cont.)

- **Virial Equation of State**

$$P = \frac{RT}{v} + \frac{a(T)}{v^2} + \frac{b(T)}{v^3} + \frac{c(T)}{v^4} + \frac{d(T)}{v^5} + \ldots$$

$a(T)$, $b(T)$, $c(T)$ etc called virial coefficients.

Get from experimental data or statistical mechanics

Note: as $P \rightarrow 0$, a, b, c, etc $\rightarrow 0$ so that $P = \dfrac{RT}{v}$

Requires computer for practical application

Energy Analysis of Closed Systems

Friday, September 23, 2022 10:05 AM

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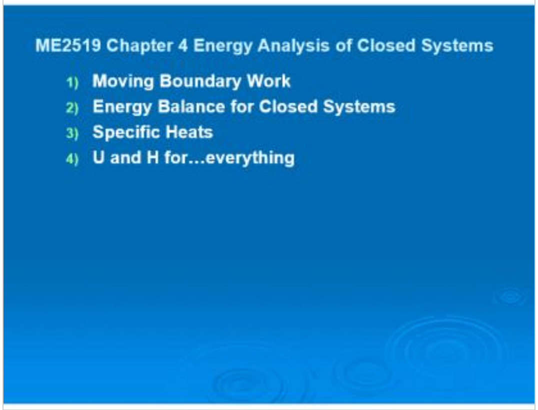
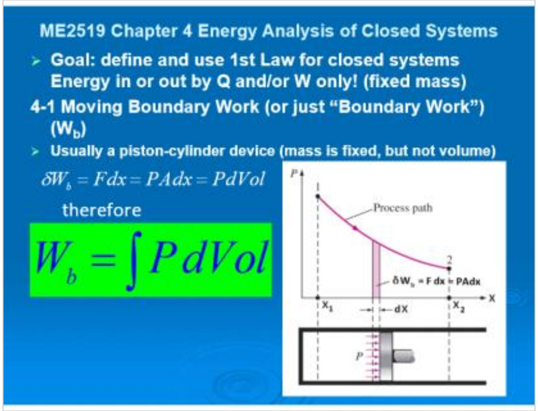
4-1+dtd+...



ME2519 Chapter 4 Energy Analysis of Closed Systems

1) Moving Boundary Work
2) Energy Balance for Closed Systems
3) Specific Heats
4) U and H for…everything



ME2519 Chapter 4 Energy Analysis of Closed Systems

- Goal: define and use 1st Law for closed systems Energy in or out by Q and/or W only! (fixed mass)

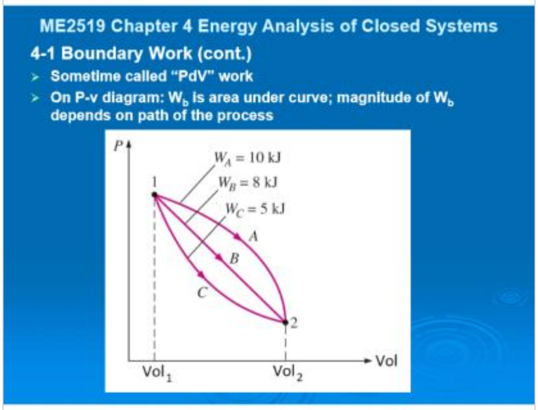
4-1 Moving Boundary Work (or just "Boundary Work") (W_b)

- Usually a piston-cylinder device (mass is fixed, but not volume)

$$\delta W_b = Fdx = PAdx = PdVol$$

therefore

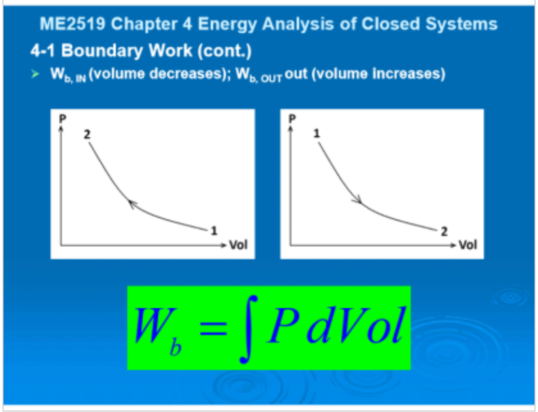
$$W_b = \int P\,dVol$$



ME2519 Chapter 4 Energy Analysis of Closed Systems

4-1 Boundary Work (cont.)

- Sometime called "PdV" work
- On P-v diagram: W_b is area under curve; magnitude of W_b depends on path of the process



ME2519 Chapter 4 Energy Analysis of Closed Systems

4-1 Boundary Work (cont.)

- $W_{b,\,IN}$ (volume decreases); $W_{b,\,OUT}$ out (volume increases)

$$W_b = \int P\,dVol$$

Ex: 4-8

Vol = Const

Given: $P_1 = 1\text{mPa}$ $\quad Vol_2 = .4\ Vol_1$

Find: W_b when $P_1 = 1\text{MPa}$, 250°C

Wb_{total}

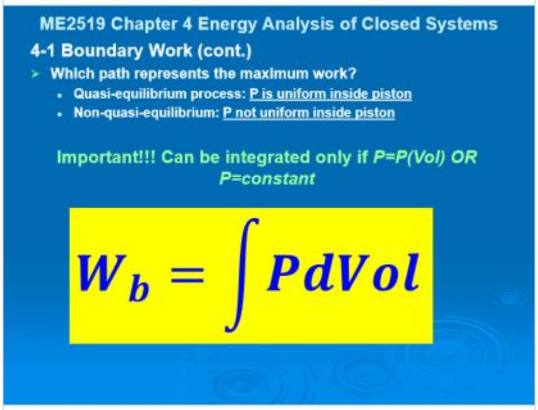
T_2

$P_1, T_1 \xrightarrow{SH} v_1 \rightarrow Vol_1 = mv_1$

$P_1, 250°C \xrightarrow{SH} v_2 \rightarrow Vol_2 = mv_2$

$W_b = \int P_d\ Vol = P\Delta Vol$

$W_{b\ total} = P\Delta Vol = P(V_1 d_1 - .4Vol_1)$



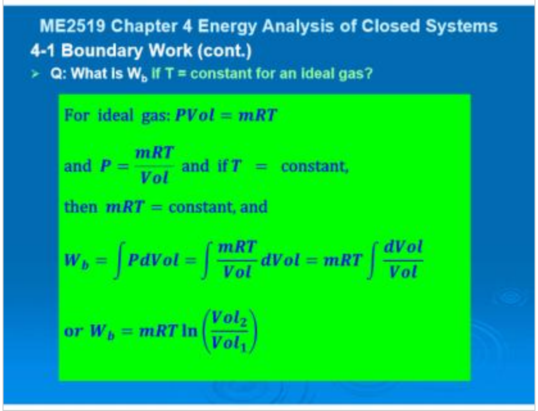
ME2519 Chapter 4 Energy Analysis of Closed Systems

4-1 Boundary Work (cont.)

- Which path represents the maximum work?
  - Quasi-equilibrium process: P is uniform inside piston
  - Non-quasi-equilibrium: P not uniform inside piston

Important!!! Can be integrated only if *P=P(Vol) OR P=constant*

$$W_b = \int PdVol$$



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4-1 Boundary Work (cont.)

- Q: What is W_b if T = constant for an ideal gas?

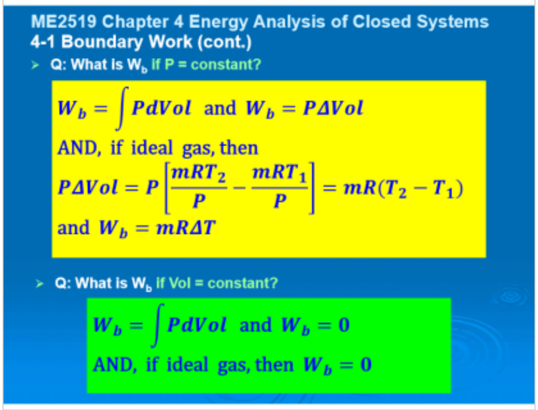
For ideal gas: $PVol = mRT$

and $P = \dfrac{mRT}{Vol}$ and if $T = $ constant,

then $mRT = $ constant, and

$$W_b = \int PdVol = \int \frac{mRT}{Vol}dVol = mRT\int\frac{dVol}{Vol}$$

or $W_b = mRT\ln\left(\dfrac{Vol_2}{Vol_1}\right)$



ME2519 Chapter 4 Energy Analysis of Closed Systems

4-1 Boundary Work (cont.)

- Q: What is W_b if P = constant?

$W_b = \int PdVol$ and $W_b = P\Delta Vol$

AND, if ideal gas, then

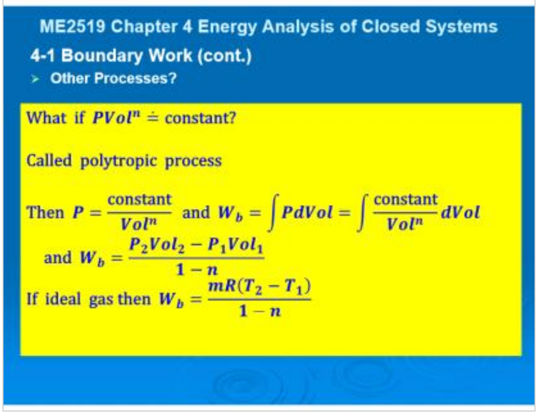
$$P\Delta Vol = P\left[\frac{mRT_2}{P} - \frac{mRT_1}{P}\right] = mR(T_2 - T_1)$$

and $W_b = mR\Delta T$

- Q: What is W_b if Vol = constant?

$W_b = \int PdVol$ and $W_b = 0$

AND, if ideal gas, then $W_b = 0$



ME2519 Chapter 4 Energy Analysis of Closed Systems

4-1 Boundary Work (cont.)

- Other Processes?

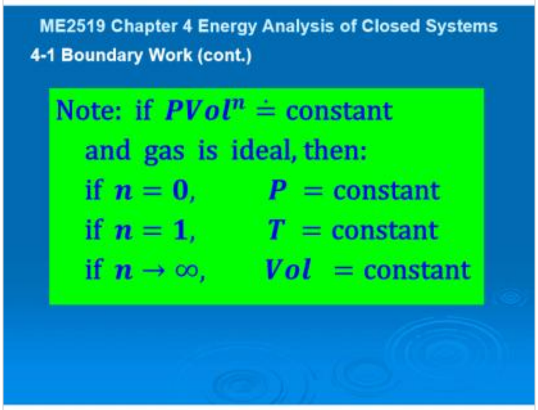
What if $PVol^n \doteq$ constant?

Called polytropic process

Then $P = \dfrac{\text{constant}}{Vol^n}$ and $W_b = \int PdVol = \int \dfrac{\text{constant}}{Vol^n}dVol$

and $W_b = \dfrac{P_2Vol_2 - P_1Vol_1}{1-n}$

If ideal gas then $W_b = \dfrac{mR(T_2 - T_1)}{1-n}$



ME2519 Chapter 4 Energy Analysis of Closed Systems

4-1 Boundary Work (cont.)

Note: if $PVol^n \doteq$ constant

and gas is ideal, then:

if $n = 0$, P = constant

if $n = 1$, T = constant

if $n \to \infty$, Vol = constant

HW 3b

Saturday, September 24, 2022 7:38 PM

3–71 A 400-L rigid tank contains 5 kg of air at 25°C. Determine the reading on the pressure gage if the atmospheric pressure is 97 kPa.

$P vol = m R T$

$P_g = P - P_{atm}$

$P_g = \frac{mRT}{v} - P_{atm}$

← Table A-1

$P_g = \frac{(.287\ kJ/kg-K)(273+25)K(5\ kg)}{400L\left(\frac{1m^3}{1000L}\right)} - 97\ kPa$

$P_g = 972.075\ kPa$

3–77 A mass of 0.1 kg of helium fills a 0.2 m^3 rigid vessel at 350 kPa. The vessel is heated until the pressure is 700 kPa. Calculate the temperature change of helium (in °C and K) as a result of this heating.

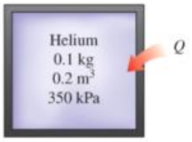


FIGURE P3–77

$P_1 vol = m R T_1$

$T_1 = \frac{P_1 vol}{mR}$

$T_1 = \frac{(350\ kPa)(.2m^3)}{(.1\ kg)(2.0769\ kJ/kg-K)}$ ← A-1

$T_1 = 337\ °K$

$T_2 = \frac{P_2\ vol}{mR}$

$T_2 = \frac{700\ kPa\ (.2m^3)}{.1\ kg\ (2.0769\ kJ/kg-K)} = 674\ °K$

$\Delta T = T_2 - T_1 = 674 - 337 = 337\ °K$

$\Delta T = 337\ °C$

Energy Balance for Closed Systems

Monday, September 26, 2022 10:00 AM

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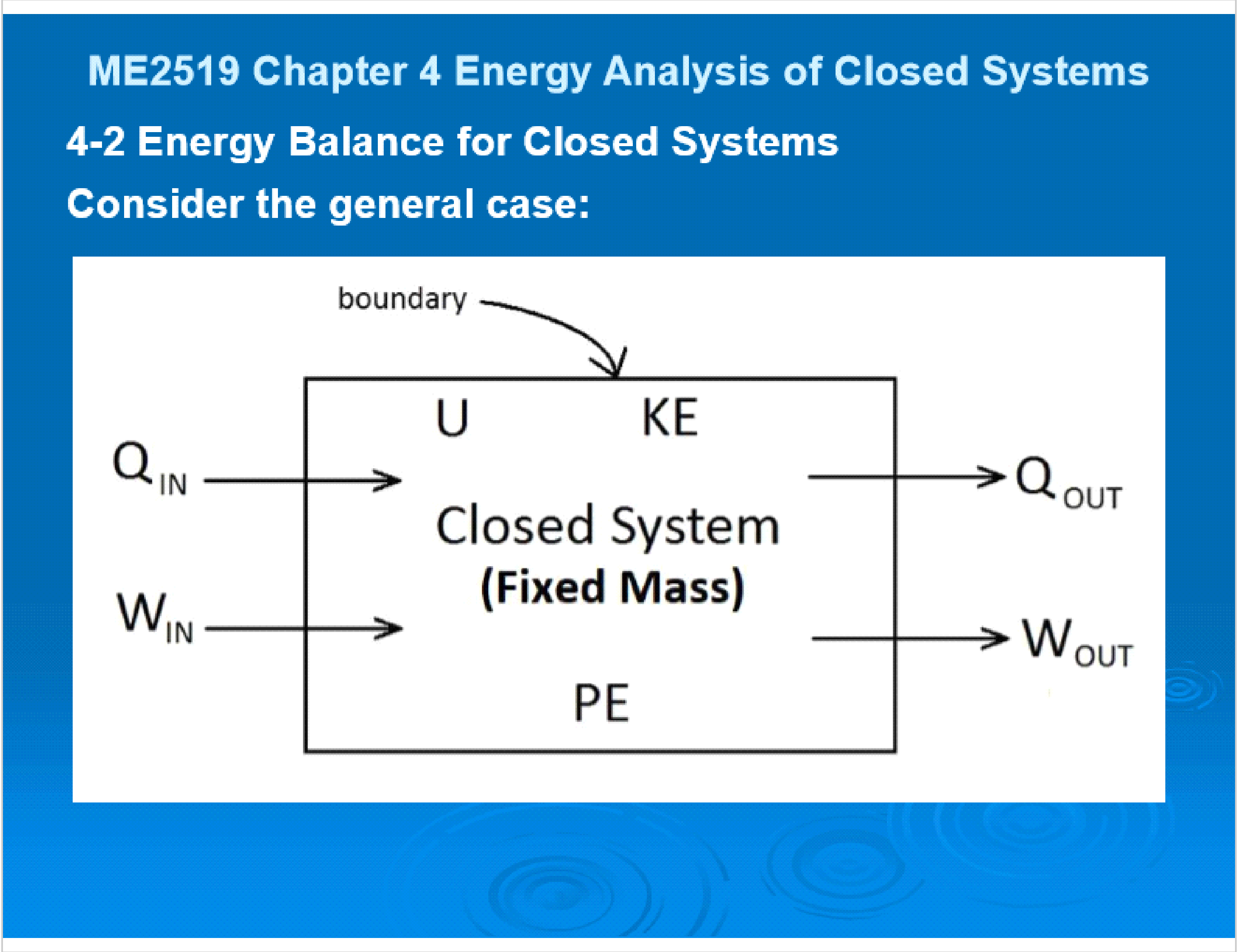
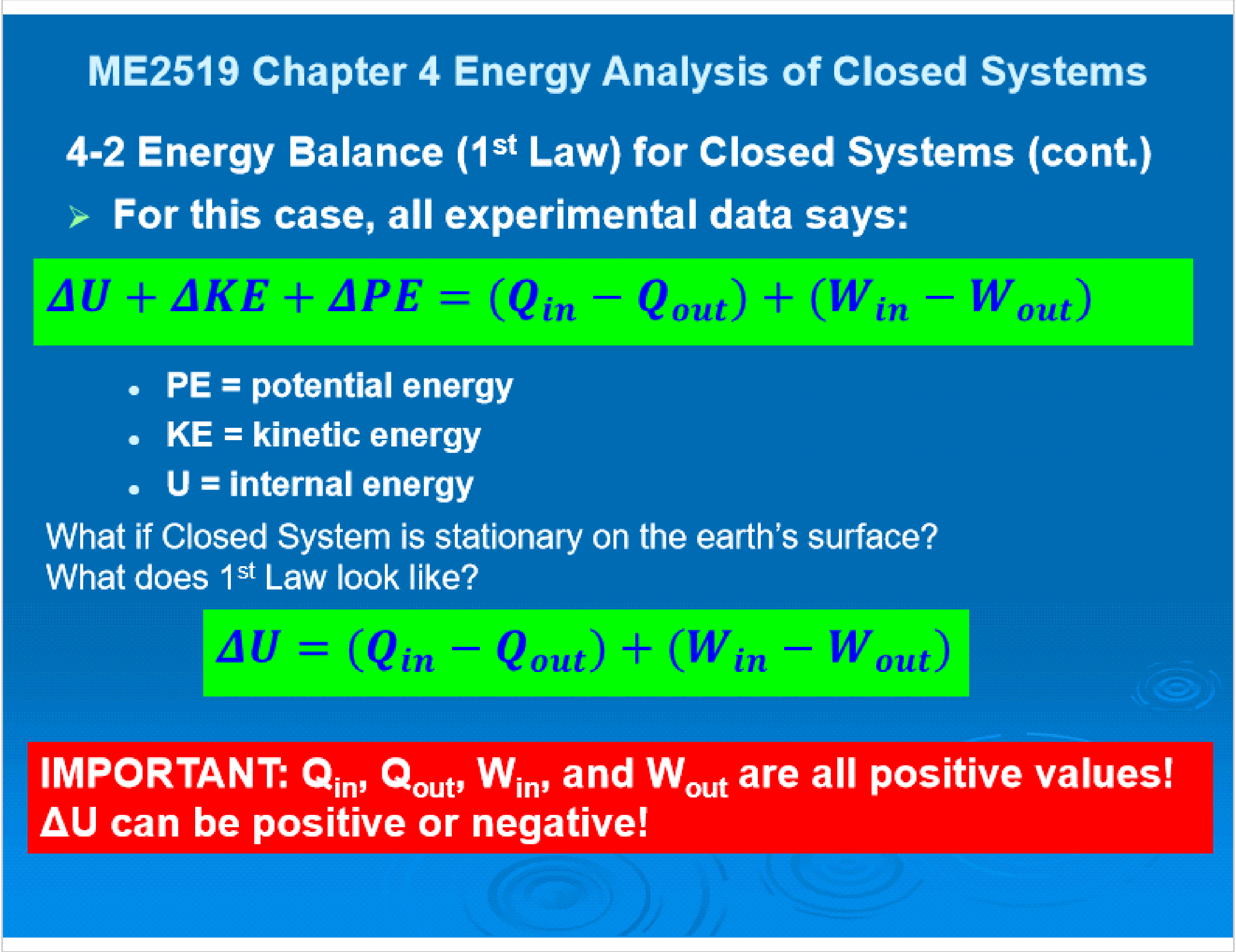
+4-2+dtd...



ME2519 Chapter 4 Energy Analysis of Closed Systems

4-2 Energy Balance for Closed Systems

Consider the general case:



ME2519 Chapter 4 Energy Analysis of Closed Systems

4-2 Energy Balance (1st Law) for Closed Systems (cont.)

- **For this case, all experimental data says:**

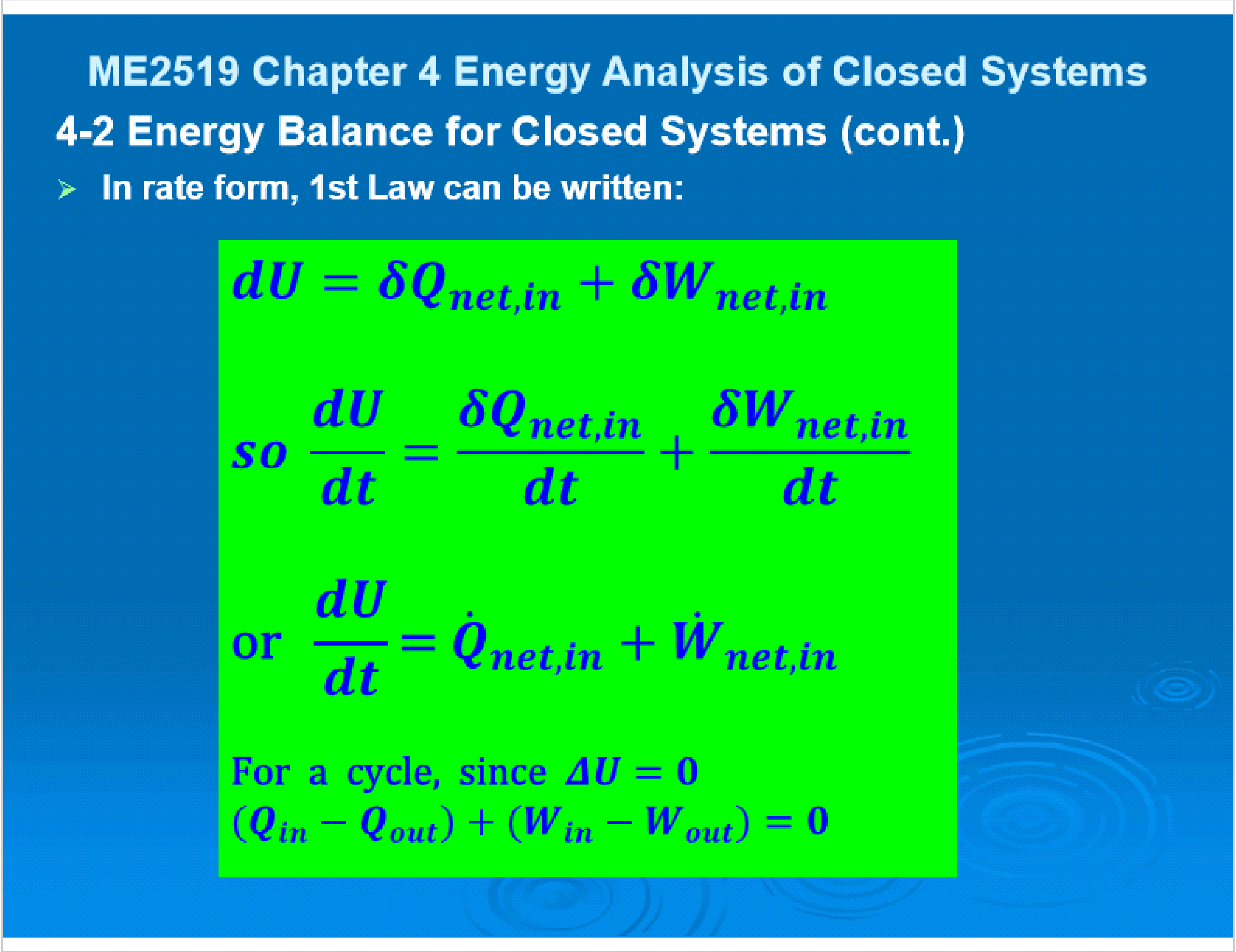
$$\Delta U + \Delta KE + \Delta PE = (Q_{in} - Q_{out}) + (W_{in} - W_{out})$$

- PE = potential energy
- KE = kinetic energy
- U = internal energy

What if Closed System is stationary on the earth's surface?
What does 1st Law look like?

$$\Delta U = (Q_{in} - Q_{out}) + (W_{in} - W_{out})$$

IMPORTANT: Q_{in}, Q_{out}, W_{in}, and W_{out} are all positive values!
ΔU can be positive or negative!



ME2519 Chapter 4 Energy Analysis of Closed Systems

4-2 Energy Balance for Closed Systems (cont.)

- In rate form, 1st Law can be written:

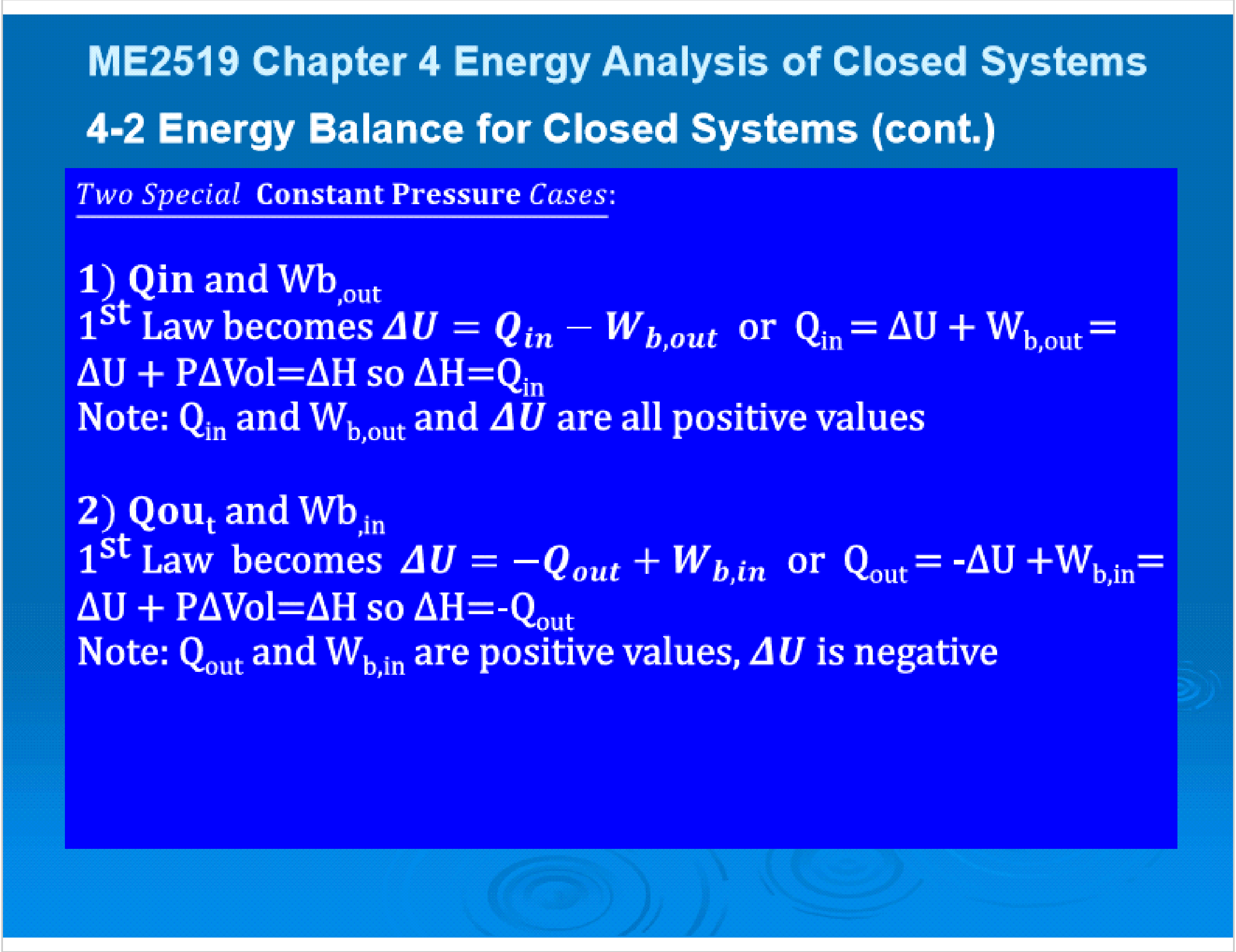
$$dU = \delta Q_{net,in} + \delta W_{net,in}$$

$$so \ \frac{dU}{dt} = \frac{\delta Q_{net,in}}{dt} + \frac{\delta W_{net,in}}{dt}$$

$$\text{or} \quad \frac{dU}{dt} = \dot{Q}_{net,in} + \dot{W}_{net,in}$$

For a cycle, since $\Delta U = 0$

$$(Q_{in} - Q_{out}) + (W_{in} - W_{out}) = 0$$



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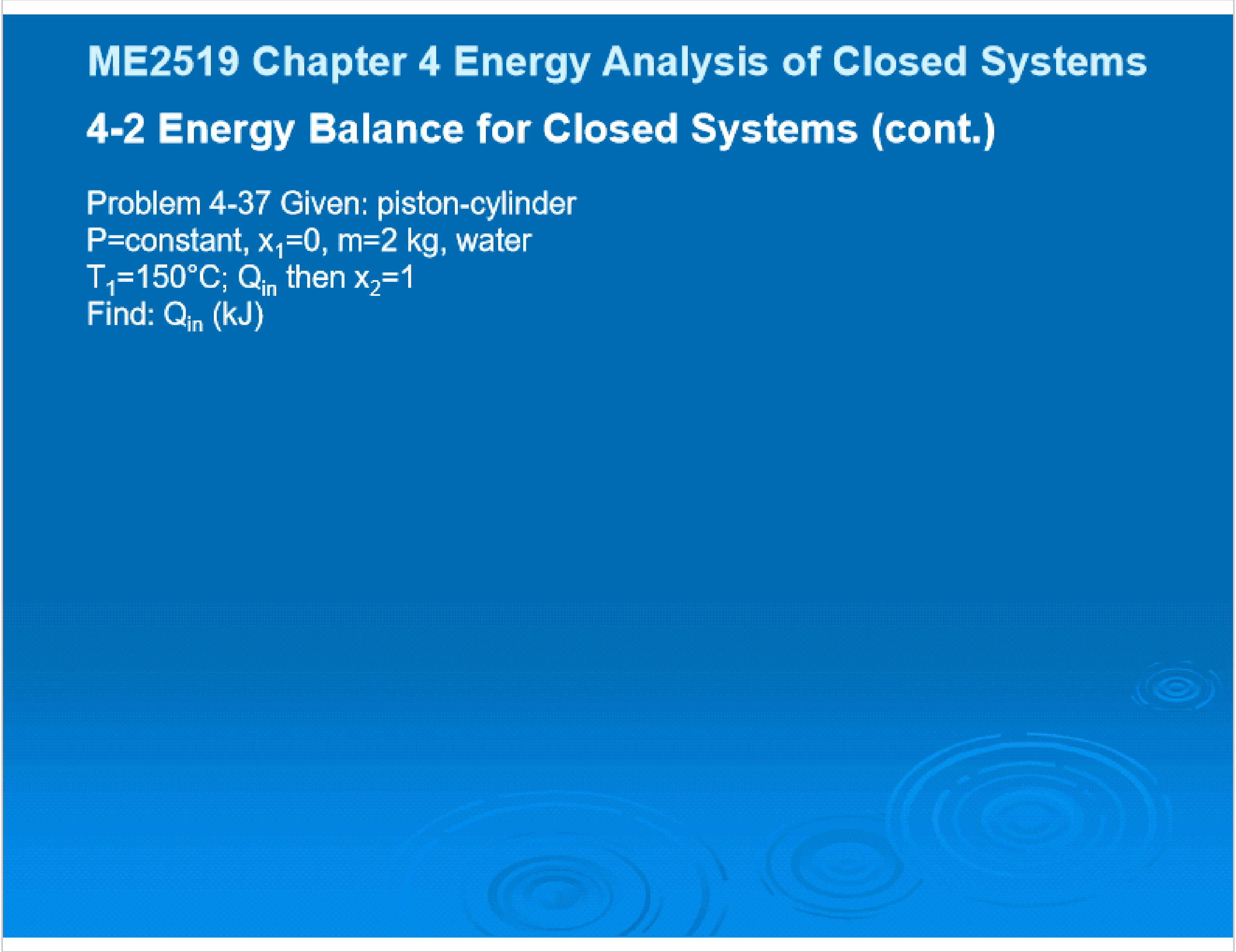
4-2 Energy Balance for Closed Systems (cont.)

Two Special **Constant Pressure** *Cases*:

1) Qin and $Wb_{,out}$
1^{st} Law becomes $\Delta U = Q_{in} - W_{b,out}$ or $Q_{in} = \Delta U + W_{b,out} =$
$\Delta U + P\Delta Vol = \Delta H$ so $\Delta H = Q_{in}$
Note: Q_{in} and $W_{b,out}$ and ΔU are all positive values

2) Qou$_t$ and $Wb_{,in}$
1^{st} Law becomes $\Delta U = -Q_{out} + W_{b,in}$ or $Q_{out} = -\Delta U + W_{b,in} =$
$\Delta U + P\Delta Vol = \Delta H$ so $\Delta H = -Q_{out}$
Note: Q_{out} and $W_{b,in}$ are positive values, ΔU is negative



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4-2 Energy Balance for Closed Systems (cont.)

Problem 4-37 Given: piston-cylinder
P=constant, x_1=0, m=2 kg, water
T_1=150°C; Q_{in} then x_2=1
Find: Q_{in} (kJ)

HW 4a

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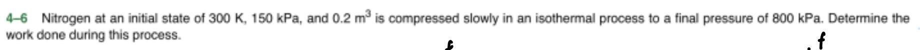
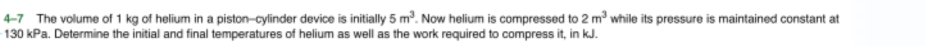


4–6 Nitrogen at an initial state of 300 K, 150 kPa, and 0.2 m³ is compressed slowly in an isothermal process to a final pressure of 800 kPa. Determine the work done during this process.

$W_b = \int P\,dVol = \int_i^f \frac{\text{Constant}}{} dVol = \text{Const} \ln Vol \Big|_i^f = \text{Constant}(\ln Vol_f - \ln Vol_i)$

$W_b = P_1 Vol_1 \ln \frac{Vol_2}{Vol_1} = P_1 Vol_1 \ln \frac{P_2}{P_1}$

$W_b = 150\text{ kPa}\,(.2m^3) \ln\left(\frac{800\text{ kPa}}{150\text{ kPa}}\right) = 50.22\text{ kJ}$



4–7 The volume of 1 kg of helium in a piston–cylinder device is initially 5 m³. Now helium is compressed to 2 m³ while its pressure is maintained constant at 130 kPa. Determine the initial and final temperatures of helium as well as the work required to compress it, in kJ.

$Pv = mRT$ $R_{helium} = 2.0769\text{ kJ/kg}\cdot K$

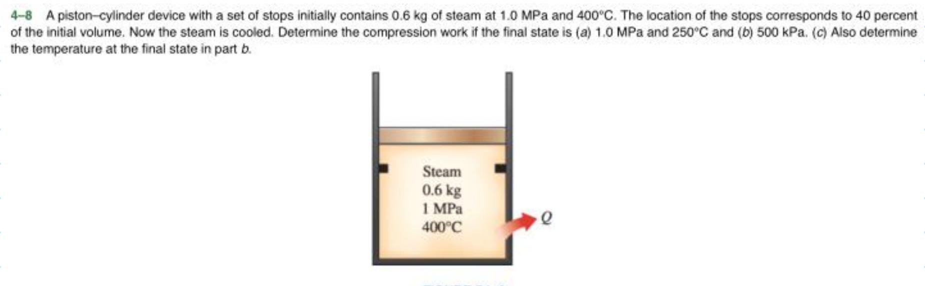
$T = \frac{Pv}{mR}$

$T_1 = \frac{130\text{ kPa}(5m^3)}{(1\text{ kg})(2.0769\text{ kJ/kg}\cdot k)} = 312.966K$

$T_2 = \frac{130\text{ kPa}(2m^3)}{(1\text{ kg})(2.0769\text{ kJ/kg}\cdot k)} = 125.187\text{ K}$

$W_b = \int P\,dVol = P\int dVol = P(Vol_2 - Vol_1)$

$W_b = 130\text{ kPa}(2-5)m^3 = -390\text{ kJ}\ [W_{in}] = 390\text{ kJ}$



4–8 A piston–cylinder device with a set of stops initially contains 0.6 kg of steam at 1.0 MPa and 400°C. The location of the stops corresponds to 40 percent of the initial volume. Now the steam is cooled. Determine the compression work if the final state is (a) 1.0 MPa and 250°C and (b) 500 kPa. (c) Also determine the temperature at the final state in part b.

FIGURE P4–8

a. $Vol_1 = m\overset{\text{A-6}}{v} = .6\text{ kg}(.30661\text{ m}^3/\text{kg}) = .184\text{ m}^3$

$Vol_2 = .6\text{ kg}(.23275\text{ m}^3/\text{kg}) = .140\text{ m}^3$

$W_b = P(Vol_2 - Vol_1) = 1.0\text{ MPa}(.140 - .184)\frac{1000\text{ kPa}}{1\text{ MPa}} = \overset{W_{in}}{-44.316}\text{ kJ} = 44.316\text{ kJ}$

b. $W_b = P(Vol_1(.4) - Vol_1) = 1\text{ MPa}\ \frac{1000\text{ kPa}}{\text{MPa}}(-.6(.184\text{ m}^3)) = 110.38\text{ kJ}$

c. $v = \frac{Vol_1(.4)}{} \quad \frac{.184m^3(.4)}{} = .12267$

MPa

c. $v = \frac{V_{b1}(.4)}{m} = \frac{.184 m^3 (.4)}{.6 kg} = .12267$

p= 500 kPa   Table A-5

$T_2 = 151.83$ °C $v_f < v < v_g$, sat. mixture

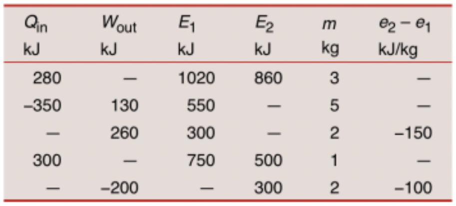
4–17 A frictionless piston–cylinder device contains 5 kg of nitrogen at 100 kPa and 250 K. Nitrogen is now compressed slowly according to the relation $PV^{1.4}$ = constant until it reaches a final temperature of 450 K. Calculate the work input during this process. *Answer:* 742 kJ

FIGURE P4–17

$w_b = \int P dvol = \frac{mR(T_2-T_1)}{1-n}$ $R_{nitrogen} = .2968$ kJ/kg·K

$w_b = \frac{5 kg (450 K - 250 K)(.2968)}{1-1.4} = 742$ kJ

4–29 Complete each line of the following table on the basis of the conservation of energy principle for a closed system.



Q_{in} kJ	W_{out} kJ	E_1 kJ	E_2 kJ	m kg	$e_2 - e_1$ kJ/kg
280	—	1020	860	3	—
–350	130	550	—	5	—
—	260	300	—	2	–150
300	—	750	500	1	—
—	–200	—	300	2	–100

FIGURE P4–29

$E_2 - E_1 = Q_{in} - Q_{out} + W_{in} - W_{out}$

$e_2 - e_1 = \frac{E_2 - E_1}{m}$

a. $W_{out} = -E_2 + E_1 + Q_{in} - \overset{0}{\cancel{Q_{out}}} + \overset{0}{\cancel{W_{in}}} = -860 + 1020 + 280 = 440$ kJ

$e_2 - e_1 = \frac{860-1020}{3} = -53.3$

b. $E_2 = Q_{in} - W_{out} + E_1 = -350 - 130 + 550 = 70$

$e_2 - e_1 = \frac{70-550}{5} = -96$

c. $E_2 = m(e_2 - e_1) + E_1 = 2(-150) + 300 = 0$

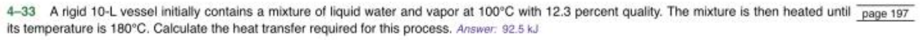
$Q_{in} = W_{out} + E_2 - E_1 = 260 + 0 - 300 = -40$

d. $W_{out} = -E_2 + E_1 + Q_{in} = -500 + 750 + 300 = 550$

$e_2 - e_1 = \frac{E_2 - E_1}{m} = \frac{500 - 750}{1} = -250$

e. $E_1 = E_2 - (e_2 - e_1)m = 300 - (-100)(2) = 500$

$Q_{in} = W_{out} + E_2 - E_1 = -200 + 300 - 500 = -400$



4–33 A rigid 10-L vessel initially contains a mixture of liquid water and vapor at 100°C with 12.3 percent quality. The mixture is then heated until its temperature is 180°C. Calculate the heat transfer required for this process. *Answer:* 92.5 kJ page 197

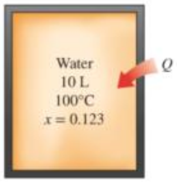


FIGURE P4–33

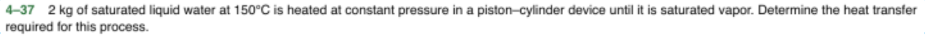
$v_1 = v_f + x_1(v_g - v_f) = .00143 + .123(1.672 - .00143) = .2066\ m^3/kg$

$u_1 = u_f + x_1(u_g - u_f) = 419.06 + .123(2506 - 419.06) = 675\ 75$ kJ/kg

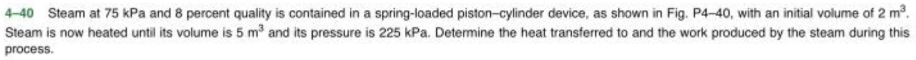
$m = \frac{Vol}{v_1} = \frac{10\ L}{.2066\ \frac{m^3}{kg}}\ \frac{m^3}{1000\ L} = .04841$ kg

$u_2 = 2582.8$ kJ/kg A-4, superheated vapor

$\Delta U = m(u_2 - u_1) = (2582.8 - 675.75)\ .0481 = 92.22$ kJ



4–37 2 kg of saturated liquid water at 150°C is heated at constant pressure in a piston–cylinder device until it is saturated vapor. Determine the heat transfer required for this process.



4–40 Steam at 75 kPa and 8 percent quality is contained in a spring-loaded piston–cylinder device, as shown in Fig. P4–40, with an initial volume of 2 m^3. Steam is now heated until its volume is 5 m^3 and its pressure is 225 kPa. Determine the heat transferred to and the work produced by the steam during this process.

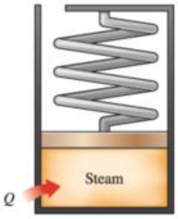


FIGURE P4–40

Pressure is not constat because of sping

4–42 An insulated tank is divided into two parts by a partition. One part of the tank contains 2.5 kg of compressed liquid water at 60°C and 600 kPa while the other part is evacuated. The partition is now removed, and the water expands to fill the entire tank. Determine the final temperature of the water and the volume of the tank for a final pressure of 10 kPa.

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FIGURE P4–42

Specific Heats and Internal Energy

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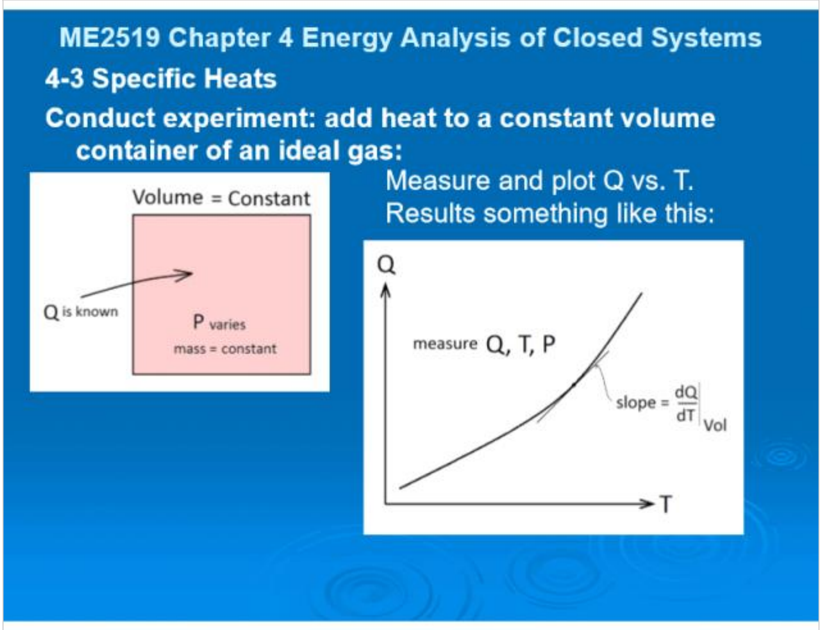

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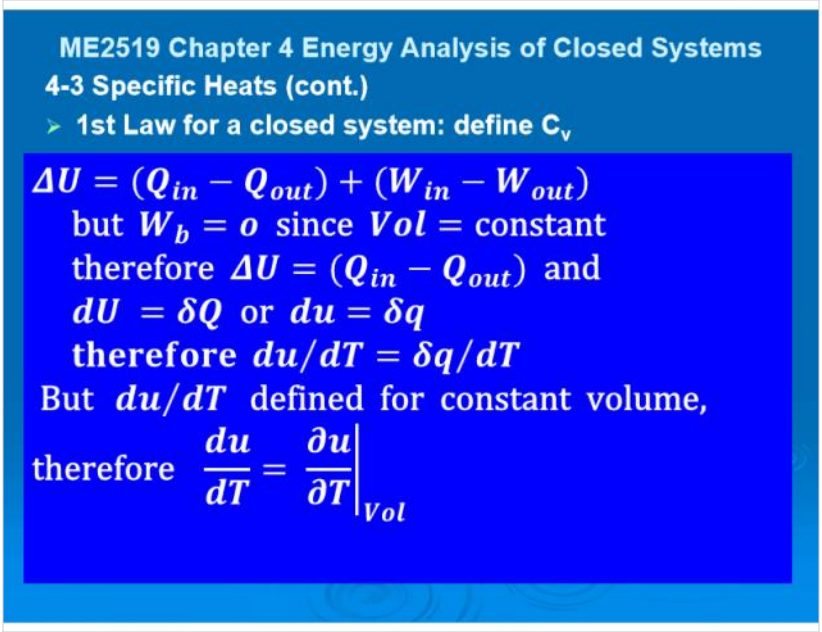
4-3 Specific Heats

Conduct experiment: add heat to a constant volume container of an ideal gas:

Measure and plot Q vs. T.
Results something like this:



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4-3 Specific Heats (cont.)

- **1st Law for a closed system: define C_v**

$$\Delta U = (Q_{in} - Q_{out}) + (W_{in} - W_{out})$$

but $W_b = o$ since $Vol =$ constant

therefore $\Delta U = (Q_{in} - Q_{out})$ and

$dU = \delta Q$ or $du = \delta q$

therefore $du/dT = \delta q/dT$

But du/dT defined for constant volume,

therefore $\dfrac{du}{dT} = \left.\dfrac{\partial u}{\partial T}\right|_{Vol}$

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4-3 Specific Heats (cont.)

- **IMPORTANT:**
  - **Value of this partial derivative is value based on measured data**
  - **this value is strictly a function of *P* and *T* (2 properties), therefore this partial derivative is a property**
  - **It is called "Specific heat at constant volume" or C_V. That is,**

$$c_V = \left.\frac{\partial u}{\partial T}\right|_{Vol}$$

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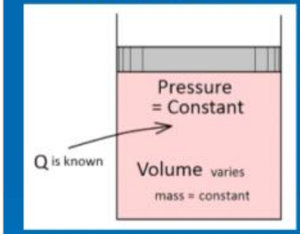
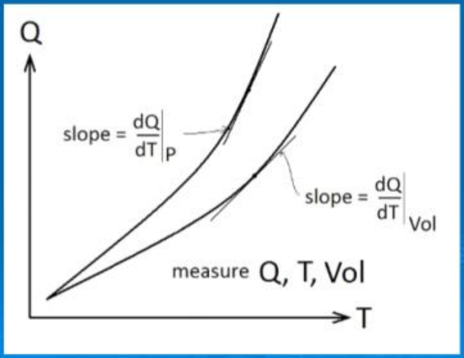
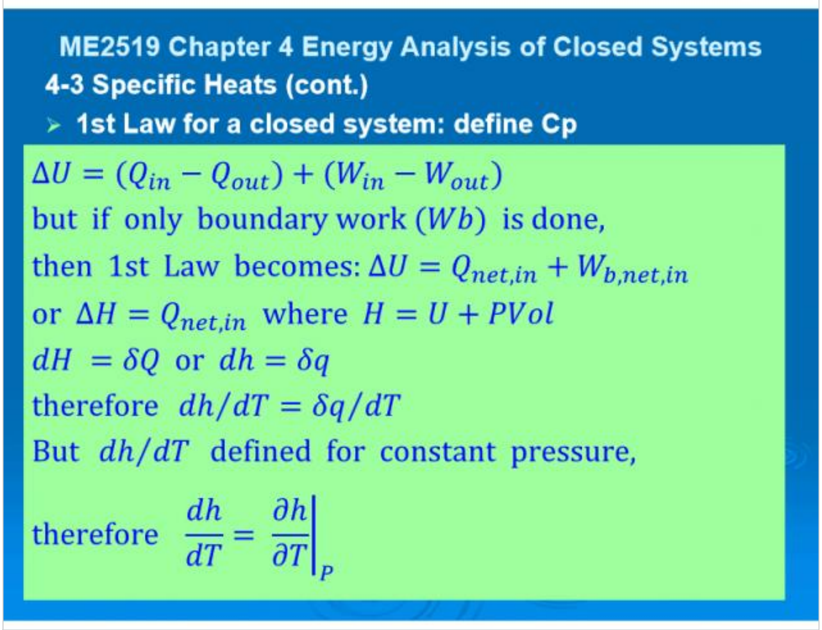
4-3 Specific Heats (cont.)

- **Next, conduct a similar experiment with a piston/cylinder, and add Q at constant P. Measure Q, T, and Volume.**







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4-3 Specific Heats (cont.)

- 1st Law for a closed system: define Cp

$\Delta U = (Q_{in} - Q_{out}) + (W_{in} - W_{out})$

but if only boundary work (Wb) is done,

then 1st Law becomes: $\Delta U = Q_{net,in} + W_{b,net,in}$

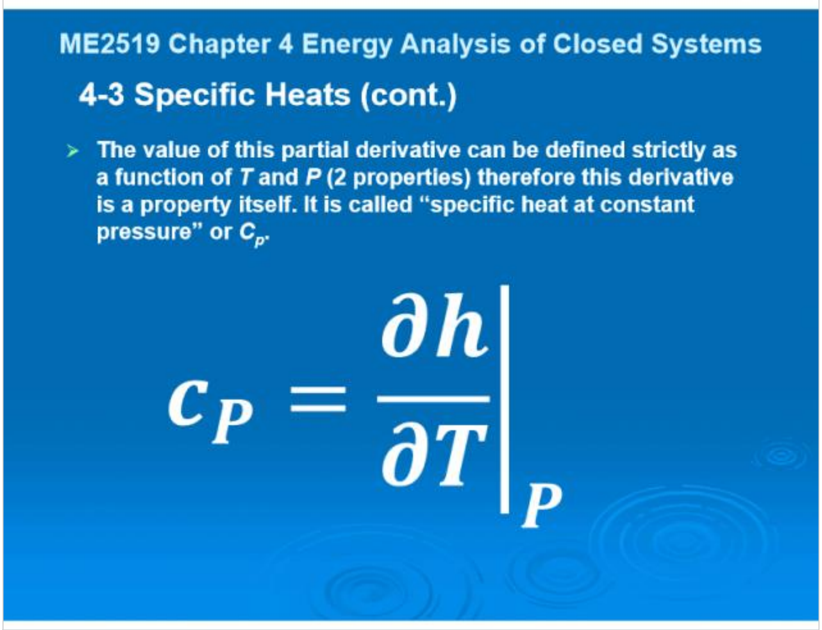
or $\Delta H = Q_{net,in}$ where $H = U + PVol$

$dH = \delta Q$ or $dh = \delta q$

therefore $dh/dT = \delta q/dT$

But dh/dT defined for constant pressure,

therefore $\dfrac{dh}{dT} = \left.\dfrac{\partial h}{\partial T}\right|_P$



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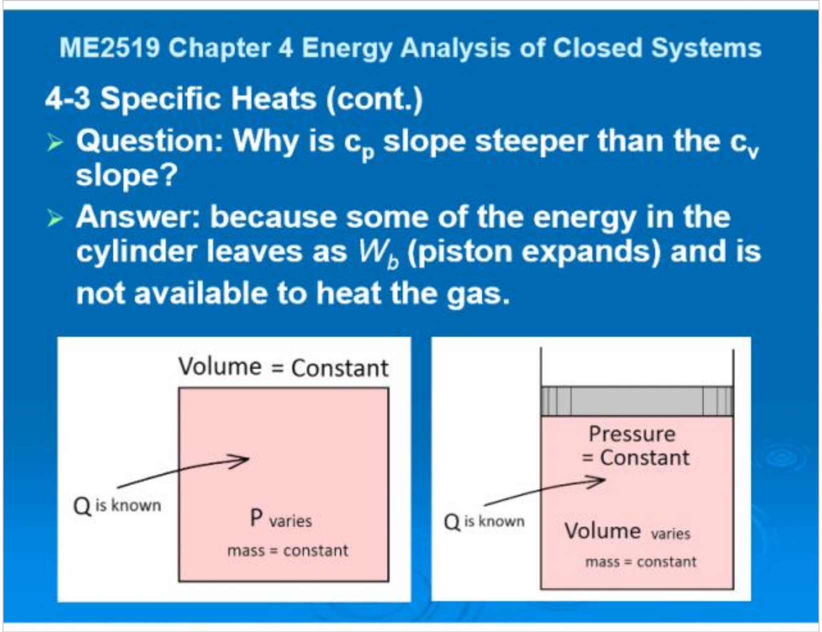
4-3 Specific Heats (cont.)

- The value of this partial derivative can be defined strictly as a function of *T* and *P* (2 properties) therefore this derivative is a property itself. It is called "specific heat at constant pressure" or C_p.

$$c_P = \left.\frac{\partial h}{\partial T}\right|_P$$



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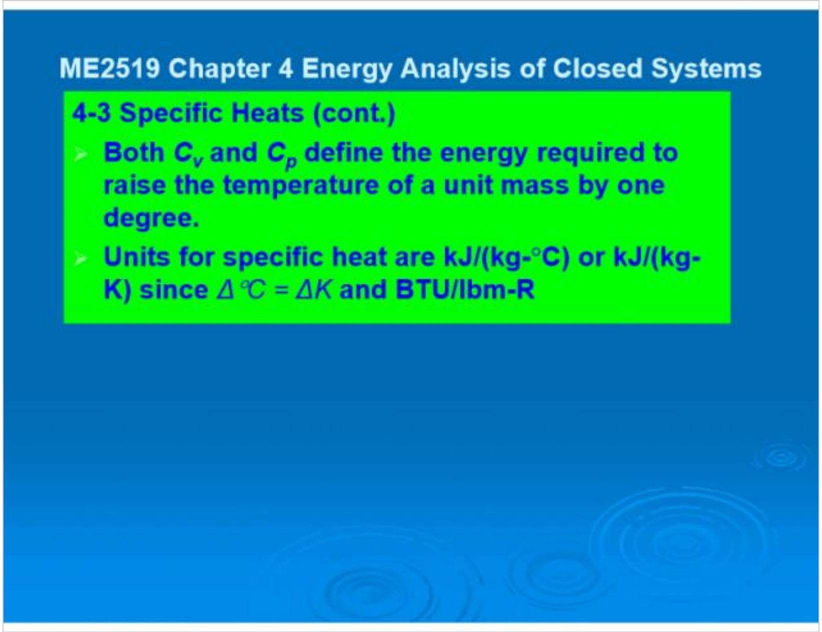
4-3 Specific Heats (cont.)

- **Question: Why is c_p slope steeper than the c_v slope?**
- **Answer: because some of the energy in the cylinder leaves as W_b (piston expands) and is not available to heat the gas.**



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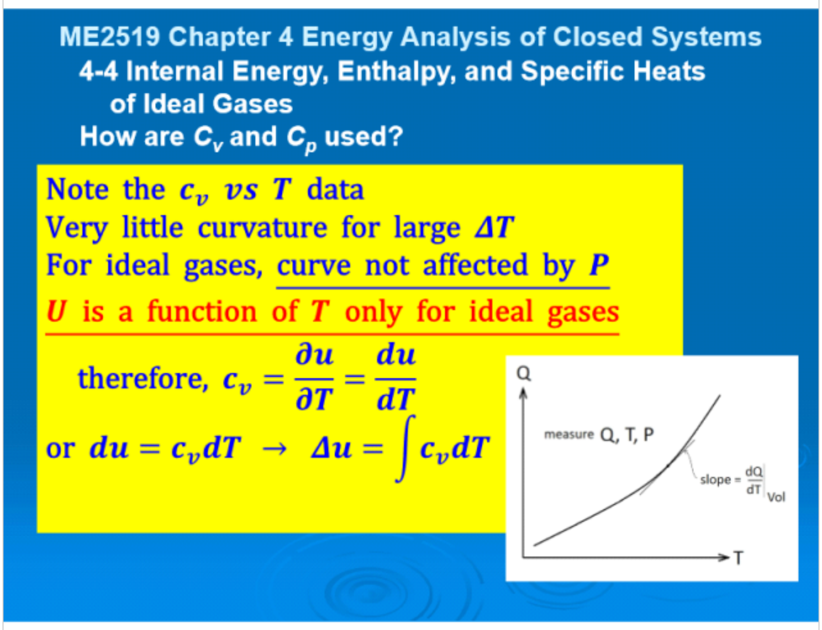
4-3 Specific Heats (cont.)

- **Both C_v and C_p define the energy required to raise the temperature of a unit mass by one degree.**
- **Units for specific heat are kJ/(kg-°C) or kJ/(kg-K) since $\Delta °C = \Delta K$ and BTU/lbm-R**



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4-4 Internal Energy, Enthalpy, and Specific Heats of Ideal Gases

How are C_v and C_p used?

Note the c_v vs T data

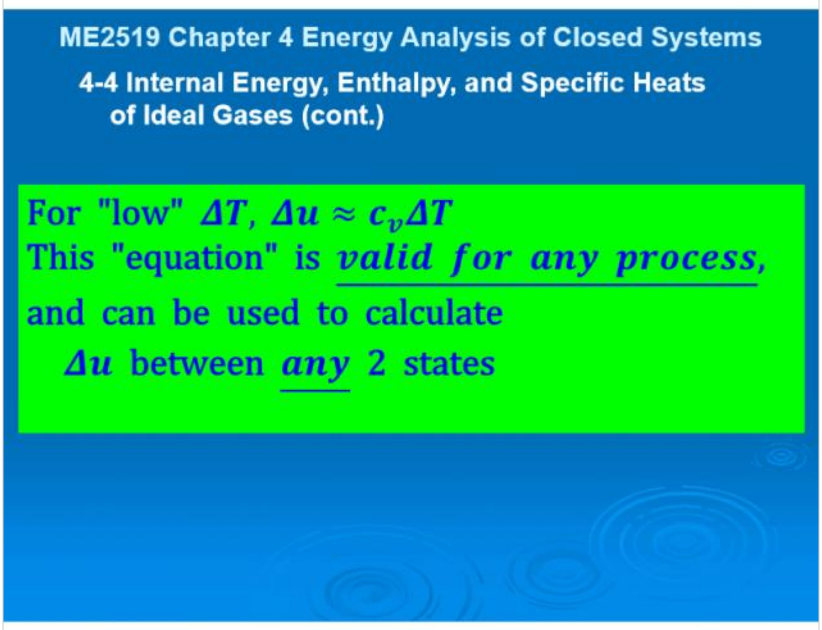
Very little curvature for large ΔT

For ideal gases, curve not affected by P

U is a function of T only for ideal gases

therefore, $c_v = \frac{\partial u}{\partial T} = \frac{du}{dT}$

or $du = c_v dT \ \rightarrow \ \Delta u = \int c_v dT$



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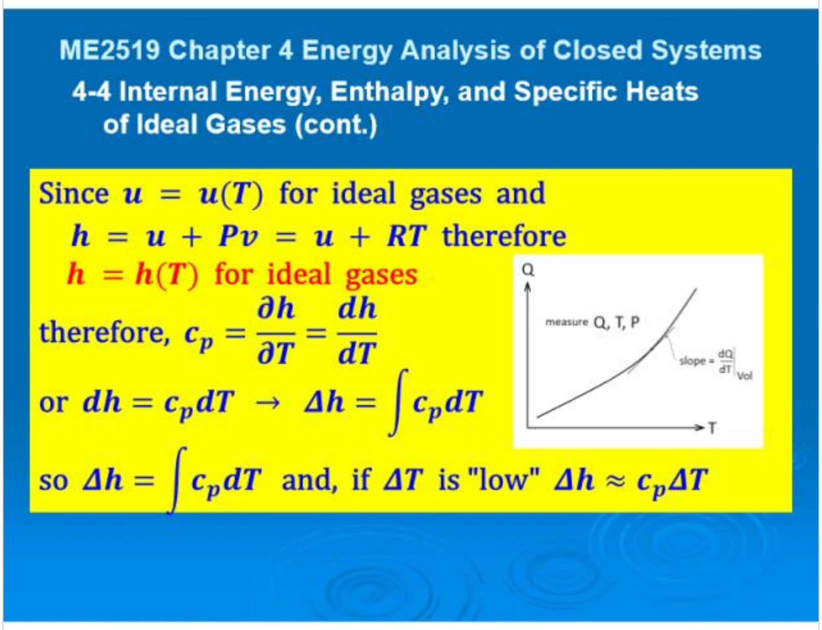
4-4 Internal Energy, Enthalpy, and Specific Heats of Ideal Gases (cont.)

For "low" ΔT, $\Delta u \approx c_v \Delta T$

This "equation" is $\underline{valid\ for\ any\ process,}$

and can be used to calculate

Δu between $\underline{any}$ 2 states



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4-4 Internal Energy, Enthalpy, and Specific Heats of Ideal Gases (cont.)

Since $u = u(T)$ for ideal gases and

$h = u + Pv = u + RT$ therefore

$h = h(T)$ for ideal gases

therefore, $c_p = \frac{\partial h}{\partial T} = \frac{dh}{dT}$

or $dh = c_p dT \rightarrow \Delta h = \int c_p dT$

so $\Delta h = \int c_p dT$ and, if ΔT is "low" $\Delta h \approx c_p \Delta T$

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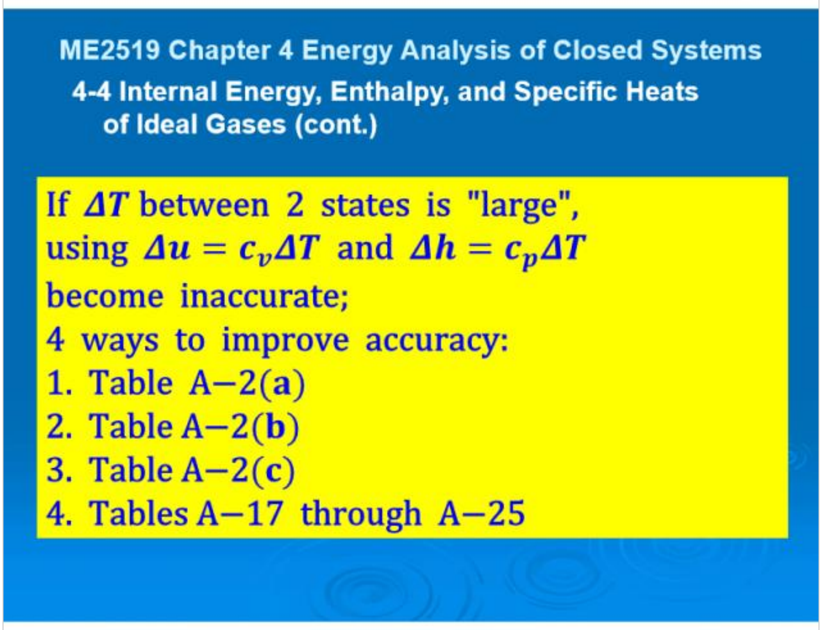
4-4 Internal Energy, Enthalpy, and Specific Heats of Ideal Gases (cont.)

For "low" ΔT, $\Delta h \approx c_p \Delta T$

This "equation" is $\underline{valid\ for\ any\ process,}$

and can be used to calculate

Δh between $\underline{any}$ 2 states



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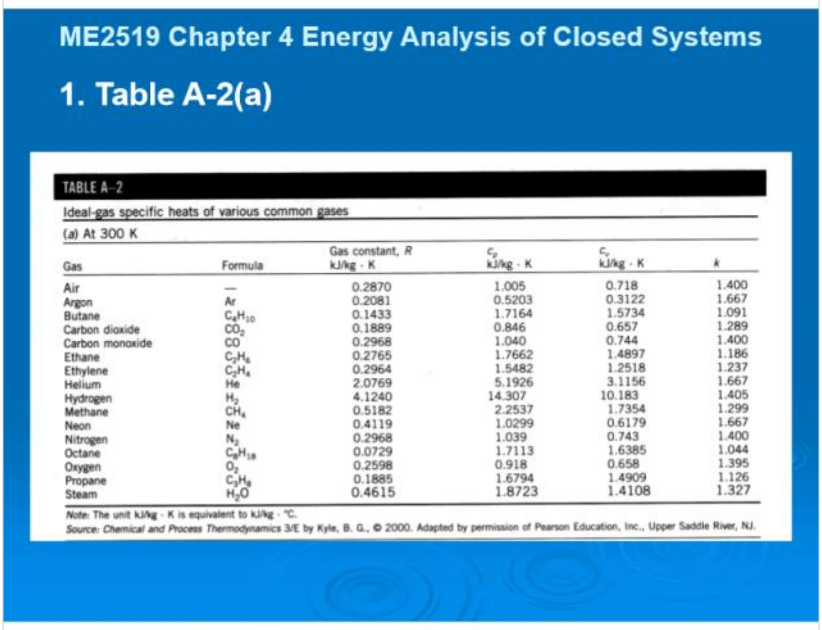
4-4 Internal Energy, Enthalpy, and Specific Heats of Ideal Gases (cont.)

If $\boldsymbol{\Delta T}$ between 2 states is "large",
using $\boldsymbol{\Delta u = c_v \Delta T}$ and $\boldsymbol{\Delta h = c_p \Delta T}$
become inaccurate;
4 ways to improve accuracy:

1. Table A−2(**a**)
2. Table A−2(**b**)
3. Table A−2(**c**)
4. Tables A−17 through A−25



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1. Table A-2(a)

TABLE A–2

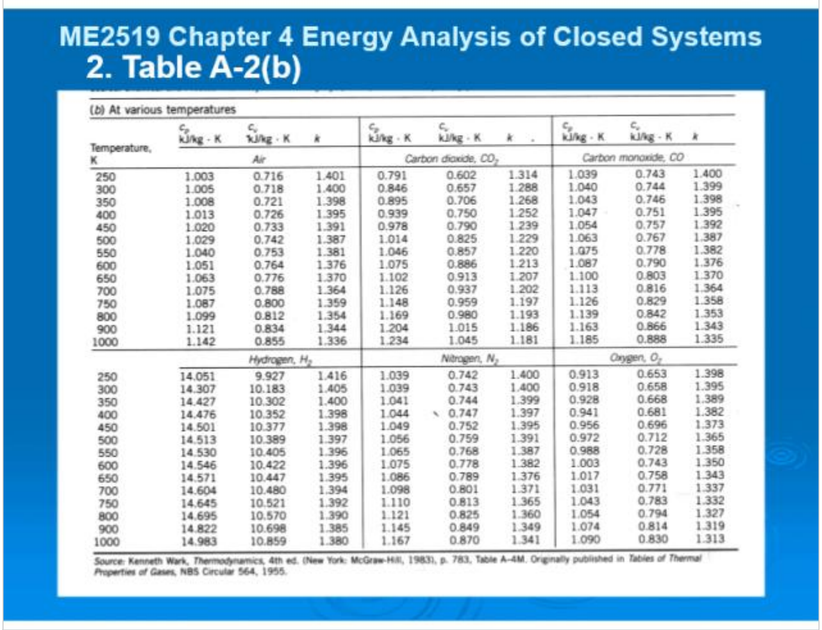
Ideal-gas specific heats of various common gases

(*a*) At 300 K

Gas	Formula	Gas constant, *R* kJ/kg · K	c_p kJ/kg · K	c_v kJ/kg · K	*k*
Air	—	0.2870	1.005	0.718	1.400
Argon	Ar	0.2081	0.5203	0.3122	1.667
Butane	C_4H_{10}	0.1433	1.7164	1.5734	1.091
Carbon dioxide	CO_2	0.1889	0.846	0.657	1.289
Carbon monoxide	CO	0.2968	1.040	0.744	1.400
Ethane	C_2H_6	0.2765	1.7662	1.4897	1.186
Ethylene	C_2H_4	0.2964	1.5482	1.2518	1.237
Helium	He	2.0769	5.1926	3.1156	1.667
Hydrogen	H_2	4.1240	14.307	10.183	1.405
Methane	CH_4	0.5182	2.2537	1.7354	1.299
Neon	Ne	0.4119	1.0299	0.6179	1.667
Nitrogen	N_2	0.2968	1.039	0.743	1.400
Octane	C_8H_{18}	0.0729	1.7113	1.6385	1.044
Oxygen	O_2	0.2598	0.918	0.658	1.395
Propane	C_3H_8	0.1885	1.6794	1.4909	1.126
Steam	H_2O	0.4615	1.8723	1.4108	1.327

Note: The unit kJ/kg · K is equivalent to kJ/kg · °C.

Source: Chemical and Process Thermodynamics 3/E by Kyle, B. G., © 2000. Adapted by permission of Pearson Education, Inc., Upper Saddle River, NJ.



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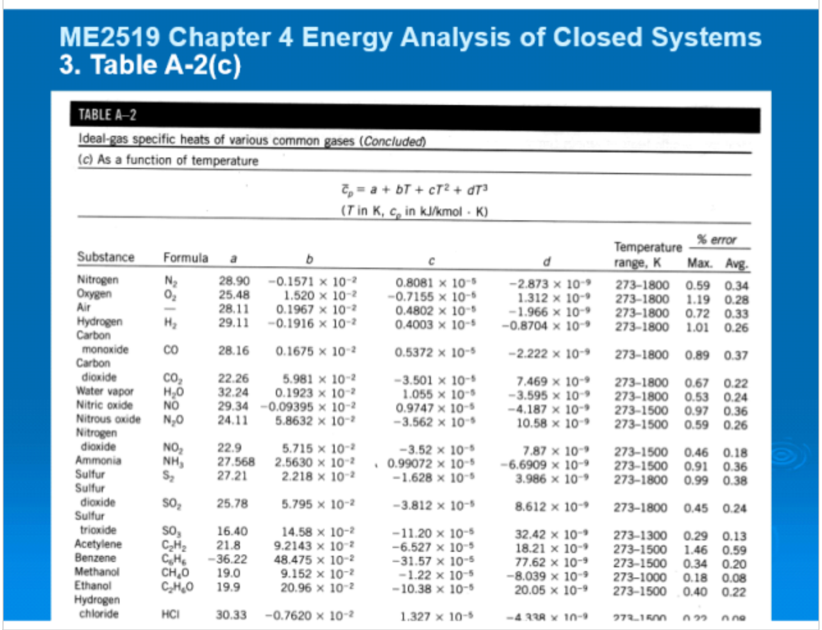
2. Table A-2(b)

(*b*) At various temperatures

Temperature, K	c_p kJ/kg · K	c_v kJ/kg · K	k	c_p kJ/kg · K	c_v kJ/kg · K	k	c_p kJ/kg · K	c_v kJ/kg · K	k
	Air			*Carbon dioxide, CO_2*			*Carbon monoxide, CO*		
250	1.003	0.716	1.401	0.791	0.602	1.314	1.039	0.743	1.400
300	1.005	0.718	1.400	0.846	0.657	1.288	1.040	0.744	1.399
350	1.008	0.721	1.398	0.895	0.706	1.268	1.043	0.746	1.398
400	1.013	0.726	1.395	0.939	0.750	1.252	1.047	0.751	1.395
450	1.020	0.733	1.391	0.978	0.790	1.239	1.054	0.757	1.392
500	1.029	0.742	1.387	1.014	0.825	1.229	1.063	0.767	1.387
550	1.040	0.753	1.381	1.046	0.857	1.220	1.075	0.778	1.382
600	1.051	0.764	1.376	1.075	0.886	1.213	1.087	0.790	1.376
650	1.063	0.776	1.370	1.102	0.913	1.207	1.100	0.803	1.370
700	1.075	0.788	1.364	1.126	0.937	1.202	1.113	0.816	1.364
750	1.087	0.800	1.359	1.148	0.959	1.197	1.126	0.829	1.358
800	1.099	0.812	1.354	1.169	0.980	1.193	1.139	0.842	1.353
900	1.121	0.834	1.344	1.204	1.015	1.186	1.163	0.866	1.343
1000	1.142	0.855	1.336	1.234	1.045	1.181	1.185	0.888	1.335
	Hydrogen, H_2			*Nitrogen, N_2*			*Oxygen, O_2*		
250	14.051	9.927	1.416	1.039	0.742	1.400	0.913	0.653	1.398
300	14.307	10.183	1.405	1.039	0.743	1.400	0.918	0.658	1.395
350	14.427	10.302	1.400	1.041	0.744	1.399	0.928	0.668	1.389
400	14.476	10.352	1.398	1.044	0.747	1.397	0.941	0.681	1.382
450	14.501	10.377	1.398	1.049	0.752	1.395	0.956	0.696	1.373
500	14.513	10.389	1.397	1.056	0.759	1.391	0.972	0.712	1.365
550	14.530	10.405	1.396	1.065	0.768	1.387	0.988	0.728	1.358
600	14.546	10.422	1.396	1.075	0.778	1.382	1.003	0.743	1.350
650	14.571	10.447	1.395	1.086	0.789	1.376	1.017	0.758	1.343
700	14.604	10.480	1.394	1.098	0.801	1.371	1.031	0.771	1.337
750	14.645	10.521	1.392	1.110	0.813	1.365	1.043	0.783	1.332
800	14.695	10.570	1.390	1.121	0.825	1.360	1.054	0.794	1.327
900	14.822	10.698	1.385	1.145	0.849	1.349	1.074	0.814	1.319
1000	14.983	10.859	1.380	1.167	0.870	1.341	1.090	0.830	1.313

Source: Kenneth Wark, *Thermodynamics*, 4th ed. (New York: McGraw-Hill, 1983), p. 783, Table A-4M. Originally published in *Tables of Thermal Properties of Gases*, NBS Circular 564, 1955.



ME2519 Chapter 4 Energy Analysis of Closed Systems
3. Table A-2(c)

TABLE A–2

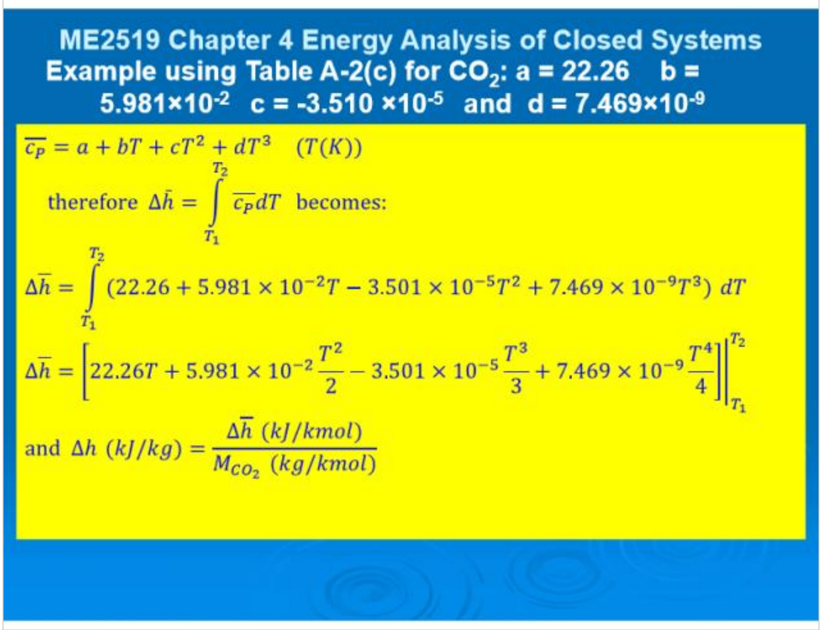
Ideal-gas specific heats of various common gases (*Concluded*)

(*c*) As a function of temperature

$$\bar{c}_p = a + bT + cT^2 + dT^3$$

(T in K, c_p in kJ/kmol · K)

Substance	Formula	a	b	c	d	Temperature range, K	% error Max.	% error Avg.
Nitrogen	N_2	28.90	-0.1571×10^{-2}	0.8081×10^{-5}	-2.873×10^{-9}	273–1800	0.59	0.34
Oxygen	O_2	25.48	1.520×10^{-2}	-0.7155×10^{-5}	1.312×10^{-9}	273–1800	1.19	0.28
Air	—	28.11	0.1967×10^{-2}	0.4802×10^{-5}	-1.966×10^{-9}	273–1800	0.72	0.33
Hydrogen	H_2	29.11	-0.1916×10^{-2}	0.4003×10^{-5}	-0.8704×10^{-9}	273–1800	1.01	0.26
Carbon monoxide	CO	28.16	0.1675×10^{-2}	0.5372×10^{-5}	-2.222×10^{-9}	273–1800	0.89	0.37
Carbon dioxide	CO_2	22.26	5.981×10^{-2}	-3.501×10^{-5}	7.469×10^{-9}	273–1800	0.67	0.22
Water vapor	H_2O	32.24	0.1923×10^{-2}	1.055×10^{-5}	-3.595×10^{-9}	273–1800	0.53	0.24
Nitric oxide	NO	29.34	-0.09395×10^{-2}	0.9747×10^{-5}	-4.187×10^{-9}	273–1500	0.97	0.36
Nitrous oxide	N_2O	24.11	5.8632×10^{-2}	-3.562×10^{-5}	10.58×10^{-9}	273–1500	0.59	0.26
Nitrogen dioxide	NO_2	22.9	5.715×10^{-2}	-3.52×10^{-5}	7.87×10^{-9}	273–1500	0.46	0.18
Ammonia	NH_3	27.568	2.5630×10^{-2}	0.99072×10^{-5}	-6.6909×10^{-9}	273–1500	0.91	0.36
Sulfur	S_2	27.21	2.218×10^{-2}	-1.628×10^{-5}	3.986×10^{-9}	273–1800	0.99	0.38
Sulfur dioxide	SO_2	25.78	5.795×10^{-2}	-3.812×10^{-5}	8.612×10^{-9}	273–1800	0.45	0.24
Sulfur trioxide	SO_3	16.40	14.58×10^{-2}	-11.20×10^{-5}	32.42×10^{-9}	273–1300	0.29	0.13
Acetylene	C_2H_2	21.8	9.2143×10^{-2}	-6.527×10^{-5}	18.21×10^{-9}	273–1500	1.46	0.59
Benzene	C_6H_6	−36.22	48.475×10^{-2}	-31.57×10^{-5}	77.62×10^{-9}	273–1500	0.34	0.20
Methanol	CH_4O	19.0	9.152×10^{-2}	-1.22×10^{-5}	-8.039×10^{-9}	273–1000	0.18	0.08
Ethanol	C_2H_6O	19.9	20.96×10^{-2}	-10.38×10^{-5}	20.05×10^{-9}	273–1500	0.40	0.22
Hydrogen chloride	HCl	30.33	-0.7620×10^{-2}	1.327×10^{-5}	-4.338×10^{-9}	273–1500	0.22	0.08



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Example using Table A-2(c) for CO_2: a = 22.26 b = 5.981×10^{-2} c = -3.510×10^{-5} and d = 7.469×10^{-9}

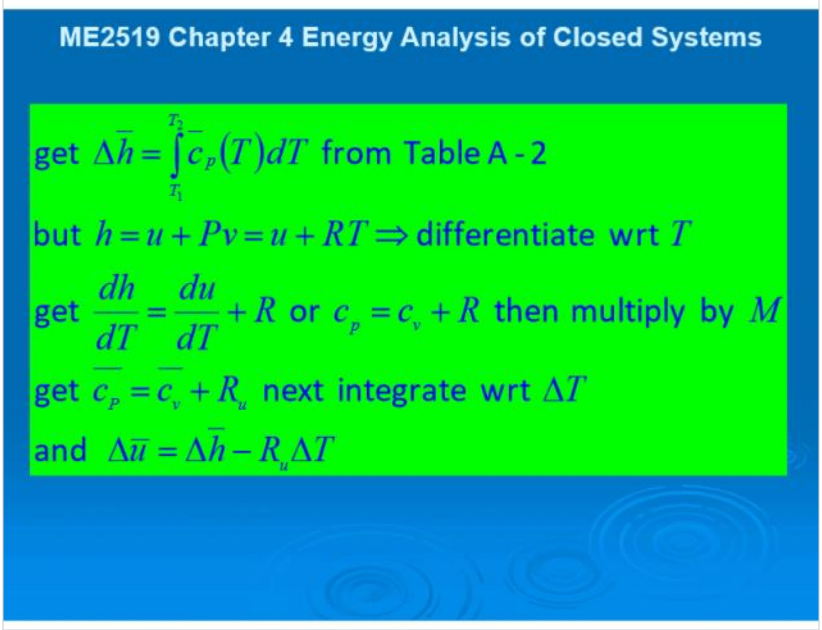
$\overline{c_P} = a + bT + cT^2 + dT^3 \quad (T(K))$

therefore $\Delta\bar{h} = \int_{T_1}^{T_2} \overline{c_P}dT$ becomes:

$$\Delta\bar{h} = \int_{T_1}^{T_2} (22.26 + 5.981\times10^{-2}T - 3.501\times10^{-5}T^2 + 7.469\times10^{-9}T^3)\ dT$$

$$\Delta\bar{h} = \left[22.26T + 5.981\times10^{-2}\frac{T^2}{2} - 3.501\times10^{-5}\frac{T^3}{3} + 7.469\times10^{-9}\frac{T^4}{4}\right]\Bigg|_{T_1}^{T_2}$$

and $\Delta h\ (kJ/kg) = \dfrac{\Delta\bar{h}\ (kJ/kmol)}{M_{CO_2}\ (kg/kmol)}$



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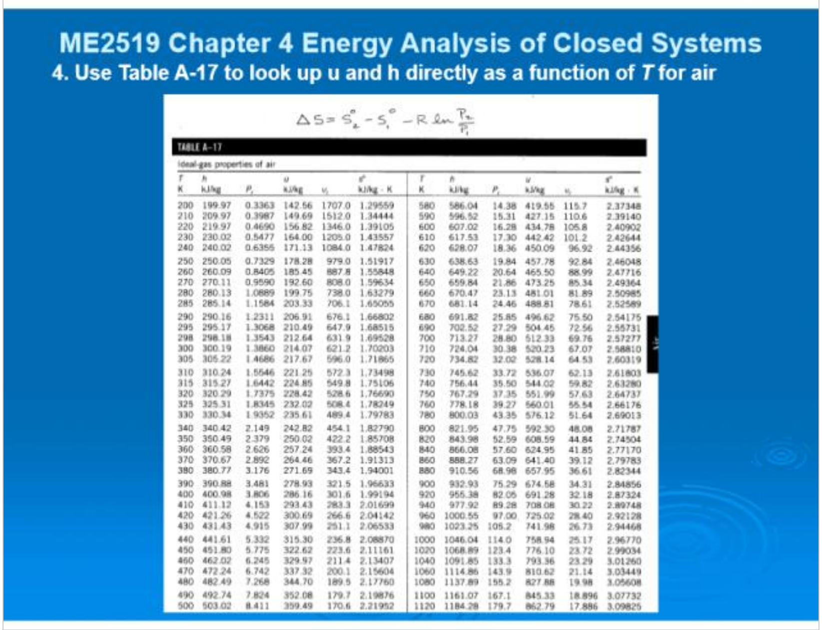
get $\Delta\bar{h} = \int_{T_1}^{T_2} \bar{c}_p(T)dT$ from Table A - 2

but $h = u + Pv = u + RT \Rightarrow$ differentiate wrt T

get $\dfrac{dh}{dT} = \dfrac{du}{dT} + R$ or $c_p = c_v + R$ then multiply by M

get $\bar{c}_P = \bar{c}_v + R_u$ next integrate wrt ΔT

and $\Delta\bar{u} = \Delta\bar{h} - R_u\Delta T$



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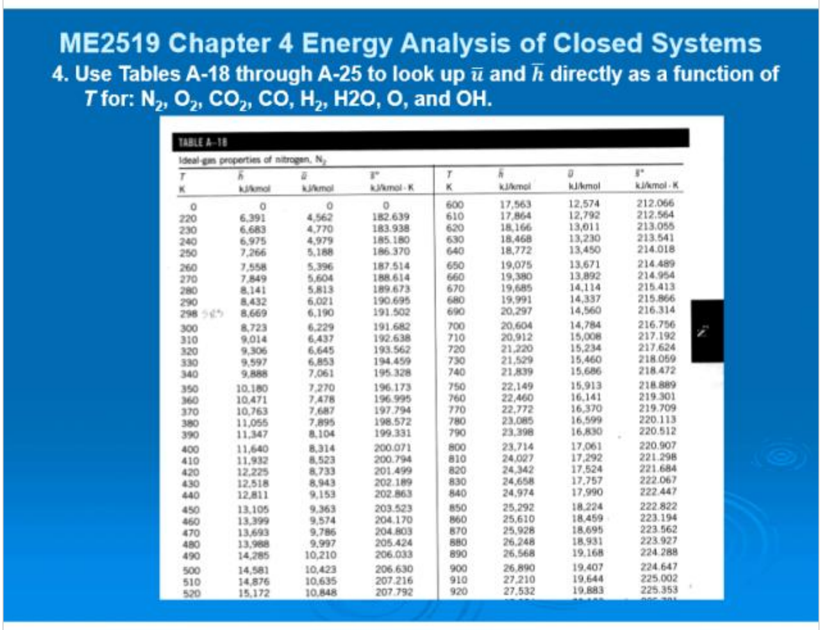
4. Use Table A-17 to look up u and h directly as a function of *T* for air

$$\Delta S = S_2^\circ - S_1^\circ - R \ln \frac{P_2}{P_1}$$

TABLE A-17

Ideal-gas properties of air

T K	h kJ/kg	P_r	u kJ/kg	v_r	s° kJ/kg · K	T K	h kJ/kg	P_r	u kJ/kg	v_r	s° kJ/kg · K
200	199.97	0.3363	142.56	1707.0	1.29559	580	586.04	14.38	419.55	115.7	2.37348
210	209.97	0.3987	149.69	1512.0	1.34444	590	596.52	15.31	427.15	110.6	2.39140
220	219.97	0.4690	156.82	1346.0	1.39105	600	607.02	16.28	434.78	105.8	2.40902
230	230.02	0.5477	164.00	1205.0	1.43557	610	617.53	17.30	442.42	101.2	2.42644
240	240.02	0.6355	171.13	1084.0	1.47824	620	628.07	18.36	450.09	96.92	2.44356
250	250.05	0.7329	178.28	979.0	1.51917	630	638.63	19.84	457.78	92.84	2.46048
260	260.09	0.8405	185.45	887.8	1.55848	640	649.22	20.64	465.50	88.99	2.47716
270	270.11	0.9590	192.60	808.0	1.59634	650	659.84	21.86	473.25	85.34	2.49364
280	280.13	1.0889	199.75	738.0	1.63279	660	670.47	23.13	481.01	81.89	2.50985
285	285.14	1.1584	203.33	706.1	1.65055	670	681.14	24.46	488.81	78.61	2.52589
290	290.16	1.2311	206.91	676.1	1.66802	680	691.82	25.85	496.62	75.50	2.54175
295	295.17	1.3068	210.49	647.9	1.68515	690	702.52	27.29	504.45	72.56	2.55731
298	298.18	1.3543	212.64	631.9	1.69528	700	713.27	28.80	512.33	69.76	2.57277
300	300.19	1.3860	214.07	621.2	1.70203	710	724.04	30.38	520.23	67.07	2.58810
305	305.22	1.4686	217.67	596.0	1.71865	720	734.82	32.02	528.14	64.53	2.60319
310	310.24	1.5546	221.25	572.3	1.73498	730	745.62	33.72	536.07	62.13	2.61803
315	315.27	1.6442	224.85	549.8	1.75106	740	756.44	35.50	544.02	59.82	2.63280
320	320.29	1.7375	228.42	528.6	1.76690	750	767.29	37.35	551.99	57.63	2.64737
325	325.31	1.8345	232.02	508.4	1.78249	760	778.18	39.27	560.01	55.54	2.66176
330	330.34	1.9352	235.61	489.4	1.79783	780	800.03	43.35	576.12	51.64	2.69013
340	340.42	2.149	242.82	454.1	1.82790	800	821.95	47.75	592.30	48.08	2.71787
350	350.49	2.379	250.02	422.2	1.85708	820	843.98	52.59	608.59	44.84	2.74504
360	360.58	2.626	257.24	393.4	1.88543	840	866.08	57.60	624.95	41.85	2.77170
370	370.67	2.892	264.46	367.2	1.91313	860	888.27	63.09	641.40	39.12	2.79783
380	380.77	3.176	271.69	343.4	1.94001	880	910.56	68.98	657.95	36.61	2.82344
390	390.88	3.481	278.93	321.5	1.96633	900	932.93	75.29	674.58	34.31	2.84856
400	400.98	3.806	286.16	301.6	1.99194	920	955.38	82.05	691.28	32.18	2.87324
410	411.12	4.153	293.43	283.3	2.01699	940	977.92	89.28	708.08	30.22	2.89748
420	421.26	4.522	300.69	266.6	2.04142	960	1000.55	97.00	725.02	28.40	2.92128
430	431.43	4.915	307.99	251.1	2.06533	980	1023.25	105.2	741.98	26.73	2.94468
440	441.61	5.332	315.30	236.8	2.08870	1000	1046.04	114.0	758.94	25.17	2.96770
450	451.80	5.775	322.62	223.6	2.11161	1020	1068.89	123.4	776.10	23.72	2.99034
460	462.02	6.245	329.97	211.4	2.13407	1040	1091.85	133.3	793.36	23.29	3.01260
470	472.24	6.742	337.32	200.1	2.15604	1060	1114.86	143.9	810.62	21.14	3.03449
480	482.49	7.268	344.70	189.5	2.17760	1080	1137.89	155.2	827.88	19.98	3.05608
490	492.74	7.824	352.08	179.7	2.19876	1100	1161.07	167.1	845.33	18.896	3.07732
500	503.02	8.411	359.49	170.6	2.21952	1120	1184.28	179.7	862.79	17.886	3.09825



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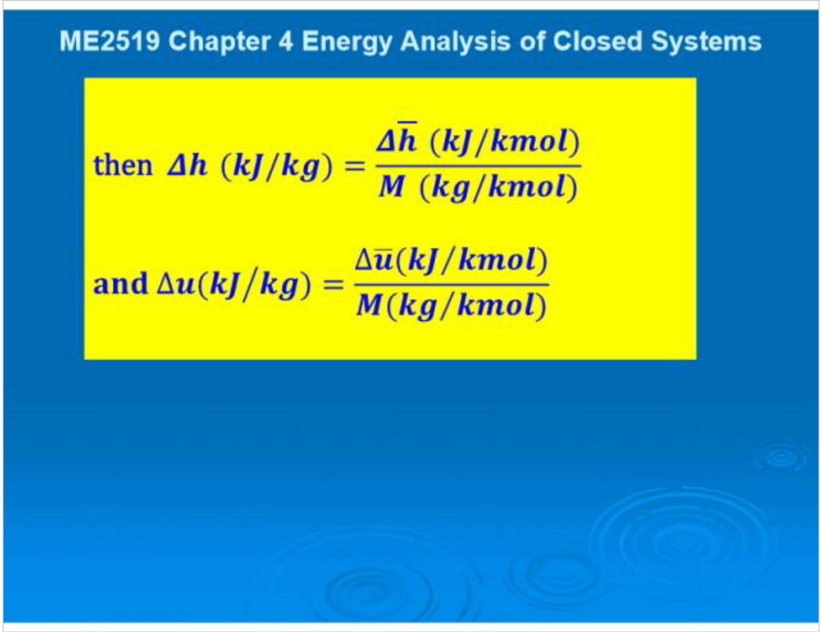
4. Use Tables A-18 through A-25 to look up $\overline{u}$ and $\overline{h}$ directly as a function of *T* for: N_2, O_2, CO_2, CO, H_2, H2O, O, and OH.

TABLE A-18

Ideal-gas properties of nitrogen, N_2

T K	$\overline{h}$ kJ/kmol	$\overline{u}$ kJ/kmol	$\overline{s}^\circ$ kJ/kmol · K	T K	$\overline{h}$ kJ/kmol	$\overline{u}$ kJ/kmol	$\overline{s}^\circ$ kJ/kmol · K
0	0	0	0	600	17,563	12,574	212.066
220	6,391	4,562	182.639	610	17,864	12,792	212.564
230	6,683	4,770	183.938	620	18,166	13,011	213.055
240	6,975	4,979	185.180	630	18,468	13,230	213.541
250	7,266	5,188	186.370	640	18,772	13,450	214.018
260	7,558	5,396	187.514	650	19,075	13,671	214.489
270	7,849	5,604	188.614	660	19,380	13,892	214.954
280	8,141	5,813	189.673	670	19,685	14,114	215.413
290	8,432	6,021	190.695	680	19,991	14,337	215.866
298	8,669	6,190	191.502	690	20,297	14,560	216.314
300	8,723	6,229	191.682	700	20,604	14,784	216.756
310	9,014	6,437	192.638	710	20,912	15,008	217.192
320	9,306	6,645	193.562	720	21,220	15,234	217.624
330	9,597	6,853	194.459	730	21,529	15,460	218.059
340	9,888	7,061	195.328	740	21,839	15,686	218.472
350	10,180	7,270	196.173	750	22,149	15,913	218.889
360	10,471	7,478	196.995	760	22,460	16,141	219.301
370	10,763	7,687	197.794	770	22,772	16,370	219.709
380	11,055	7,895	198.572	780	23,085	16,599	220.113
390	11,347	8,104	199.331	790	23,398	16,830	220.512
400	11,640	8,314	200.071	800	23,714	17,061	220.907
410	11,932	8,523	200.794	810	24,027	17,292	221.298
420	12,225	8,733	201.499	820	24,342	17,524	221.684
430	12,518	8,943	202.189	830	24,658	17,757	222.067
440	12,811	9,153	202.863	840	24,974	17,990	222.447
450	13,105	9,363	203.523	850	25,292	18,224	222.822
460	13,399	9,574	204.170	860	25,610	18,459	223.194
470	13,693	9,786	204.803	870	25,928	18,695	223.562
480	13,988	9,997	205.424	880	26,248	18,931	223.927
490	14,285	10,210	206.033	890	26,568	19,168	224.288
500	14,581	10,423	206.630	900	26,890	19,407	224.647
510	14,876	10,635	207.216	910	27,210	19,644	225.002
520	15,172	10,848	207.792	920	27,532	19,883	225.353



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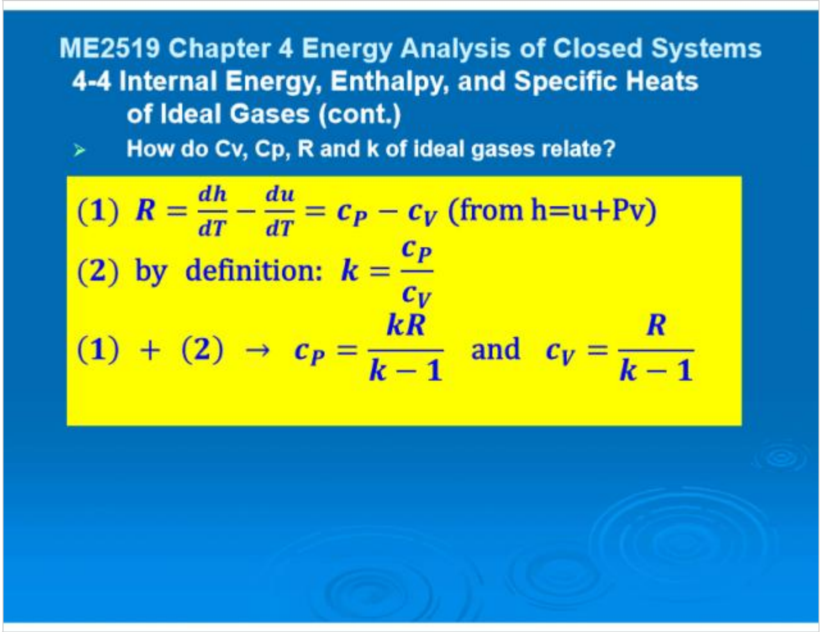
$$\text{then } \Delta h\ (kJ/kg) = \frac{\Delta \bar{h}\ (kJ/kmol)}{M\ (kg/kmol)}$$

$$\text{and } \Delta u (kJ/kg) = \frac{\Delta \bar{u} (kJ/kmol)}{M (kg/kmol)}$$



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4-4 Internal Energy, Enthalpy, and Specific Heats of Ideal Gases (cont.)

- How do Cv, Cp, R and k of ideal gases relate?

$$(1)\ R = \frac{dh}{dT} - \frac{du}{dT} = c_P - c_V \text{ (from h=u+Pv)}$$

$$(2)\ \text{by definition: } k = \frac{c_P}{c_V}$$

$$(1) + (2) \rightarrow c_P = \frac{kR}{k-1} \text{ and } c_V = \frac{R}{k-1}$$

4-52 $T =$ const

Find ΔV Δh

$Pv = RT \rightarrow v_1 , v_2$

$\Delta h = c_p \Delta T = 0$

4-61 Ideal gas Vol = Const

Find P_2 and Q_{out}

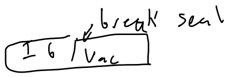
$P Vol = mRT$

$Q_{out} = m(u_1 - u_2)$

$Q_{out} = m\, c_v (T_1 - T_2)$

$P_2 Vol = mRT_2$

4-65 Ideal Gas



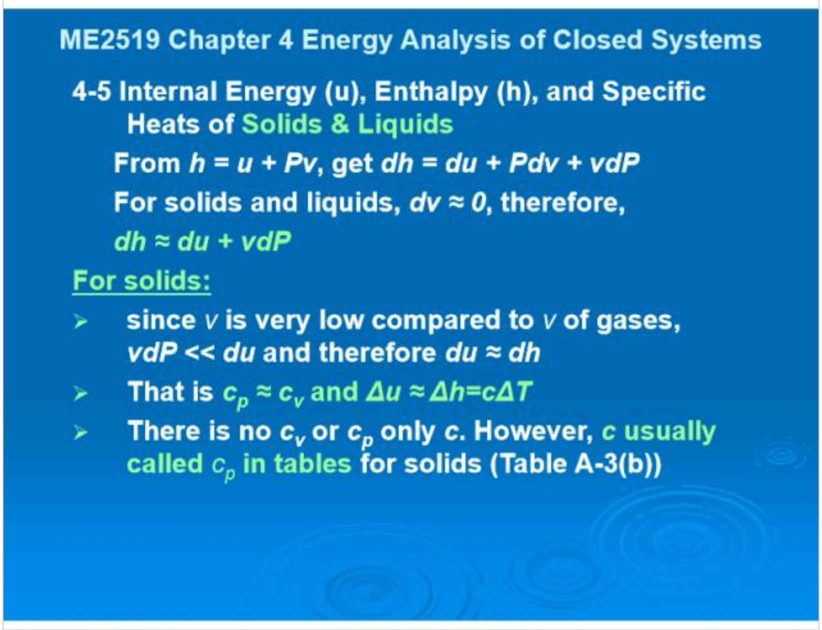
$\frac{Vol_2}{Vol_1}$

Find T_2 P_2

$T =$ constant

$PVol = mRT$

$\frac{T_2}{P_2} = \frac{2T_1}{P_1}$



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4-5 Internal Energy (u), Enthalpy (h), and Specific Heats of Solids & Liquids

From $h = u + Pv$, get $dh = du + Pdv + vdP$

For solids and liquids, $dv \approx 0$, therefore,

$dh \approx du + vdP$

For solids:

- since v is very low compared to v of gases, $vdP << du$ and therefore $du \approx dh$
- That is $c_p \approx c_v$ and $\Delta u \approx \Delta h = c\Delta T$
- There is no c_v or c_p only c. However, c usually called c_p in tables for solids (Table A-3(b))

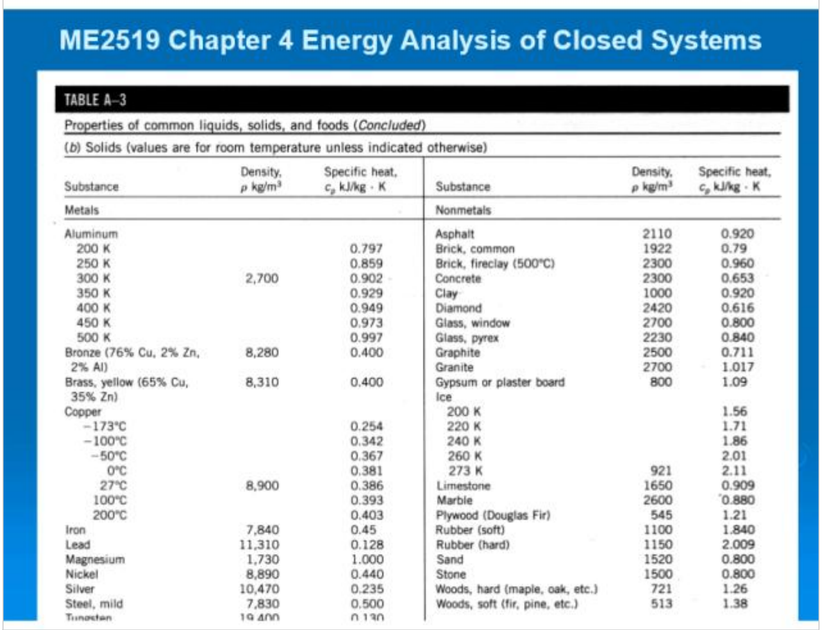

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TABLE A–3

Properties of common liquids, solids, and foods (*Concluded*)

(*b*) Solids (values are for room temperature unless indicated otherwise)

Substance	Density, ρ kg/m³	Specific heat, c_p kJ/kg · K	Substance	Density, ρ kg/m³	Specific heat, c_p kJ/kg · K
Metals			Nonmetals		
Aluminum			Asphalt	2110	0.920
200 K		0.797	Brick, common	1922	0.79
250 K		0.859	Brick, fireclay (500°C)	2300	0.960
300 K	2,700	0.902	Concrete	2300	0.653
350 K		0.929	Clay	1000	0.920
400 K		0.949	Diamond	2420	0.616
450 K		0.973	Glass, window	2700	0.800
500 K		0.997	Glass, pyrex	2230	0.840
Bronze (76% Cu, 2% Zn, 2% Al)	8,280	0.400	Graphite	2500	0.711
			Granite	2700	1.017
Brass, yellow (65% Cu, 35% Zn)	8,310	0.400	Gypsum or plaster board	800	1.09
			Ice		
Copper			200 K		1.56
−173°C		0.254	220 K		1.71
−100°C		0.342	240 K		1.86
−50°C		0.367	260 K		2.01
0°C		0.381	273 K	921	2.11
27°C	8,900	0.386	Limestone	1650	0.909
100°C		0.393	Marble	2600	0.880
200°C		0.403	Plywood (Douglas Fir)	545	1.21
Iron	7,840	0.45	Rubber (soft)	1100	1.840
Lead	11,310	0.128	Rubber (hard)	1150	2.009
Magnesium	1,730	1.000	Sand	1520	0.800
Nickel	8,890	0.440	Stone	1500	0.800
Silver	10,470	0.235	Woods, hard (maple, oak, etc.)	721	1.26
Steel, mild	7,830	0.500	Woods, soft (fir, pine, etc.)	513	1.38
Tungsten	19,400	0.130			

ME2519 Chapter 4 Energy Analysis of Closed Systems

4-5 Internal Energy (u), Enthalpy (h), and Specific Heats of Solids & Liquids (cont.)

For liquids:

Calculation of Δu and Δh depends on the process:

- **For a constant P process:**
  - $dh \approx du + vdP$, $vdP = 0$
  - **therefore $\Delta u \approx \Delta h = C\Delta T$**
  - **process is the heating or cooling of a liquid that remains in the liquid state (i.e. it's subcooled and remains subcooled)**
  - **c values in Table A-3(a)**
- **For a constant T process:**
  - $du << vdP$ **since** du **is driven by** T
  - **therefore,** $\Delta u \approx 0$ **and** $\Delta h \approx v\Delta P$.
  - **process occurs in a pump:** P **increases with very little change in** T

ME2519 Chapter 4 Energy Analysis of Closed Systems

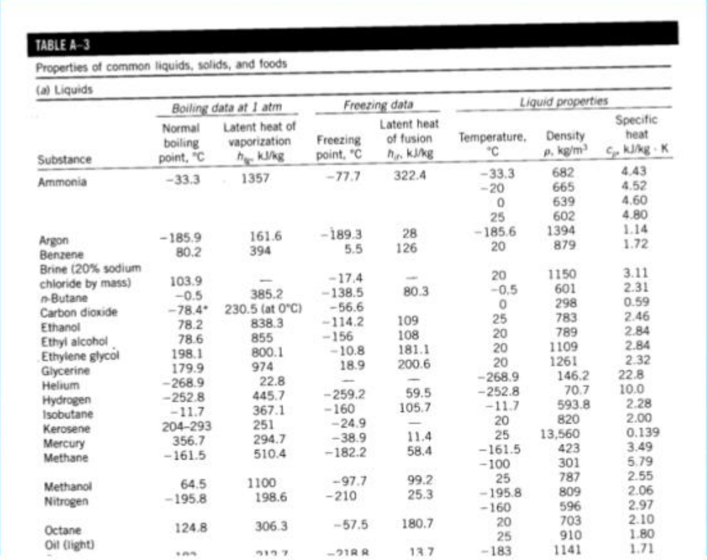


TABLE A–3

Properties of common liquids, solids, and foods

(a) Liquids

	Boiling data at 1 atm		*Freezing data*		*Liquid properties*		
Substance	Normal boiling point, °C	Latent heat of vaporization h_{fg}, kJ/kg	Freezing point, °C	Latent heat of fusion h_{if}, kJ/kg	Temperature, °C	Density ρ, kg/m³	Specific heat c_p, kJ/kg · K
Ammonia	−33.3	1357	−77.7	322.4	−33.3	682	4.43
					−20	665	4.52
					0	639	4.60
					25	602	4.80
Argon	−185.9	161.6	−189.3	28	−185.6	1394	1.14
Benzene	80.2	394	5.5	126	20	879	1.72
Brine (20% sodium chloride by mass)	103.9	—	−17.4	—	20	1150	3.11
n-Butane	−0.5	385.2	−138.5	80.3	−0.5	601	2.31
Carbon dioxide	−78.4*	230.5 (at 0°C)	−56.6		0	298	0.59
Ethanol	78.2	838.3	−114.2	109	25	783	2.46
Ethyl alcohol	78.6	855	−156	108	20	789	2.84
Ethylene glycol	198.1	800.1	−10.8	181.1	20	1109	2.84
Glycerine	179.9	974	18.9	200.6	20	1261	2.32
Helium	−268.9	22.8	—	—	−268.9	146.2	22.8
Hydrogen	−252.8	445.7	−259.2	59.5	−252.8	70.7	10.0
Isobutane	−11.7	367.1	−160	105.7	−11.7	593.8	2.28
Kerosene	204–293	251	−24.9	—	20	820	2.00
Mercury	356.7	294.7	−38.9	11.4	25	13,560	0.139
Methane	−161.5	510.4	−182.2	58.4	−161.5	423	3.49
					−100	301	5.79
Methanol	64.5	1100	−97.7	99.2	25	787	2.55
Nitrogen	−195.8	198.6	−210	25.3	−195.8	809	2.06
					−160	596	2.97
Octane	124.8	306.3	−57.5	180.7	20	703	2.10
Oil (light)					25	910	1.80
	[illegible]	[illegible]	[illegible]	13.7	−183	1141	1.71

HW 4b

Tuesday, October 4, 2022 1:10 PM

4–52 Neon is compressed from 100 kPa and 20°C to 500 kPa in an isothermal compressor. Determine the change in the specific volume and specific enthalpy of neon caused by this compression.

$Pv = RT$ $\qquad R_{Neon} = .4119 \frac{kJ}{kg\cdot K}$

$v_1 = \frac{RT}{P_1} = \frac{.4119 \frac{kJ}{kg\cdot K}(293\,K)}{100\,kPa} = 1.207 \frac{m^3}{kg}$

$v_2 = \frac{RT}{P_2} = \frac{.4119\, kJ/kg\cdot K\,(293\,K)}{500} = .241 \frac{m^3}{kg}$

$\Delta v = v_2 - v_1 = \boxed{-.965 \frac{m^3}{kg}}$

T = Constant

$\Delta T = 0$

$\boxed{\Delta h = C_p \cancelto{0}{\Delta T} = 0}$

4–61 A 3-m^3 rigid tank contains hydrogen at 250 kPa and 550 K. The gas is now cooled until its temperature drops to 350 K. Determine (*a*) the final pressure in the tank and (*b*) the amount of heat transfer.

$\Delta u = -Q_{out}$

$m(u_1 - u_2) = -Q_{out}$ $\qquad T_{avg} = 450$

$Q_{out} = m C_v (T_1 - T_2)$ $\qquad C_{v\,H_2} @ T_{avg} (A\text{-}2): 10.377 \frac{kJ}{kg}$

$P Vol = m R T$ $\qquad R_{H_2} = 4.1240 \frac{kJ}{kg\cdot k}$

$m = \frac{P_1 Vol}{R T_1} = \frac{250\,kPa\,(3\,m^3)}{(4.124\,kJ/kg\cdot k)(550\,k)}$

$m = .331\,kg$

$Q_{out} = .331\,kg\,(10.377 \frac{kJ}{kg\cdot K})(550\,k - 350\,k) = \boxed{686.249\,kJ}$

$P_2 = \frac{m R T_2}{Vol} = \frac{.331\,kg\,(4.124\,kJ/kg\cdot k)(350\,k)}{3\,m^3} = \boxed{154.09\,kPa}$

4–65 An insulated rigid tank is divided into two equal parts by a partition. Initially, one part contains 4 kg of an ideal gas at 800 kPa and 50°C, and the other part is evacuated. The partition is now removed, and the gas expands into the entire tank. Determine the final temperature and pressure in the tank.

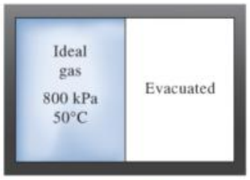


FIGURE P4–65

$\boxed{T = Const}$ $\qquad \Delta U + \cancelto{0}{\Delta KE} + \cancelto{0}{\Delta PE} = \cancelto{0}{Q_{in}} - \cancelto{0}{Q_{out}} + \cancelto{0}{W_{in}} - \cancelto{0}{W_{out}}$

FIGURE P4–65

$$\boxed{\begin{array}{l} T = \text{Const} \\ T_1 = T_2 = 50°C \end{array}}$$

$$\Delta U + \Delta \cancel{KE}^{0} + \Delta \cancel{PE}^{0} = \cancel{Q_{in}}^{0} - \cancel{Q_{out}}^{0} + \cancel{W_{in}}^{0} - \cancel{W_{out}}^{0}$$

$$\Delta U = 0 = m(u_2 - u_1)$$

$$T_2 = T_1$$

$$P\,Vol = mRT$$

$$\frac{Vol_2}{Vol_1} = \frac{2}{1} = \frac{mRT_2\,P_1}{mRT_1\,P_2} = \frac{P_1}{P_2}$$

$$P_2 = \frac{P_1}{2} = \frac{800\text{ kPa}}{2} = \boxed{400\text{ kPa}}$$

4–84 Consider a 1000-W iron whose base plate is made of 0.5-cm-thick aluminum alloy 2024-T6 ($\rho = 2770\ \text{kg/m}^3$ and $c_p = 875\ \text{J/kg·°C}$). The base plate has a surface area of 0.03 m^2. Initially, the iron is in thermal equilibrium with the ambient air at 22°C. Assuming 90 percent of the heat generated in the resistance wires is transferred to the plate, determine the minimum time needed for the plate temperature to reach 200°C.

FIGURE P4–84

$$\dot{Q}_{out} = Q_{in}\,n = 1000\,W \cdot .9 = 900\,W$$

$$\Delta U + \Delta \cancel{KE}^{0} + \Delta \cancel{PE}^{0} = Q_{in} - \cancel{Q_{out}}^{0} + \cancel{W_{in}}^{0} - \cancel{W_{out}}^{0}$$

$$\Delta U = Q_{in} = \dot{Q}\Delta t$$

$$\Delta t = \frac{\Delta U}{\dot{Q}} = \frac{m\,c_p(T_2 - T_1)}{\dot{Q}}$$

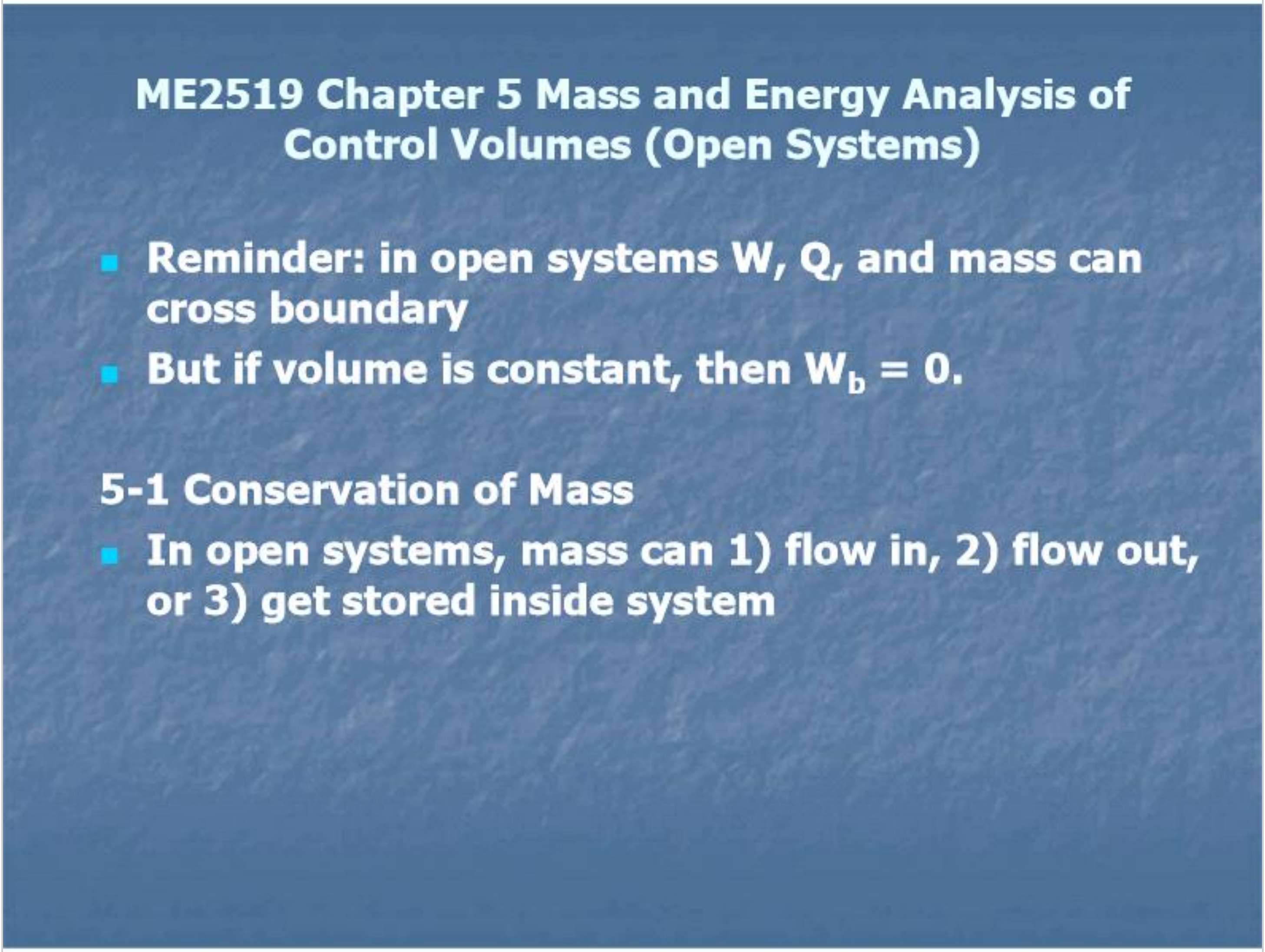
$$\Delta t = (2770\tfrac{kg}{m^3})(.03\,m^2)(.005\,m)\,\frac{875\,J/kg\cdot C\,(200-22)C}{.9\,kW}\;\frac{1\,kJ}{1000\,J}$$

$$\boxed{\Delta t = 71.9\,s}$$

Open Systems

Monday, October 3, 2022 10:02 AM

PDF+Slides +5-1+thru...

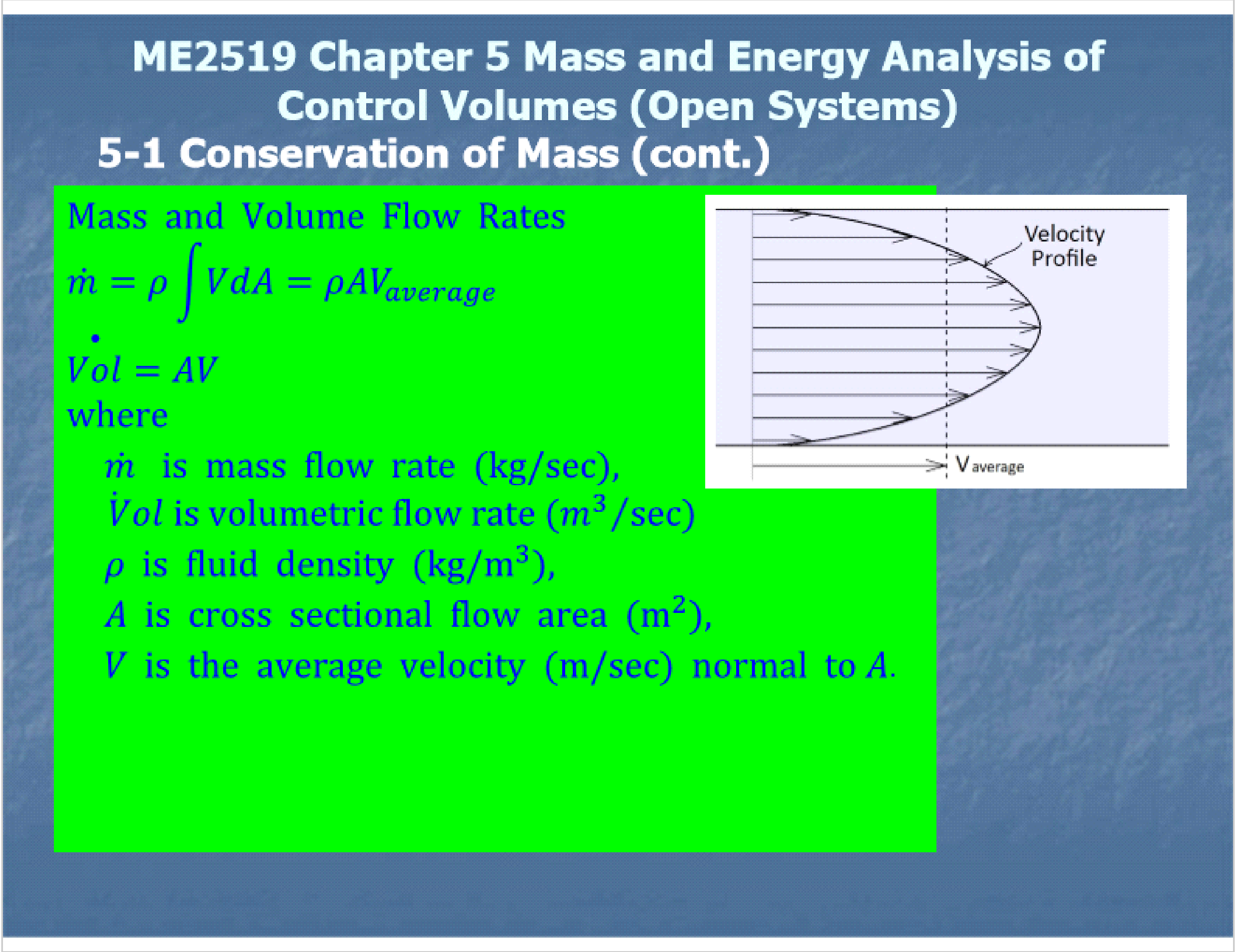


ME2519 Chapter 5 Mass and Energy Analysis of Control Volumes (Open Systems)

- **Reminder: in open systems W, Q, and mass can cross boundary**
- **But if volume is constant, then $W_b = 0$.**

5-1 Conservation of Mass

- **In open systems, mass can 1) flow in, 2) flow out, or 3) get stored inside system**



ME2519 Chapter 5 Mass and Energy Analysis of Control Volumes (Open Systems)

5-1 Conservation of Mass (cont.)

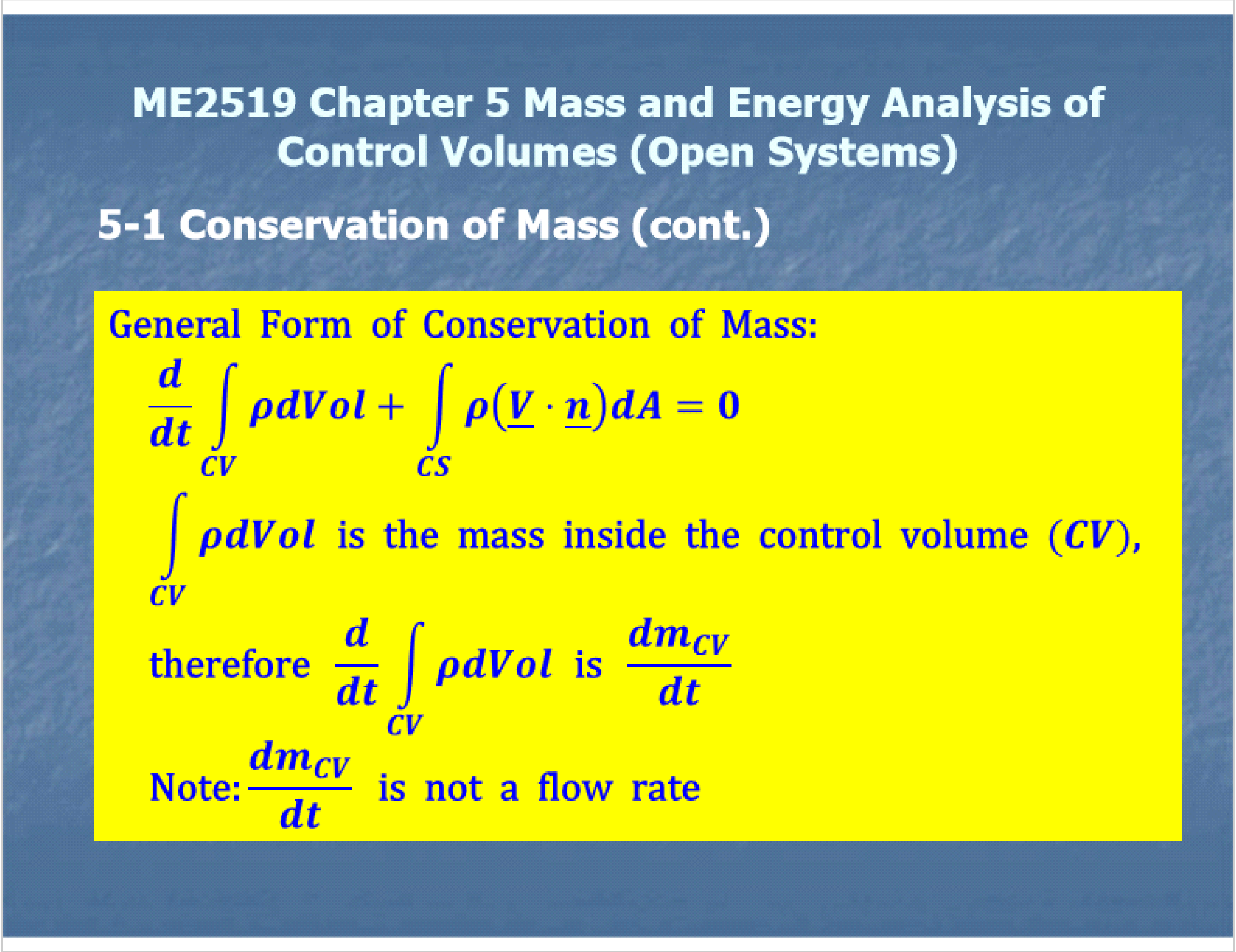
Mass and Volume Flow Rates

$$\dot{m} = \rho \int V dA = \rho A V_{average}$$

$$\dot{Vol} = AV$$

where

$\dot{m}$ is mass flow rate (kg/sec),
$\dot{Vol}$ is volumetric flow rate (m^3/sec)
ρ is fluid density (kg/m^3),
A is cross sectional flow area (m^2),
V is the average velocity (m/sec) normal to A.



ME2519 Chapter 5 Mass and Energy Analysis of Control Volumes (Open Systems)

5-1 Conservation of Mass (cont.)

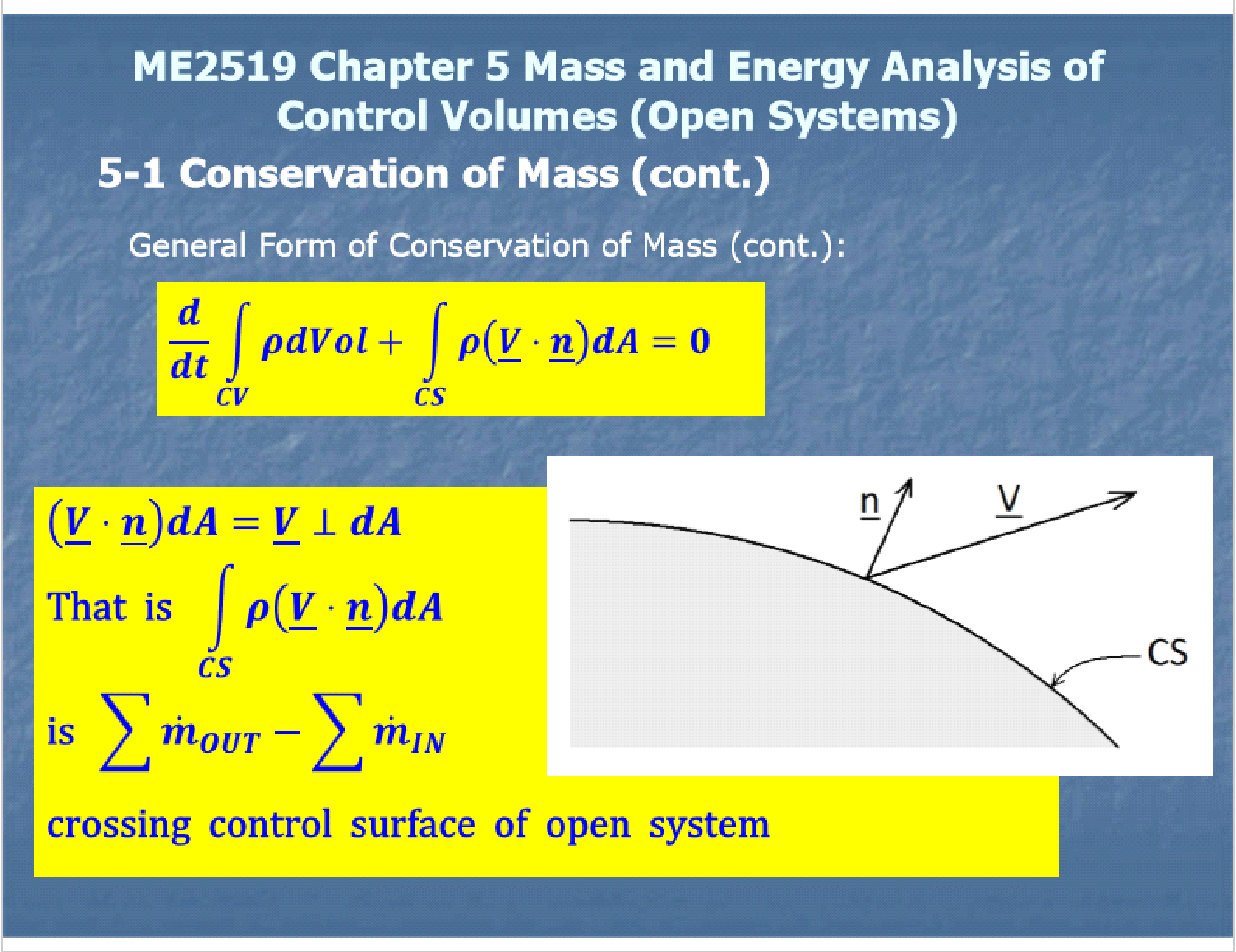
General Form of Conservation of Mass:

$$\frac{d}{dt}\int_{CV}\rho dVol+\int_{CS}\rho(\underline{V}\cdot\underline{n})dA=0$$

$\int_{CV}\rho dVol$ is the mass inside the control volume (CV),

therefore $\frac{d}{dt}\int_{CV}\rho dVol$ is $\frac{dm_{CV}}{dt}$

Note: $\frac{dm_{CV}}{dt}$ is not a flow rate



ME2519 Chapter 5 Mass and Energy Analysis of Control Volumes (Open Systems)

5-1 Conservation of Mass (cont.)

General Form of Conservation of Mass (cont.):

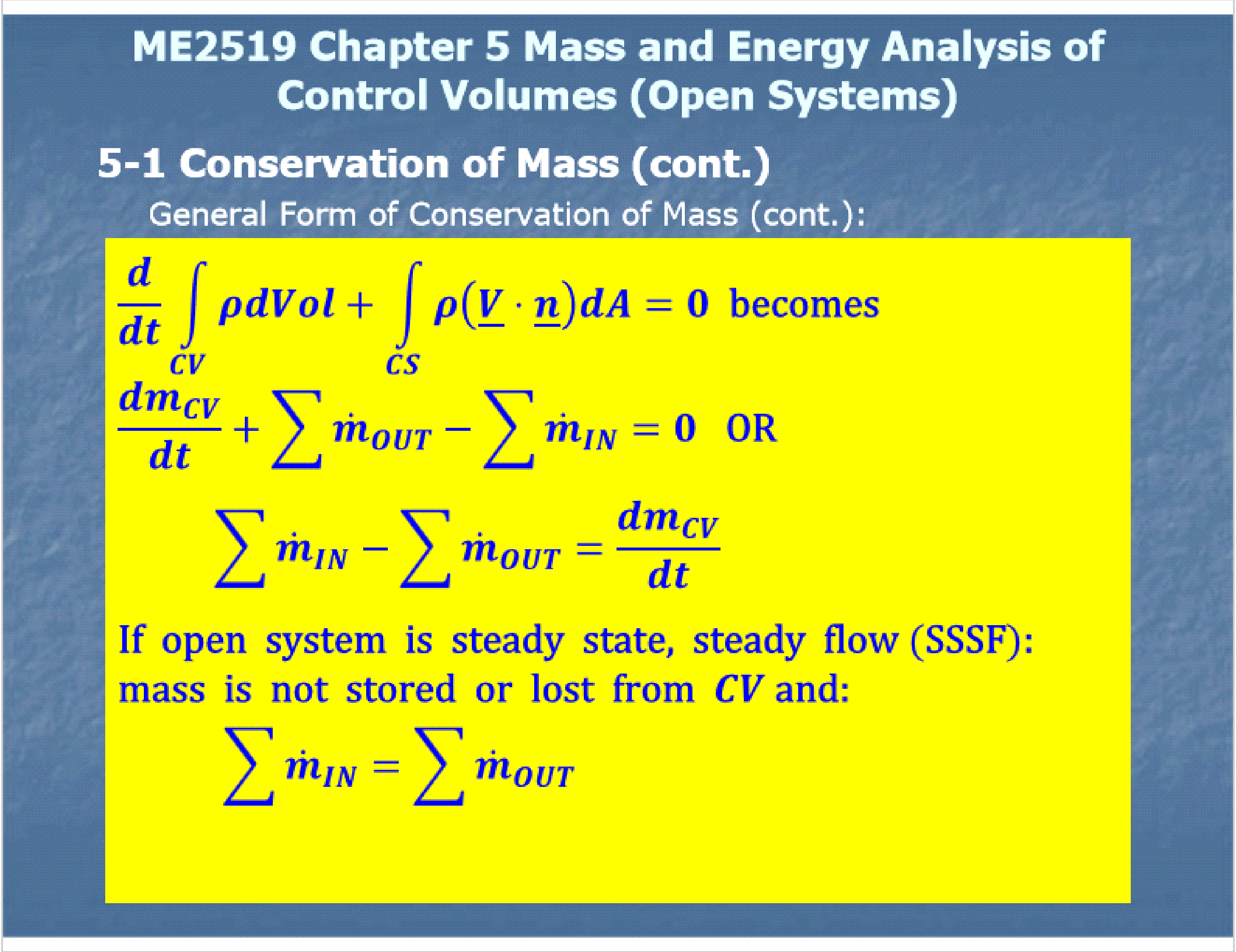
$$\frac{d}{dt}\int_{CV} \rho dVol + \int_{CS} \rho(\underline{V}\cdot\underline{n})dA = 0$$

$$(\underline{V}\cdot\underline{n})dA = \underline{V}\perp dA$$

That is $\int_{CS} \rho(\underline{V}\cdot\underline{n})dA$

is $\sum \dot{m}_{OUT} - \sum \dot{m}_{IN}$

crossing control surface of open system



ME2519 Chapter 5 Mass and Energy Analysis of Control Volumes (Open Systems)

5-1 Conservation of Mass (cont.)

General Form of Conservation of Mass (cont.):

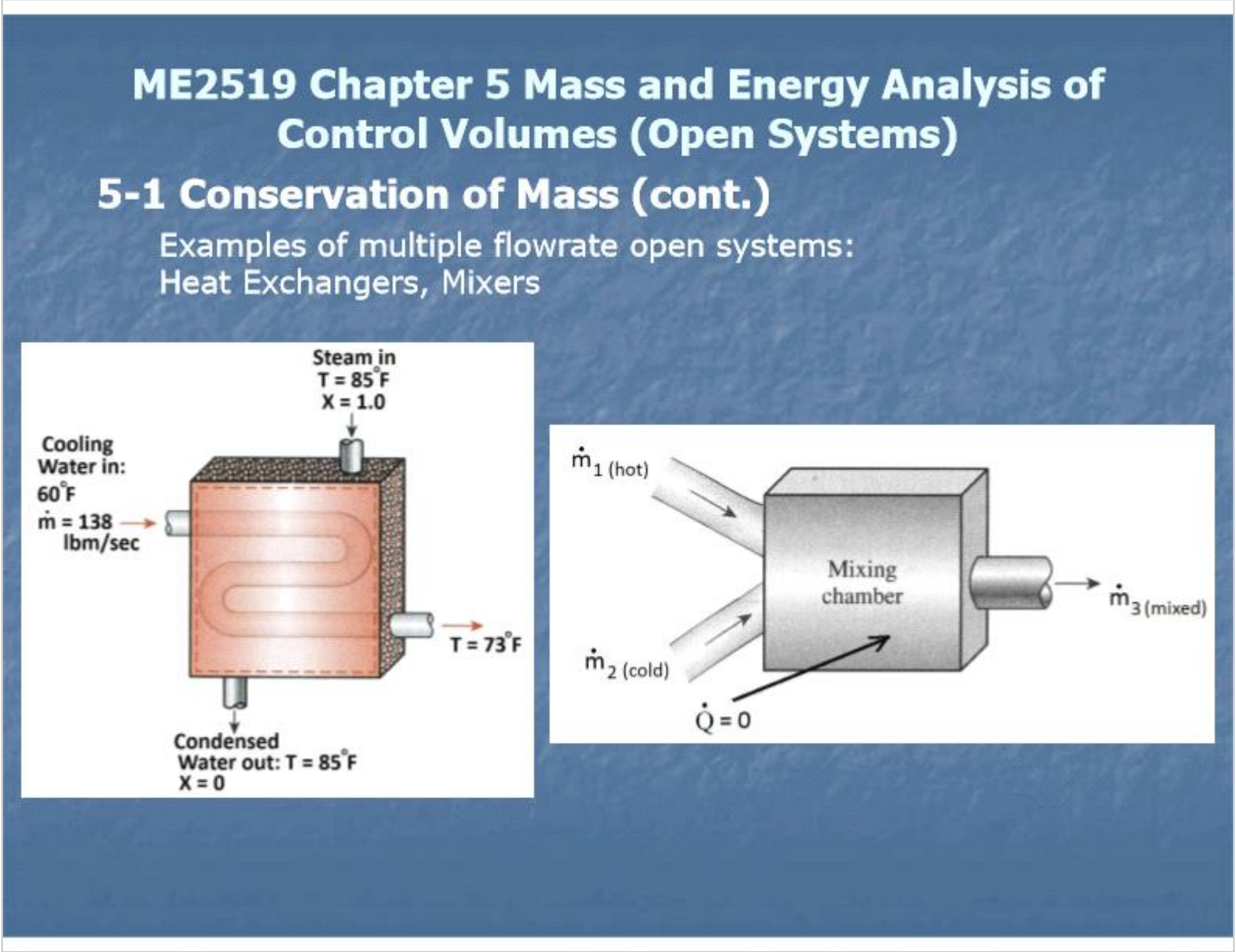
$$\frac{d}{dt}\int_{CV}\rho dVol+\int_{CS}\rho(\underline{V}\cdot\underline{n})dA=0 \text{ becomes}$$

$$\frac{dm_{CV}}{dt}+\sum\dot{m}_{OUT}-\sum\dot{m}_{IN}=0 \text{ OR}$$

$$\sum\dot{m}_{IN}-\sum\dot{m}_{OUT}=\frac{dm_{CV}}{dt}$$

If open system is steady state, steady flow (SSSF): mass is not stored or lost from CV and:

$$\sum\dot{m}_{IN}=\sum\dot{m}_{OUT}$$



ME2519 Chapter 5 Mass and Energy Analysis of Control Volumes (Open Systems)

5-1 Conservation of Mass (cont.)

Examples of multiple flowrate open systems:
Heat Exchangers, Mixers

ME2519 Chapter 5 Mass and Energy Analysis of Control Volumes (Open Systems)

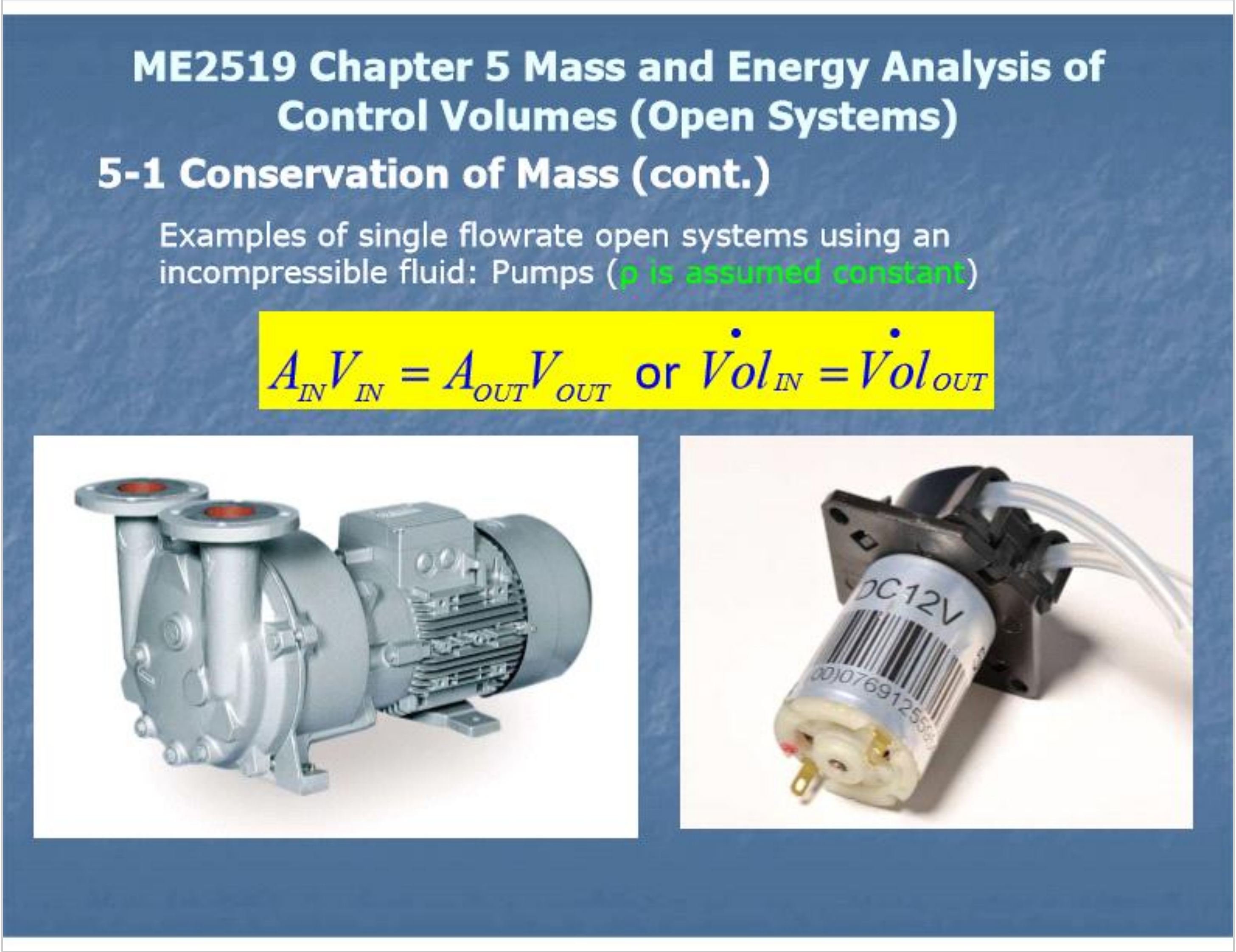
5-1 Conservation of Mass (cont.)

Examples of single flowrate open systems: Compressors

$\dot{m}_{IN} = \dot{m}_{OUT}$ therefore

$\rho_{IN} A_{IN} V_{IN} = \rho_{OUT} A_{OUT} V_{OUT}$

Car AC: note the two lines going into the AC compressor: the **larger** is the low pressure inlet;
the **smaller** is the high pressure discharge

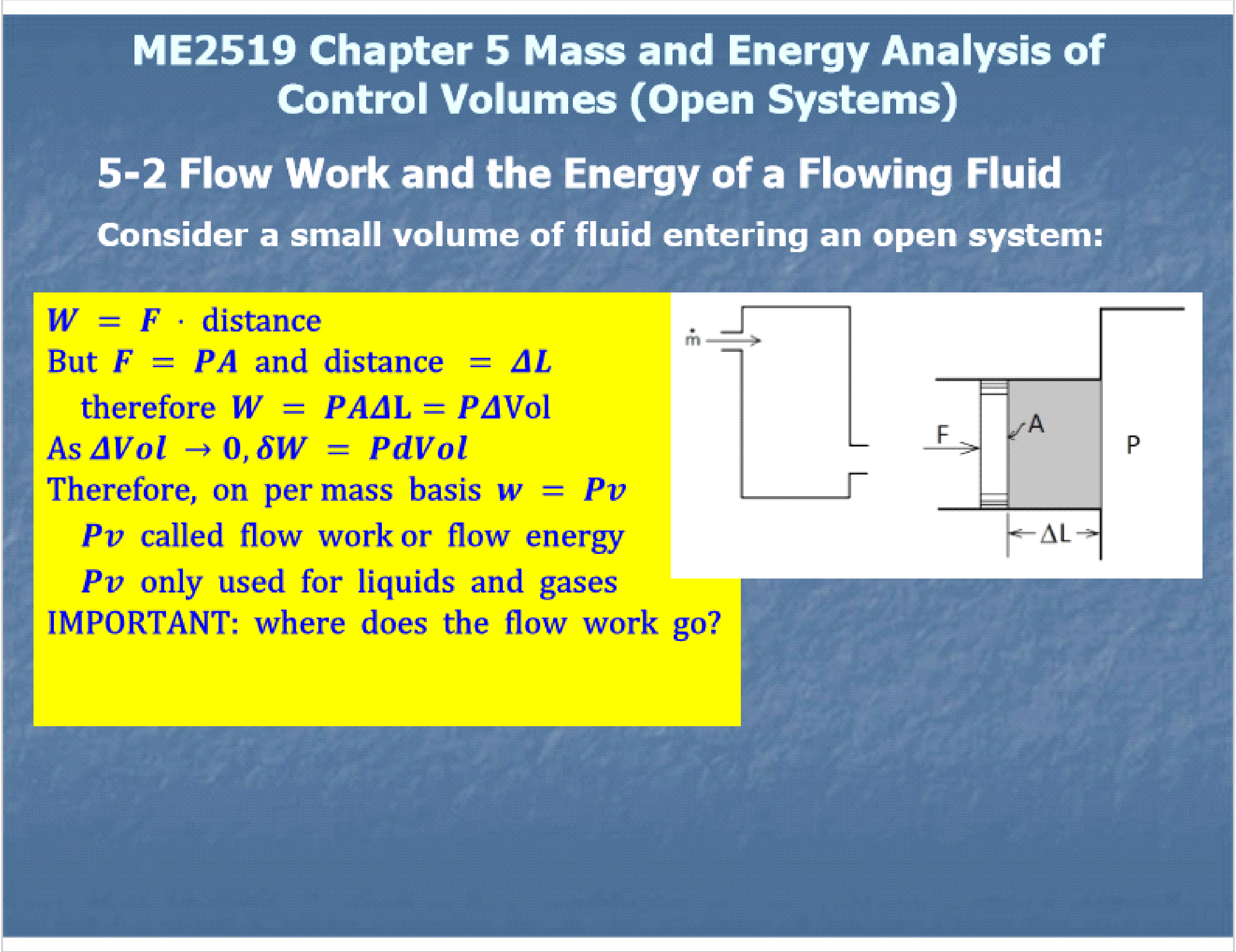


ME2519 Chapter 5 Mass and Energy Analysis of Control Volumes (Open Systems)

5-1 Conservation of Mass (cont.)

Examples of single flowrate open systems using an incompressible fluid: Pumps (ρ is assumed constant)

$$A_{IN}V_{IN} = A_{OUT}V_{OUT} \text{ or } \dot{Vol}_{IN} = \dot{Vol}_{OUT}$$



ME2519 Chapter 5 Mass and Energy Analysis of Control Volumes (Open Systems)

5-2 Flow Work and the Energy of a Flowing Fluid

Consider a small volume of fluid entering an open system:

$\boldsymbol{W} = \boldsymbol{F} \cdot$ distance

But $\boldsymbol{F} = \boldsymbol{PA}$ and distance $= \boldsymbol{\Delta L}$

therefore $\boldsymbol{W} = \boldsymbol{PA\Delta}\mathrm{L} = \boldsymbol{P\Delta}\mathrm{Vol}$

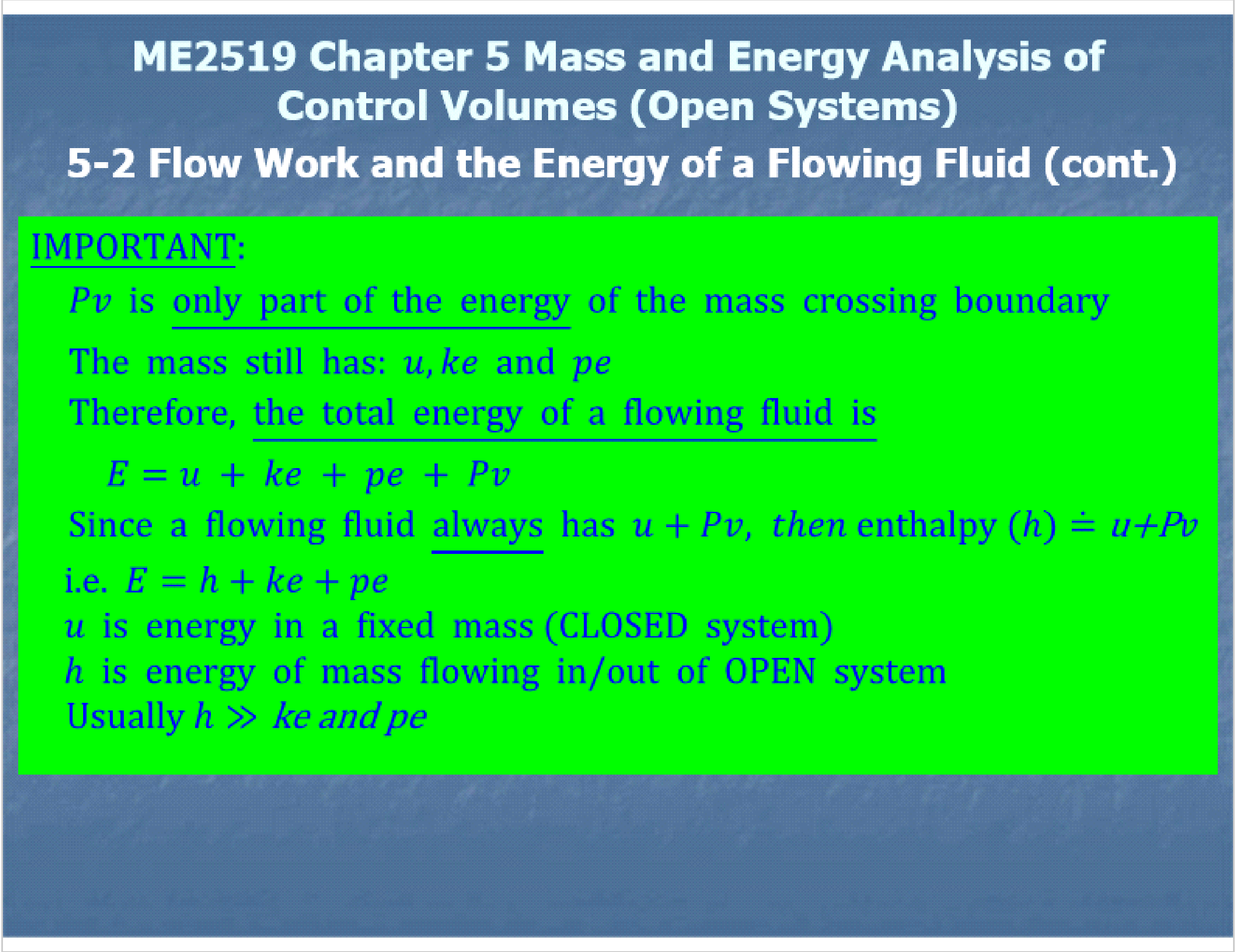
As $\boldsymbol{\Delta Vol} \rightarrow \mathbf{0}, \boldsymbol{\delta W} = \boldsymbol{PdVol}$

Therefore, on per mass basis $\boldsymbol{w} = \boldsymbol{Pv}$

$\boldsymbol{Pv}$ called flow work or flow energy

$\boldsymbol{Pv}$ only used for liquids and gases

IMPORTANT: where does the flow work go?



ME2519 Chapter 5 Mass and Energy Analysis of Control Volumes (Open Systems)

5-2 Flow Work and the Energy of a Flowing Fluid (cont.)

IMPORTANT:

Pv is only part of the energy of the mass crossing boundary

The mass still has: u, ke and pe

Therefore, the total energy of a flowing fluid is

$$E = u + ke + pe + Pv$$

Since a flowing fluid always has $u + Pv$, *then* enthalpy $(h) \doteq u+Pv$

i.e. $E = h + ke + pe$

u is energy in a fixed mass (CLOSED system)

h is energy of mass flowing in/out of OPEN system

Usually $h \gg ke \text{ and } pe$

Energy Analysis of Steady Flow Systems

Friday, October 14, 2022 10:00 AM

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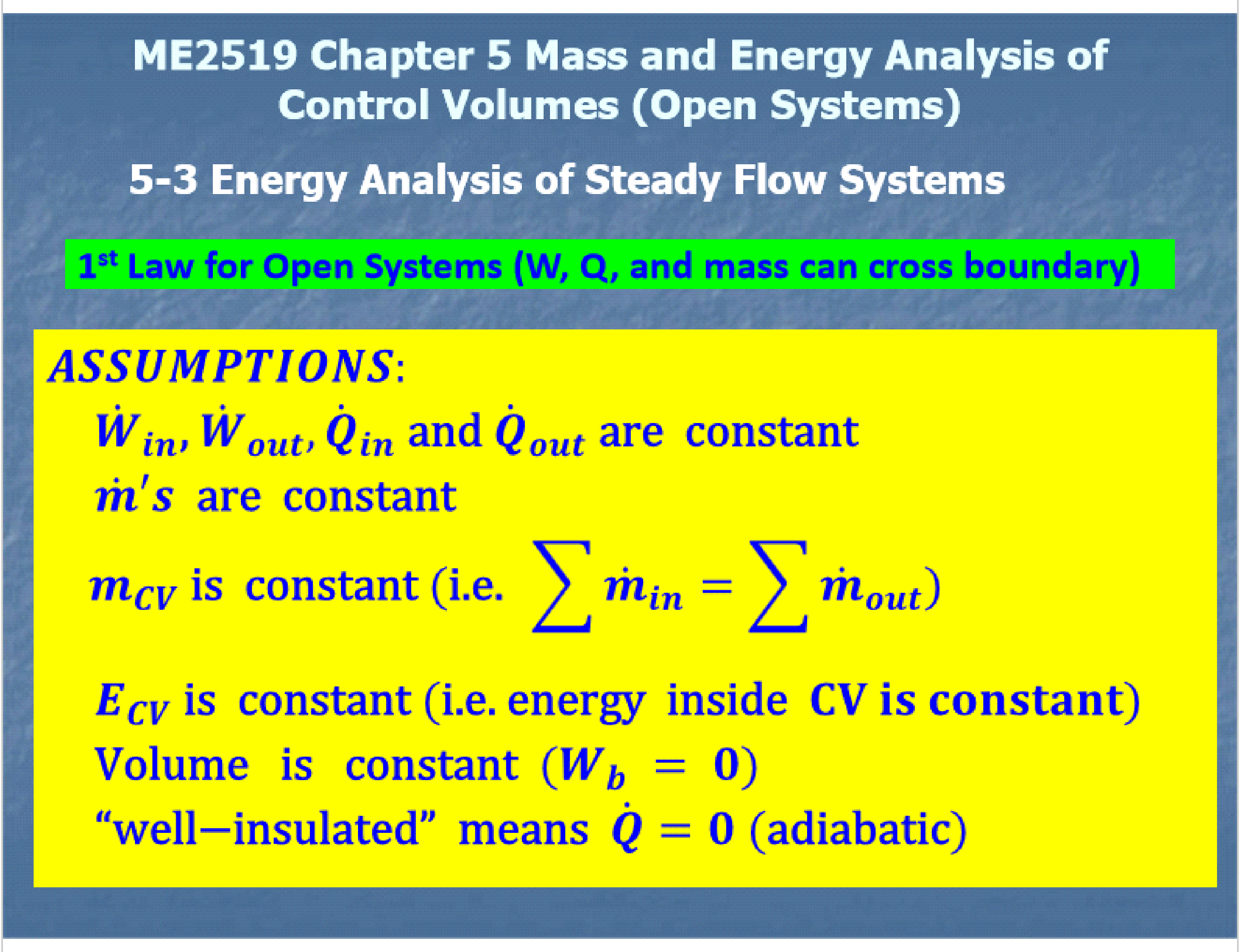


ME2519 Chapter 5 Mass and Energy Analysis of Control Volumes (Open Systems)

5-3 Energy Analysis of Steady Flow Systems

1st Law for Open Systems (W, Q, and mass can cross boundary)

ASSUMPTIONS:

$\dot{W}_{in}, \dot{W}_{out}, \dot{Q}_{in}$ and $\dot{Q}_{out}$ are constant

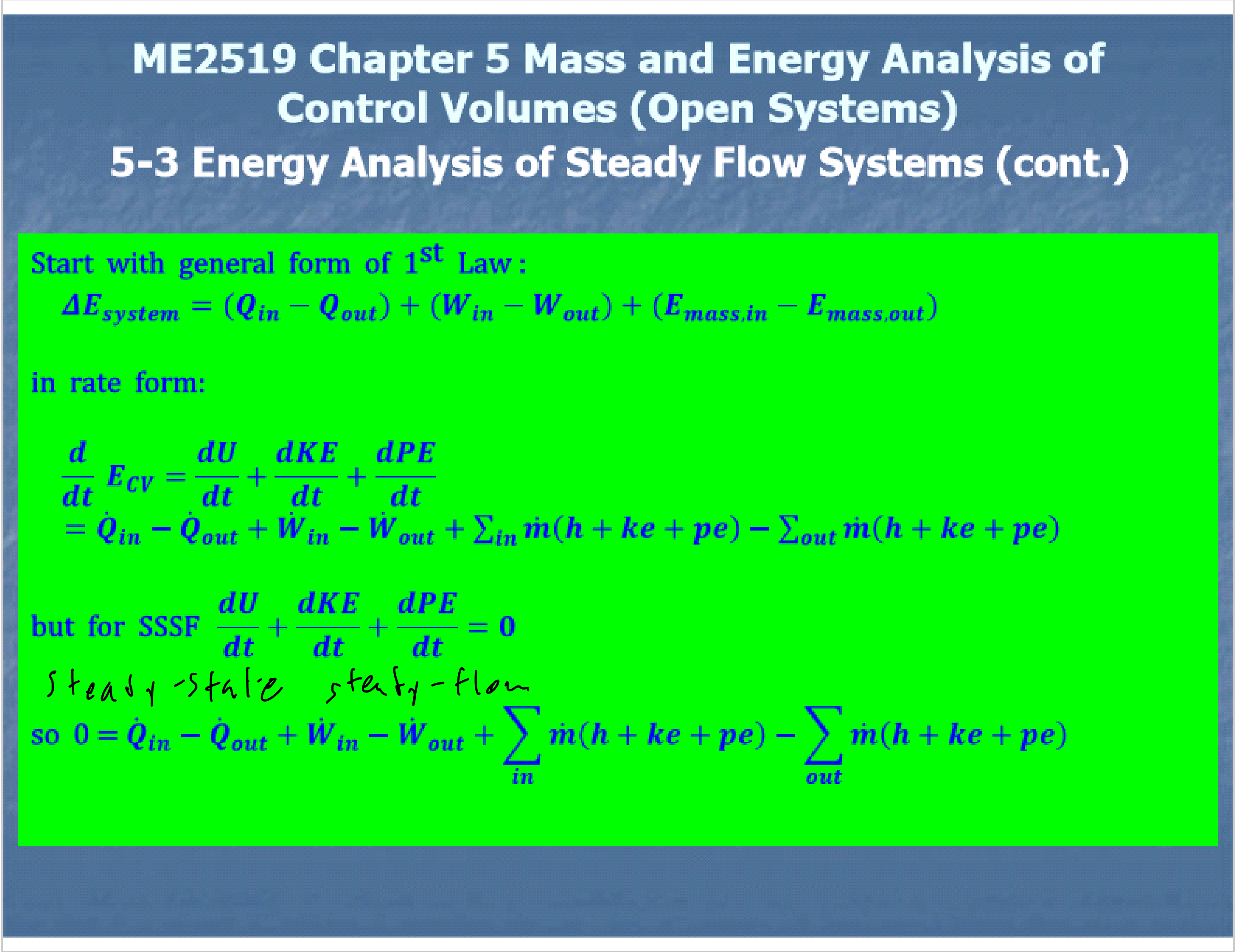
$\dot{m}'s$ are constant

m_{CV} is constant (i.e. $\sum \dot{m}_{in} = \sum \dot{m}_{out}$)

E_{CV} is constant (i.e. energy inside CV is constant)

Volume is constant ($W_b = 0$)

"well–insulated" means $\dot{Q} = 0$ (adiabatic)



ME2519 Chapter 5 Mass and Energy Analysis of Control Volumes (Open Systems)

5-3 Energy Analysis of Steady Flow Systems (cont.)

Start with general form of 1^{st} Law:

$$\Delta E_{system} = (Q_{in} - Q_{out}) + (W_{in} - W_{out}) + (E_{mass,in} - E_{mass,out})$$

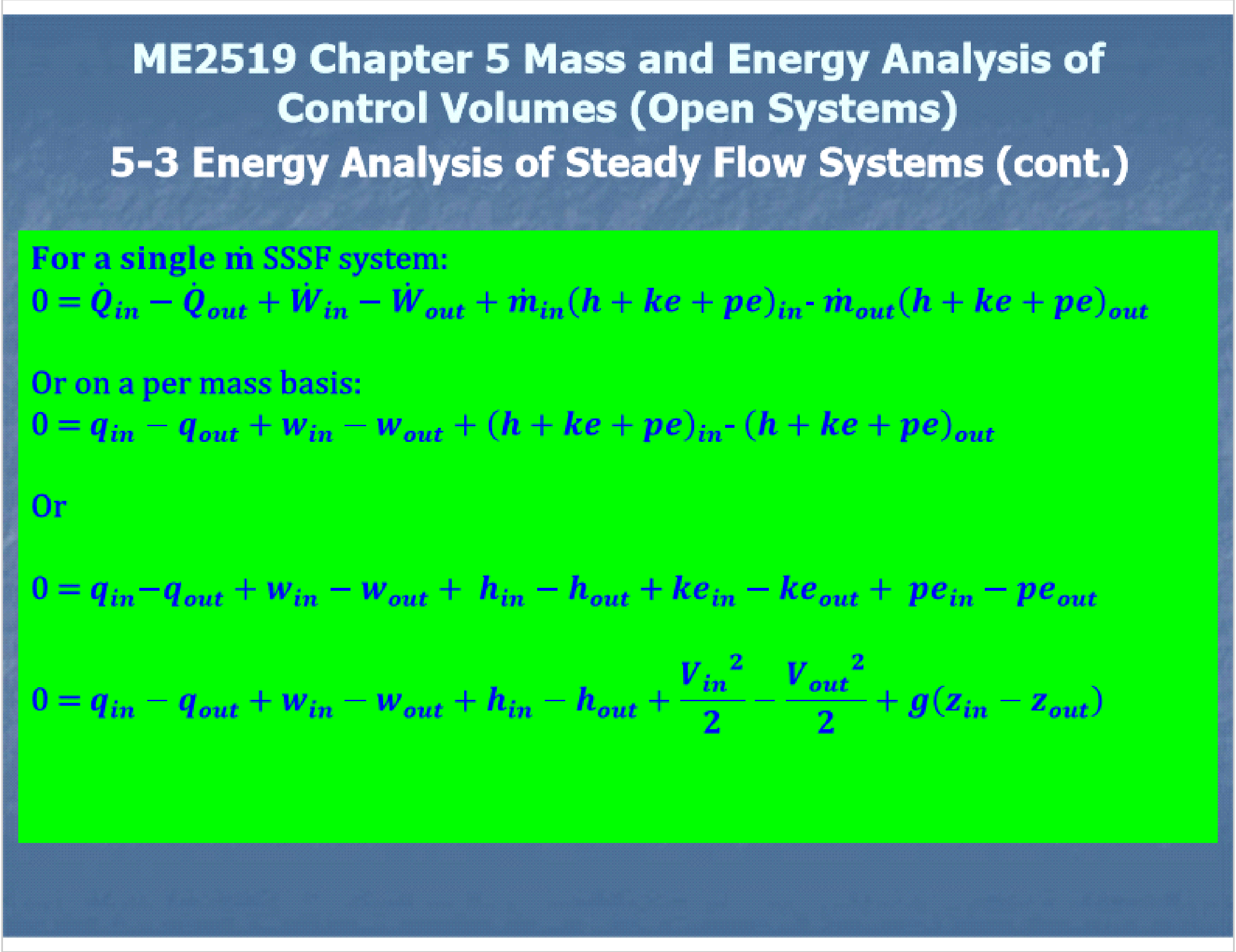
in rate form:

$$\frac{d}{dt}E_{CV} = \frac{dU}{dt} + \frac{dKE}{dt} + \frac{dPE}{dt}$$
$$= \dot{Q}_{in} - \dot{Q}_{out} + \dot{W}_{in} - \dot{W}_{out} + \textstyle\sum_{in}\dot{m}(h + ke + pe) - \textstyle\sum_{out}\dot{m}(h + ke + pe)$$

but for SSSF $\frac{dU}{dt} + \frac{dKE}{dt} + \frac{dPE}{dt} = 0$

steady-state steady-flow

so $0 = \dot{Q}_{in} - \dot{Q}_{out} + \dot{W}_{in} - \dot{W}_{out} + \sum_{in}\dot{m}(h + ke + pe) - \sum_{out}\dot{m}(h + ke + pe)$



ME2519 Chapter 5 Mass and Energy Analysis of Control Volumes (Open Systems)

5-3 Energy Analysis of Steady Flow Systems (cont.)

For a single ṁ SSSF system:

$$0 = \dot{Q}_{in} - \dot{Q}_{out} + \dot{W}_{in} - \dot{W}_{out} + \dot{m}_{in}(h + ke + pe)_{in} \text{-} \, \dot{m}_{out}(h + ke + pe)_{out}$$

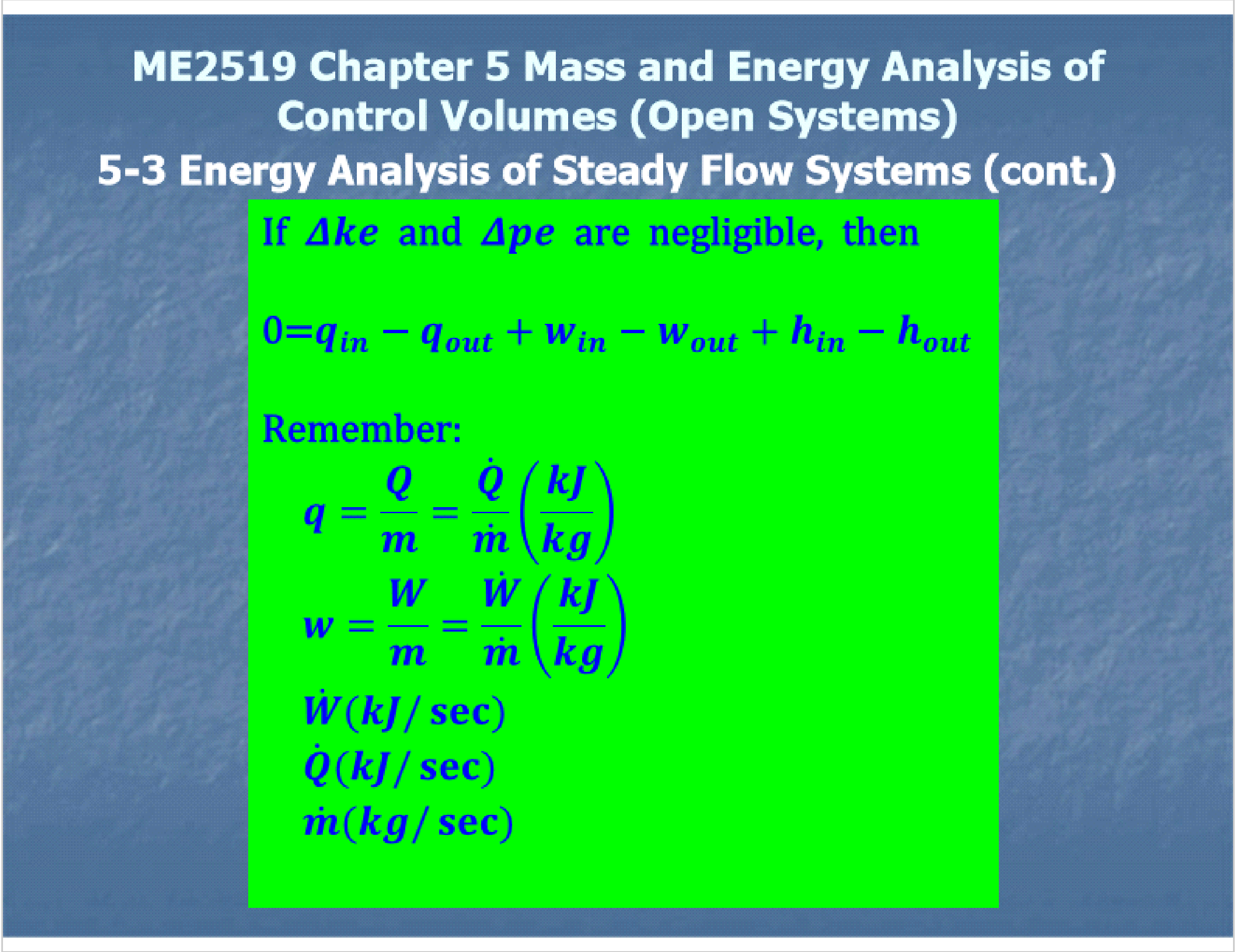
Or on a per mass basis:

$$0 = q_{in} - q_{out} + w_{in} - w_{out} + (h + ke + pe)_{in} \text{-} \, (h + ke + pe)_{out}$$

Or

$$0 = q_{in} - q_{out} + w_{in} - w_{out} + \; h_{in} - h_{out} + ke_{in} - ke_{out} + \; pe_{in} - pe_{out}$$

$$0 = q_{in} - q_{out} + w_{in} - w_{out} + h_{in} - h_{out} + \frac{{V_{in}}^2}{2} - \frac{{V_{out}}^2}{2} + g(z_{in} - z_{out})$$



ME2519 Chapter 5 Mass and Energy Analysis of Control Volumes (Open Systems)

5-3 Energy Analysis of Steady Flow Systems (cont.)

If Δke and Δpe are negligible, then

$$0 = q_{in} - q_{out} + w_{in} - w_{out} + h_{in} - h_{out}$$

Remember:

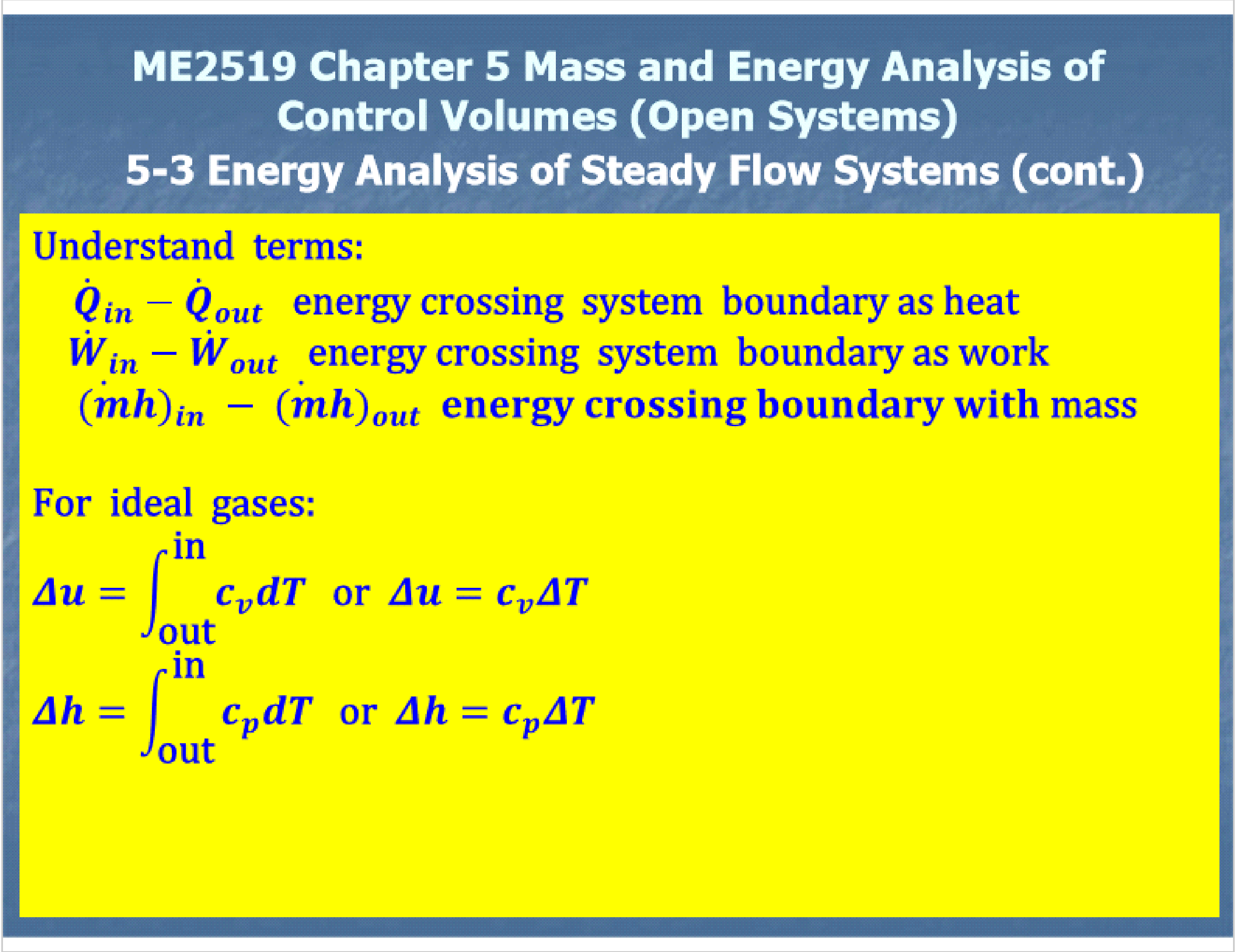
$$q = \frac{Q}{m} = \frac{\dot{Q}}{\dot{m}}\left(\frac{kJ}{kg}\right)$$

$$w = \frac{W}{m} = \frac{\dot{W}}{\dot{m}}\left(\frac{kJ}{kg}\right)$$

$$\dot{W}(kJ/\sec)$$

$$\dot{Q}(kJ/\sec)$$

$$\dot{m}(kg/\sec)$$



ME2519 Chapter 5 Mass and Energy Analysis of Control Volumes (Open Systems)

5-3 Energy Analysis of Steady Flow Systems (cont.)

Understand terms:

$\dot{Q}_{in} - \dot{Q}_{out}$ energy crossing system boundary as heat

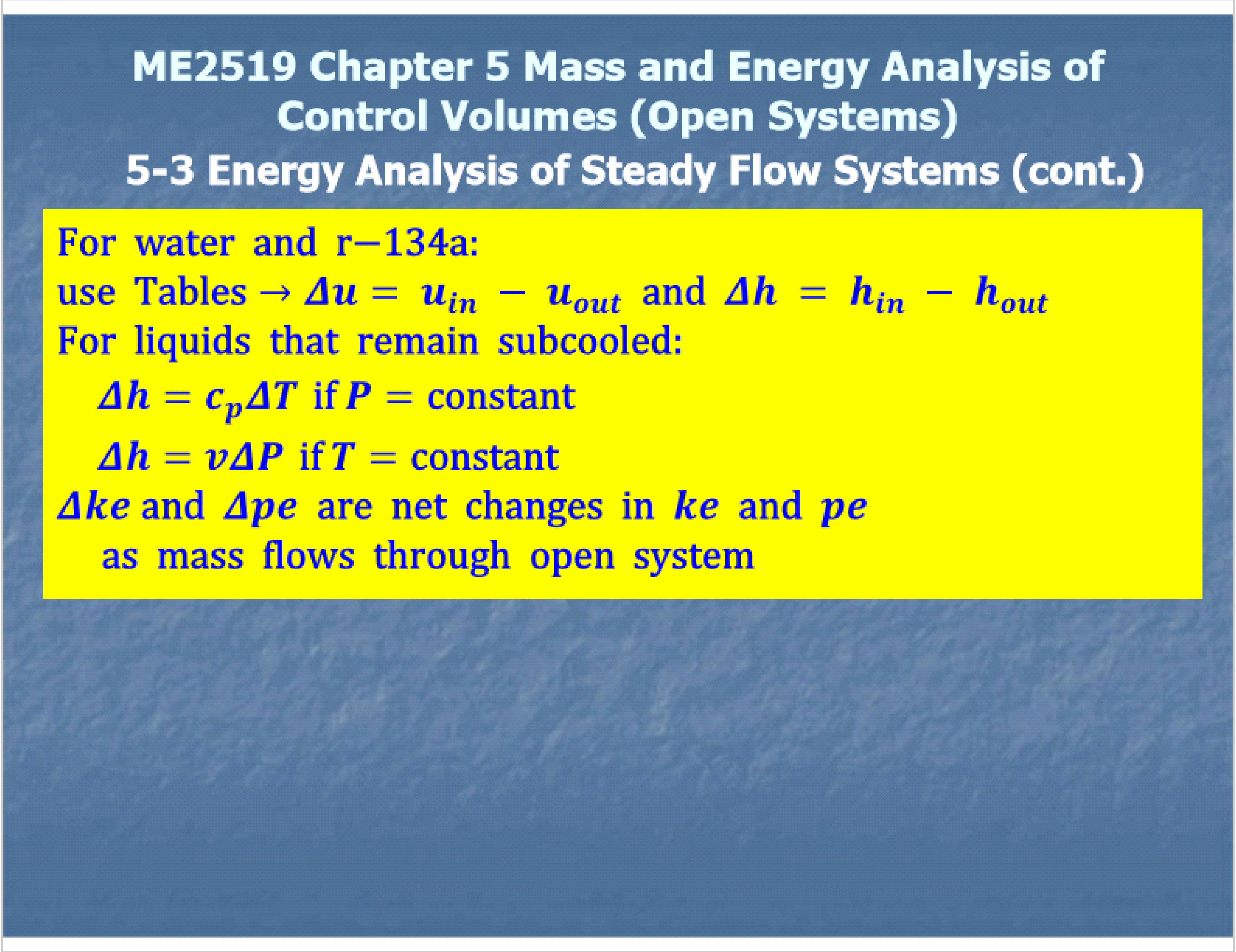
$\dot{W}_{in} - \dot{W}_{out}$ energy crossing system boundary as work

$(\dot{m}h)_{in} - (\dot{m}h)_{out}$ **energy crossing boundary with** mass

For ideal gases:

$$\Delta u = \int_{\text{out}}^{\text{in}} c_v dT \quad \text{or} \quad \Delta u = c_v \Delta T$$

$$\Delta h = \int_{\text{out}}^{\text{in}} c_p dT \quad \text{or} \quad \Delta h = c_p \Delta T$$



ME2519 Chapter 5 Mass and Energy Analysis of Control Volumes (Open Systems)

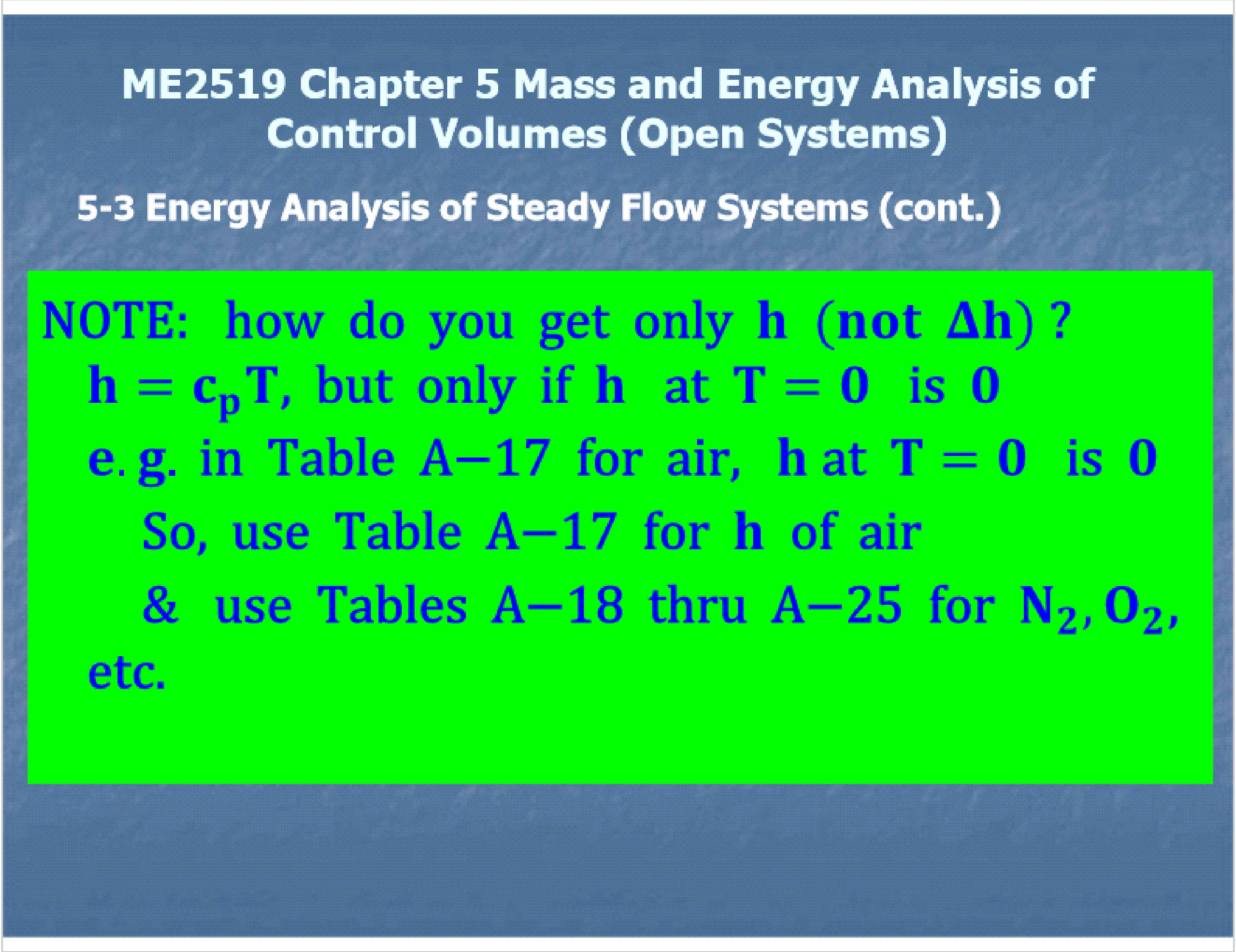
5-3 Energy Analysis of Steady Flow Systems (cont.)

For water and r−134a:
use Tables → $\Delta u = u_{in} - u_{out}$ and $\Delta h = h_{in} - h_{out}$
For liquids that remain subcooled:

$\Delta h = c_p \Delta T$ if P = constant

$\Delta h = v \Delta P$ if T = constant

Δke and Δpe are net changes in ke and pe
as mass flows through open system



ME2519 Chapter 5 Mass and Energy Analysis of Control Volumes (Open Systems)

5-3 Energy Analysis of Steady Flow Systems (cont.)

NOTE: how do you get only $\mathbf{h}$ (not $\mathbf{\Delta h}$)?

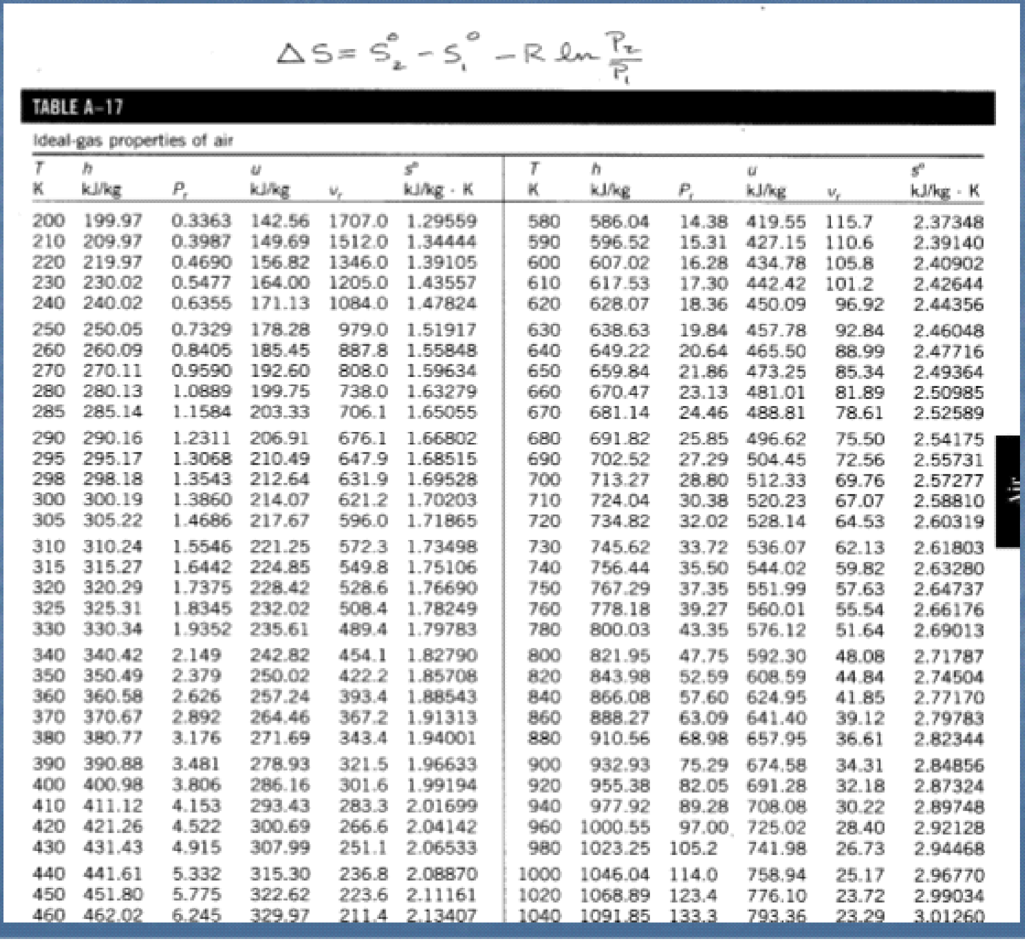
$\mathbf{h} = \mathbf{c_p T}$, but only if $\mathbf{h}$ at $\mathbf{T = 0}$ is $\mathbf{0}$

$\mathbf{e.g.}$ in Table A–17 for air, $\mathbf{h}$ at $\mathbf{T = 0}$ is $\mathbf{0}$

So, use Table A–17 for $\mathbf{h}$ of air

& use Tables A–18 thru A–25 for N_2, O_2, etc.

ME2519 Chapter 5 Mass and Energy Analysis of Control Volumes (Open Systems)



$$\Delta S = S_2^\circ - S_1^\circ - R \ln \frac{P_2}{P_1}$$

TABLE A-17

Ideal-gas properties of air

T K	h kJ/kg	P_r	u kJ/kg	v_r	s° kJ/kg · K	T K	h kJ/kg	P_r	u kJ/kg	v_r	s° kJ/kg · K
200	199.97	0.3363	142.56	1707.0	1.29559	580	586.04	14.38	419.55	115.7	2.37348
210	209.97	0.3987	149.69	1512.0	1.34444	590	596.52	15.31	427.15	110.6	2.39140
220	219.97	0.4690	156.82	1346.0	1.39105	600	607.02	16.28	434.78	105.8	2.40902
230	230.02	0.5477	164.00	1205.0	1.43557	610	617.53	17.30	442.42	101.2	2.42644
240	240.02	0.6355	171.13	1084.0	1.47824	620	628.07	18.36	450.09	96.92	2.44356
250	250.05	0.7329	178.28	979.0	1.51917	630	638.63	19.84	457.78	92.84	2.46048
260	260.09	0.8405	185.45	887.8	1.55848	640	649.22	20.64	465.50	88.99	2.47716
270	270.11	0.9590	192.60	808.0	1.59634	650	659.84	21.86	473.25	85.34	2.49364
280	280.13	1.0889	199.75	738.0	1.63279	660	670.47	23.13	481.01	81.89	2.50985
285	285.14	1.1584	203.33	706.1	1.65055	670	681.14	24.46	488.81	78.61	2.52589
290	290.16	1.2311	206.91	676.1	1.66802	680	691.82	25.85	496.62	75.50	2.54175
295	295.17	1.3068	210.49	647.9	1.68515	690	702.52	27.29	504.45	72.56	2.55731
298	298.18	1.3543	212.64	631.9	1.69528	700	713.27	28.80	512.33	69.76	2.57277
300	300.19	1.3860	214.07	621.2	1.70203	710	724.04	30.38	520.23	67.07	2.58810
305	305.22	1.4686	217.67	596.0	1.71865	720	734.82	32.02	528.14	64.53	2.60319
310	310.24	1.5546	221.25	572.3	1.73498	730	745.62	33.72	536.07	62.13	2.61803
315	315.27	1.6442	224.85	549.8	1.75106	740	756.44	35.50	544.02	59.82	2.63280
320	320.29	1.7375	228.42	528.6	1.76690	750	767.29	37.35	551.99	57.63	2.64737
325	325.31	1.8345	232.02	508.4	1.78249	760	778.18	39.27	560.01	55.54	2.66176
330	330.34	1.9352	235.61	489.4	1.79783	780	800.03	43.35	576.12	51.64	2.69013
340	340.42	2.149	242.82	454.1	1.82790	800	821.95	47.75	592.30	48.08	2.71787
350	350.49	2.379	250.02	422.2	1.85708	820	843.98	52.59	608.59	44.84	2.74504
360	360.58	2.626	257.24	393.4	1.88543	840	866.08	57.60	624.95	41.85	2.77170
370	370.67	2.892	264.46	367.2	1.91313	860	888.27	63.09	641.40	39.12	2.79783
380	380.77	3.176	271.69	343.4	1.94001	880	910.56	68.98	657.95	36.61	2.82344
390	390.88	3.481	278.93	321.5	1.96633	900	932.93	75.29	674.58	34.31	2.84856
400	400.98	3.806	286.16	301.6	1.99194	920	955.38	82.05	691.28	32.18	2.87324
410	411.12	4.153	293.43	283.3	2.01699	940	977.92	89.28	708.08	30.22	2.89748
420	421.26	4.522	300.69	266.6	2.04142	960	1000.55	97.00	725.02	28.40	2.92128
430	431.43	4.915	307.99	251.1	2.06533	980	1023.25	105.2	741.98	26.73	2.94468
440	441.61	5.332	315.30	236.8	2.08870	1000	1046.04	114.0	758.94	25.17	2.96770
450	451.80	5.775	322.62	223.6	2.11161	1020	1068.89	123.4	776.10	23.72	2.99034
460	462.02	6.245	329.97	211.4	2.13407	1040	1091.85	133.3	793.36	23.29	3.01260

Air

ME2519 Chapter 5 Mass and Energy Analysis of Control Volumes (Open Systems)

Use Tables A-18 through A-25 to look up $\bar{u}$ and $\bar{h}$ as a function of T for: N_2, O_2, CO_2, CO, H_2, H_2O, O, and OH.

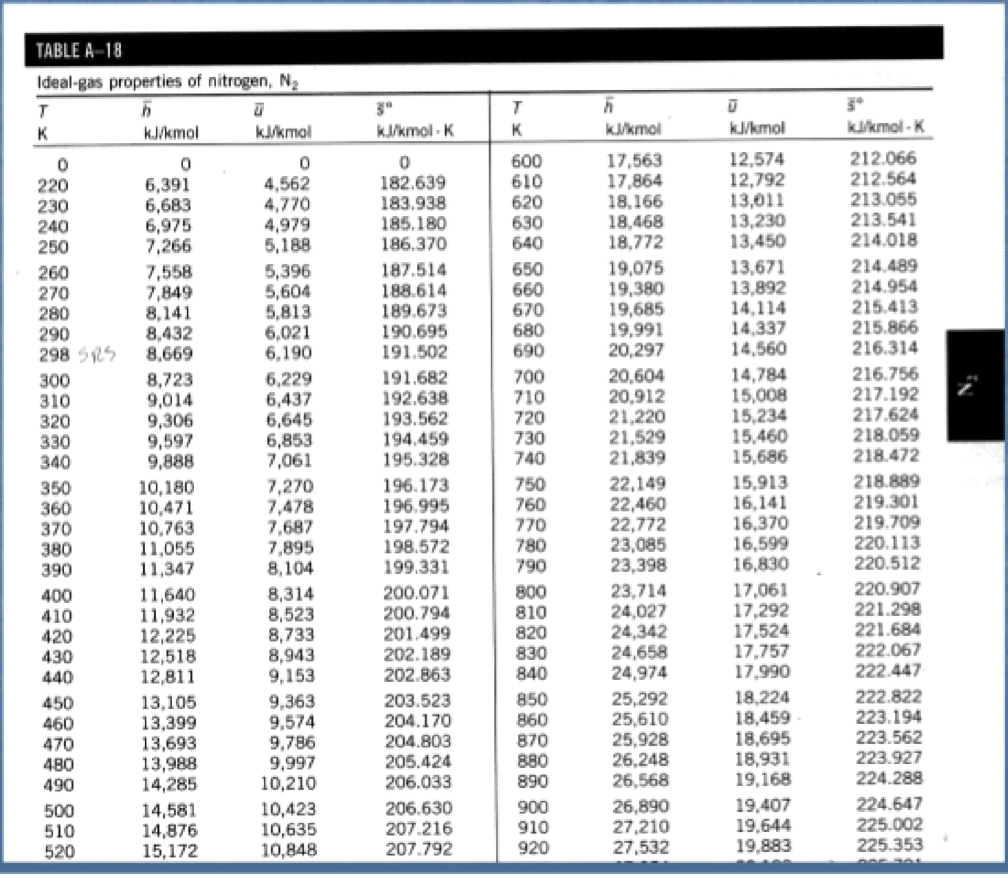
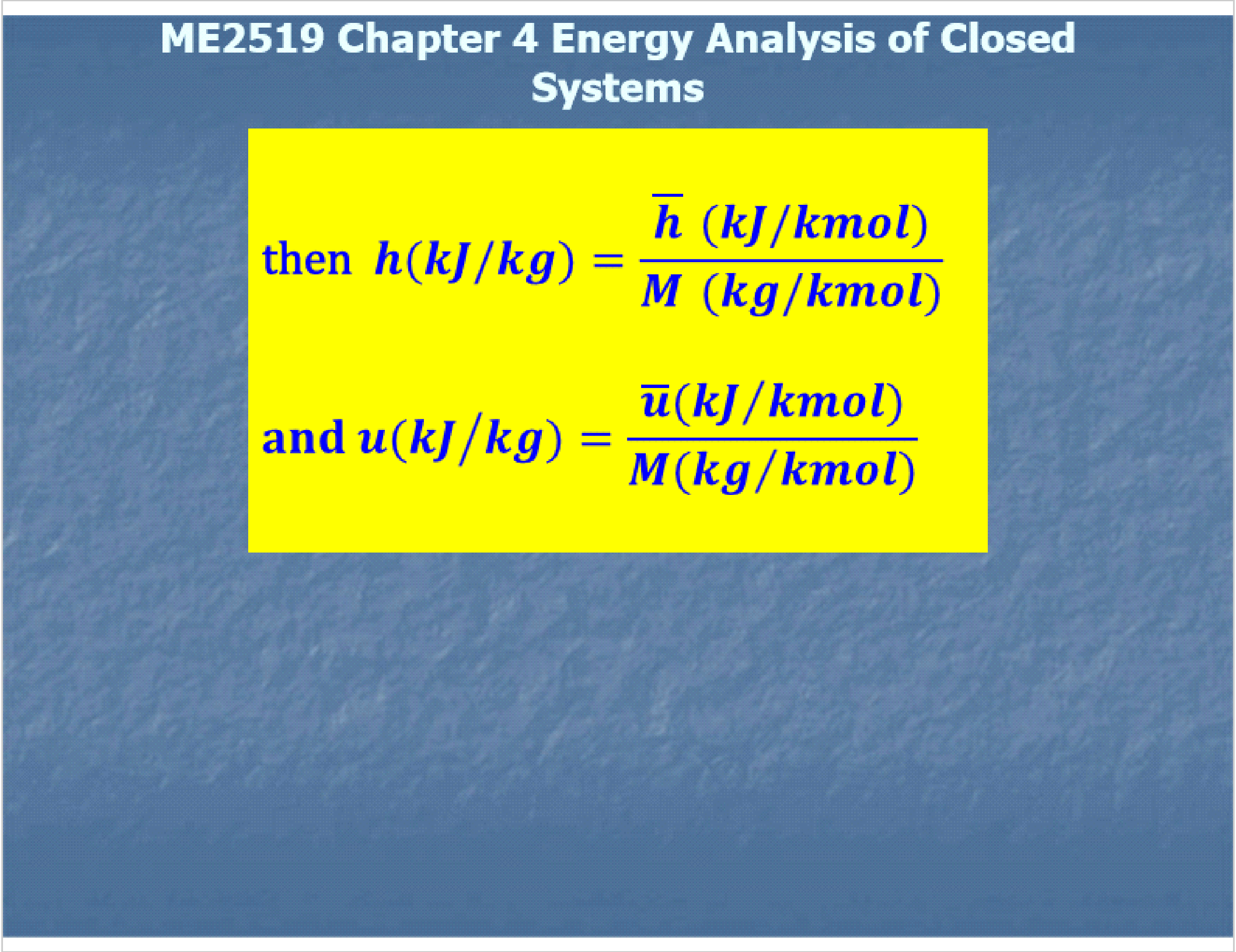


TABLE A–18

Ideal-gas properties of nitrogen, N_2

T K	$\bar{h}$ kJ/kmol	$\bar{u}$ kJ/kmol	$\bar{s}°$ kJ/kmol · K
0	0	0	0
220	6,391	4,562	182.639
230	6,683	4,770	183.938
240	6,975	4,979	185.180
250	7,266	5,188	186.370
260	7,558	5,396	187.514
270	7,849	5,604	188.614
280	8,141	5,813	189.673
290	8,432	6,021	190.695
298	8,669	6,190	191.502
300	8,723	6,229	191.682
310	9,014	6,437	192.638
320	9,306	6,645	193.562
330	9,597	6,853	194.459
340	9,888	7,061	195.328
350	10,180	7,270	196.173
360	10,471	7,478	196.995
370	10,763	7,687	197.794
380	11,055	7,895	198.572
390	11,347	8,104	199.331
400	11,640	8,314	200.071
410	11,932	8,523	200.794
420	12,225	8,733	201.499
430	12,518	8,943	202.189
440	12,811	9,153	202.863
450	13,105	9,363	203.523
460	13,399	9,574	204.170
470	13,693	9,786	204.803
480	13,988	9,997	205.424
490	14,285	10,210	206.033
500	14,581	10,423	206.630
510	14,876	10,635	207.216
520	15,172	10,848	207.792
600	17,563	12,574	212.066
610	17,864	12,792	212.564
620	18,166	13,011	213.055
630	18,468	13,230	213.541
640	18,772	13,450	214.018
650	19,075	13,671	214.489
660	19,380	13,892	214.954
670	19,685	14,114	215.413
680	19,991	14,337	215.866
690	20,297	14,560	216.314
700	20,604	14,784	216.756
710	20,912	15,008	217.192
720	21,220	15,234	217.624
730	21,529	15,460	218.059
740	21,839	15,686	218.472
750	22,149	15,913	218.889
760	22,460	16,141	219.301
770	22,772	16,370	219.709
780	23,085	16,599	220.113
790	23,398	16,830	220.512
800	23,714	17,061	220.907
810	24,027	17,292	221.298
820	24,342	17,524	221.684
830	24,658	17,757	222.067
840	24,974	17,990	222.447
850	25,292	18,224	222.822
860	25,610	18,459	223.194
870	25,928	18,695	223.562
880	26,248	18,931	223.927
890	26,568	19,168	224.288
900	26,890	19,407	224.647
910	27,210	19,644	225.002
920	27,532	19,883	225.353



ME2519 Chapter 4 Energy Analysis of Closed Systems

$$\text{then } \boldsymbol{h(kJ/kg) = \frac{\bar{h}\ (kJ/kmol)}{M\ (kg/kmol)}}$$

$$\textbf{and } \boldsymbol{u(kJ/kg) = \frac{\bar{u}(kJ/kmol)}{M(kg/kmol)}}$$

Charging and Discharging: Unsteady Flow Processes

Friday, October 21, 2022 10:19 AM

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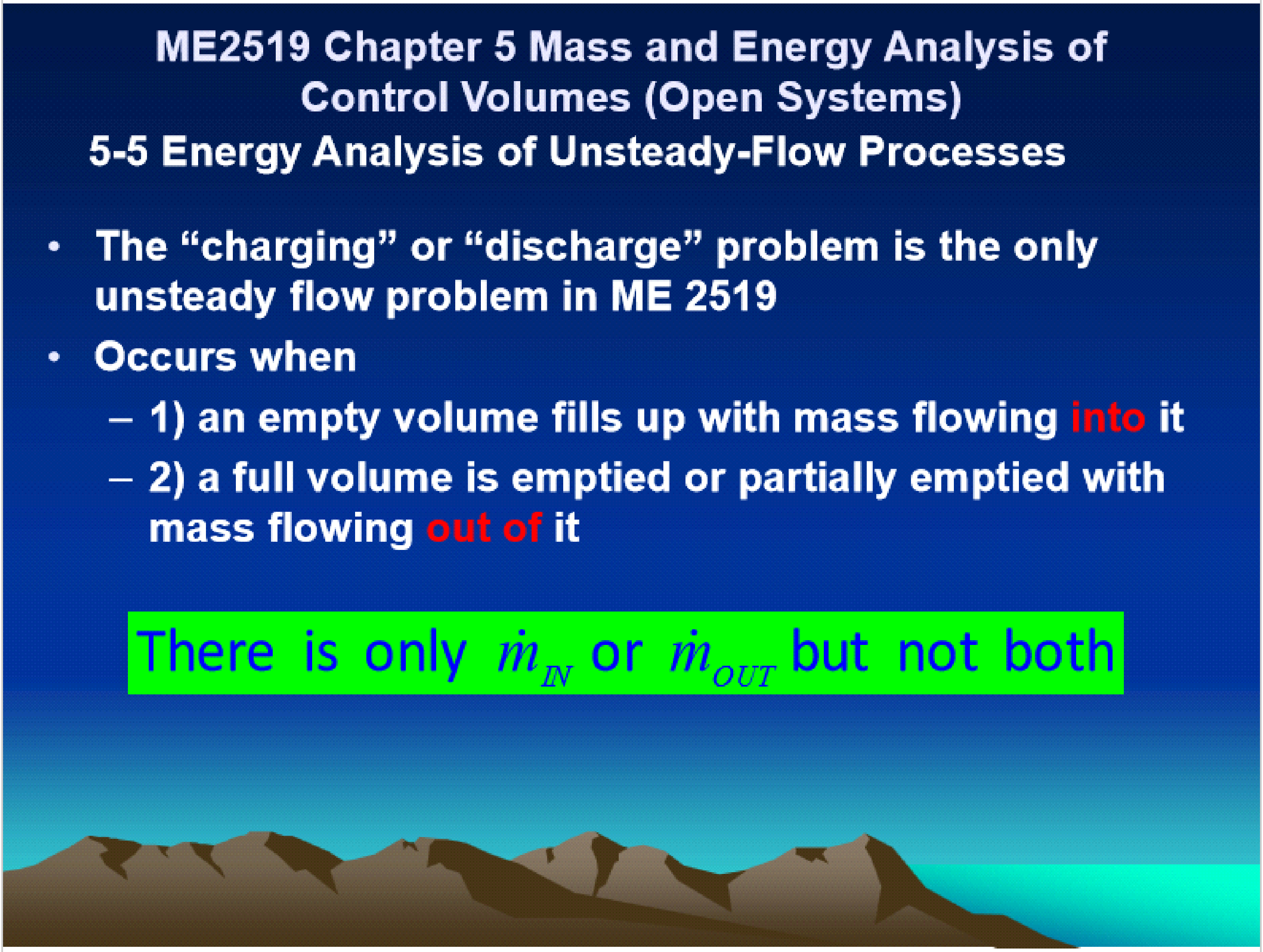
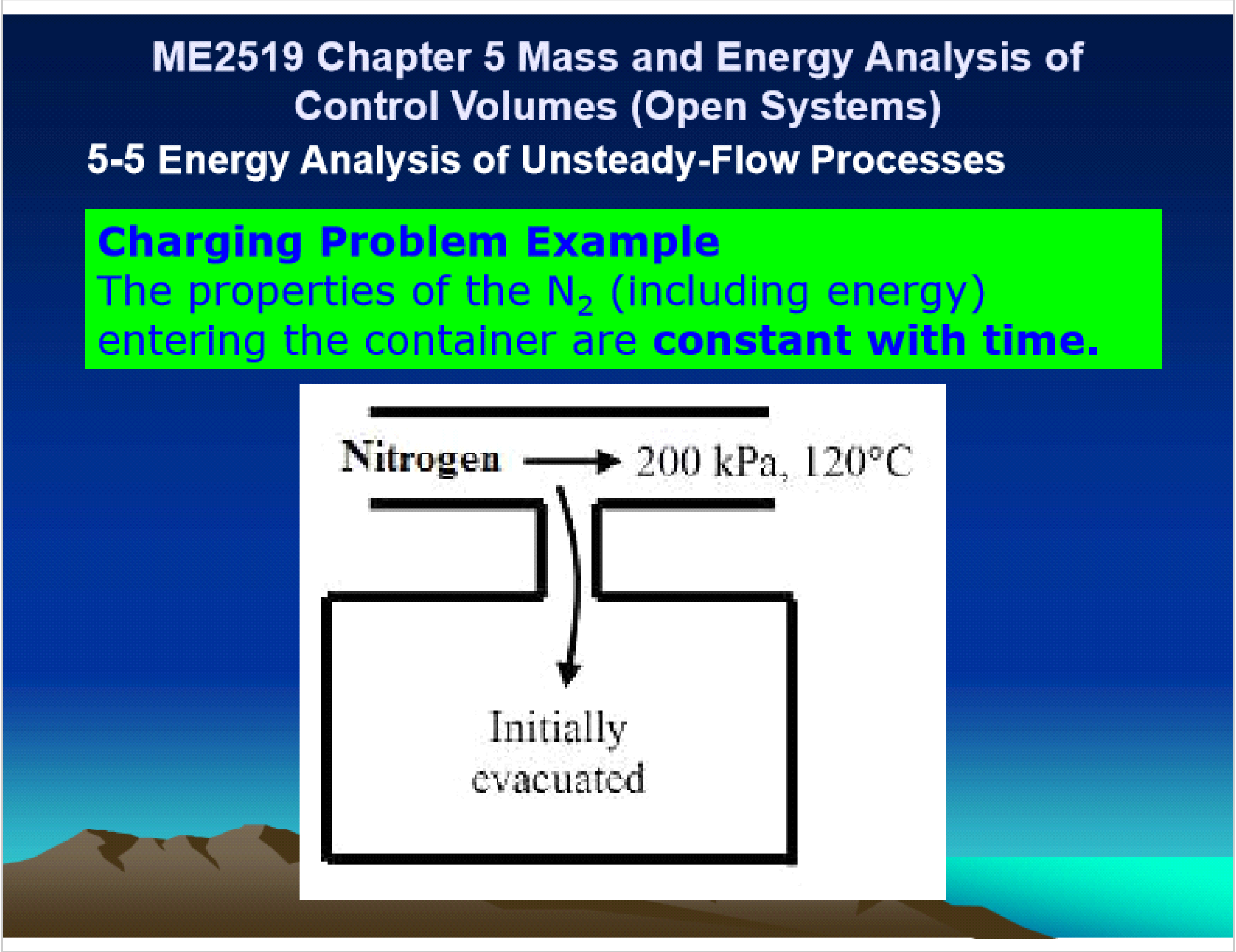


ME2519 Chapter 5 Mass and Energy Analysis of Control Volumes (Open Systems)

5-5 Energy Analysis of Unsteady-Flow Processes

- The "charging" or "discharge" problem is the only unsteady flow problem in ME 2519
- Occurs when
  - 1) an empty volume fills up with mass flowing into it
  - 2) a full volume is emptied or partially emptied with mass flowing out of it

There is only $\dot{m}_{IN}$ or $\dot{m}_{OUT}$ but not both

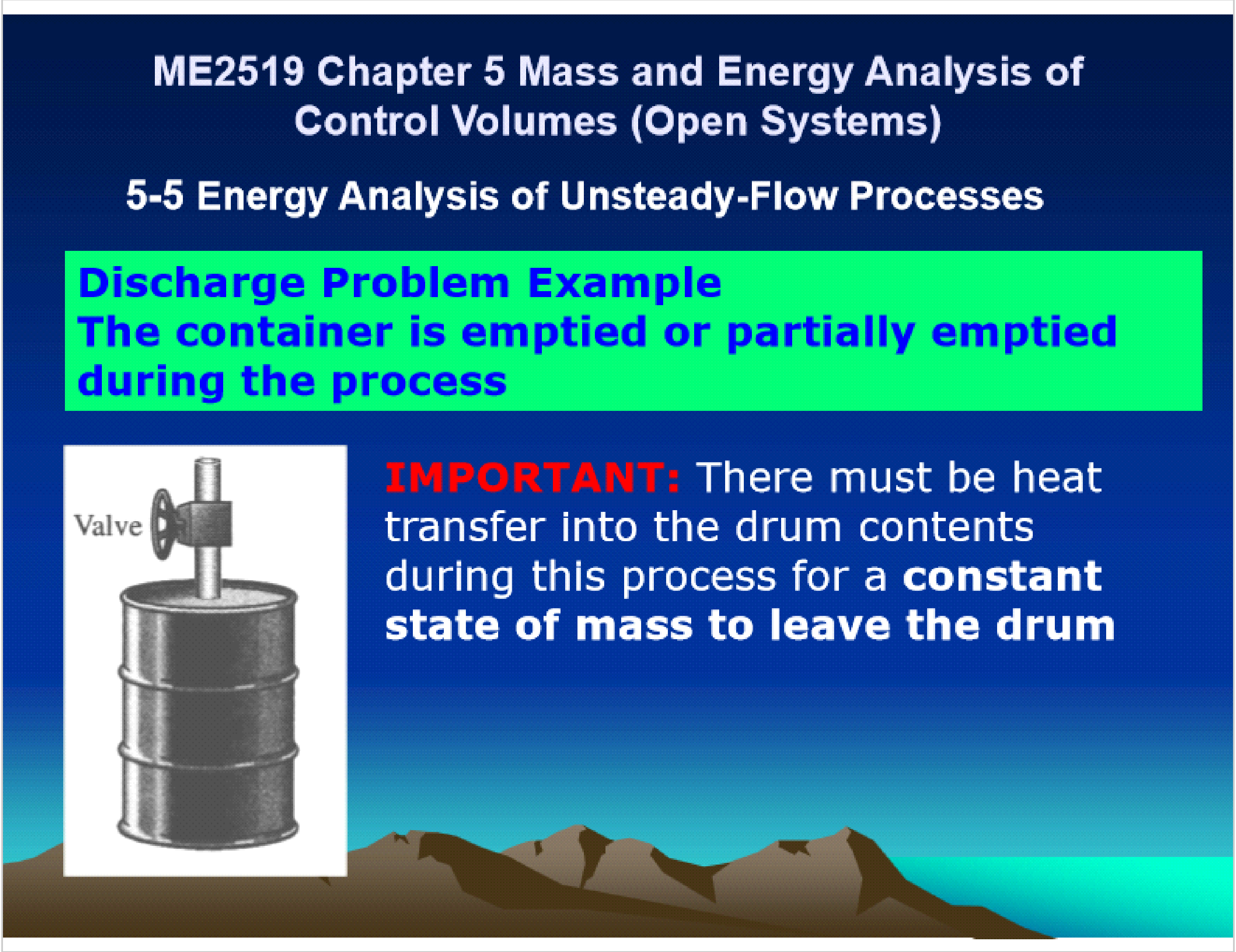


ME2519 Chapter 5 Mass and Energy Analysis of Control Volumes (Open Systems)

5-5 Energy Analysis of Unsteady-Flow Processes

Charging Problem Example

The properties of the N_2 (including energy) entering the container are **constant with time.**

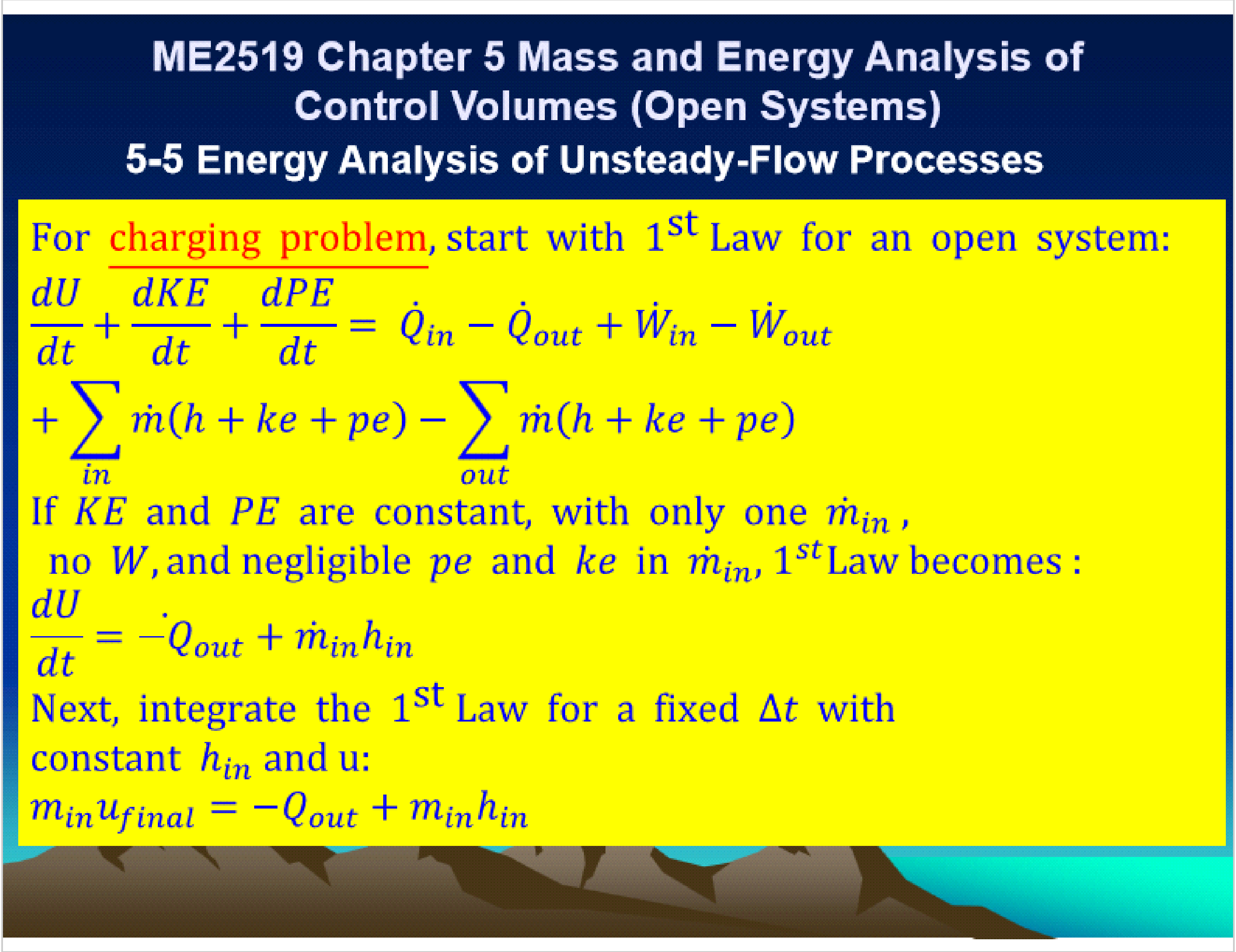


ME2519 Chapter 5 Mass and Energy Analysis of Control Volumes (Open Systems)

5-5 Energy Analysis of Unsteady-Flow Processes

Discharge Problem Example
The container is emptied or partially emptied during the process

IMPORTANT: There must be heat transfer into the drum contents during this process for a **constant state of mass to leave the drum**



ME2519 Chapter 5 Mass and Energy Analysis of Control Volumes (Open Systems)

5-5 Energy Analysis of Unsteady-Flow Processes

For charging problem, start with 1^{st} Law for an open system:

$$\frac{dU}{dt}+\frac{dKE}{dt}+\frac{dPE}{dt}=\dot{Q}_{in}-\dot{Q}_{out}+\dot{W}_{in}-\dot{W}_{out}$$

$$+\sum_{in}\dot{m}(h+ke+pe)-\sum_{out}\dot{m}(h+ke+pe)$$

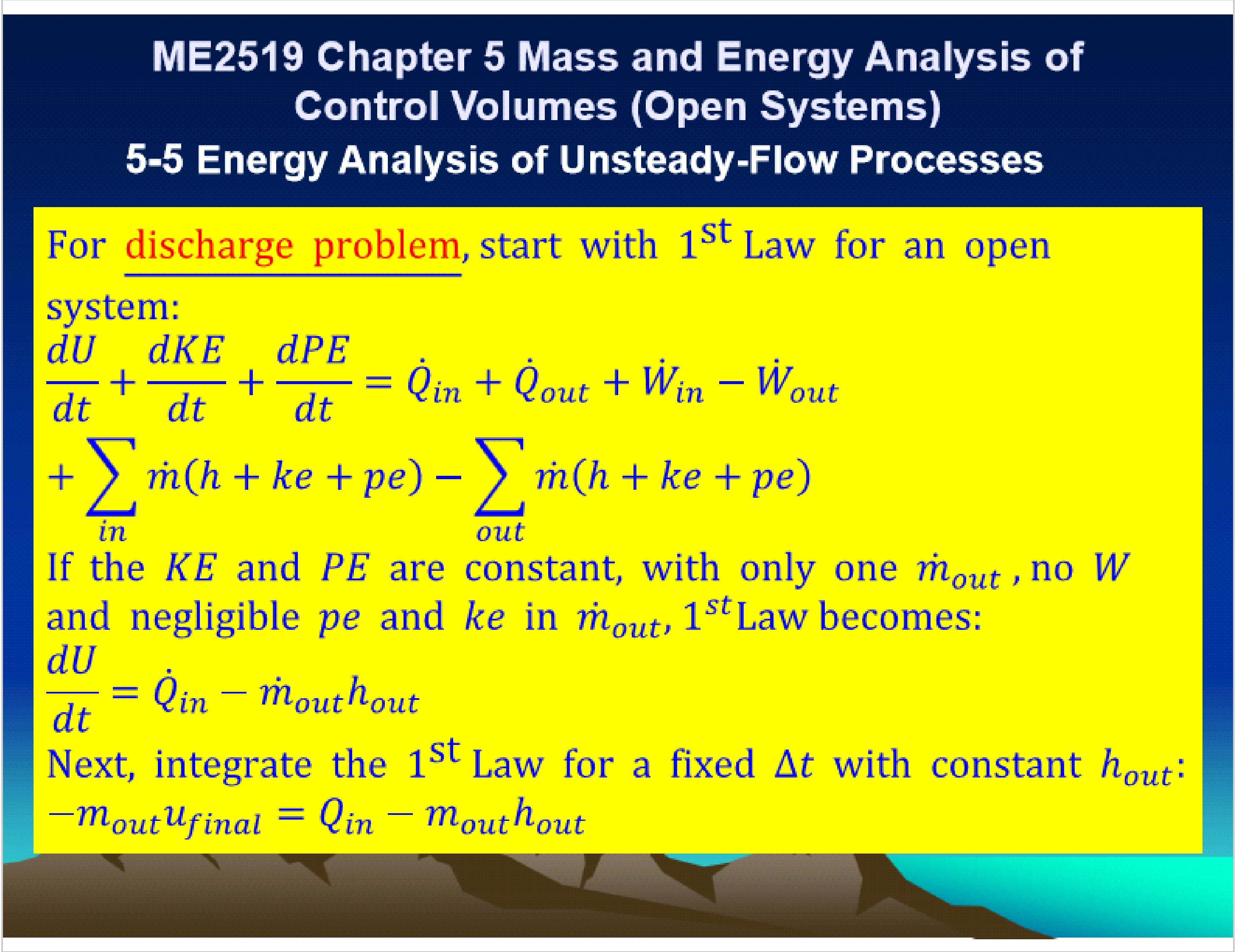
If KE and PE are constant, with only one $\dot{m}_{in}$,

no W, and negligible pe and ke in $\dot{m}_{in}$, 1^{st} Law becomes :

$$\frac{dU}{dt}=-\dot{Q}_{out}+\dot{m}_{in}h_{in}$$

Next, integrate the 1^{st} Law for a fixed Δt with constant h_{in} and u:

$$m_{in}u_{final}=-Q_{out}+m_{in}h_{in}$$



ME2519 Chapter 5 Mass and Energy Analysis of Control Volumes (Open Systems)

5-5 Energy Analysis of Unsteady-Flow Processes

For discharge problem, start with 1^{st} Law for an open system:

$$\frac{dU}{dt}+\frac{dKE}{dt}+\frac{dPE}{dt}=\dot{Q}_{in}+\dot{Q}_{out}+\dot{W}_{in}-\dot{W}_{out}$$

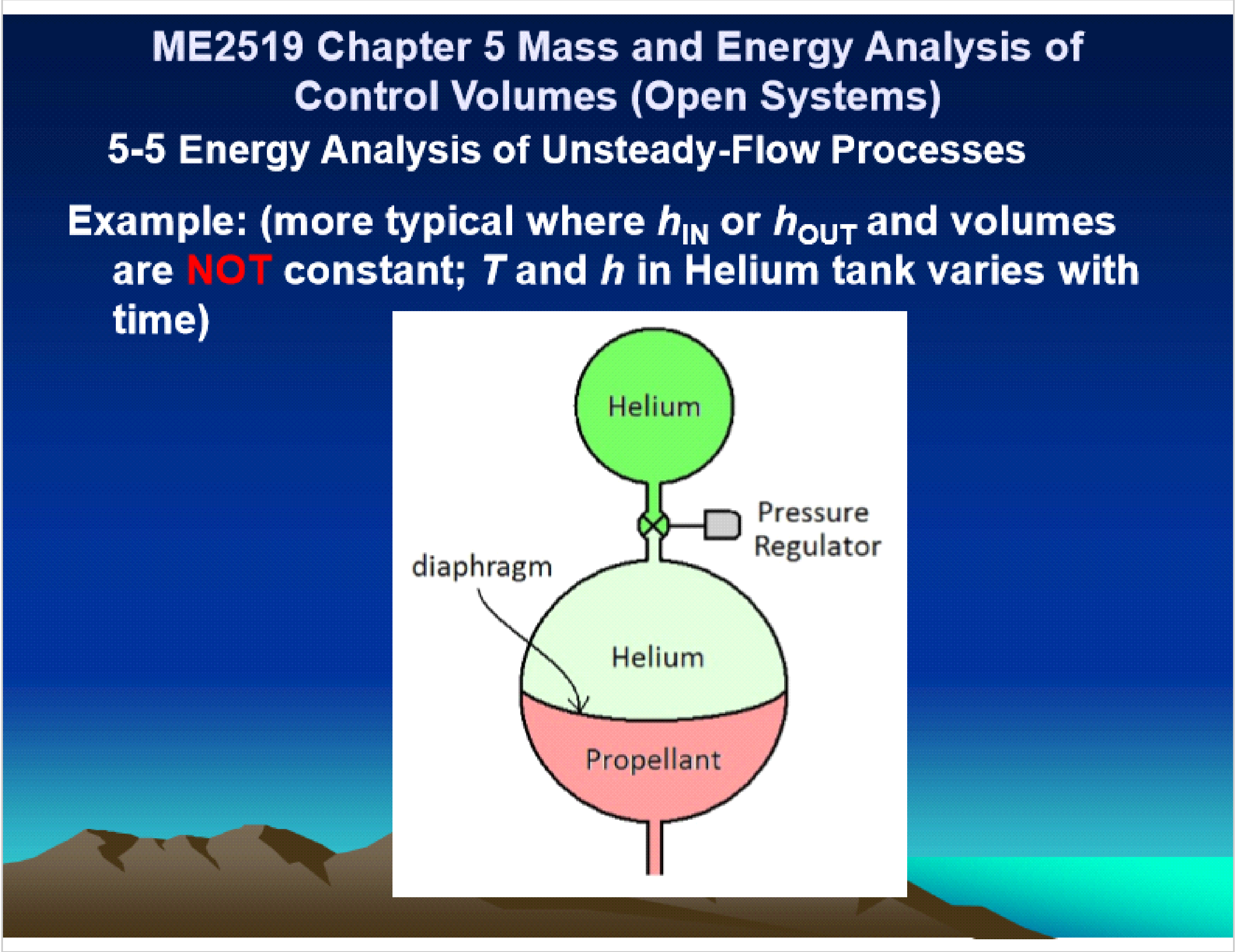
$$+\sum_{in}\dot{m}(h+ke+pe)-\sum_{out}\dot{m}(h+ke+pe)$$

If the KE and PE are constant, with only one $\dot{m}_{out}$, no W and negligible pe and ke in $\dot{m}_{out}$, 1^{st} Law becomes:

$$\frac{dU}{dt}=\dot{Q}_{in}-\dot{m}_{out}h_{out}$$

Next, integrate the 1^{st} Law for a fixed Δt with constant h_{out}:

$$-m_{out}u_{final}=Q_{in}-m_{out}h_{out}$$



ME2519 Chapter 5 Mass and Energy Analysis of Control Volumes (Open Systems)

5-5 Energy Analysis of Unsteady-Flow Processes

Example: (more typical where h_{IN} or h_{OUT} and volumes are NOT constant; T and h in Helium tank varies with time)

2nd Law and Thermal Reservoirs

Monday, October 24, 2022 10:06 AM

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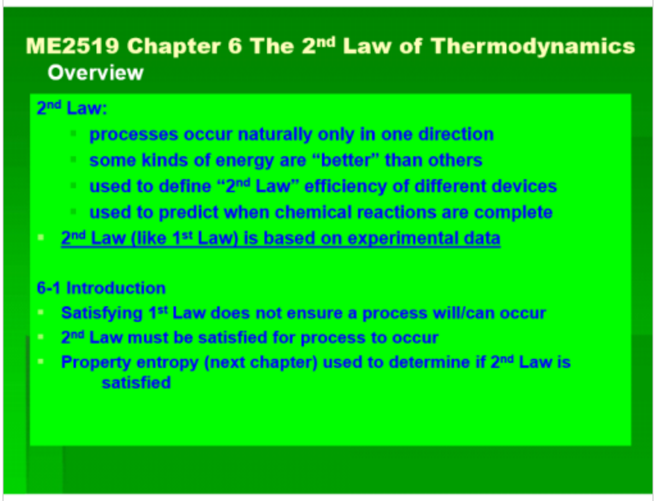


ME2519 Chapter 6 The 2nd Law of Thermodynamics

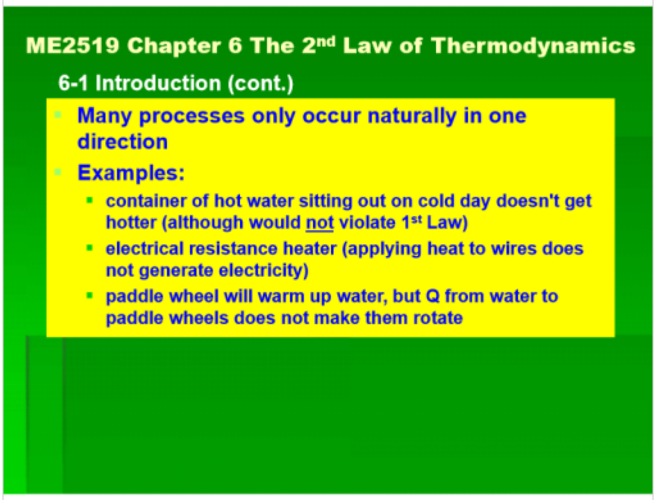
Overview

2nd Law:

- processes occur naturally only in one direction
- some kinds of energy are "better" than others
- used to define "2nd Law" efficiency of different devices
- used to predict when chemical reactions are complete
- 2nd Law (like 1st Law) is based on experimental data

6-1 Introduction

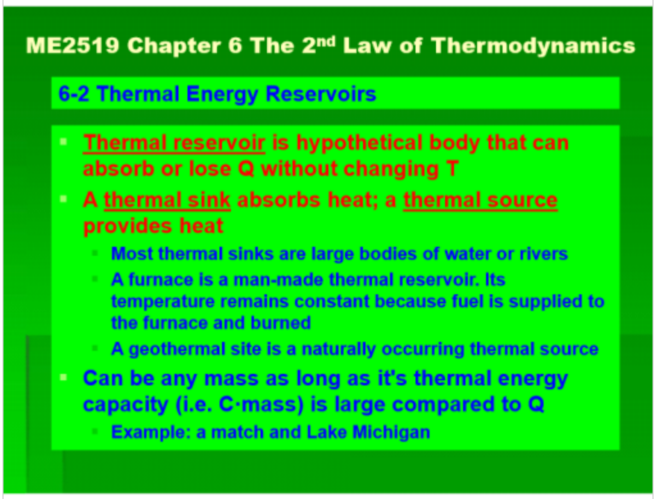
- Satisfying 1st Law does not ensure a process will/can occur
- 2nd Law must be satisfied for process to occur
- Property entropy (next chapter) used to determine if 2nd Law is satisfied



ME2519 Chapter 6 The 2nd Law of Thermodynamics

6-1 Introduction (cont.)

- Many processes only occur naturally in one direction
- Examples:
  - container of hot water sitting out on cold day doesn't get hotter (although would not violate 1st Law)
  - electrical resistance heater (applying heat to wires does not generate electricity)
  - paddle wheel will warm up water, but Q from water to paddle wheels does not make them rotate



ME2519 Chapter 6 The 2nd Law of Thermodynamics

6-2 Thermal Energy Reservoirs

- Thermal reservoir is hypothetical body that can absorb or lose Q without changing T
- A thermal sink absorbs heat; a thermal source provides heat
  - Most thermal sinks are large bodies of water or rivers
  - A furnace is a man-made thermal reservoir. Its temperature remains constant because fuel is supplied to the furnace and burned
  - A geothermal site is a naturally occurring thermal source
- Can be any mass as long as it's thermal energy capacity (i.e. C·mass) is large compared to Q
  - Example: a match and Lake Michigan

FIGURE 6–4
Processes occur in a certain direction, and not in the reverse direction.

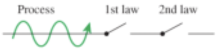


FIGURE 6–5
A process must satisfy both the first and second laws of thermodynamics to proceed.

FIGURE 6–1
A cup of hot coffee does not get hotter in a cooler room.

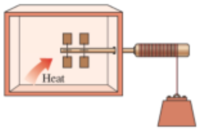


FIGURE 6–3
Transferring heat to a paddle wheel will not cause it to rotate.

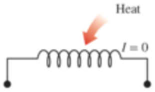


FIGURE 6–2
Transferring heat to a wire will not generate electricity.

The Second Law of Thermodynamics: Kelvin–Planck Statement

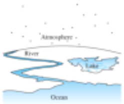
We demonstrated earlier with reference to the heat engine shown in Fig. 6–15 that, even under ideal conditions, a heat engine must reject some heat to a low-temperature reservoir in order to complete the cycle. That is, no heat engine can convert all the heat it receives to useful work. This limitation on the thermal efficiency of heat engines forms the basis for the Kelvin–Planck statement of the second law of thermodynamics, which is expressed as follows:

It is impossible for any device that operates on a cycle to receive heat from a single reservoir and produce a net amount of work.

That is, a heat engine must exchange heat with a low-temperature sink as well as a high-temperature source to keep operating. The Kelvin–Planck statement can also be expressed as *no heat engine can have a thermal efficiency of 100 percent* (Fig. 6–16), or as *for a power plant to operate, the working fluid must exchange heat with the environment as well as the furnace.*

6–2 ■ THERMAL ENERGY RESERVOIRS

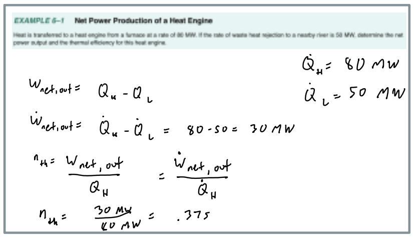
In the development of the second law of thermodynamics, it is very convenient to have a hypothetical body with a relatively large *thermal energy capacity* (mass × specific heat) that can supply or absorb finite amounts of heat without undergoing any change in temperature. Such a body is called a **thermal energy reservoir**, or just a reservoir. In practice, large bodies of water such as oceans, lakes, and rivers as well as the atmospheric air can be modeled accurately as thermal energy reservoirs because of their large thermal energy storage capabilities or thermal masses (Fig. 6–6). The atmosphere, for example, does not warm up as a result of heat losses from residential buildings in winter. Likewise, megajoules of waste energy dumped into large rivers by power plants do not cause any significant change in water temperature.



$$\eta_{th} = \frac{W_{net,out}}{Q_H} \quad \text{or} \quad \eta_{th} = 1 - \frac{Q_L}{Q_H}$$

Q_H = magnitude of heat transfer between the cyclic device and the high-temperature medium at temperature T_H
Q_L = magnitude of heat transfer between the cyclic device and the low-temperature medium at temperature T_L

$$W_{net,out} = Q_H - Q_L$$



EXAMPLE 6–1 Net Power Production of a Heat Engine

Heat is transferred to a heat engine from a furnace at a rate of 80 MW. If the rate of waste heat rejection to a nearby river is 50 MW, determine the net power output and the thermal efficiency for this heat engine.

$\dot{Q}_H = 80\ MW$

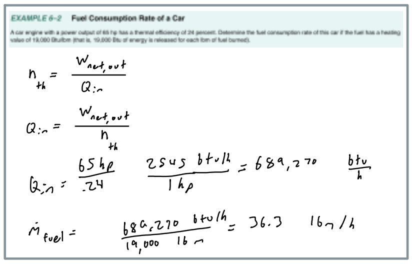
$\dot{Q}_L = 50\ MW$

$W_{net,out} = Q_H - Q_L$

$\dot{W}_{net,out} = \dot{Q}_H - \dot{Q}_L = 80 - 50 = 30\ MW$

$n_{th} = \frac{W_{net,out}}{Q_H} = \frac{\dot{W}_{net,out}}{\dot{Q}_H}$

$n_{th} = \frac{30\ MW}{80\ MW} = .375$



EXAMPLE 6–2 Fuel Consumption Rate of a Car

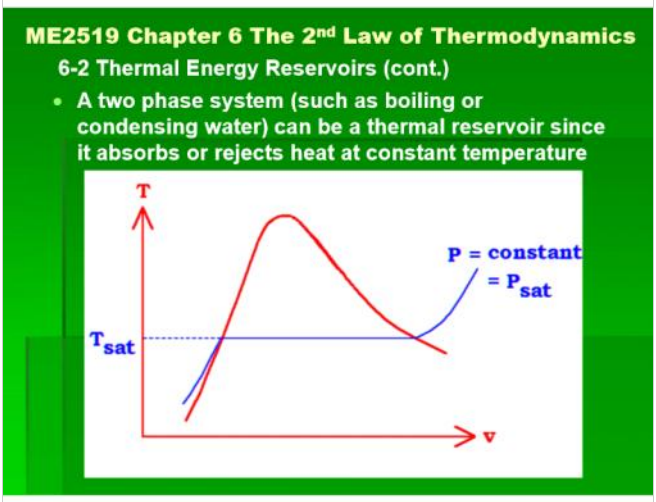
A car engine with a power output of 65 hp has a thermal efficiency of 24 percent. Determine the fuel consumption rate of this car if the fuel has a heating value of 19,000 Btu/lbm (that is, 19,000 Btu of energy is released for each lbm of fuel burned).

$n_{th} = \frac{W_{net,out}}{Q_{in}}$

$Q_{in} = \frac{W_{net,out}}{n_{th}}$

$Q_{in} = \frac{65\ hp}{.24} \quad \frac{2545\ btu/h}{1\ hp} = 689,270 \quad \frac{btu}{h}$

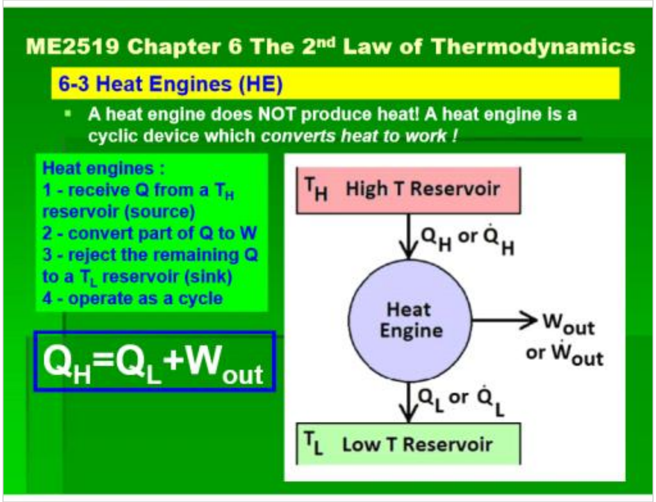
$\dot{m}_{fuel} = \frac{689,270\ btu/h}{19,000\ \frac{btu}{lbm}} = 36.3 \quad lbm/h$



ME2519 Chapter 6 The 2nd Law of Thermodynamics

6-2 Thermal Energy Reservoirs (cont.)

- A two phase system (such as boiling or condensing water) can be a thermal reservoir since it absorbs or rejects heat at constant temperature



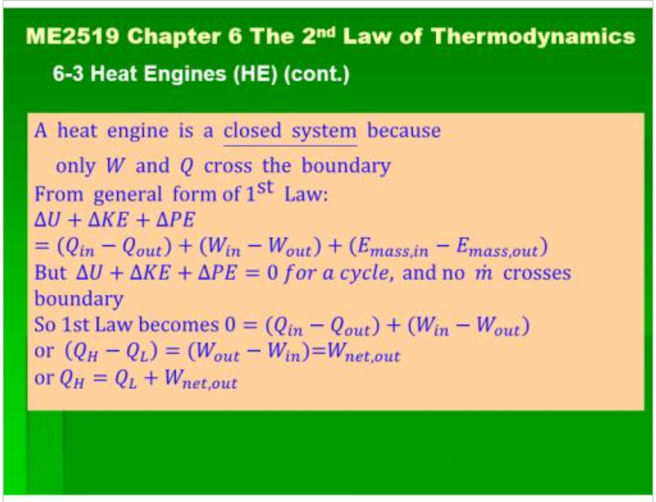
ME2519 Chapter 6 The 2nd Law of Thermodynamics

6-3 Heat Engines (HE)

- A heat engine does NOT produce heat! A heat engine is a cyclic device which *converts heat to work !*

Heat engines :
1 - receive Q from a T_H reservoir (source)
2 - convert part of Q to W
3 - reject the remaining Q to a T_L reservoir (sink)
4 - operate as a cycle

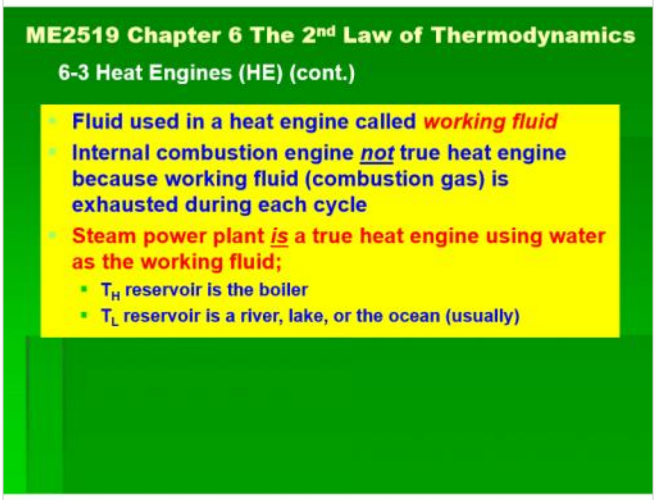
$$\boxed{Q_H=Q_L+W_{out}}$$



ME2519 Chapter 6 The 2nd Law of Thermodynamics

6-3 Heat Engines (HE) (cont.)

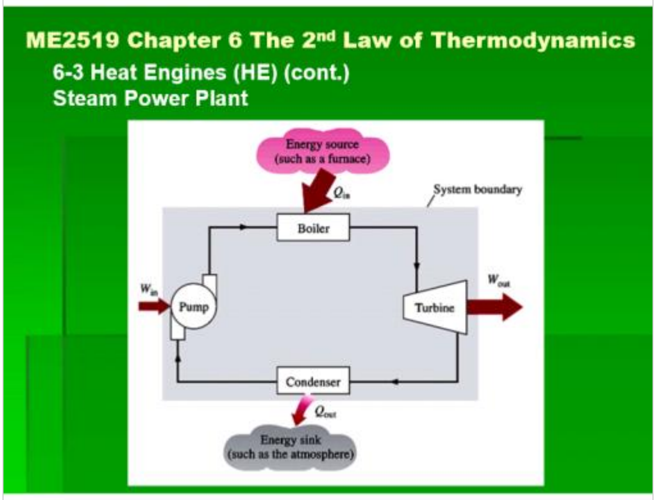
A heat engine is a $\underline{\text{closed system}}$ because
only W and Q cross the boundary
From general form of 1^{st} Law:
$\Delta U + \Delta KE + \Delta PE$
$= (Q_{in} - Q_{out}) + (W_{in} - W_{out}) + (E_{mass,in} - E_{mass,out})$
But $\Delta U + \Delta KE + \Delta PE = 0$ *for a cycle*, and no $\dot{m}$ crosses boundary
So 1st Law becomes $0 = (Q_{in} - Q_{out}) + (W_{in} - W_{out})$
or $(Q_H - Q_L) = (W_{out} - W_{in}) = W_{net,out}$
or $Q_H = Q_L + W_{net,out}$



ME2519 Chapter 6 The 2nd Law of Thermodynamics

6-3 Heat Engines (HE) (cont.)

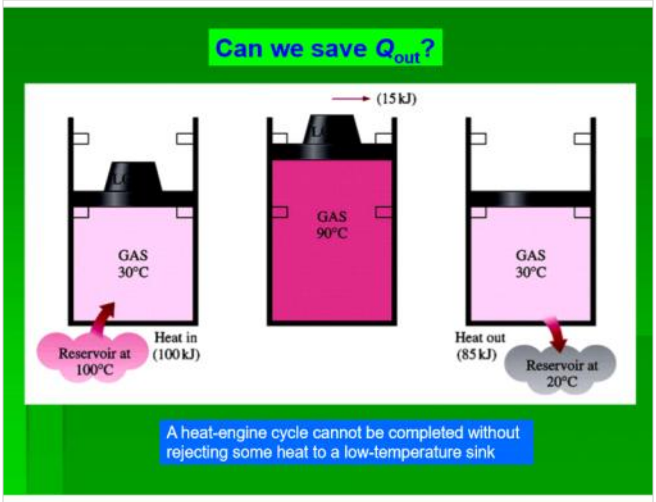
- Fluid used in a heat engine called *working fluid*
- Internal combustion engine *not* true heat engine because working fluid (combustion gas) is exhausted during each cycle
- Steam power plant *is* a true heat engine using water as the working fluid;
  - T_H reservoir is the boiler
  - T_L reservoir is a river, lake, or the ocean (usually)



ME2519 Chapter 6 The 2nd Law of Thermodynamics

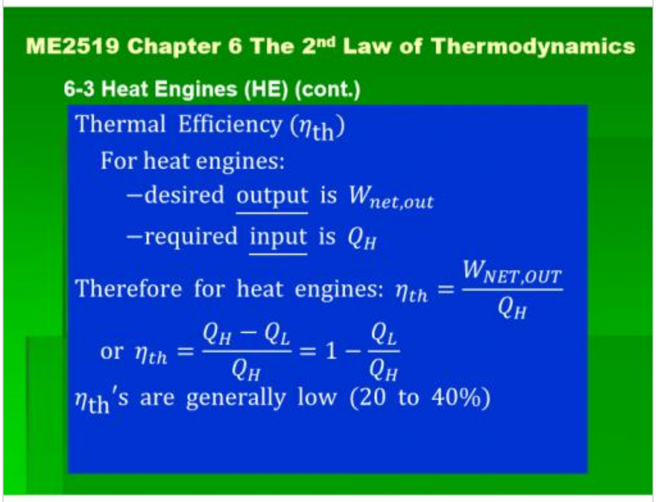
6-3 Heat Engines (HE) (cont.)

Steam Power Plant



Can we save Q_{out}?

A heat-engine cycle cannot be completed without rejecting some heat to a low-temperature sink



ME2519 Chapter 6 The 2nd Law of Thermodynamics

6-3 Heat Engines (HE) (cont.)

Thermal Efficiency (η_{th})

For heat engines:

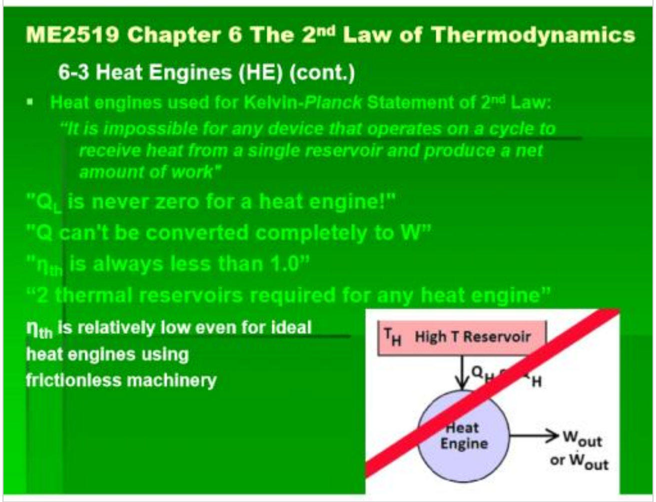
−desired output is $W_{net,out}$

−required input is Q_H

Therefore for heat engines: $\eta_{th} = \dfrac{W_{NET,OUT}}{Q_H}$

or $\eta_{th} = \dfrac{Q_H - Q_L}{Q_H} = 1 - \dfrac{Q_L}{Q_H}$

η_{th}'s are generally low (20 to 40%)



ME2519 Chapter 6 The 2nd Law of Thermodynamics

6-3 Heat Engines (HE) (cont.)

- Heat engines used for Kelvin-*Planck* Statement of 2nd Law:

  "It is impossible for any device that operates on a cycle to receive heat from a single reservoir and produce a net amount of work"

"Q_L is never zero for a heat engine!"

"Q can't be converted completely to W"

"η_{th} is always less than 1.0"

"2 thermal reservoirs required for any heat engine"

η_{th} is relatively low even for ideal heat engines using frictionless machinery

Refrigerators and Heat Pumps

Wednesday, October 26, 2022 10:02 AM

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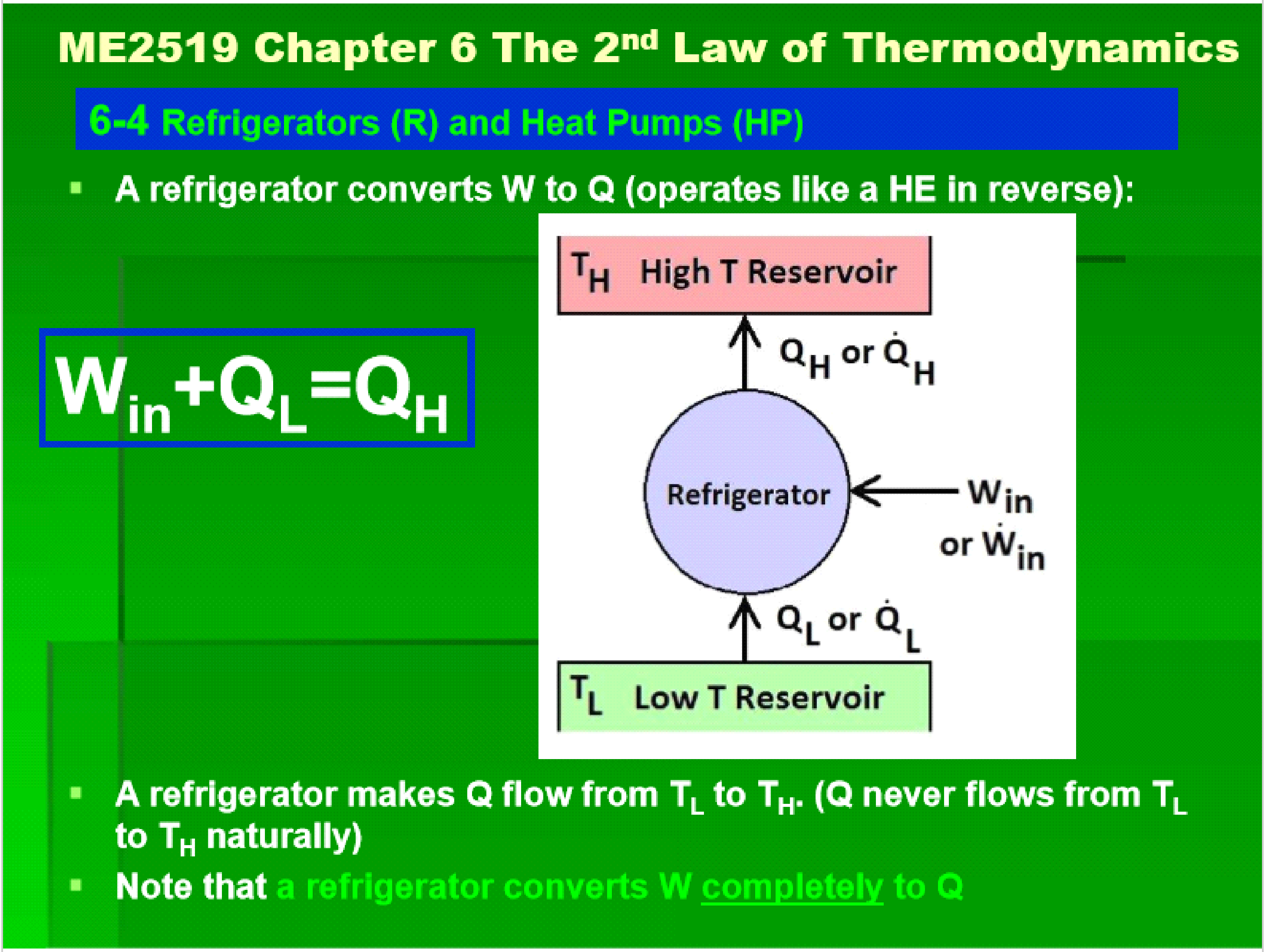


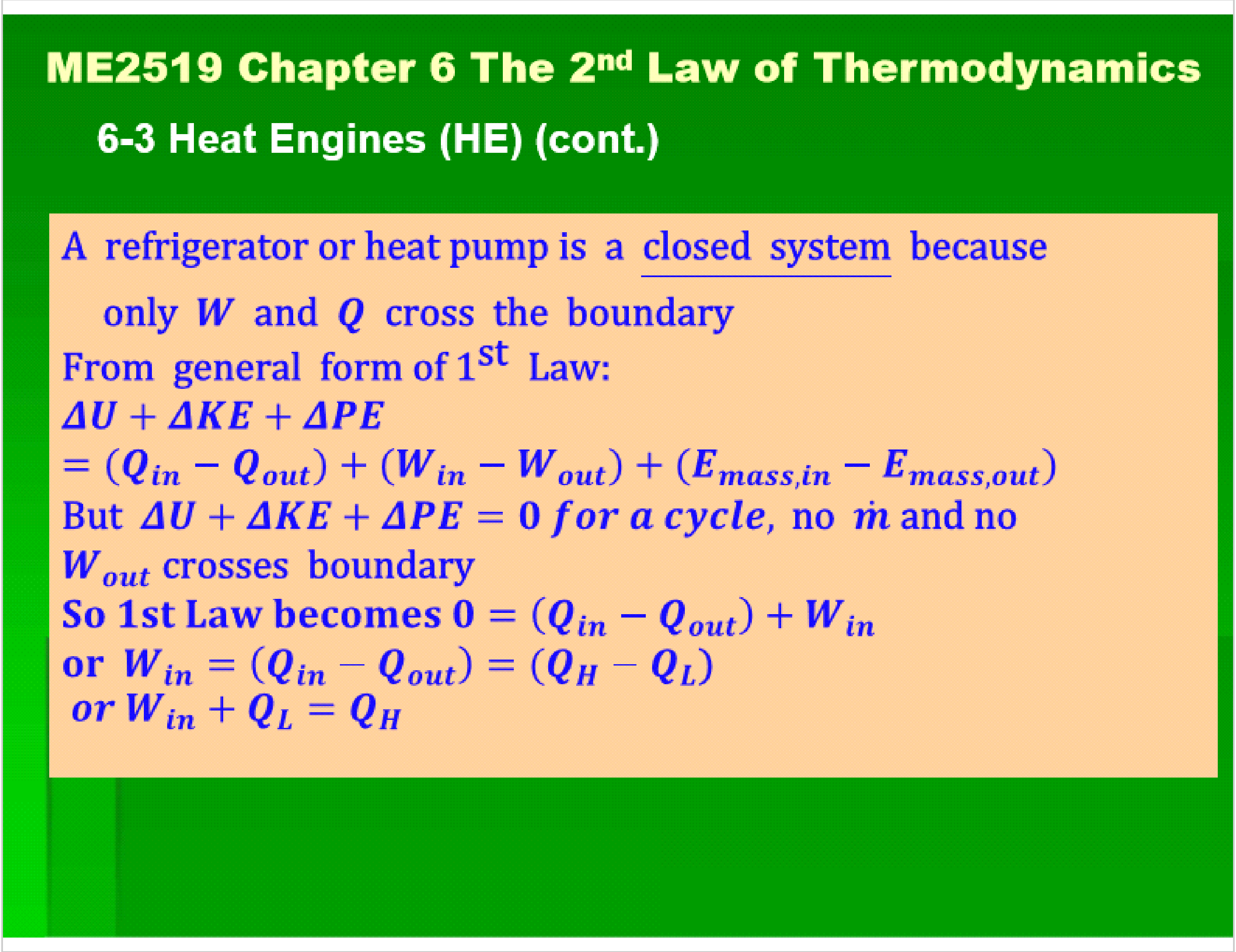
ME2519 Chapter 6 The 2nd Law of Thermodynamics

6-4 Refrigerators (R) and Heat Pumps (HP)

- A refrigerator converts W to Q (operates like a HE in reverse):

$$\boxed{W_{in}+Q_L=Q_H}$$

- A refrigerator makes Q flow from T_L to T_H. (Q never flows from T_L to T_H naturally)
- Note that a refrigerator converts W <u>completely</u> to Q



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6-3 Heat Engines (HE) (cont.)

A refrigerator or heat pump is a closed system because only W and Q cross the boundary

From general form of 1^{st} Law:

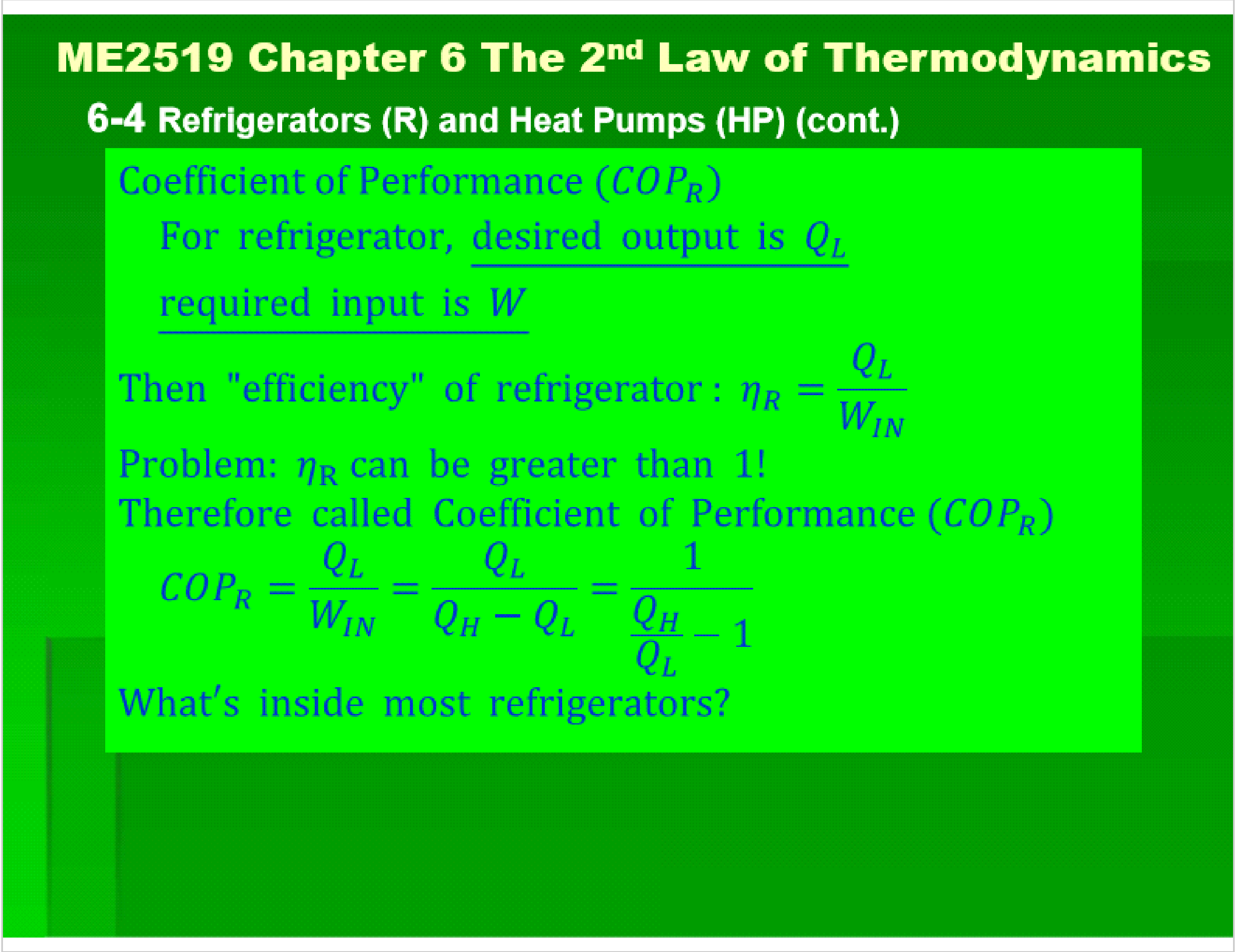
$$\Delta U + \Delta KE + \Delta PE$$
$$= (Q_{in} - Q_{out}) + (W_{in} - W_{out}) + (E_{mass,in} - E_{mass,out})$$

But $\Delta U + \Delta KE + \Delta PE = 0\ for\ a\ cycle$, no $\dot{m}$ and no W_{out} crosses boundary

So 1st Law becomes $0 = (Q_{in} - Q_{out}) + W_{in}$

or $W_{in} = (Q_{in} - Q_{out}) = (Q_H - Q_L)$

$or\ W_{in} + Q_L = Q_H$



ME2519 Chapter 6 The 2nd Law of Thermodynamics

6-4 Refrigerators (R) and Heat Pumps (HP) (cont.)

Coefficient of Performance (COP_R)

For refrigerator, desired output is Q_L

required input is W

Then "efficiency" of refrigerator : $\eta_R = \dfrac{Q_L}{W_{IN}}$

Problem: η_R can be greater than 1!

Therefore called Coefficient of Performance (COP_R)

$$COP_R = \frac{Q_L}{W_{IN}} = \frac{Q_L}{Q_H - Q_L} = \frac{1}{\frac{Q_H}{Q_L} - 1}$$

What′s inside most refrigerators?

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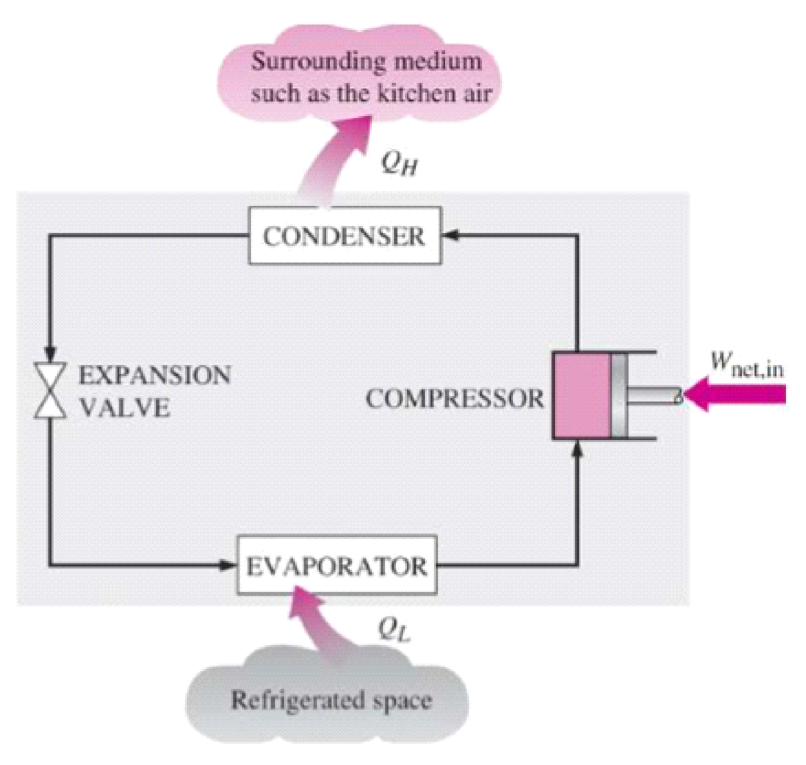
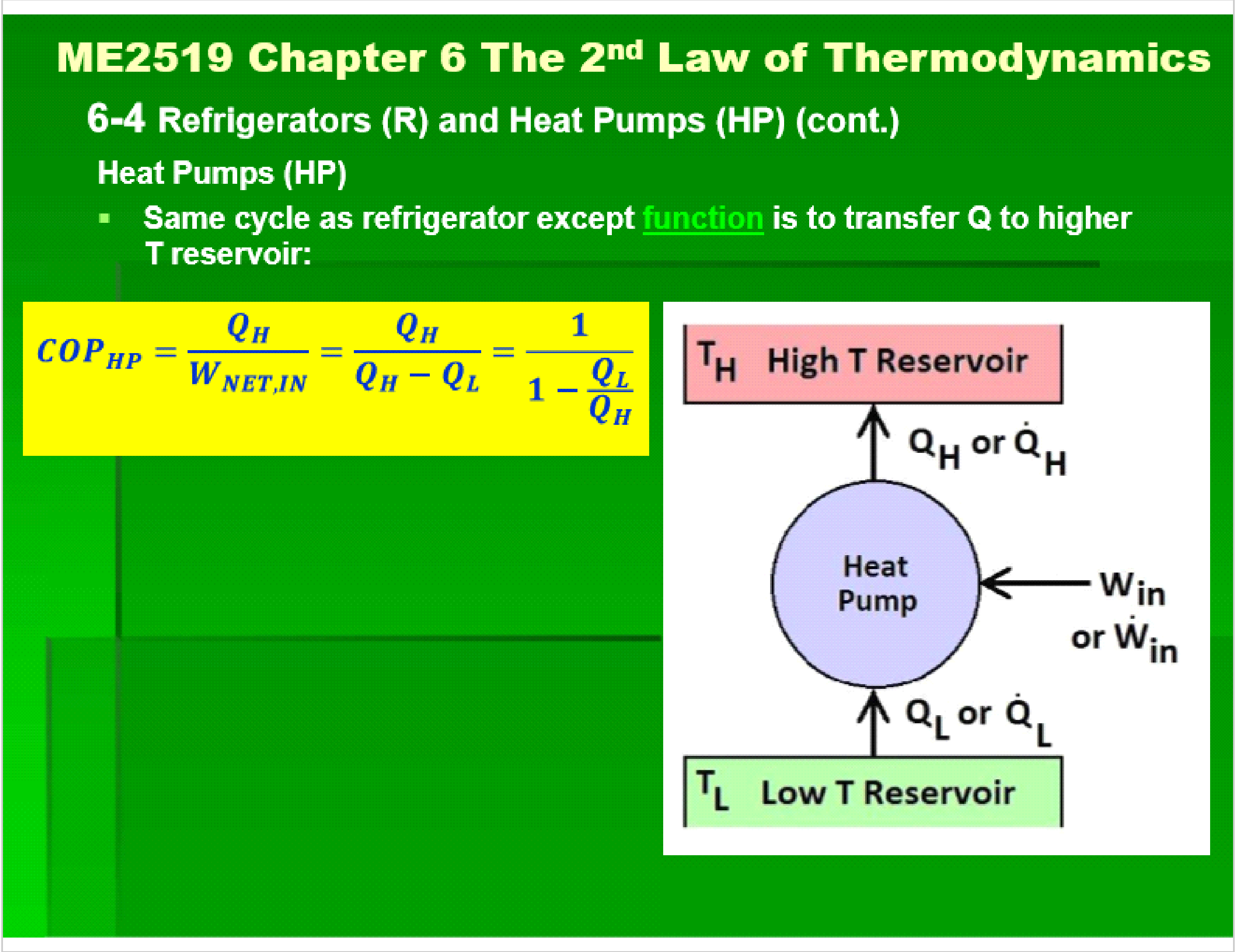
6-4 Refrigerators (R) and Heat Pumps (HP) (cont.)



- Air conditioners are refrigerators where house is the inside of the refrigerator!



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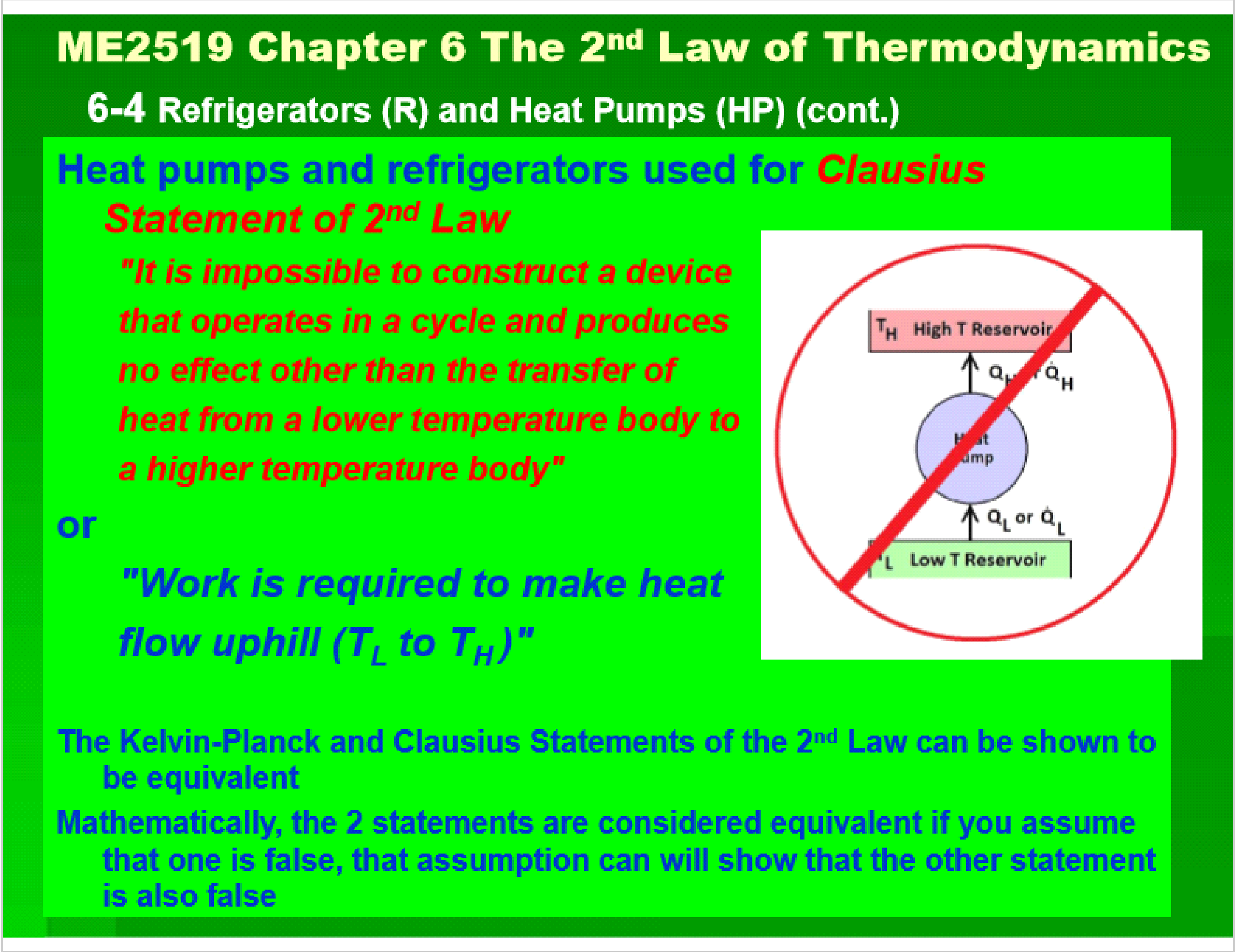
6-4 Refrigerators (R) and Heat Pumps (HP) (cont.)

Heat Pumps (HP)

- Same cycle as refrigerator except function is to transfer Q to higher T reservoir:

$$COP_{HP} = \frac{Q_H}{W_{NET,IN}} = \frac{Q_H}{Q_H - Q_L} = \frac{1}{1 - \frac{Q_L}{Q_H}}$$



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6-4 Refrigerators (R) and Heat Pumps (HP) (cont.)

Heat pumps and refrigerators used for *Clausius Statement of 2nd Law*

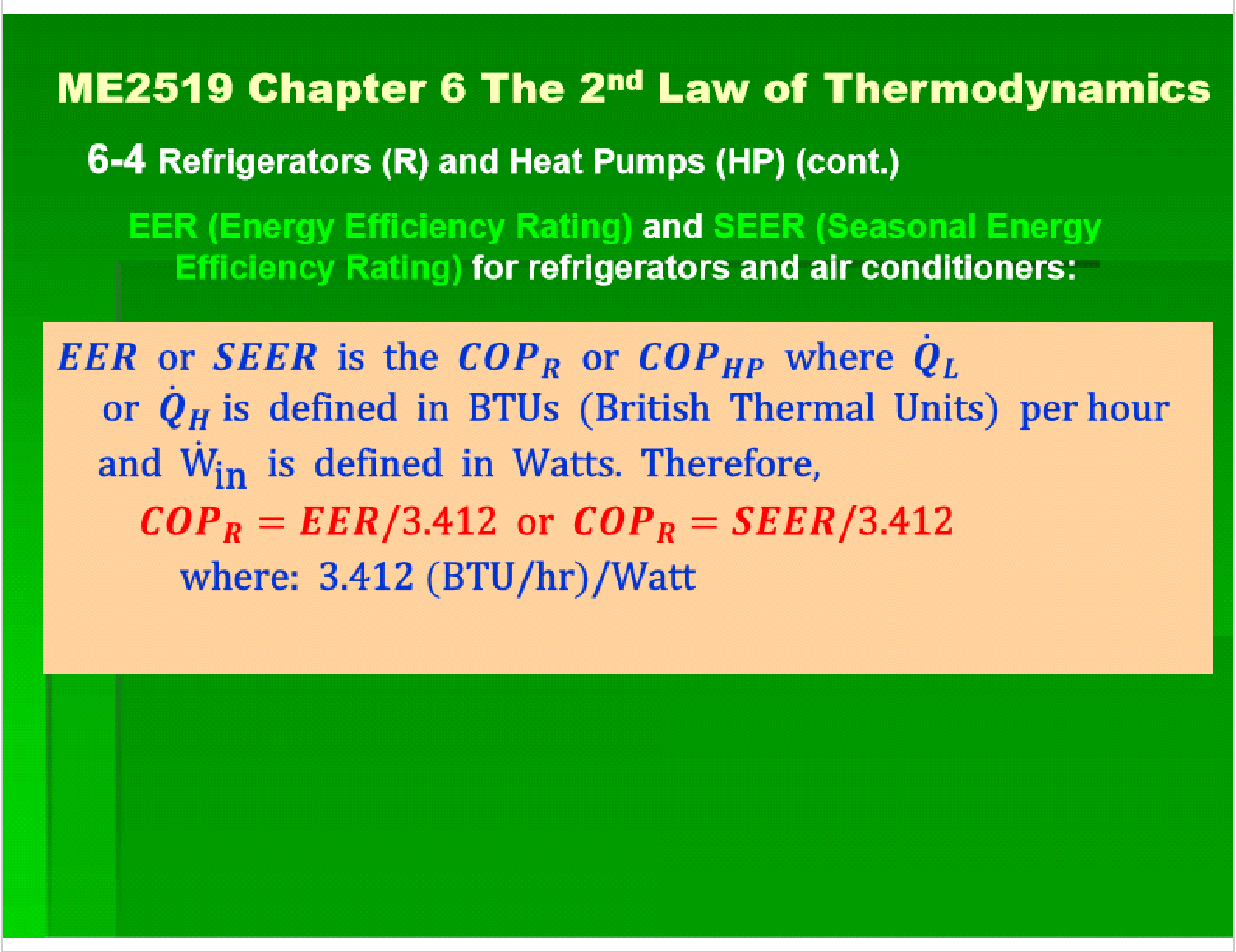
> ***"It is impossible to construct a device that operates in a cycle and produces no effect other than the transfer of heat from a lower temperature body to a higher temperature body"***

or

> ***"Work is required to make heat flow uphill (T_L to T_H)"***

The Kelvin-Planck and Clausius Statements of the 2nd Law can be shown to be equivalent

Mathematically, the 2 statements are considered equivalent if you assume that one is false, that assumption can will show that the other statement is also false



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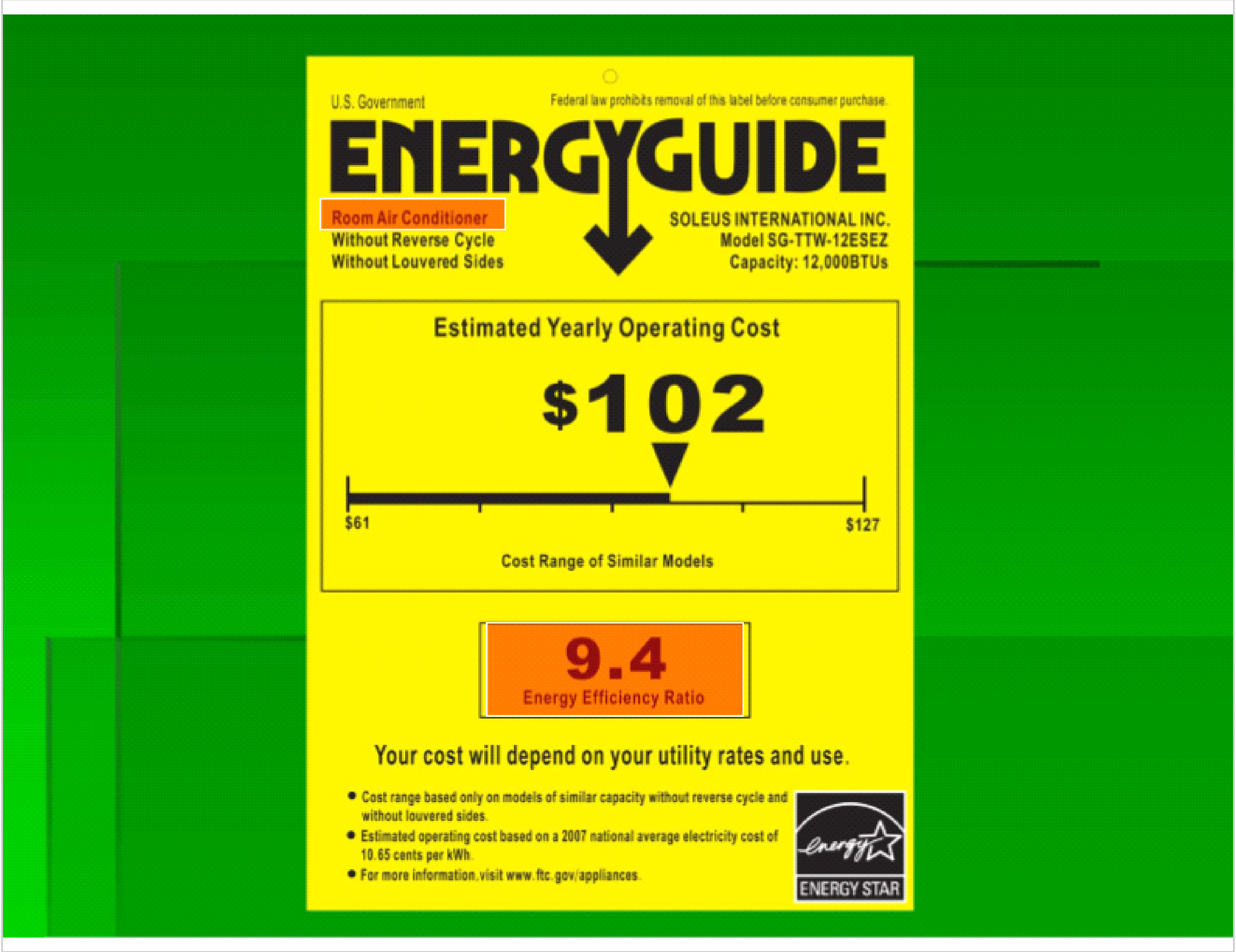
6-4 Refrigerators (R) and Heat Pumps (HP) (cont.)

EER (Energy Efficiency Rating) and SEER (Seasonal Energy Efficiency Rating) for refrigerators and air conditioners:

EER or $SEER$ is the COP_R or COP_{HP} where $\dot{Q}_L$ or $\dot{Q}_H$ is defined in BTUs (British Thermal Units) per hour and $\dot{\mathrm{W}}_{\mathrm{in}}$ is defined in Watts. Therefore,

$$COP_R = EER/3.412 \text{ or } COP_R = SEER/3.412$$

where: 3.412 (BTU/hr)/Watt



U.S. Government

Federal law prohibits removal of this label before consumer purchase.

ENERGYGUIDE

Room Air Conditioner
Without Reverse Cycle
Without Louvered Sides

SOLEUS INTERNATIONAL INC.
Model SG-TTW-12ESEZ
Capacity: 12,000BTUs

Estimated Yearly Operating Cost

$102

Cost Range of Similar Models

9.4
Energy Efficiency Ratio

Your cost will depend on your utility rates and use.

- Cost range based only on models of similar capacity without reverse cycle and without louvered sides.
- Estimated operating cost based on a 2007 national average electricity cost of 10.65 cents per kWh.
- For more information, visit www.ftc.gov/appliances.

ENERGY STAR

U.S. Government

Federal law prohibits removal of this label before consumer purchase.

ENERGYGUIDE

Room Air Conditioner

WITH REVERSE CYCLE
WITH LOUVERED SIDES

Friedrich Air Conditioning Co.
Model: YS10N10
Capacity: 9400BTUs

Estimated Yearly Operating Cost

$68

$61

$192

Cost Range of Similar Models

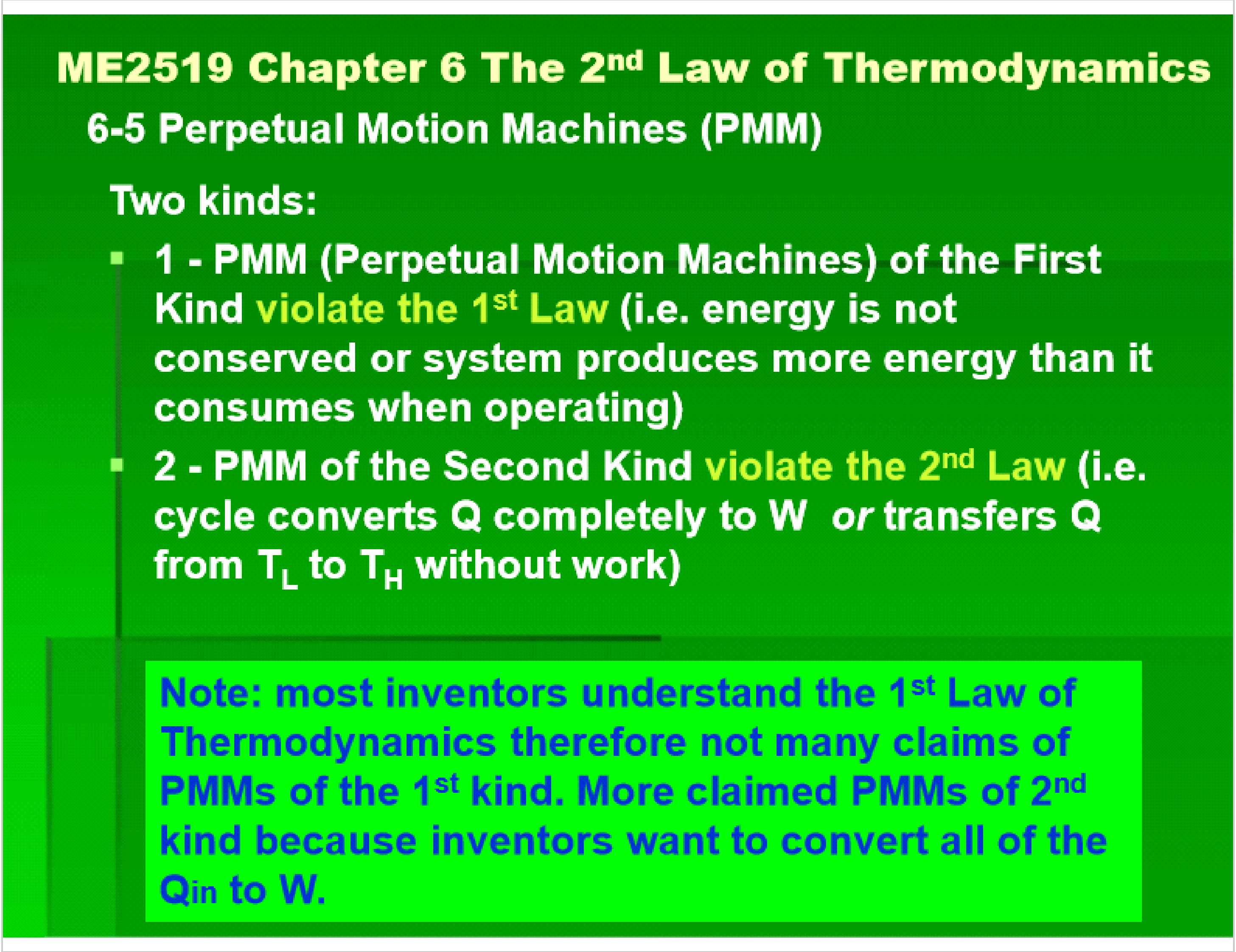
11.0

Energy Efficiency Ratio

Your cost will depend on your utility rates and use.

- Cost range based only on models of similar capacity and WITH LOUVERED SIDES
- Estimated operating cost based on a 2007 national average electricity cost of .1065 cents per kWh.
- For more information, visit www.ftc.gov/appliances.

energy ENERGY STAR



ME2519 Chapter 6 The 2nd Law of Thermodynamics

6-5 Perpetual Motion Machines (PMM)

Two kinds:

- 1 - PMM (Perpetual Motion Machines) of the First Kind violate the 1st Law (i.e. energy is not conserved or system produces more energy than it consumes when operating)
- 2 - PMM of the Second Kind violate the 2nd Law (i.e. cycle converts Q completely to W *or* transfers Q from T_L to T_H without work)

Note: most inventors understand the 1st Law of Thermodynamics therefore not many claims of PMMs of the 1st kind. More claimed PMMs of 2nd kind because inventors want to convert all of the Q_{in} to W.

Homework 6a

Thursday, October 27, 2022 11:13 AM

6–19 A 600-MW steam power plant, which is cooled by a nearby river, has a thermal efficiency of 40 percent. Determine the rate of heat transfer to the river water. Will the actual heat transfer rate be higher or lower than this value? Why?

$$\eta_{th} = \frac{W_{net,out}}{Q_H}$$

$$Q_H = \frac{W_{net,out}}{\eta_{th}} = \frac{600\ MW}{.4} = 1500\ MW$$

$$W_{net,out} = Q_H - Q_L$$

$$Q_L = Q_H - W_{net,out} = 1500MW - 600\ MW = \boxed{900MW}$$

Not all the heat from the power plant will go into the river, so it will be lower.

6–22 A steam power plant with a power output of 150 MW consumes coal at a rate of 60 tons/h. If the heating value of the coal is 30,000 kJ/kg, determine the overall efficiency of this plant. *Answer: 30.0 percent*

$h_v = 30000\ kJ/kg$

$\dot{m} = 60\ tons/h$

$$Q_H = \dot{m} h_v = 60\ tons/h\ (30,000\ kJ/kg) \frac{1000\ kg}{1\ ton} \frac{1h}{3600sec} = 500\ MW$$

$$\eta_{th} = \frac{W_{net,out}}{Q_H} = \frac{150\ MW}{500MW} = \boxed{.30}$$

6–25 A coal-burning steam power plant produces a net power of 300 MW with an overall thermal efficiency of 32 percent. The actual gravimetric air–fuel ratio in the furnace is calculated to be 12 kg air/kg fuel. The heating value of the coal is 28,000 kJ/kg. Determine (*a*) the amount of coal consumed during a 24-hour period and (*b*) the rate of air flowing through the furnace. *Answers: (a) 2.89 × 10^6 kg, (b) 402 kg/s*

$W_{net,out} = 300\ MW$

$\eta_{th} = .32$

$h_v = 2\ 800\ kJ/kg$

$$\eta_{th} = \frac{W_{net,out}}{Q_H}$$

$$Q_H = \frac{W_{net,out}}{\eta_{th}} = \frac{300MW}{.32} = 937.5\ MW$$

$$\dot{m} = \frac{Q_H}{h_v} = \frac{937.5MW}{2800\ kJ/kg} \frac{1000\ kJ}{MW} = 33.48\ \frac{kg}{s}$$

$$m = \dot{m} t = 33.48\ 24\ h\ \frac{3600s}{1h} = \boxed{2.89\ \times 10^6\ kg}$$

$$\dot{m}_{air} = \dot{m}_{coal} \left(\frac{\dot{m}_{air}}{\dot{m}_{coal}}\right) = 33.48\left(\frac{12\ kg\ air}{1\ kg\ coal}\right) = \boxed{402\ kg/s}$$

6–42 An automotive air conditioner produces a 1-kW cooling effect while consuming 0.75 kW of power. What is the rate at which heat is rejected from this air conditioner?

$$\boxed{\dot{Q}_H = \dot{W}_{in} + \dot{Q}_L = 1kW + .75\ kW = 1.75\ kW}$$

6–42 An automotive air conditioner produces a 1-kW cooling effect while consuming 0.75 kW of power. What is the rate at which heat is rejected from this air conditioner?

$$\boxed{\dot{Q}_H = \dot{W}_{in} + \dot{Q}_L = 1\,kW + .75\,kW = 1.75\,kW}$$

6–48 An air conditioner removes heat steadily from a house at a rate of 750 kJ/min while drawing electric power at a rate of 5.25 kW. Determine (*a*) the COP of this air conditioner and (*b*) the rate of heat transfer to the outside air. *Answers:* (*a*) 2.38, (*b*) 1065 kJ/min

$$COP_R = \frac{\dot{Q}_L}{\dot{W}_{in}} = \frac{750\ kJ/min}{5.25\ kW}\ \frac{1\,min}{60\,s} = \boxed{2.381}$$

$$\dot{Q}_H = \dot{W}_{in} + \dot{Q}_L = 5.25\,kW + 750\,\frac{kJ}{min}\ \frac{1\,min}{60\,s} = 17.75\,kW\ \frac{60\,s}{1\,min} = \boxed{1065\ \frac{kJ}{s}}$$

6–57 Refrigerant-134a enters the condenser of a residential heat pump at 800 kPa and 35°C at a rate of 0.018 kg/s and leaves at 800 kPa as a saturated liquid. If the compressor consumes 1.2 kW of power, determine (*a*) the COP of the heat pump and (*b*) the rate of heat absorption from the outside air.

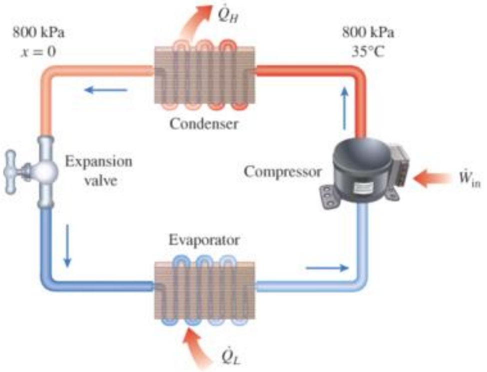


FIGURE P6–57

$P_1 = 800\ kPa$

$T_1 = 35\ °C$

$\dot{m} = .018\ kg/s$

$x_2 = 0$

$\dot{W}_{in} = 1.2\ kW$

$$h_1 = 267.34 + \left(\frac{35 - 31.31}{40 - 31.31}\right)(276.46 - 267.34) = 271.21\ \frac{kJ}{kg}$$

A-13

$$h_2 = h_f = 95.48\ \frac{kJ}{kg}$$

A-12

$$\dot{Q}_H = \dot{m}(h_1 - h_2) = .058\,(271.21 - 95.48)$$

$$= 3.163\ kW$$

$$COP_{HP} = \frac{\dot{Q}_H}{\dot{W}_{in}} = \frac{1.2}{3.163} = \boxed{2.636}$$

$$\dot{Q}_L = \dot{Q}_H - \dot{W}_{in} = 3.163 - 1.2 = \boxed{1.963\ kW}$$

Carnot Cycle

Friday, October 28, 2022 10:03 AM

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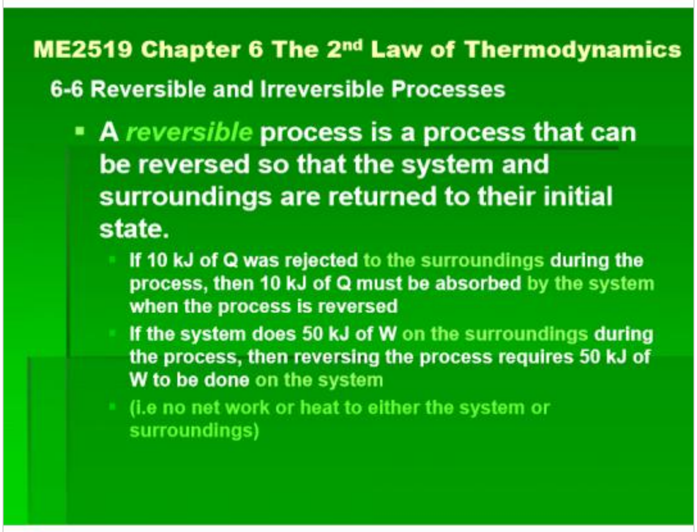


ME2519 Chapter 6 The 2nd Law of Thermodynamics

6-6 Reversible and Irreversible Processes

- A *reversible* process is a process that can be reversed so that the system and surroundings are returned to their initial state.
  - If 10 kJ of Q was rejected to the surroundings during the process, then 10 kJ of Q must be absorbed by the system when the process is reversed
  - If the system does 50 kJ of W on the surroundings during the process, then reversing the process requires 50 kJ of W to be done on the system
  - (i.e no net work or heat to either the system or surroundings)

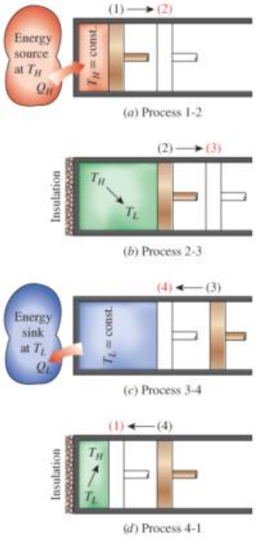


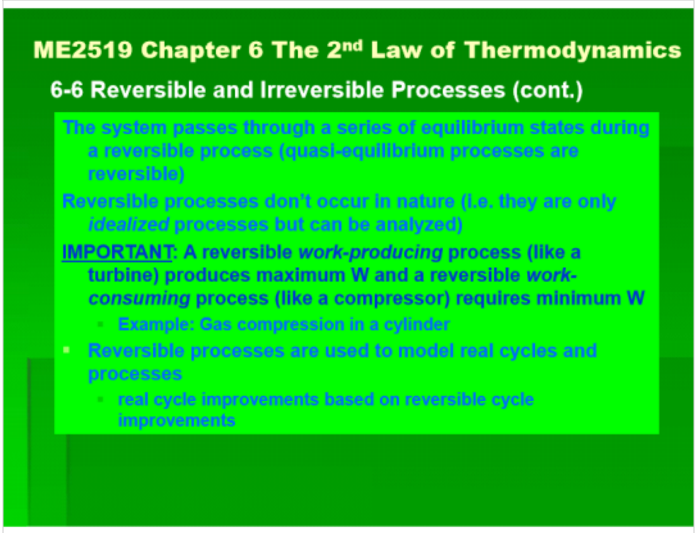
FIGURE 6–36
Execution of the Carnot cycle in a closed system.

Reversible Isothermal Expansion (process 1-2, T_H = constant). Initially (state 1), the temperature of the gas is T_H and the cylinder head is in close contact with a source at temperature T_H. The gas is allowed to expand slowly, doing work on the surroundings. As the gas expands, the temperature of the gas tends to decrease. But as soon as the temperature drops by an infinitesimal amount dT, some heat is transferred from the reservoir into the gas, raising the gas temperature to T_H. Thus, the gas temperature is kept constant at T_H. Since the temperature difference between the gas and the reservoir never exceeds a differential amount dT, this is a reversible heat transfer process. It continues until the piston reaches position 2. The amount of total heat transferred to the gas during this process is Q_H.

Reversible Adiabatic Expansion (process 2-3, temperature drops from T_H to T_L). At state 2, the reservoir that was in contact with the cylinder head is removed and replaced by insulation so that the system becomes adiabatic. The gas continues to expand slowly, doing work on the surroundings until its temperature drops from T_H to T_L (state 3). The piston is assumed to be frictionless and the process to be quasi-equilibrium, so the process is reversible as well as adiabatic.

Reversible Isothermal Compression (process 3-4, T_L = constant). At state 3, the insulation at the cylinder head is removed, and the cylinder is brought into contact with a sink at temperature T_L. Now the piston is pushed inward by an external force, doing work on the gas. As the gas is compressed, its temperature tends to rise. But as soon as it rises by an infinitesimal amount dT, heat is transferred from the gas to the sink, causing the gas temperature to drop to T_L. Thus, the gas temperature remains constant at T_L. Since the temperature difference between the gas and the sink never exceeds a differential amount dT, this is a reversible heat transfer process. It continues until the piston reaches state 4. The amount of heat rejected from the gas during this process is Q_L.

Reversible Adiabatic Compression (process 4-1, temperature rises from T_L to T_H). State 4 is such that when the low-temperature reservoir is removed, the insulation is put back on the cylinder head, and the gas is compressed in a reversible manner, so the gas returns to its initial state (state 1). The temperature rises from T_L to T_H during this reversible adiabatic compression process, which completes the cycle.



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6-6 Reversible and Irreversible Processes (cont.)

- The system passes through a series of equilibrium states during a reversible process (quasi-equilibrium processes are reversible)
- Reversible processes don't occur in nature (i.e. they are only *idealized* processes but can be analyzed)
- **IMPORTANT**: A reversible *work-producing* process (like a turbine) produces maximum W and a reversible *work-consuming* process (like a compressor) requires minimum W
  - Example: Gas compression in a cylinder
- Reversible processes are used to model real cycles and processes
  - real cycle improvements based on reversible cycle improvements

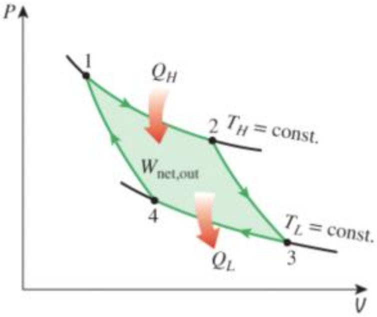

FIGURE 6–37
P-V diagram of the Carnot cycle.

The Carnot principles.

1. The efficiency of an irreversible heat engine is always less than the efficiency of a reversible one operating between the same two reservoirs.
2. The efficiencies of all reversible heat engines operating between the same two reservoirs are the same.

ME2519 Chapter 6 The 2nd Law of Thermodynamics

6-6 Reversible and Irreversible Processes (cont.)

What causes a process to become irreversible?

IRREVERSIBILITIES!

- Friction (contrast with spring force)
- Unrestrained expansion or compression (abrupt duct expansion vs smooth duct transition)
- Mixing of two gases (scramjet mixing and burning of hydrogen and air)
- Q transfer across a finite T gradient (next chapter: how to get Q with no ΔT)
- Electric resistance (electric resistance heating vs heating of wiring)
- Inelastic (plastic) deformation of solids (bent paper clips don't bend back like a piece of rubber)
- Chemical reactions (vinegar and baking soda; never goes in reverse)

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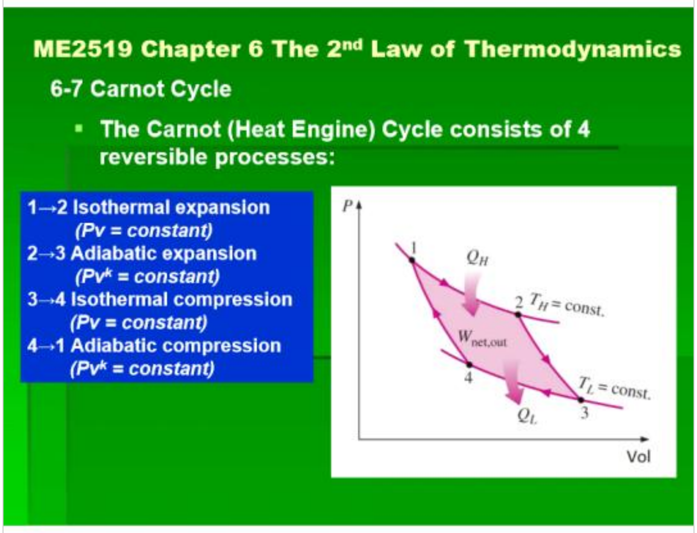
6-6 Reversible and Irreversible Processes (cont.)

- ***internally*** **reversible process means the only irreversibilities are** ***in the surroundings***
- ***externally*** **reversible process means the only irreversibilities are** ***in the system***
- ***totally*** **reversible process means there are no irreversibilities** ***in the system or the surroundings***



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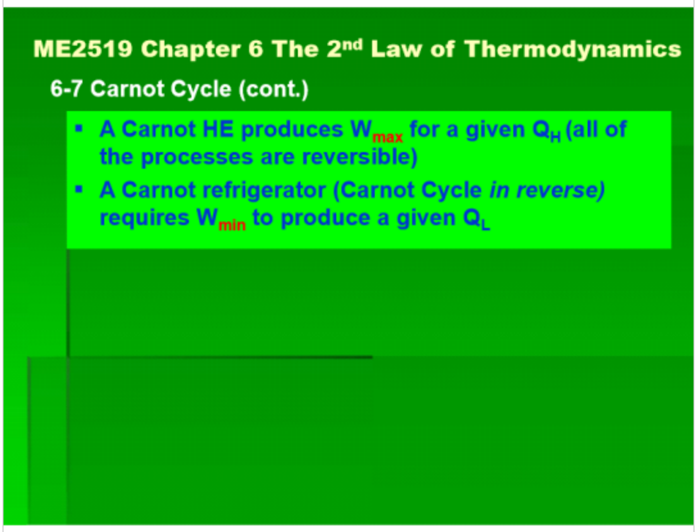
6-7 Carnot Cycle

- **The Carnot (Heat Engine) Cycle consists of 4 reversible processes:**

1→2 Isothermal expansion
(Pv = constant)
2→3 Adiabatic expansion
(Pv^k = constant)
3→4 Isothermal compression
(Pv = constant)
4→1 Adiabatic compression
(Pv^k = constant)



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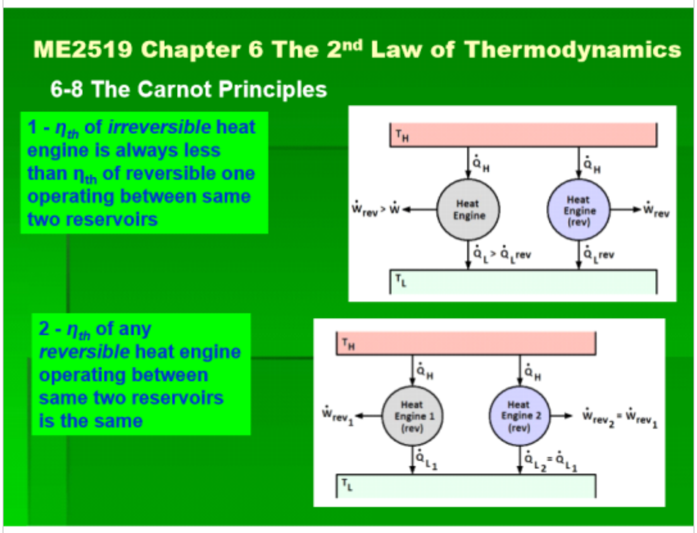
6-7 Carnot Cycle (cont.)

- A Carnot HE produces W_{max} for a given Q_H (all of the processes are reversible)
- A Carnot refrigerator (Carnot Cycle *in reverse)* requires W_{min} to produce a given Q_L



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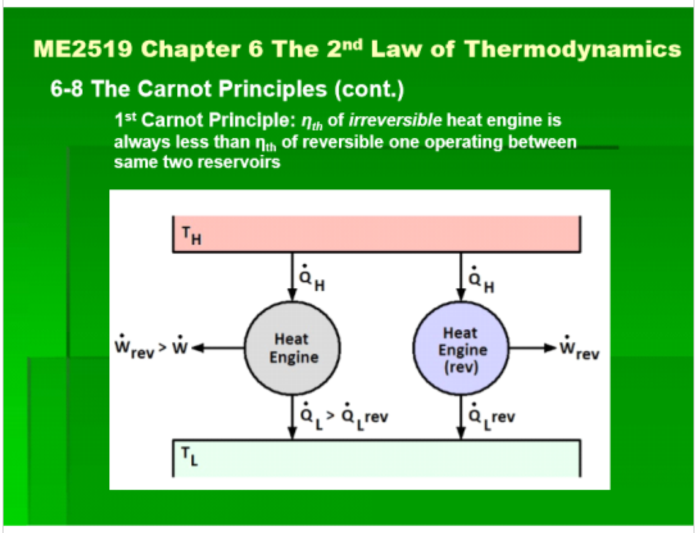
6-8 The Carnot Principles

1 - η_{th} of *irreversible* heat engine is always less than η_{th} of reversible one operating between same two reservoirs

2 - η_{th} of any *reversible* heat engine operating between same two reservoirs is the same



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6-8 The Carnot Principles (cont.)

1st Carnot Principle: η_{th} of *irreversible* heat engine is always less than η_{th} of reversible one operating between same two reservoirs

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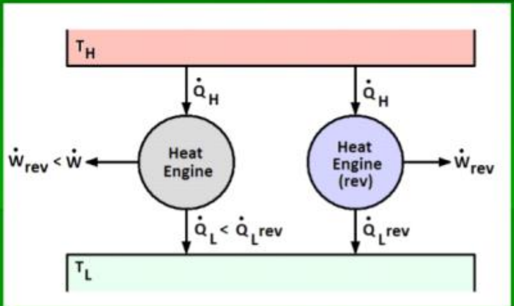
6-8 The Carnot Principles (cont.)

1st Carnot Principle:



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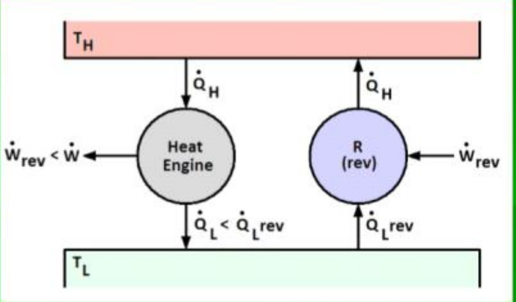
6-8 The Carnot Principles (cont.)

1st Carnot Principle:



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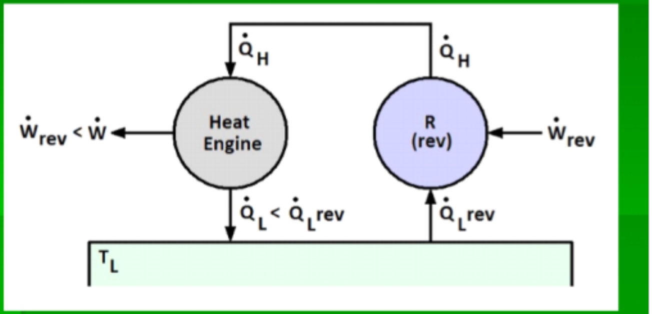
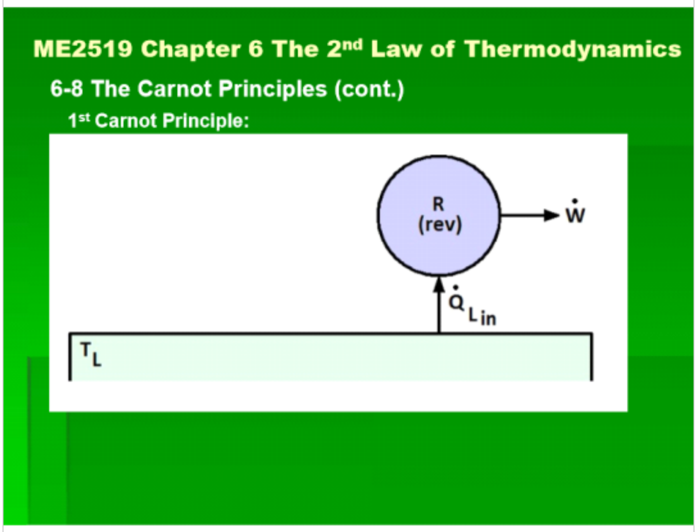
6-8 The Carnot Principles (cont.)

1st Carnot Principle:





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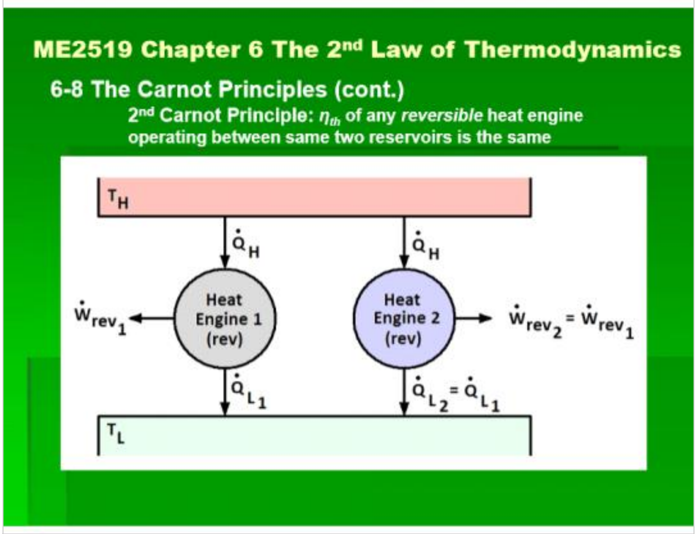
6-8 The Carnot Principles (cont.)

1st Carnot Principle:



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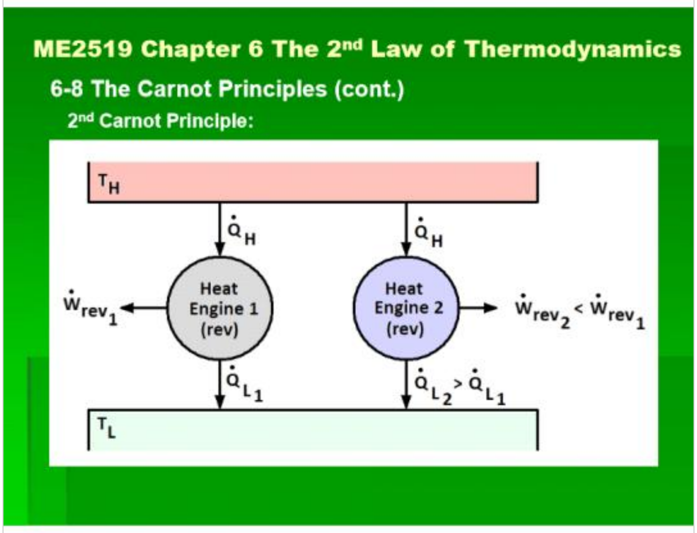
6-8 The Carnot Principles (cont.)

2nd Carnot Principle: η_{th} of any *reversible* heat engine operating between same two reservoirs is the same



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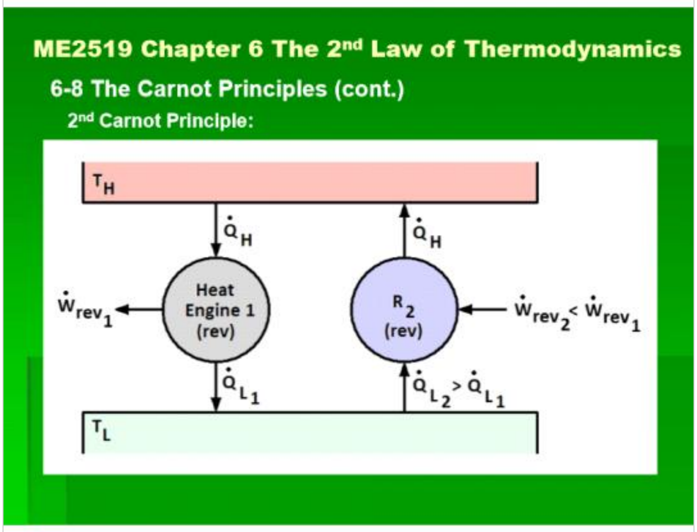
6-8 The Carnot Principles (cont.)

2nd Carnot Principle:



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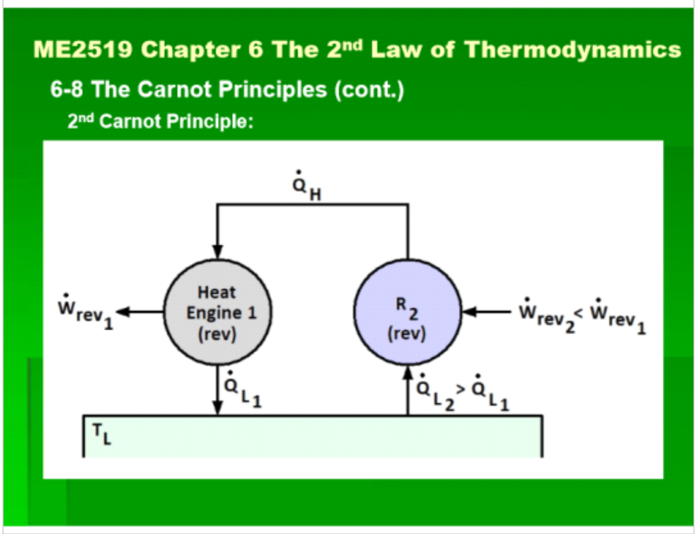
6-8 The Carnot Principles (cont.)

2nd Carnot Principle:



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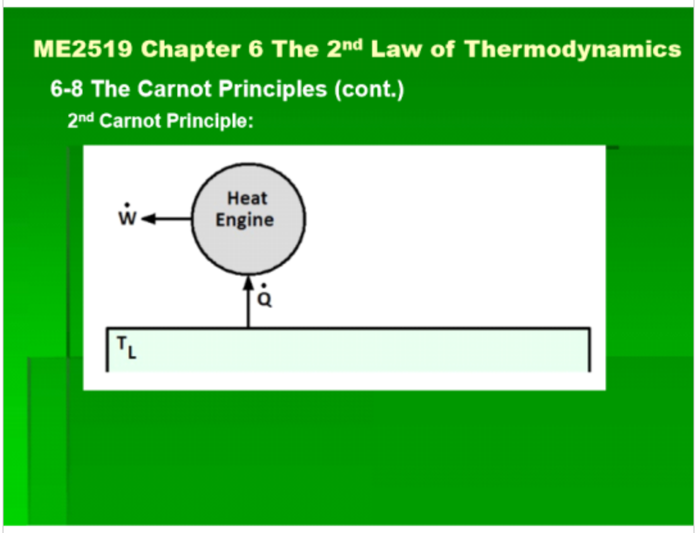
6-8 The Carnot Principles (cont.)

2nd Carnot Principle:



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6-8 The Carnot Principles (cont.)

2nd Carnot Principle:

Thermodynamic Temperature Scale

Monday, October 31, 2022 10:03 AM

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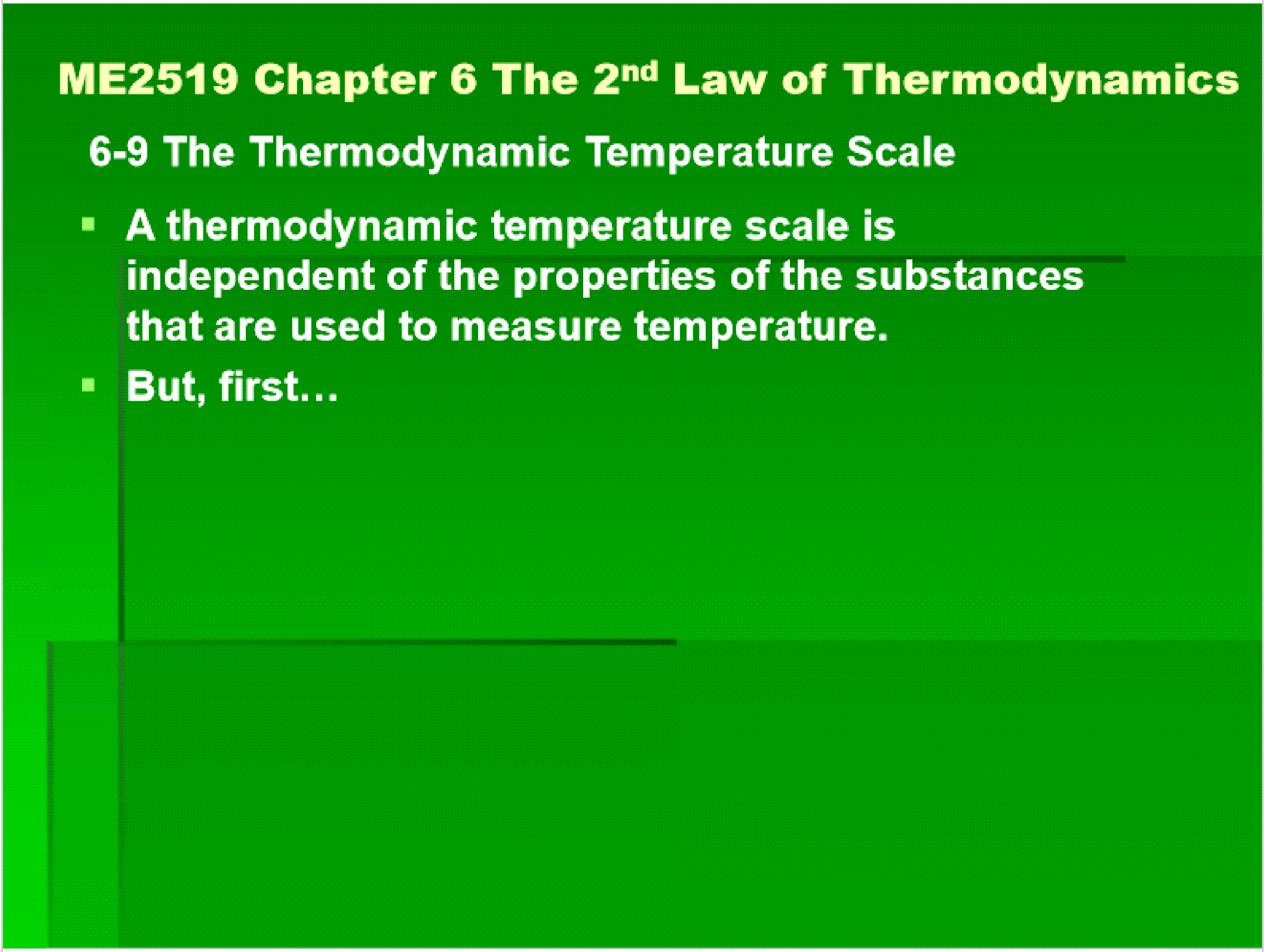
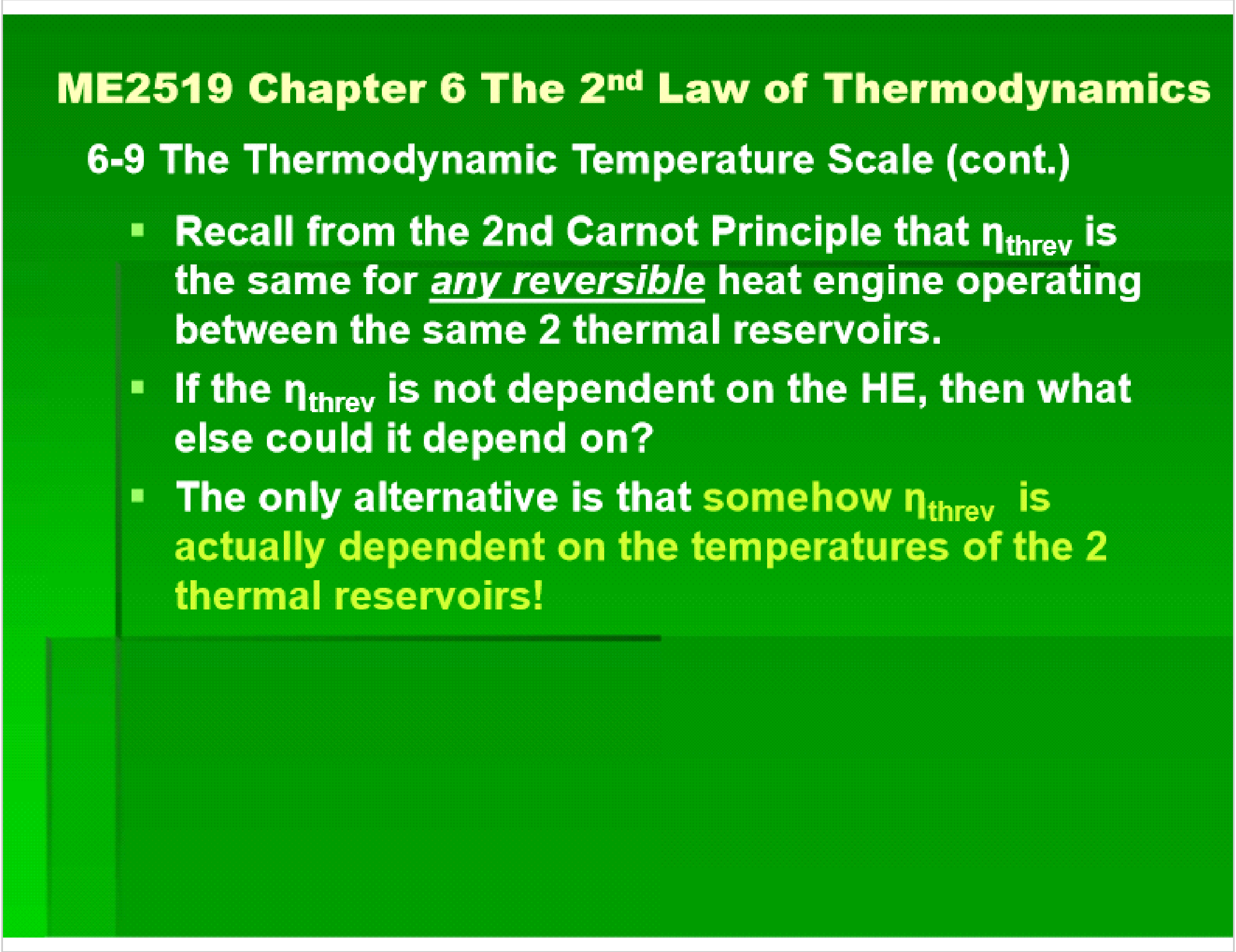


ME2519 Chapter 6 The 2nd Law of Thermodynamics

6-9 The Thermodynamic Temperature Scale

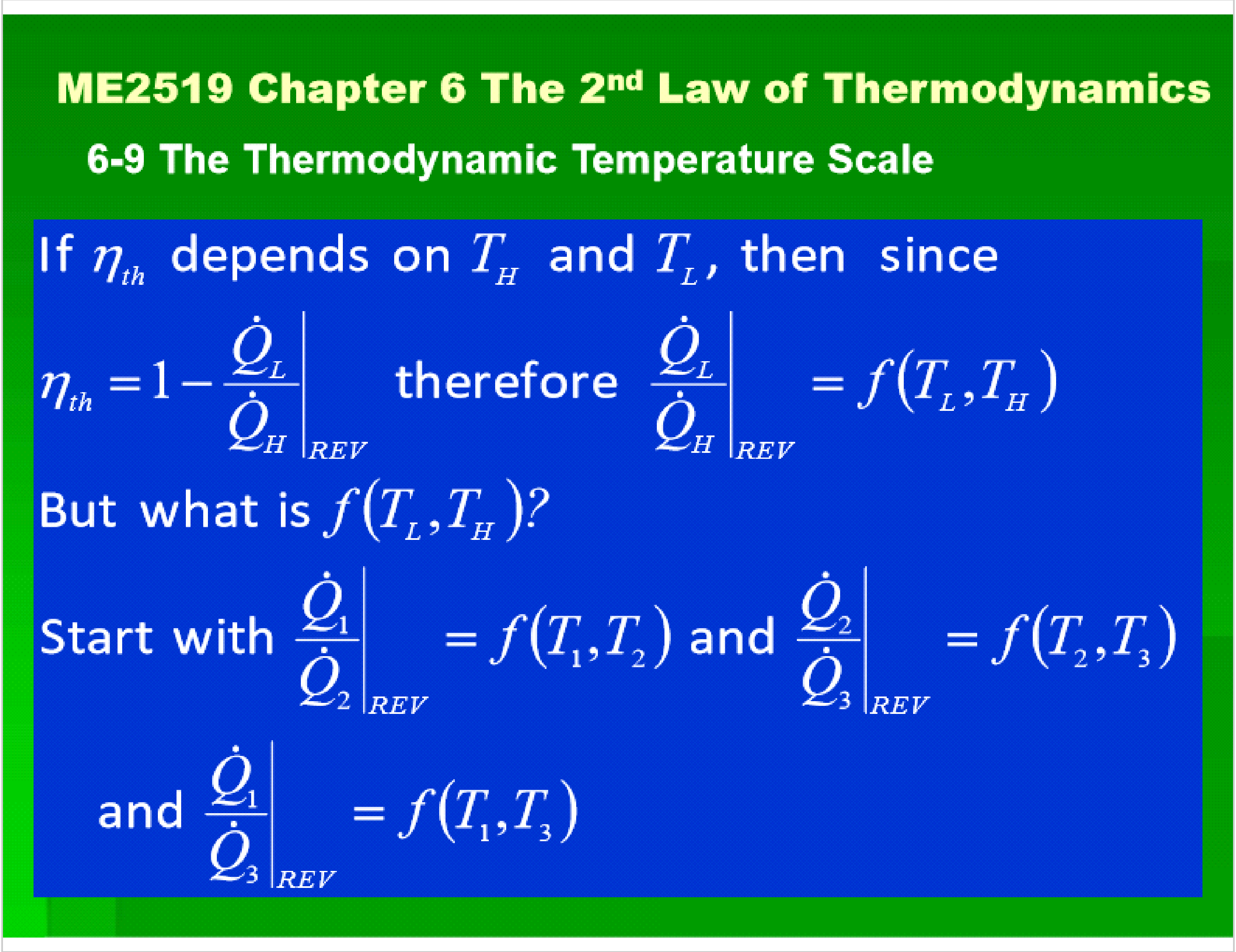
- A thermodynamic temperature scale is independent of the properties of the substances that are used to measure temperature.
- But, first…



ME2519 Chapter 6 The 2nd Law of Thermodynamics

6-9 The Thermodynamic Temperature Scale (cont.)

- Recall from the 2nd Carnot Principle that η_{threv} is the same for ***any reversible*** heat engine operating between the same 2 thermal reservoirs.
- If the η_{threv} is not dependent on the HE, then what else could it depend on?
- The only alternative is that somehow η_{threv} is actually dependent on the temperatures of the 2 thermal reservoirs!



ME2519 Chapter 6 The 2nd Law of Thermodynamics

6-9 The Thermodynamic Temperature Scale

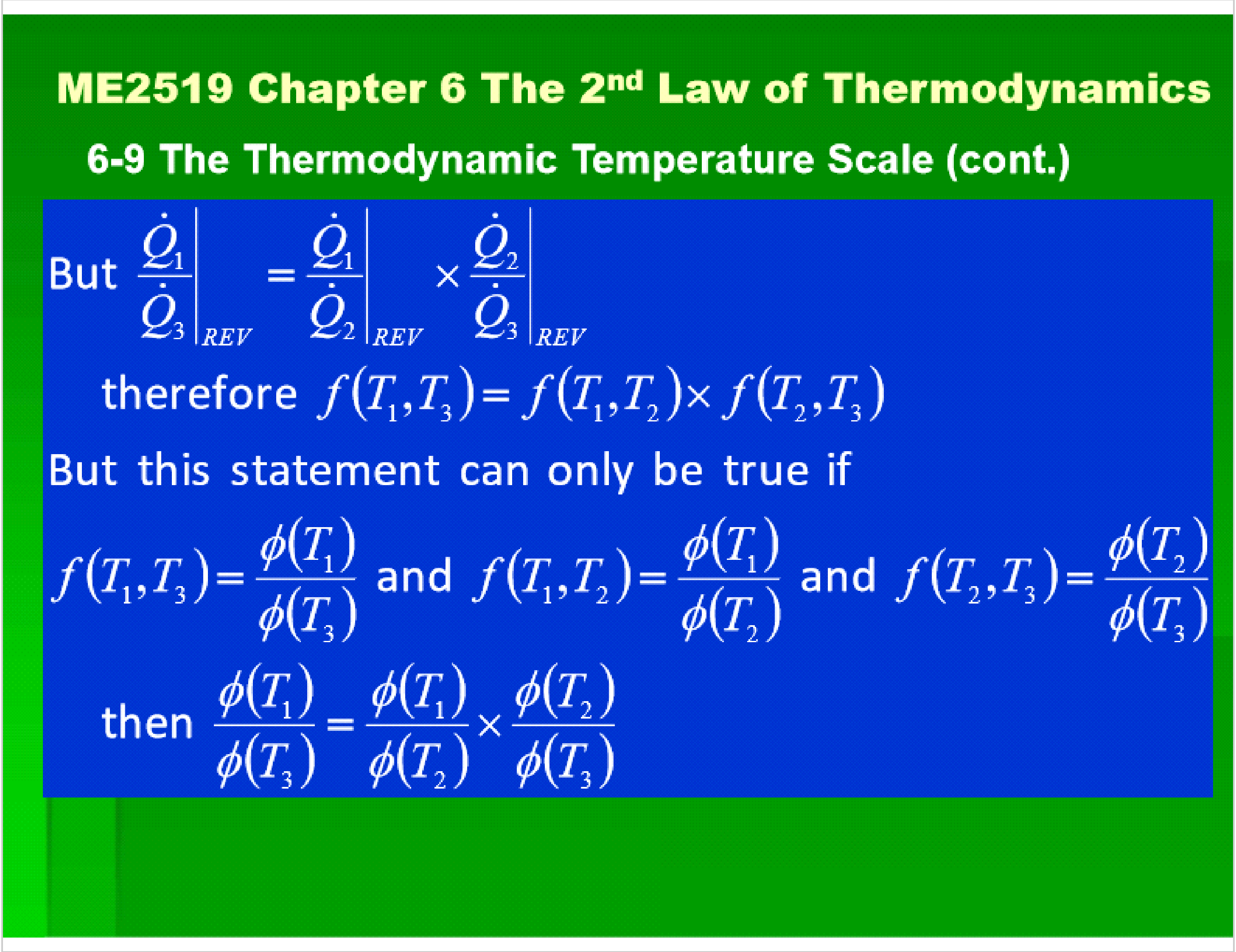
If η_{th} depends on T_H and T_L, then since

$$\eta_{th} = 1 - \left.\frac{\dot{Q}_L}{\dot{Q}_H}\right|_{REV} \quad \text{therefore} \quad \left.\frac{\dot{Q}_L}{\dot{Q}_H}\right|_{REV} = f\left(T_L, T_H\right)$$

But what is $f\left(T_L, T_H\right)$?

Start with $\left.\frac{\dot{Q}_1}{\dot{Q}_2}\right|_{REV} = f\left(T_1, T_2\right)$ and $\left.\frac{\dot{Q}_2}{\dot{Q}_3}\right|_{REV} = f\left(T_2, T_3\right)$

and $\left.\frac{\dot{Q}_1}{\dot{Q}_3}\right|_{REV} = f\left(T_1, T_3\right)$



ME2519 Chapter 6 The 2nd Law of Thermodynamics

6-9 The Thermodynamic Temperature Scale (cont.)

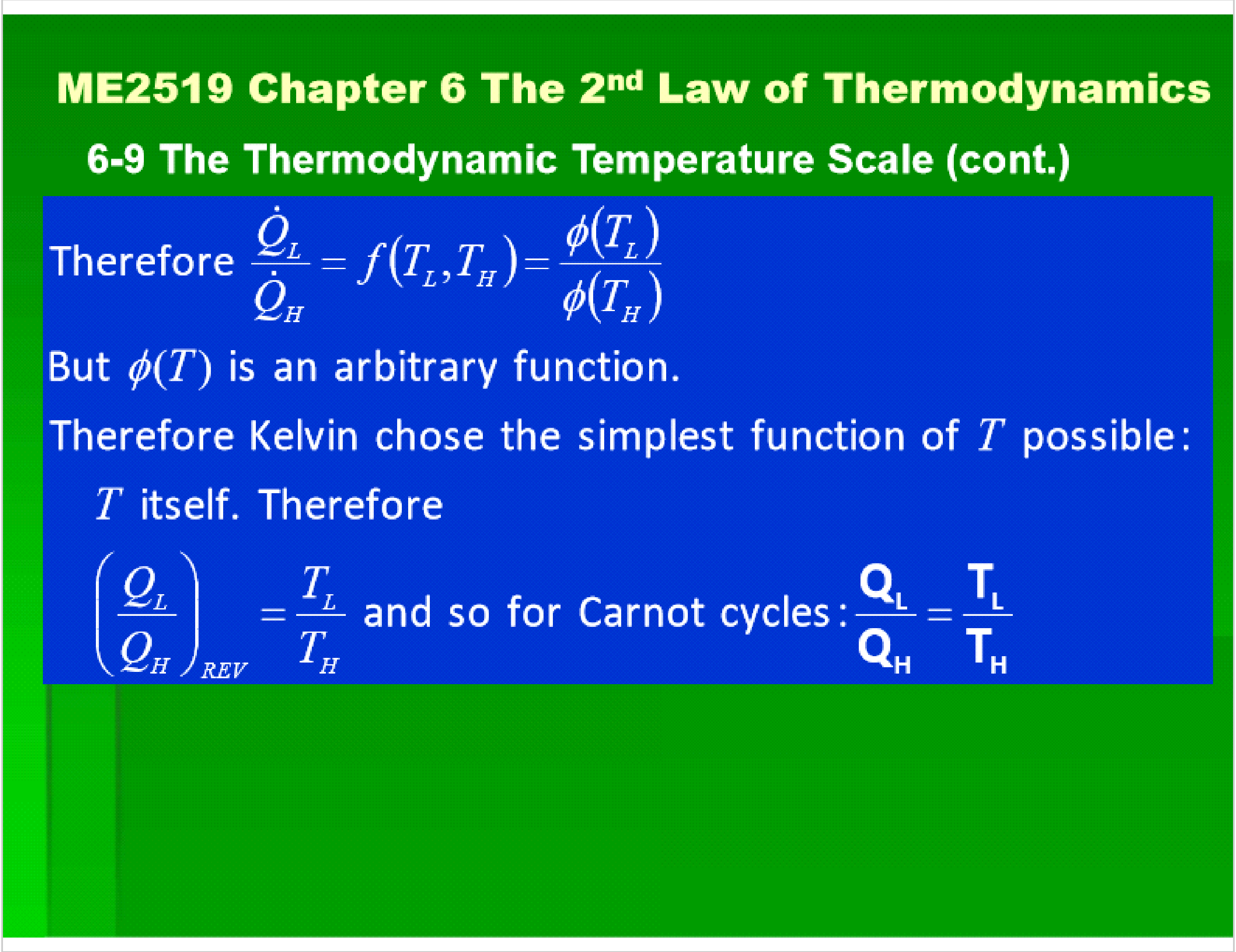
But $$\left.\frac{\dot{Q}_1}{\dot{Q}_3}\right|_{REV} = \left.\frac{\dot{Q}_1}{\dot{Q}_2}\right|_{REV} \times \left.\frac{\dot{Q}_2}{\dot{Q}_3}\right|_{REV}$$

therefore $f(T_1,T_3) = f(T_1,T_2) \times f(T_2,T_3)$

But this statement can only be true if

$f(T_1,T_3) = \dfrac{\phi(T_1)}{\phi(T_3)}$ and $f(T_1,T_2) = \dfrac{\phi(T_1)}{\phi(T_2)}$ and $f(T_2,T_3) = \dfrac{\phi(T_2)}{\phi(T_3)}$

then $$\frac{\phi(T_1)}{\phi(T_3)} = \frac{\phi(T_1)}{\phi(T_2)} \times \frac{\phi(T_2)}{\phi(T_3)}$$



ME2519 Chapter 6 The 2nd Law of Thermodynamics

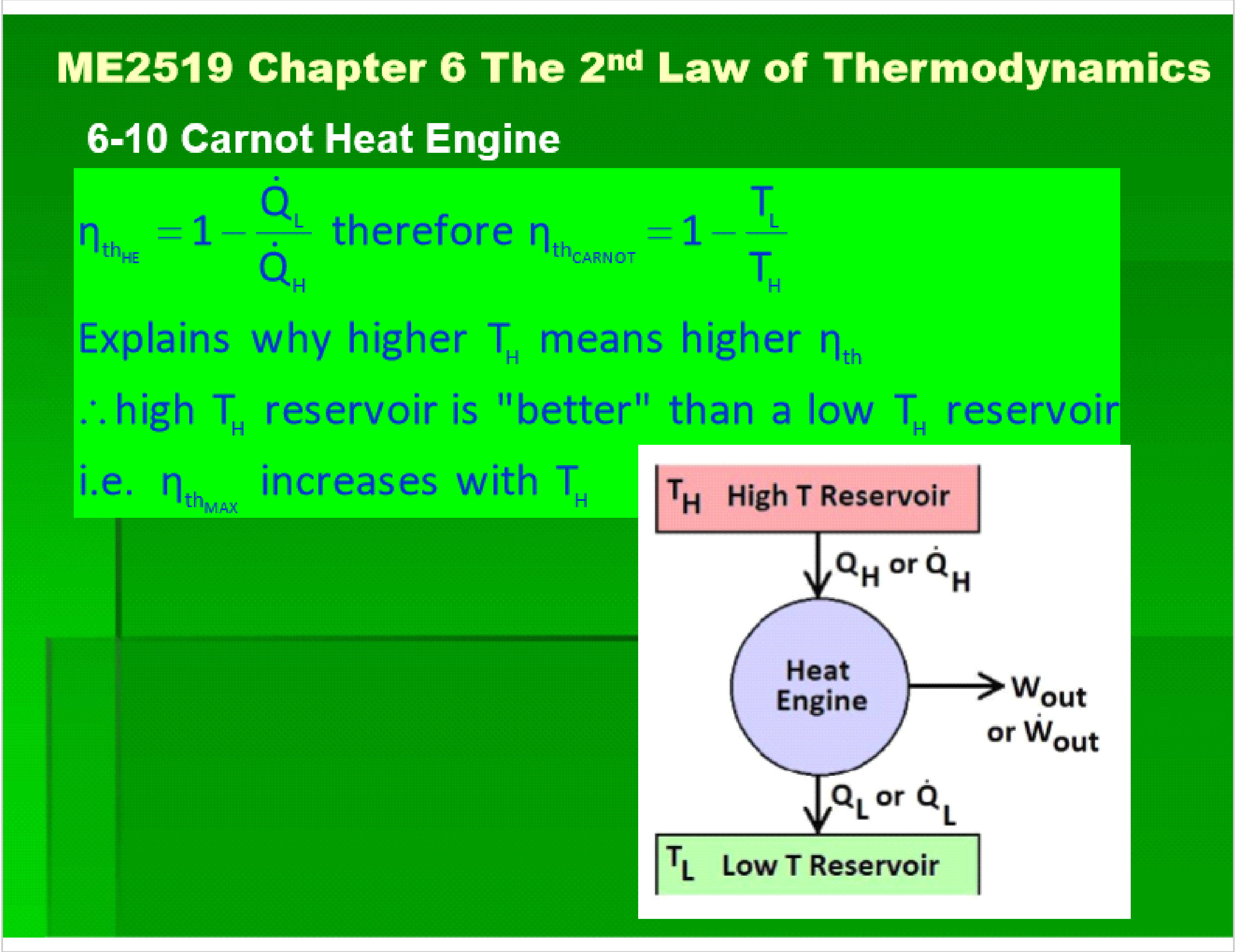
6-9 The Thermodynamic Temperature Scale (cont.)

Therefore $\frac{\dot{Q}_L}{\dot{Q}_H} = f(T_L, T_H) = \frac{\phi(T_L)}{\phi(T_H)}$

But $\phi(T)$ is an arbitrary function.

Therefore Kelvin chose the simplest function of T possible: T itself. Therefore

$\left(\frac{Q_L}{Q_H}\right)_{REV} = \frac{T_L}{T_H}$ and so for Carnot cycles: $\frac{Q_L}{Q_H} = \frac{T_L}{T_H}$



ME2519 Chapter 6 The 2nd Law of Thermodynamics

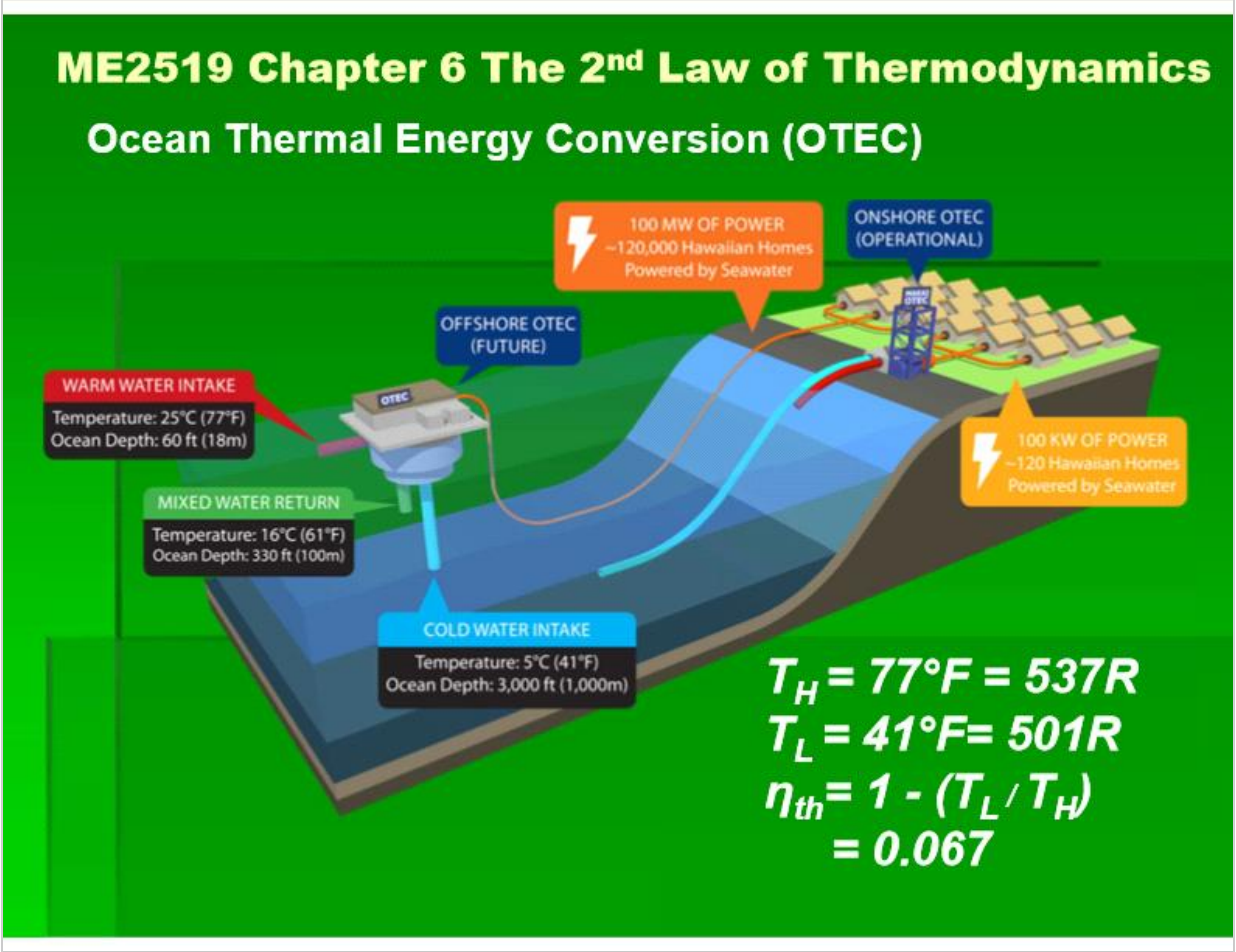
6-10 Carnot Heat Engine

$$\eta_{th_{HE}} = 1 - \frac{\dot{Q}_L}{\dot{Q}_H} \quad \text{therefore } \eta_{th_{CARNOT}} = 1 - \frac{T_L}{T_H}$$

Explains why higher T_H means higher η_{th}

$\therefore$ high T_H reservoir is "better" than a low T_H reservoir

i.e. $\eta_{th_{MAX}}$ increases with T_H



ME2519 Chapter 6 The 2nd Law of Thermodynamics

Ocean Thermal Energy Conversion (OTEC)

100 MW OF POWER
~120,000 Hawaiian Homes
Powered by Seawater

ONSHORE OTEC
(OPERATIONAL)

OFFSHORE OTEC
(FUTURE)

WARM WATER INTAKE
Temperature: 25°C (77°F)
Ocean Depth: 60 ft (18m)

MIXED WATER RETURN
Temperature: 16°C (61°F)
Ocean Depth: 330 ft (100m)

COLD WATER INTAKE
Temperature: 5°C (41°F)
Ocean Depth: 3,000 ft (1,000m)

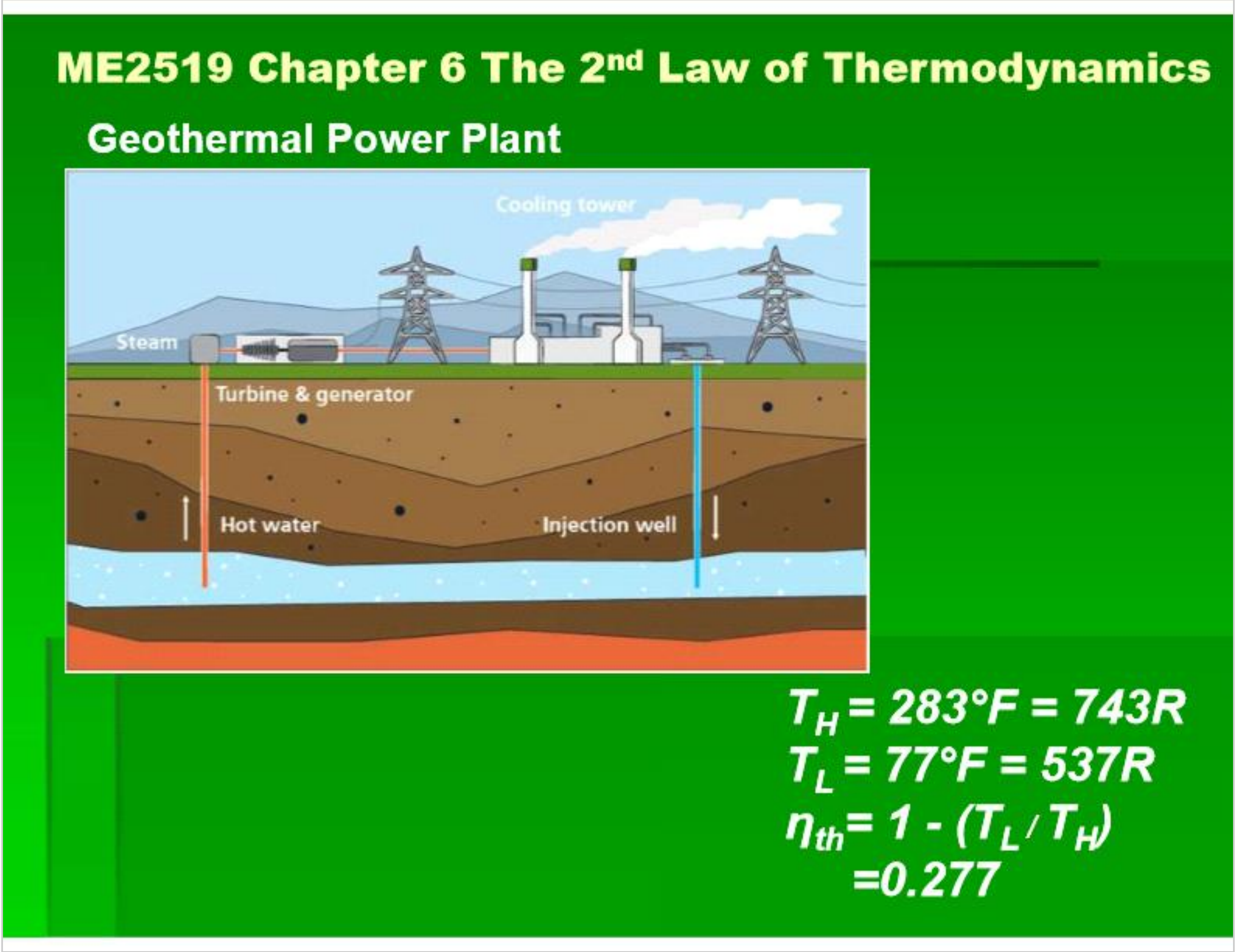
100 KW OF POWER
~120 Hawaiian Homes
Powered by Seawater

T_H = 77°F = 537R

T_L = 41°F= 501R

η_{th}= 1 - (T_L / T_H)

= 0.067



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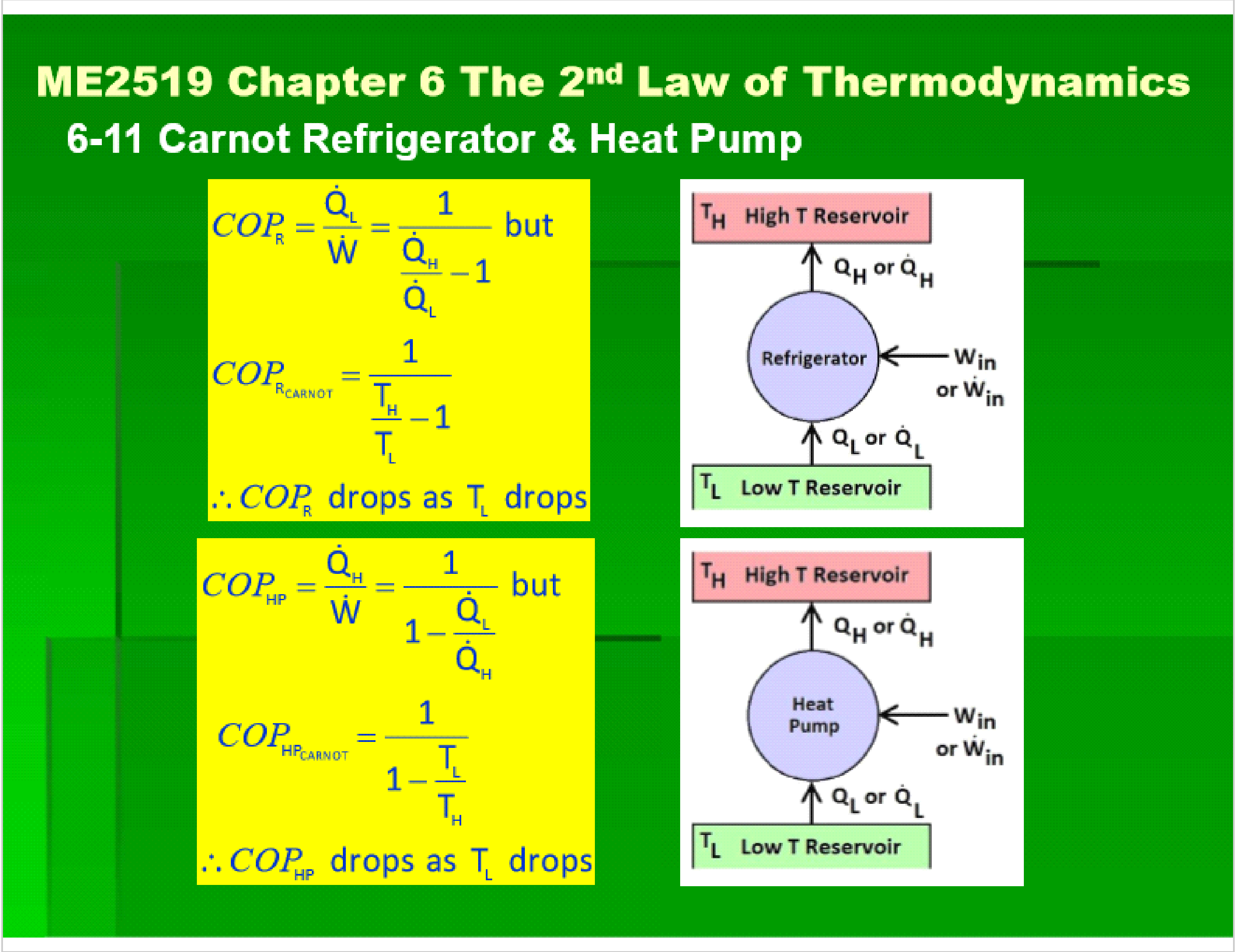
Geothermal Power Plant

$T_H = 283°F = 743R$

$T_L = 77°F = 537R$

$\eta_{th} = 1 - (T_L / T_H)$

$= 0.277$



ME2519 Chapter 6 The 2nd Law of Thermodynamics

6-11 Carnot Refrigerator & Heat Pump

$$COP_R = \frac{\dot{Q}_L}{\dot{W}} = \frac{1}{\frac{\dot{Q}_H}{\dot{Q}_L} - 1} \text{ but}$$

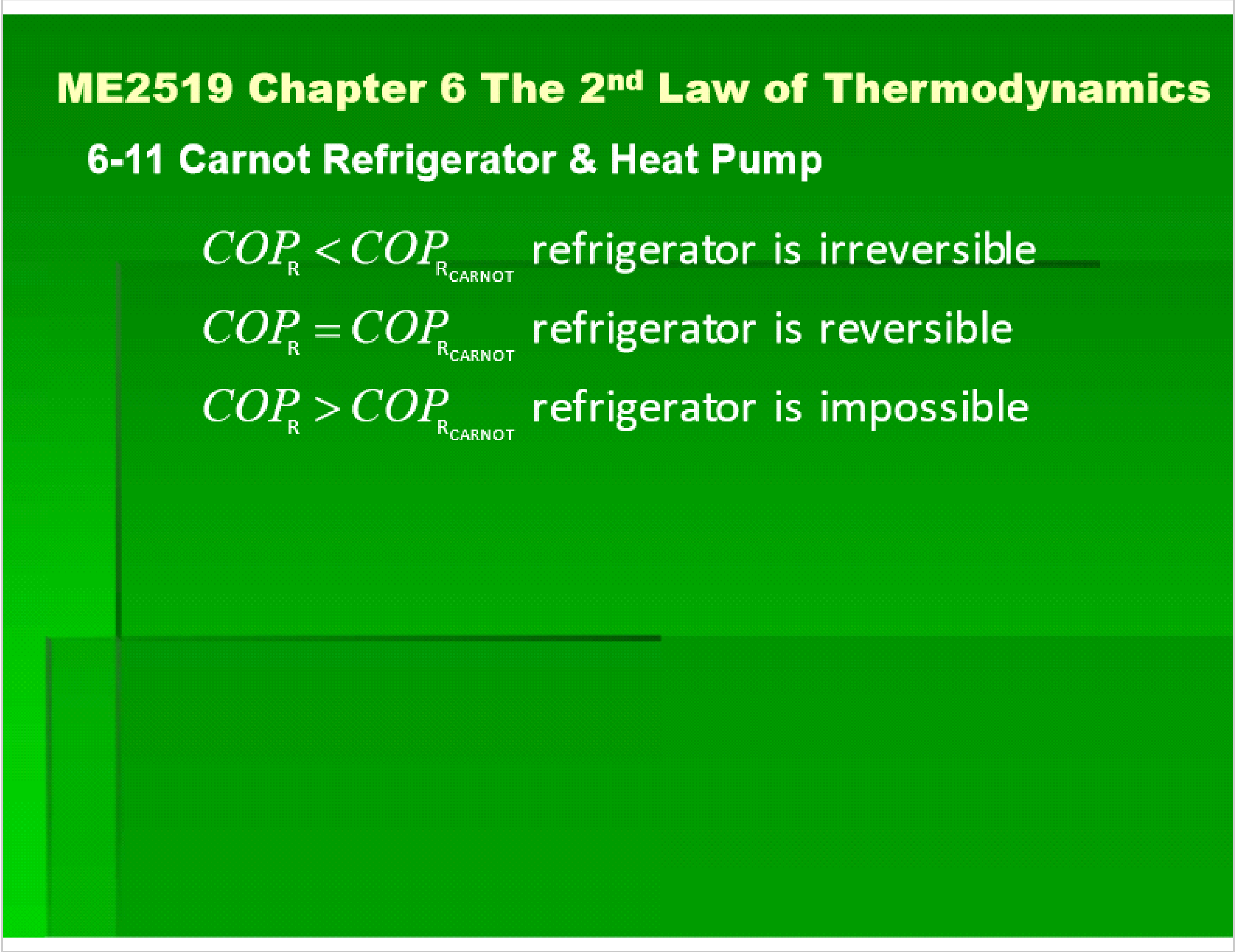
$$COP_{R_{CARNOT}} = \frac{1}{\frac{T_H}{T_L} - 1}$$

$\therefore COP_R$ drops as T_L drops

$$COP_{HP} = \frac{\dot{Q}_H}{\dot{W}} = \frac{1}{1 - \frac{\dot{Q}_L}{\dot{Q}_H}} \text{ but}$$

$$COP_{HP_{CARNOT}} = \frac{1}{1 - \frac{T_L}{T_H}}$$

$\therefore COP_{HP}$ drops as T_L drops



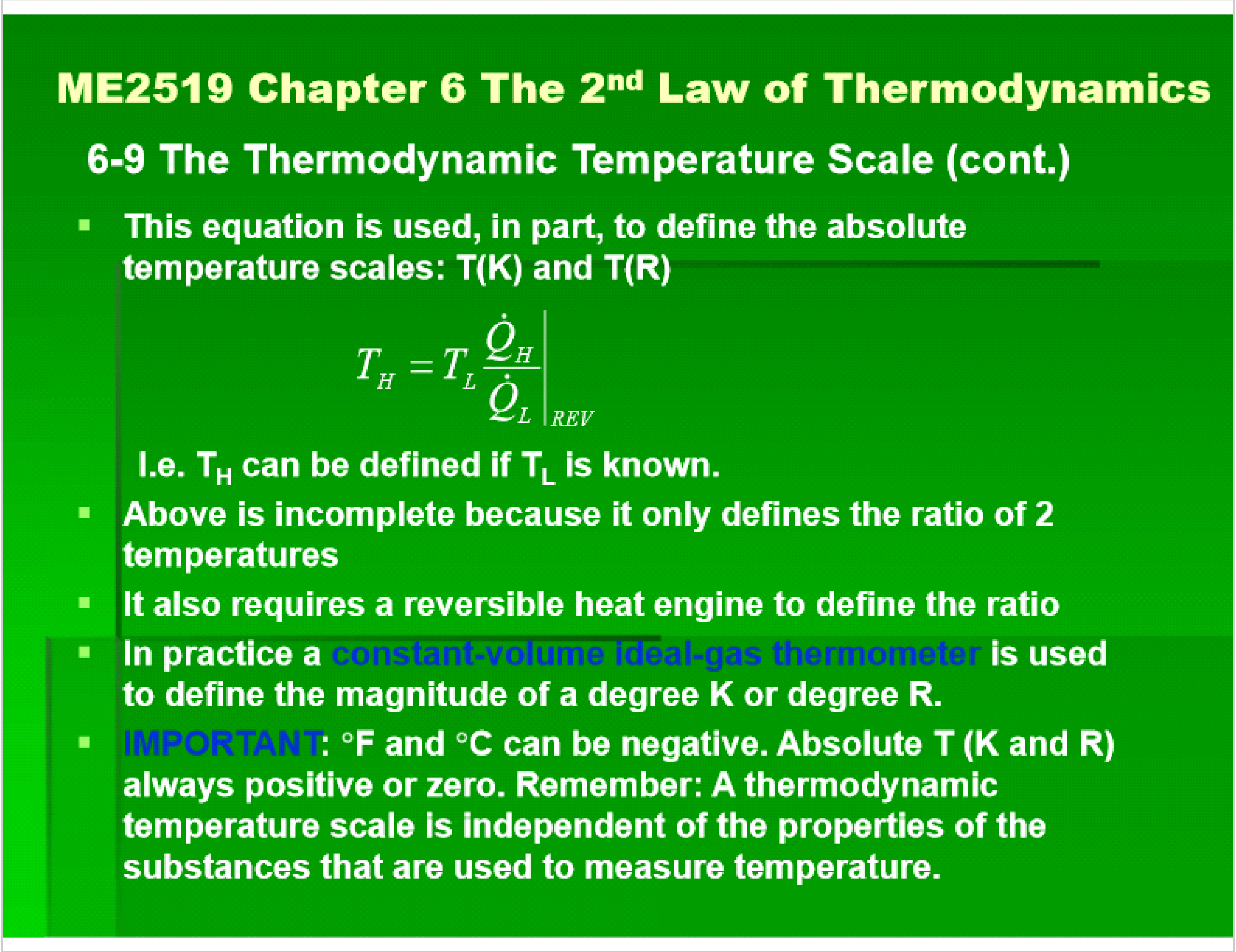
ME2519 Chapter 6 The 2nd Law of Thermodynamics

6-11 Carnot Refrigerator & Heat Pump

$COP_R < COP_{R_{CARNOT}}$ refrigerator is irreversible

$COP_R = COP_{R_{CARNOT}}$ refrigerator is reversible

$COP_R > COP_{R_{CARNOT}}$ refrigerator is impossible



ME2519 Chapter 6 The 2nd Law of Thermodynamics

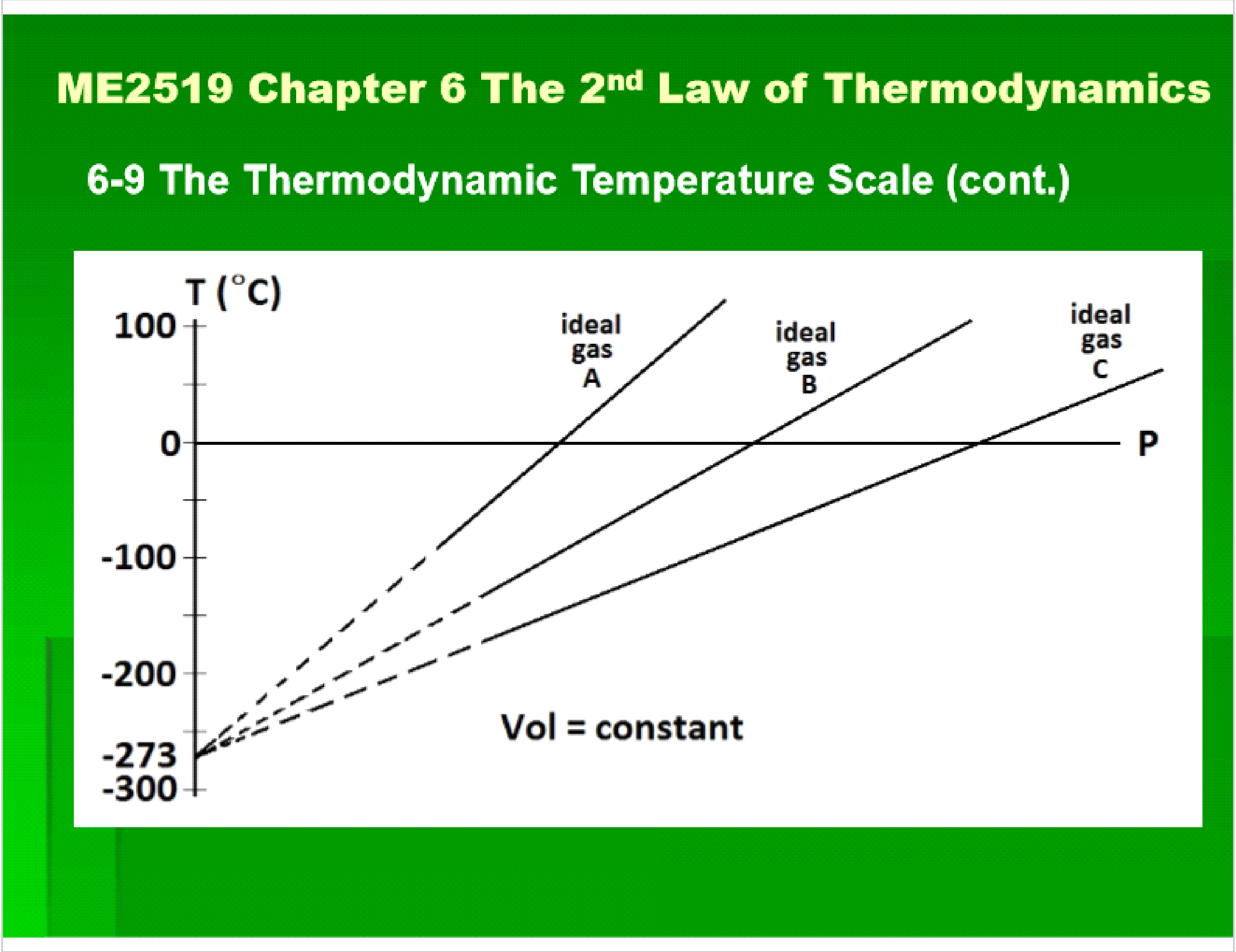
6-9 The Thermodynamic Temperature Scale (cont.)

- This equation is used, in part, to define the absolute temperature scales: T(K) and T(R)

$$T_H = T_L \left.\frac{\dot{Q}_H}{\dot{Q}_L}\right|_{REV}$$

I.e. T_H can be defined if T_L is known.

- Above is incomplete because it only defines the ratio of 2 temperatures
- It also requires a reversible heat engine to define the ratio
- In practice a constant-volume ideal-gas thermometer is used to define the magnitude of a degree K or degree R.
- IMPORTANT: °F and °C can be negative. Absolute T (K and R) always positive or zero. Remember: A thermodynamic temperature scale is independent of the properties of the substances that are used to measure temperature.



ME2519 Chapter 6 The 2nd Law of Thermodynamics

6-9 The Thermodynamic Temperature Scale (cont.)

Homework 6b

Tuesday, November 1, 2022 10:24 AM

6–82 An inventor claims to have developed a heat engine that receives 700 kJ of heat from a source at 500 K and produces 300 kJ of net work while rejecting the waste heat to a sink at 290 K. Is this a reasonable claim? Why?

$\eta_{th} = \frac{W_{out}}{Q_H} = \frac{300}{700} = .4286$

$Q_H = 700kJ$

$T_H = 500K$

$\eta_{th\ carnot} = 1 - \frac{T_L}{T_H} = 1 - \frac{290}{500} = .42$

$Q_L = 700kJ$

$T_L = 290\ k$

$\boxed{\eta_{th} > \eta_{th}\ \text{carnot, therefore this heat engine is impossible.}}$

6–85 A heat engine operates between a source at 477°C and a sink at 25°C. If heat is supplied to the heat engine at a steady rate of 65,000 kJ/min, determine the maximum power output of this heat engine.

$\eta_{th\,max} = 1 - \frac{T_L}{T_H} = 1 - \frac{298}{750} = .6027$

$\dot{Q}_H = 65,000\ kJ/min$

$T_H = 477°C = 750\ K$

$T_L = 25°C = 298\ K$

$\eta_{th} = \frac{\dot{W}_{out}}{\dot{Q}_H}$

$W_{out} = \dot{Q}_H\, \eta_{th}$

$\dot{W}_{out} = .6027\ (65,000\ kJ/min)\ \frac{1min}{60sec}$

$\boxed{\dot{W}_{out} = 652.93\ kW}$

6–88 In tropical climates, the water near the surface of the ocean remains warm throughout the year as a result of solar energy absorption. In the deeper parts of the ocean, however, the water remains at a relatively low temperature since the sun's rays cannot penetrate very far. It is proposed to take advantage of this temperature difference and construct a power plant that will absorb heat from the warm water near the surface and reject the waste heat to the cold water a few hundred meters below. Determine the maximum thermal efficiency of such a plant if the water temperatures at the two respective locations are 24 and 3°C. page 314

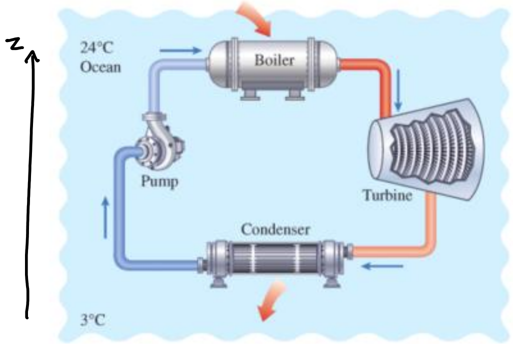


FIGURE P6–88

$T_H = 24°C = 297k$

$T_L = 3°C = 276\ k$

$\eta_{th\,max} = 1 - \frac{T_L}{T_H} = 1 - \frac{276}{297} = \boxed{.071}$

6–98 Determine the minimum work per unit of heat transfer from the source reservoir that is required to drive a heat pump with thermal energy reservoirs at 460 K and 535 K.

$T_L = 460\ k$

$T_H = 535\ K$

$q_L = 1\ kJ$

$W_{in} = q_H - q_L$

$\frac{W_{in}}{q_L} = \frac{q_H}{q_L} - 1$

$\frac{q_H}{q_L} = \frac{T_H}{T_L}$

$$\frac{q_H}{q_L} = \frac{T_H}{T_L}$$

$$\frac{W_{in}}{q_L} = \frac{T_H}{T_L} - 1 = \frac{535}{460} - 1 = \boxed{.163}$$

6–106 A heat pump is used to heat a house and maintain it at 24°C. On a winter day when the outdoor air temperature is –5°C, the house is estimated to lose heat at a rate of 80,000 kJ/h. Determine the minimum power required to operate this heat pump.

$$COP_{HP} = \frac{\dot{Q}_H}{\dot{W}_{in}} = \frac{1}{1 - \frac{T_L}{T_H}}$$

$T_H = 24°C = 297K$

$T_L = -5°C = 268K$

$\dot{Q}_H = 80,000 kJ/h$

$$COP_{HP} = \frac{1}{1 - \frac{268}{297}} = 10.2414$$

$$COP_{HP} = \frac{\dot{Q}_H}{\dot{W}_{in}} \quad 8$$

$$\dot{W}_{in} = \frac{\dot{Q}_H}{COP_{HP}} = \frac{80,000\ kJ/h}{10.2414} \frac{1h}{3600s} = \boxed{2.17\ kW}$$

6–110 A completely reversible heat pump has a COP of 1.6 and a sink temperature of 300 K. Calculate (*a*) the temperature of the source and (*b*) the rate of heat transfer to the sink when 1.5 kW of power is supplied to this heat pump.

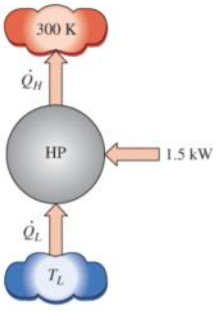


FIGURE P6–110

$$COP_{HP} = \frac{\dot{Q}_H}{\dot{W}_{in}} = \frac{1}{1 - \frac{T_L}{T_H}}$$

$COP_{HP} = 1.6$

$T_H = 300K$

$\dot{W}_{in} = 1.5kW$

$$COP_{HP} = \frac{1}{1 - \frac{T_L}{T_H}}$$

$$-\frac{T_L}{T_H} = \frac{1}{COP} - 1$$

$$T_H\left(1 - \frac{1}{COP}\right) = T_L$$

$$T_L = 300\left(1 - \frac{1}{1.6}\right) = \boxed{112.5\ K}$$

$$COP_{HP} = \frac{\dot{Q}_H}{\dot{W}}$$

$$COP_{HP} = \frac{\dot{Q}_H}{\dot{W}_{in}}$$

$$\dot{Q}_H = COP_{HP} \, W_{in} = 1.5 \, kW \, (1.6) = \boxed{2.4 \, kW}$$

Entropy

Monday, November 7, 2022 9:57 AM

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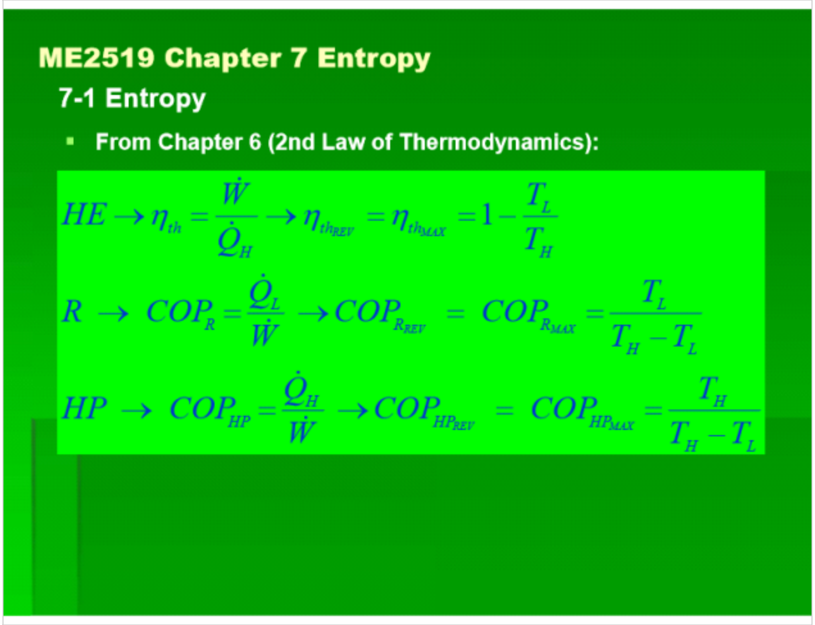


ME2519 Chapter 7 Entropy

7-1 Entropy

- From Chapter 6 (2nd Law of Thermodynamics):

$$HE \rightarrow \eta_{th} = \frac{\dot{W}}{\dot{Q}_H} \rightarrow \eta_{th_{REV}} = \eta_{th_{MAX}} = 1 - \frac{T_L}{T_H}$$

$$R \rightarrow COP_R = \frac{\dot{Q}_L}{\dot{W}} \rightarrow COP_{R_{REV}} = COP_{R_{MAX}} = \frac{T_L}{T_H - T_L}$$

$$HP \rightarrow COP_{HP} = \frac{\dot{Q}_H}{\dot{W}} \rightarrow COP_{HP_{REV}} = COP_{HP_{MAX}} = \frac{T_H}{T_H - T_L}$$

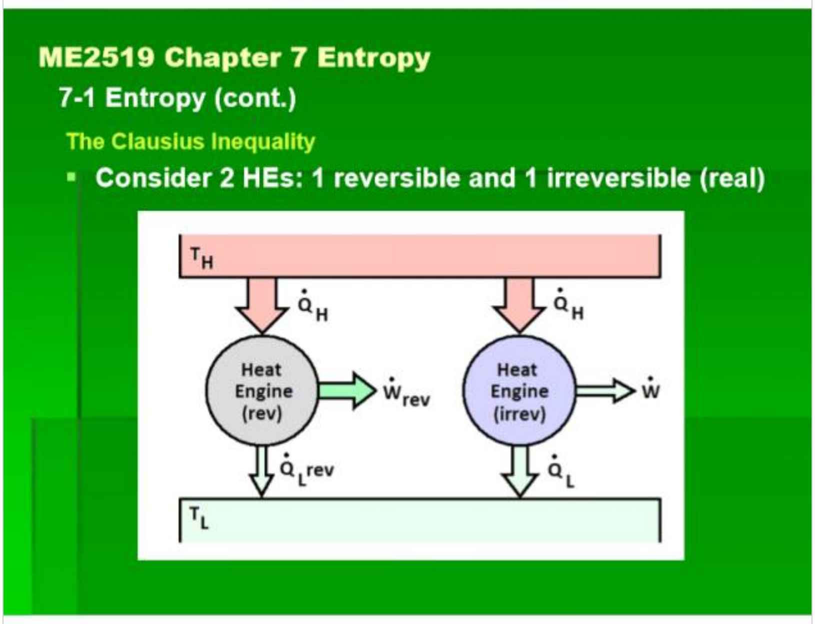
Clausius Inequality

$$\oint \frac{\delta Q}{T} \leq 0$$

< 0 irreversible

= 0 reversible

$$dS = \left(\frac{\delta Q}{T}\right)_{\text{int rev}} \qquad \text{(kJ/K)}$$



ME2519 Chapter 7 Entropy

7-1 Entropy (cont.)

The Clausius Inequality

- Consider 2 HEs: 1 reversible and 1 irreversible (real)

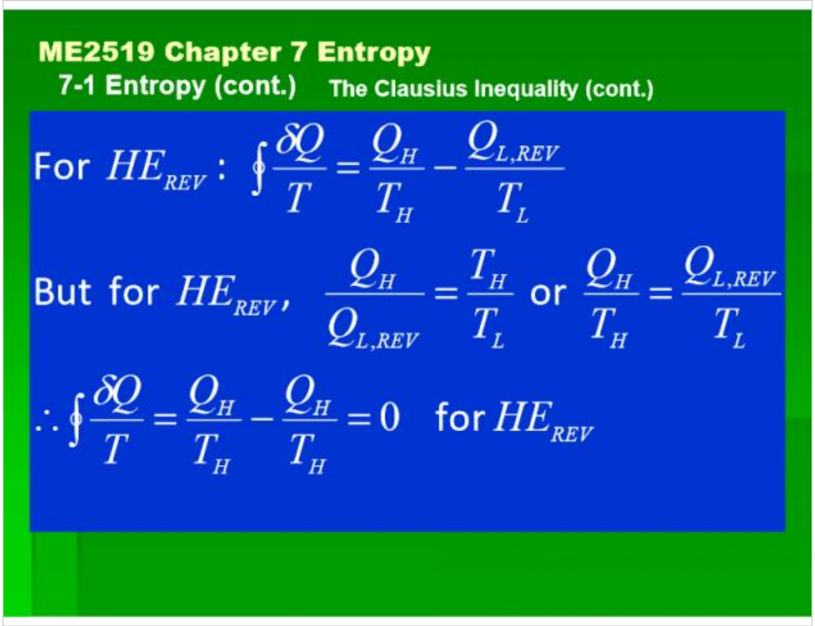
Internally reversible process:

$$\Delta S = \frac{Q}{T_0} \qquad \text{(kJ/K)}$$

$$S_{gen} \begin{cases} > 0 & \text{irreversible process} \\ = 0 & \text{reversible process} \\ < 0 & \text{impossible process} \end{cases}$$

Isentropic: internally reversible, adiabadic, delta s is zero

Entropy: a thermodynamic quantity representing the unavailability of a system's thermal energy for conversion into mechanical work, often interpreted as the degree of disorder or randomness in the system.



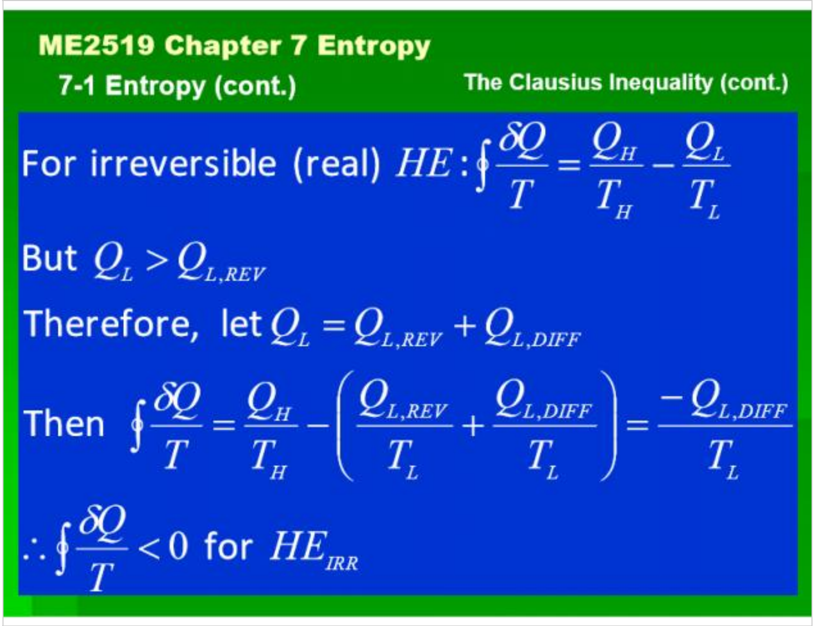
ME2519 Chapter 7 Entropy

7-1 Entropy (cont.) **The Clausius Inequality (cont.)**

For HE_{REV} : $\oint \frac{\delta Q}{T} = \frac{Q_H}{T_H} - \frac{Q_{L,REV}}{T_L}$

But for HE_{REV}, $\frac{Q_H}{Q_{L,REV}} = \frac{T_H}{T_L}$ or $\frac{Q_H}{T_H} = \frac{Q_{L,REV}}{T_L}$

$\therefore \oint \frac{\delta Q}{T} = \frac{Q_H}{T_H} - \frac{Q_H}{T_H} = 0$ for HE_{REV}



ME2519 Chapter 7 Entropy

7-1 Entropy (cont.) **The Clausius Inequality (cont.)**

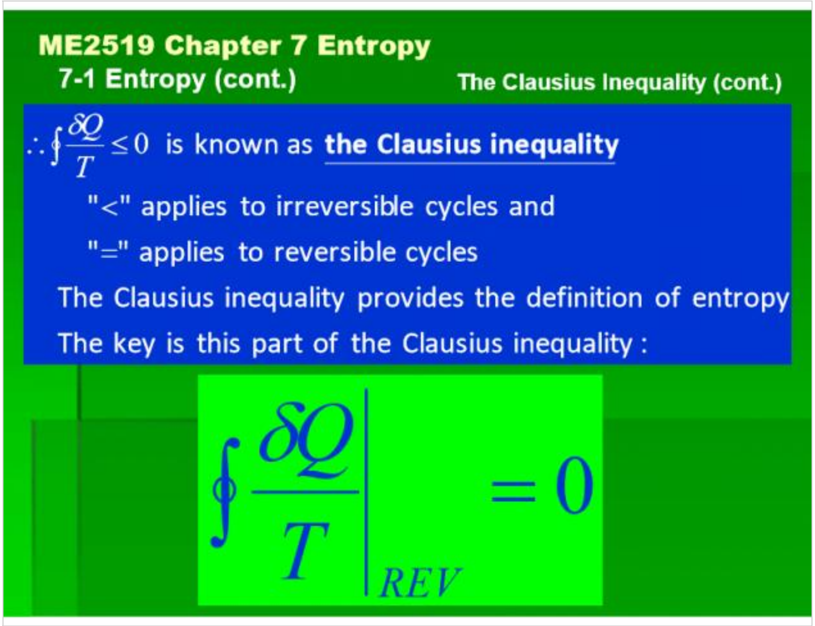
For irreversible (real) HE: $\oint \frac{\delta Q}{T} = \frac{Q_H}{T_H} - \frac{Q_L}{T_L}$

But $Q_L > Q_{L,REV}$

Therefore, let $Q_L = Q_{L,REV} + Q_{L,DIFF}$

Then $\oint \frac{\delta Q}{T} = \frac{Q_H}{T_H} - \left(\frac{Q_{L,REV}}{T_L} + \frac{Q_{L,DIFF}}{T_L} \right) = \frac{-Q_{L,DIFF}}{T_L}$

$\therefore \oint \frac{\delta Q}{T} < 0$ for HE_{IRR}



ME2519 Chapter 7 Entropy

7-1 Entropy (cont.) **The Clausius Inequality (cont.)**

$\therefore \oint \frac{\delta Q}{T} \leq 0$ is known as **the Clausius inequality**

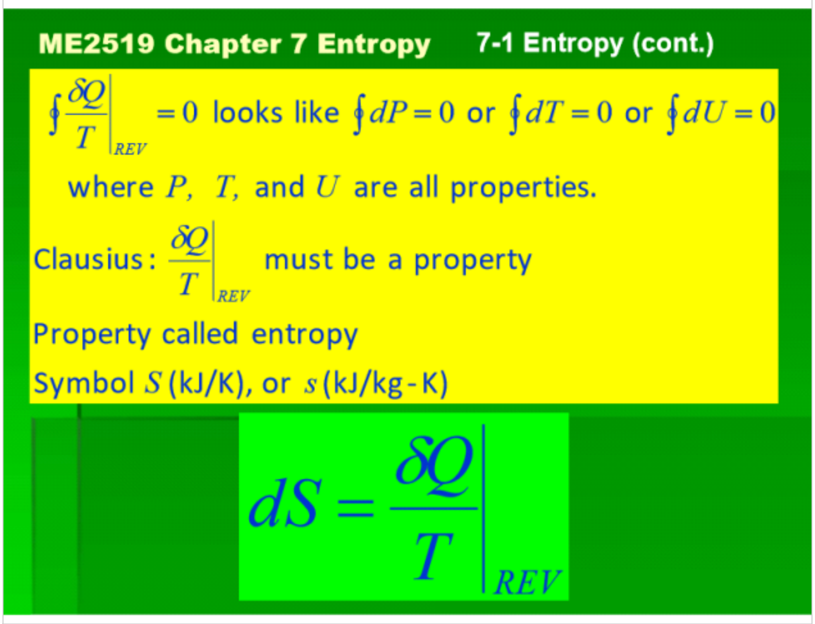
"<" applies to irreversible cycles and

"=" applies to reversible cycles

The Clausius inequality provides the definition of entropy

The key is this part of the Clausius inequality :

$$\oint \frac{\delta Q}{T} \bigg|_{REV} = 0$$



ME2519 Chapter 7 Entropy 7-1 Entropy (cont.)

$\oint \frac{\delta Q}{T}\Big|_{REV} = 0$ looks like $\oint dP = 0$ or $\oint dT = 0$ or $\oint dU = 0$

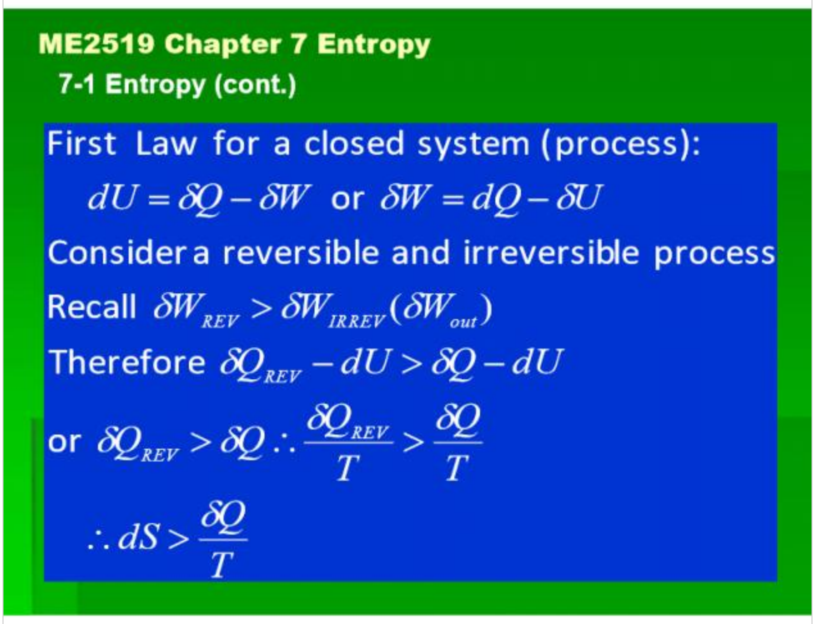
where P, T, and U are all properties.

Clausius: $\frac{\delta Q}{T}\Big|_{REV}$ must be a property

Property called entropy

Symbol S (kJ/K), or s (kJ/kg - K)

$$dS = \frac{\delta Q}{T}\Big|_{REV}$$



ME2519 Chapter 7 Entropy

7-1 Entropy (cont.)

First Law for a closed system (process):

$dU = \delta Q - \delta W$ or $\delta W = dQ - \delta U$

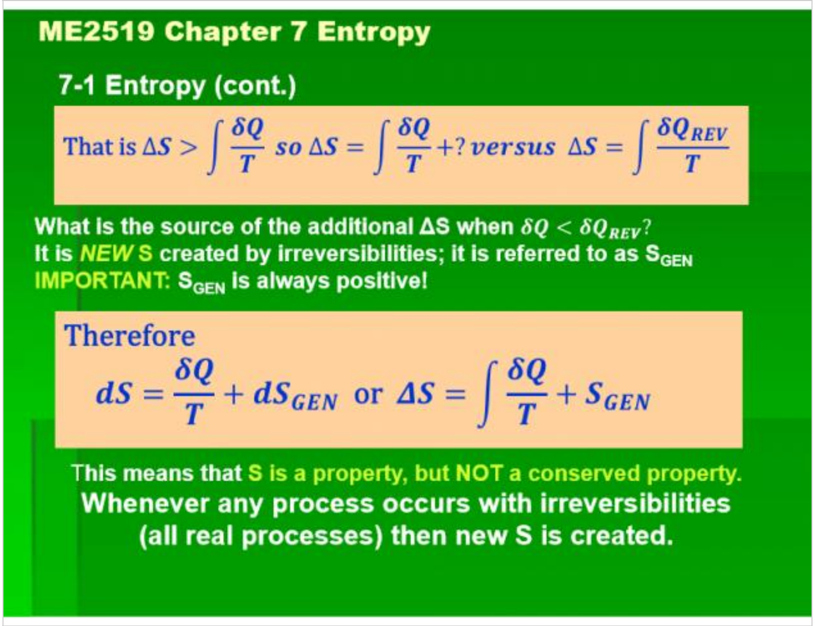
Consider a reversible and irreversible process

Recall $\delta W_{REV} > \delta W_{IRREV} (\delta W_{out})$

Therefore $\delta Q_{REV} - dU > \delta Q - dU$

or $\delta Q_{REV} > \delta Q \therefore \frac{\delta Q_{REV}}{T} > \frac{\delta Q}{T}$

$\therefore dS > \frac{\delta Q}{T}$



ME2519 Chapter 7 Entropy

7-1 Entropy (cont.)

That is $\Delta S > \int \frac{\delta Q}{T}$ $so\ \Delta S = \int \frac{\delta Q}{T} + ?\ versus\ \ \Delta S = \int \frac{\delta Q_{REV}}{T}$

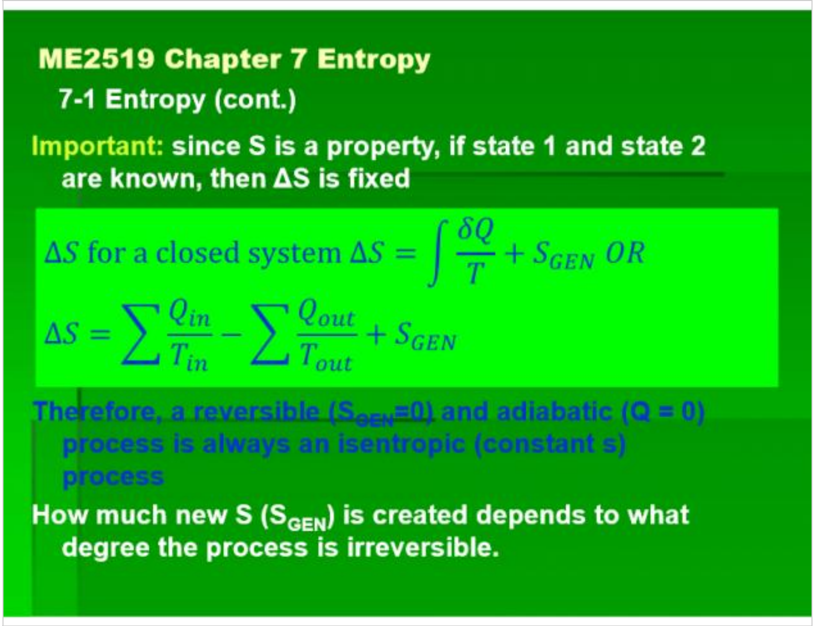
What is the source of the additional ΔS when $\delta Q < \delta Q_{REV}$?
It is *NEW* S created by irreversibilities; it is referred to as S_{GEN}
IMPORTANT: S_{GEN} is always positive!

Therefore

$$dS = \frac{\delta Q}{T} + dS_{GEN} \text{ or } \Delta S = \int \frac{\delta Q}{T} + S_{GEN}$$

This means that S is a property, but NOT a conserved property.

Whenever any process occurs with irreversibilities (all real processes) then new S is created.



ME2519 Chapter 7 Entropy

7-1 Entropy (cont.)

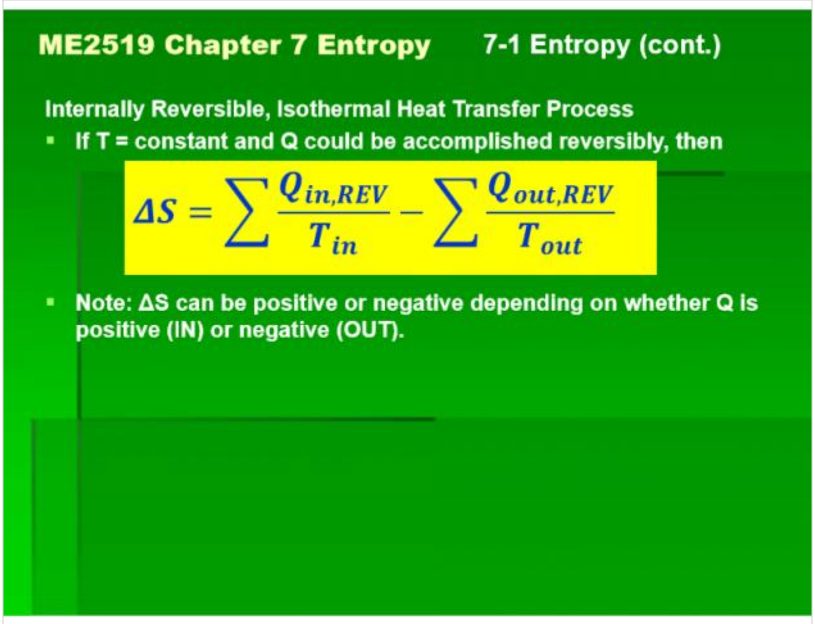
Important: since S is a property, if state 1 and state 2 are known, then ΔS is fixed

ΔS for a closed system $\Delta S = \int \frac{\delta Q}{T} + S_{GEN}\ OR$

$$\Delta S = \sum \frac{Q_{in}}{T_{in}} - \sum \frac{Q_{out}}{T_{out}} + S_{GEN}$$

Therefore, a reversible (S_{GEN}=0) and adiabatic (Q = 0) process is always an isentropic (constant s) process

How much new S (S_{GEN}) is created depends to what degree the process is irreversible.



ME2519 Chapter 7 Entropy

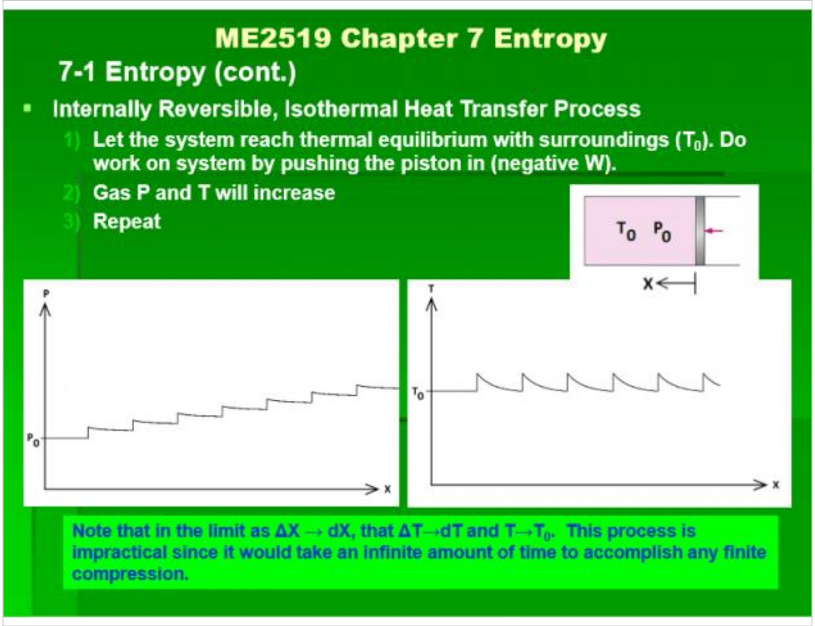
7-1 Entropy (cont.)

Internally Reversible, Isothermal Heat Transfer Process

- **If T = constant and Q could be accomplished reversibly, then**

$$\Delta S = \sum \frac{Q_{in,REV}}{T_{in}} - \sum \frac{Q_{out,REV}}{T_{out}}$$

- **Note: ΔS can be positive or negative depending on whether Q is positive (IN) or negative (OUT).**



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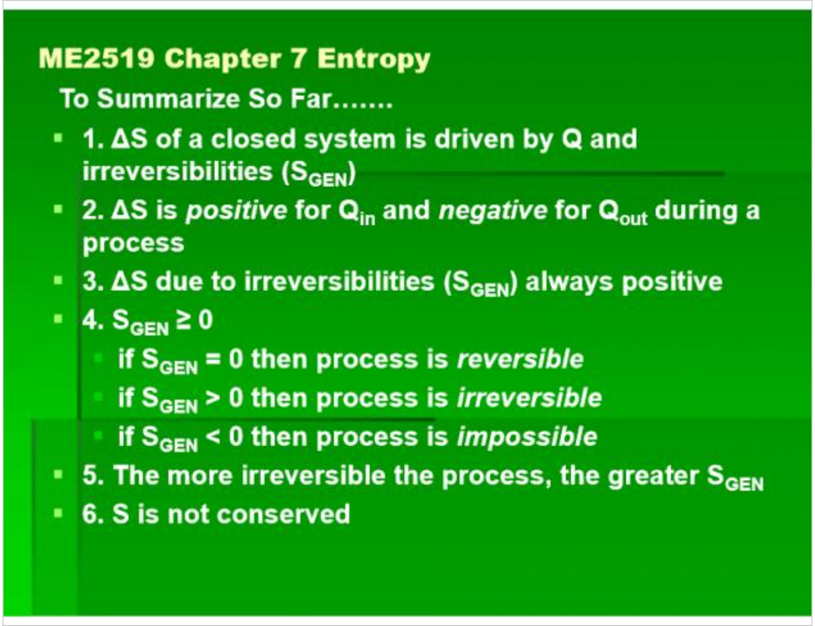
7-1 Entropy (cont.)

- Internally Reversible, Isothermal Heat Transfer Process
  1) Let the system reach thermal equilibrium with surroundings (T_0). Do work on system by pushing the piston in (negative W).
  2) Gas P and T will increase
  3) Repeat

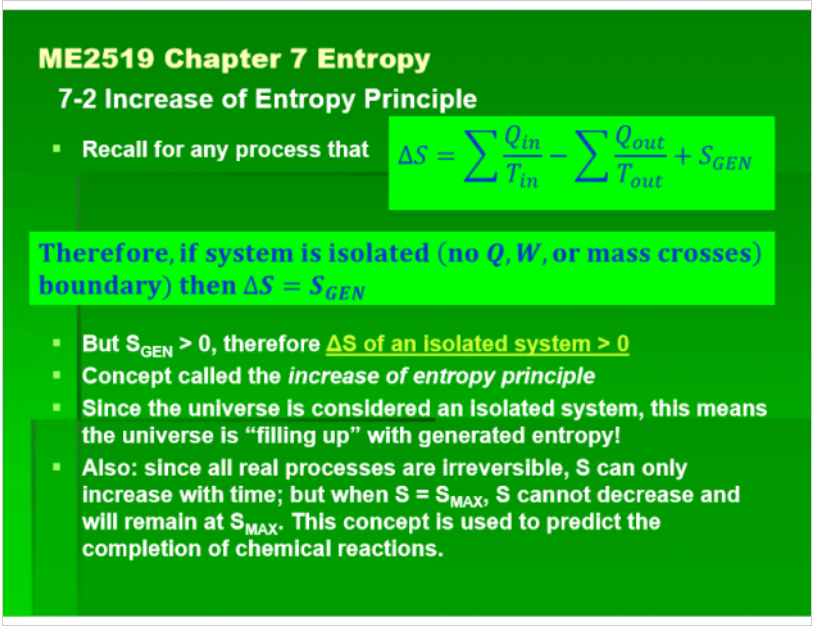
Note that in the limit as $\Delta X \rightarrow dX$, that $\Delta T \rightarrow dT$ and $T \rightarrow T_0$. This process is impractical since it would take an infinite amount of time to accomplish any finite compression.



ME2519 Chapter 7 Entropy

To Summarize So Far…….

- 1. ΔS of a closed system is driven by Q and irreversibilities (S_{GEN})
- 2. ΔS is *positive* for Q_{in} and *negative* for Q_{out} during a process
- 3. ΔS due to irreversibilities (S_{GEN}) always positive
- 4. $S_{GEN} \geq 0$
  - if $S_{GEN} = 0$ then process is *reversible*
  - if $S_{GEN} > 0$ then process is *irreversible*
  - if $S_{GEN} < 0$ then process is *impossible*
- 5. The more irreversible the process, the greater S_{GEN}
- 6. S is not conserved



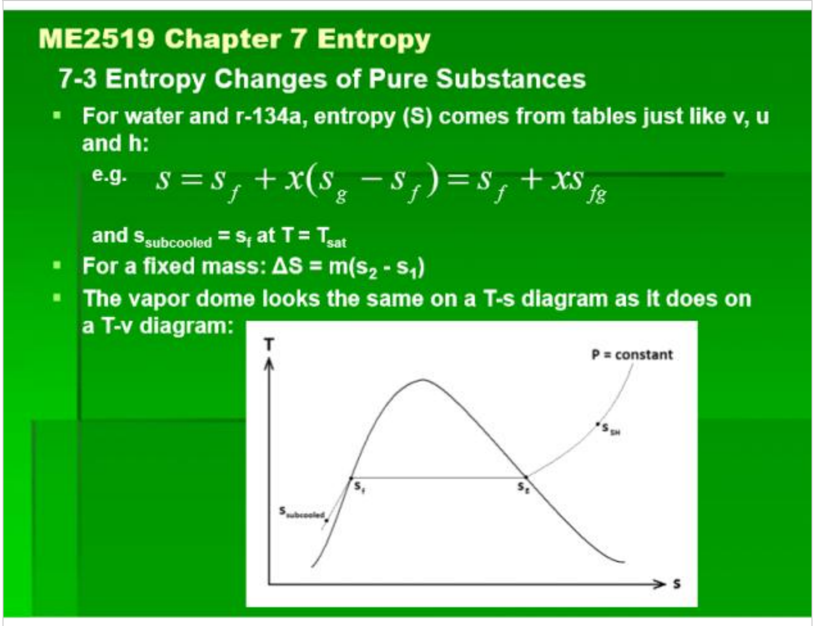
ME2519 Chapter 7 Entropy

7-2 Increase of Entropy Principle

- Recall for any process that $\Delta S = \sum \frac{Q_{in}}{T_{in}} - \sum \frac{Q_{out}}{T_{out}} + S_{GEN}$

Therefore, if system is isolated (no Q, W, or mass crosses) boundary) then $\Delta S = S_{GEN}$

- But $S_{GEN} > 0$, therefore ΔS of an isolated system > 0
- Concept called the *increase of entropy principle*
- Since the universe is considered an isolated system, this means the universe is “filling up” with generated entropy!
- Also: since all real processes are irreversible, S can only increase with time; but when $S = S_{MAX}$, S cannot decrease and will remain at S_{MAX}. This concept is used to predict the completion of chemical reactions.



ME2519 Chapter 7 Entropy

7-3 Entropy Changes of Pure Substances

- For water and r-134a, entropy (S) comes from tables just like v, u and h:

  e.g. $s = s_f + x(s_g - s_f) = s_f + xs_{fg}$

  and $s_{subcooled} = s_f$ at $T = T_{sat}$
- For a fixed mass: $\Delta S = m(s_2 - s_1)$
- The vapor dome looks the same on a T-s diagram as it does on a T-v diagram:

Isentropic Process

Wednesday, November 9, 2022 10:05 AM

PDF+Slides+
7-4+to+7-...

ME2519 Chapter 7 Entropy
7-4 Isentropic Process

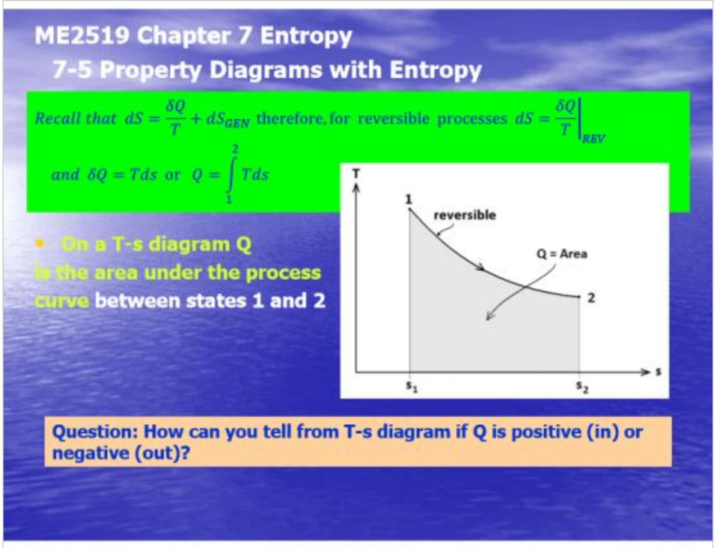
Recall that $\Delta s = s_2 - s_1 = \sum \frac{Q_{in}}{T_{in}} - \sum \frac{Q_{out}}{T_{out}} + S_{gen}$

Therefore, if process is adiabatic ($Q = 0$) and reversible ($s_{GEN} = 0$) then process is isentropic

Question: BUT is an isentropic process always adiabatic and reversible?

What if $s_{gen} = +35 \frac{kJ}{kg-K}$, and $\sum \frac{Q_{in}}{T_{in}} - \sum \frac{Q_{out}}{T_{out}} = -35 \frac{kJ}{kg-K}$

In this case the process is isentropic, but not adiabatic or reversible. But, **in ME2519, when we say isentropic, we mean adiabatic ($\boldsymbol{q = 0}$) and reversible ($\boldsymbol{s_{GEN} = 0}$).**



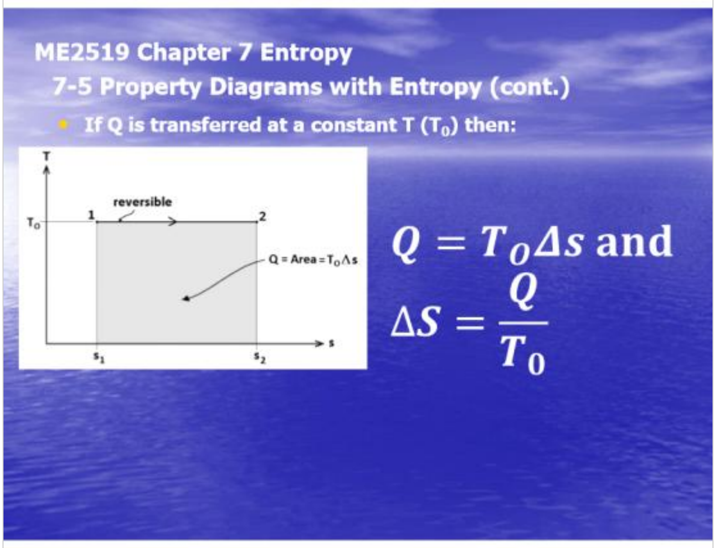
ME2519 Chapter 7 Entropy
7-5 Property Diagrams with Entropy

Recall that $dS = \frac{\delta Q}{T} + dS_{GEN}$ therefore, for reversible processes $dS = \left.\frac{\delta Q}{T}\right|_{REV}$

and $\delta Q = Tds$ or $Q = \int_1^2 Tds$

- On a T-s diagram Q is the area under the process curve between states 1 and 2

Question: How can you tell from T-s diagram if Q is positive (in) or negative (out)?



ME2519 Chapter 7 Entropy
7-5 Property Diagrams with Entropy (cont.)

- If Q is transferred at a constant T (T_0) then:

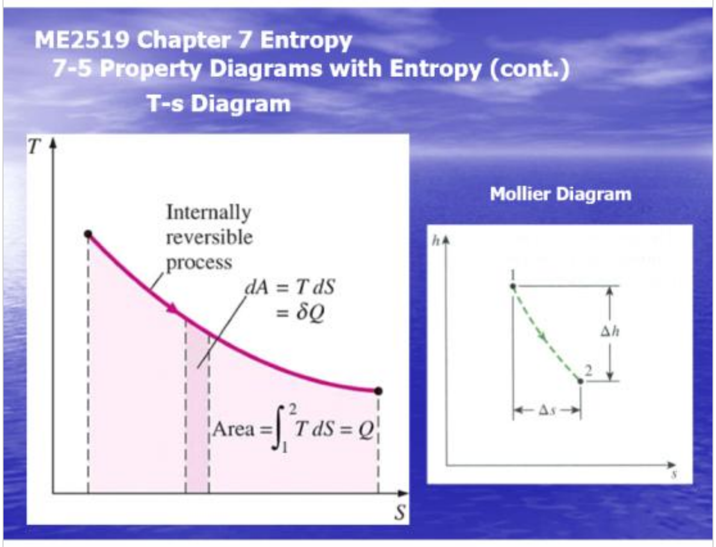
$$Q = T_O \Delta s \text{ and}$$

$$\Delta S = \frac{Q}{T_0}$$

FIGURE 7–26
As in mechanical systems, friction in the workplace is bound to generate entropy and reduce performance.

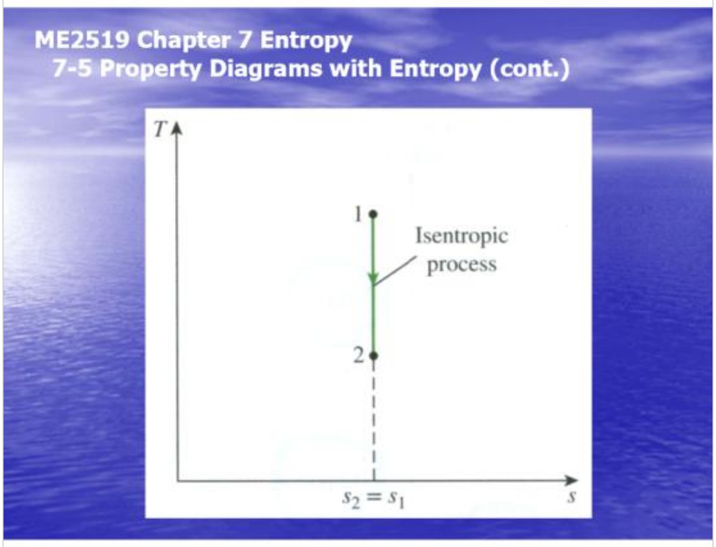
We also know that *unrestrained expansion* (or explosion) and uncontrolled electron exchange (chemical reactions) generate entropy and are highly irreversible. Likewise, unrestrained opening of the mouth to scatter angry words is highly irreversible since this generates entropy, and it can cause considerable damage. A person who gets up in anger is bound to sit down at a loss. Hopefully, someday we will be able to come up with some procedures to quantify entropy generated during nontechnical activities, and maybe even pinpoint its primary sources and magnitude.

Third Law of Thermodynamics: the entropy of a pure crystalline substance at absolute zero temperature is zero (since there is no uncertainty about the state of the molecules at that instant)

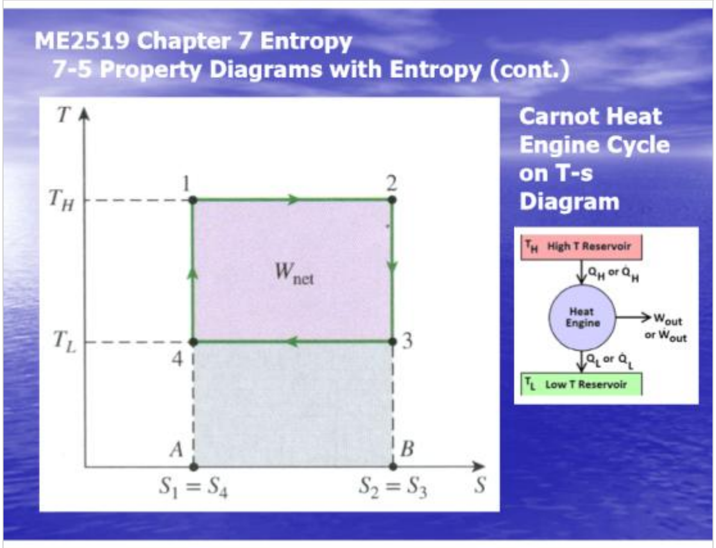


ME2519 Chapter 7 Entropy
7-5 Property Diagrams with Entropy (cont.)
T-s Diagram

Mollier Diagram

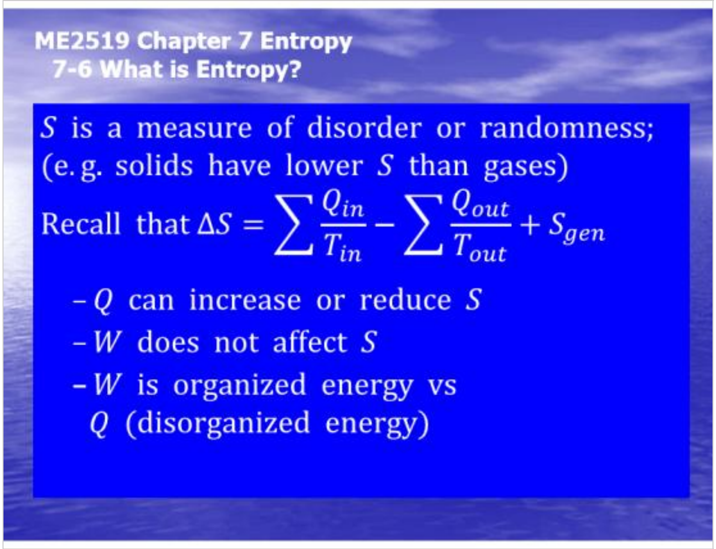


ME2519 Chapter 7 Entropy
7-5 Property Diagrams with Entropy (cont.)



ME2519 Chapter 7 Entropy
7-5 Property Diagrams with Entropy (cont.)

Carnot Heat Engine Cycle on T-s Diagram

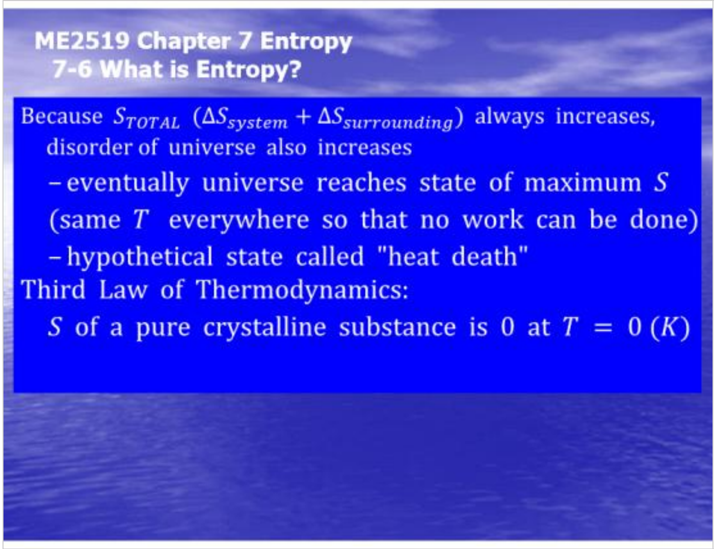


ME2519 Chapter 7 Entropy
7-6 What is Entropy?

S is a measure of disorder or randomness; (e.g. solids have lower S than gases)

Recall that $\Delta S = \sum \frac{Q_{in}}{T_{in}} - \sum \frac{Q_{out}}{T_{out}} + S_{gen}$

- Q can increase or reduce S
- W does not affect S
- W is organized energy vs Q (disorganized energy)



ME2519 Chapter 7 Entropy
7-6 What is Entropy?

Because S_{TOTAL} $(\Delta S_{system} + \Delta S_{surrounding})$ always increases, disorder of universe also increases

- eventually universe reaches state of maximum S (same T everywhere so that no work can be done)
- hypothetical state called "heat death"

Third Law of Thermodynamics:

S of a pure crystalline substance is 0 at $T = 0\ (K)$

Homework 7a

Thursday, November 10, 2022 12:01 PM

7–20 In Prob. 7–19, assume that the heat is transferred from the cold reservoir to the hot reservoir contrary to the Clausius statement of the second law. Prove that this violates the increase of entropy principle—as it must according to Clausius.

$$\Delta S_H = \frac{Q_{in}}{T_H}$$

$$\Delta S_L = \frac{Q_{out}}{T_L} = \frac{-Q_{in}}{T_L} \qquad Q_{out} = -Q_{in}$$

$$\Delta S_T = \Delta S_H + \Delta S_L = \frac{Q_{in}}{T_H} - \frac{Q_{in}}{T_L}$$

$T_H > T_L \therefore \Delta S_T$ is negative.

Hence, this violates increase of S principle.

7–24 Air is compressed by a 40-kW compressor from P_1 to P_2. The air temperature is maintained constant at 25°C during this process as a result of heat transfer to the surrounding medium at 20°C. Determine the rate of entropy change of the air. State the assumptions made in solving this problem. *Answer:* −0.134 KW/K

1st law SSSF $\qquad T_1 = T_2 = 25°C = 298\ K$

$$0 = -\dot{Q}_{out} + \dot{W}_{in} + \dot{m}(\cancel{h_1 - h_2}) \to 0 \qquad W_{in} = 40\ kW$$

$$\dot{Q}_{out} = \dot{W}_{in} \qquad h_1 = h_2 \qquad \dot{Q}_{out} = 20°C = 293\ K$$

$$\Delta S_{air} = \frac{-\dot{Q}_{out}}{T_{air}} = \frac{-40\ kW}{298\ K} = -.134\ \frac{kW}{K}$$

ΔS assumes no irreversibilities in compression.

Air is losing Q, ΔS negative.

7–34 The radiator of a steam heating system has a volume of 20 L and is filled with superheated water vapor at 200 kPa and 150°C. At this moment both the inlet and the exit valves to the radiator are closed. After a while the temperature of the steam drops to 40°C as a result of heat transfer to the room air. Determine the entropy change of the steam during this process. *Answer:* −0.132 kJ/K

A-6:

$v_1 = .95986\ m^3/kg = v_2$

$s_1 = 7.281\ kJ/kg\text{-}k$

$Vol = 20L = .02\ m$

$T_1 = 150°C$

$P_1 = 200\ kPa$

A-4:

$v_f = .001008$

$v_g = 19.515$

$s_f = .5724$

$s_g = 8.2556$

$$m = \frac{Vol}{v_1} = \qquad T_2 = 40°C$$

$$m = \frac{.02}{.95986} = .02084\ kg$$

$$x_2 = \frac{v_2 - v_f}{v_g - v_f} = \frac{.95986 - .001008}{19.515 - .001008} = .0491$$

$$s_2 = s_f + x_2(s_g - s_f) = .5724 + .0491(8.2556 - .5724) = .94993$$

$$\Delta S = m(s_2 - s_1) = .02084(.94993 - 7.281)$$

$$\boxed{\Delta S = -.132\ kJ/K}$$

7–36 An insulated piston–cylinder device contains 0.05 m^3 of saturated refrigerant- 134a vapor at 0.8-MPa pressure. The refrigerant is now allowed to expand in a reversible manner until the pressure drops to 0.4 MPa. Determine (*a*) the final temperature in the cylinder and (*b*) the work done by the refrigerant.

7–36 An insulated piston–cylinder device contains 0.05 m³ of saturated refrigerant- 134a vapor at 0.8-MPa pressure. The refrigerant is now allowed to expand in a reversible manner until the pressure drops to 0.4 MPa. Determine (a) the final temperature in the cylinder and (b) the work done by the refrigerant.

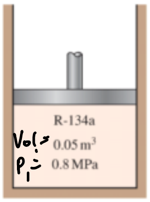


FIGURE P7–36

A-12:

$u_1 = u_g = 246.82$

$v_1 = v_g = 91853$

$s_1 = s_g = .025645$

$P_2 = .4\ MPa$

$x = 1$

$m = \frac{Vol.}{v_1} = \frac{.05}{.91853} = 1.95kg$

isentropic: $S_1 = S_2$

A-12:

$s_g = .92711$

$s_f = .24757$

$x_2 = \frac{S_2 - S_f}{S_g - S_f} = \frac{91853 - .24757}{.92711 - .24757} = .987$

$\boxed{T_{sat} = 8.91\ °C}$

$u_g = 235.1$

$u_f = 63.61$

$u_2 = u_f + x_2(u_g - u_f) = 63.61 + .987(235.1 - 63.61) = 232.93$

1st law closed system:

$\Delta U = -W_{bout} = -m(u_2 - u_1) = -1.95(232.93 - 246.82) = \boxed{27.08\ kJ}$

7–48 Water vapor enters a compressor at 35 kPa and 160°C and leaves at 300 kPa with the same specific entropy as at the inlet. What are the temperature and the specific enthalpy of water at the compressor exit?

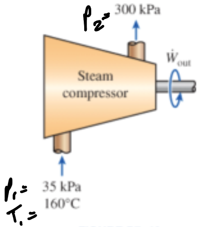


FIGURE P7–48

isentropic: $s_1 = s_2$

A-6:

$s_{P_1} = 8.6893 + \left(\frac{160-250}{200-150}\right)(8.9049 - 8.6893) = 8.73242$

$s_{P_2} = 8.73242 + \left(\frac{35-10}{50-10}\right)(7.98488 - 8.73242) = 8.2652$

$T_2 = 400 + \left(\frac{8.2652 - 8.0347}{8.3271 - 8.0347}\right)(500 - 400) = \boxed{478.8\ °C}$

↓

$T_2 = \quad + \left(\frac{\quad}{8.3271 - 8.0347}\right)(500-400) =$

$$h_2 = 3275.5 + .788\,(3486.6 - 3275.5) = \boxed{3441.8\ \frac{kJ}{kg}}$$

T ds Relations

Friday, November 11, 2022 10:03 AM

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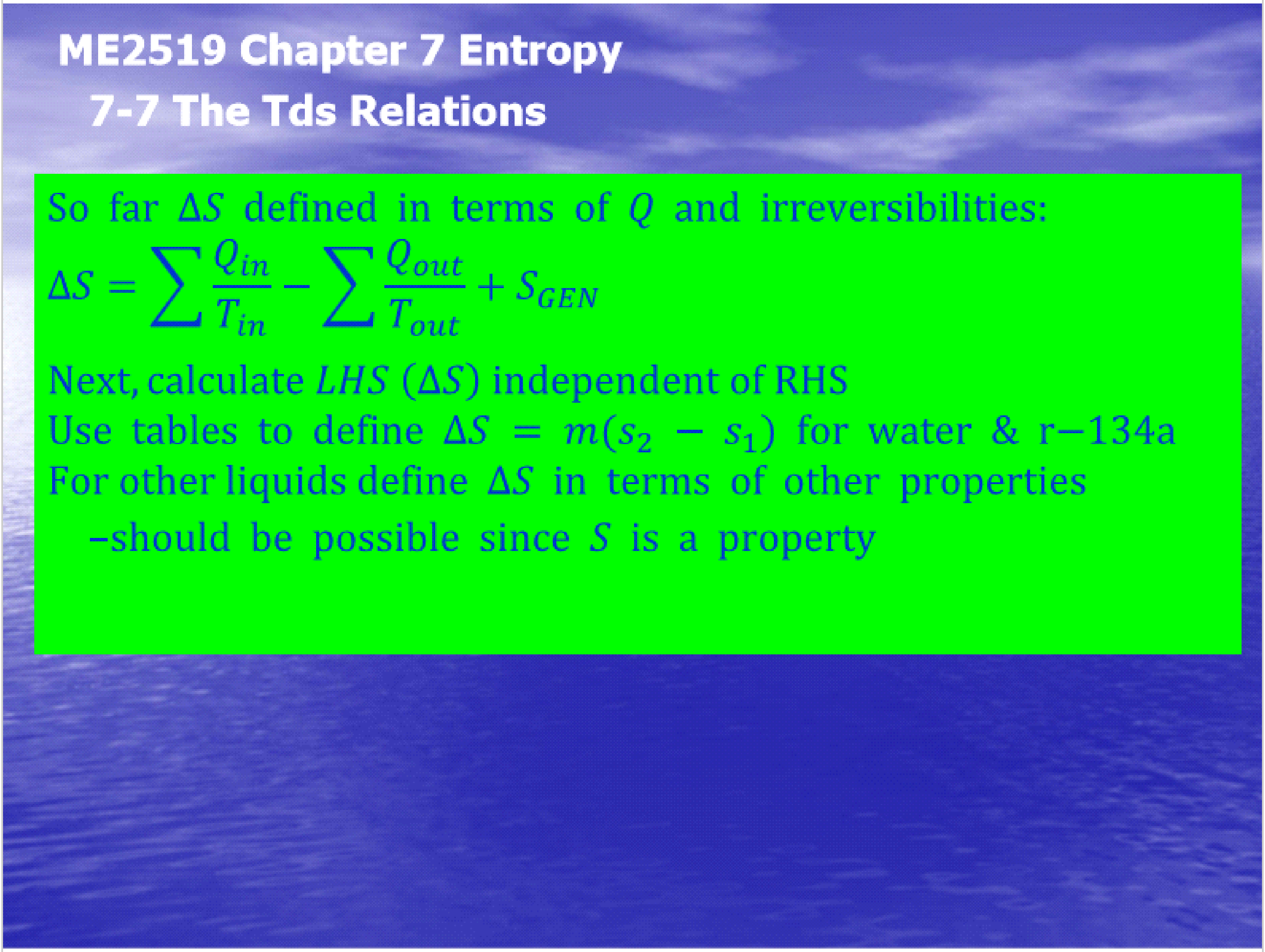
+7-7+and...



ME2519 Chapter 7 Entropy

7-7 The Tds Relations

So far ΔS defined in terms of Q and irreversibilities:

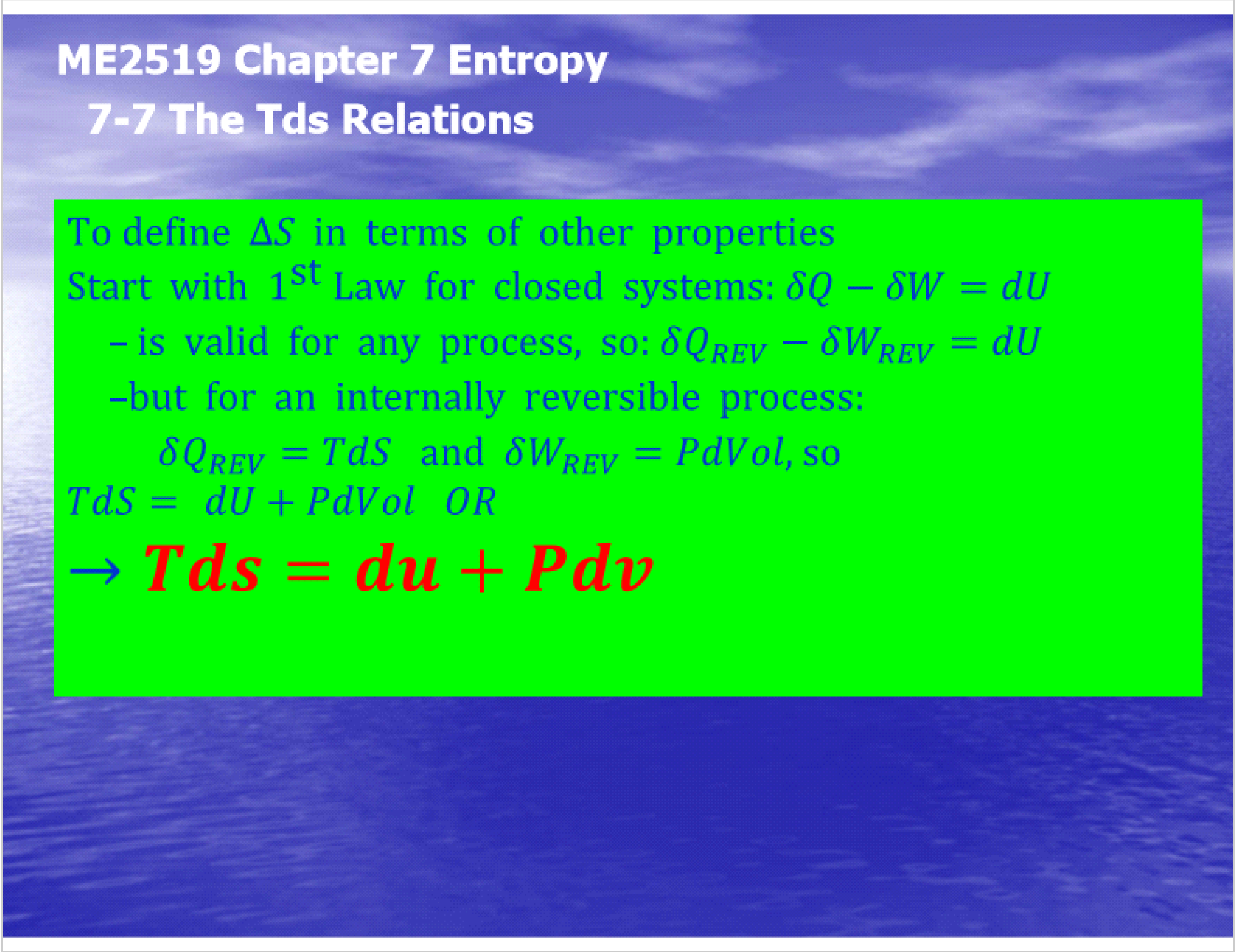
$$\Delta S = \sum \frac{Q_{in}}{T_{in}} - \sum \frac{Q_{out}}{T_{out}} + S_{GEN}$$

Next, calculate LHS (ΔS) independent of RHS

Use tables to define $\Delta S = m(s_2 - s_1)$ for water & r−134a

For other liquids define ΔS in terms of other properties

–should be possible since S is a property



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7-7 The Tds Relations

To define ΔS in terms of other properties

Start with 1^{st} Law for closed systems: $\delta Q - \delta W = dU$

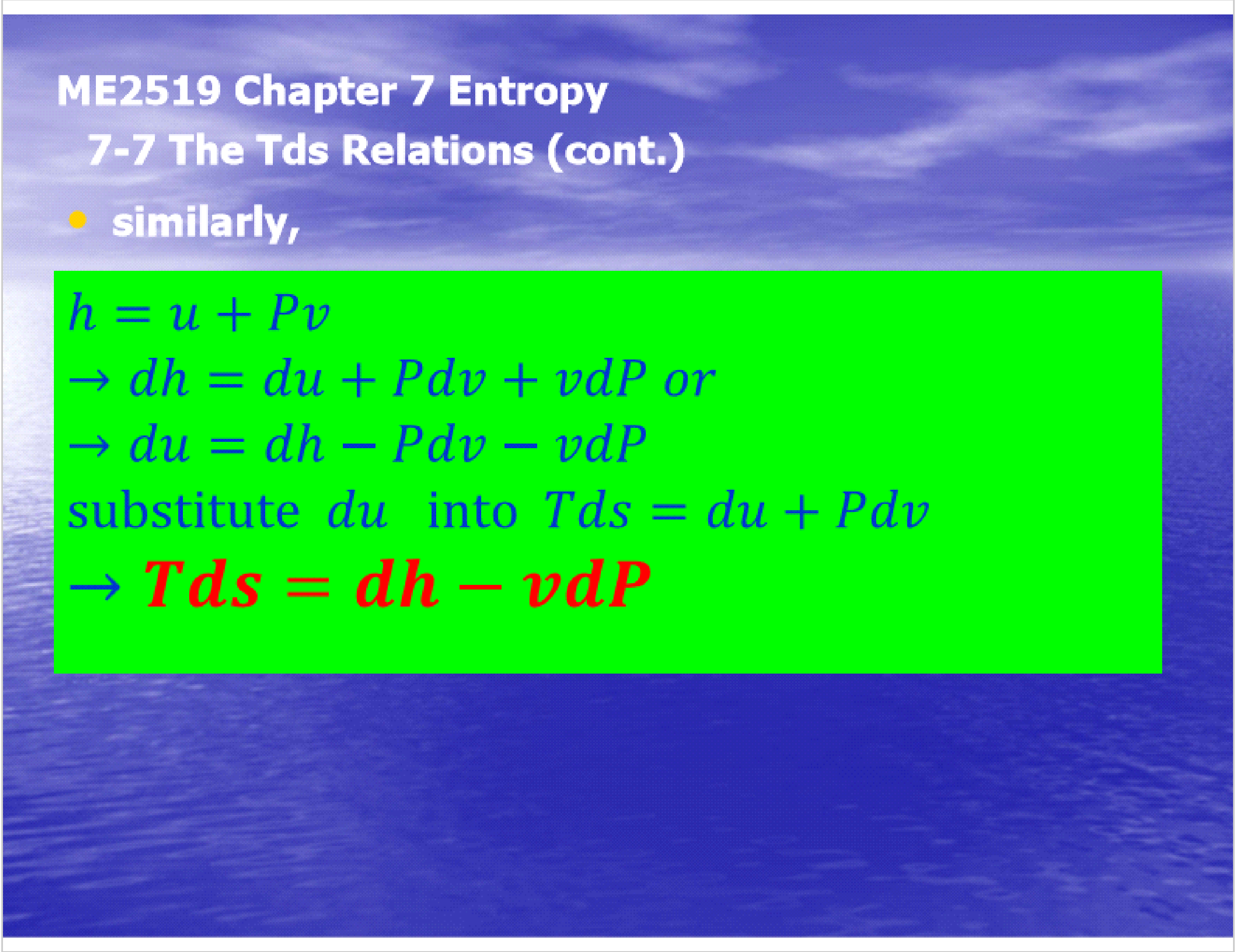
– is valid for any process, so: $\delta Q_{REV} - \delta W_{REV} = dU$

–but for an internally reversible process:

$\delta Q_{REV} = TdS$ and $\delta W_{REV} = PdVol$, so

$TdS = dU + PdVol \quad OR$

$$\rightarrow \boldsymbol{Tds = du + Pdv}$$



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7-7 The Tds Relations (cont.)

- similarly,

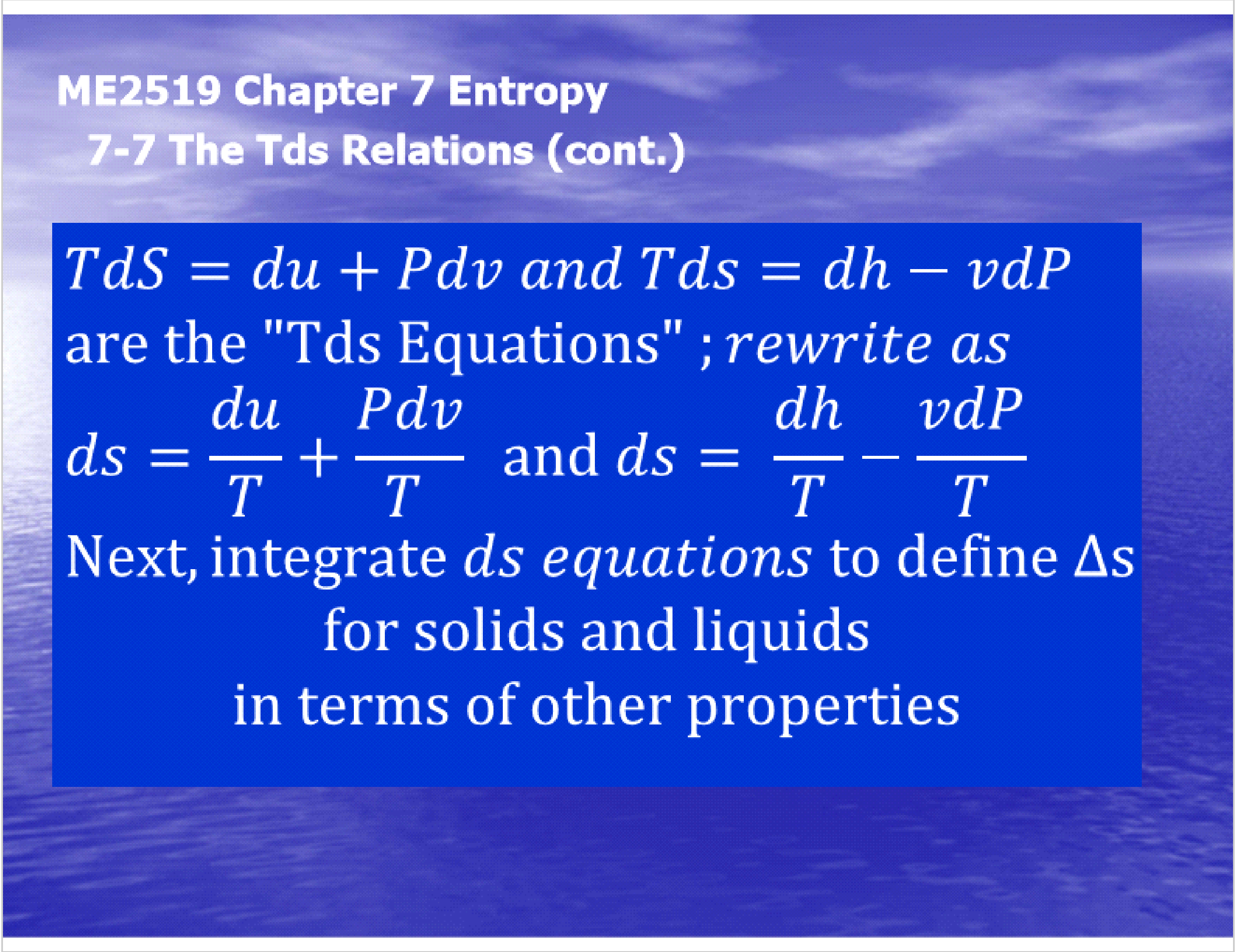
$$h = u + Pv$$

$$\rightarrow dh = du + Pdv + vdP \ or$$

$$\rightarrow du = dh - Pdv - vdP$$

substitute du into $Tds = du + Pdv$

$$\rightarrow \boldsymbol{Tds = dh - vdP}$$



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7-7 The Tds Relations (cont.)

$TdS = du + Pdv \; and \; Tds = dh - vdP$

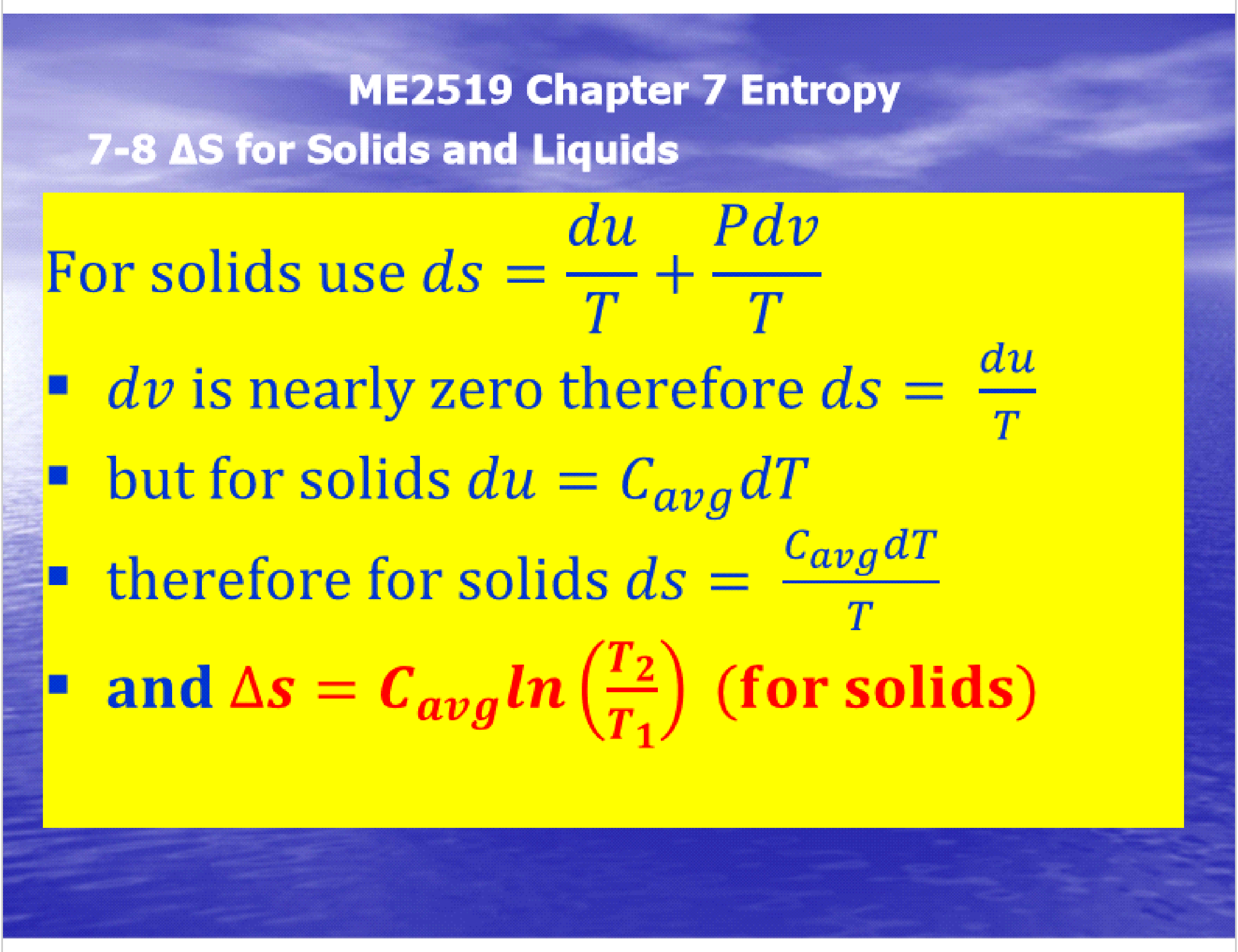
are the "Tds Equations" ; *rewrite as*

$$ds = \frac{du}{T} + \frac{Pdv}{T} \quad \text{and } ds = \frac{dh}{T} - \frac{vdP}{T}$$

Next, integrate *ds equations* to define Δs

for solids and liquids

in terms of other properties



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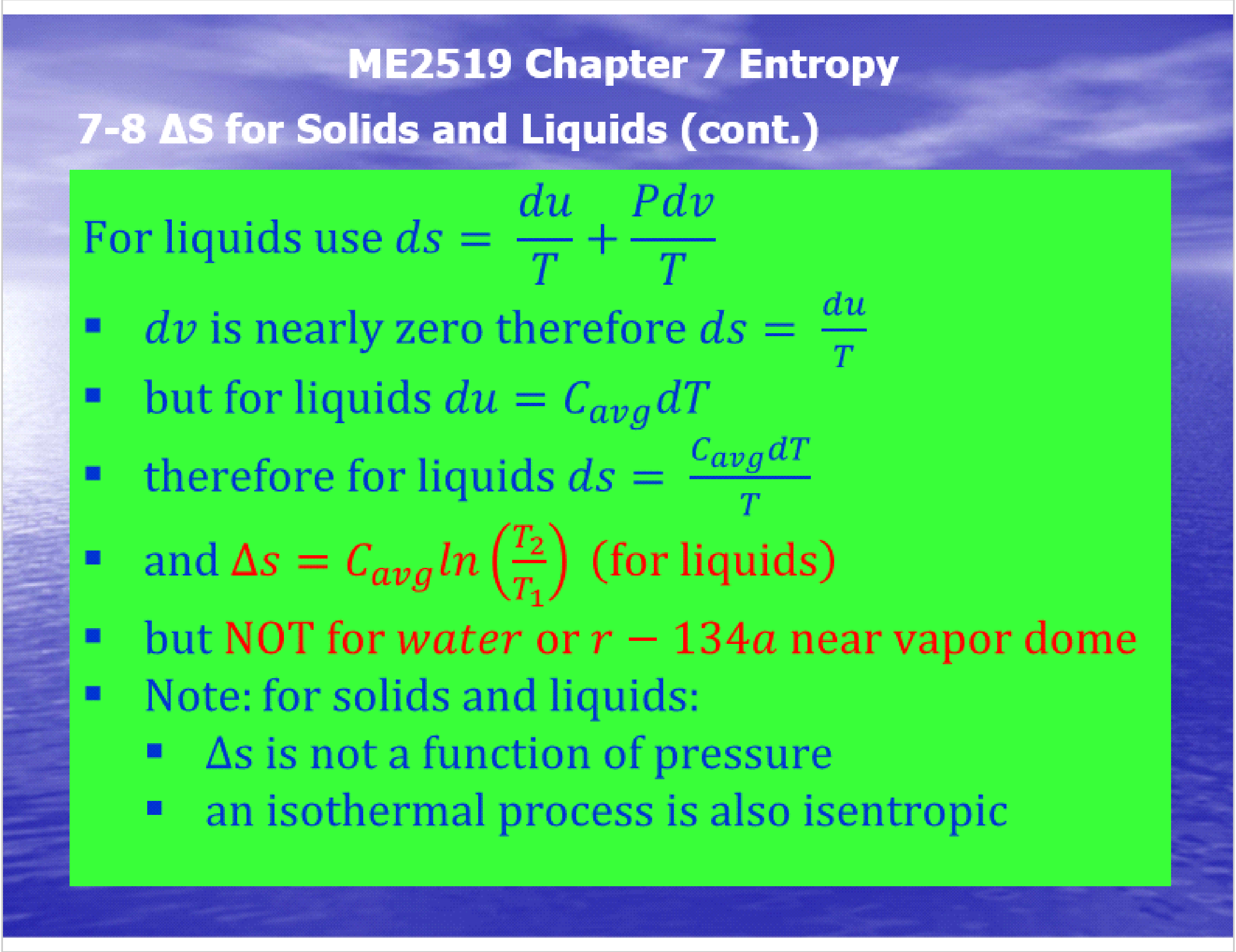
7-8 ΔS for Solids and Liquids

For solids use $ds = \frac{du}{T} + \frac{Pdv}{T}$

- dv is nearly zero therefore $ds = \frac{du}{T}$
- but for solids $du = C_{avg}dT$
- therefore for solids $ds = \frac{C_{avg}dT}{T}$
- **and $\Delta s = C_{avg} ln\left(\frac{T_2}{T_1}\right)$ (for solids)**



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7-8 ΔS for Solids and Liquids (cont.)

For liquids use $ds = \frac{du}{T} + \frac{Pdv}{T}$

- dv is nearly zero therefore $ds = \frac{du}{T}$
- but for liquids $du = C_{avg}dT$
- therefore for liquids $ds = \frac{C_{avg}dT}{T}$
- and $\Delta s = C_{avg}ln\left(\frac{T_2}{T_1}\right)$ (for liquids)
- but NOT for $water$ or $r - 134a$ near vapor dome
- Note: for solids and liquids:
  - Δs is not a function of pressure
  - an isothermal process is also isentropic

ΔS Ideal Gasses

Friday, November 11, 2022 10:26 AM

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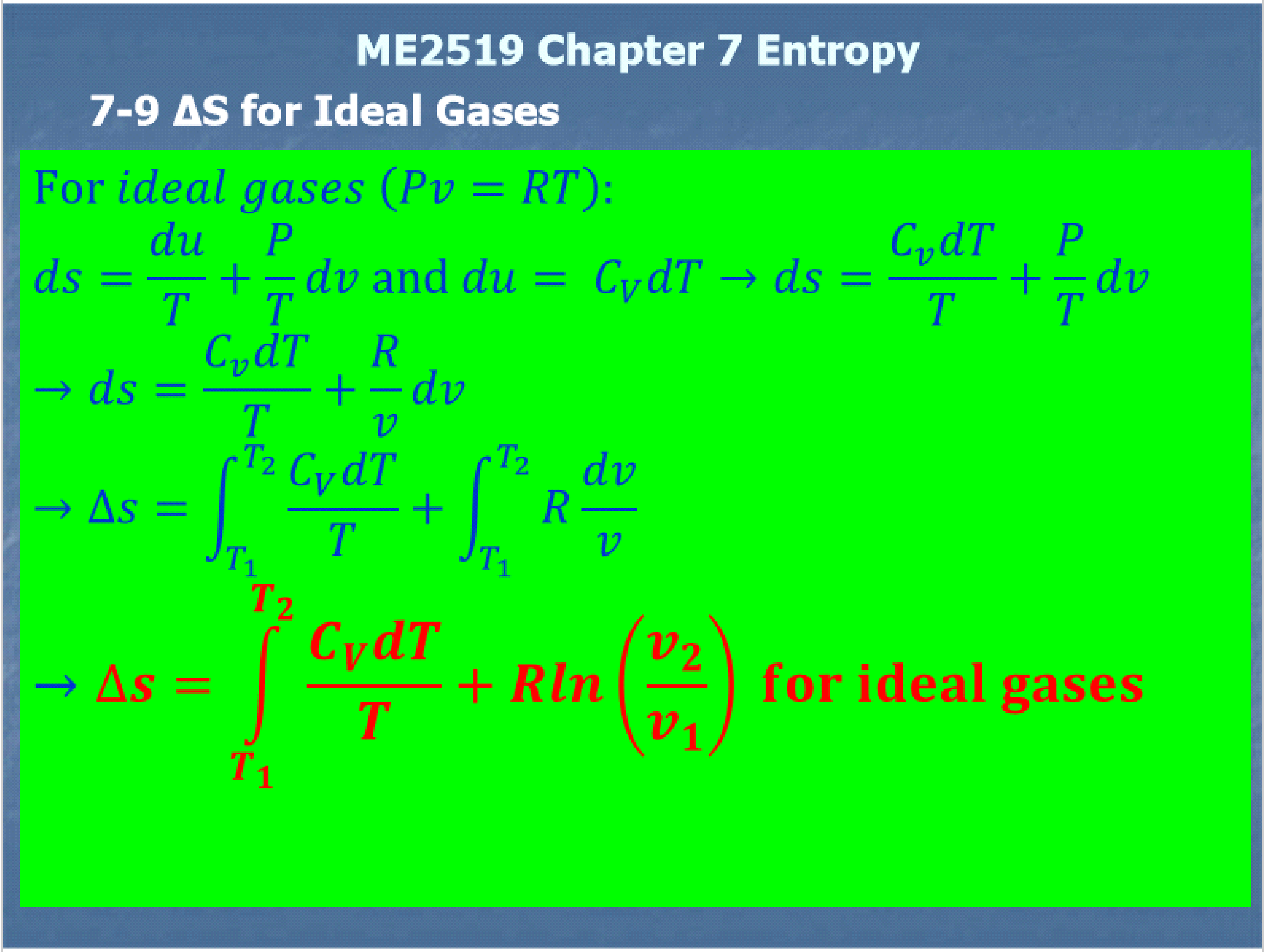

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7-9 ΔS for Ideal Gases

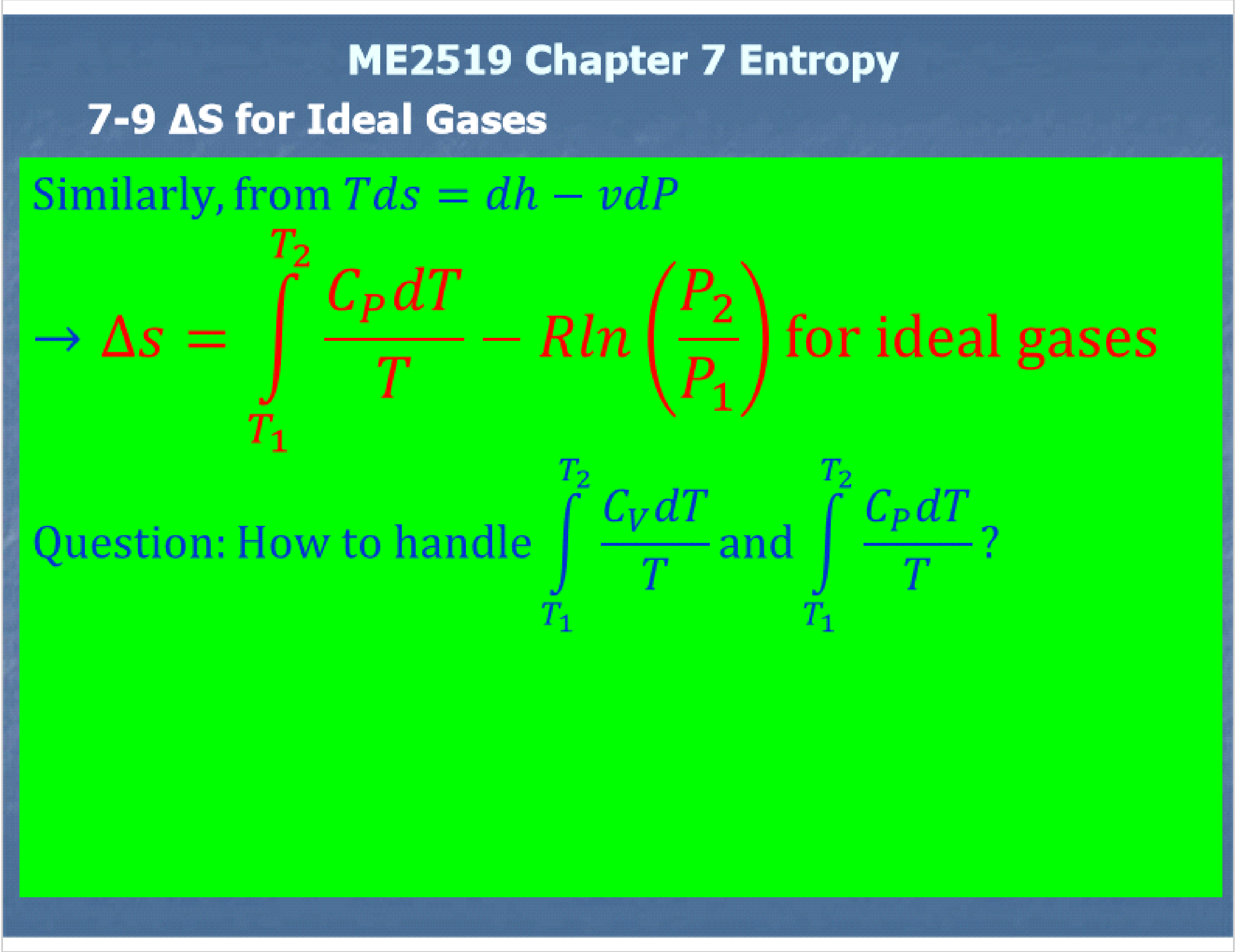
For ideal gases ($Pv = RT$):

$$ds = \frac{du}{T} + \frac{P}{T}dv \text{ and } du = C_V dT \rightarrow ds = \frac{C_v dT}{T} + \frac{P}{T}dv$$

$$\rightarrow ds = \frac{C_v dT}{T} + \frac{R}{v}dv$$

$$\rightarrow \Delta s = \int_{T_1}^{T_2} \frac{C_V dT}{T} + \int_{T_1}^{T_2} R\frac{dv}{v}$$

$$\rightarrow \Delta s = \int_{T_1}^{T_2} \frac{C_V dT}{T} + R\ln\left(\frac{v_2}{v_1}\right) \text{ for ideal gases}$$



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7-9 ΔS for Ideal Gases

Similarly, from $Tds = dh - vdP$

$$\rightarrow \Delta s = \int_{T_1}^{T_2} \frac{C_P dT}{T} - Rln\left(\frac{P_2}{P_1}\right) \text{ for ideal gases}$$

Question: How to handle $\int_{T_1}^{T_2} \frac{C_V dT}{T}$ and $\int_{T_1}^{T_2} \frac{C_P dT}{T}$?

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- **Answer 1: Use Table A-2 (a)**

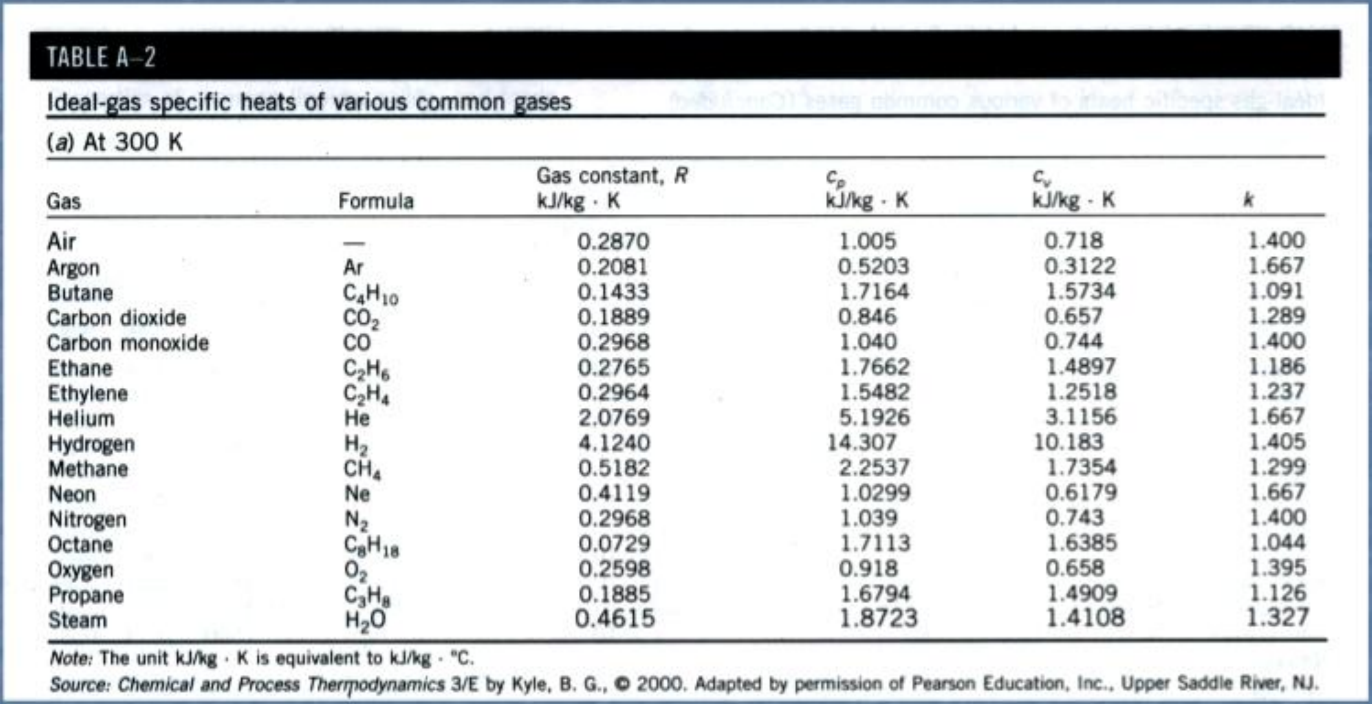


TABLE A–2

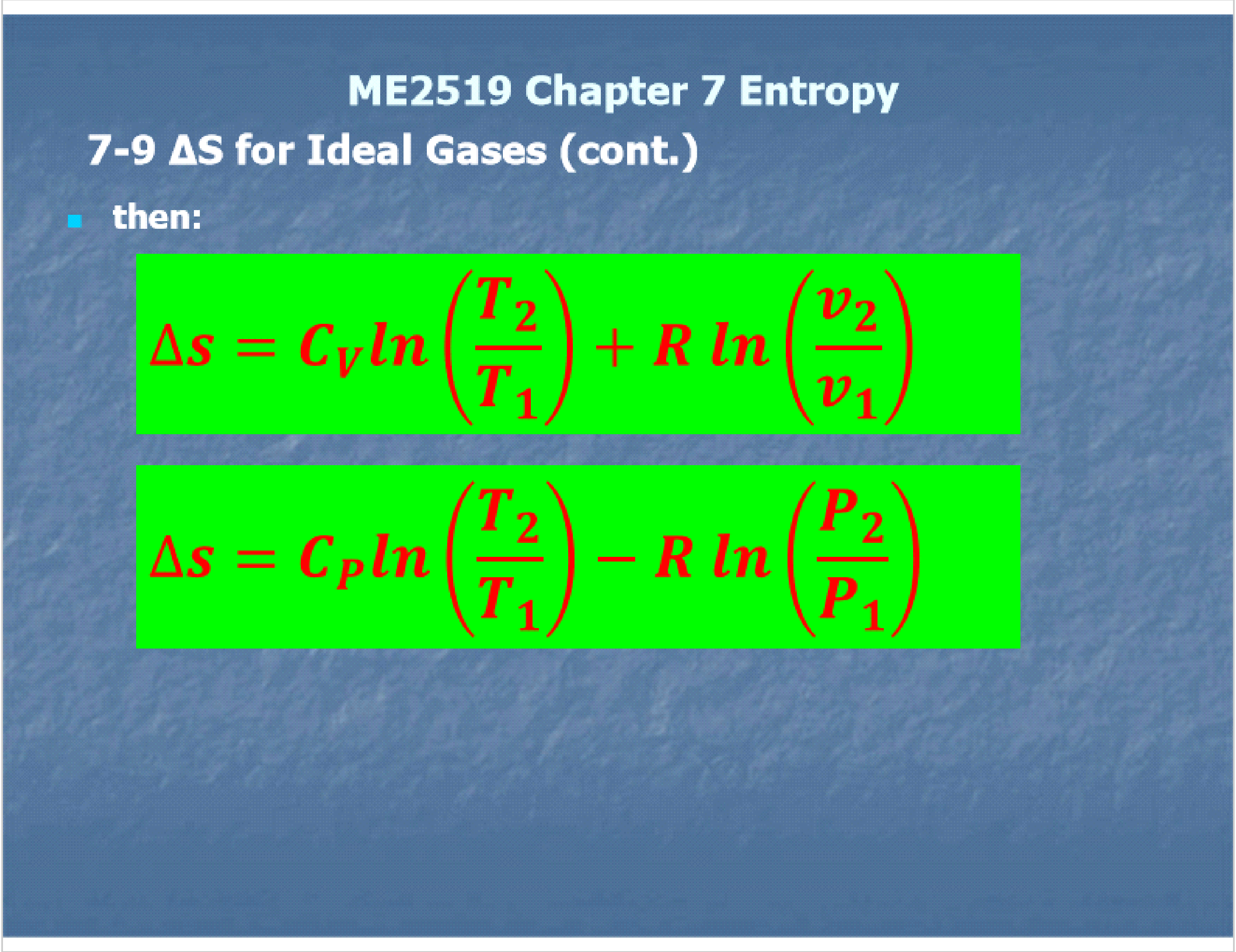
Ideal-gas specific heats of various common gases

(*a*) At 300 K

Gas	Formula	Gas constant, *R* kJ/kg · K	c_p kJ/kg · K	c_v kJ/kg · K	*k*
Air	—	0.2870	1.005	0.718	1.400
Argon	Ar	0.2081	0.5203	0.3122	1.667
Butane	C_4H_{10}	0.1433	1.7164	1.5734	1.091
Carbon dioxide	CO_2	0.1889	0.846	0.657	1.289
Carbon monoxide	CO	0.2968	1.040	0.744	1.400
Ethane	C_2H_6	0.2765	1.7662	1.4897	1.186
Ethylene	C_2H_4	0.2964	1.5482	1.2518	1.237
Helium	He	2.0769	5.1926	3.1156	1.667
Hydrogen	H_2	4.1240	14.307	10.183	1.405
Methane	CH_4	0.5182	2.2537	1.7354	1.299
Neon	Ne	0.4119	1.0299	0.6179	1.667
Nitrogen	N_2	0.2968	1.039	0.743	1.400
Octane	C_8H_{18}	0.0729	1.7113	1.6385	1.044
Oxygen	O_2	0.2598	0.918	0.658	1.395
Propane	C_3H_8	0.1885	1.6794	1.4909	1.126
Steam	H_2O	0.4615	1.8723	1.4108	1.327

Note: The unit kJ/kg · K is equivalent to kJ/kg · °C.

Source: Chemical and Process Thermodynamics 3/E by Kyle, B. G., © 2000. Adapted by permission of Pearson Education, Inc., Upper Saddle River, NJ.



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7-9 ΔS for Ideal Gases (cont.)

- then:

$$\Delta s = C_V ln\left(\frac{T_2}{T_1}\right) + R\ ln\left(\frac{v_2}{v_1}\right)$$

$$\Delta s = C_P ln\left(\frac{T_2}{T_1}\right) - R\ ln\left(\frac{P_2}{P_1}\right)$$

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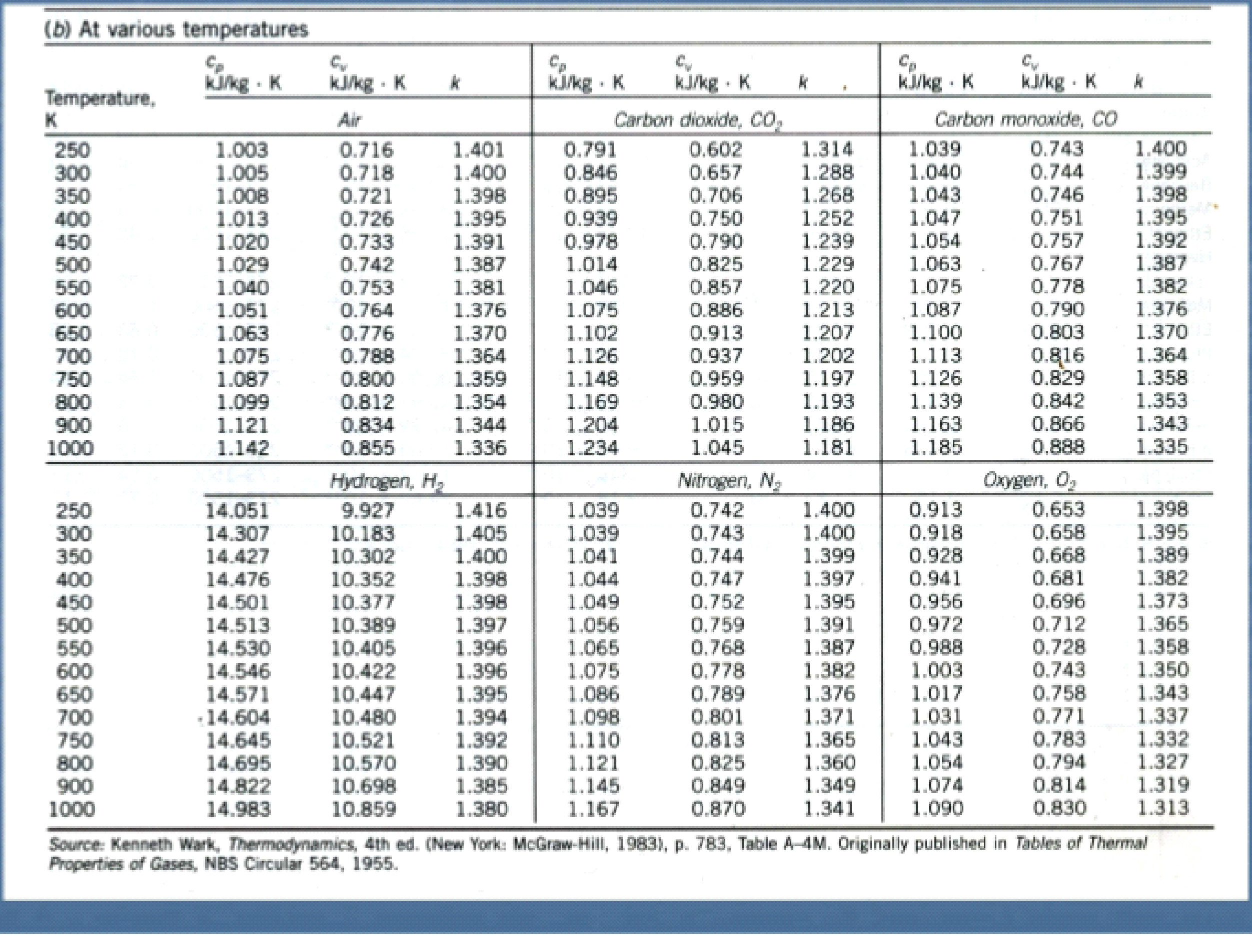
- **Answer 2: use Table A-2(b)**



(*b*) At various temperatures

Temperature, K	c_p kJ/kg · K	c_v kJ/kg · K	k	c_p kJ/kg · K	c_v kJ/kg · K	k	c_p kJ/kg · K	c_v kJ/kg · K	k
	Air			*Carbon dioxide, CO_2*			*Carbon monoxide, CO*		
250	1.003	0.716	1.401	0.791	0.602	1.314	1.039	0.743	1.400
300	1.005	0.718	1.400	0.846	0.657	1.288	1.040	0.744	1.399
350	1.008	0.721	1.398	0.895	0.706	1.268	1.043	0.746	1.398
400	1.013	0.726	1.395	0.939	0.750	1.252	1.047	0.751	1.395
450	1.020	0.733	1.391	0.978	0.790	1.239	1.054	0.757	1.392
500	1.029	0.742	1.387	1.014	0.825	1.229	1.063	0.767	1.387
550	1.040	0.753	1.381	1.046	0.857	1.220	1.075	0.778	1.382
600	1.051	0.764	1.376	1.075	0.886	1.213	1.087	0.790	1.376
650	1.063	0.776	1.370	1.102	0.913	1.207	1.100	0.803	1.370
700	1.075	0.788	1.364	1.126	0.937	1.202	1.113	0.816	1.364
750	1.087	0.800	1.359	1.148	0.959	1.197	1.126	0.829	1.358
800	1.099	0.812	1.354	1.169	0.980	1.193	1.139	0.842	1.353
900	1.121	0.834	1.344	1.204	1.015	1.186	1.163	0.866	1.343
1000	1.142	0.855	1.336	1.234	1.045	1.181	1.185	0.888	1.335
	Hydrogen, H_2			*Nitrogen, N_2*			*Oxygen, O_2*		
250	14.051	9.927	1.416	1.039	0.742	1.400	0.913	0.653	1.398
300	14.307	10.183	1.405	1.039	0.743	1.400	0.918	0.658	1.395
350	14.427	10.302	1.400	1.041	0.744	1.399	0.928	0.668	1.389
400	14.476	10.352	1.398	1.044	0.747	1.397	0.941	0.681	1.382
450	14.501	10.377	1.398	1.049	0.752	1.395	0.956	0.696	1.373
500	14.513	10.389	1.397	1.056	0.759	1.391	0.972	0.712	1.365
550	14.530	10.405	1.396	1.065	0.768	1.387	0.988	0.728	1.358
600	14.546	10.422	1.396	1.075	0.778	1.382	1.003	0.743	1.350
650	14.571	10.447	1.395	1.086	0.789	1.376	1.017	0.758	1.343
700	14.604	10.480	1.394	1.098	0.801	1.371	1.031	0.771	1.337
750	14.645	10.521	1.392	1.110	0.813	1.365	1.043	0.783	1.332
800	14.695	10.570	1.390	1.121	0.825	1.360	1.054	0.794	1.327
900	14.822	10.698	1.385	1.145	0.849	1.349	1.074	0.814	1.319
1000	14.983	10.859	1.380	1.167	0.870	1.341	1.090	0.830	1.313

Source: Kenneth Wark, *Thermodynamics*, 4th ed. (New York: McGraw-Hill, 1983), p. 783, Table A–4M. Originally published in *Tables of Thermal Properties of Gases*, NBS Circular 564, 1955.

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7-9 ΔS for Ideal Gases (cont.)

- **Answer 2:** Table A-2(b) provides values of C_v and C_p as a function of T.
  - Calculate $T_{average}$ for C_{vavg} & $C_{Pavg,}$ then

$$\Delta s = C_{V,avg} ln\left(\frac{T_2}{T_1}\right) + R\ ln\left(\frac{v_2}{v_1}\right)$$

$$\Delta s = C_{P,avg} ln\left(\frac{T_2}{T_1}\right) - R\ ln\left(\frac{P_2}{P_1}\right)$$

  - Table A-2(b) has data for air, CO_2, CO, H_2, N_2, and O_2.

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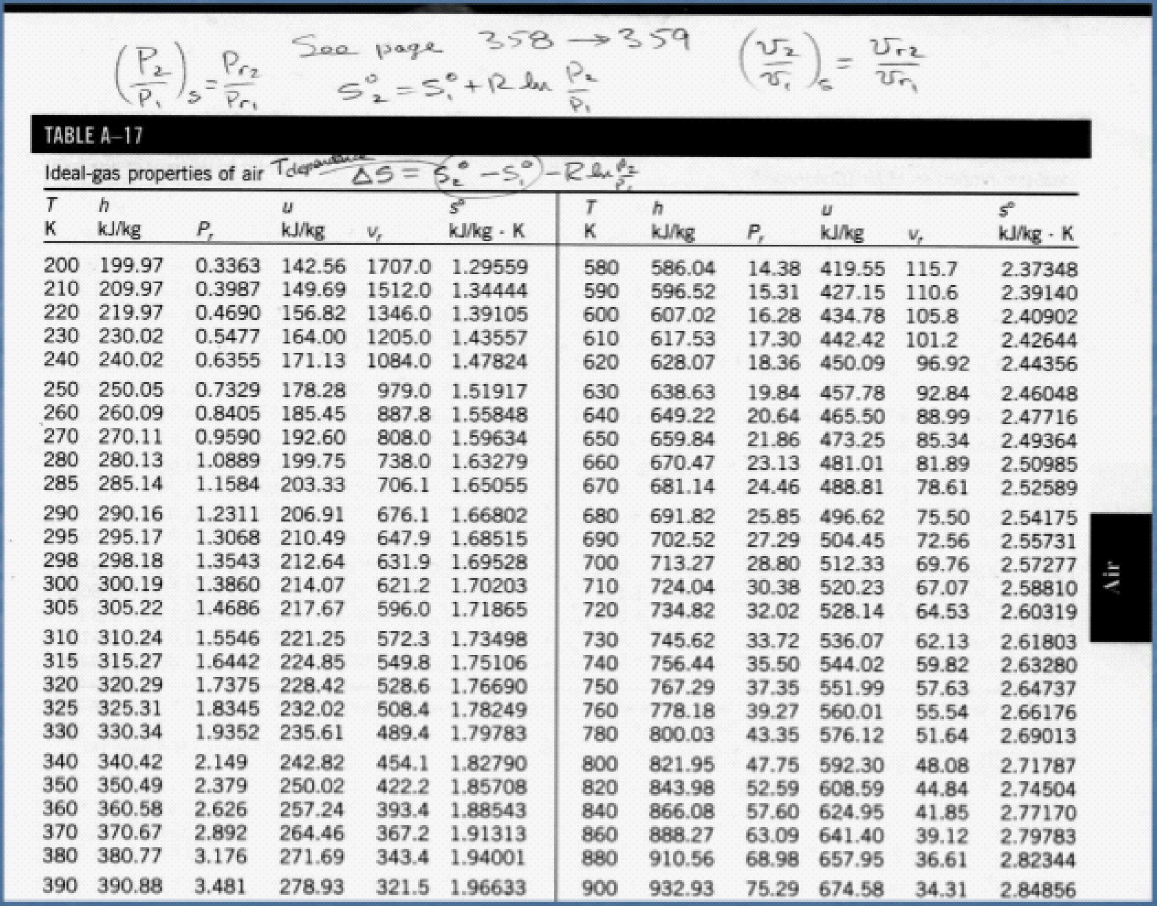
Answer 3: use Table A-17 (air only)



$\left(\frac{P_2}{P_1}\right)_s = \frac{P_{r2}}{P_{r1}}$ See page 358 → 359 $\left(\frac{v_2}{v_1}\right)_s = \frac{v_{r2}}{v_{r1}}$

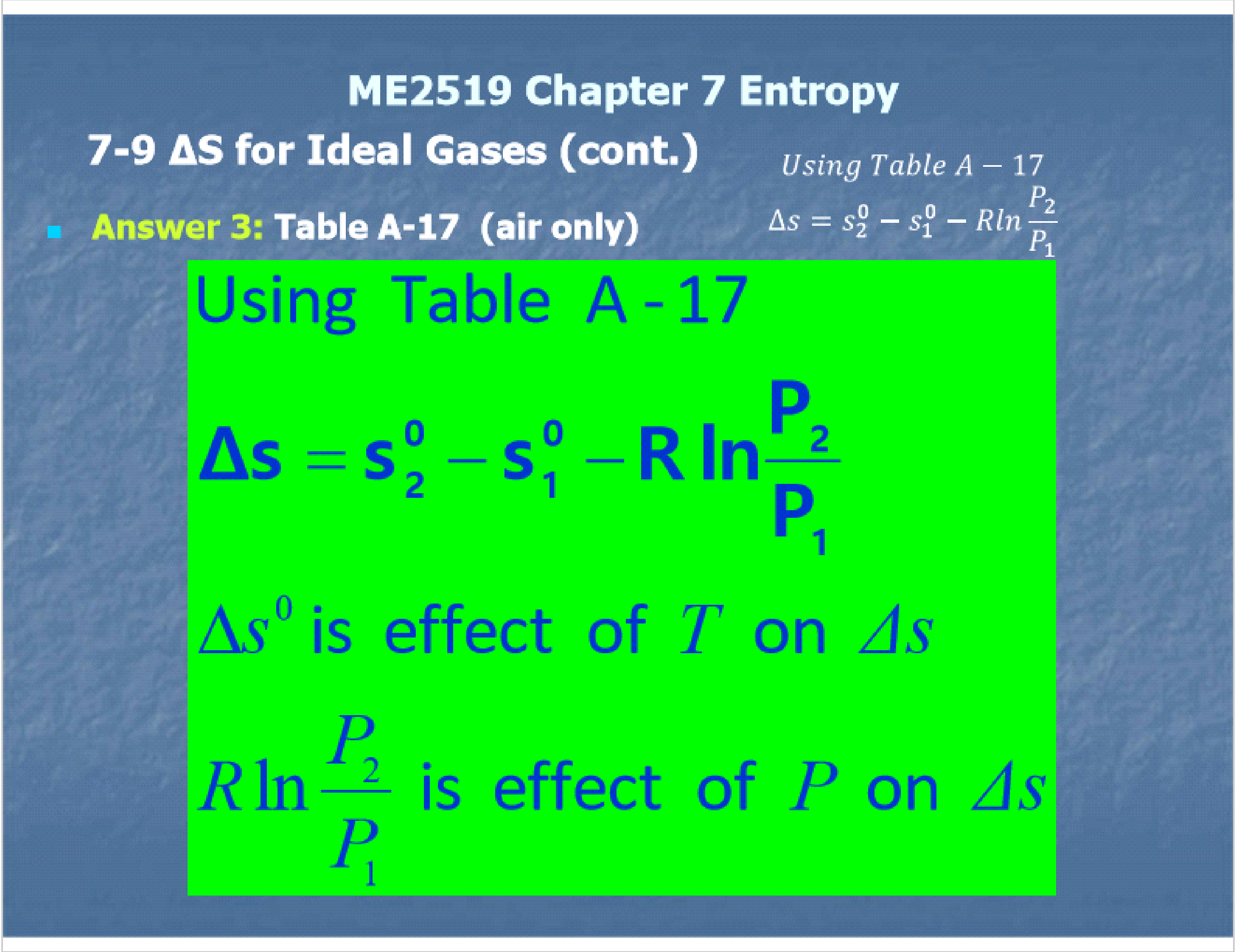
$s_2^\circ = s_1^\circ + R \ln \frac{P_2}{P_1}$

TABLE A–17

Ideal-gas properties of air T dependence $\Delta s = \boxed{s_2^\circ - s_1^\circ} - R \ln \frac{P_2}{P_1}$

T K	h kJ/kg	P_r	u kJ/kg	v_r	s° kJ/kg · K	T K	h kJ/kg	P_r	u kJ/kg	v_r	s° kJ/kg · K
200	199.97	0.3363	142.56	1707.0	1.29559	580	586.04	14.38	419.55	115.7	2.37348
210	209.97	0.3987	149.69	1512.0	1.34444	590	596.52	15.31	427.15	110.6	2.39140
220	219.97	0.4690	156.82	1346.0	1.39105	600	607.02	16.28	434.78	105.8	2.40902
230	230.02	0.5477	164.00	1205.0	1.43557	610	617.53	17.30	442.42	101.2	2.42644
240	240.02	0.6355	171.13	1084.0	1.47824	620	628.07	18.36	450.09	96.92	2.44356
250	250.05	0.7329	178.28	979.0	1.51917	630	638.63	19.84	457.78	92.84	2.46048
260	260.09	0.8405	185.45	887.8	1.55848	640	649.22	20.64	465.50	88.99	2.47716
270	270.11	0.9590	192.60	808.0	1.59634	650	659.84	21.86	473.25	85.34	2.49364
280	280.13	1.0889	199.75	738.0	1.63279	660	670.47	23.13	481.01	81.89	2.50985
285	285.14	1.1584	203.33	706.1	1.65055	670	681.14	24.46	488.81	78.61	2.52589
290	290.16	1.2311	206.91	676.1	1.66802	680	691.82	25.85	496.62	75.50	2.54175
295	295.17	1.3068	210.49	647.9	1.68515	690	702.52	27.29	504.45	72.56	2.55731
298	298.18	1.3543	212.64	631.9	1.69528	700	713.27	28.80	512.33	69.76	2.57277
300	300.19	1.3860	214.07	621.2	1.70203	710	724.04	30.38	520.23	67.07	2.58810
305	305.22	1.4686	217.67	596.0	1.71865	720	734.82	32.02	528.14	64.53	2.60319
310	310.24	1.5546	221.25	572.3	1.73498	730	745.62	33.72	536.07	62.13	2.61803
315	315.27	1.6442	224.85	549.8	1.75106	740	756.44	35.50	544.02	59.82	2.63280
320	320.29	1.7375	228.42	528.6	1.76690	750	767.29	37.35	551.99	57.63	2.64737
325	325.31	1.8345	232.02	508.4	1.78249	760	778.18	39.27	560.01	55.54	2.66176
330	330.34	1.9352	235.61	489.4	1.79783	780	800.03	43.35	576.12	51.64	2.69013
340	340.42	2.149	242.82	454.1	1.82790	800	821.95	47.75	592.30	48.08	2.71787
350	350.49	2.379	250.02	422.2	1.85708	820	843.98	52.59	608.59	44.84	2.74504
360	360.58	2.626	257.24	393.4	1.88543	840	866.08	57.60	624.95	41.85	2.77170
370	370.67	2.892	264.46	367.2	1.91313	860	888.27	63.09	641.40	39.12	2.79783
380	380.77	3.176	271.69	343.4	1.94001	880	910.56	68.98	657.95	36.61	2.82344
390	390.88	3.481	278.93	321.5	1.96633	900	932.93	75.29	674.58	34.31	2.84856

Air



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7-9 ΔS for Ideal Gases (cont.)

$Using\ Table\ A - 17$

$$\Delta s = s_2^0 - s_1^0 - Rln\frac{P_2}{P_1}$$

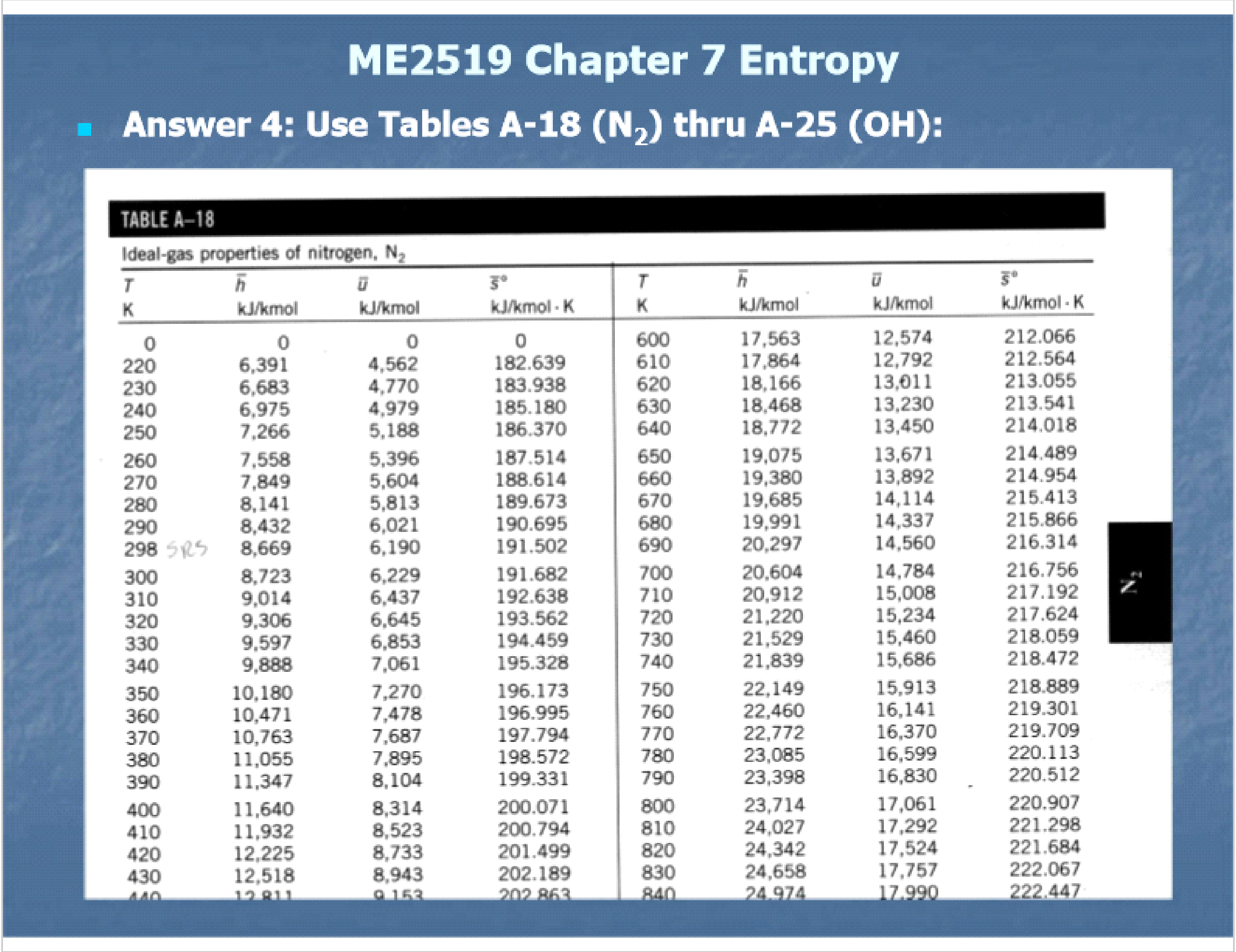
- **Answer 3:** **Table A-17 (air only)**

Using Table A - 17

$$\Delta s = s_2^0 - s_1^0 - R\ln\frac{P_2}{P_1}$$

Δs^0 is effect of T on Δs

$R\ln\frac{P_2}{P_1}$ is effect of P on Δs



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- **Answer 4: Use Tables A-18 (N_2) thru A-25 (OH):**

TABLE A–18

Ideal-gas properties of nitrogen, N_2

T K	$\bar{h}$ kJ/kmol	$\bar{u}$ kJ/kmol	$\bar{s}^\circ$ kJ/kmol · K	T K	$\bar{h}$ kJ/kmol	$\bar{u}$ kJ/kmol	$\bar{s}^\circ$ kJ/kmol · K
0	0	0	0	600	17,563	12,574	212.066
220	6,391	4,562	182.639	610	17,864	12,792	212.564
230	6,683	4,770	183.938	620	18,166	13,011	213.055
240	6,975	4,979	185.180	630	18,468	13,230	213.541
250	7,266	5,188	186.370	640	18,772	13,450	214.018
260	7,558	5,396	187.514	650	19,075	13,671	214.489
270	7,849	5,604	188.614	660	19,380	13,892	214.954
280	8,141	5,813	189.673	670	19,685	14,114	215.413
290	8,432	6,021	190.695	680	19,991	14,337	215.866
298 SRS	8,669	6,190	191.502	690	20,297	14,560	216.314
300	8,723	6,229	191.682	700	20,604	14,784	216.756
310	9,014	6,437	192.638	710	20,912	15,008	217.192
320	9,306	6,645	193.562	720	21,220	15,234	217.624
330	9,597	6,853	194.459	730	21,529	15,460	218.059
340	9,888	7,061	195.328	740	21,839	15,686	218.472
350	10,180	7,270	196.173	750	22,149	15,913	218.889
360	10,471	7,478	196.995	760	22,460	16,141	219.301
370	10,763	7,687	197.794	770	22,772	16,370	219.709
380	11,055	7,895	198.572	780	23,085	16,599	220.113
390	11,347	8,104	199.331	790	23,398	16,830	220.512
400	11,640	8,314	200.071	800	23,714	17,061	220.907
410	11,932	8,523	200.794	810	24,027	17,292	221.298
420	12,225	8,733	201.499	820	24,342	17,524	221.684
430	12,518	8,943	202.189	830	24,658	17,757	222.067
440	12,811	9,153	202.863	840	24,974	17,990	222.447

N_2

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7-9 ΔS for Ideal Gases (cont.)

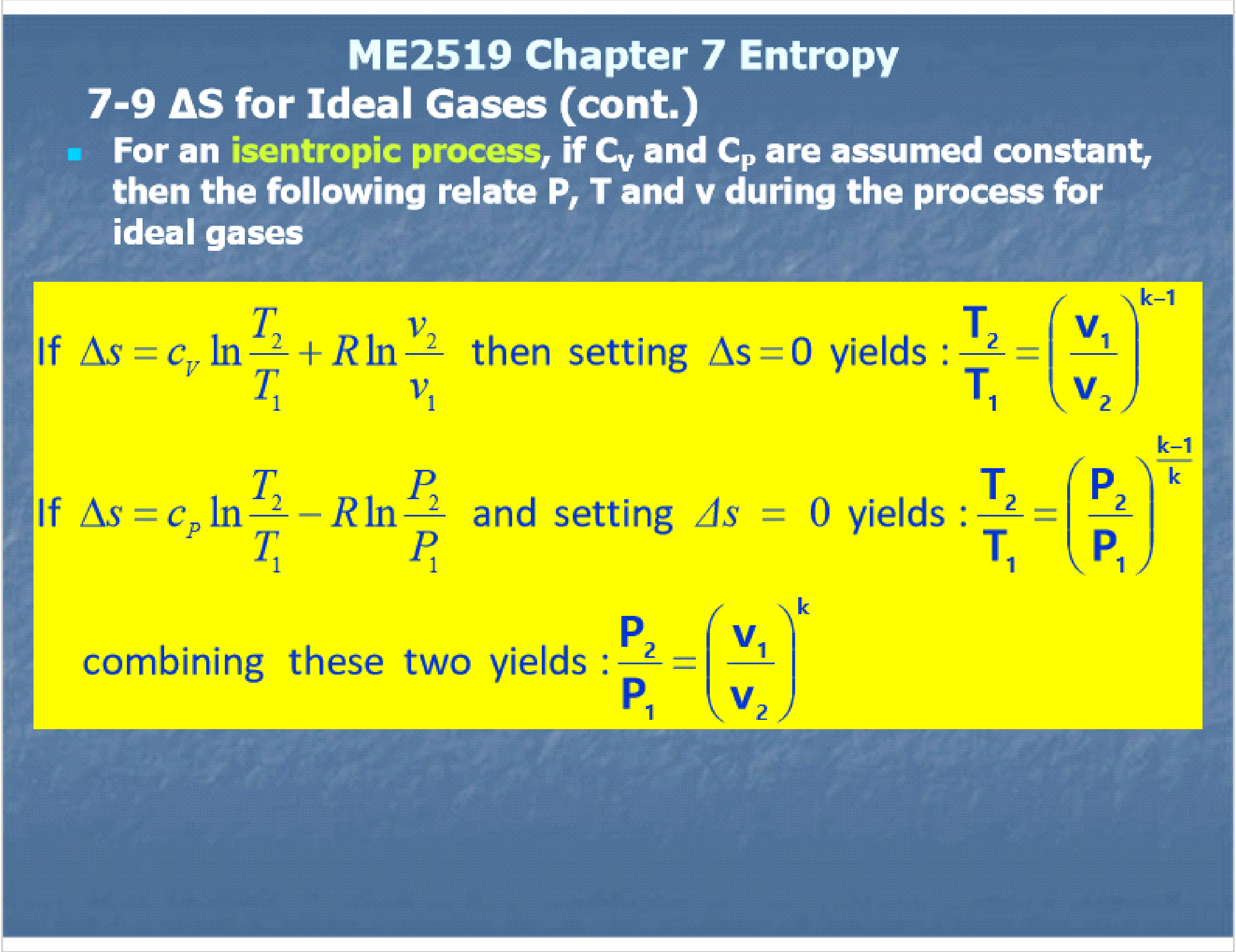
- **Answer 4:** For N_2, O_2, CO_2, CO, H_2, H_2O, O, and OH use Tables A-18 through A-25:

For these gases $\Delta s = \dfrac{\Delta \overline{s^0}}{M} - R\ln\dfrac{P_2}{P_1}$

M is the molar mass of the gas

$\overline{s^0}$ is the effect of T on Δs

$R\ln\dfrac{P_2}{P_1}$ is the effect of P on Δs



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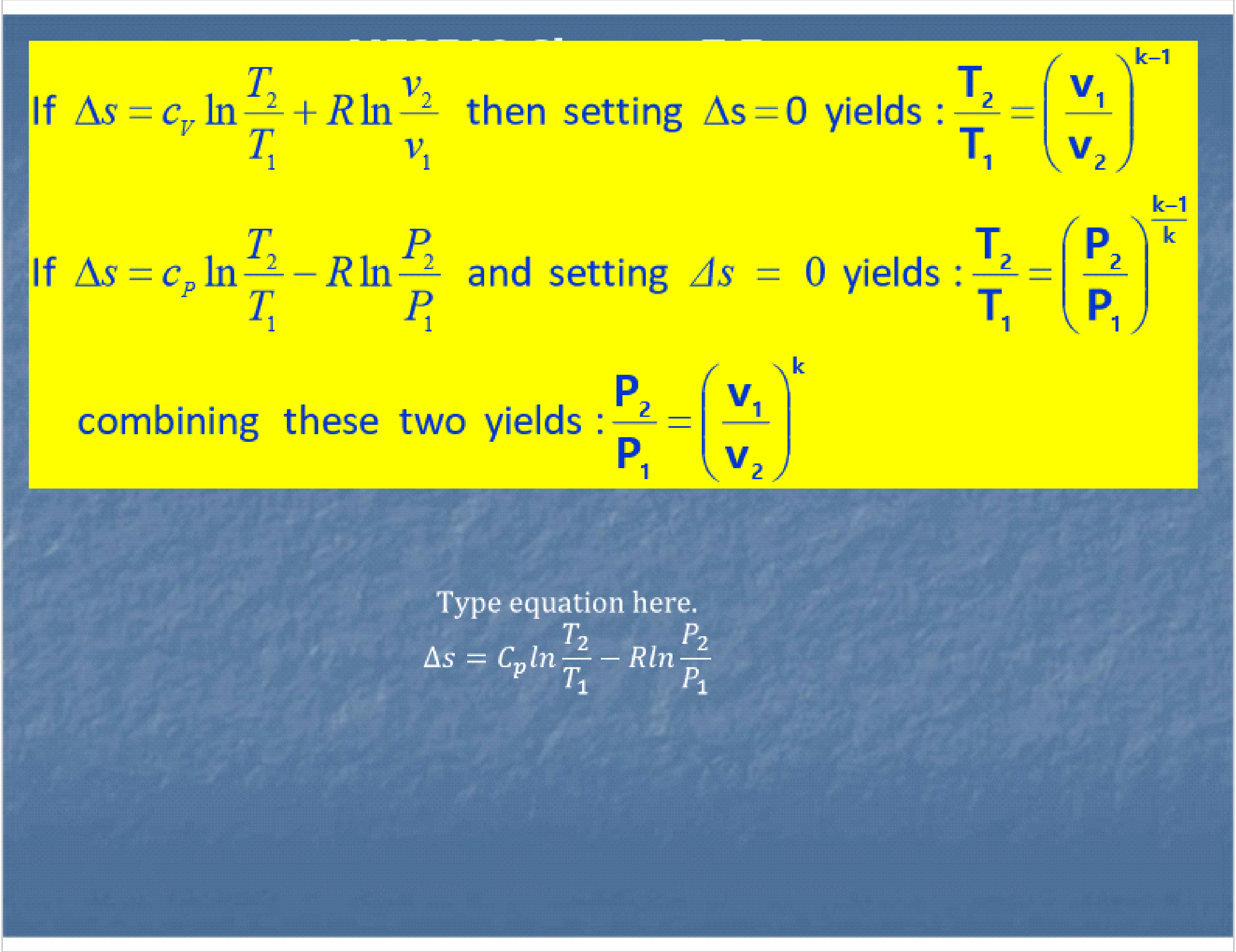
7-9 ΔS for Ideal Gases (cont.)

- For an isentropic process, if C_V and C_P are assumed constant, then the following relate P, T and v during the process for ideal gases

If $\Delta s = c_V \ln \frac{T_2}{T_1} + R \ln \frac{v_2}{v_1}$ then setting $\Delta s = 0$ yields : $\frac{T_2}{T_1} = \left(\frac{v_1}{v_2}\right)^{k-1}$

If $\Delta s = c_P \ln \frac{T_2}{T_1} - R \ln \frac{P_2}{P_1}$ and setting $\Delta s = 0$ yields : $\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}}$

combining these two yields : $\frac{P_2}{P_1} = \left(\frac{v_1}{v_2}\right)^{k}$



If $\Delta s = c_V \ln\frac{T_2}{T_1} + R\ln\frac{v_2}{v_1}$ then setting $\Delta s = 0$ yields : $\frac{T_2}{T_1} = \left(\frac{v_1}{v_2}\right)^{k-1}$

If $\Delta s = c_p \ln\frac{T_2}{T_1} - R\ln\frac{P_2}{P_1}$ and setting $\Delta s = 0$ yields : $\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}}$

combining these two yields : $\frac{P_2}{P_1} = \left(\frac{v_1}{v_2}\right)^{k}$

Type equation here.

$$\Delta s = C_p ln\frac{T_2}{T_1} - Rln\frac{P_2}{P_1}$$

Reversible Work

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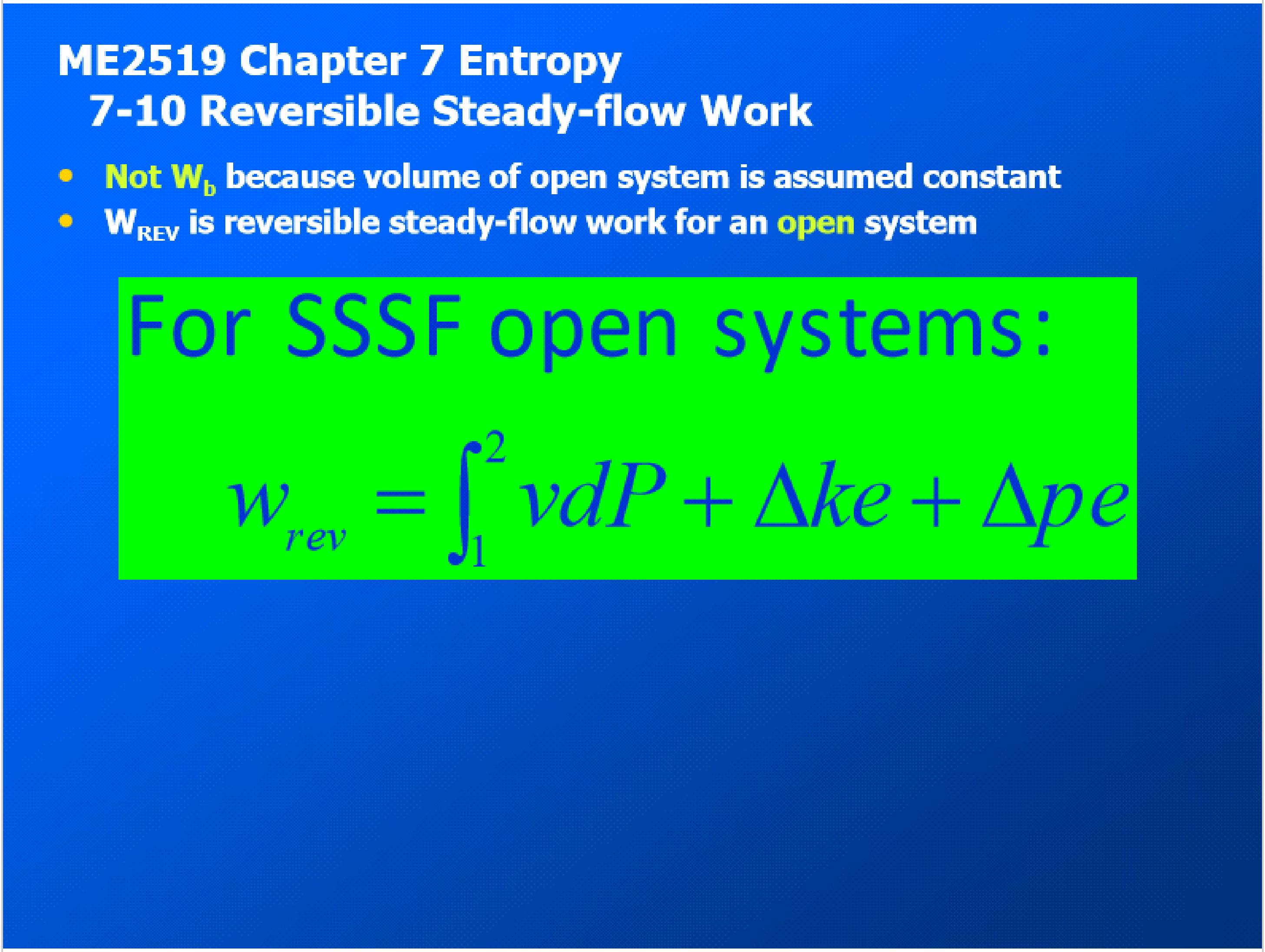

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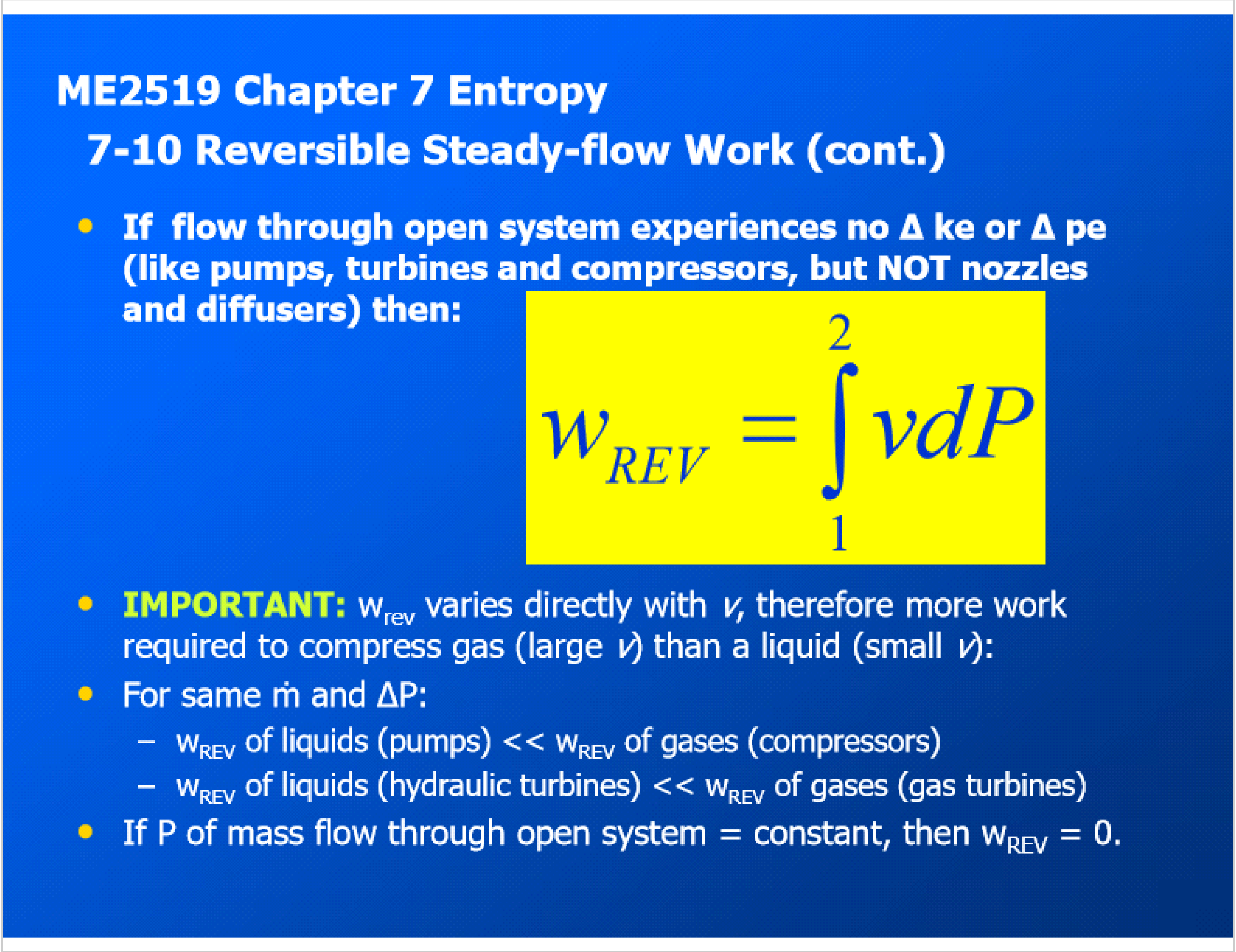
7-10 Reversible Steady-flow Work

- Not W_b because volume of open system is assumed constant
- W_{REV} is reversible steady-flow work for an open system

For SSSF open systems:

$$w_{rev} = \int_1^2 vdP + \Delta ke + \Delta pe$$



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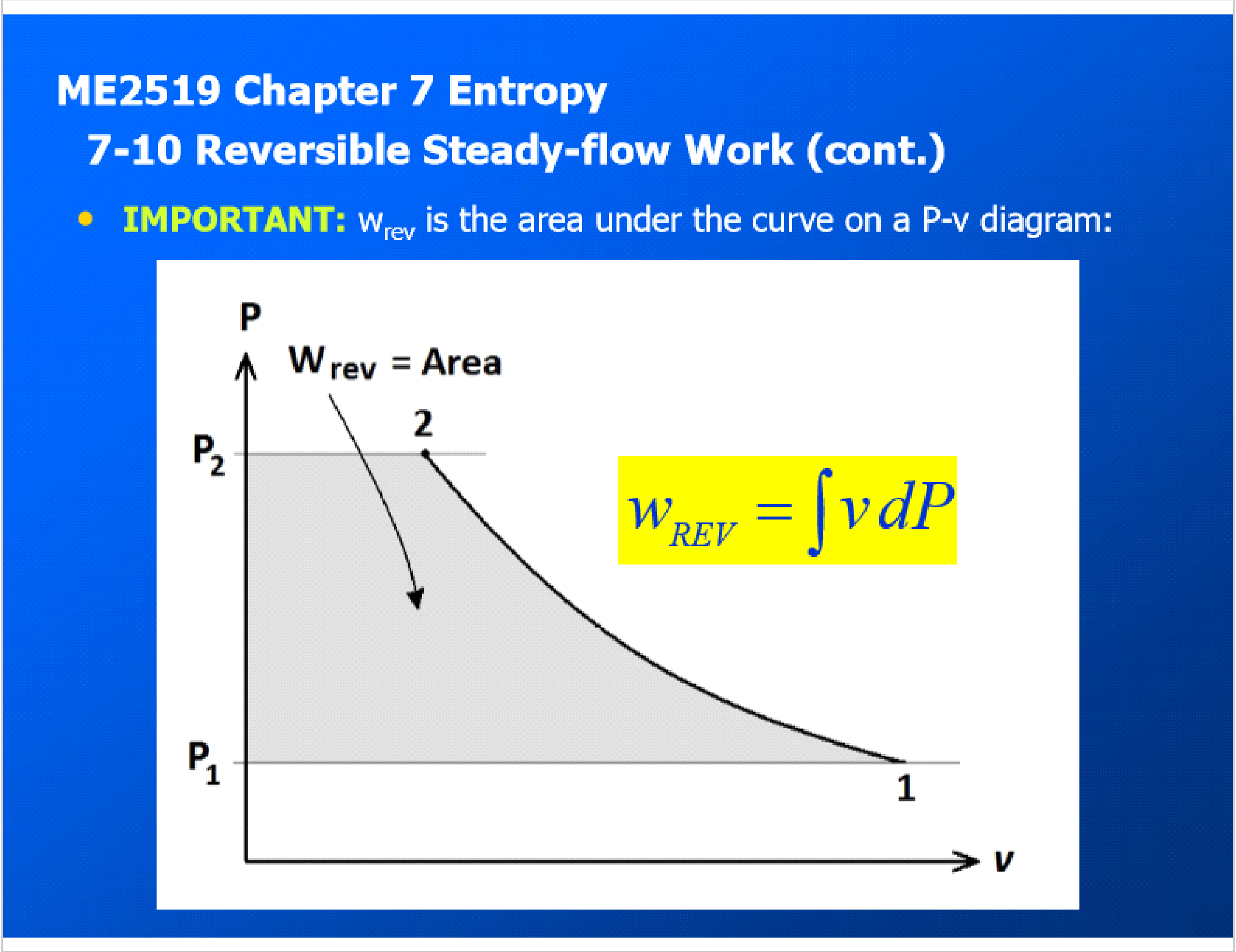
7-10 Reversible Steady-flow Work (cont.)

- **If flow through open system experiences no Δ ke or Δ pe (like pumps, turbines and compressors, but NOT nozzles and diffusers) then:**

$$w_{REV} = \int_{1}^{2} v dP$$

- **IMPORTANT:** w_{rev} varies directly with *v*, therefore more work required to compress gas (large *v*) than a liquid (small *v*):
- For same ṁ and ΔP:
  - w_{REV} of liquids (pumps) << w_{REV} of gases (compressors)
  - w_{REV} of liquids (hydraulic turbines) << w_{REV} of gases (gas turbines)
- If P of mass flow through open system = constant, then w_{REV} = 0.



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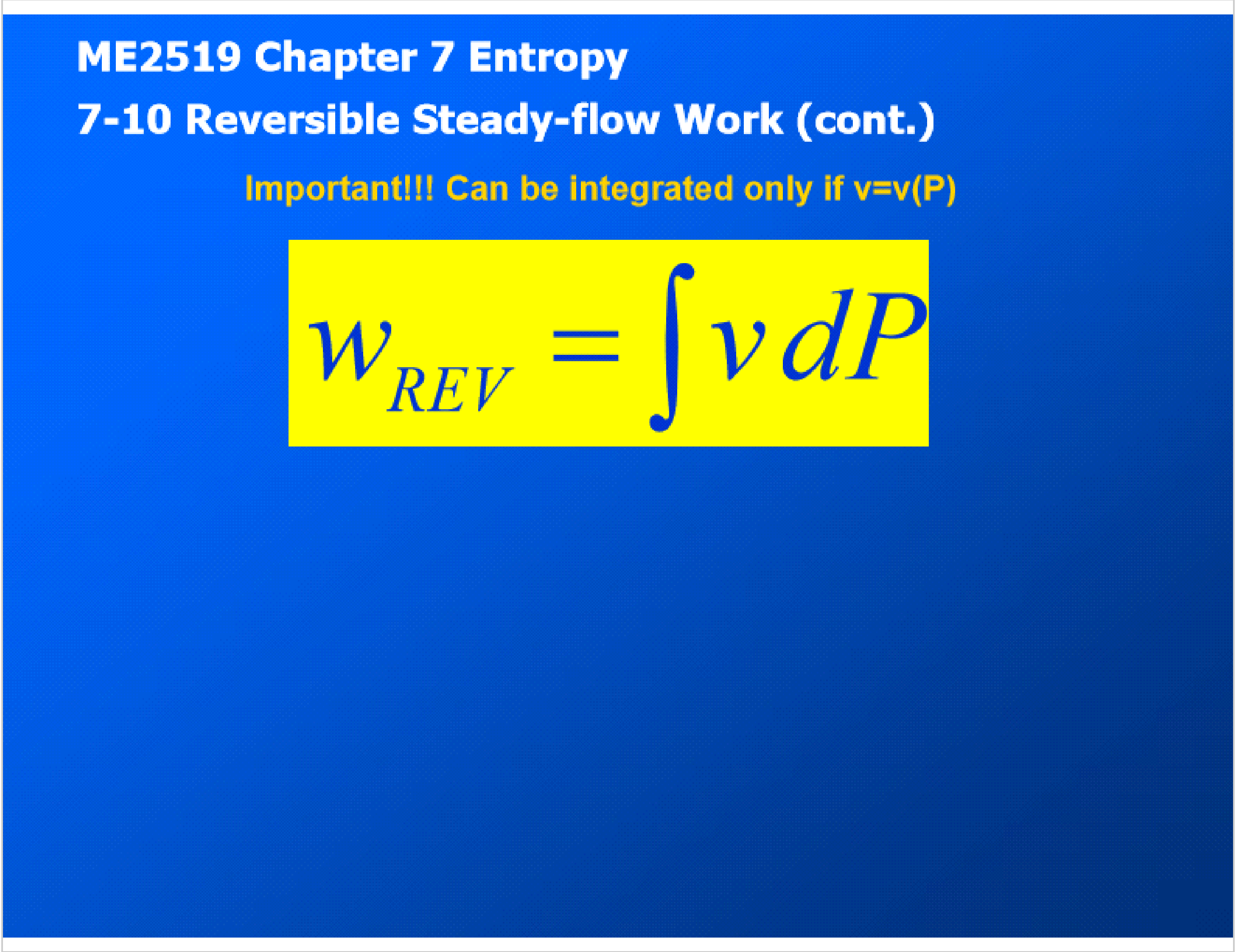
7-10 Reversible Steady-flow Work (cont.)

- **IMPORTANT:** w_{rev} is the area under the curve on a P-v diagram:

$$w_{REV} = \int v\,dP$$



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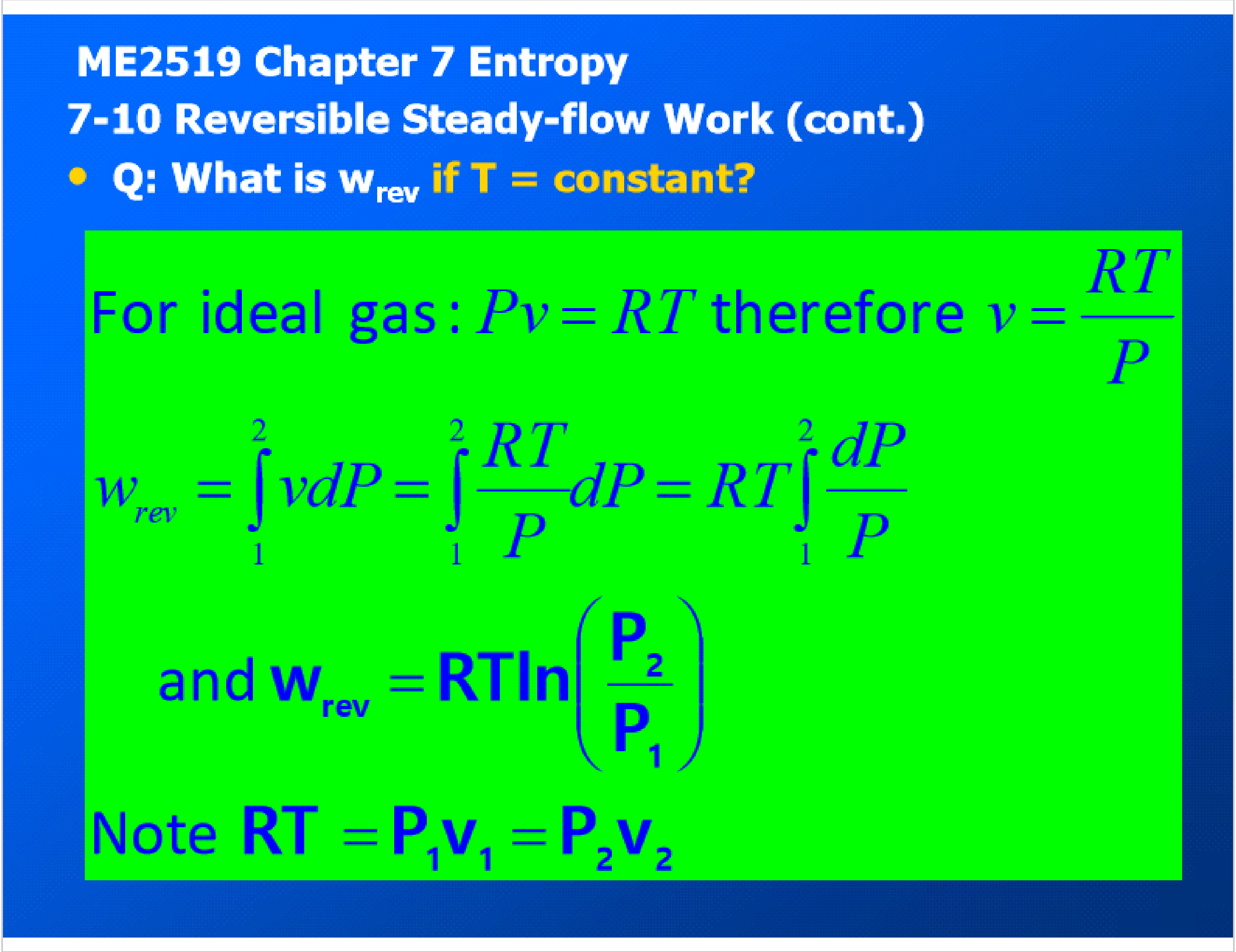
7-10 Reversible Steady-flow Work (cont.)

Important!!! Can be integrated only if v=v(P)

$$w_{REV} = \int v\,dP$$



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7-10 Reversible Steady-flow Work (cont.)

- Q: What is w_{rev} if T = constant?

For ideal gas: $Pv = RT$ therefore $v = \frac{RT}{P}$

$$w_{rev} = \int_1^2 v dP = \int_1^2 \frac{RT}{P} dP = RT \int_1^2 \frac{dP}{P}$$

and $\mathbf{w_{rev}} = \mathbf{RT\ln\left(\frac{P_2}{P_1}\right)}$

Note $\mathbf{RT = P_1 v_1 = P_2 v_2}$

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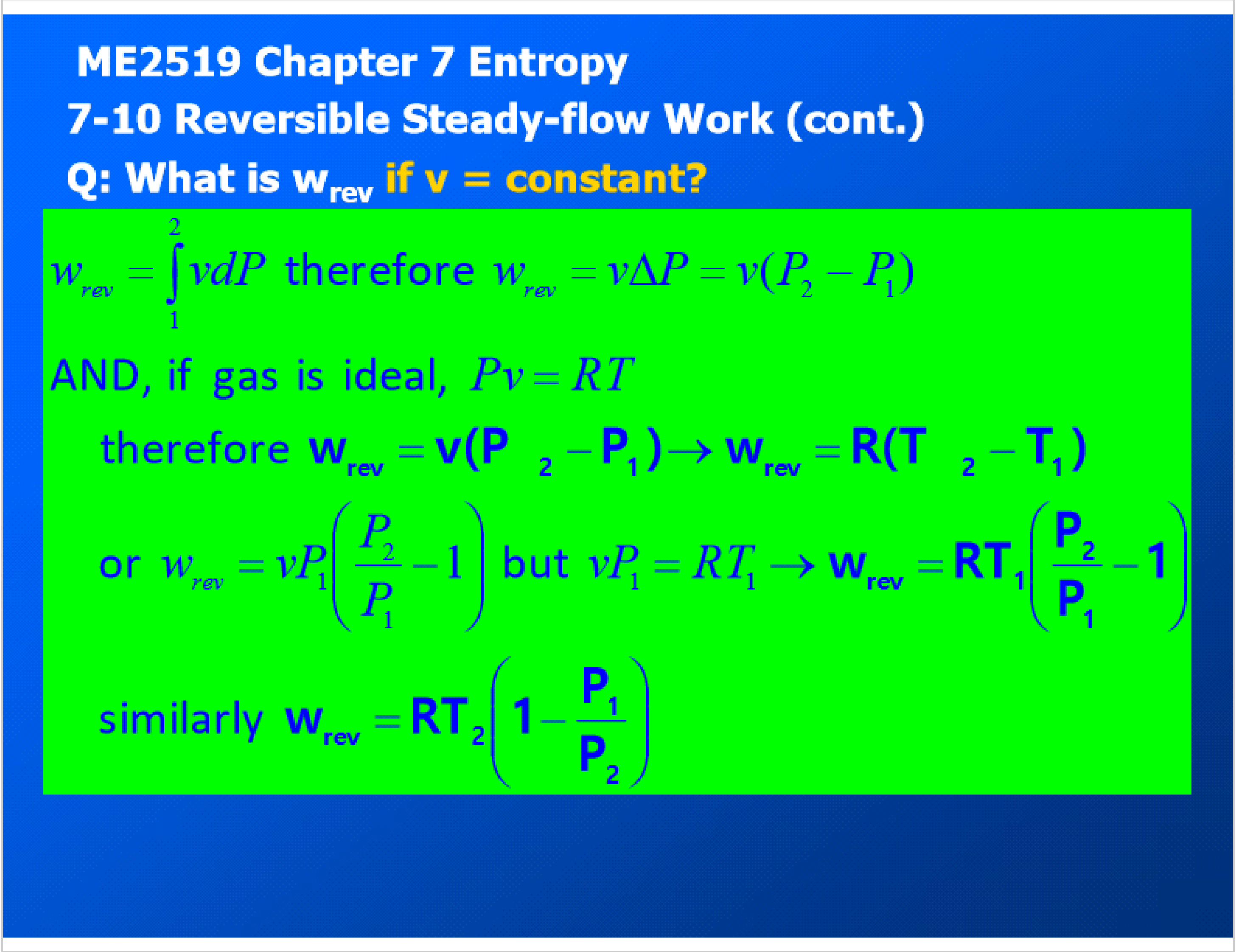
7-10 Reversible Steady-flow Work (cont.)

Q: What is w_{rev} if P = constant?

$w_{rev} = \int vdP$ therefore $\mathbf{w_{rev} = 0}$

AND, if gas is ideal, then $w_{rev} = 0$



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7-10 Reversible Steady-flow Work (cont.)

Q: What is w_{rev} if v = constant?

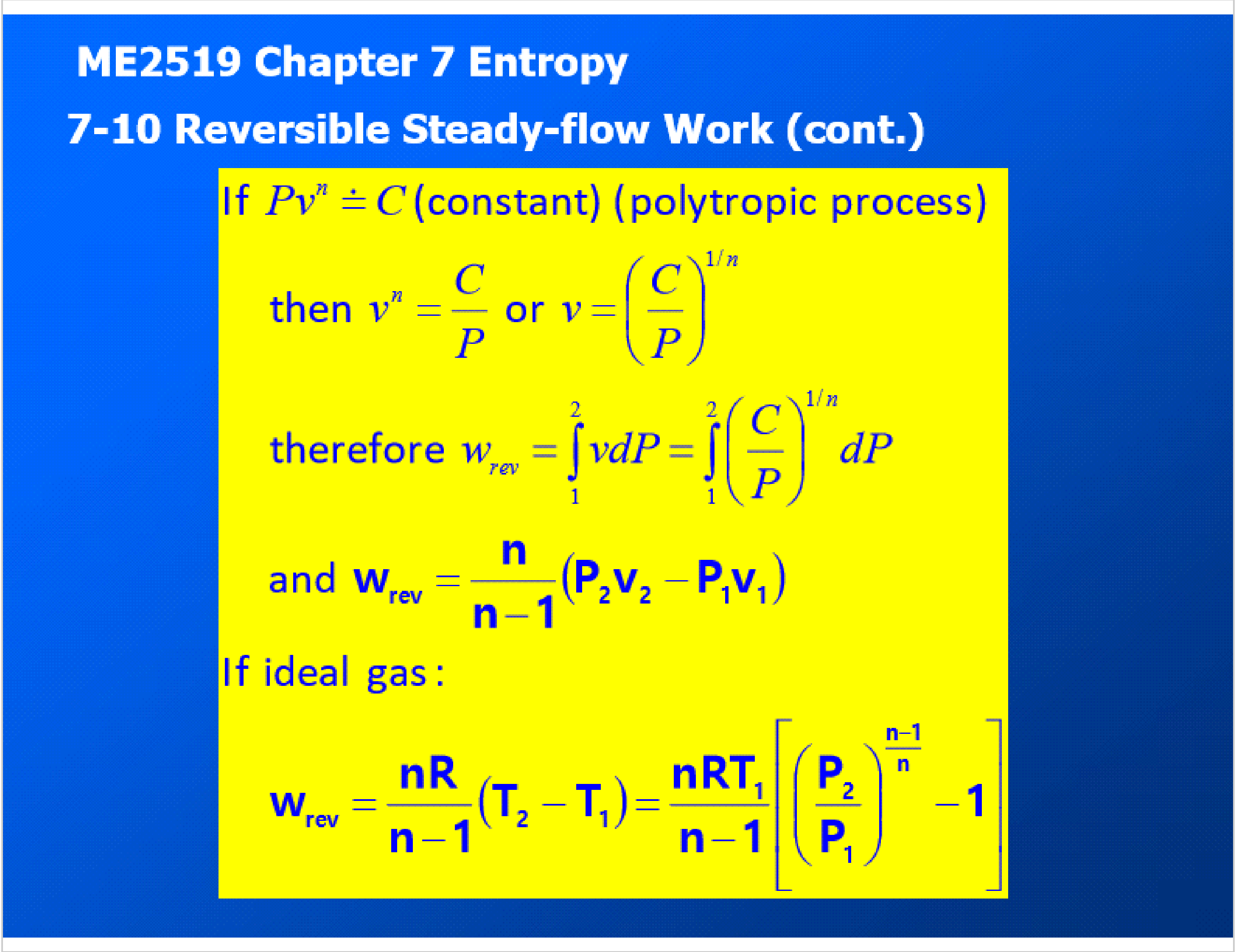
$w_{rev} = \int_1^2 v dP$ therefore $w_{rev} = v\Delta P = v(P_2 - P_1)$

AND, if gas is ideal, $Pv = RT$

therefore $\mathbf{w_{rev} = v(P_2 - P_1) \rightarrow w_{rev} = R(T_2 - T_1)}$

or $w_{rev} = vP_1\left(\frac{P_2}{P_1} - 1\right)$ but $vP_1 = RT_1 \rightarrow \mathbf{w_{rev} = RT_1\left(\frac{P_2}{P_1} - 1\right)}$

similarly $\mathbf{w_{rev} = RT_2\left(1 - \frac{P_1}{P_2}\right)}$



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7-10 Reversible Steady-flow Work (cont.)

If $Pv^n \doteq C$ (constant) (polytropic process)

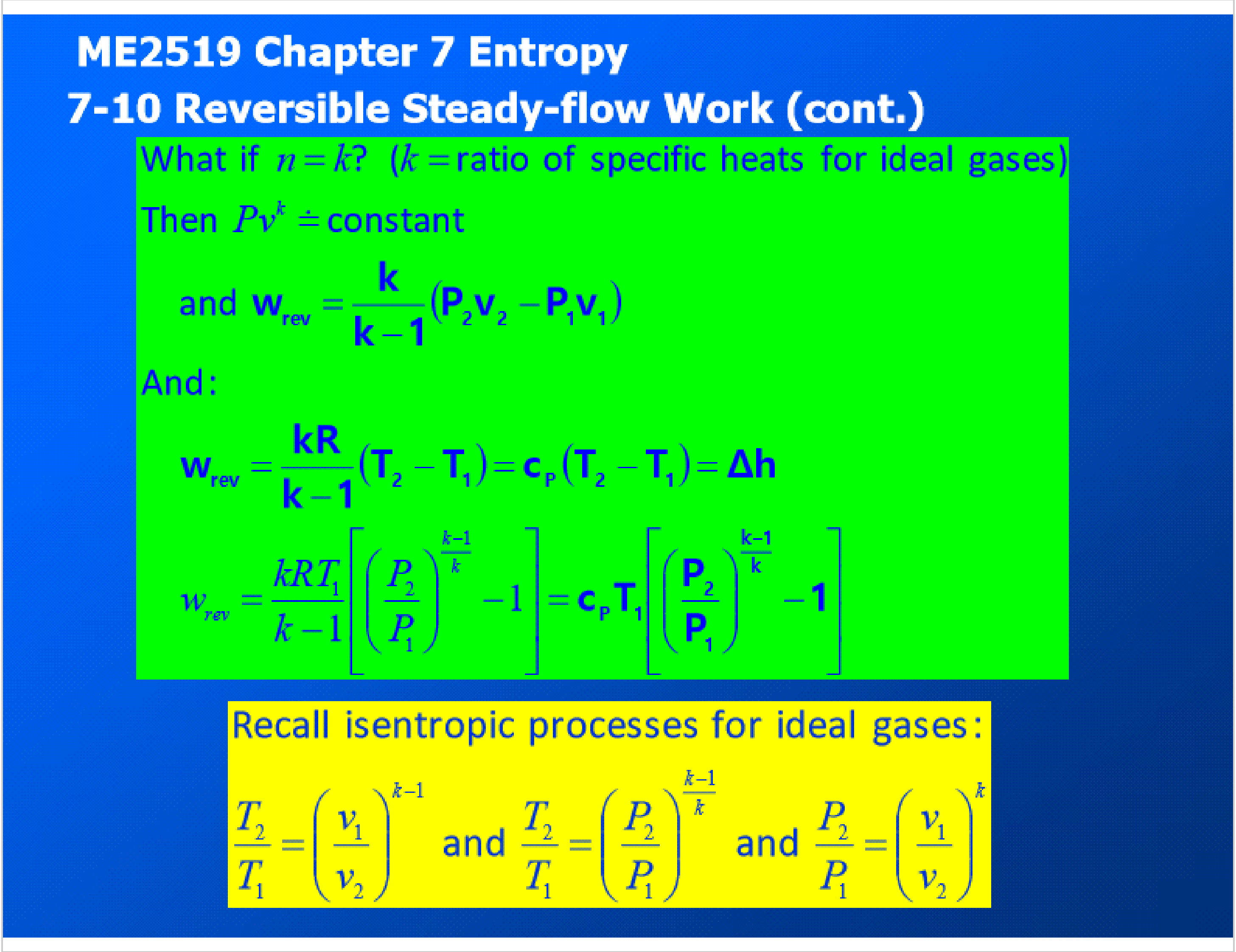
$$\text{then } v^n = \frac{C}{P} \text{ or } v = \left(\frac{C}{P}\right)^{1/n}$$

$$\text{therefore } w_{rev} = \int_1^2 v dP = \int_1^2 \left(\frac{C}{P}\right)^{1/n} dP$$

$$\text{and } \mathbf{w}_{\mathbf{rev}} = \frac{\mathbf{n}}{\mathbf{n}-\mathbf{1}}\left(\mathbf{P}_2\mathbf{v}_2 - \mathbf{P}_1\mathbf{v}_1\right)$$

If ideal gas:

$$\mathbf{w}_{\mathbf{rev}} = \frac{\mathbf{nR}}{\mathbf{n}-\mathbf{1}}\left(\mathbf{T}_2 - \mathbf{T}_1\right) = \frac{\mathbf{nRT}_1}{\mathbf{n}-\mathbf{1}}\left[\left(\frac{\mathbf{P}_2}{\mathbf{P}_1}\right)^{\frac{\mathbf{n}-\mathbf{1}}{\mathbf{n}}} - \mathbf{1}\right]$$



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7-10 Reversible Steady-flow Work (cont.)

What if $n = k$? ($k =$ ratio of specific heats for ideal gases)

Then $Pv^k \doteq \text{constant}$

$$\text{and } \mathbf{w_{rev}} = \frac{\mathbf{k}}{\mathbf{k-1}}(\mathbf{P_2 v_2 - P_1 v_1})$$

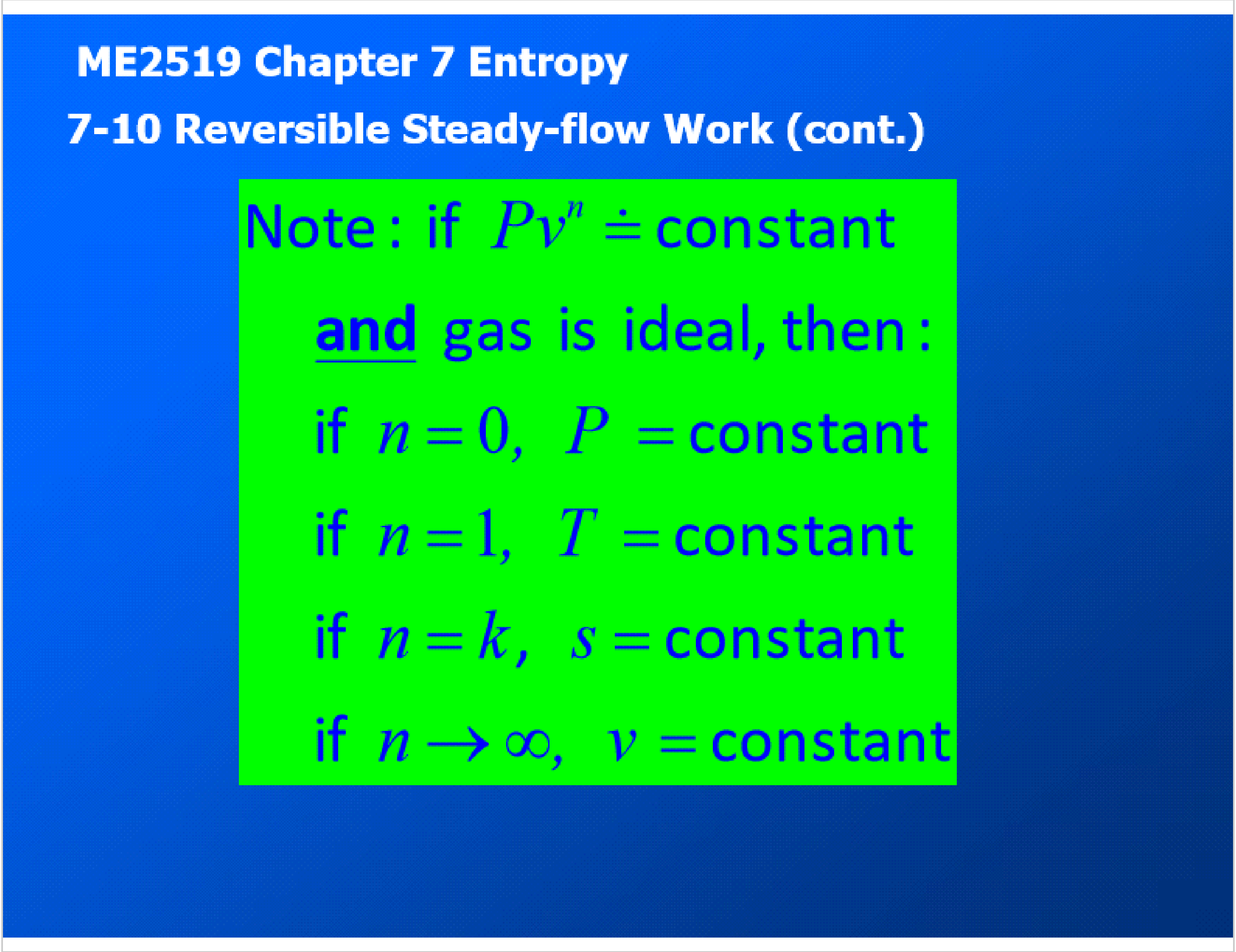
And:

$$\mathbf{w_{rev}} = \frac{\mathbf{kR}}{\mathbf{k-1}}(\mathbf{T_2 - T_1}) = \mathbf{c_P}(\mathbf{T_2 - T_1}) = \mathbf{\Delta h}$$

$$w_{rev} = \frac{kRT_1}{k-1}\left[\left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}} - 1\right] = \mathbf{c_P T_1}\left[\left(\frac{\mathbf{P_2}}{\mathbf{P_1}}\right)^{\frac{\mathbf{k-1}}{\mathbf{k}}} - \mathbf{1}\right]$$

Recall isentropic processes for ideal gases:

$$\frac{T_2}{T_1} = \left(\frac{v_1}{v_2}\right)^{k-1} \text{ and } \frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}} \text{ and } \frac{P_2}{P_1} = \left(\frac{v_1}{v_2}\right)^{k}$$



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7-10 Reversible Steady-flow Work (cont.)

Note: if $Pv^n \doteq$ constant

and gas is ideal, then:

if $n = 0$, P = constant

if $n = 1$, T = constant

if $n = k$, s = constant

if $n \to \infty$, v = constant

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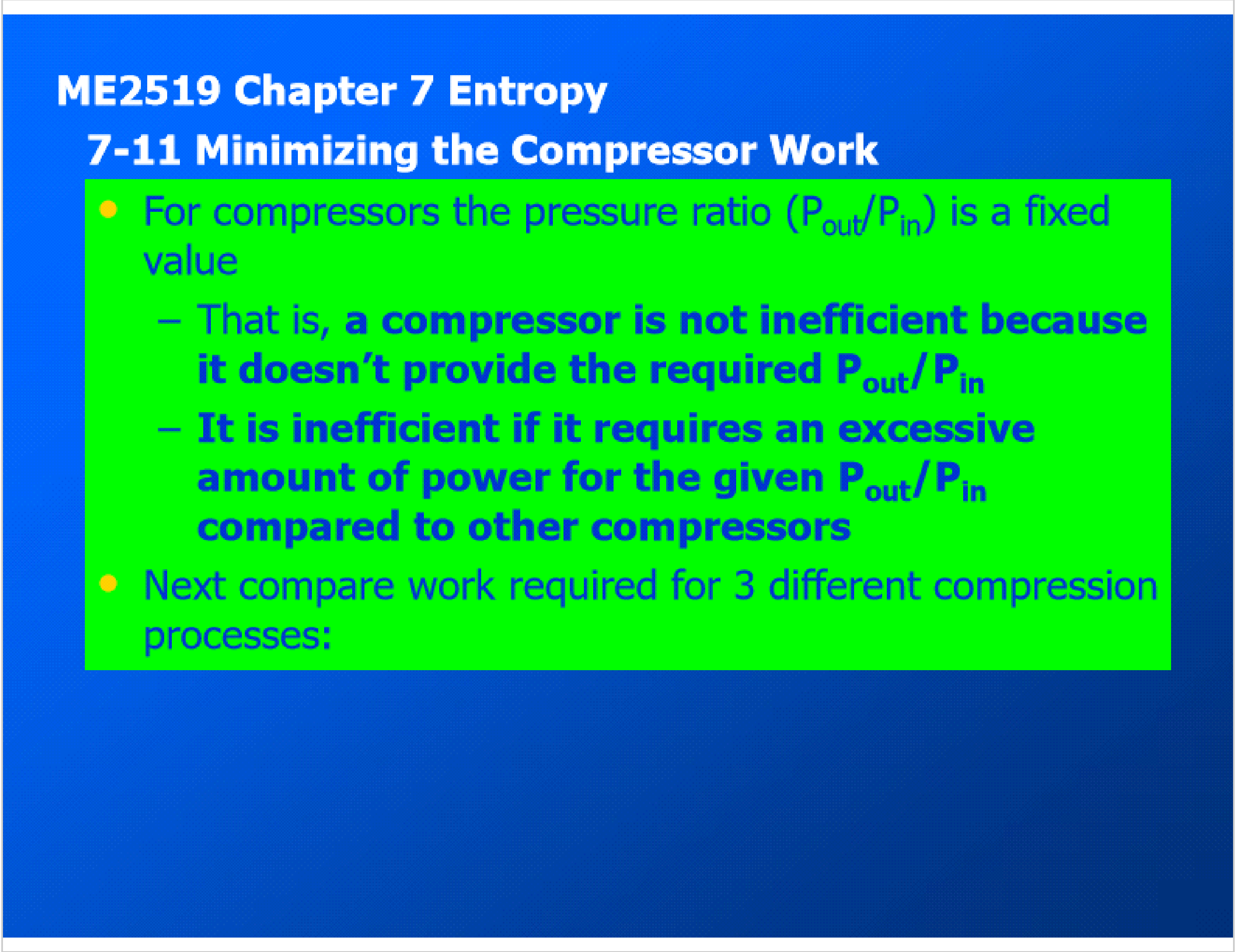
7-11 Minimizing the Compressor Work

$$w_{REV} = \int_1^2 v\,dP$$

- For a given ṁ and ΔP, w_{REV} required can be reduced if v is reduced:
- Done in practice by cooling the gas as it moves through a compressor
- Called **multistage compression with intercooling or just "compressor intercooling"**
- Intercooling only possible with a multistage compressor
- A multistage compressor has multiple rows of rotor and stator blades



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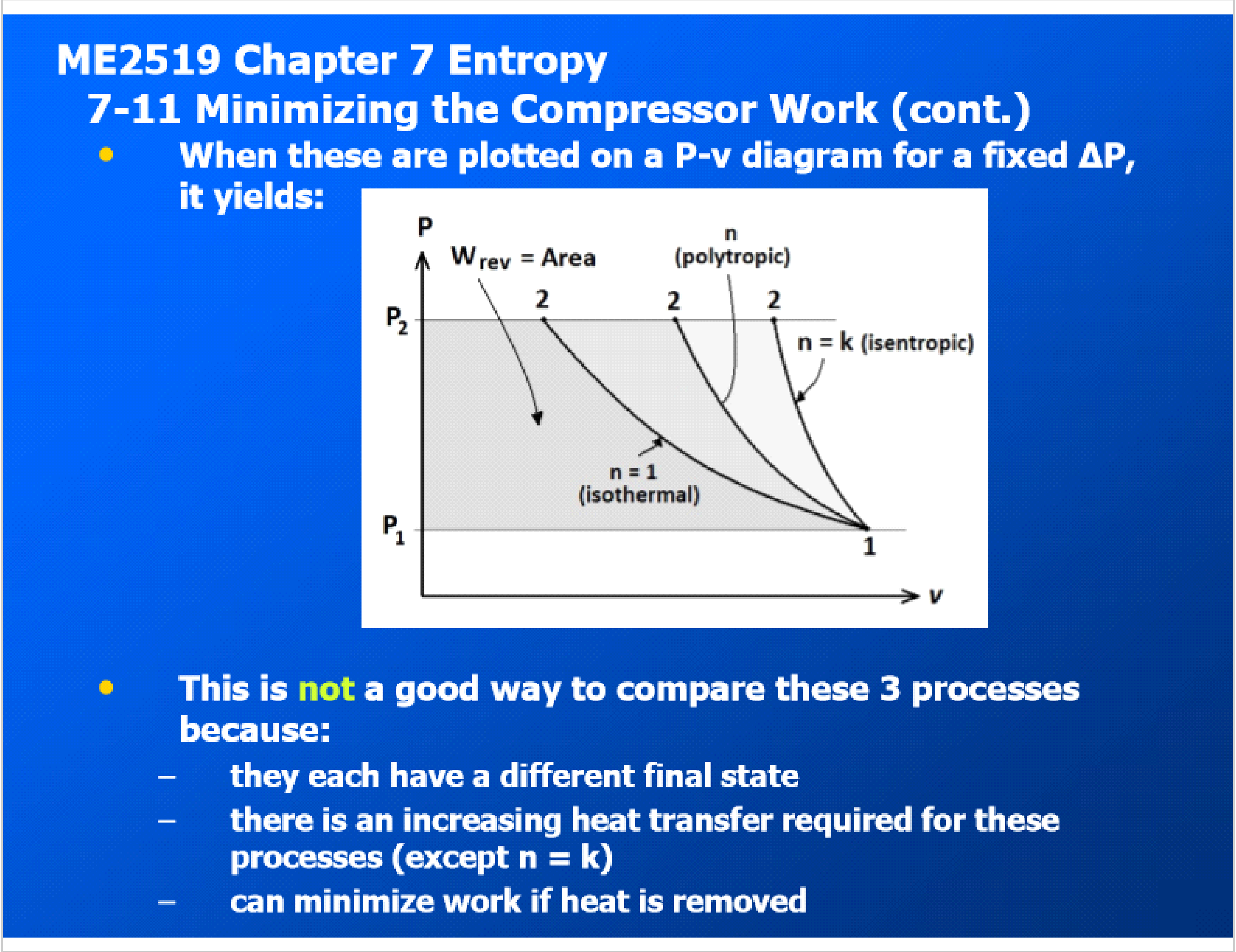
7-11 Minimizing the Compressor Work

- For compressors the pressure ratio (P_{out}/P_{in}) is a fixed value
  - That is, **a compressor is not inefficient because it doesn't provide the required P_{out}/P_{in}**
  - **It is inefficient if it requires an excessive amount of power for the given P_{out}/P_{in} compared to other compressors**
- Next compare work required for 3 different compression processes:



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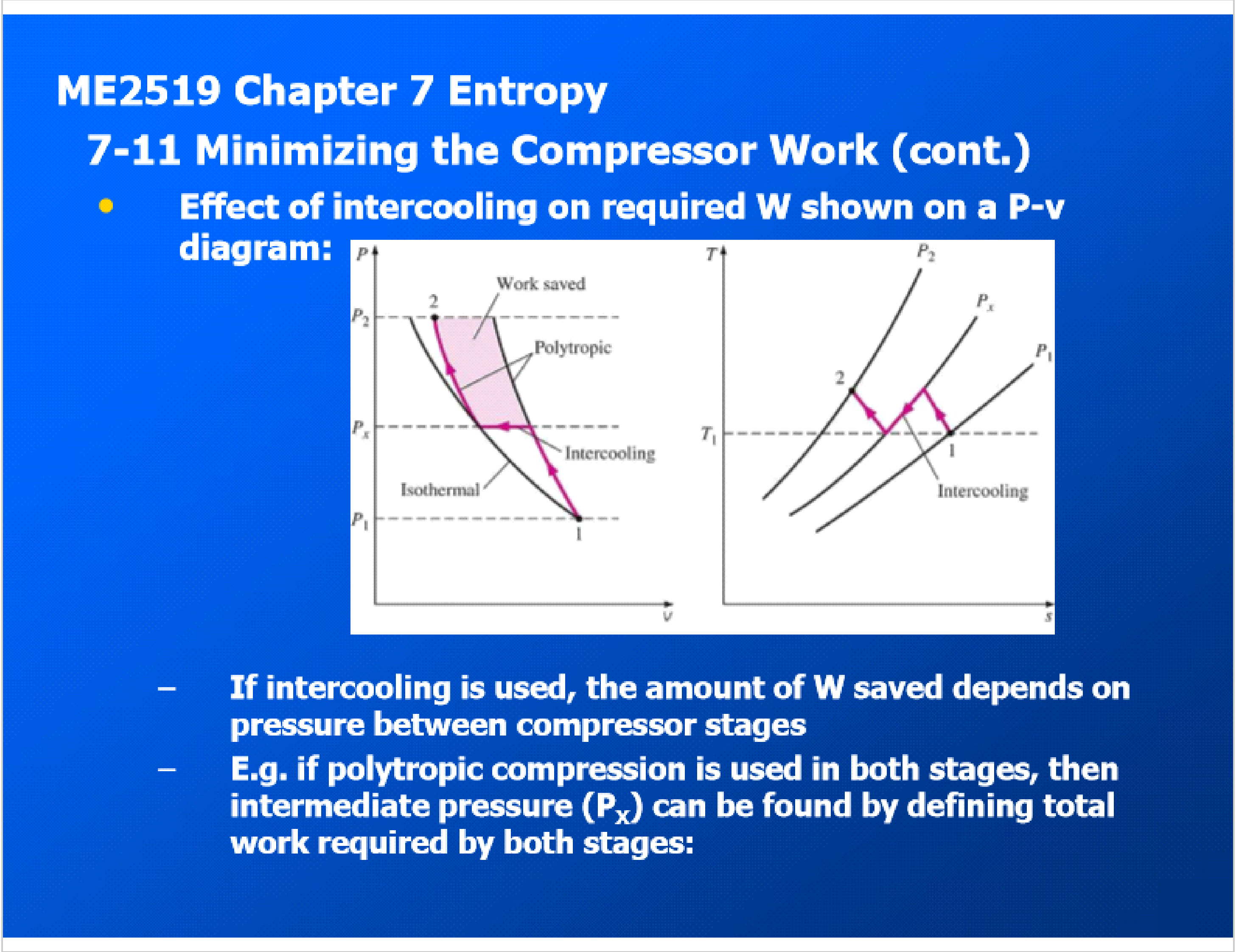
7-11 Minimizing the Compressor Work (cont.)

- When these are plotted on a P-v diagram for a fixed ΔP, it yields:

- This is not a good way to compare these 3 processes because:
  - they each have a different final state
  - there is an increasing heat transfer required for these processes (except n = k)
  - can minimize work if heat is removed



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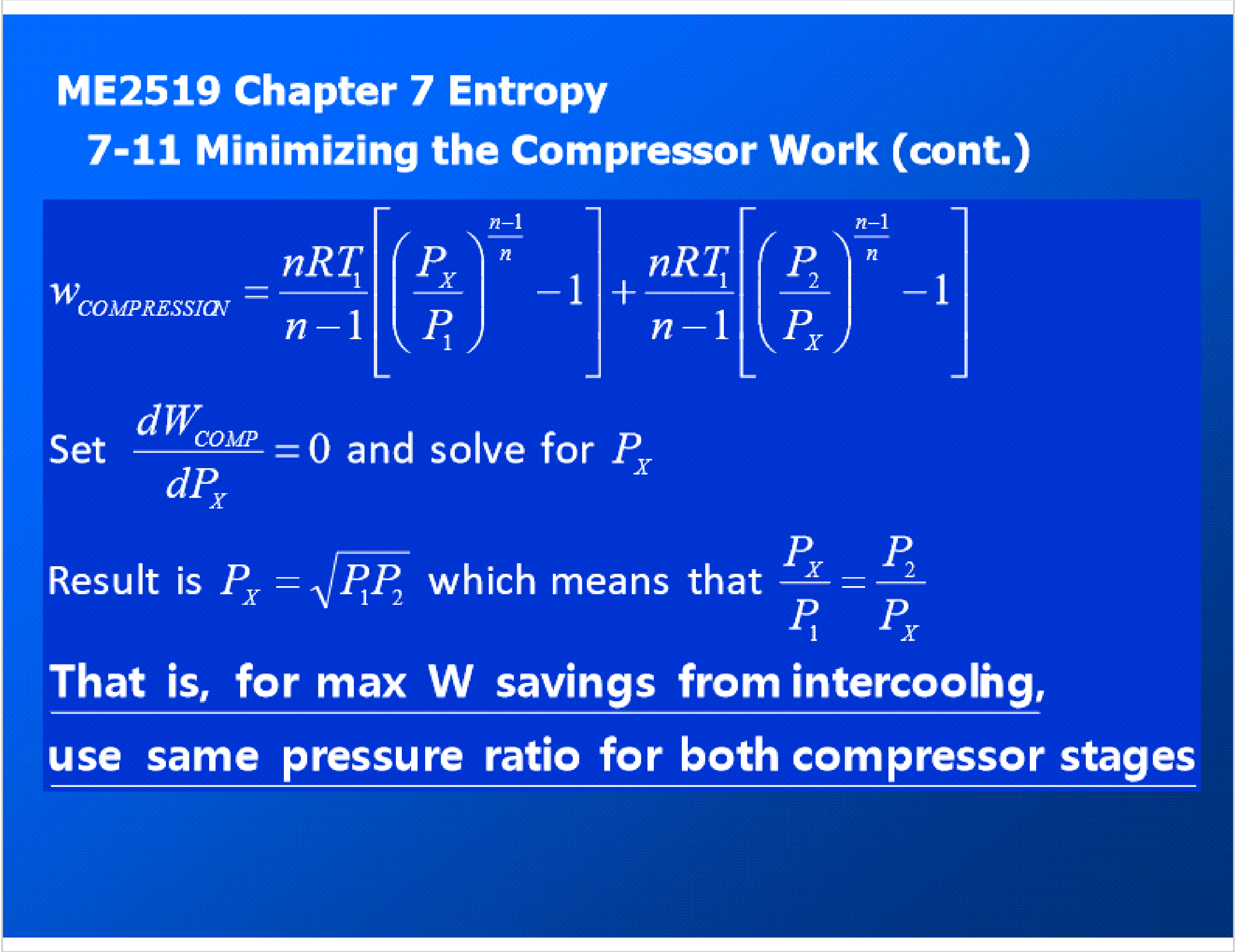
7-11 Minimizing the Compressor Work (cont.)

- **Effect of intercooling on required W shown on a P-v diagram:**

  - **If intercooling is used, the amount of W saved depends on pressure between compressor stages**
  - **E.g. if polytropic compression is used in both stages, then intermediate pressure (P_X) can be found by defining total work required by both stages:**



ME2519 Chapter 7 Entropy

7-11 Minimizing the Compressor Work (cont.)

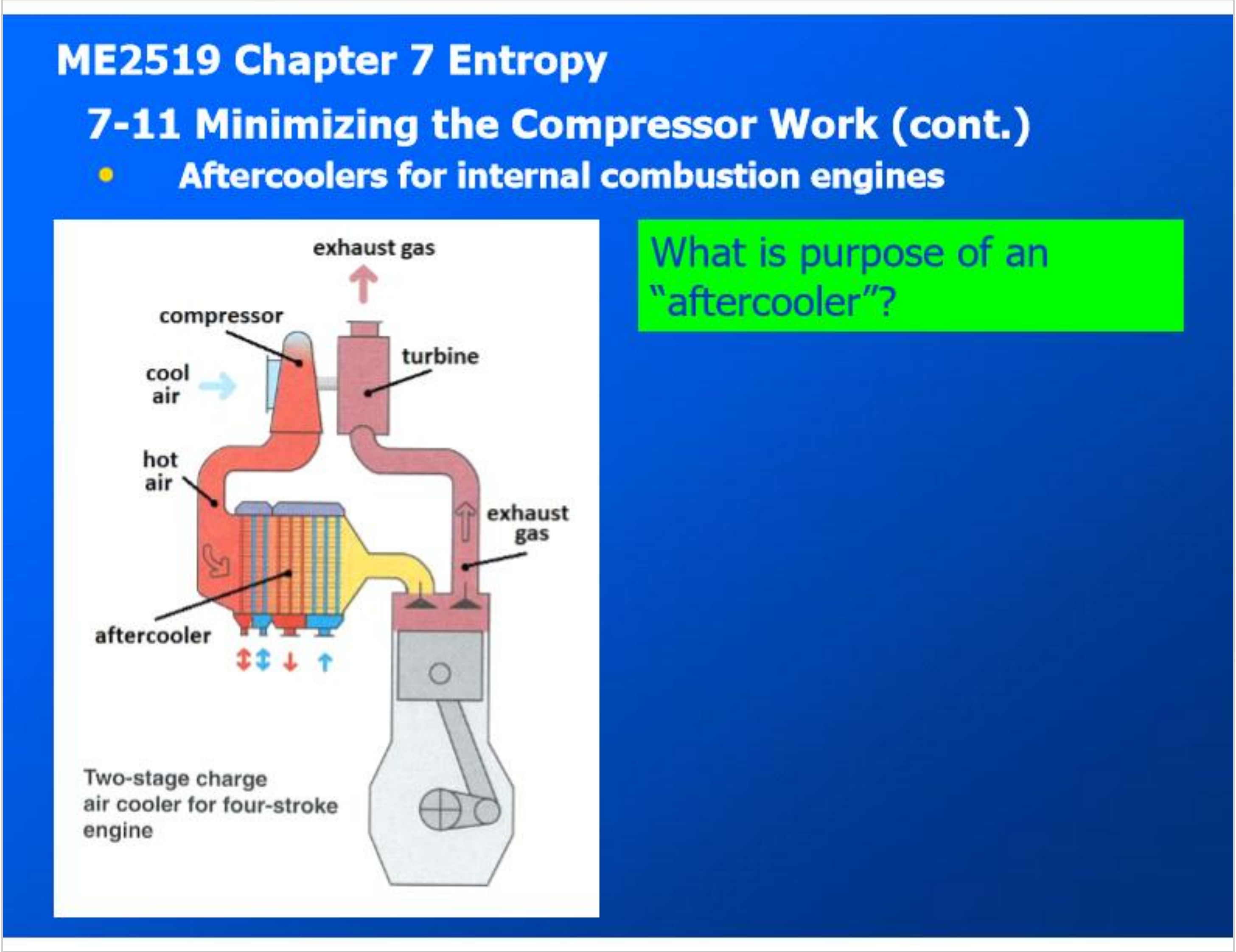
$$w_{COMPRESSION} = \frac{nRT_1}{n-1}\left[\left(\frac{P_X}{P_1}\right)^{\frac{n-1}{n}} - 1\right] + \frac{nRT_1}{n-1}\left[\left(\frac{P_2}{P_X}\right)^{\frac{n-1}{n}} - 1\right]$$

Set $\frac{dW_{COMP}}{dP_X} = 0$ and solve for P_X

Result is $P_X = \sqrt{P_1 P_2}$ which means that $\frac{P_X}{P_1} = \frac{P_2}{P_X}$

That is, for max W savings from intercooling,

use same pressure ratio for both compressor stages



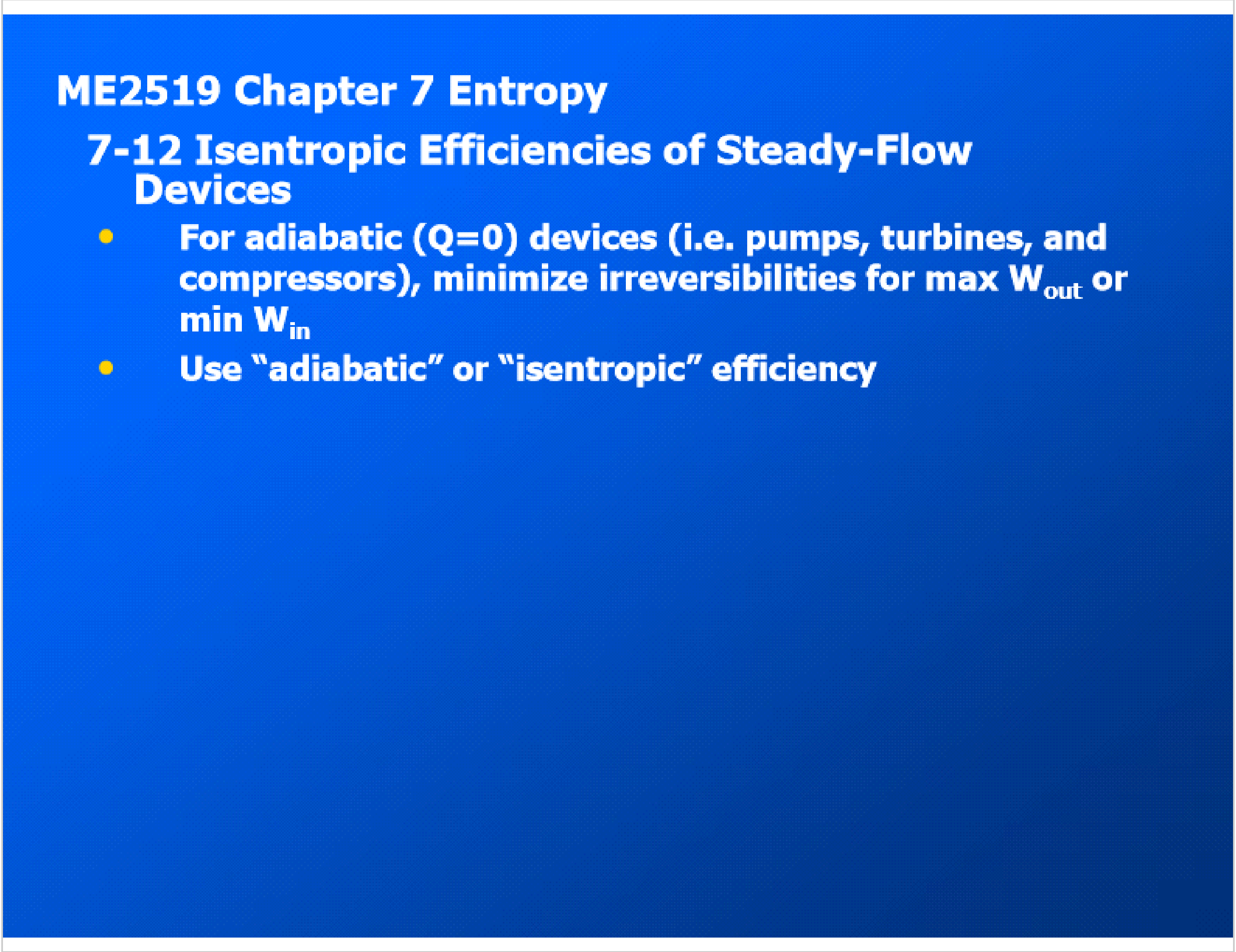
ME2519 Chapter 7 Entropy

7-11 Minimizing the Compressor Work (cont.)

- **Aftercoolers for internal combustion engines**

Two-stage charge air cooler for four-stroke engine

What is purpose of an "aftercooler"?



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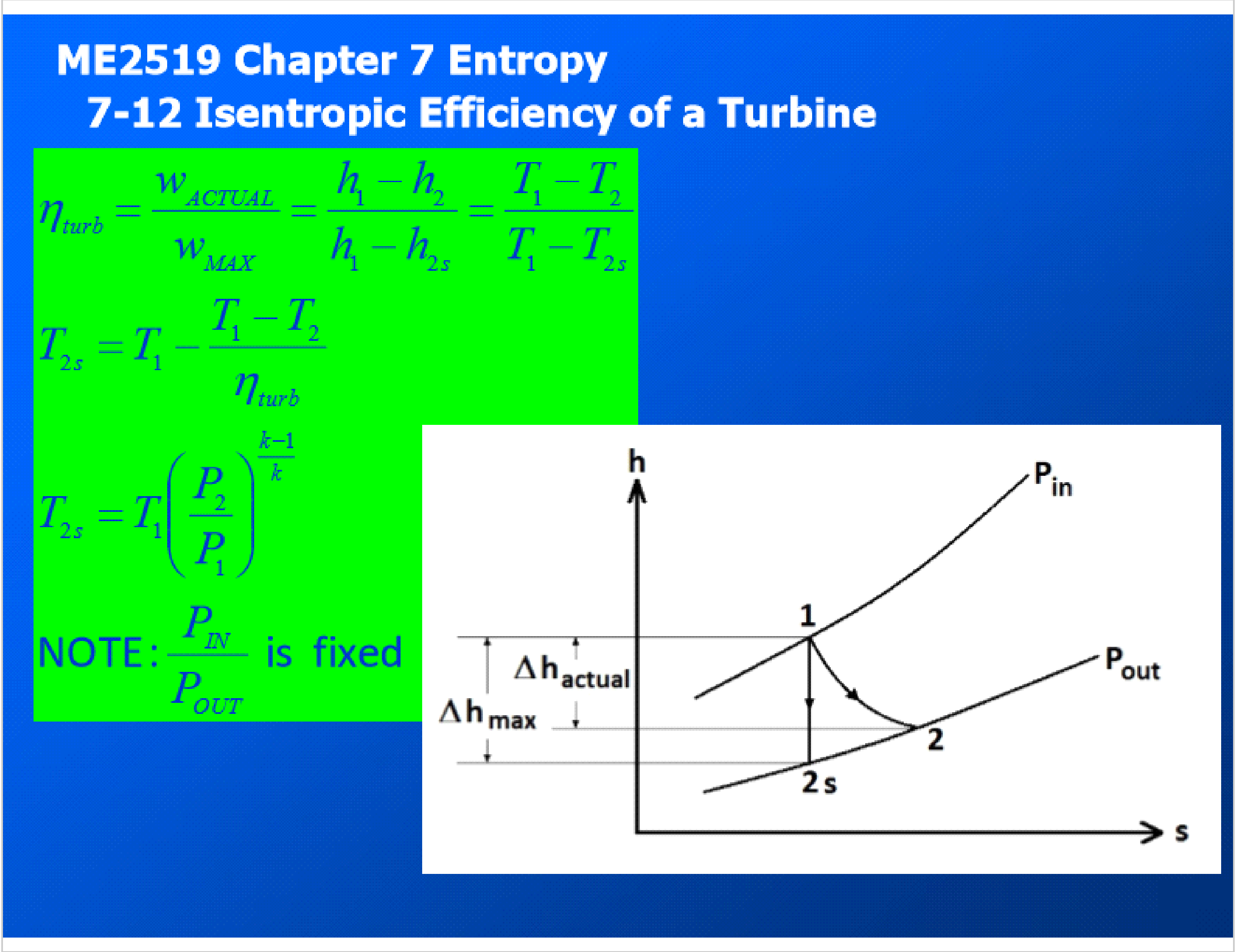
7-12 Isentropic Efficiencies of Steady-Flow Devices

- For adiabatic (Q=0) devices (i.e. pumps, turbines, and compressors), minimize irreversibilities for max W_{out} or min W_{in}
- Use “adiabatic” or “isentropic” efficiency



ME2519 Chapter 7 Entropy

7-12 Isentropic Efficiency of a Turbine

$$\eta_{turb} = \frac{w_{ACTUAL}}{w_{MAX}} = \frac{h_1 - h_2}{h_1 - h_{2s}} = \frac{T_1 - T_2}{T_1 - T_{2s}}$$

$$T_{2s} = T_1 - \frac{T_1 - T_2}{\eta_{turb}}$$

$$T_{2s} = T_1 \left(\frac{P_2}{P_1} \right)^{\frac{k-1}{k}}$$

$$\text{NOTE:} \frac{P_{IN}}{P_{OUT}} \text{ is fixed}$$

ME2519 Chapter 7 Entropy

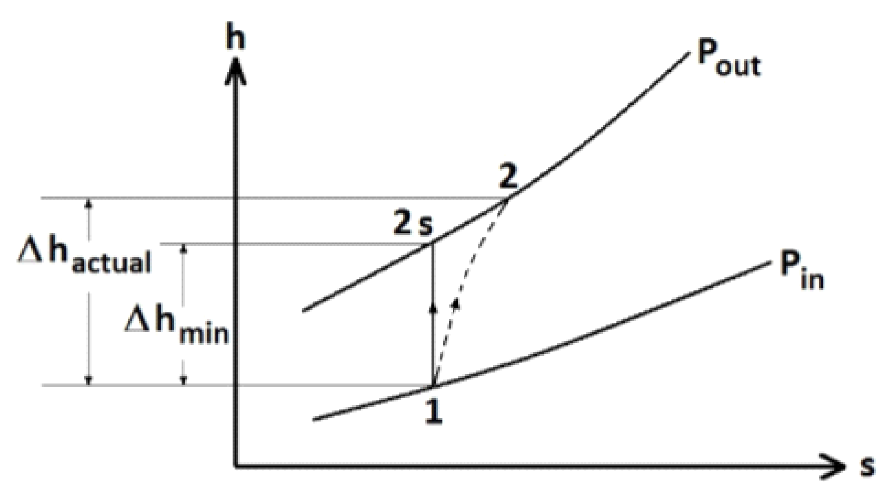
7-12 Isentropic Efficiency of a Compressor

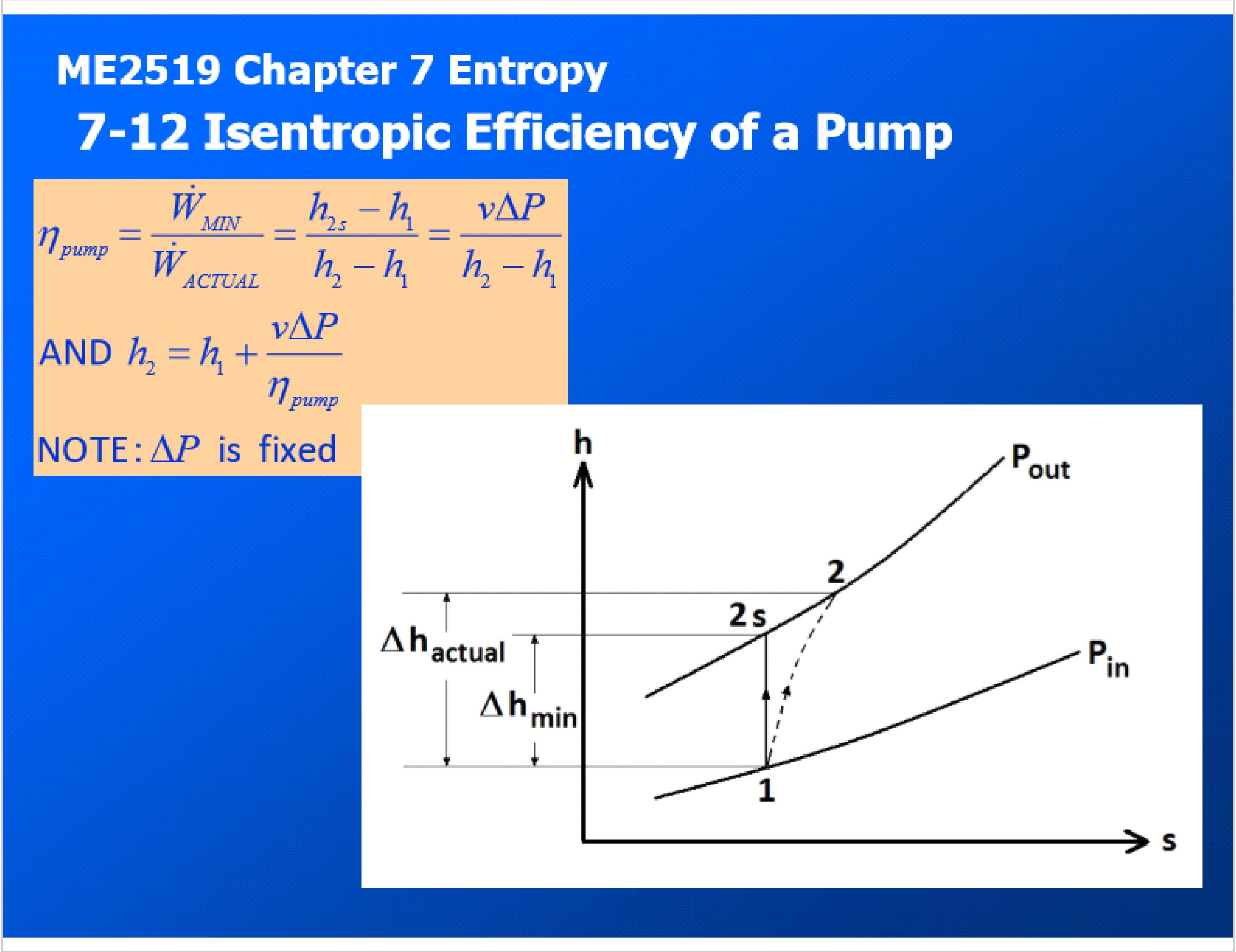
$$\eta_{compressor} = \frac{w_{MIN}}{w_{ACTUAL}} = \frac{h_1 - h_{2s}}{h_1 - h_2} = \frac{T_1 - T_{2s}}{T_1 - T_2}$$

$$T_{2s} = T_1 - \eta_{compressor}(T_1 - T_2)$$

$$T_{2s} = T_1\left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}}$$

$$\text{NOTE:}\ \frac{P_2}{P_1}\ \text{is fixed}$$





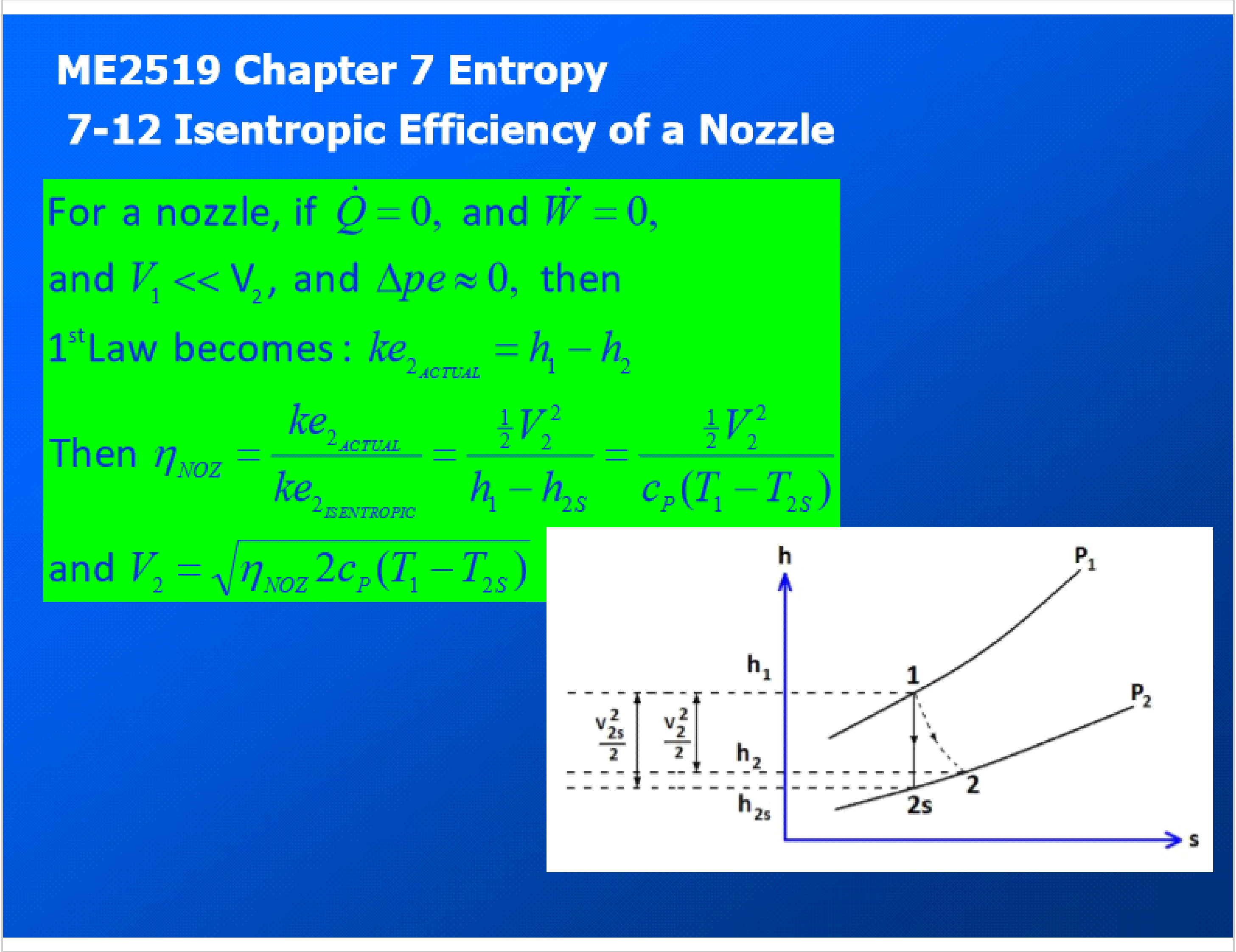
ME2519 Chapter 7 Entropy

7-12 Isentropic Efficiency of a Pump

$$\eta_{pump} = \frac{\dot{W}_{MIN}}{\dot{W}_{ACTUAL}} = \frac{h_{2s} - h_1}{h_2 - h_1} = \frac{v\Delta P}{h_2 - h_1}$$

AND $h_2 = h_1 + \dfrac{v\Delta P}{\eta_{pump}}$

NOTE: ΔP is fixed



ME2519 Chapter 7 Entropy

7-12 Isentropic Efficiency of a Nozzle

For a nozzle, if $\dot{Q}=0,$ and $\dot{W}=0,$

and $V_1 << V_2$, and $\Delta pe \approx 0$, then

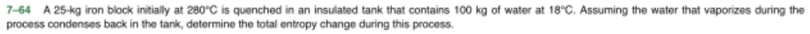
1st Law becomes: $ke_{2_{ACTUAL}} = h_1 - h_2$

Then $$\eta_{NOZ} = \frac{ke_{2_{ACTUAL}}}{ke_{2_{ISENTROPIC}}} = \frac{\frac{1}{2}V_2^2}{h_1 - h_{2S}} = \frac{\frac{1}{2}V_2^2}{c_P(T_1 - T_{2S})}$$

and $$V_2 = \sqrt{\eta_{NOZ} 2c_P(T_1 - T_{2S})}$$

Homework 7b

Tuesday, November 15, 2022 10:42 AM



7–64 A 25-kg iron block initially at 280°C is quenched in an insulated tank that contains 100 kg of water at 18°C. Assuming the water that vaporizes during the process condenses back in the tank, determine the total entropy change during this process.

1st law closed system:

$m_i = 25\text{ kg}$

$m_w = 100\text{ kg}$

$T_{1,i} = 280°C = 553\text{ K}$

$T_{1,w} = 18°C = 291\text{ K}$

$\Delta U = 0$

$\Delta U = \Delta U_i + \Delta U_w = m_i C_i \Delta T_i + m_w C_w \Delta T_w = 0$

$T_{2w} = T_{2i} = T_2$

$m_i C_i (T_2 - T_{1i}) = -m_w C_w (T_2 - T_{1w})$

$T_2 = \dfrac{m_i C_i T_{1i} + m_w C_w T_{1w}}{m_i C_i + m_w C_w}$ C_i and C_w from A-3

$T_2 = \dfrac{25\text{ kg}(.453)(553\text{ k}) + 100\text{ kg}(4.18)(291\text{ K})}{25(.453)\text{ kg} + 100\text{ kg}(4.18)} = 297.9\text{ K}$

$\Delta S_T = \Delta S_w + \Delta S_i$

$= m_i C_i \ln\frac{T_2}{T_{1i}} + m_w C_w \ln\frac{T_2}{T_{1w}} = 25\text{ kg}(.453)\ln\frac{297.9}{553} + 100\text{ kg}(4.18)\ln\frac{297.9}{291}$

$\boxed{\Delta S_T = 2.837\ \frac{\text{kJ}}{\text{K}}}$

7–75 Determine the final temperature when air is expanded isentropically from 1000 kPa and 477°C to 100 kPa in a piston–cylinder device.

$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}}$

$T_1 = 477°C = 750\text{ K}$

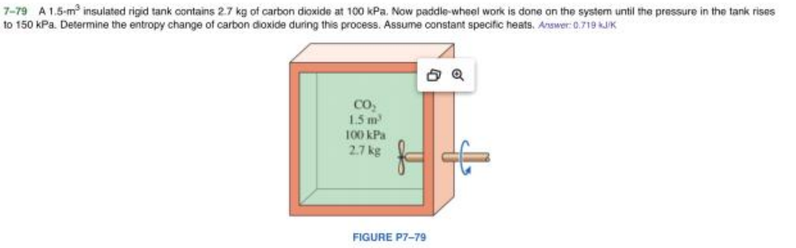
$P_1 = 1000\text{ kPa}$

$P_2 = 100\text{ kPa}$

$k = 1.387$

(air A-2 @~500°C)

$T_2 = 750\text{ K}\left(\frac{100}{1000}\right)^{\frac{1.387-1}{1.387}} = \boxed{394.5\text{ K or } 121.5°C}$



7–79 A 1.5-m³ insulated rigid tank contains 2.7 kg of carbon dioxide at 100 kPa. Now paddle-wheel work is done on the system until the pressure in the tank rises to 150 kPa. Determine the entropy change of carbon dioxide during this process. Assume constant specific heats. *Answer: 0.719 kJ/K*

FIGURE P7–79

$v = \frac{Vol}{m} = \frac{1.5\text{ m}^3}{2.7\text{ kg}} = .5556\ \frac{\text{m}^3}{\text{kg}}$

$Vol = 1.5\text{ m}^3$

$m = 2.7\text{ kg}$

$P_1 = 100\text{ kPa}$

$P_2 = 150\text{ kPa}$

$P_1 v = R T_1$

$T_1 = \frac{P_1 v}{R} = \frac{100\text{ kPa}(.5556\ \frac{\text{m}^3}{\text{kg}})}{.1889} = 294.1\text{ K}$

$\nwarrow$ A-2

$T_2 = \frac{P_2 v}{R} = \frac{150\text{ kPa}(.5556\text{ m}^3/\text{kg})}{.1889} = 441.2\text{ K}$

$T_{Avg} = \sim 350\text{ K}$ $C_v = .706\ \frac{\text{kJ}}{\text{kg}\cdot\text{K}}$ (A-2)

$\Delta S = m\left(C_v \ln\frac{T_2}{T_1} + \cancel{R \ln\frac{V_2}{V_1}}^{0}\right)$

$\Delta S = m\left(c_v \ln \frac{T_2}{T_1} + \cancel{R \ln \frac{V_2}{V_1}}^{\,0}\right)$

$\Delta S = 2.7\,\text{kg}\left(.706 \frac{kJ}{kg\cdot k} \ln \frac{441.7}{296.1}\right) = \boxed{.777 \frac{kJ}{K}}$

7–86 Air at 27°C and 100 kPa is contained in a piston–cylinder device. When the air is compressed adiabatically, a minimum work input of 1000 kJ will increase the pressure to 600 kPa. Assuming air has constant specific heats evaluated at 300 K, determine the mass of air in the device.

$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{K-1}{K}}$

$T_2 = (300\,k)\left(\frac{600}{100}\right)^{\frac{.4}{1.4}} = 500.6\,K$

$T_1 = 27°C : 300\,k$

$P_1 = 100\,kPa$

$P_2 = 600\,kPa$

$W_{in} = 1000\,kJ$

1st Law closed system:

$\Delta U = W_{in}$

$\Delta U = m c_v (T_2 - T_1) = W_{in}$

$m = \frac{W_{in}}{c_v (T_2 - T_1)} = \frac{1000\,kJ}{.718\ (500.6 - 300)\,k} = \boxed{6.943\,kg}$

A-2

7–101 Calculate the work produced, in kJ/kg, for the reversible steady-flow process 1–3 shown in Fig. P7–101.

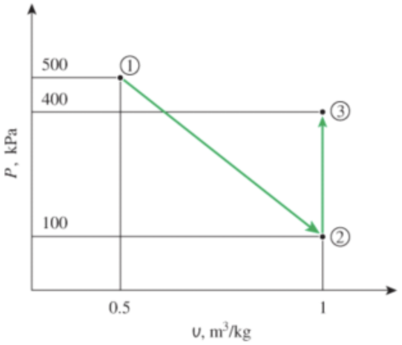


FIGURE P7–101

$W_{rev,SSSF} = \int v\,dP = v_{avg}\,\Delta P$

$1 \to 2: \frac{1 + .5}{2} \frac{m^3}{kg} (100 - 500)\,kPa = -300 \frac{kJ}{kg}$

$2 \to 3: 1 \frac{m^3}{kg} (400 - 100)\,kPa = 300 \frac{kJ}{kg}$

$W_{13} = W_{23} + W_{12} = -300 + 300 = \boxed{0}$

7–104 Saturated water vapor at 150°C is compressed in a reversible steady-flow device to 1000 kPa while its specific volume remains constant. Determine the work required in kJ/kg.

$W_{rev} = \int_1^2 v\,dP$

$W_{rev} = v(P_2 - P_1)$

$T = 150\,°C$

$x_1 = 1$

$P_2 = 1000\,kPa$

$v = const.$

A-4:

$v = .39248\,m^3/kg$

$P_1 = 476.16\,kPa$

$W_{rev} = .39248 \frac{m^3}{kg} (1000\,kPa - 476.16\,kPa)$

$\boxed{W_{rev} = 205.6 \frac{kJ}{kg}}$

7–106 Water enters the pump of a steam power plant as saturated liquid at 20 kPa at a rate of 45 kg/s and exits at 6 MPa. Neglecting the changes in kinetic potential energies and assuming the process to be reversible, determine the power input to the pump.

$v = .001017\,m^3$

$P_1 = 20\,kPa$

7–106 Water enters the pump of a steam power plant as saturated liquid at 20 kPa at a rate of 45 kg/s and exits at 6 MPa. Neglecting the changes in kinetic potential energies and assuming the process to be reversible, determine the power input to the pump.

$v_f = .001017 \ \frac{m^3}{kg}$

$P_1 = 20 kPa$
$\dot{m} = 45 \ kg/s$
$P_2 = 6 \ MPa$
$x_1 = 0$

$\dot{W}_{rev,SSSF} : \ \dot{m} \ w_{rev,SSSF}$

$= \dot{m} v \Delta P = \dot{m} v (P_2 - P_1)$

$\dot{W} = 45 \ kg/s \ (.001017 \ \frac{m^3}{kg})(6{,}000 \ kPa - 20 \ kPa)$

$\boxed{\dot{W} = 272.67 \ kW}$

7–116 Argon gas enters an adiabatic turbine at 800°C and 1.5 MPa at a rate of 80 kg/min and exhausts at 200 kPa. If the power output of the turbine is 370 kW, determine the isentropic efficiency of the turbine.

$T_1 = 800°C = 1073 K$
$P_1 = 1.5 \ MPa$
$\dot{m} = 80 \ kg/min = 480 \ kg/s$
$\dot{W}_{out} = 370 \ kW$
$P_2 = 200 kPa$

SSSF 1st law;

$0 = -W_{out} + \dot{m}(h_1 - h_2)$

$W_{out} : \ \dot{m} \ C_p (T_1 - T_2)$

$\frac{T_2}{T_1} : \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}}$

$T_2 = 1073K \left(\frac{200}{1500}\right)^{\frac{1.667-1}{1.667}} = 479.1K$

$W_{out} = 240 \ kg/s \ (.5203 \ \frac{kJ}{kg \cdot K} (1073 - 479.1) K$

A-2

$\dot{W}_{out} = 412 \ kW$

$\eta_{is,e} = \frac{370}{412} = \boxed{.898}$

7–119 Steam at 4 MPa and 350°C is expanded in an adiabatic turbine to 120 kPa. What is the isentropic efficiency of this turbine if the steam is exhausted as a saturated vapor?

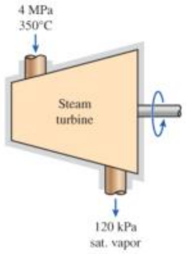


FIGURE P7–119

$P_1 = 4 \ MPa$
$T_1 = 350°C + 623K$
$P_2 = 120 kPa$
$x_2 = 1$

A-6: $s_1 = 6.5843 \ kJ/kg \cdot k$
$h_1 = 3093.7 \ kJ/kg$

A-5: $h_2 = h_g = 2675.6 \ \frac{kJ}{kg} + \frac{120 - 101.325}{125 - 101.325} (2684.9 - 2675.6) = 2682.96 \ \frac{kJ}{kg}$

$s_{f \ 120kPa} = 1.3069 + \frac{120 - 101.325}{125 - 101.325} (1.3741 - 1.3069) = 1.36$

$s_{g \ 120kPa} = 7.3545 + \frac{120 - 101.325}{125 - 101.325} (7.2841 - 7.3545) = 7.299$

$s_f < s_2 < s_g \rightarrow$ sat. mix

$h_{f \ 120kPa} = 419.06 + .7888 (444.36 - 419.06) = 439.$

$h_{g \ 120kPa} = 2675.6 + .7888 (2684.9 - 439.0) = 2682.9$

$h_{2s} = 439 + \frac{6.5843 - 1.36}{7.299 - 1.36} (2682.9 - 439) = 2412.9$

1st law SSSF:

$0 = -\dot{W}_{out} + \dot{m}(h_1 - h_{2s})$

$\dot{W}_{out} = \dot{m}(h_1 - h_{2s})$

$\eta_{isen} = \frac{\dot{W}_{out,act}}{\dot{W}_{out\ isen}} = \frac{\dot{m}(h_1 - h_2)}{\dot{m}(h_1 - h_{2s})}$

$= \frac{3093.3 - 2682.94}{3093.3 - 2412.9}$

$\boxed{\eta_{isen} = .603}$

7–124 The adiabatic compressor of a refrigeration system compresses saturated R-134a vapor at 0°C to 600 kPa and 50°C. What is the isentropic efficiency of this compressor?

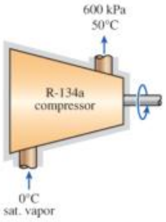


FIGURE P7–124

$\eta_{isen} = \frac{W_{in\ isen}}{W_{in\ act.}} = \frac{h_{2s} - h_1}{h_2 - h_1}$

$T_1 = 0°C = 273K$

$x_1 = 1$

$T_2 = 50°C = 323K$

$P_2 = 600\ kPa$

A-11:

$h_1 = h_g = 250.5$

$s_1 = s_g = .93158$

A-13:

$h_2 = 290.3$

$s_2 = s_1$

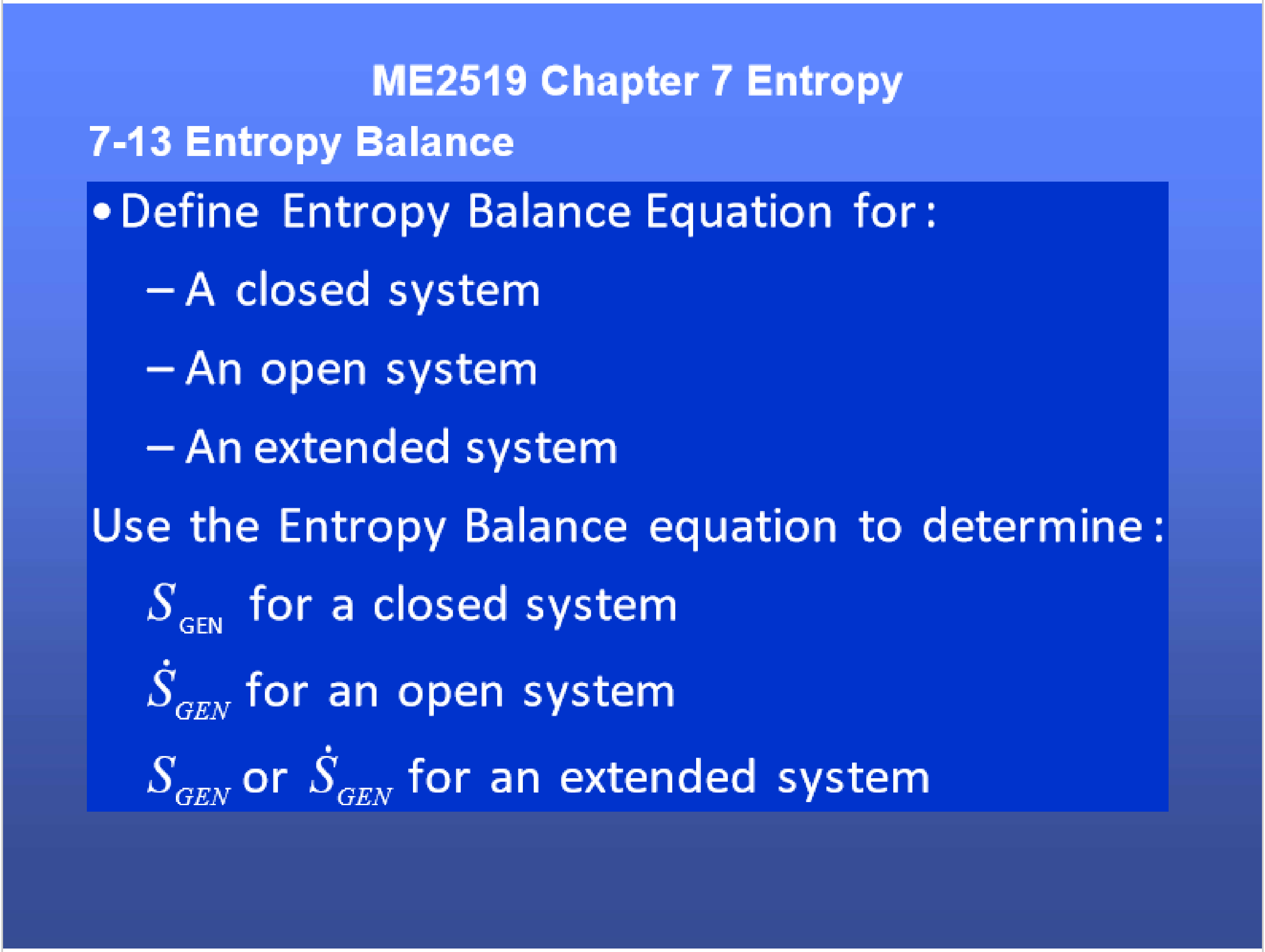
$h_{2s} = 262.46 + \frac{.93158 - .922}{.95 - .922}(270.83 - 262.46) = 265.32$

$\eta_{isen} = \frac{265.32 - 250.5}{290.3 - 250.5} = \boxed{.372}$

Entropy Balance

Wednesday, November 16, 2022 10:03 AM

PDF+Slides +7-13+dt...



ME2519 Chapter 7 Entropy

7-13 Entropy Balance

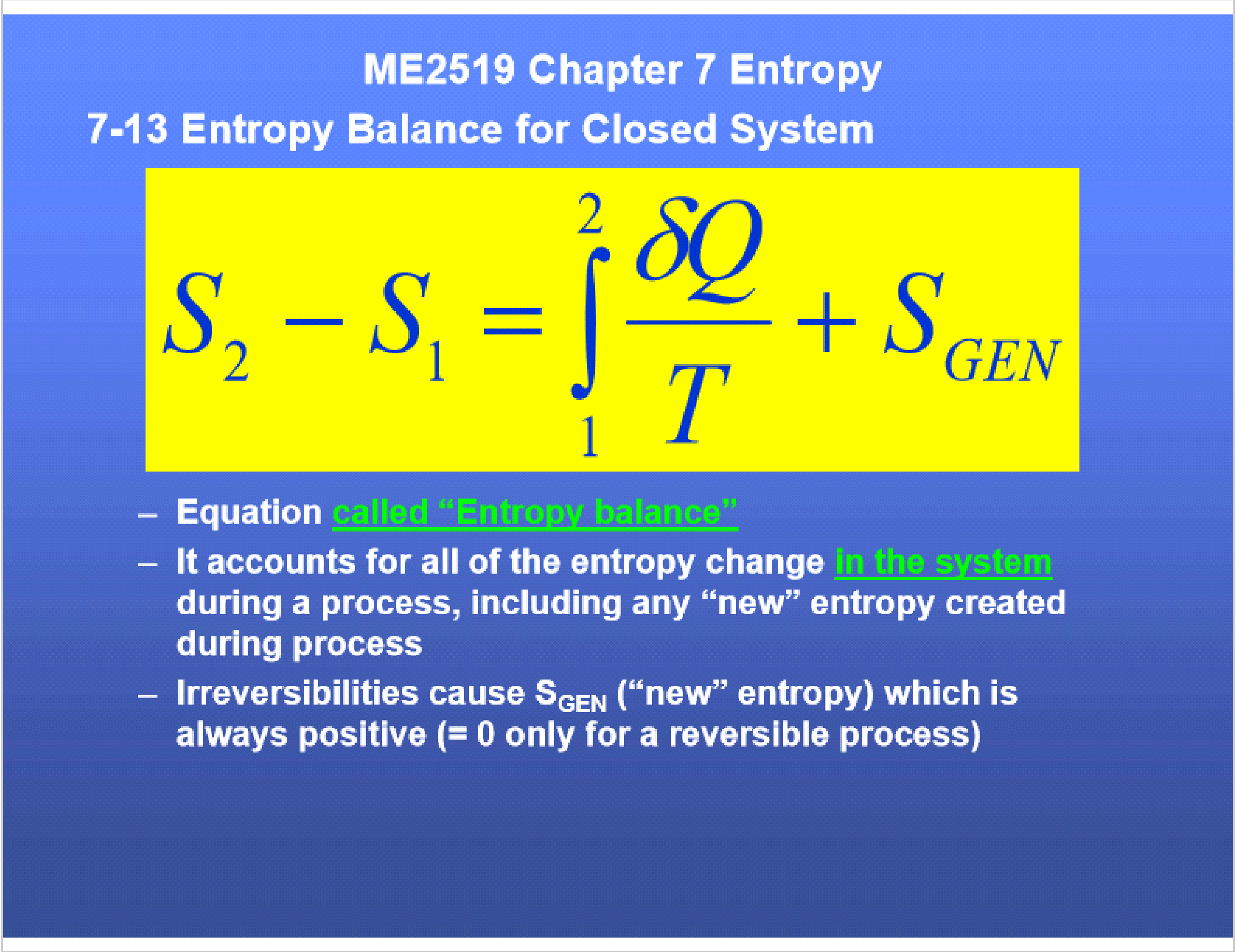
- Define Entropy Balance Equation for:
  - A closed system
  - An open system
  - An extended system

Use the Entropy Balance equation to determine:

S_{GEN} for a closed system

$\dot{S}_{GEN}$ for an open system

S_{GEN} or $\dot{S}_{GEN}$ for an extended system

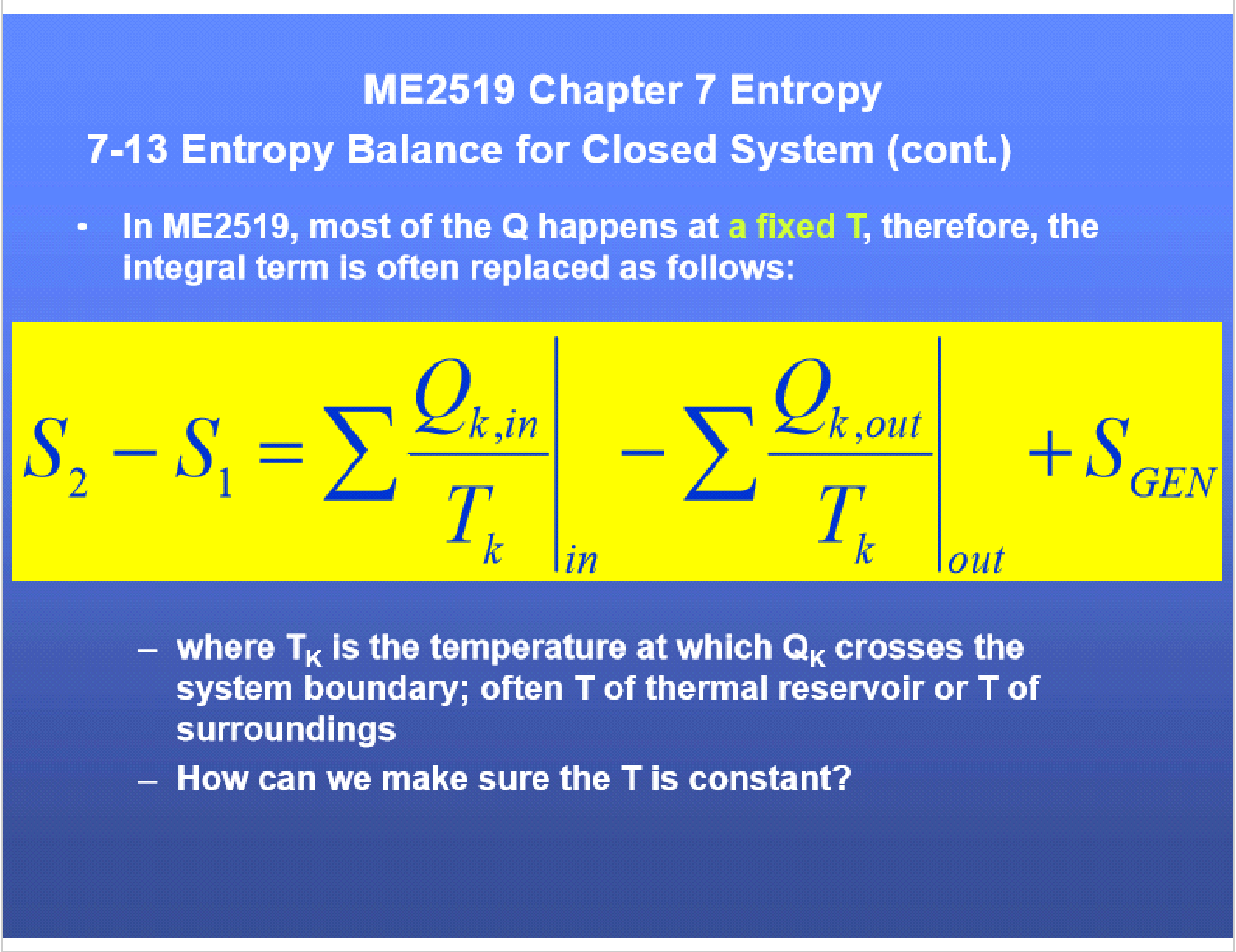


ME2519 Chapter 7 Entropy

7-13 Entropy Balance for Closed System

$$\boxed{S_2 - S_1 = \int_1^2 \frac{\delta Q}{T} + S_{GEN}}$$

- Equation called “Entropy balance”
- It accounts for all of the entropy change in the system during a process, including any “new” entropy created during process
- Irreversibilities cause S_{GEN} (“new” entropy) which is always positive (= 0 only for a reversible process)



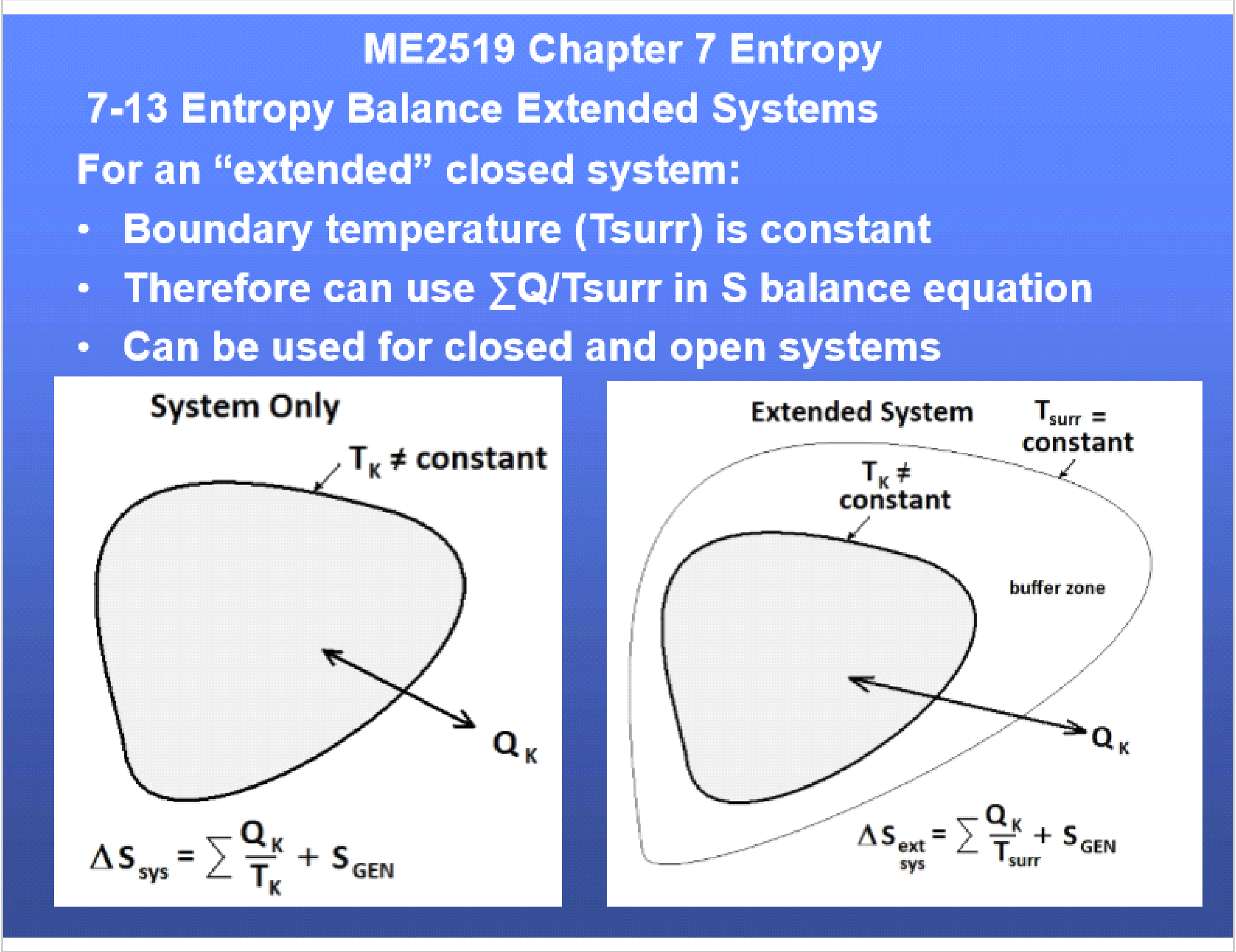
ME2519 Chapter 7 Entropy

7-13 Entropy Balance for Closed System (cont.)

- In ME2519, most of the Q happens at a fixed T, therefore, the integral term is often replaced as follows:

$$S_2 - S_1 = \sum \frac{Q_{k,in}}{T_k}\bigg|_{in} - \sum \frac{Q_{k,out}}{T_k}\bigg|_{out} + S_{GEN}$$

  - where T_K is the temperature at which Q_K crosses the system boundary; often T of thermal reservoir or T of surroundings
  - How can we make sure the T is constant?



ME2519 Chapter 7 Entropy

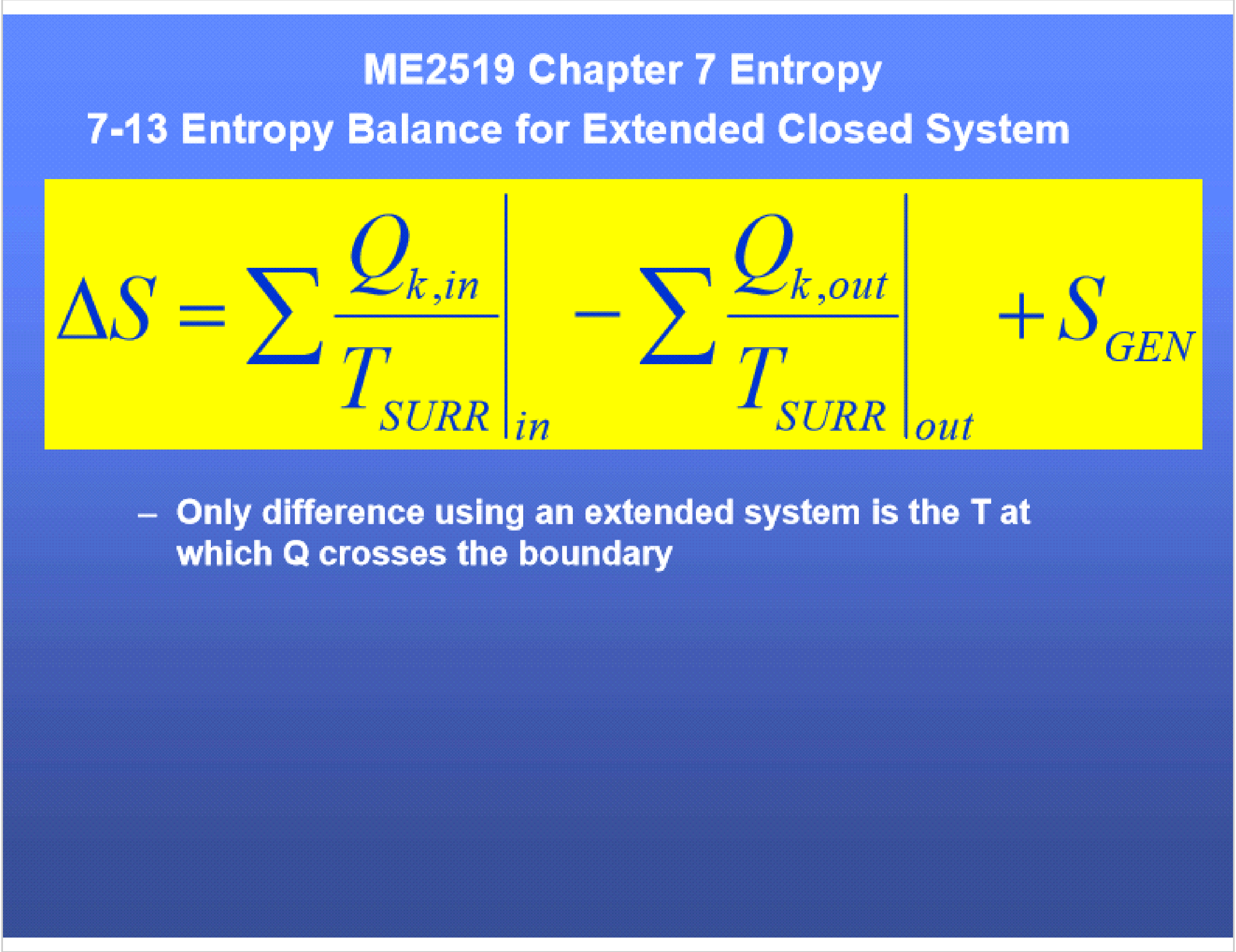
7-13 Entropy Balance Extended Systems

For an "extended" closed system:

- Boundary temperature (Tsurr) is constant
- Therefore can use ∑Q/Tsurr in S balance equation
- Can be used for closed and open systems

$$\Delta S_{sys} = \sum \frac{Q_K}{T_K} + S_{GEN}$$

$$\Delta S_{\substack{ext\\sys}} = \sum \frac{Q_K}{T_{surr}} + S_{GEN}$$

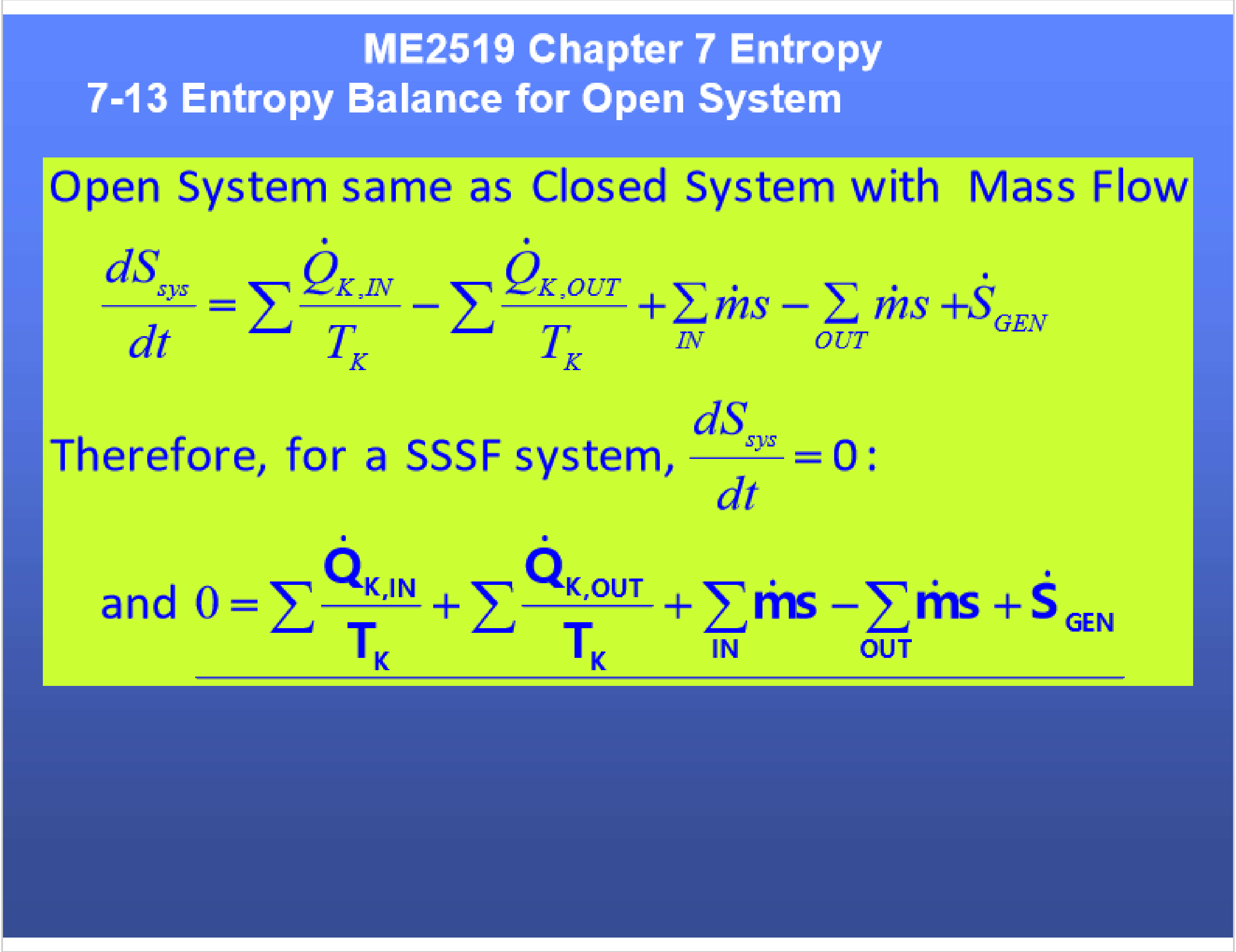


ME2519 Chapter 7 Entropy

7-13 Entropy Balance for Extended Closed System

$$\Delta S = \sum \frac{Q_{k,in}}{T_{SURR}}\bigg|_{in} - \sum \frac{Q_{k,out}}{T_{SURR}}\bigg|_{out} + S_{GEN}$$

- Only difference using an extended system is the T at which Q crosses the boundary



ME2519 Chapter 7 Entropy

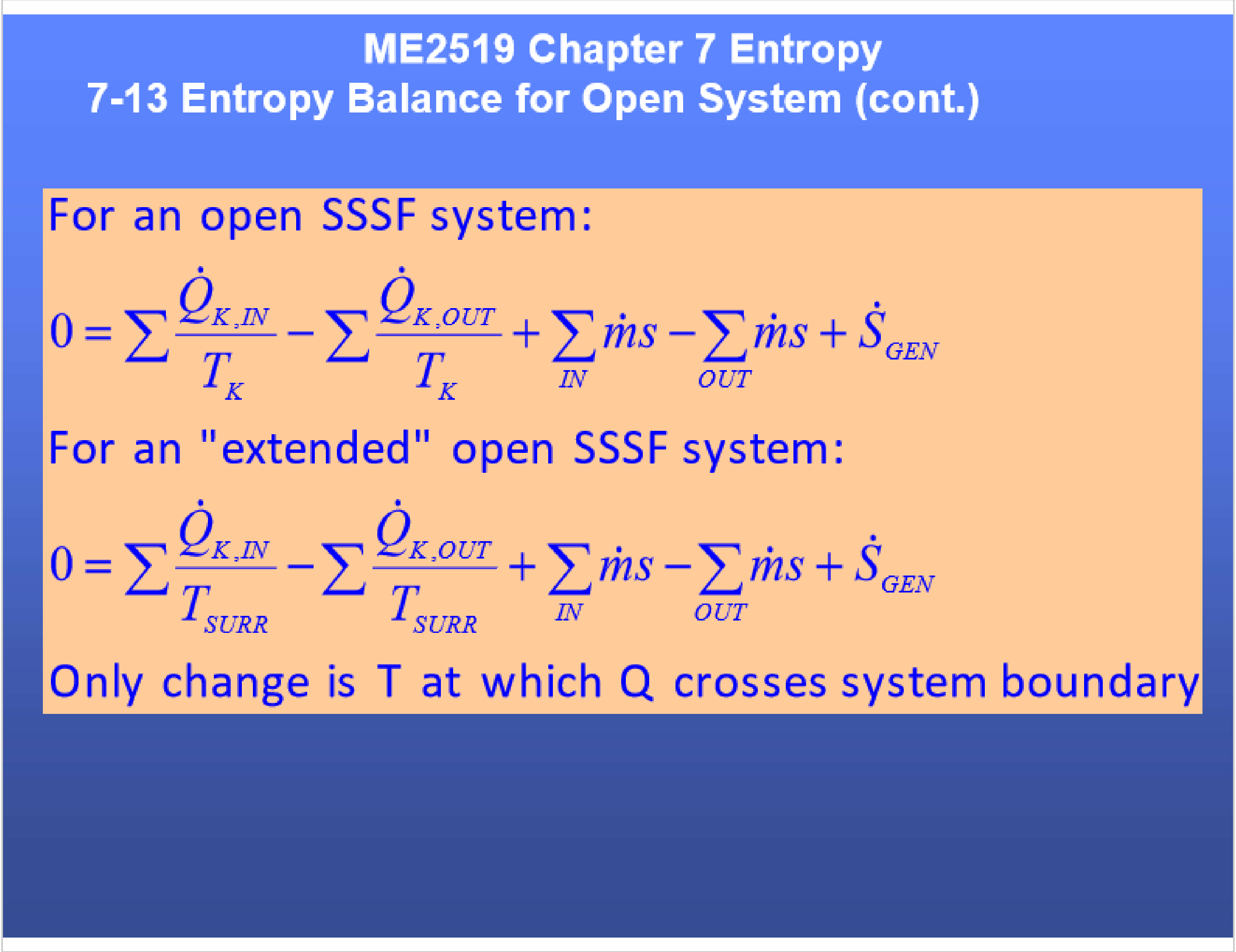
7-13 Entropy Balance for Open System

Open System same as Closed System with Mass Flow

$$\frac{dS_{sys}}{dt} = \sum \frac{\dot{Q}_{K,IN}}{T_K} - \sum \frac{\dot{Q}_{K,OUT}}{T_K} + \sum_{IN} \dot{m}s - \sum_{OUT} \dot{m}s + \dot{S}_{GEN}$$

Therefore, for a SSSF system, $\frac{dS_{sys}}{dt} = 0$:

and $0 = \sum \frac{\dot{Q}_{K,IN}}{T_K} + \sum \frac{\dot{Q}_{K,OUT}}{T_K} + \sum_{IN} \dot{m}s - \sum_{OUT} \dot{m}s + \dot{S}_{GEN}$



ME2519 Chapter 7 Entropy

7-13 Entropy Balance for Open System (cont.)

For an open SSSF system:

$$0=\sum\frac{\dot{Q}_{K,IN}}{T_K}-\sum\frac{\dot{Q}_{K,OUT}}{T_K}+\sum_{IN}\dot{m}s-\sum_{OUT}\dot{m}s+\dot{S}_{GEN}$$

For an "extended" open SSSF system:

$$0=\sum\frac{\dot{Q}_{K,IN}}{T_{SURR}}-\sum\frac{\dot{Q}_{K,OUT}}{T_{SURR}}+\sum_{IN}\dot{m}s-\sum_{OUT}\dot{m}s+\dot{S}_{GEN}$$

Only change is T at which Q crosses system boundary

Homework 7c

Wednesday, November 16, 2022 1:06 PM

7–136 Air enters a compressor steadily at the ambient conditions of 100 kPa and 22°C and leaves at 800 kPa. Heat is lost from the compressor in the amount of 120 kJ/kg, and the air experiences an entropy decrease of 0.40 kJ/kg·K. Using constant specific heats, determine (*a*) the exit temperature of the air, (*b*) the work input to the compressor, and (*c*) the entropy generation during this process.

a. $\Delta s = C_p \ln \frac{T_2}{T_1} - R \ln \frac{P_2}{P_1}$

$P_1 = 100\,kPa$
$T_1 = 22^\circ C = 295\,K$
$P_2 = 800\,kPa$
$q_{out} = 120\ kJ/kg$
$\Delta s = -.4\ kJ/kg \cdot K$
$C = const$

$T_2 = T_1 e^{\frac{\Delta s + R \ln \frac{P_2}{P_1}}{c_p}}$

$T_2 = (295K) e^{\frac{-.4 + .287 \ln \frac{800}{100}}{1.005}}$

$\boxed{T_2 = 358.811\ K}$

b. 1st law SSSF

$0 = -q_{out} + w_{in} + h_1 - h_2$

$w_{in} = q_{out} - c_p (T_1 - T_2)$

$w_{in} = 120 - 1.005 (295 - 358.811) = \boxed{188.1 \frac{kJ}{kg}}$

c. $0 = -\Sigma \frac{q_{out}}{T_{out}} + s_{in} - s_{out} + s_{gen}$

$s_{gen} = \frac{q_{out}}{T_{out}} + \Delta s = \frac{120}{295} - .4$

$\boxed{s_{gen} = .00678 \frac{kJ}{kg \cdot K}}$

7–141 Cold water (c_p = 4.18 kJ/kg·°C) leading to a shower enters a well-insulated, thin-walled, double-pipe, counterflow heat exchanger at 10°C at a rate of 0.95 kg/s and is heated to 70°C by hot water (c_p = 4.19 kJ/kg·°C) that enters at 85°C at a rate of 1.6 kg/s. Determine (*a*) the rate of heat transfer and (*b*) the rate of entropy generation in the heat exchanger.

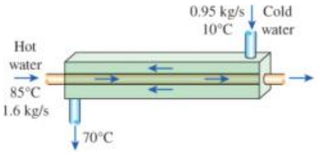


FIGURE P7–141

a. 1st law SSSF cold water:

$c_{p_c} = 4.18\ kJ/kg\,^\circ C$
$T_{1_c} = 10^\circ C = 283\ K$
$\dot{m}_c = .95\ kg/s$
$T_{2_c} = 70^\circ C = 343K$

$0 = \dot{Q}_{in} + \dot{m}_c (h_1) - \dot{m}_c h_2$

$\dot{Q}_{in} = \dot{m}_c (h_2 - h_1) = \dot{m}_c C_{p_c} (T_{2_c} - T_{1_c})$

$\dot{Q}_{in} = (.95\ kg/s)(4.18\,kJ/kg \cdot K)(343 - 283)K$

$c_{p_h} = 4.19\ kJ/kg\,^\circ C$
$T_{1_h} = 85^\circ C = 358\ K$
$\dot{m}_h = 1.6\ kg/s$

$\boxed{\dot{Q}_{in} = 238.26 \frac{kJ}{s}}$

$T_{1h} = 85°C = 358\ K$

$\dot{m}_h = 1.6\ kg/s$

$$\boxed{\dot{Q}_{in} = 238.26\ \frac{kJ}{s}}$$

b. 1st law Hot:

$$\dot{Q}_{in} = \dot{m}_h\ c_{p_h}(T_2 - T_1)$$

$$T_{2_h} = -\frac{\dot{Q}_{out}}{\dot{m}_h c_{ph}} + T_{1_h}$$

$$T_{2h} = -\frac{238.26}{1.6(4.19)} + 358 = 322.5\ K$$

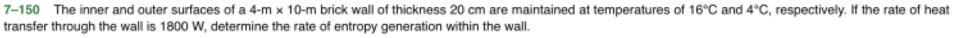
1st law S-balance

$$0 = \Sigma_{in} \dot{m}s - \Sigma_{out} \dot{m}s + \dot{S}_{gen}$$

$$\dot{S}_{gen} = \dot{m}_c\ c_{pc} \ln \frac{T_{2c}}{T_{1c}} + \dot{m}_h\ c_{ph} \ln \frac{T_{2h}}{T_{1h}}$$

$$\dot{S}_{gen} = .95 \frac{kg}{s} \left(4.18 \frac{kJ}{kg\,K}\right) \ln \frac{343}{283} + 1.6 \frac{kg}{s} \left(4.19 \frac{kJ}{kg\,K}\right) \ln \frac{322.5}{358}$$

$$\boxed{\dot{S}_{gen} = .0636\ \frac{kW}{s}}$$



7–150 The inner and outer surfaces of a 4-m × 10-m brick wall of thickness 20 cm are maintained at temperatures of 16°C and 4°C, respectively. If the rate of heat transfer through the wall is 1800 W, determine the rate of entropy generation within the wall.

$$\cancel{\frac{d}{dt}} S \Big|_{CS} ^{\,0} = \Sigma \frac{\dot{Q}_{in}}{T_{in}} - \frac{\dot{Q}_{out}}{T_{out}} + \dot{S}_{gen}$$

$A = 4(10)\ m^2 = 40\ m$

$th = .2\ m$

$T_1 = 16°C = 289\ K$

$T_2 = 4°C = 277\ K$

$\dot{Q} = 1800\ W$

$$\dot{S}_{gen} = \frac{\dot{Q}}{T_2} - \frac{\dot{Q}}{T_1}$$

$$\dot{S}_{gen} = \frac{1800\ W}{277\ K} - \frac{1800\ W}{284\ K}$$

$$\boxed{\dot{S}_{gen} = .2648\ \frac{W}{K}}$$

Exergy

Friday, November 18, 2022 10:13 AM

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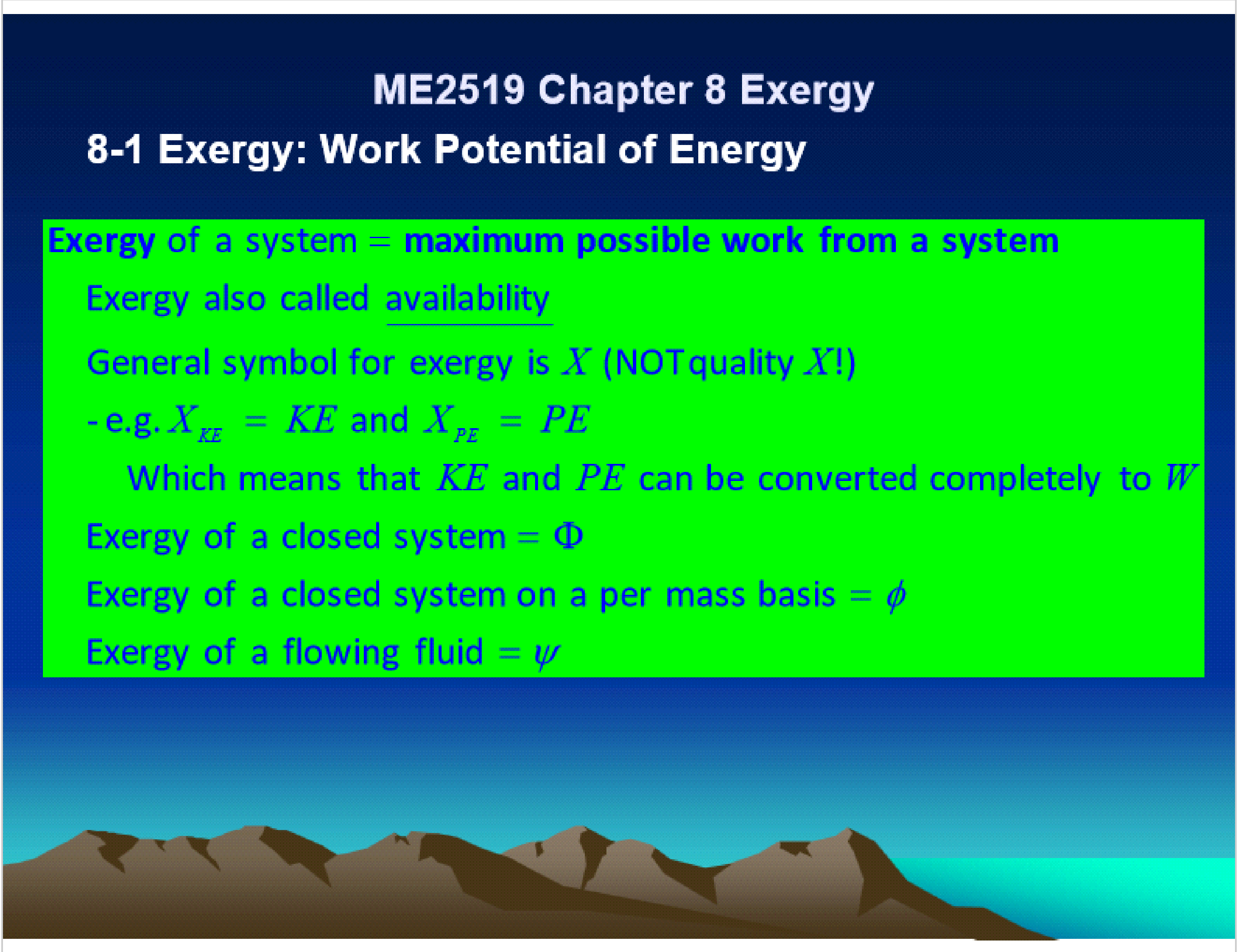


ME2519 Chapter 8 Exergy

8-1 Exergy: Work Potential of Energy

Exergy of a system = **maximum possible work from a system**

Exergy also called availability

General symbol for exergy is X (NOT quality X!)

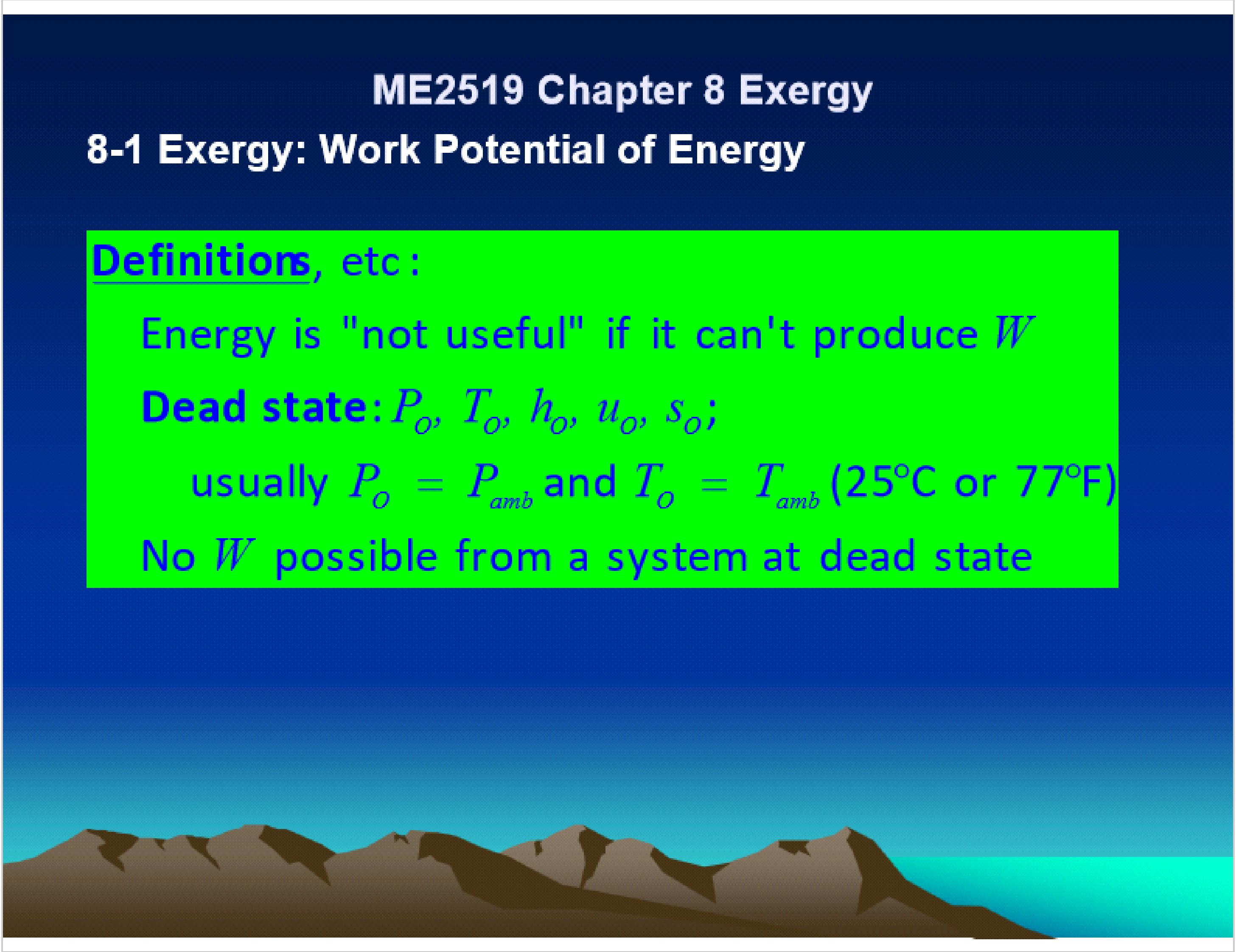
- e.g. $X_{KE} = KE$ and $X_{PE} = PE$

Which means that KE and PE can be converted completely to W

Exergy of a closed system = Φ

Exergy of a closed system on a per mass basis = ϕ

Exergy of a flowing fluid = ψ



ME2519 Chapter 8 Exergy

8-1 Exergy: Work Potential of Energy

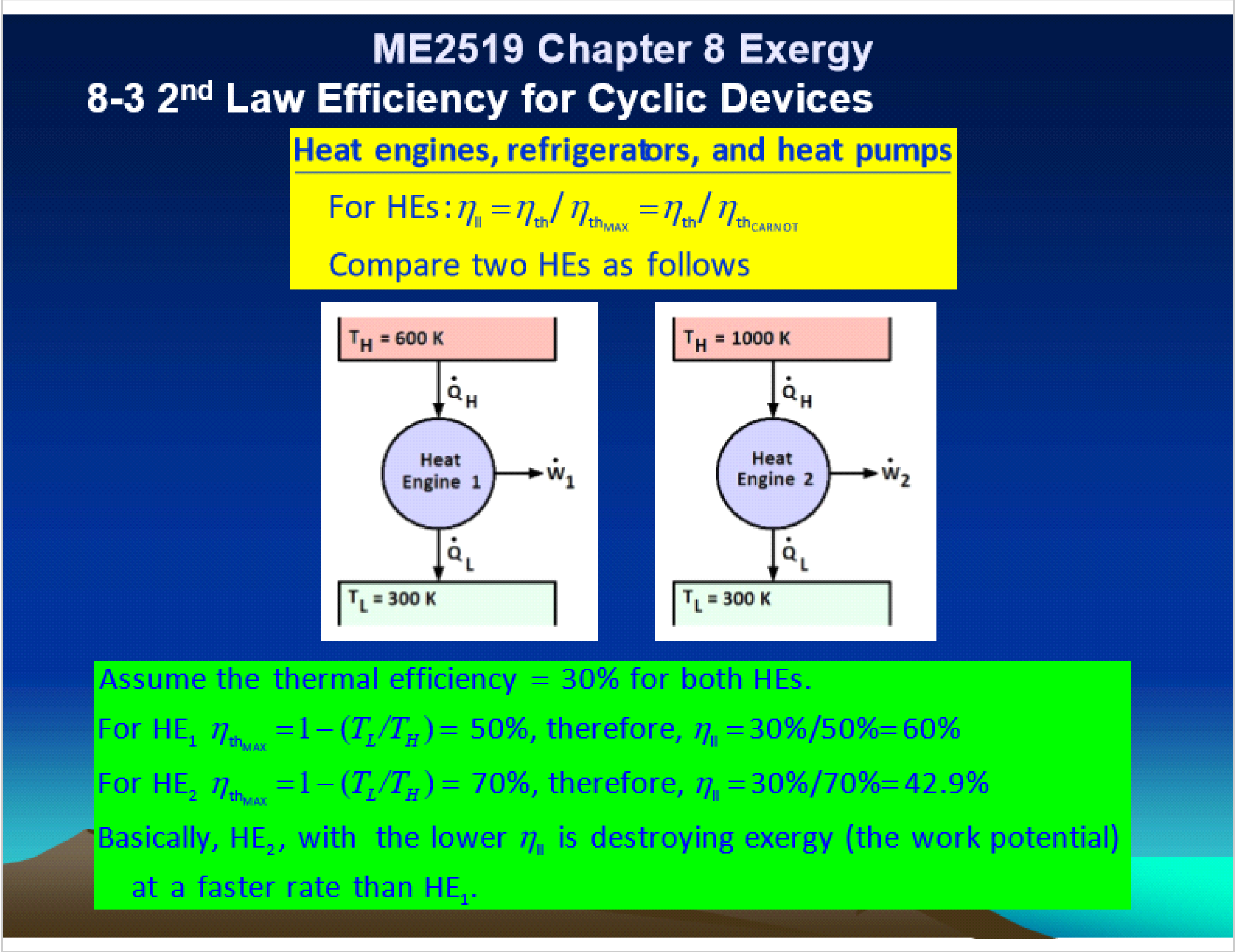
Definitions, etc:

Energy is "not useful" if it can't produce W

Dead state: P_o, T_o, h_o, u_o, s_o;

usually $P_o = P_{amb}$ and $T_o = T_{amb}$ (25°C or 77°F)

No W possible from a system at dead state



ME2519 Chapter 8 Exergy

8-3 2nd Law Efficiency for Cyclic Devices

Heat engines, refrigerators, and heat pumps

For HEs: $\eta_{II} = \eta_{th} / \eta_{th_{MAX}} = \eta_{th} / \eta_{th_{CARNOT}}$

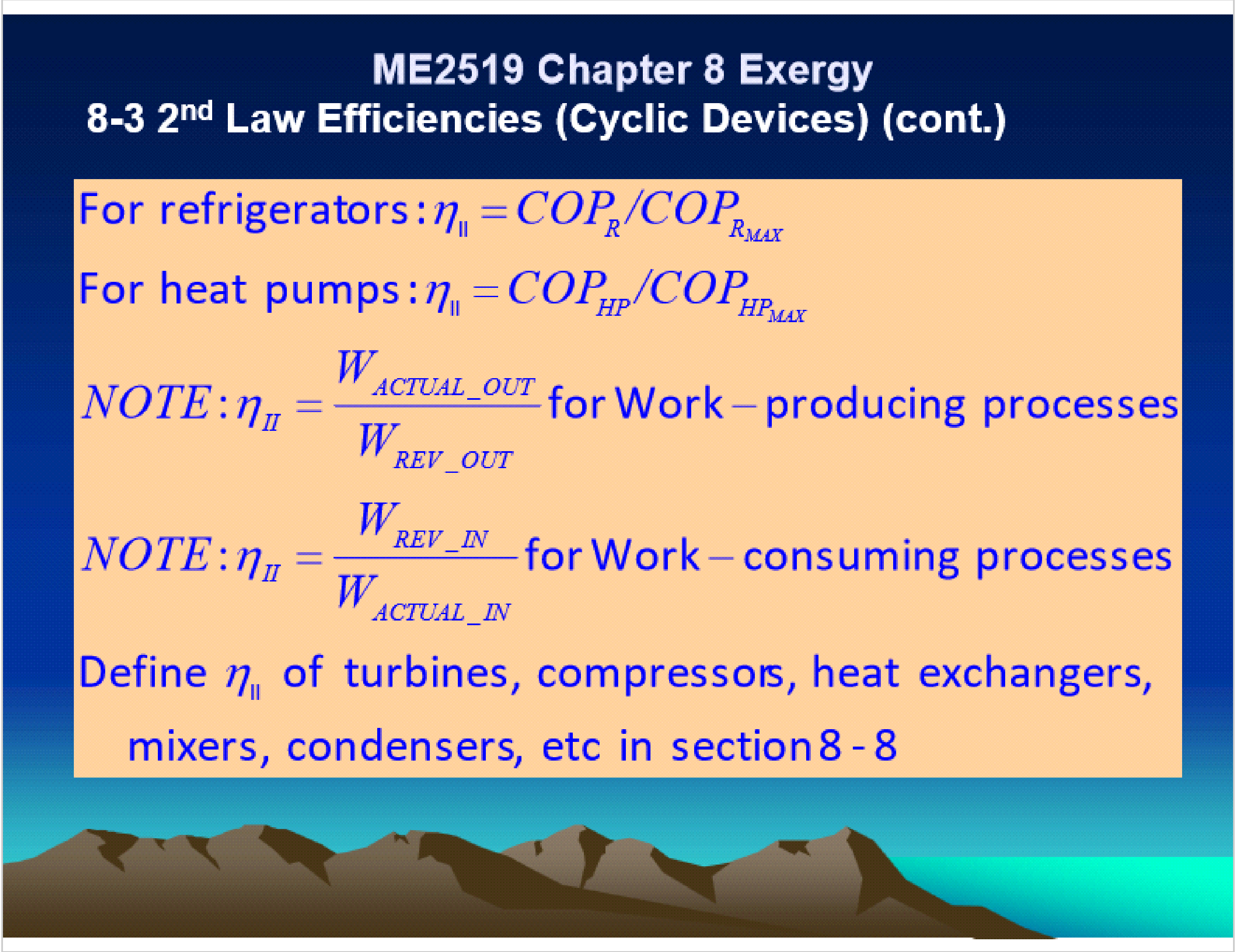
Compare two HEs as follows

Assume the thermal efficiency = 30% for both HEs.

For HE_1 $\eta_{th_{MAX}} = 1 - (T_L/T_H) = 50\%$, therefore, $\eta_{II} = 30\%/50\% = 60\%$

For HE_2 $\eta_{th_{MAX}} = 1 - (T_L/T_H) = 70\%$, therefore, $\eta_{II} = 30\%/70\% = 42.9\%$

Basically, HE_2, with the lower η_{II} is destroying exergy (the work potential) at a faster rate than HE_1.



ME2519 Chapter 8 Exergy

8-3 2nd Law Efficiencies (Cyclic Devices) (cont.)

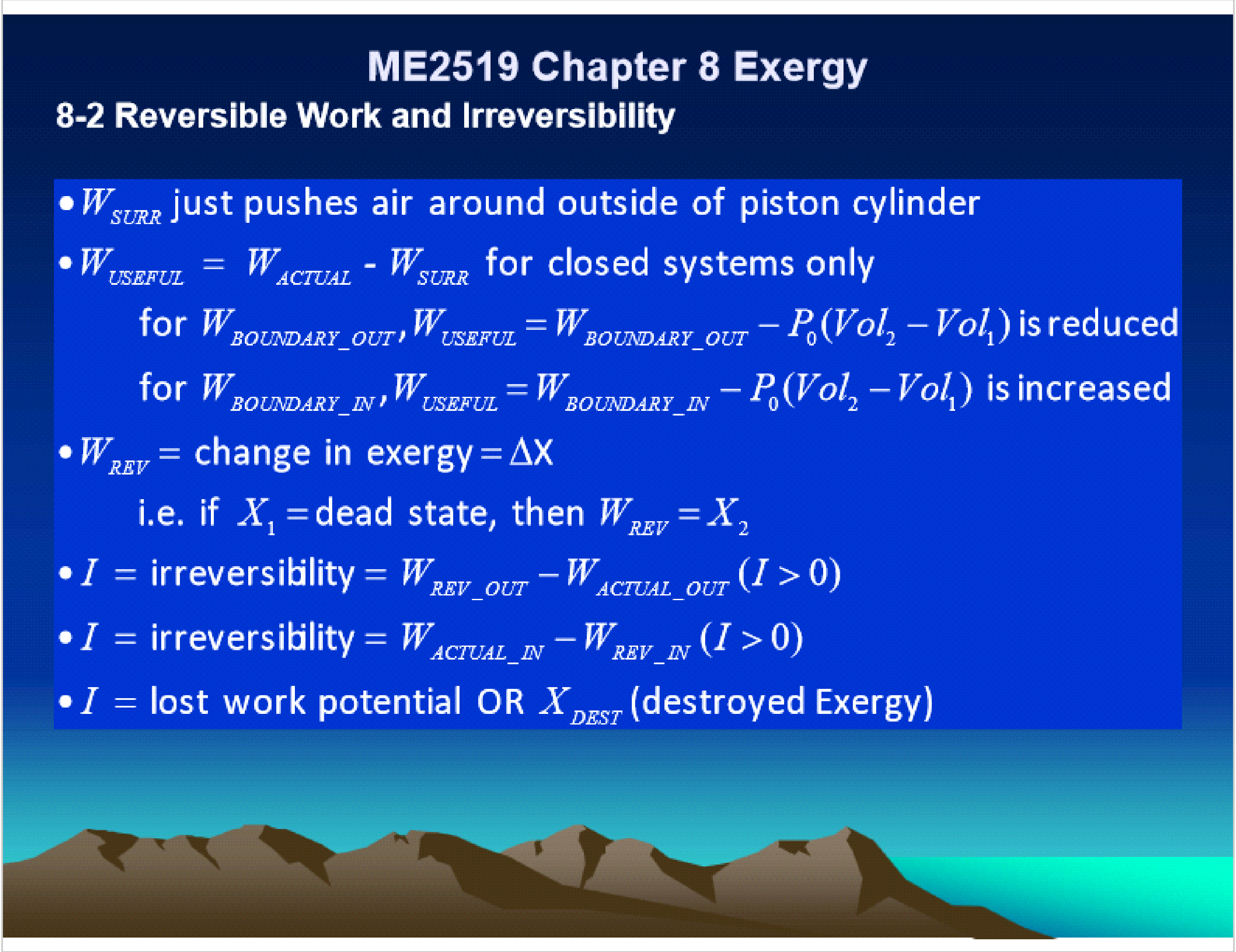
For refrigerators: $\eta_{II} = COP_R / COP_{R_{MAX}}$

For heat pumps: $\eta_{II} = COP_{HP} / COP_{HP_{MAX}}$

$$NOTE : \eta_{II} = \frac{W_{ACTUAL\_OUT}}{W_{REV\_OUT}} \text{ for Work} - \text{producing processes}$$

$$NOTE : \eta_{II} = \frac{W_{REV\_IN}}{W_{ACTUAL\_IN}} \text{ for Work} - \text{consuming processes}$$

Define η_{II} of turbines, compressors, heat exchangers, mixers, condensers, etc in section 8-8



ME2519 Chapter 8 Exergy

8-2 Reversible Work and Irreversibility

- W_{SURR} just pushes air around outside of piston cylinder
- $W_{USEFUL} = W_{ACTUAL}$ - W_{SURR} for closed systems only

  for $W_{BOUNDARY\_OUT}, W_{USEFUL} = W_{BOUNDARY\_OUT} - P_0(Vol_2 - Vol_1)$ is reduced

  for $W_{BOUNDARY\_IN}, W_{USEFUL} = W_{BOUNDARY\_IN} - P_0(Vol_2 - Vol_1)$ is increased
- W_{REV} = change in exergy $= \Delta$X

  i.e. if $X_1 =$ dead state, then $W_{REV} = X_2$
- I = irreversibility $= W_{REV\_OUT} - W_{ACTUAL\_OUT}$ $(I > 0)$
- I = irreversibility $= W_{ACTUAL\_IN} - W_{REV\_IN}$ $(I > 0)$
- I = lost work potential OR X_{DEST} (destroyed Exergy)

Homework 8a

Tuesday, November 22, 2022 6:00 PM

8–17 Consider a thermal energy reservoir at 1500 K that can supply heat at a rate of 150,000 kJ/h. Determine the exergy of this supplied energy, assuming an environment temperature of 25°C.

$$\dot{X} = \left(1 - \frac{T_L}{T_H}\right)\dot{Q}_{out}$$

$T_H = 1500\ K$

$T_L = 25°C = 298\ K$

$\dot{Q}_{out} = 150,000\ kJ/h = 41.667\ kJ/s$

$$\dot{X} = \left(1 - \frac{298}{1500}\right)(41.666\ kJ/s)$$

$$\boxed{X = 33.39\ kW}$$

8–22 A house that is losing heat at a rate of 35,000 kJ/h when the outside temperature drops to 4°C is to be heated by electric resistance heaters. If the house is be maintained at 25°C at all times, determine the reversible work input for this process and the irreversibility. *Answer:* 0.685 kW, 9.04 kW

$$COP_{HP} = \frac{\dot{Q}_H}{\dot{W}_{in,rev}} = \frac{1}{1 - \frac{T_L}{T_H}}$$

$\dot{Q}_H = 35,000\ kJ/h = 9.722\ kJ/s$

$T_L = 4°C = 277\ K$

$T_H = 25°C = 298\ K$

$$\dot{W}_{in,rev} = \dot{Q}_H\left(1 - \frac{T_L}{T_H}\right)$$

$$\dot{W}_{in,rev} = 9.722\ kJ/s\left(1 - \frac{277}{298}\right)$$

$$\boxed{W_{in,rev} = .685\ kW}$$

$$I = \dot{Q}_H - \dot{W}_{in,rev} = 9.722 - .685$$

$$\boxed{I = 9.0371\ kW}$$

Exergy for Closed Systems

Monday, November 28, 2022 10:04 AM

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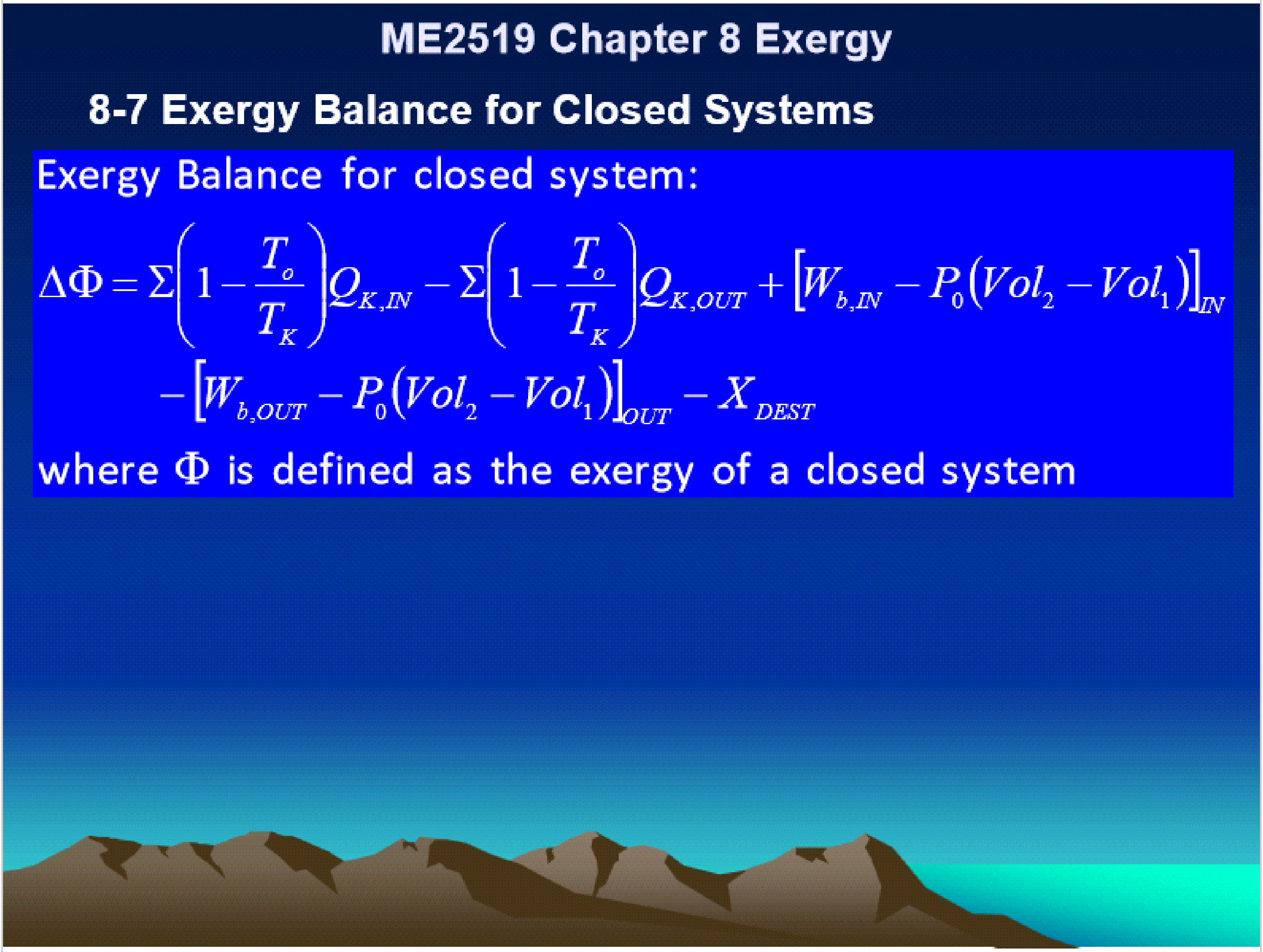
+8-7+dtd...



ME2519 Chapter 8 Exergy

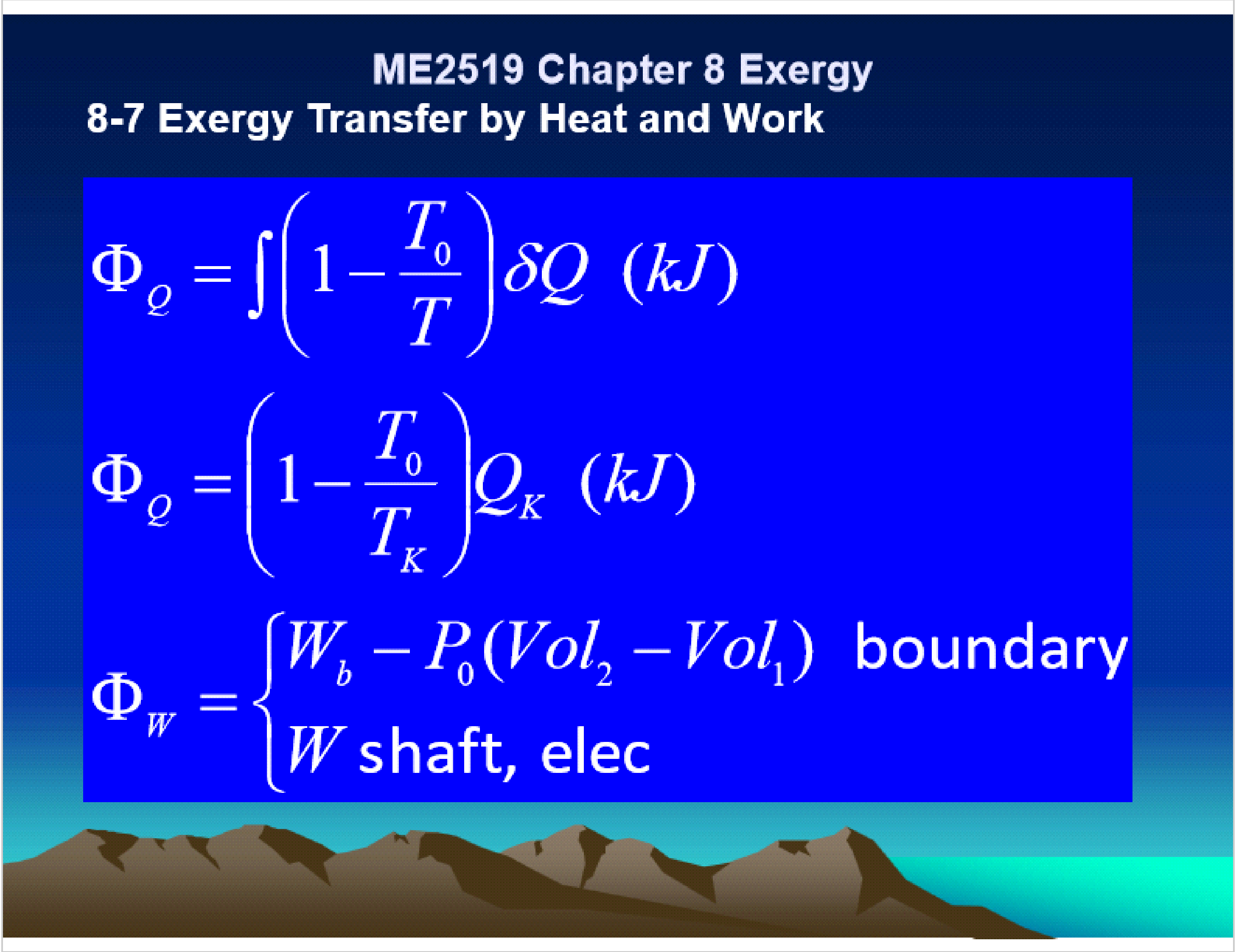
8-7 Exergy Balance for Closed Systems

Exergy Balance for closed system:

$$\Delta\Phi = \Sigma\left(1-\frac{T_o}{T_K}\right)Q_{K,IN} - \Sigma\left(1-\frac{T_o}{T_K}\right)Q_{K,OUT} + \left[W_{b,IN} - P_0\left(Vol_2 - Vol_1\right)\right]_{IN}$$

$$- \left[W_{b,OUT} - P_0\left(Vol_2 - Vol_1\right)\right]_{OUT} - X_{DEST}$$

where Φ is defined as the exergy of a closed system



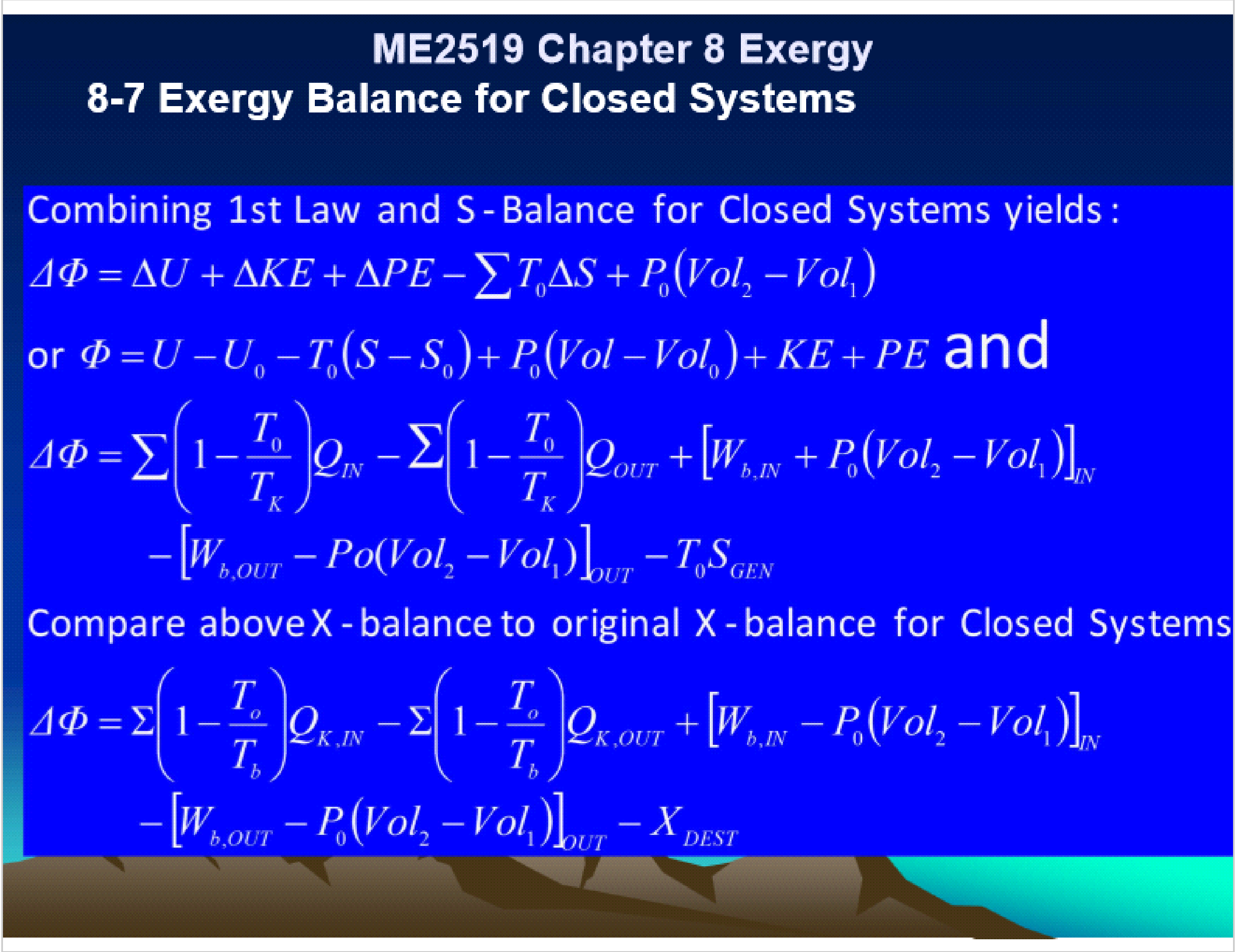
ME2519 Chapter 8 Exergy

8-7 Exergy Transfer by Heat and Work

$$\Phi_Q = \int \left(1-\frac{T_0}{T}\right)\delta Q \quad (kJ)$$

$$\Phi_Q = \left(1-\frac{T_0}{T_K}\right)Q_K \quad (kJ)$$

$$\Phi_W = \begin{cases} W_b - P_0(Vol_2 - Vol_1) & \text{boundary} \\ W & \text{shaft, elec} \end{cases}$$



ME2519 Chapter 8 Exergy

8-7 Exergy Balance for Closed Systems

Combining 1st Law and S-Balance for Closed Systems yields:

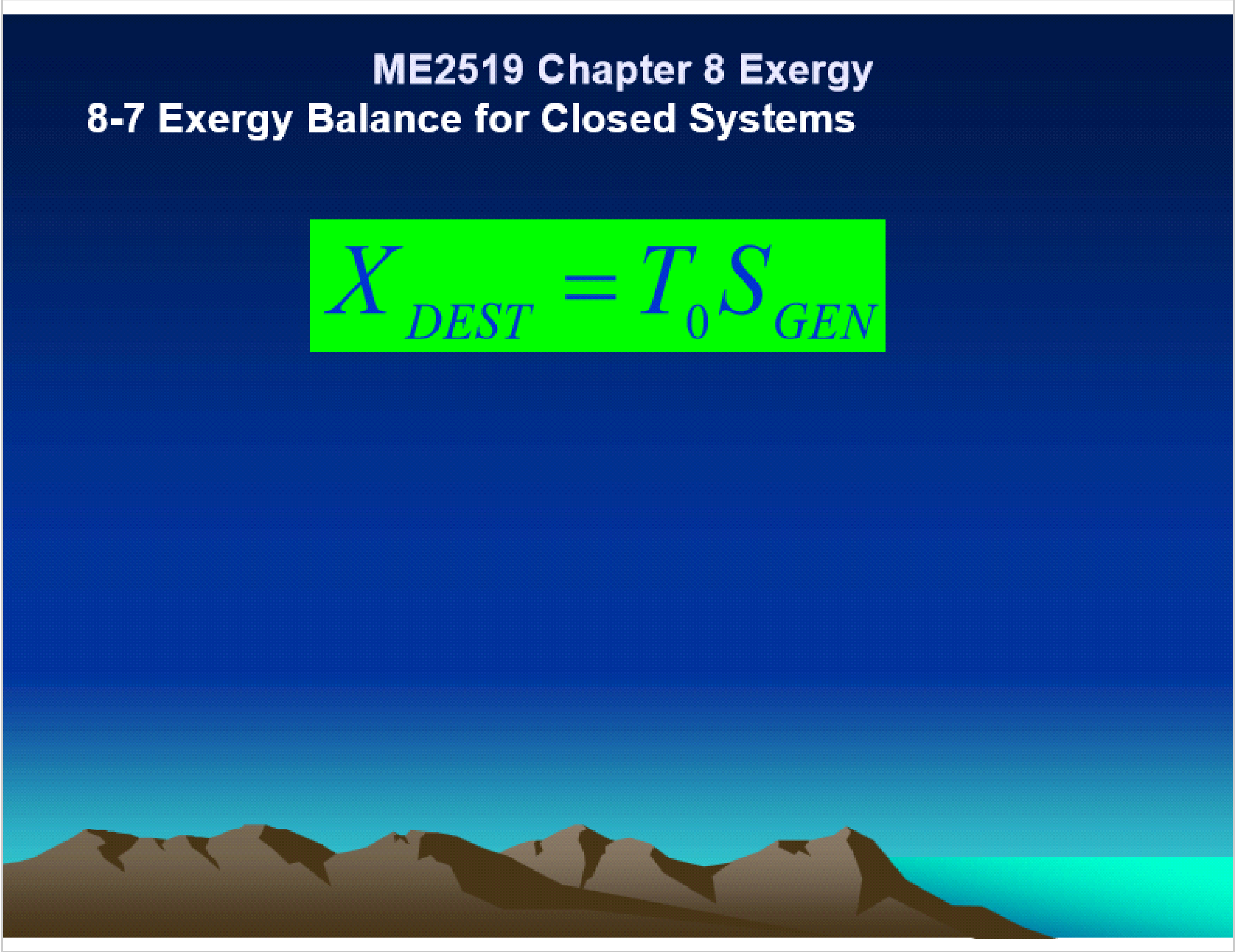
$$\mathit{\Delta\Phi} = \Delta U + \Delta KE + \Delta PE - \sum T_0 \Delta S + P_0\left(Vol_2 - Vol_1\right)$$

or $\Phi = U - U_0 - T_0\left(S - S_0\right) + P_0\left(Vol - Vol_0\right) + KE + PE$ and

$$\mathit{\Delta\Phi} = \sum\left(1 - \frac{T_0}{T_K}\right)Q_{IN} - \sum\left(1 - \frac{T_0}{T_K}\right)Q_{OUT} + \left[W_{b,IN} + P_0\left(Vol_2 - Vol_1\right)\right]_{IN} - \left[W_{b,OUT} - Po(Vol_2 - Vol_1)\right]_{OUT} - T_0 S_{GEN}$$

Compare above X-balance to original X-balance for Closed Systems

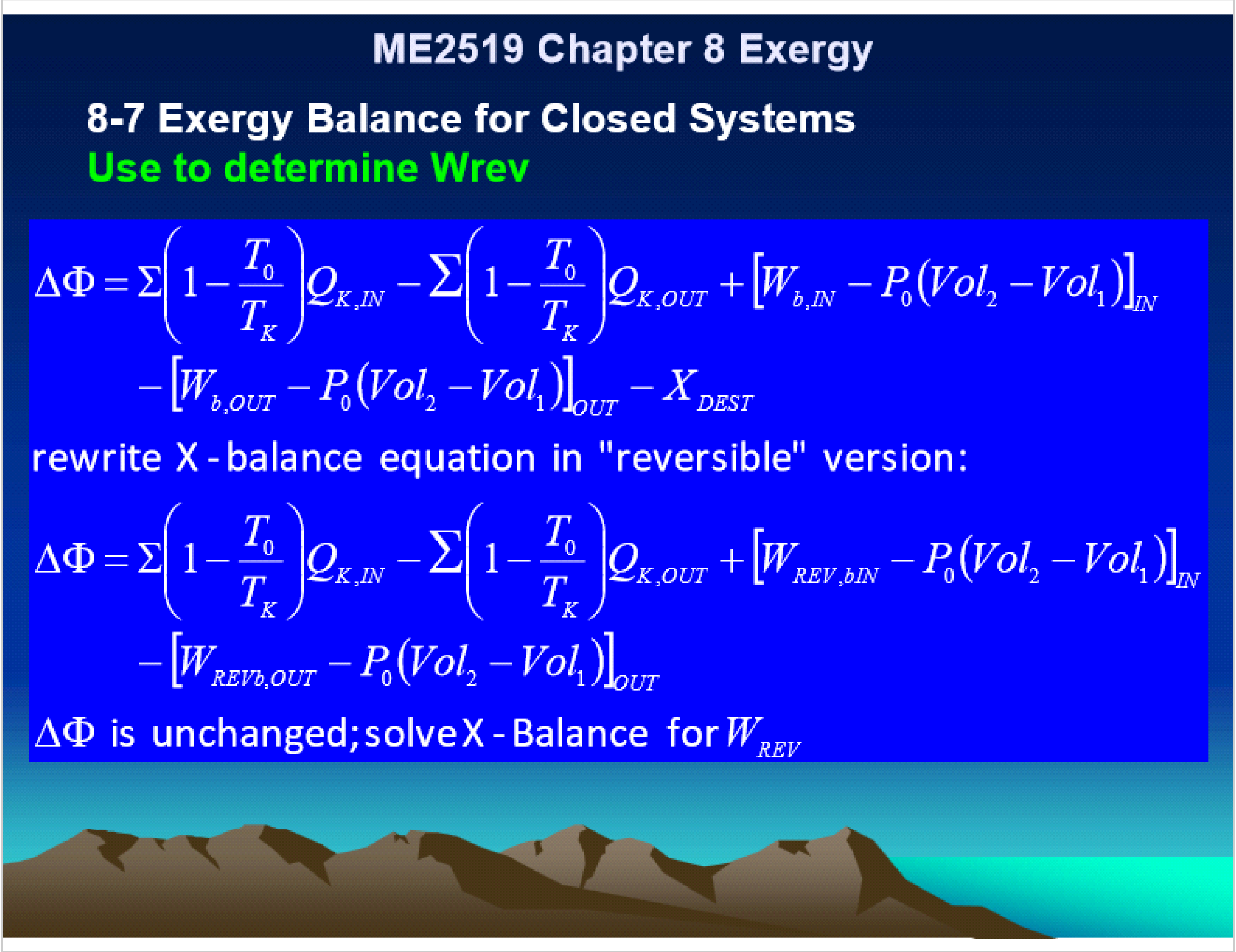
$$\mathit{\Delta\Phi} = \Sigma\left(1 - \frac{T_o}{T_b}\right)Q_{K,IN} - \Sigma\left(1 - \frac{T_o}{T_b}\right)Q_{K,OUT} + \left[W_{b,IN} - P_0\left(Vol_2 - Vol_1\right)\right]_{IN} - \left[W_{b,OUT} - P_0\left(Vol_2 - Vol_1\right)\right]_{OUT} - X_{DEST}$$



ME2519 Chapter 8 Exergy

8-7 Exergy Balance for Closed Systems

$$X_{DEST} = T_0 S_{GEN}$$



ME2519 Chapter 8 Exergy

8-7 Exergy Balance for Closed Systems

Use to determine Wrev

$$\Delta\Phi = \Sigma\left(1-\frac{T_0}{T_K}\right)Q_{K,IN} - \Sigma\left(1-\frac{T_0}{T_K}\right)Q_{K,OUT} + \left[W_{b,IN} - P_0\left(Vol_2 - Vol_1\right)\right]_{IN}$$

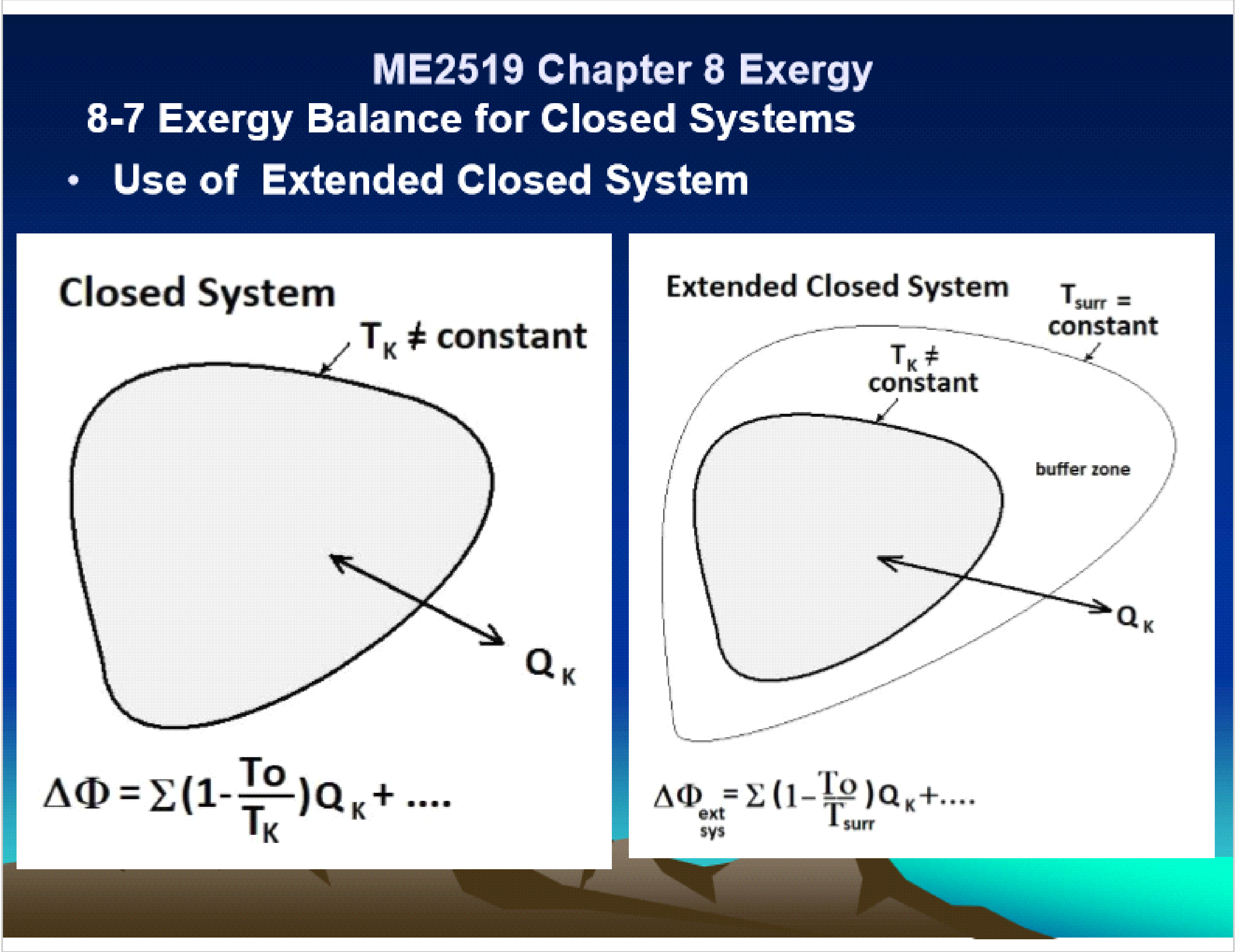
$$- \left[W_{b,OUT} - P_0\left(Vol_2 - Vol_1\right)\right]_{OUT} - X_{DEST}$$

rewrite X-balance equation in "reversible" version:

$$\Delta\Phi = \Sigma\left(1-\frac{T_0}{T_K}\right)Q_{K,IN} - \Sigma\left(1-\frac{T_0}{T_K}\right)Q_{K,OUT} + \left[W_{REV,bIN} - P_0\left(Vol_2 - Vol_1\right)\right]_{IN}$$

$$- \left[W_{REVb,OUT} - P_0\left(Vol_2 - Vol_1\right)\right]_{OUT}$$

$\Delta\Phi$ is unchanged; solve X-Balance for W_{REV}



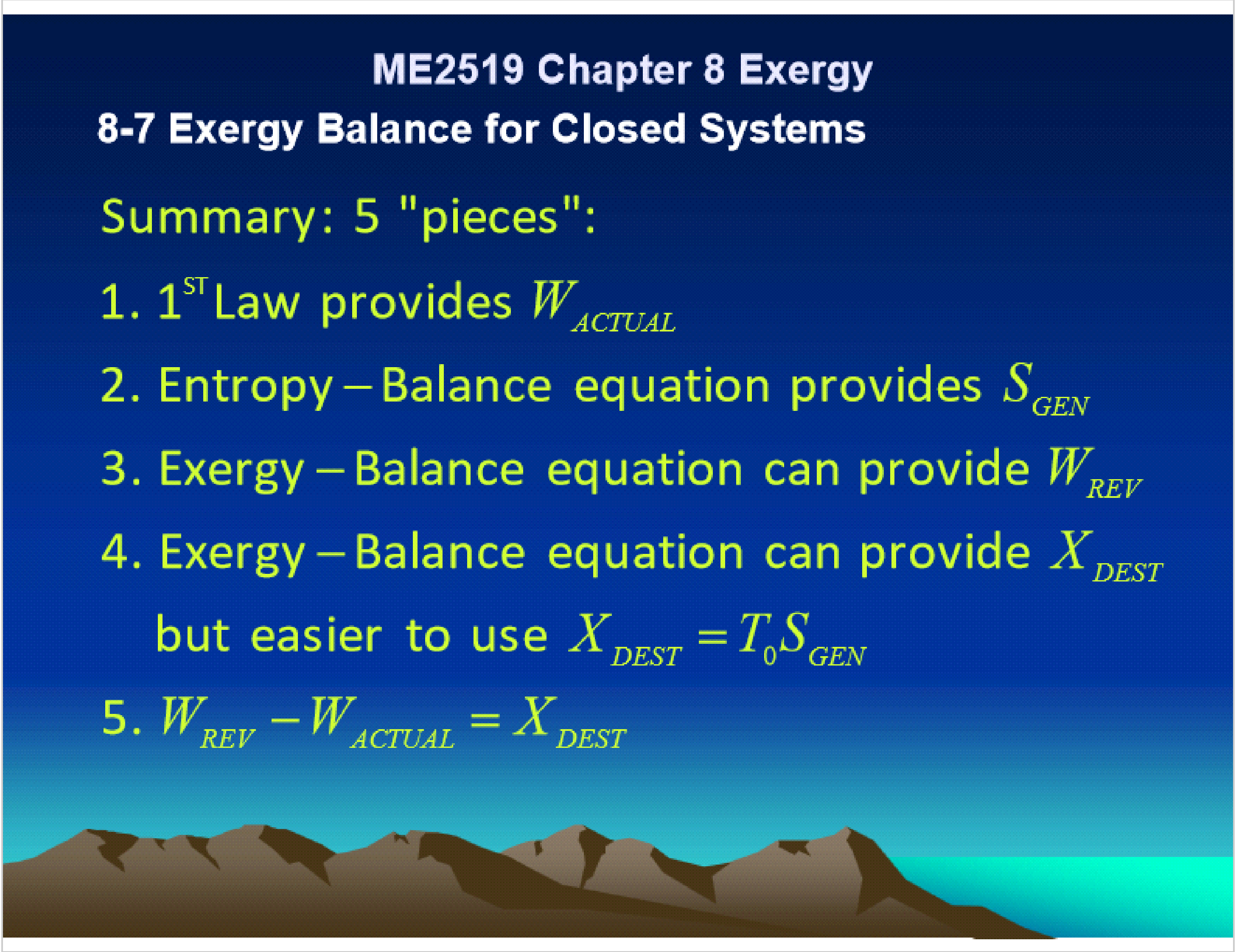
ME2519 Chapter 8 Exergy

8-7 Exergy Balance for Closed Systems

- Use of Extended Closed System

$$\Delta\Phi = \Sigma(1-\frac{To}{T_K})Q_K + ...$$

$$\Delta\Phi_{\substack{ext\\sys}} = \Sigma(1-\frac{To}{T_{surr}})Q_K + ...$$



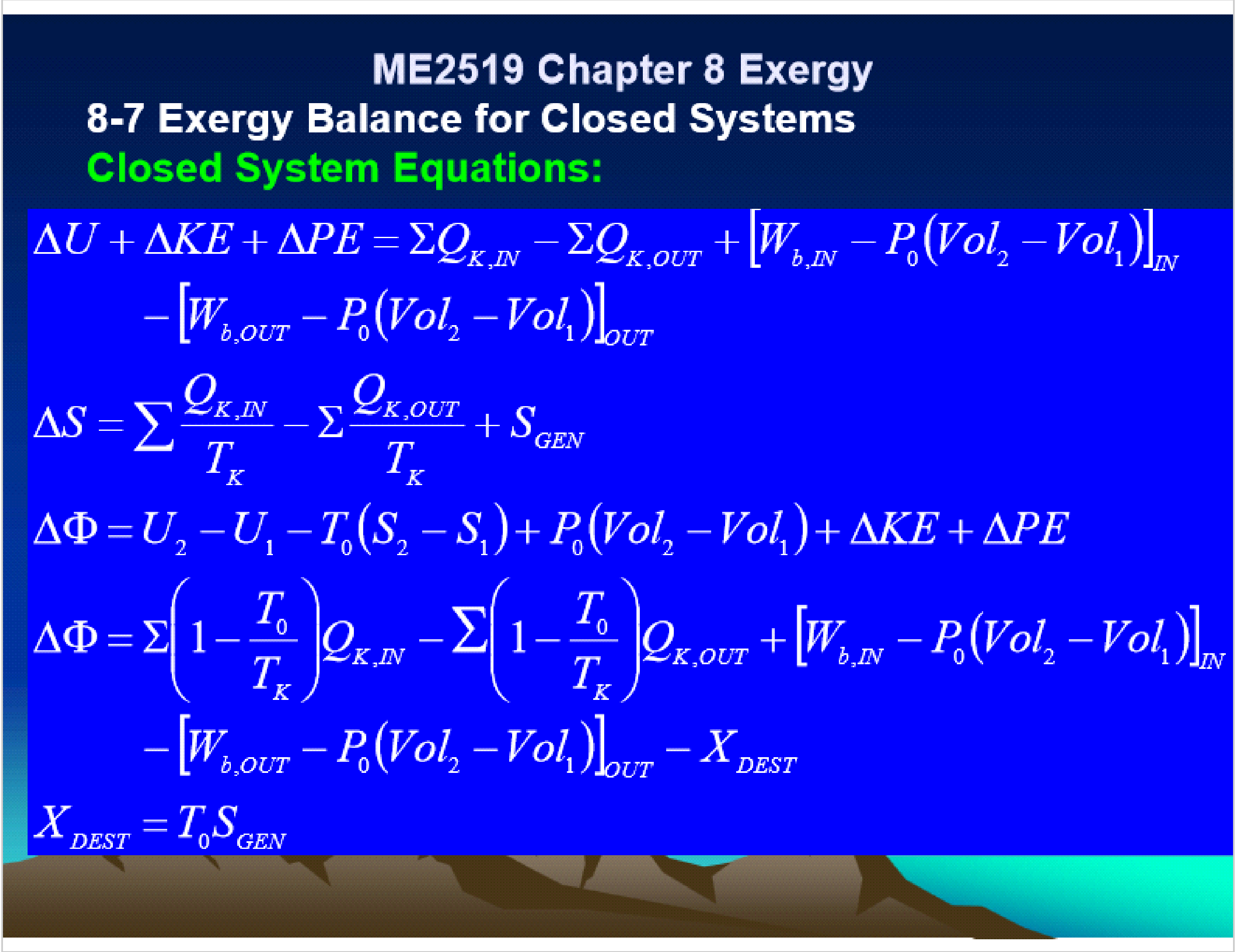
ME2519 Chapter 8 Exergy

8-7 Exergy Balance for Closed Systems

Summary: 5 "pieces":

1. 1^{ST} Law provides W_{ACTUAL}
2. $\text{Entropy} - \text{Balance equation provides } S_{GEN}$
3. $\text{Exergy} - \text{Balance equation can provide } W_{REV}$
4. $\text{Exergy} - \text{Balance equation can provide } X_{DEST}$

   but easier to use $X_{DEST} = T_0 S_{GEN}$
5. $W_{REV} - W_{ACTUAL} = X_{DEST}$



ME2519 Chapter 8 Exergy

8-7 Exergy Balance for Closed Systems

Closed System Equations:

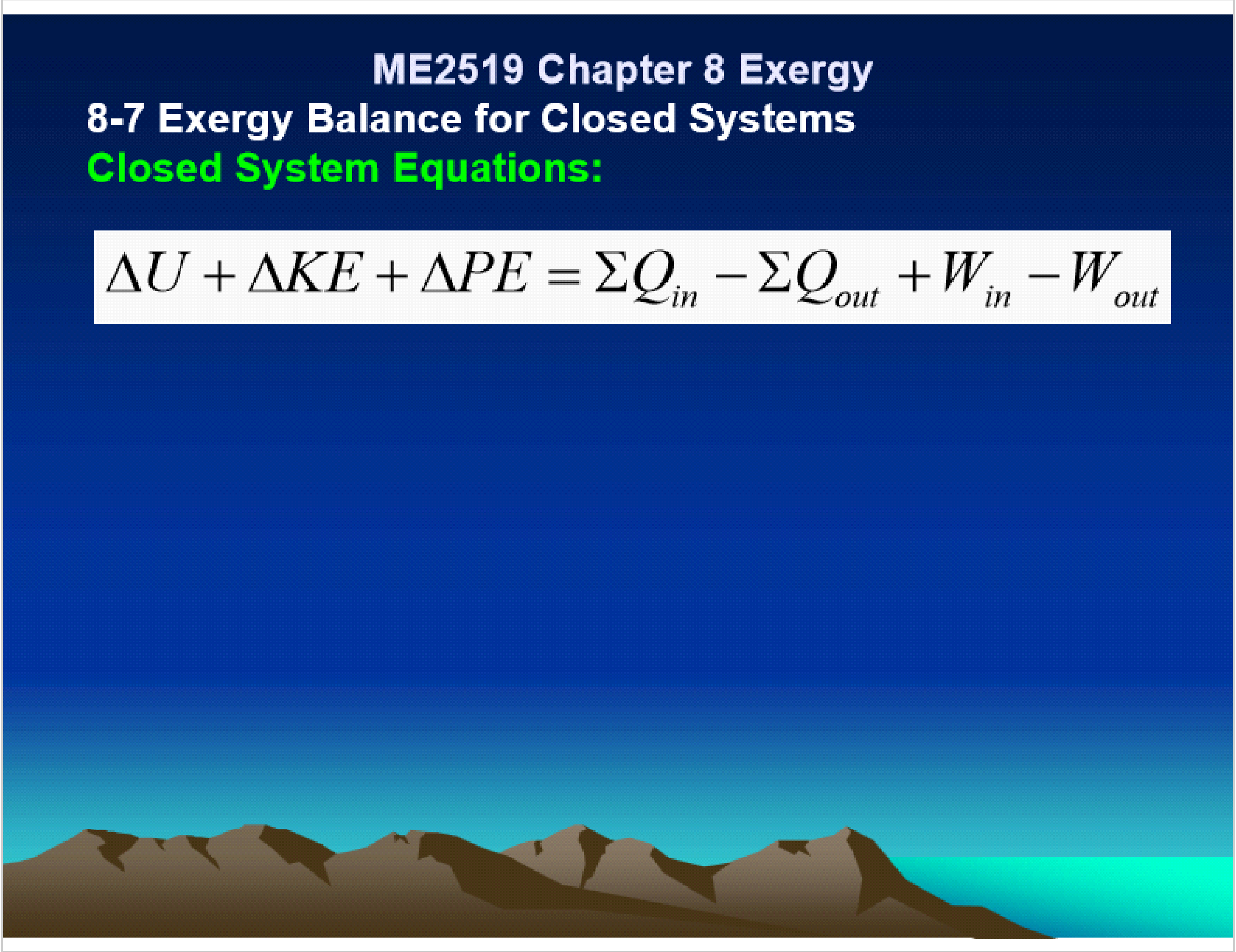
$$\Delta U + \Delta KE + \Delta PE = \Sigma Q_{K,IN} - \Sigma Q_{K,OUT} + \left[W_{b,IN} - P_0\left(Vol_2 - Vol_1\right)\right]_{IN} - \left[W_{b,OUT} - P_0\left(Vol_2 - Vol_1\right)\right]_{OUT}$$

$$\Delta S = \sum \frac{Q_{K,IN}}{T_K} - \Sigma \frac{Q_{K,OUT}}{T_K} + S_{GEN}$$

$$\Delta\Phi = U_2 - U_1 - T_0\left(S_2 - S_1\right) + P_0\left(Vol_2 - Vol_1\right) + \Delta KE + \Delta PE$$

$$\Delta\Phi = \Sigma\left(1 - \frac{T_0}{T_K}\right)Q_{K,IN} - \sum\left(1 - \frac{T_0}{T_K}\right)Q_{K,OUT} + \left[W_{b,IN} - P_0\left(Vol_2 - Vol_1\right)\right]_{IN} - \left[W_{b,OUT} - P_0\left(Vol_2 - Vol_1\right)\right]_{OUT} - X_{DEST}$$

$$X_{DEST} = T_0 S_{GEN}$$

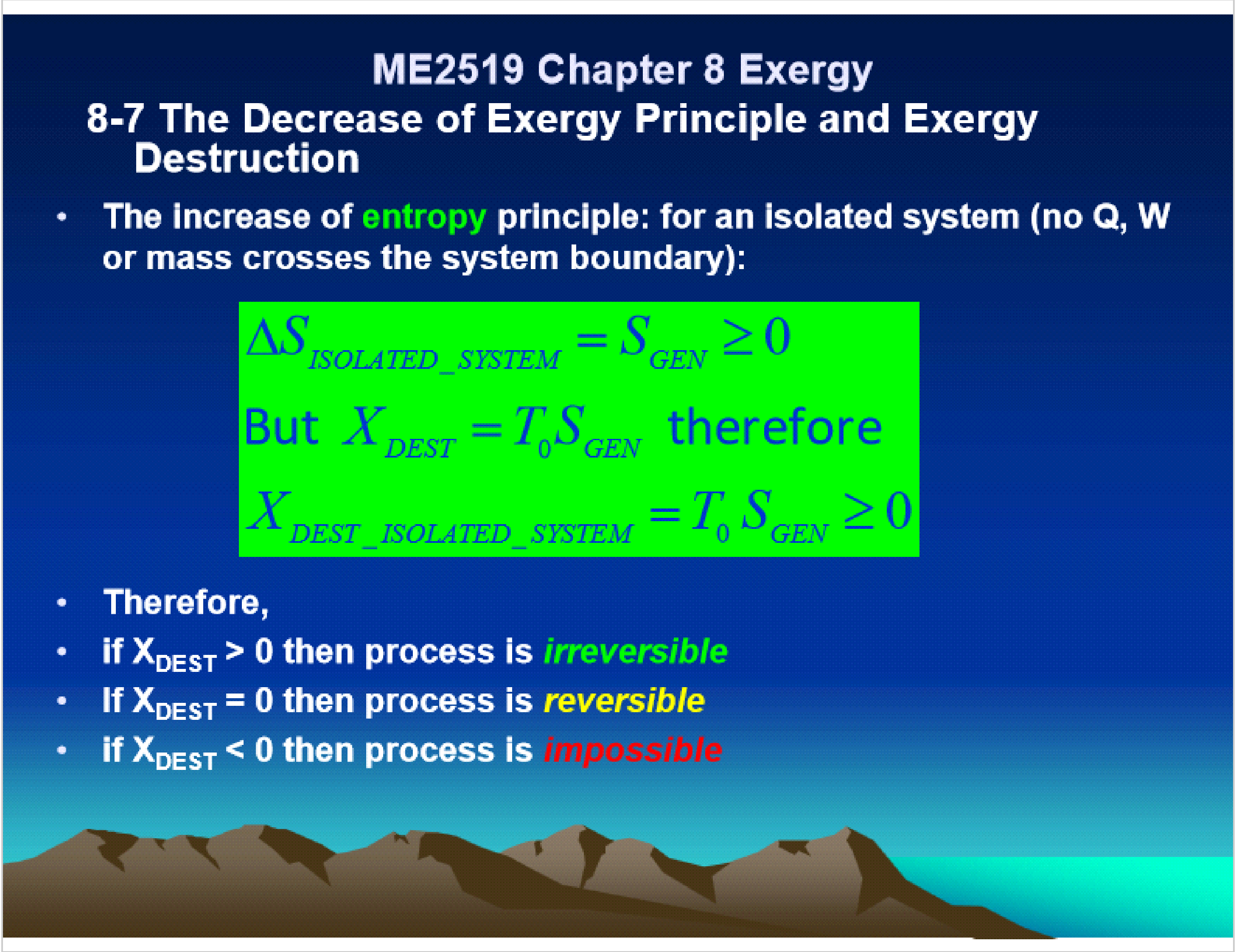


ME2519 Chapter 8 Exergy

8-7 Exergy Balance for Closed Systems

Closed System Equations:

$$\Delta U + \Delta KE + \Delta PE = \Sigma Q_{in} - \Sigma Q_{out} + W_{in} - W_{out}$$



ME2519 Chapter 8 Exergy

8-7 The Decrease of Exergy Principle and Exergy Destruction

- The increase of entropy principle: for an isolated system (no Q, W or mass crosses the system boundary):

$$\Delta S_{ISOLATED\_SYSTEM} = S_{GEN} \geq 0$$

But $X_{DEST} = T_0 S_{GEN}$ therefore

$$X_{DEST\_ISOLATED\_SYSTEM} = T_0 S_{GEN} \geq 0$$

- Therefore,
- if $X_{DEST} > 0$ then process is *irreversible*
- If $X_{DEST} = 0$ then process is ***reversible***
- if $X_{DEST} < 0$ then process is *impossible*

Homework 8b

Friday, December 2, 2022 10:27 AM

8–28 A mass of 8 kg of helium undergoes a process from an initial state of 3 m^3/kg and 15°C to a final state of 0.5 m^3/kg and 80°C. Assuming the surroundings to be at 25°C and 100 kPa, determine the increase in the useful work potential of the helium during this process.

$\Delta \Phi = \Delta U + \Delta \cancelto{0}{KE} + \Delta \cancelto{0}{PE} - T_0 \Delta S + P_0(\Delta V_{ol})$

$M = 8kg$

$v_1 = 3\ m^3/kg$

$T_1 = 15°C = 288\ K$

$\Delta U = M\Delta u = m C_v \Delta T$

$\Delta U = 8kg(3.1156\ \frac{kJ}{kg \cdot k})(358-288) = 1620.1\ kJ$

A-2

$v_2 = .5\ m^3/kg$

$T_2 = 80°C = 358$

$T_0 = 25°C = 298\ K$

$P_0 = 100\ kPa$

$\Delta S = M \Delta s = m(C_v \ln \frac{T_2}{T_1} + R \ln \frac{V_2}{V_1})$

$= 8kg(3.1156\ \frac{kJ}{kg \cdot k} \ln \frac{358}{298} + 2.0769\ \frac{kJ}{kg \cdot k} \ln \frac{.5}{3}$

$\Delta S = -24.698\ \frac{kJ}{K}$

$T_0 \Delta S = 298(-24.698) = -7360\ kJ$

$P_0 \Delta S = P_0(m v_2 - m v_1) = 100kPa(8kg)(.5-3)$

$= -2000\ kJ$

$\Delta \Phi = 1620.1\ kJ - 7360\ kJ - 2000\ kJ$

$\boxed{\Delta \Phi = 6980.1\ kJ}$

8–31 The radiator of a steam heating system has a volume of 20 L and is filled with superheated water vapor at 200 kPa and 200°C. At this moment both the inlet and the exit valves to the radiator are closed. After a while it is observed that the temperature of the steam drops to 80°C as a result of heat transfer to the room air, which is at 21°C. Assuming the surroundings to be at 0°C, determine (*a*) the amount of heat transfer to the room and (*b*) the maximum amount of heat that can be supplied to the room if this heat from the radiator is supplied to a heat engine that is driving a heat pump. Assume the heat engine operates between the radiator and the surroundings. *Answer: (a) 30.3 kJ, (b) 116 kJ*

page 462

b) 116 kJ

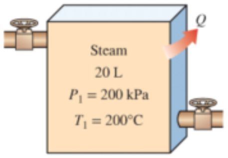


FIGURE P8–31

$Vol = 20L = .02\ m^3$

$T_1 = 200°C = 473\ K$

$P_1 = 200\ kPa$

$T_2 = 80°C = 353\ K$

$T_{air} = 21°C = 294K$

$T_0 = 0°C = 273\ K$

a.

A-6:

$v_1 = 1.08049\ m^3/kg$

$u_1 = 2654.6\ kJ/kg$

$s_1 = 7.5081\ kJ/kg \cdot K$

$M = \frac{Vol}{v} = \frac{.02}{1.08049} = .01851\ kg$

A-4: Sat. mix

$V_1 = V_2$

$x_2 = \frac{V_2 - V_f}{V_g - V_f} = \frac{1.08049 - .001029}{3.4053 - .001029} = .3171$

$$u_2 = u_f + x_2 u_{fg} = 334.97 + .3171(2146.6) = 1015.7$$

$$s_2 = s_f + x_2 s_{fg} = 1.0756 + 3171(6.57553) = 3.148$$

$$\Delta U = -Q_{out}$$

$$Q_{out} = -m\Delta u = .01851(2654.6 - 10157)$$

$$\boxed{Q_{out} = 30.34\ kJ}$$

b. $$\Delta \Phi = \left(1 - \frac{T_0}{T_{in}}\right)\cancelto{0}{Q_{in}} - \cancelto{0}{\left(1 - \frac{T_0}{T_{out}}\right)} Q_{out} - W_{out,rev} - \cancelto{0}{X_{des}} + \cancelto{0}{W_{in}}$$

$$u_2 - u_1 - T_0 \Delta S + P_0 \cancelto{0, const.}{\Delta Vol} = -W_{out,rev}$$

$$W_{out,rev} = U_1 - U_2 + T_0 \Delta S$$

$$= .01851(2654.6 - 1015.7 + 273(3.148 - 7.5081))$$

$$= 8.3\ kJ$$

$$Q_{H\,max} = COP\ W_{in}$$

$$= \frac{1}{1 - \frac{T_L}{T_H}} W_{out,rev} = \frac{1}{1 - \frac{273}{294}}(8.3)$$

$$\boxed{Q_{H,max} = 116.2\ kJ}$$

8–34 A piston–cylinder device contains 8 kg of refrigerant-134a at 0.7 MPa and 60°C. The refrigerant is now cooled at constant pressure until it exists as a liquid at 20°C. If the surroundings are at 100 kPa and 20°C, determine (*a*) the exergy of the refrigerant at the initial and the final states and (*b*) the exergy destroyed during this process.

a. A-17:

$m = 8\ kg$
$P_1 = .7\ MPa$
$T_1 = 60°C = 333\ K$

$T_2 = 20°C = 293\ K$
$T_0 = 20°C = 293\ K$
$P_0 = 100\ kPa$

$v_1 = .034875$
$u_1 = 274.07$
$s_1 = 1.0257$

$Vol_1 = m v_1 = .279\ m^3$

A-11:

$v_2 = .000816$
$u_2 = 78.85$
$s_2 = .30062$

$$\Phi = U - U_0 - T_0(S - S_0) + P_0(Vol - Vol_0) + \cancelto{0}{KE} + \cancelto{0}{PE}$$

$$\Phi = m(u_1 - u_0 - T_0(s_1 - s_0) + P_0(v_1 - v_0))$$

$$\Phi_1 = 8(274.07 - 248.81 - 293(1.0257 - 1.0919) + 100(.034875 - .23373))$$

$$\boxed{\Phi_1 = 197.85\ kJ}$$

$$\Phi_2 = 8(78.85 - 248.81 - 293(.30062 - 1.0919 + 100(.000816 - .23373)))$$

$$\boxed{\Phi_2 = 308.47 \text{ kJ}}$$

b. $\Delta \Phi = W_{b,in} + P_0 \Delta Vol - X_{des}$

$= P(Vol_1 - Vol_2) - P_0(Vol_1 - Vol_2) - X_{des}$

$X_{des} = \Phi_1 - \Phi_2 + (P + P_0)(Vol_1 - Vol_2)$

$X_{des} = 197.85 - 308.47 + (700 \text{ kPa} - 100 \text{ kPa})(.279 - .006528)$

$$\boxed{X_{des} = 52.9 \text{ kJ}}$$

8–48 A piston–cylinder device initially contains 1.4 kg of refrigerant-134a at 100 kPa and 20°C. Heat is now transferred to the refrigerant from a source at 150°C, and the piston, which is resting on a set of stops, starts moving when the pressure inside reaches 120 kPa. Heat transfer continues until the temperature reaches 80°C. Assuming the surroundings to be at 25°C and 100 kPa, determine (*a*) the work done, (*b*) the heat transfer, (*c*) the exergy destroyed, and (*d*) the second-law efficiency of this process. *Answer:* (*a*) 0.497 kJ, (*b*) 67.9 kJ, (*c*) 14.8 kJ, (*d*) 26.2 percent

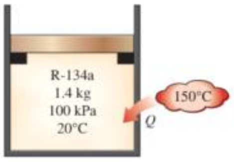


FIGURE P8–48

$m = 1.4 \text{ kg}$

$P_1 = 100 \text{ kPa}$

$T_1 = 20°C = 293 K$

$T_s = 150°C = 423 K$

$P_s = 120 \text{ kPa}$

$T_2 = 80°C = 353 K$

$T_0 = 25°C = 298 K$

$P_0 = 100 \text{ kPa}$

a. A-13:

$v_1 = .23373$

$u_1 = 248.81$

$s_1 = 1.0919$

A-13: Avg values

$v_2 = (.28465 + .20242)/2 = .24354$

$u_2 = (247.1 + 246.78)/2 = 246.94$

$s_2 = (1.2573 + 1.2289)/2 = 1.2431$

$W_{out} = P \Delta V_{ol} = 120 \text{ kPa} (1.4 \text{ kg})(.24354 - .23373)$

$$\boxed{W_{out} = 1.648 \text{ kJ}}$$

b. $\Delta U = Q_{in} - W_{out}$

$Q_{in} = m(u_2 - u_1) + W_{out} = 1.4(246.94 - 248.81) + 1.648$

$$\boxed{Q_{in} = 66.07 \text{ kJ}}$$

c. $\Delta S = \frac{Q_{in}}{T_{in}} - \cancel{\frac{Q_{out}}{T_{out}}}^{0} + S_{gen}$

$S_{gen} = m(s_2 - s_1) - \frac{Q_{in}}{T_{in}} = 1.4(1.2431 - 1.0919) - \frac{69.07}{423}$

$S_{gen} = .04849 \frac{\text{kJ}}{\text{K}}$

$X_{des} = T_0 S_{gen} = 298(.04849)$

$$\boxed{X_{des} = 14.45 \text{ kJ}}$$

$$\boxed{x_{des} = 14.45\ kJ}$$

d. $\Delta \Phi = \left(1 - \frac{T_0}{T_{in}}\right) Q_{in} - \left(1 - \frac{T_0}{T_{out}}\right) \cancel{Q_{out}}^{0} + \cancel{W_{in}}^{0} - W_{out}$

$= \left(1 - \frac{T_0}{T_{in}}\right) Q_{in} - (W_{b\,out} - P_0 m (v_2 - v_1)$

$\Delta \Phi = \left(1 - \frac{298}{423}\right)(64.07) - 16.48 + 100(1.4)(.24754 - .22377)$

$\Delta \Phi = 20.125\ kJ$

$\eta_{II} = 1 - \frac{x_{des}}{\Delta \Phi} = 1 - \frac{14.45}{20.125}$

$$\boxed{\eta_{II} = 28.2\%}$$

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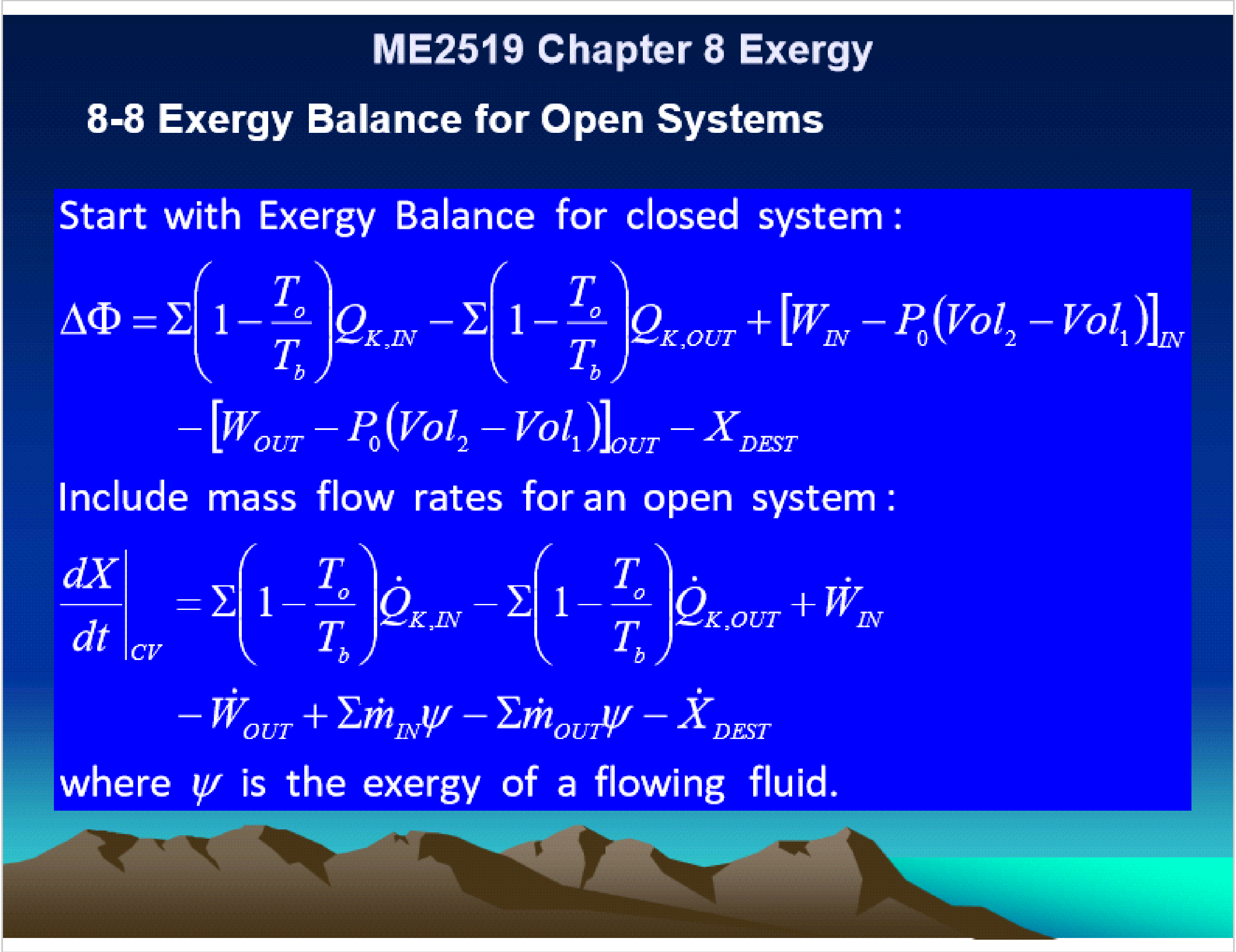


ME2519 Chapter 8 Exergy

8-8 Exergy Balance for Open Systems

Start with Exergy Balance for closed system:

$$\Delta\Phi = \Sigma\left(1-\frac{T_o}{T_b}\right)Q_{K,IN} - \Sigma\left(1-\frac{T_o}{T_b}\right)Q_{K,OUT} + \left[W_{IN} - P_0\left(Vol_2 - Vol_1\right)\right]_{IN}$$

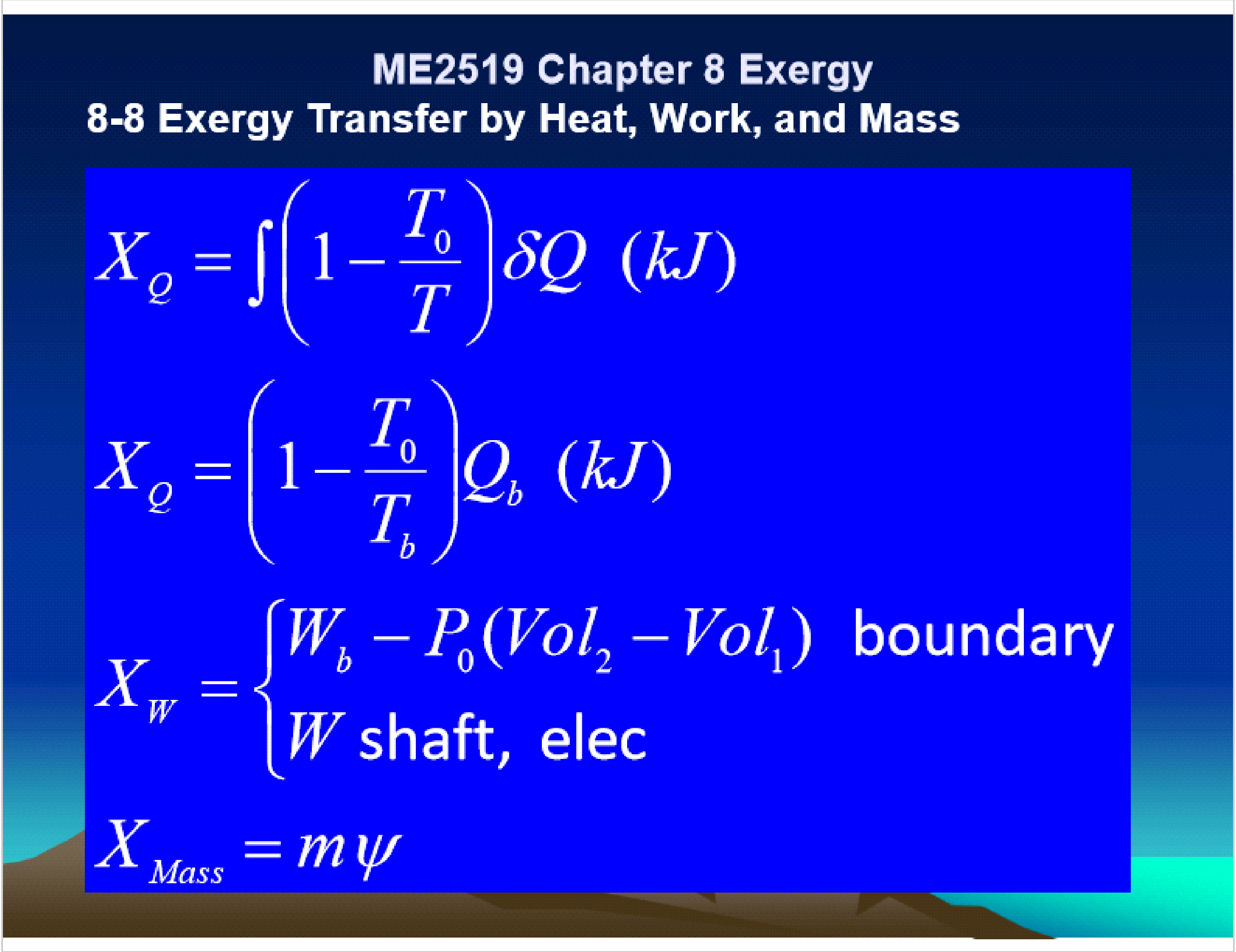
$$- \left[W_{OUT} - P_0\left(Vol_2 - Vol_1\right)\right]_{OUT} - X_{DEST}$$

Include mass flow rates for an open system:

$$\left.\frac{dX}{dt}\right|_{CV} = \Sigma\left(1-\frac{T_o}{T_b}\right)\dot{Q}_{K,IN} - \Sigma\left(1-\frac{T_o}{T_b}\right)\dot{Q}_{K,OUT} + \dot{W}_{IN}$$

$$- \dot{W}_{OUT} + \Sigma\dot{m}_{IN}\psi - \Sigma\dot{m}_{OUT}\psi - \dot{X}_{DEST}$$

where ψ is the exergy of a flowing fluid.



ME2519 Chapter 8 Exergy

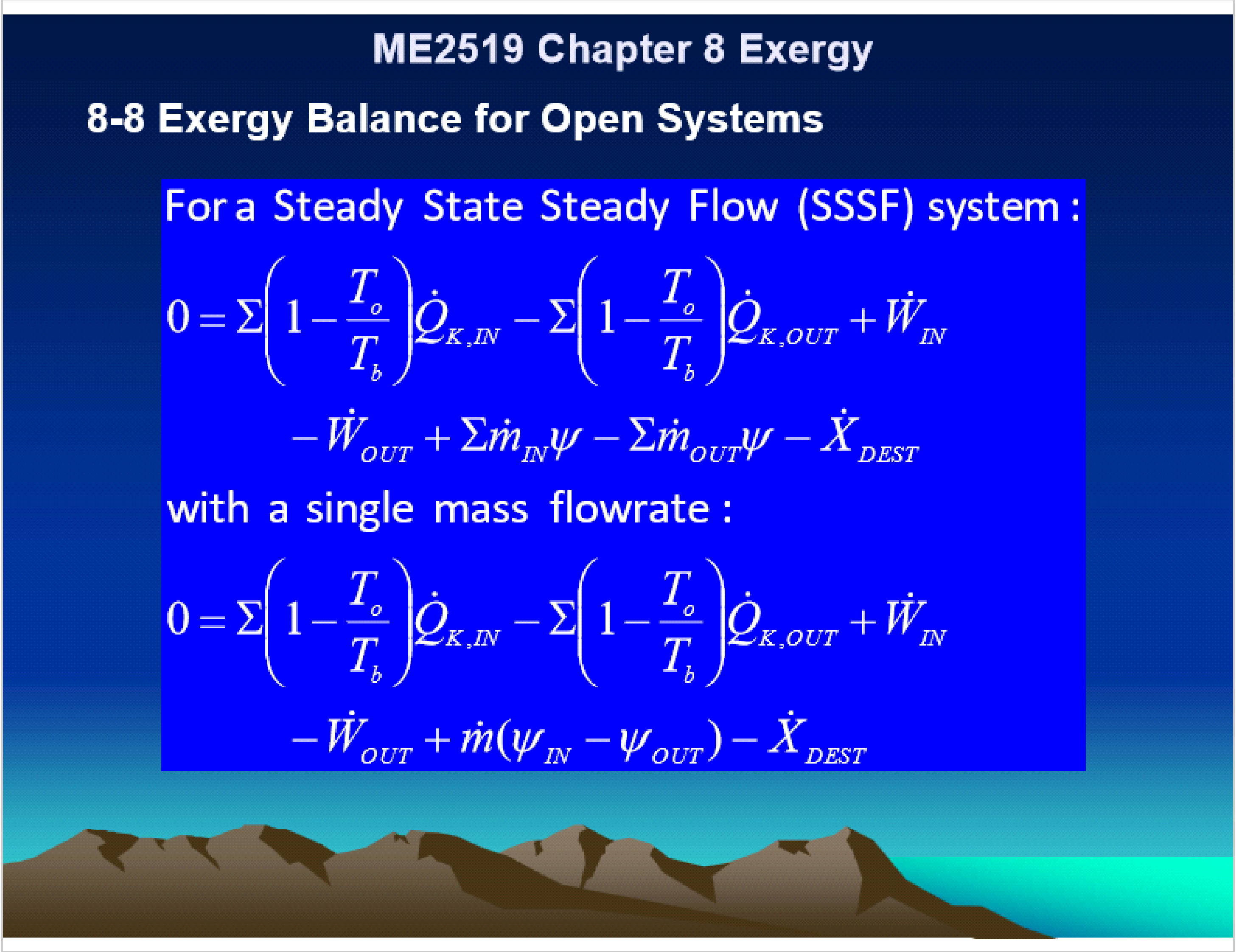
8-8 Exergy Transfer by Heat, Work, and Mass

$$X_Q = \int \left(1 - \frac{T_0}{T}\right) \delta Q \ \ (kJ)$$

$$X_Q = \left(1 - \frac{T_0}{T_b}\right) Q_b \ \ (kJ)$$

$$X_W = \begin{cases} W_b - P_0(Vol_2 - Vol_1) & \text{boundary} \\ W \text{ shaft, elec} & \end{cases}$$

$$X_{Mass} = m\psi$$



ME2519 Chapter 8 Exergy

8-8 Exergy Balance for Open Systems

For a Steady State Steady Flow (SSSF) system :

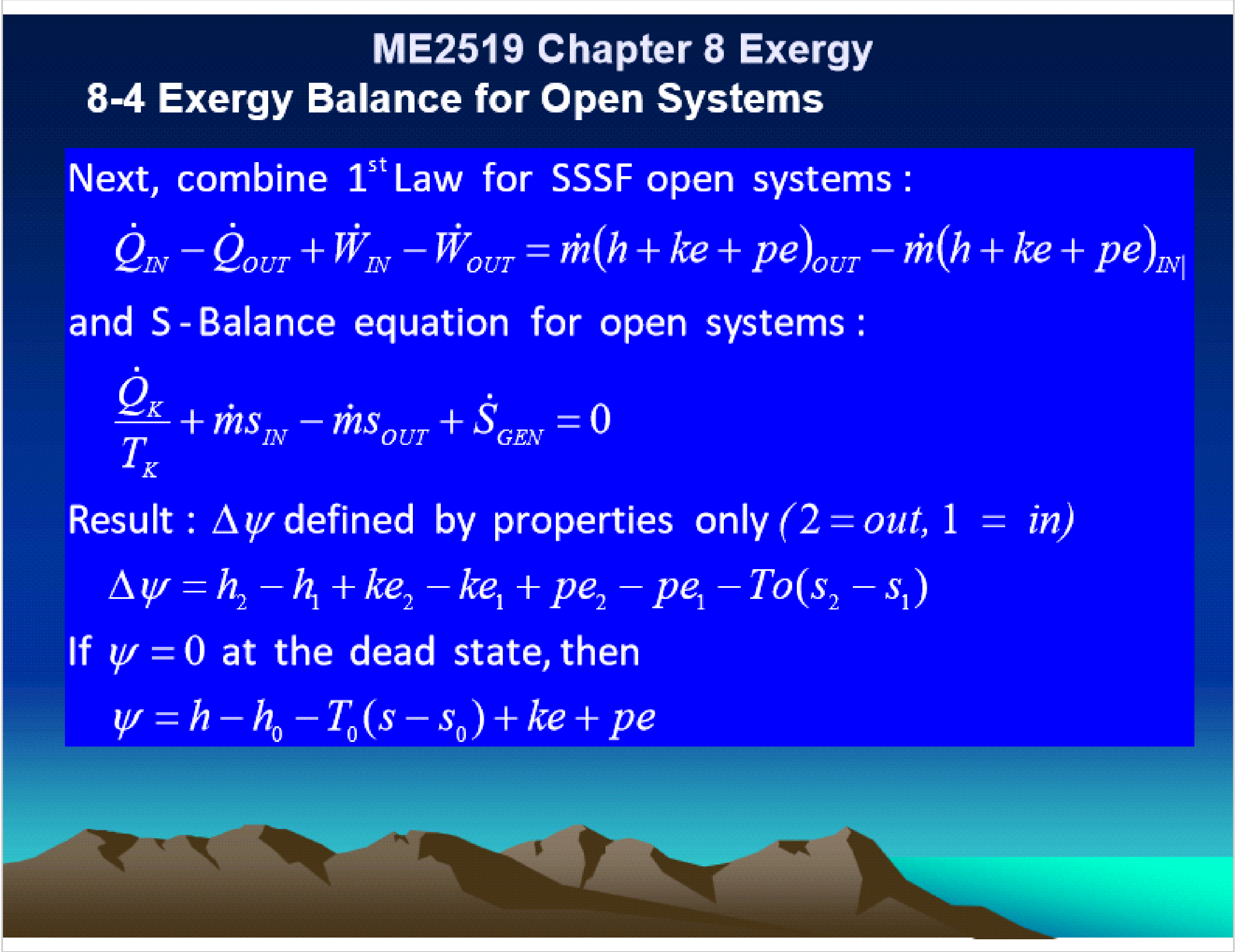
$$0 = \Sigma\left(1 - \frac{T_o}{T_b}\right)\dot{Q}_{K,IN} - \Sigma\left(1 - \frac{T_o}{T_b}\right)\dot{Q}_{K,OUT} + \dot{W}_{IN}$$

$$- \dot{W}_{OUT} + \Sigma\dot{m}_{IN}\psi - \Sigma\dot{m}_{OUT}\psi - \dot{X}_{DEST}$$

with a single mass flowrate :

$$0 = \Sigma\left(1 - \frac{T_o}{T_b}\right)\dot{Q}_{K,IN} - \Sigma\left(1 - \frac{T_o}{T_b}\right)\dot{Q}_{K,OUT} + \dot{W}_{IN}$$

$$- \dot{W}_{OUT} + \dot{m}(\psi_{IN} - \psi_{OUT}) - \dot{X}_{DEST}$$



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8-4 Exergy Balance for Open Systems

Next, combine 1st Law for SSSF open systems:

$$\dot{Q}_{IN} - \dot{Q}_{OUT} + \dot{W}_{IN} - \dot{W}_{OUT} = \dot{m}(h + ke + pe)_{OUT} - \dot{m}(h + ke + pe)_{IN}$$

and S-Balance equation for open systems:

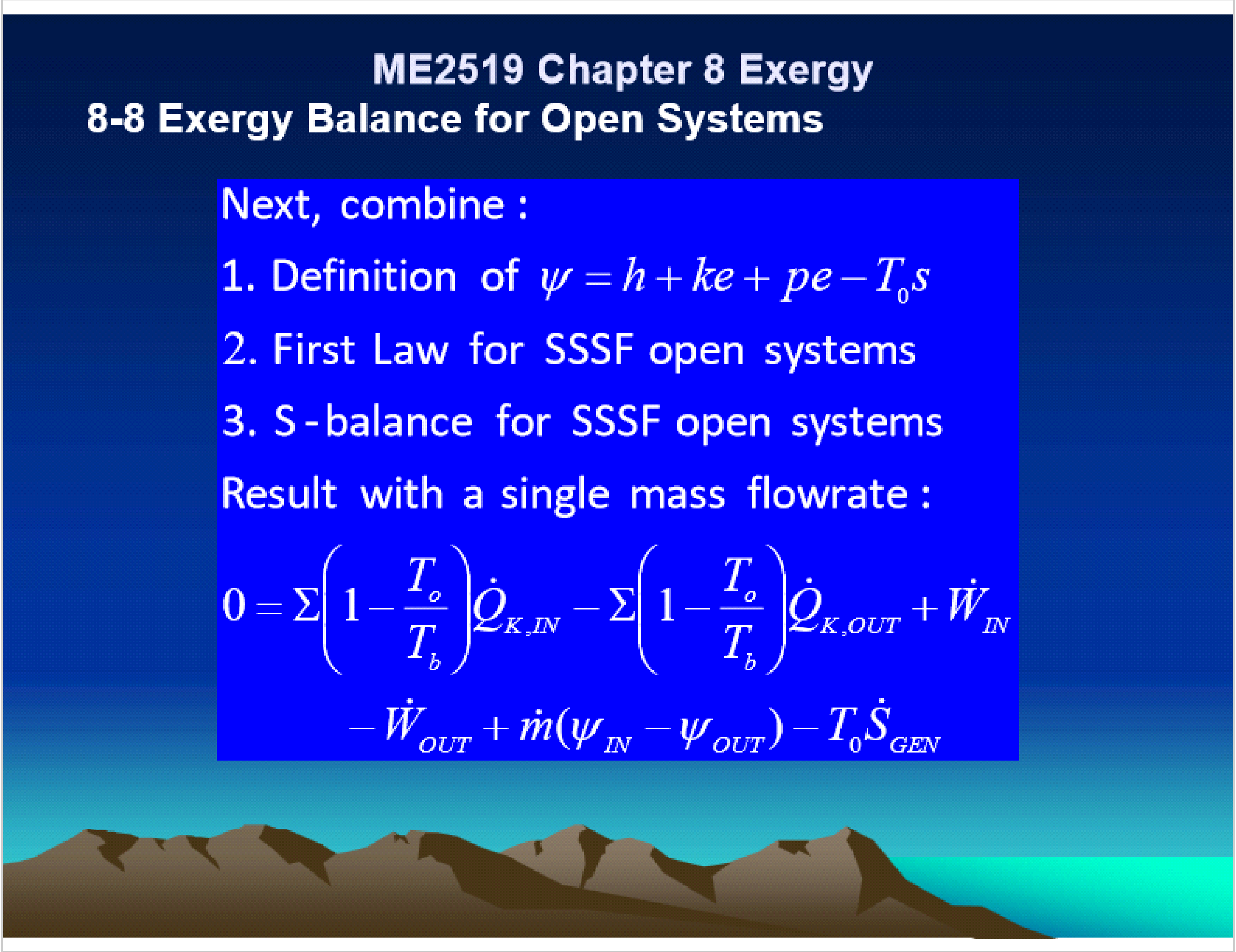
$$\frac{\dot{Q}_K}{T_K} + \dot{m}s_{IN} - \dot{m}s_{OUT} + \dot{S}_{GEN} = 0$$

Result : $\Delta\psi$ defined by properties only $(2 = out, 1 = in)$

$$\Delta\psi = h_2 - h_1 + ke_2 - ke_1 + pe_2 - pe_1 - To(s_2 - s_1)$$

If $\psi = 0$ at the dead state, then

$$\psi = h - h_0 - T_0(s - s_0) + ke + pe$$



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8-8 Exergy Balance for Open Systems

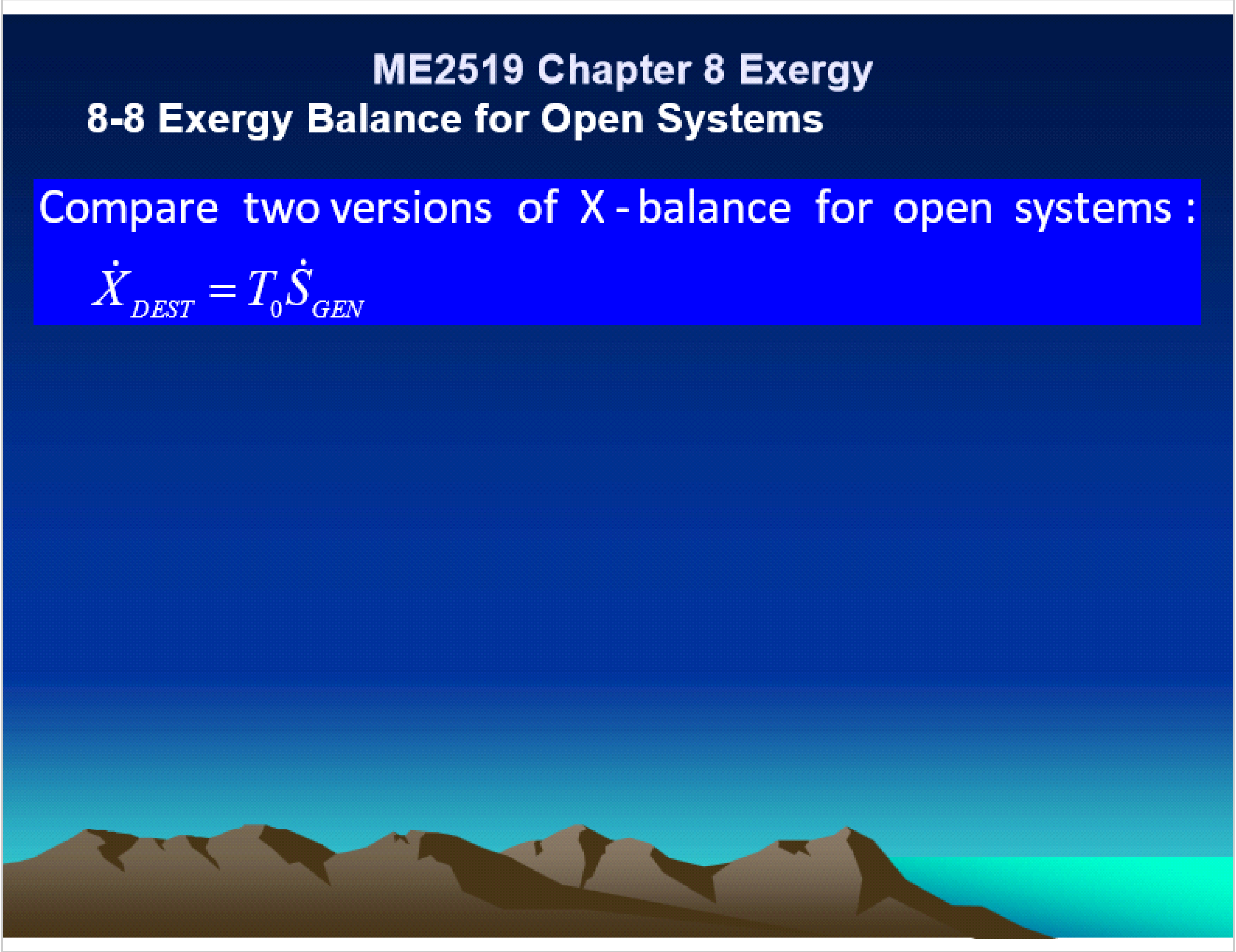
Next, combine :

1. Definition of $\psi = h + ke + pe - T_0 s$
2. First Law for SSSF open systems
3. S-balance for SSSF open systems

Result with a single mass flowrate :

$$0 = \Sigma\left(1 - \frac{T_o}{T_b}\right)\dot{Q}_{K,IN} - \Sigma\left(1 - \frac{T_o}{T_b}\right)\dot{Q}_{K,OUT} + \dot{W}_{IN}$$

$$-\dot{W}_{OUT} + \dot{m}(\psi_{IN} - \psi_{OUT}) - T_0 \dot{S}_{GEN}$$



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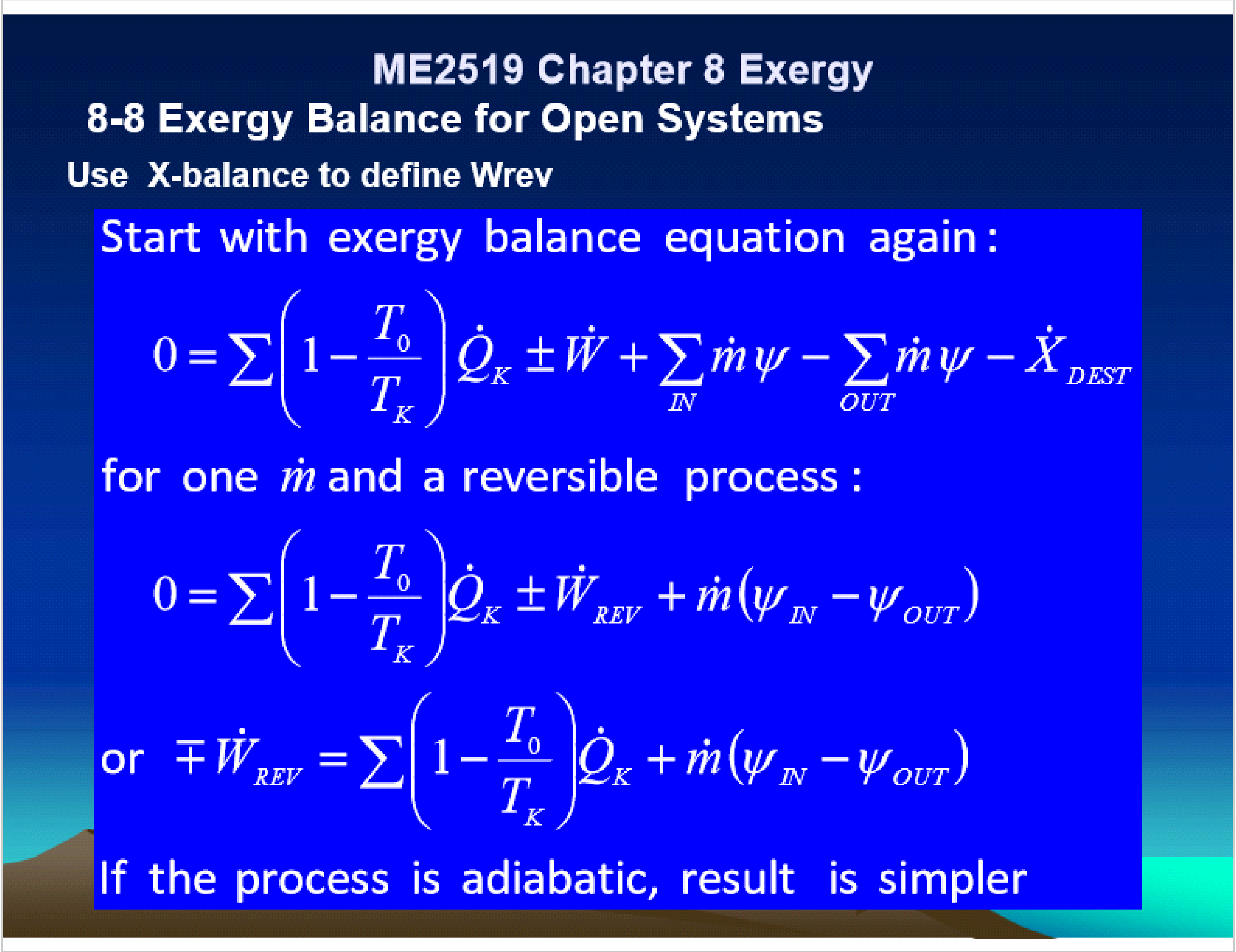
8-8 Exergy Balance for Open Systems

Compare two versions of X - balance for open systems :

$$\dot{X}_{DEST} = T_0 \dot{S}_{GEN}$$



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8-8 Exergy Balance for Open Systems

Use X-balance to define Wrev

Start with exergy balance equation again:

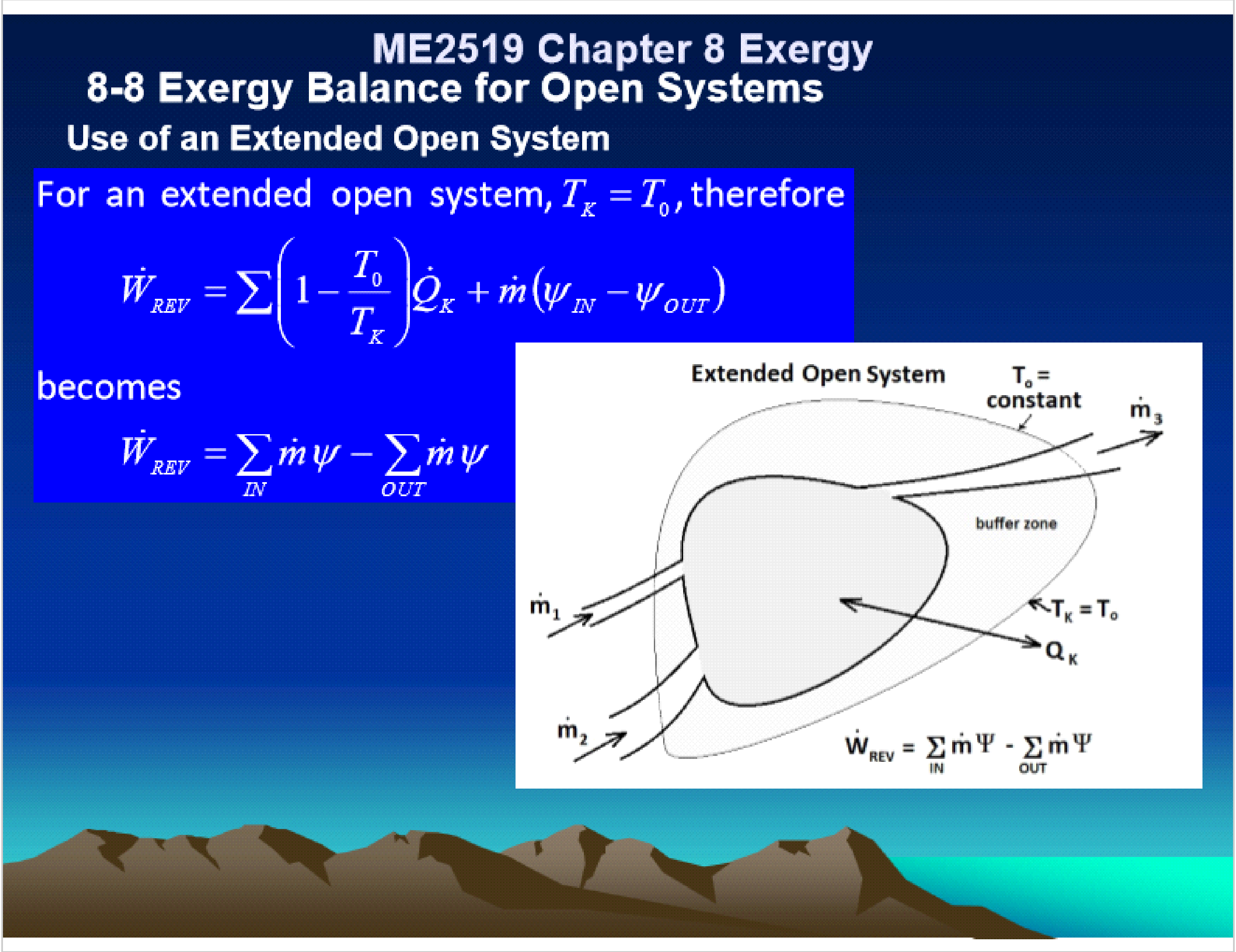
$$0=\sum\left(1-\frac{T_0}{T_K}\right)\dot{Q}_K \pm \dot{W}+\sum_{IN}\dot{m}\psi-\sum_{OUT}\dot{m}\psi-\dot{X}_{DEST}$$

for one $\dot{m}$ and a reversible process:

$$0=\sum\left(1-\frac{T_0}{T_K}\right)\dot{Q}_K \pm \dot{W}_{REV}+\dot{m}\left(\psi_{IN}-\psi_{OUT}\right)$$

or $\mp\dot{W}_{REV}=\sum\left(1-\frac{T_0}{T_K}\right)\dot{Q}_K+\dot{m}\left(\psi_{IN}-\psi_{OUT}\right)$

If the process is adiabatic, result is simpler



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8-8 Exergy Balance for Open Systems

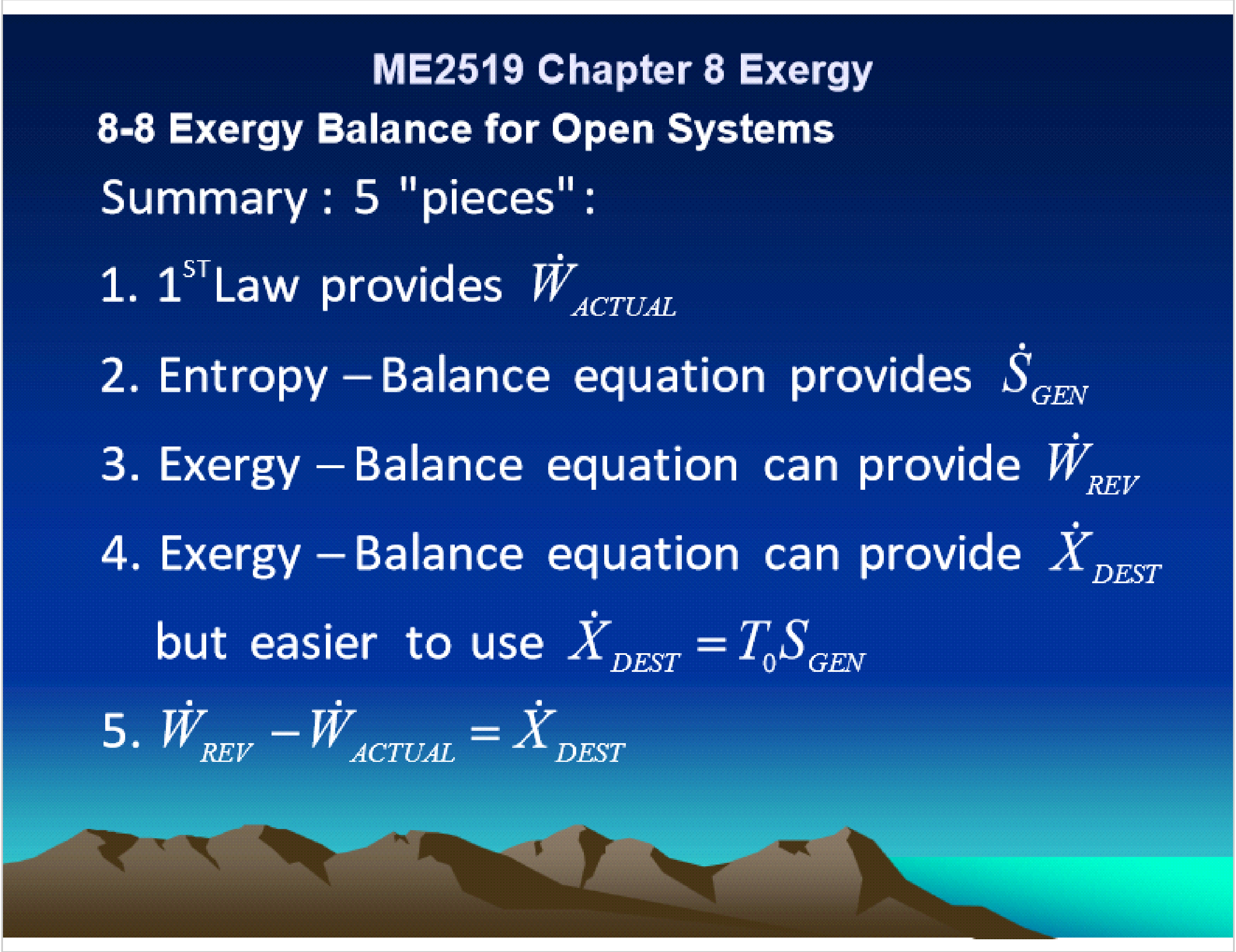
Use of an Extended Open System

For an extended open system, $T_K = T_0$, therefore

$$\dot{W}_{REV} = \sum\left(1 - \frac{T_0}{T_K}\right)\dot{Q}_K + \dot{m}\left(\psi_{IN} - \psi_{OUT}\right)$$

becomes

$$\dot{W}_{REV} = \sum_{IN}\dot{m}\,\psi - \sum_{OUT}\dot{m}\,\psi$$



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8-8 Exergy Balance for Open Systems

Summary : 5 "pieces":

1. 1^{ST} Law provides $\dot{W}_{ACTUAL}$

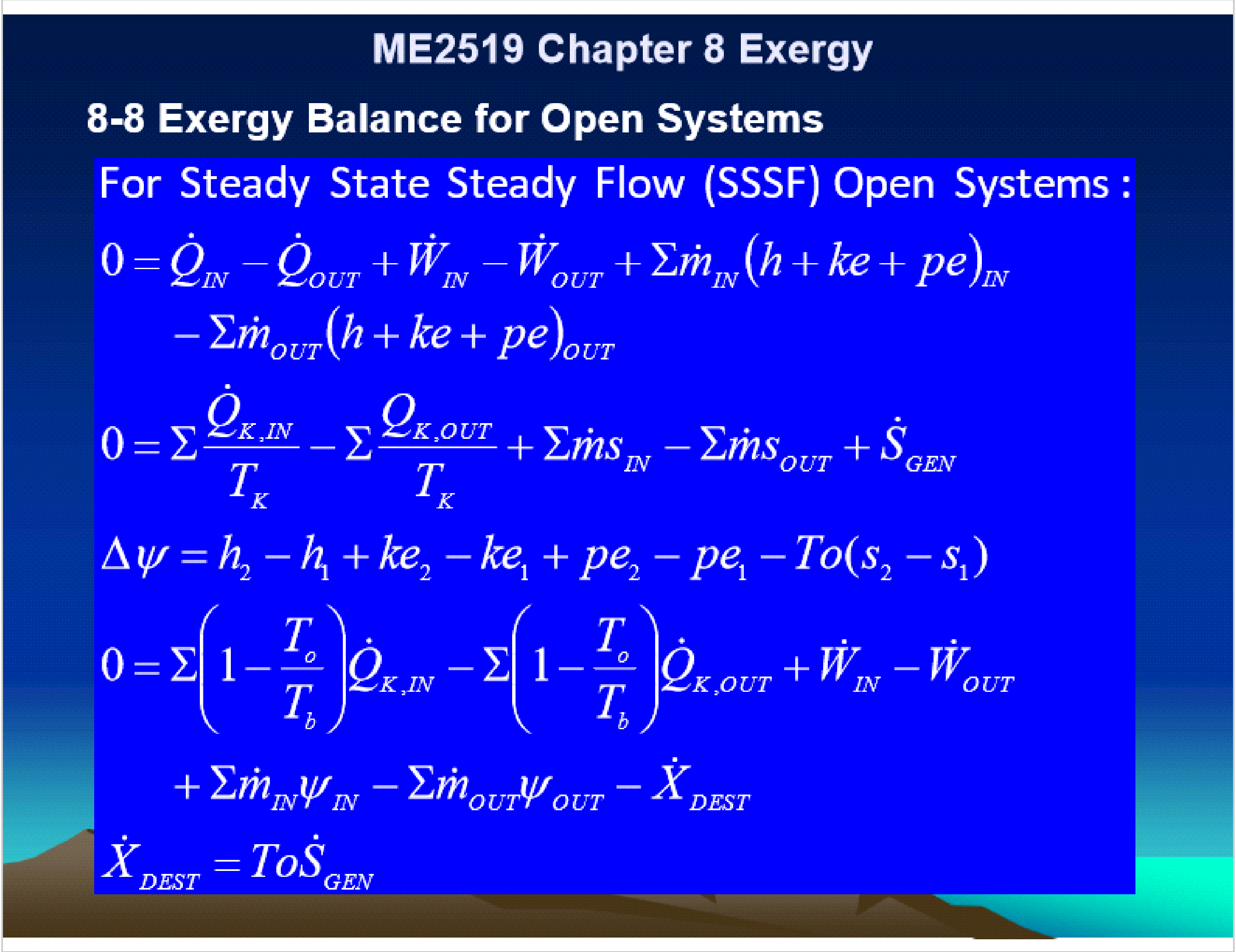
2. Entropy – Balance equation provides $\dot{S}_{GEN}$

3. Exergy – Balance equation can provide $\dot{W}_{REV}$

4. Exergy – Balance equation can provide $\dot{X}_{DEST}$

   but easier to use $\dot{X}_{DEST} = T_0 S_{GEN}$

5. $\dot{W}_{REV} - \dot{W}_{ACTUAL} = \dot{X}_{DEST}$



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8-8 Exergy Balance for Open Systems

For Steady State Steady Flow (SSSF) Open Systems :

$$0 = \dot{Q}_{IN} - \dot{Q}_{OUT} + \dot{W}_{IN} - \dot{W}_{OUT} + \Sigma\dot{m}_{IN}(h + ke + pe)_{IN}$$

$$- \Sigma\dot{m}_{OUT}(h + ke + pe)_{OUT}$$

$$0 = \Sigma\frac{\dot{Q}_{K,IN}}{T_K} - \Sigma\frac{Q_{K,OUT}}{T_K} + \Sigma\dot{m}s_{IN} - \Sigma\dot{m}s_{OUT} + \dot{S}_{GEN}$$

$$\Delta\psi = h_2 - h_1 + ke_2 - ke_1 + pe_2 - pe_1 - To(s_2 - s_1)$$

$$0 = \Sigma\left(1 - \frac{T_o}{T_b}\right)\dot{Q}_{K,IN} - \Sigma\left(1 - \frac{T_o}{T_b}\right)\dot{Q}_{K,OUT} + \dot{W}_{IN} - \dot{W}_{OUT}$$

$$+ \Sigma\dot{m}_{IN}\psi_{IN} - \Sigma\dot{m}_{OUT}\psi_{OUT} - \dot{X}_{DEST}$$

$$\dot{X}_{DEST} = To\dot{S}_{GEN}$$

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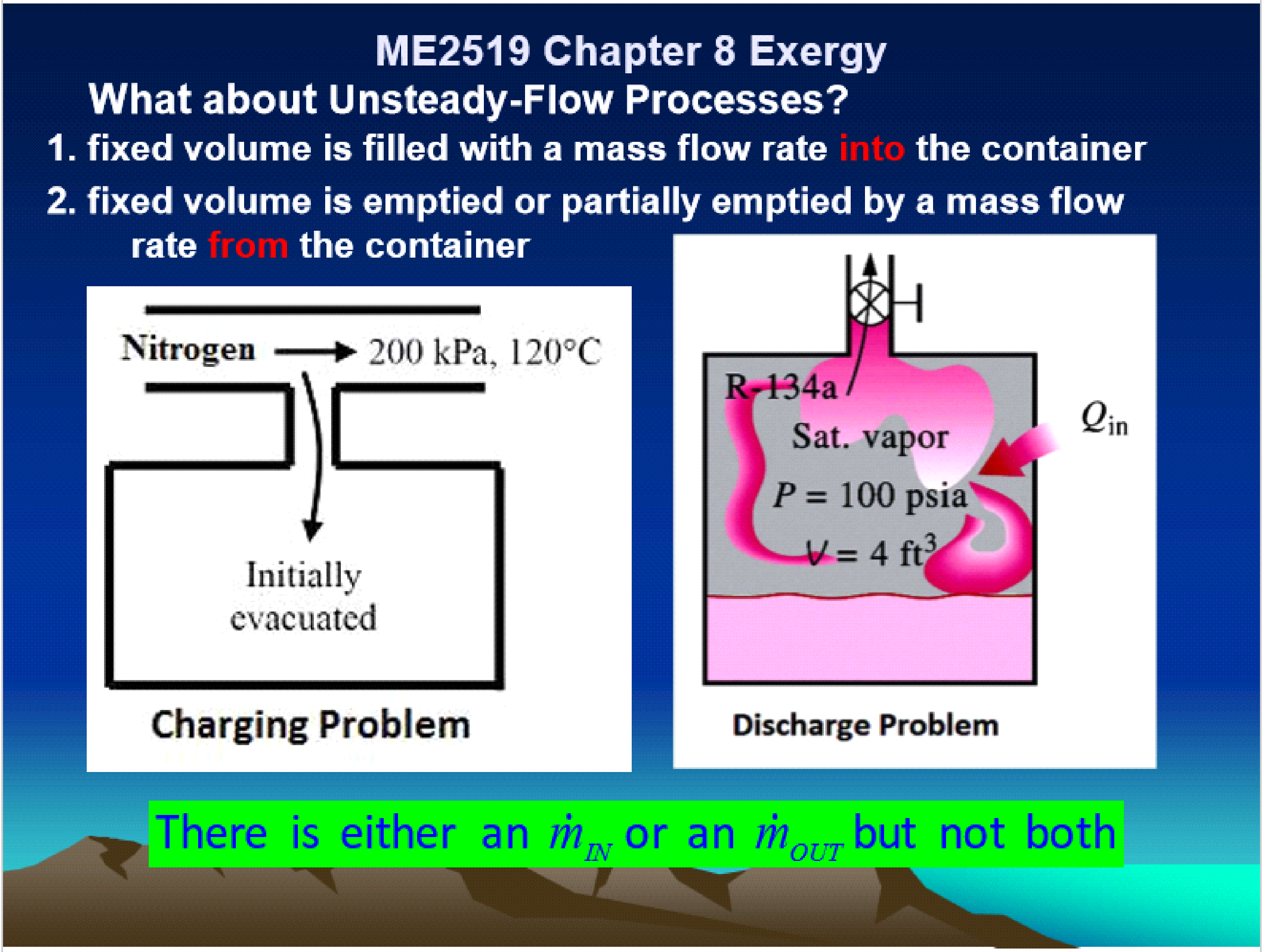

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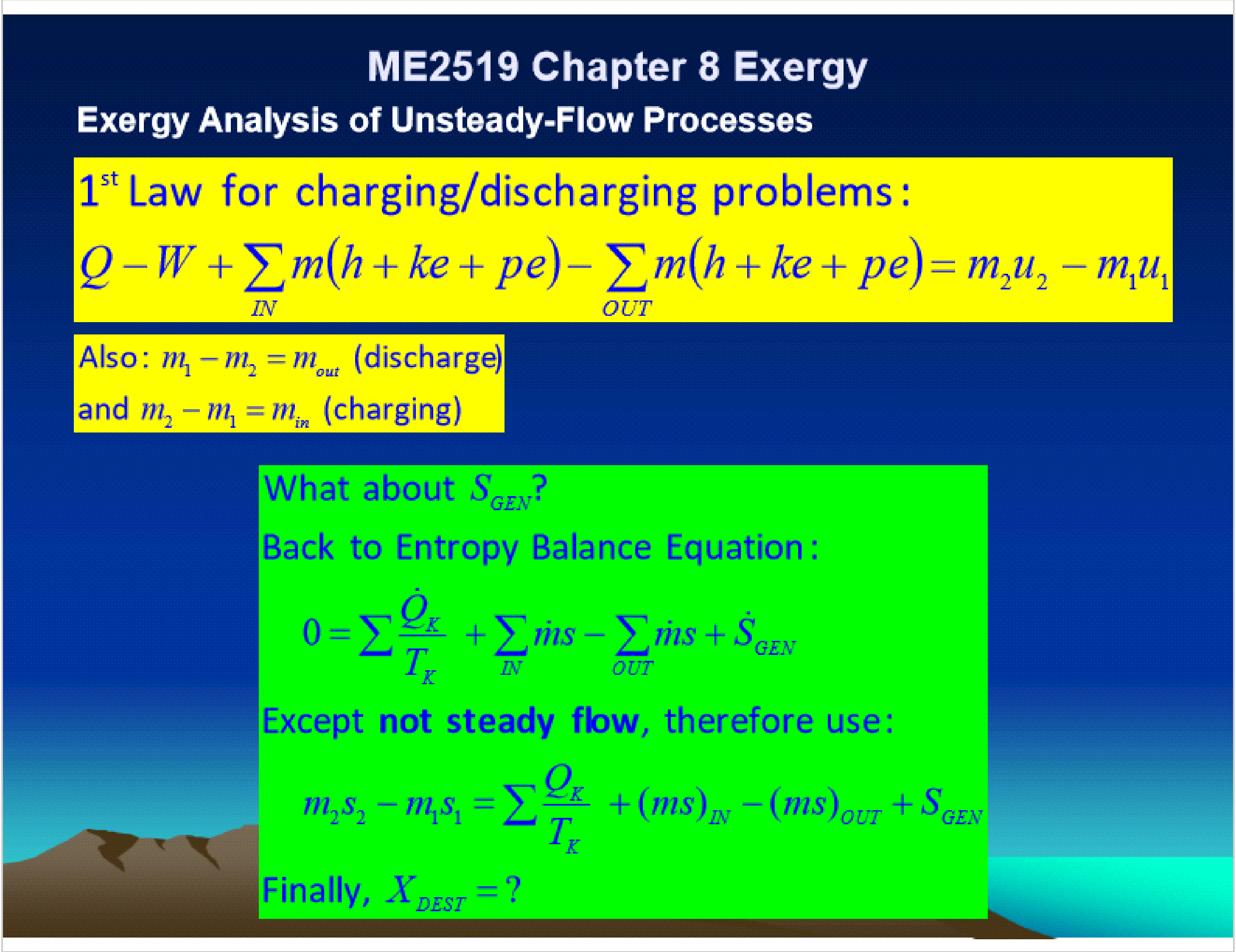
What about Unsteady-Flow Processes?

1. fixed volume is filled with a mass flow rate into the container
2. fixed volume is emptied or partially emptied by a mass flow rate from the container

Charging Problem

Discharge Problem

There is either an $\dot{m}_{IN}$ or an $\dot{m}_{OUT}$ but not both



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Exergy Analysis of Unsteady-Flow Processes

1st Law for charging/discharging problems:

$$Q - W + \sum_{IN} m\left(h + ke + pe\right) - \sum_{OUT} m\left(h + ke + pe\right) = m_2 u_2 - m_1 u_1$$

Also: $m_1 - m_2 = m_{out}$ (discharge)

and $m_2 - m_1 = m_{in}$ (charging)

What about S_{GEN}?

Back to Entropy Balance Equation:

$$0 = \sum \frac{\dot{Q}_K}{T_K} + \sum_{IN} \dot{m}s - \sum_{OUT} \dot{m}s + \dot{S}_{GEN}$$

Except **not steady flow**, therefore use:

$$m_2 s_2 - m_1 s_1 = \sum \frac{Q_K}{T_K} + (ms)_{IN} - (ms)_{OUT} + S_{GEN}$$

Finally, $X_{DEST} = ?$

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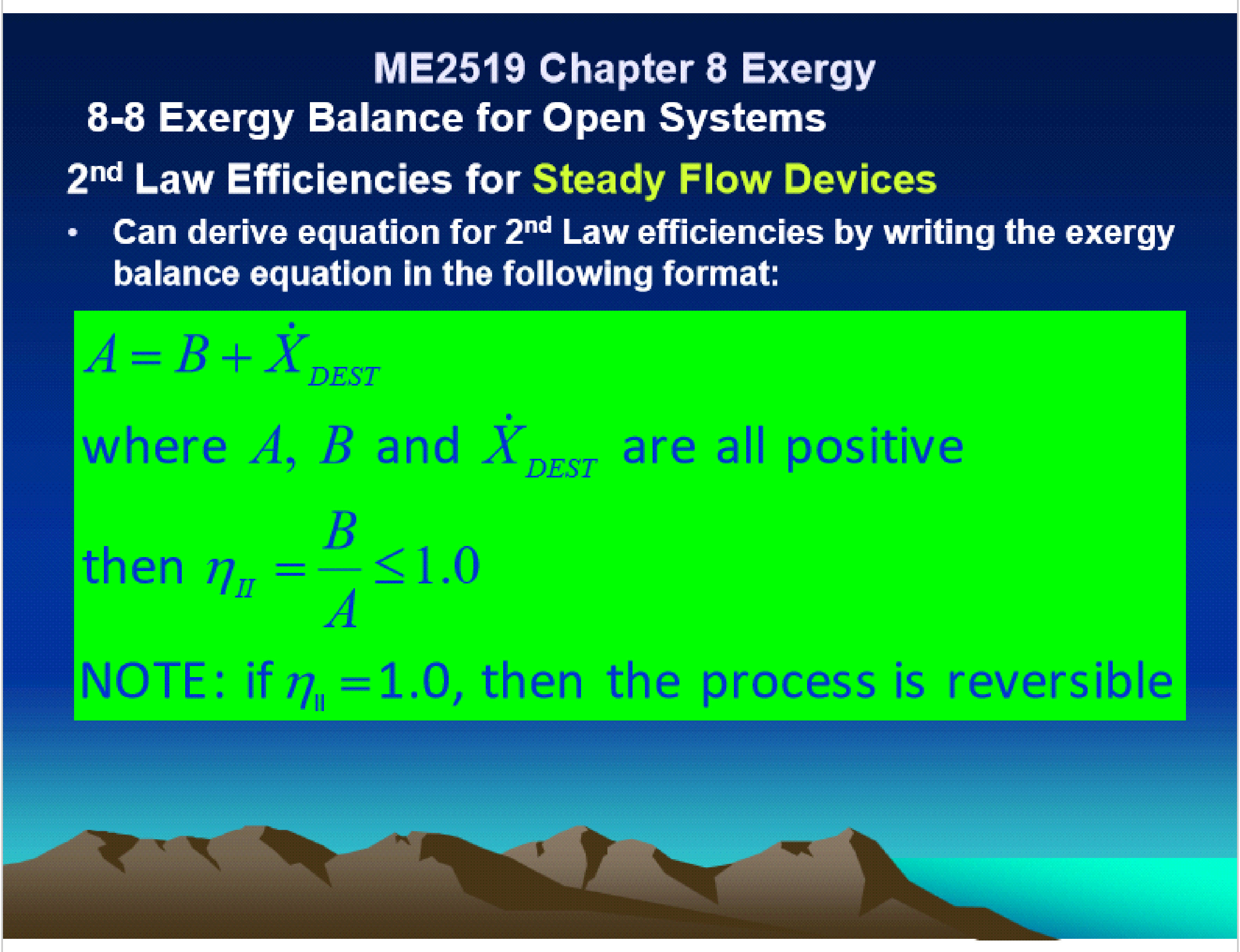

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8-8 Exergy Balance for Open Systems

2nd Law Efficiencies for Steady Flow Devices

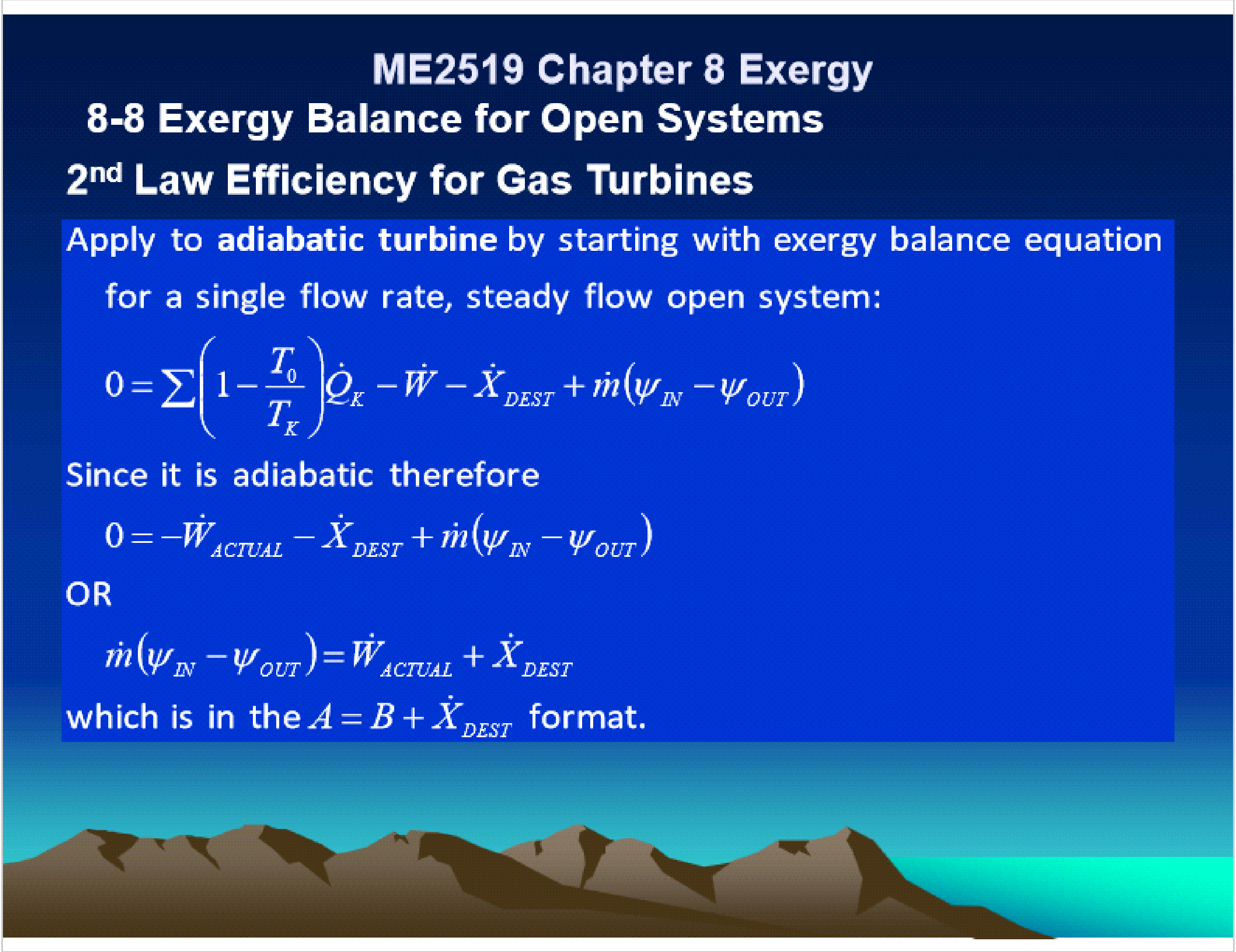
- Can derive equation for 2nd Law efficiencies by writing the exergy balance equation in the following format:

$$A = B + \dot{X}_{DEST}$$

where A, B and $\dot{X}_{DEST}$ are all positive

then $\eta_{II} = \frac{B}{A} \leq 1.0$

NOTE: if $\eta_{II} = 1.0$, then the process is reversible



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8-8 Exergy Balance for Open Systems

2nd Law Efficiency for Gas Turbines

Apply to **adiabatic turbine** by starting with exergy balance equation for a single flow rate, steady flow open system:

$$0=\sum\left(1-\frac{T_0}{T_K}\right)\dot{Q}_K-\dot{W}-\dot{X}_{DEST}+\dot{m}\left(\psi_{IN}-\psi_{OUT}\right)$$

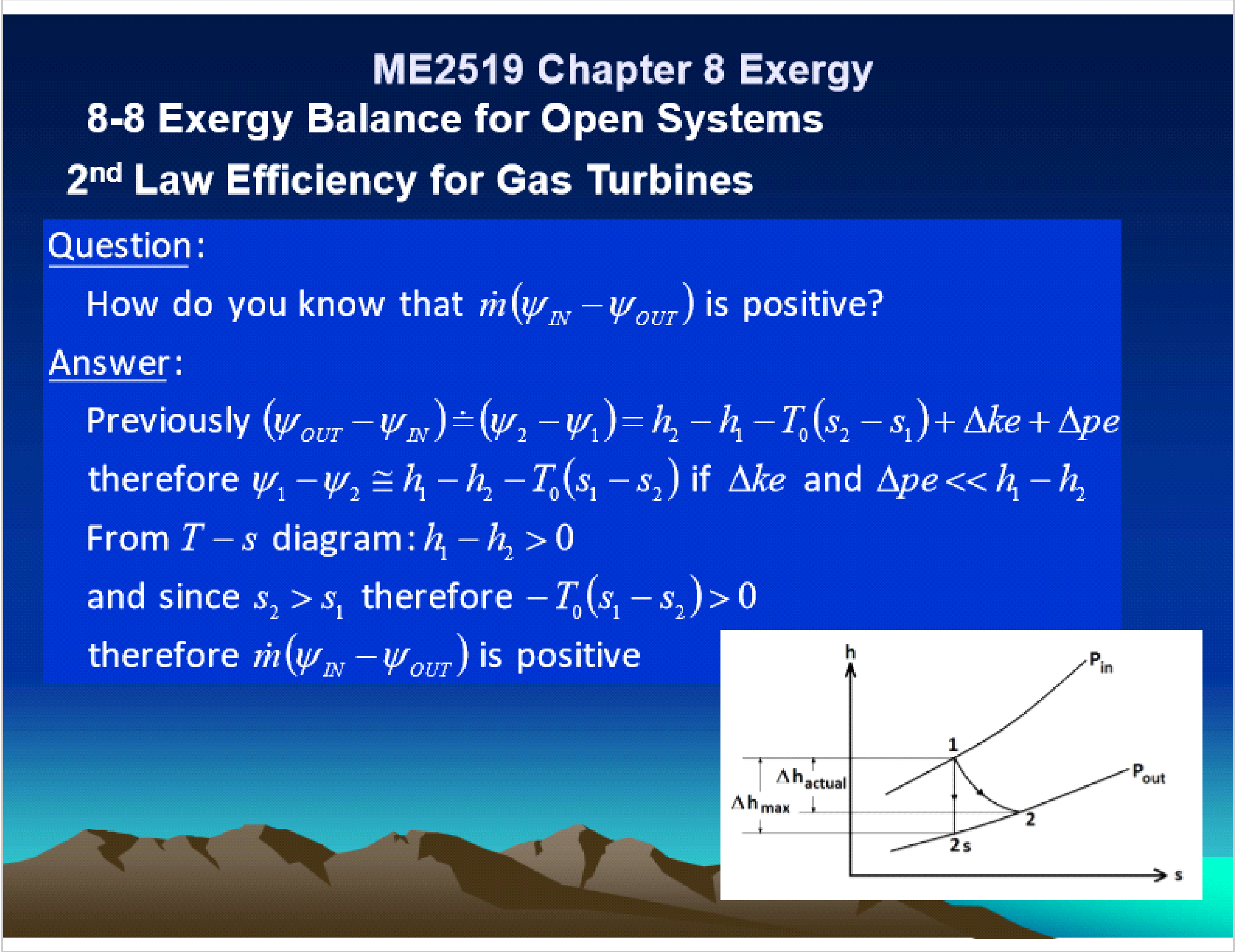
Since it is adiabatic therefore

$$0=-\dot{W}_{ACTUAL}-\dot{X}_{DEST}+\dot{m}\left(\psi_{IN}-\psi_{OUT}\right)$$

OR

$$\dot{m}\left(\psi_{IN}-\psi_{OUT}\right)=\dot{W}_{ACTUAL}+\dot{X}_{DEST}$$

which is in the $A=B+\dot{X}_{DEST}$ format.



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8-8 Exergy Balance for Open Systems

2nd Law Efficiency for Gas Turbines

Question:

How do you know that $\dot{m}(\psi_{IN}-\psi_{OUT})$ is positive?

Answer:

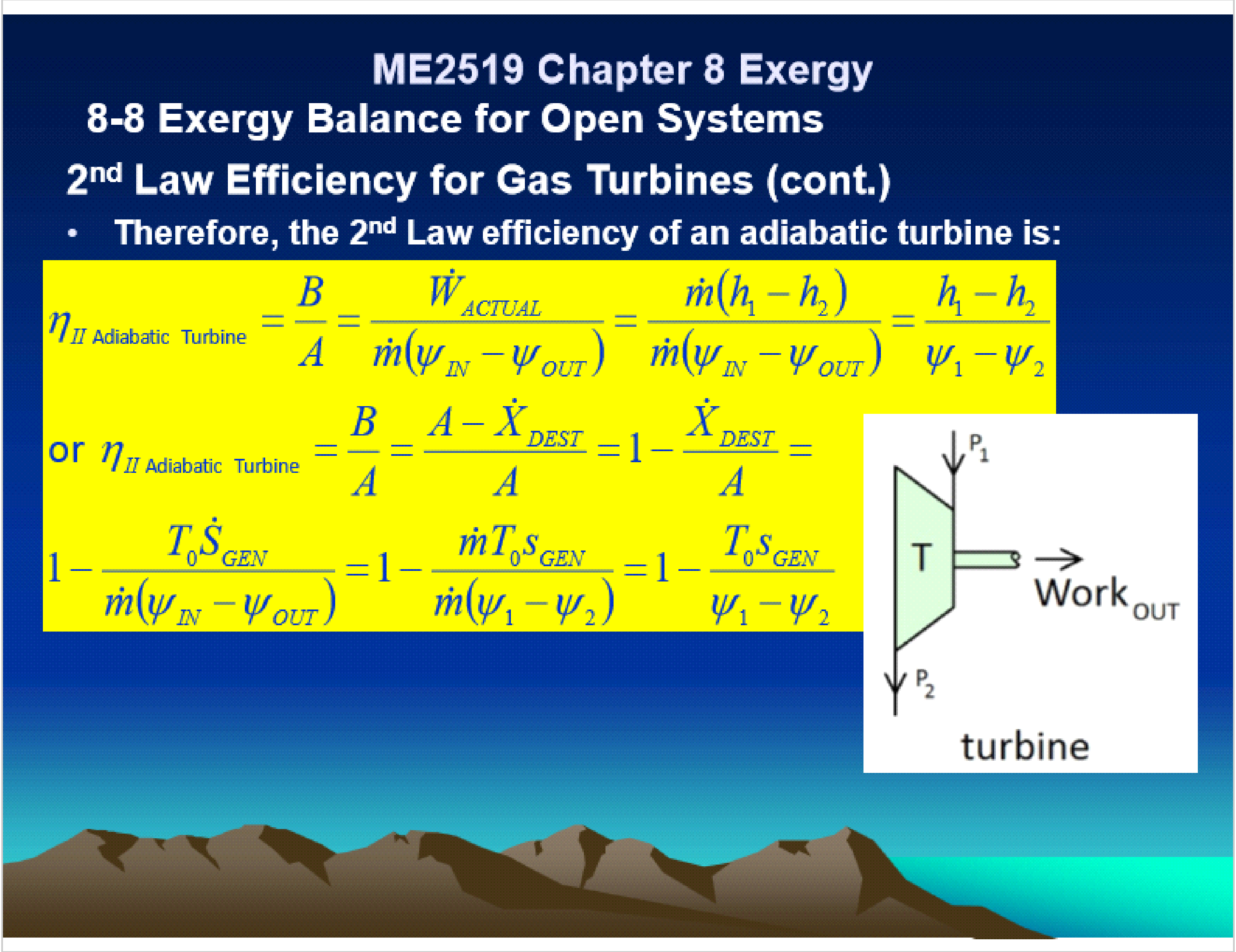
Previously $(\psi_{OUT}-\psi_{IN}) \doteq (\psi_2-\psi_1) = h_2 - h_1 - T_0(s_2 - s_1) + \Delta ke + \Delta pe$

therefore $\psi_1 - \psi_2 \cong h_1 - h_2 - T_0(s_1 - s_2)$ if Δke and $\Delta pe << h_1 - h_2$

From $T-s$ diagram: $h_1 - h_2 > 0$

and since $s_2 > s_1$ therefore $-T_0(s_1 - s_2) > 0$

therefore $\dot{m}(\psi_{IN}-\psi_{OUT})$ is positive



ME2519 Chapter 8 Exergy

8-8 Exergy Balance for Open Systems

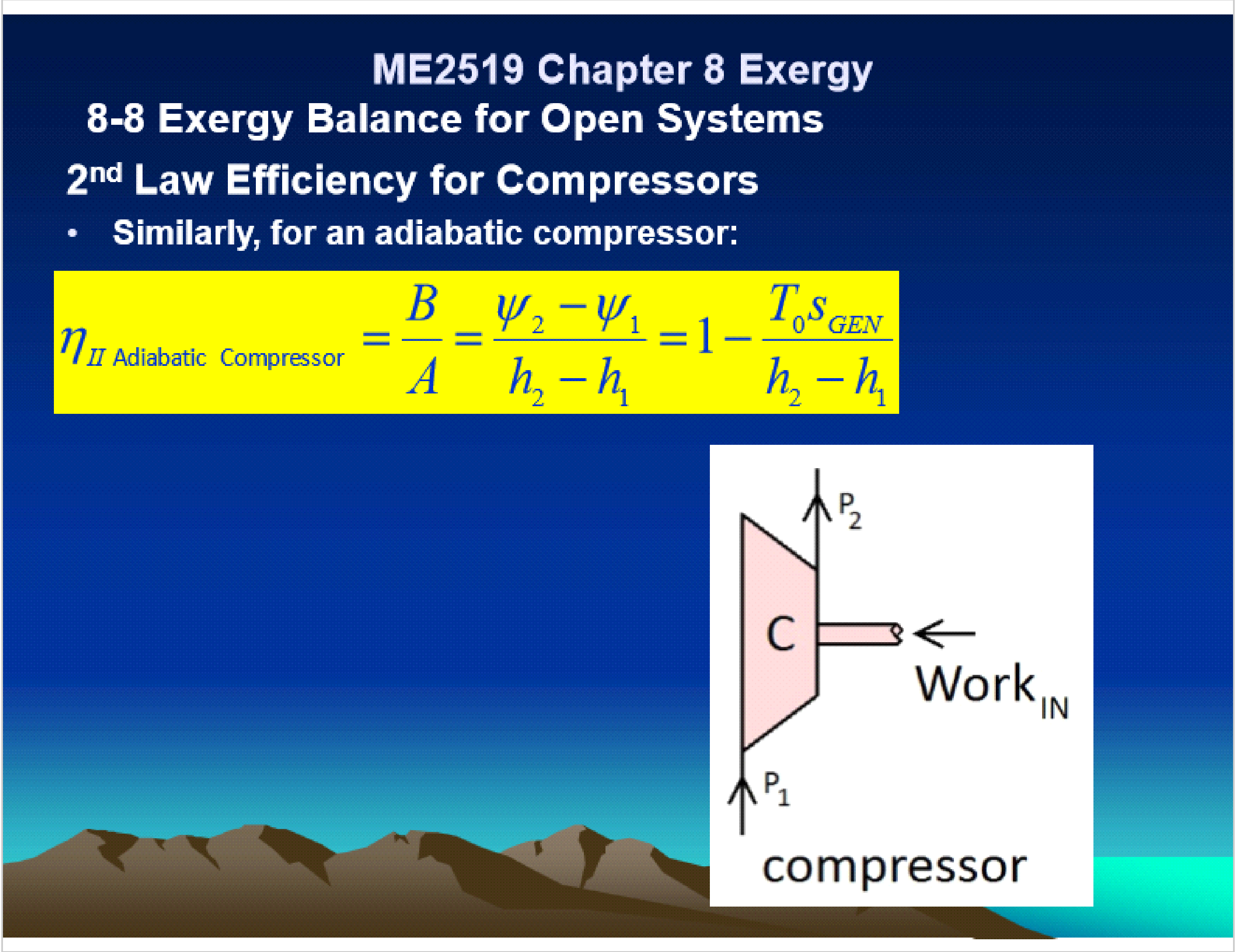
2nd Law Efficiency for Gas Turbines (cont.)

- Therefore, the 2nd Law efficiency of an adiabatic turbine is:

$$\eta_{II\ \text{Adiabatic Turbine}} = \frac{B}{A} = \frac{\dot{W}_{ACTUAL}}{\dot{m}(\psi_{IN} - \psi_{OUT})} = \frac{\dot{m}(h_1 - h_2)}{\dot{m}(\psi_{IN} - \psi_{OUT})} = \frac{h_1 - h_2}{\psi_1 - \psi_2}$$

or $\eta_{II\ \text{Adiabatic Turbine}} = \frac{B}{A} = \frac{A - \dot{X}_{DEST}}{A} = 1 - \frac{\dot{X}_{DEST}}{A} =$

$$1 - \frac{T_0 \dot{S}_{GEN}}{\dot{m}(\psi_{IN} - \psi_{OUT})} = 1 - \frac{\dot{m} T_0 s_{GEN}}{\dot{m}(\psi_1 - \psi_2)} = 1 - \frac{T_0 s_{GEN}}{\psi_1 - \psi_2}$$



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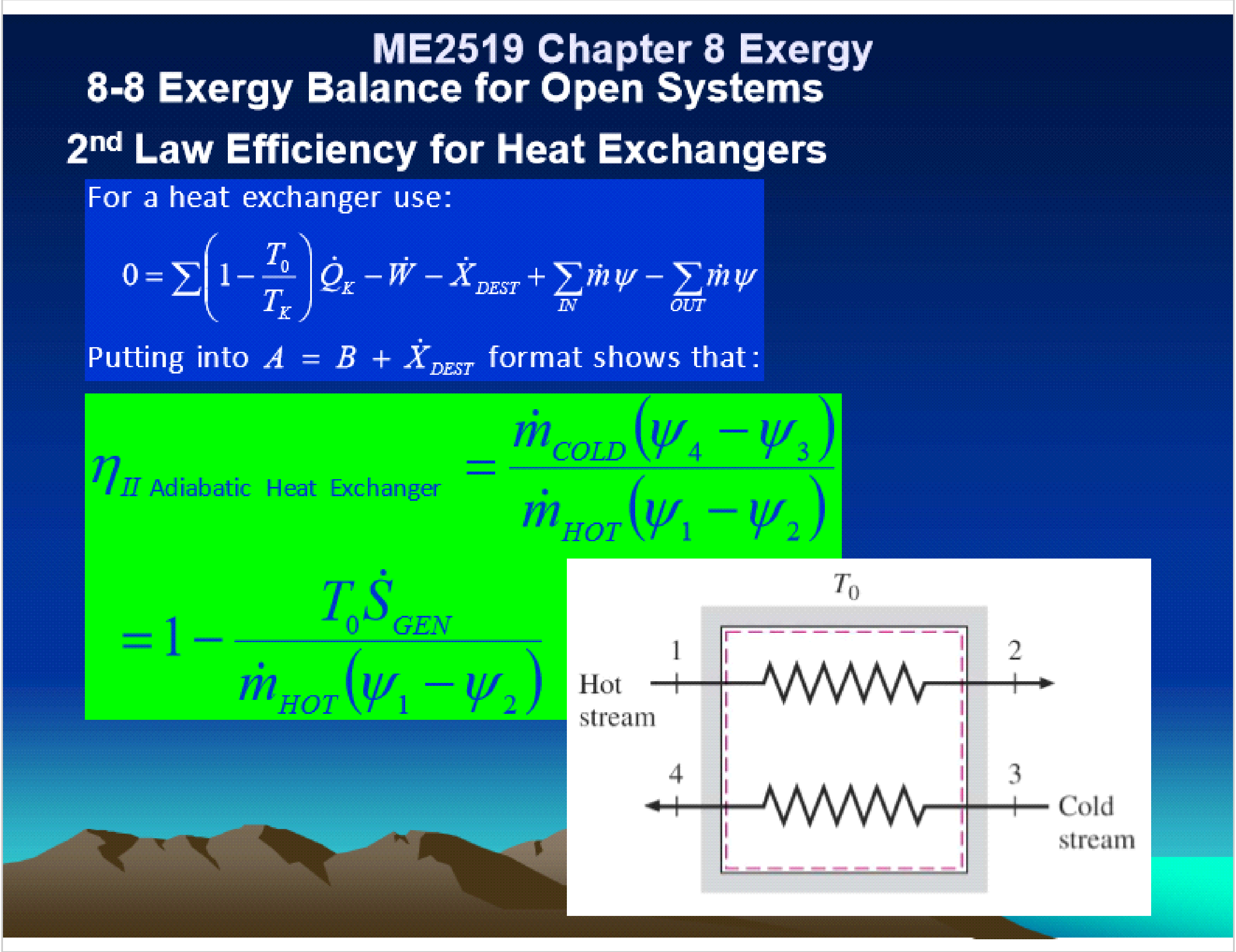
8-8 Exergy Balance for Open Systems

2nd Law Efficiency for Compressors

- Similarly, for an adiabatic compressor:

$$\eta_{II\ \text{Adiabatic Compressor}} = \frac{B}{A} = \frac{\psi_2 - \psi_1}{h_2 - h_1} = 1 - \frac{T_0 s_{GEN}}{h_2 - h_1}$$



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8-8 Exergy Balance for Open Systems

2nd Law Efficiency for Heat Exchangers

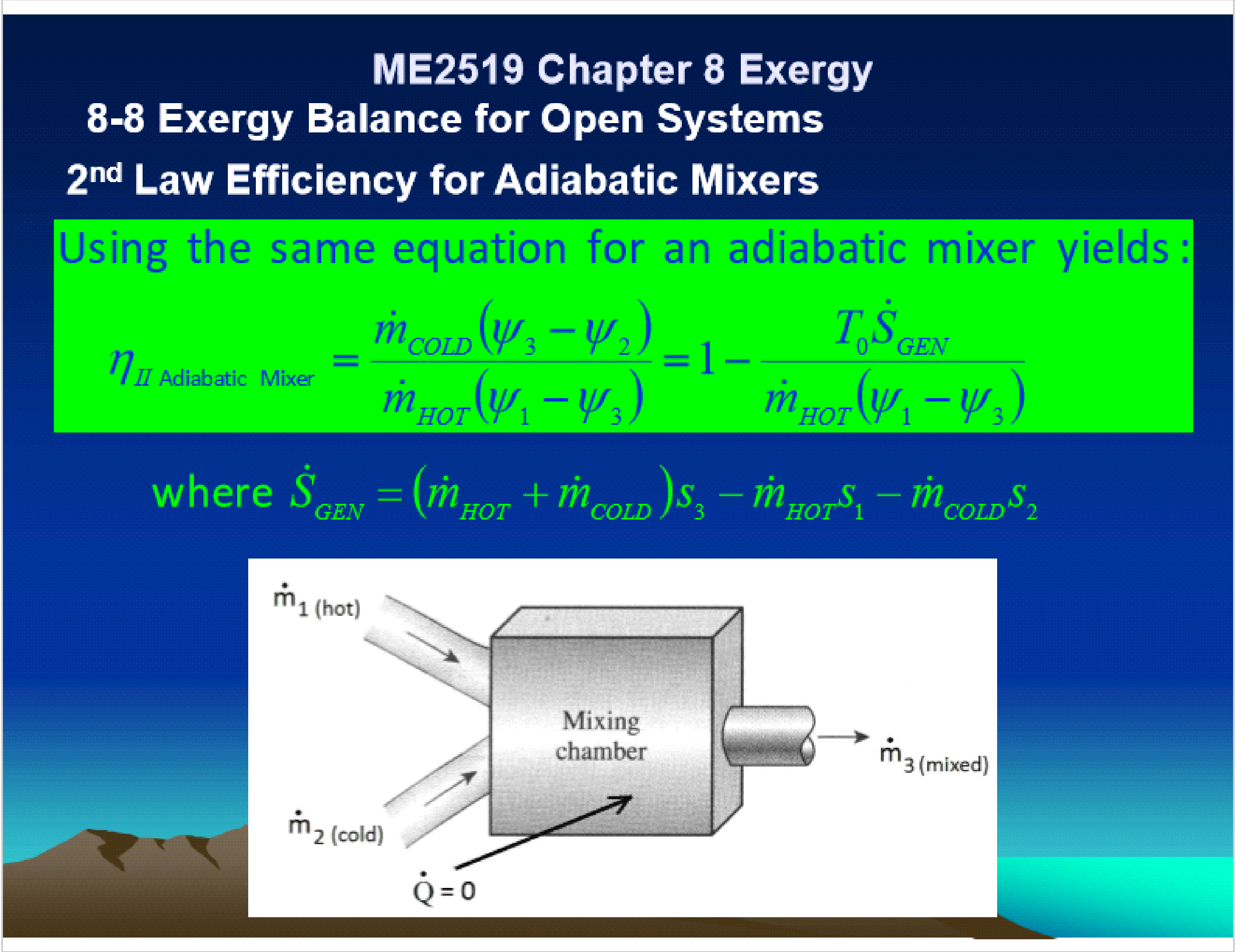
For a heat exchanger use:

$$0=\sum\left(1-\frac{T_0}{T_K}\right)\dot{Q}_K-\dot{W}-\dot{X}_{DEST}+\sum_{IN}\dot{m}\psi-\sum_{OUT}\dot{m}\psi$$

Putting into $A = B + \dot{X}_{DEST}$ format shows that:

$$\eta_{II\ \text{Adiabatic Heat Exchanger}}=\frac{\dot{m}_{COLD}\left(\psi_4-\psi_3\right)}{\dot{m}_{HOT}\left(\psi_1-\psi_2\right)}$$

$$=1-\frac{T_0\dot{S}_{GEN}}{\dot{m}_{HOT}\left(\psi_1-\psi_2\right)}$$



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8-8 Exergy Balance for Open Systems

2^{nd} Law Efficiency for Adiabatic Mixers

Using the same equation for an adiabatic mixer yields:

$$\eta_{II\ \text{Adiabatic Mixer}} = \frac{\dot{m}_{COLD}(\psi_3-\psi_2)}{\dot{m}_{HOT}(\psi_1-\psi_3)} = 1 - \frac{T_0\dot{S}_{GEN}}{\dot{m}_{HOT}(\psi_1-\psi_3)}$$

where $\dot{S}_{GEN} = (\dot{m}_{HOT}+\dot{m}_{COLD})s_3 - \dot{m}_{HOT}s_1 - \dot{m}_{COLD}s_2$

Homework 8c

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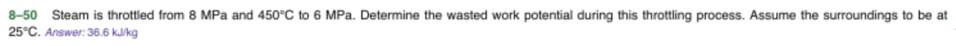


8–50 Steam is throttled from 8 MPa and 450°C to 6 MPa. Determine the wasted work potential during this throttling process. Assume the surroundings to be at 25°C. *Answer:* 36.6 kJ/kg

$P_1 = 8{,}000$ kPa

$T_2 = 450$ °C =

$P_2 = 6{,}000$ kPa

$T_0 = 25$°C = 298 K

A-6:

$h_1 = 3273.3$

$s_2 = 6.5579$

$h_2 = h_1$

$s_2 =$ h_2 interpolation:

$$s_2 = 6.5432 + \left(\frac{3273.3 - 3178.3}{3302.9 - 3178.3}\right)(6.7219 - 6.5432)$$

$s_2 = 6.679$

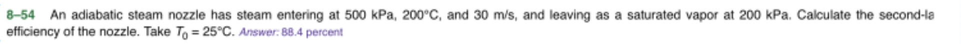
X-balance SSSF:

$$0 = \dot{m}(\psi_1 - \psi_2) - \dot{X}_{dest}$$

$$X_{dest} = \psi_1 - \psi_2 = \cancel{h_1 - h_2}\overset{0}{} - T_0(s_1 - s_2)$$

$$X_{dest} = T_0(s_2 - s_1) = 298(6.679 - 6.5579)$$

$$\boxed{X_{Des} = 36.1 \frac{kJ}{kg}}$$



8–54 An adiabatic steam nozzle has steam entering at 500 kPa, 200°C, and 30 m/s, and leaving as a saturated vapor at 200 kPa. Calculate the second-la efficiency of the nozzle. Take T_0 = 25°C. *Answer:* 88.4 percent

$P_1 = 500$ kPa

$T_1 = 200$°C

$V_1 = 30$ m/s

$x_2 = 1$

$P_2 = 200$ kPa

$T_0 = 25$°C = 298K

A-6:

$h_1 = 2855.8$

$s_1 = 7.061$

A-5:

$h_2 = h_g = 2706.3$

$s_1 = s_g = 7.127$

1st law SSSF:

$$0 = \dot{m}(h_1 + ke_1) - \dot{m}(h_2 + ke_2)$$

$$\Delta ke_{act} = \Delta h = 2855.8 - 2706.3 = 149.5$$

X balance SSSF:

$$0 = \dot{m}(\psi_1 - \psi_2) - \dot{X}_{des}$$

$$\cancel{X_{des}}\overset{0}{} = \psi_1 - \psi_2 = h_1 - h_2 - T_0(s_1 - s_2) - \Delta ke_{rev}$$

$$X_{des} = \Psi_1 - \Psi_2 = h_1 - h_2 - T_0(s_1 - s_2) - \Delta ke_{rev}$$

$$\Delta ke_{rev} = h_1 - h_2 - T_0(s_1 - s_2)$$

$$\Delta ke_{rev} = 2855.8 - 2706.3 - 298(7.061 - 7.127) = 169.168$$

$$\eta_{II} = \frac{\Delta ke_{act}}{\Delta ke_{rev}} = \frac{149.5}{169.168}$$

$$\boxed{\eta_{II} = 88.4\%}$$

8–56 Argon gas enters an adiabatic compressor at 120 kPa and 30°C with a velocity of 20 m/s and exits at 1.2 MPa, 530°C, and 80 m/s. The inlet area of the compressor is 130 cm². Assuming the surroundings to be at 25°C, determine the reversible power input and exergy destroyed. *Answer:* 126 kW, 4.12 kW

a. $C_p = .5203$, $R = .2081$

$P_1 = 120\ \text{kPa}$

$T_1 = 30°C = 303$

$V_1 = 20\ \text{m/s}$

$P_2 = 1.2\ \text{MPa}$

$T_2 = 530°C = 803\ \text{K}$

$V_2 = 80\ \text{m/s}$

$A^2 = 130\ \text{cm}^2$

$T_0 = 25°C = 298\ \text{K}$

$$v_1 = \frac{RT_1}{P_1} = \frac{.2081(303)}{120} = .5255$$

$$\dot m = P_1 A V_1 = \frac{130(20)}{.5255\ (100)^2}$$

$$\dot m = .4948$$

1st Law:

$$0 = \dot W_{in} + \dot m(h_1 - h_2 + ke_1 - ke_2)$$

$$\dot W_{in} = \dot m(C_p \Delta T + \tfrac{1}{2}V_2^2 - \tfrac{1}{2}V_1^2)$$

$$\dot W_{in} = .4948(.5203(803 - 303) + \tfrac{1}{2}(80)^2 - \tfrac{1}{2}(20)^2)$$

$$\dot W_{in} = 130.21\ \text{KW}$$

$$\Delta h = C_p \Delta T$$

X Balance:

$$0 = \dot W_{in,rev} + \dot m(\Psi_1 - \Psi_2)$$

$$\dot W_{in,rev} = \dot m(h_2 - h_1 - T_0(s_2 - s_1) + \Delta ke)$$

$$\dot W_{in,rev} = \dot m(h_2 - h_1 - T_0(C_p \ln\frac{T_2}{T_1} - R\ln\frac{P_2}{P_1}) + \tfrac{1}{2}V_2^2 - \tfrac{1}{2}V_1^2)$$

$$\dot W_{in,rev} = .4948(260.15 - 298(.027926) + 3)$$

$$\boxed{\dot W_{in,rev} = 126.09\ \text{kW}}$$

b. $X_{des} = \dot W_{in,act} - \dot W_{in,rev} = 130.21 - 126.09$

$$\boxed{X_{des} = 4.12\ \text{KW}}$$

8–68 Steam expands in a turbine steadily at a rate of 18,000 kg/h, entering at 7 MPa and 600°C and leaving at 50 kPa as saturated vapor. Assuming the surroundings to be at 100 kPa and 25°C, determine (*a*) the power potential of the steam at the inlet conditions and (*b*) the power output of the turbine if there were no irreversibilities present. *Answer:* (*a*) 7710 kW, (*b*) 5775 kW

a, $h_1 = 3650.6$

$s_1 = 7.091$

$\dot m = 18,000$

$P = 7$

a. $h_1 = 3650.6$ $\dot{m} = 18,000$

$s_1 = 7.091$

$P_1 = 7 \text{ MPa}$

$h_0 \approx h_f = 104.83$

$s_0 \approx .3672$

$T_1 = 600°C$

$\psi_1 = h_1 - h_0 - T_0(s_1 - s_0) + \overset{0}{\cancel{ke}} + \overset{0}{\cancel{pe}}$ $P_2 = 50 \text{ KPa}$

$\psi_1 = 3650.6 - 104.83 - 298(7.091 - .3672)$ $x_2 = 1$

$\psi_1 = 1542.1$ $P_0 = 100 \text{ KPa}$

$\dot{\psi} = \dot{m}\psi = 18000 \frac{kg}{hr}(1542.1)\frac{1\,hr}{3600s}$ $T_0 = 25°C$

$\boxed{\dot{\psi} = 7710.4 \text{ kW}}$

X balance:

$0 = -\dot{W}_{out,rev} + \dot{m}(\psi_1 - \psi_2) - \overset{0}{\cancel{\dot{x}_{des}}}_{rev}$

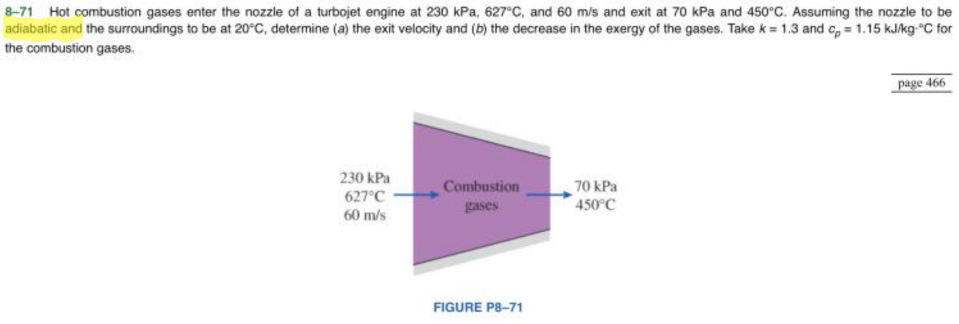
$\dot{W}_{out,rev} = \dot{m}(h_1 - h_2 - T_0(s_1 - s_2))$

$h_2 = h_g = 2645.2$

$s_2 = s_g = 7.5931$

$= \frac{18,000}{3600}(3650.6 - 2645.2) - 298(7.091 - 7.5931))$

$\boxed{\dot{W}_{out,rev} = 5775.2 \text{ kW}}$



8–71 Hot combustion gases enter the nozzle of a turbojet engine at 230 kPa, 627°C, and 60 m/s and exit at 70 kPa and 450°C. Assuming the nozzle to be adiabatic and the surroundings to be at 20°C, determine (*a*) the exit velocity and (*b*) the decrease in the exergy of the gases. Take $k = 1.3$ and $c_p = 1.15$ kJ/kg·°C for the combustion gases.

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FIGURE P8–71

a. $0 = \dot{m}(h_1 + ke_1) - \dot{m}(h_2 + ke_2)$

$P_1 = 230 \text{ KPa}$

$T_1 = 627°C = 900K$

$v_1 = 60 \text{ m/s}$

$ke_2 = \frac{v_2^2}{2} = 115(627 - 450)(1000\frac{m^2}{s^2}) + (60)^2\frac{1}{2}$ $P_2 = 70 \text{ KPa}$

$T_2 = 450°C = 723K$

$v_2 = \sqrt{2(205,350)} = \boxed{640.9 \frac{m}{s}}$ $T_0 = 20°C = 293K$

$\dot{Q} = 0$

b. $\Delta\psi = h_2 - h_1 - T_0(s_2 - s_1) + \Delta ke$

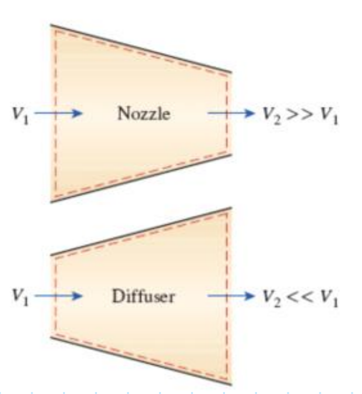
$$\Delta\psi = C_p(T_2 - T_1) - T_0(C_p(\frac{T_2}{T_1} - R\ln\frac{P_2}{P_1})) + \frac{1}{2}V_2^2 - \frac{1}{2}V_1^2$$

$$\Delta\psi = 1.15(450 - 627) - 293(.06392) + 205.35 - 1.8$$

$$\boxed{\Delta\psi = -18.73 \ \frac{kJ}{kg}}$$

Nozzles and Diffusers

Thursday, March 2, 2023 11:22 AM



- Large changes in KE
- Changes in PE negligible
- Heat transfer is usually very small because the fluid does not spend much time in the device
- No work involved

EXAMPLE 5–4 Deceleration of Air in a Diffuser

Air at 10°C and 80 kPa enters the diffuser of a jet engine steadily with a velocity of 200 m/s. The inlet area of the diffuser is 0.4 m^2. The air leaves the diffuser with a velocity that is very small compared with the inlet velocity. Determine (*a*) the mass flow rate of the air and (*b*) the temperature of the air leaving the diffuser.

SOLUTION Air enters the diffuser of a jet engine steadily at a specified velocity. The mass flow rate of air and the temperature at the diffuser exit are to be determined.

Assumptions **1** This is a steady-flow process since there is no change with time at any point and thus $\Delta m_{CV} = 0$ and $\Delta E_{CV} = 0$. **2** Air is an ideal gas since it is at a high temperature and low pressure relative to its critical-point values. **3** The potential energy change is zero, $\Delta pe = 0$. **4** Heat transfer is negligible. **5** Kinetic energy at the diffuser exit is negligible. **6** There are no work interactions.

Analysis We take the *diffuser* as the system (Fig. 5–27). This is a *control volume* since mass crosses the system boundary during the process. We observe that there is only one inlet and one exit and thus $\dot m_1 = \dot m_2 = \dot m$.

FIGURE 5–27
The diffuser of a jet engine discussed in Example 5–4.

$T_1 = 10°C = 283 K$ $V_2 \approx 0$ m/s
$P_1 = 80$ kPa
$V_1 = 200$ m/s
$A_1 = .4 m^2$

a. Ideal Gas:

$$Pv = RT \Rightarrow v = \frac{RT}{P} = \frac{.287\ kPa\cdot m^3/kg\cdot K\ (283K)}{80\ kPa} = 1.015\ \frac{m^3}{kg}$$

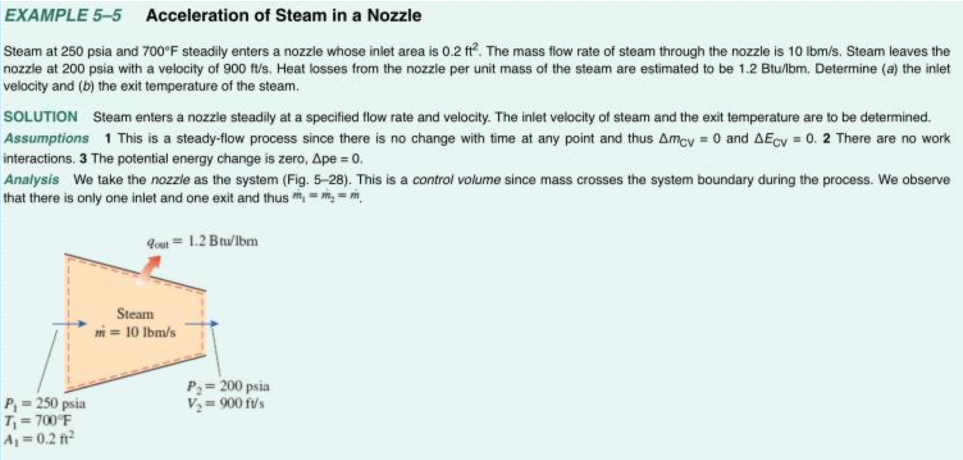
$$\dot m = \frac{AV_1}{v} = \frac{.4m^2(200m/s)}{1.015\ m^3/kg} = \boxed{78.8\ \frac{kg}{s}}$$

b. Energy balance:

$$Ke_1 + m h_1 = Ke_2 + \dot m h_2$$

$$\cancel{\dot m} C_p(T_2 - T_1) = \frac{1}{2}\cancel{\dot m}(V_2^2 - \cancel{V_1^2} \to 0)$$

$$T_2 = \frac{V_2^2}{2\,C_p} + T_1 = \frac{200\ m/s}{2(1.005\ kJ/kg\cdot K)}\left(\frac{1\ kJ/kg}{1000\ m^2/s^2}\right) + 283K = \boxed{303K}$$



EXAMPLE 5–5 **Acceleration of Steam in a Nozzle**

Steam at 250 psia and 700°F steadily enters a nozzle whose inlet area is 0.2 ft^2. The mass flow rate of steam through the nozzle is 10 lbm/s. Steam leaves the nozzle at 200 psia with a velocity of 900 ft/s. Heat losses from the nozzle per unit mass of the steam are estimated to be 1.2 Btu/lbm. Determine (*a*) the inlet velocity and (*b*) the exit temperature of the steam.

SOLUTION Steam enters a nozzle steadily at a specified flow rate and velocity. The inlet velocity of steam and the exit temperature are to be determined.

Assumptions **1** This is a steady-flow process since there is no change with time at any point and thus $\Delta m_{CV} = 0$ and $\Delta E_{CV} = 0$. **2** There are no work interactions. **3** The potential energy change is zero, $\Delta pe = 0$.

Analysis We take the *nozzle* as the system (Fig. 5–28). This is a *control volume* since mass crosses the system boundary during the process. We observe that there is only one inlet and one exit and thus $\dot{m}_1 = \dot{m}_2 = \dot{m}$.

a. h_1 (250 psia, 700°F) Table A-6E $\Rightarrow$ $h_1 = 1374.1$ BTU/lbm
$v_1 = 2.6883$ ft^3/lbm

$$\dot{m} = \frac{A_1 V_1}{v_1} \Rightarrow \quad V_1 = \frac{v_1 \dot{m}}{A_1} = \frac{2.6883 \text{ ft}^3/\text{lbm} \ (10 \text{ lbm/s})}{.2 \text{ ft}^2} = \boxed{134.4 \text{ ft/s}}$$

b. Energy balance:

$$KE_1 + \dot{m} h_1 = KE_2 + \dot{m} h_2 + \dot{m} q_{out}$$

$$h_2 = \frac{1}{2}(V_1^2 - V_2^2) + h_1 = \frac{1}{2}(134.4^2 - 900^2) \text{ ft}^2/\text{s}^2 \left(\frac{1 \text{ BTU/lbm}}{25037 \text{ ft}^2/\text{s}^2}\right) + 1374.1 \frac{\text{BTU}}{\text{lbm}} - 1.2 \frac{\text{Btu}}{\text{lbm}}$$

$$h_2 = 1354.4 \frac{\text{BTU}}{\text{lbm}}$$

Table A-6E:

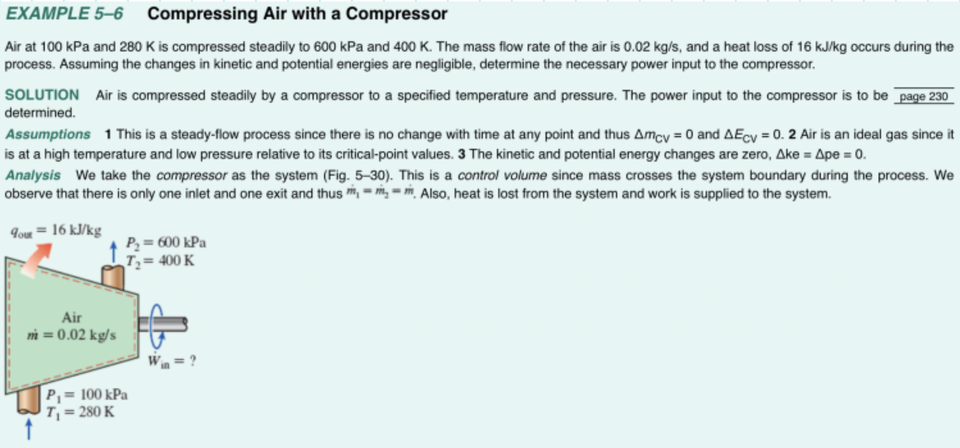
$T_2(h_2, P_2) \Rightarrow$

$$\boxed{T_2 = 662.0 \ ^\circ F}$$

Turbines and Compressors

Saturday, March 4, 2023 6:44 PM

Turbines -> Work out
Compressors <- Work in
Heat transfer is usually negligible because they are well insulated
KE and PE changes are negligible in comparison to enthalpy



EXAMPLE 5–6 Compressing Air with a Compressor

Air at 100 kPa and 280 K is compressed steadily to 600 kPa and 400 K. The mass flow rate of the air is 0.02 kg/s, and a heat loss of 16 kJ/kg occurs during the process. Assuming the changes in kinetic and potential energies are negligible, determine the necessary power input to the compressor.

SOLUTION Air is compressed steadily by a compressor to a specified temperature and pressure. The power input to the compressor is to be determined. page 230

Assumptions **1** This is a steady-flow process since there is no change with time at any point and thus $\Delta m_{CV} = 0$ and $\Delta E_{CV} = 0$. **2** Air is an ideal gas since it is at a high temperature and low pressure relative to its critical-point values. **3** The kinetic and potential energy changes are zero, $\Delta ke = \Delta pe = 0$.

Analysis We take the *compressor* as the system (Fig. 5–30). This is a *control volume* since mass crosses the system boundary during the process. We observe that there is only one inlet and one exit and thus $\dot m_1 = \dot m_2 = \dot m$. Also, heat is lost from the system and work is supplied to the system.

Energy balance:

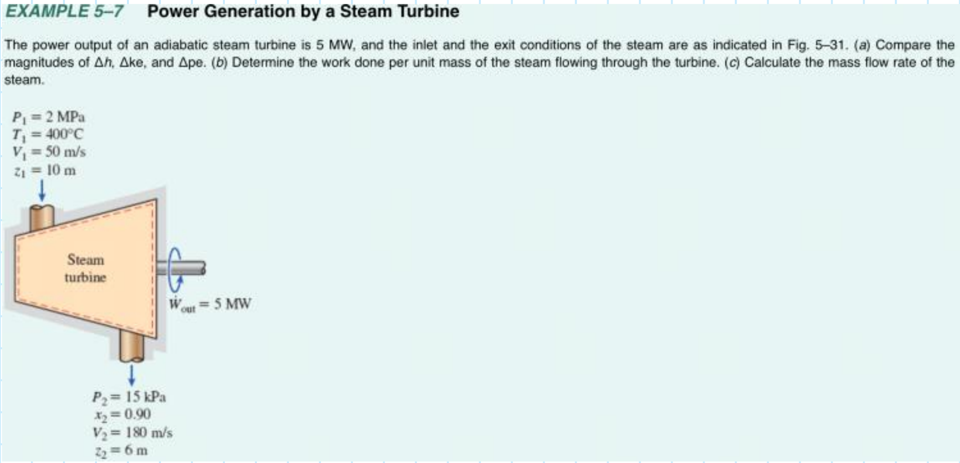
$$\dot W_{in} + \dot m h_1 = \dot m q_{out} + \dot m h_2$$

$$\dot W_{in} = \dot m(q_{out} + h_2 - h_1)$$

$$\dot W_{in} = \dot m(q_{out} + c_p(T_2 - T_1))$$

$$\dot W_{in} = .02 \text{ kg/s}(16 \text{ kJ/kg} + (1.005 \text{ kJ/kg·K})(400-280)\text{K})$$

$$\boxed{\dot W_{in} = 2.732 \text{ KW}}$$



EXAMPLE 5–7 Power Generation by a Steam Turbine

The power output of an adiabatic steam turbine is 5 MW, and the inlet and the exit conditions of the steam are as indicated in Fig. 5–31. (*a*) Compare the magnitudes of Δh, Δke, and Δpe. (*b*) Determine the work done per unit mass of the steam flowing through the turbine. (*c*) Calculate the mass flow rate of the steam.

a. $\Delta ke = \frac{1}{2}V_2^2 - \frac{1}{2}V_1^2 = \frac{1}{2}((180 \text{m/s})^2 - (50 \text{m/s})^2) \frac{1 \text{ kJ/kg}}{1000 \text{ m}^2/\text{s}^2} = \boxed{14.95 \text{ kJ/kg}}$

$\Delta pe = g(z_2 - z_1) = 9.81 \text{ m/s}^2 (6-10)\text{m} \frac{1 \text{ kJ/kg}}{1000 \text{ m}^2/\text{s}^2} = \boxed{-.04 \text{ kJ/kg}}$

$\Delta h = h_2 - h_1$

$h_1(2\,MPa, 400°C) \Rightarrow$ Table $h_1 = 328.4\ kJ/kg$

$h_2 = x\, h_{fg} + h_f = .9(2372.3) + 225.94 = 2361.01\ kJ/kg$

$\Delta h = \boxed{-887.39\ kJ/kg}$ Much larger

b. Energy balance:

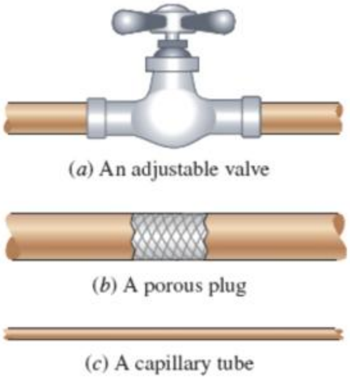
$w_{out} = -\Delta h - \Delta ke - \Delta pe$

$\boxed{v_{out} = 872.48\ kJ/kg}$

c. $\dot{m} = \frac{\dot{V}_{out}}{W_{out}} = \boxed{5.73\ kg/s}$

Throttling Valve

Saturday, March 4, 2023 7:14 PM



(*a*) An adjustable valve

(*b*) A porous plug

(*c*) A capillary tube

FIGURE 5–32

Throttling valves are devices that cause large pressure drops in the fluid.

The flow through them may be assumed to be adiabatic (Δq ≅ 0) since there is neither sufficient time nor large enough area for any effective heat transfer to take place

No work interactions

Δpe ≅ 0

Δke ≅ 0

$$u_1 + P_1 \upsilon_1 = u_2 + P_2 \upsilon_2$$

Therefore, h1 ≅ h2

Internal energy + Flow energy = Constant

T1 =T2 if working fluid is an ideal gas

EXAMPLE 5–8 **Expansion of Refrigerant-134a in a Refrigerator**

Refrigerant-134a enters the capillary tube of a refrigerator as saturated liquid at 0.8 MPa and is throttled to a pressure of 0.12 MPa. Determine the quality of the refrigerant at the final state and the temperature drop during this process.

SOLUTION Refrigerant-134a that enters a capillary tube as saturated liquid is throttled to a specified pressure. The exit quality of the refrigerant and the temperature drop are to be determined.

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Assumptions **1** Heat transfer from the tube is negligible. **2** Kinetic energy change of the refrigerant is negligible.

Analysis A capillary tube is a simple flow-restricting device that is commonly used in refrigeration applications to cause a large pressure drop in the refrigerant. Flow through a capillary tube is a throttling process; thus, the enthalpy of the refrigerant remains constant (Fig. 5–34).

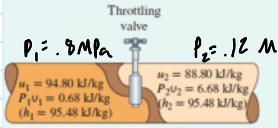


FIGURE 5–34

During a throttling process, the enthalpy (flow energy + internal energy) of a fluid remains constant. But internal and flow energies may be converted to each other.

a.

$$x_2 = \frac{h_2 - h_f}{h_{fg}}$$

$h_g (P_2 = .12MPa, h_1 = 95.48$ kJ/kg$) \Rightarrow$ Table

$h_f = 22.47$

$h_g = 236.99$

$$x_2 = \frac{9548 - 22.47}{236.99 - 22.47} = \boxed{.340}$$

b.

$$T_{2sat} - T_{1sat} = -22.32 - 3131 = \boxed{-53.63\,°C}$$

Mixing Chamber

Saturday, March 4, 2023 8:39 PM

No work interactions
Δpe ≅ 0
Δke ≅ 0
Δq ≅ 0

h1 ≅ h2

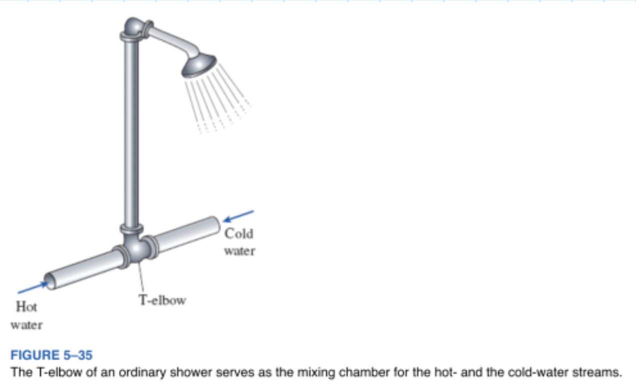
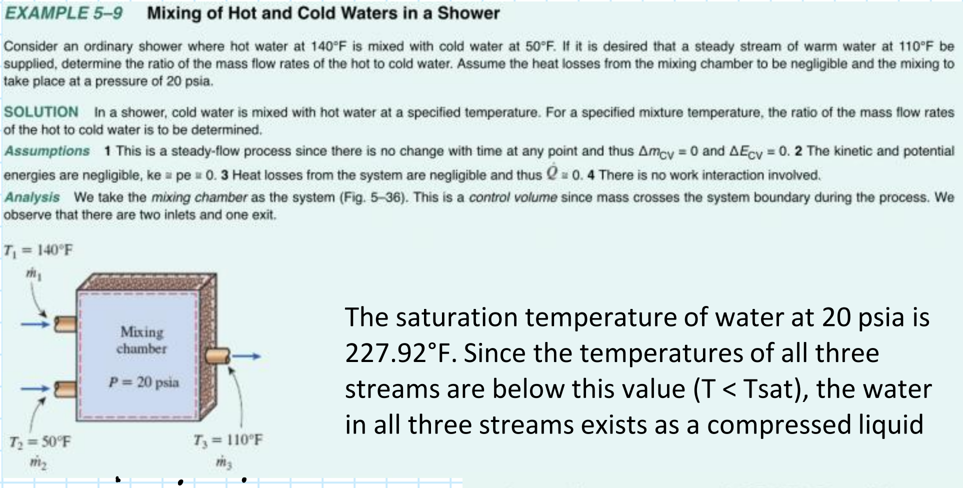


FIGURE 5–35
The T-elbow of an ordinary shower serves as the mixing chamber for the hot- and the cold-water streams.



EXAMPLE 5–9 Mixing of Hot and Cold Waters in a Shower

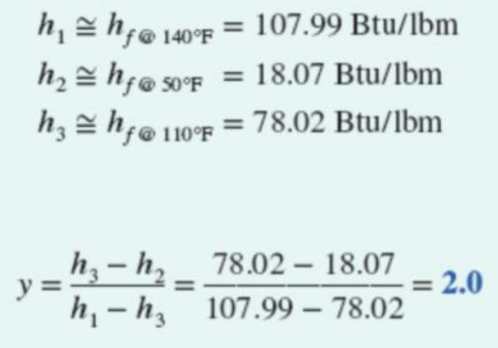
Consider an ordinary shower where hot water at 140°F is mixed with cold water at 50°F. If it is desired that a steady stream of warm water at 110°F be supplied, determine the ratio of the mass flow rates of the hot to cold water. Assume the heat losses from the mixing chamber to be negligible and the mixing to take place at a pressure of 20 psia.

SOLUTION In a shower, cold water is mixed with hot water at a specified temperature. For a specified mixture temperature, the ratio of the mass flow rates of the hot to cold water is to be determined.

Assumptions **1** This is a steady-flow process since there is no change with time at any point and thus $\Delta m_{CV} = 0$ and $\Delta E_{CV} = 0$. **2** The kinetic and potential energies are negligible, ke ≅ pe ≅ 0. **3** Heat losses from the system are negligible and thus $\dot{Q} \cong 0$. **4** There is no work interaction involved.

Analysis We take the *mixing chamber* as the system (Fig. 5–36). This is a *control volume* since mass crosses the system boundary during the process. We observe that there are two inlets and one exit.

The saturation temperature of water at 20 psia is 227.92°F. Since the temperatures of all three streams are below this value (T < Tsat), the water in all three streams exists as a compressed liquid



$$h_1 \cong h_{f @ 140°F} = 107.99 \text{ Btu/lbm}$$
$$h_2 \cong h_{f @ 50°F} = 18.07 \text{ Btu/lbm}$$
$$h_3 \cong h_{f @ 110°F} = 78.02 \text{ Btu/lbm}$$

$$y = \frac{h_3 - h_2}{h_1 - h_3} = \frac{78.02 - 18.07}{107.99 - 78.02} = \mathbf{2.0}$$

$$\dot{m}_1 + \dot{m}_2 = \dot{m}_3$$
$$\dot{m}_1 h_1 + \dot{m}_2 h_2 = \dot{m}_3 h_3$$
$$\dot{m}_1 h_1 + \dot{m}_2 h_2 = (\dot{m}_1 + \dot{m}_2) h_3$$

divide by $\dot{m}_2$

$$y h_1 + h_2 = y h_3 + h_3$$
$$y(h_1 - h_3) = h_3 - h_2$$
$$y = \frac{h_3 - h_2}{h_1 - h_3}$$

Heat Exchangers

Monday, March 6, 2023 3:37 PM

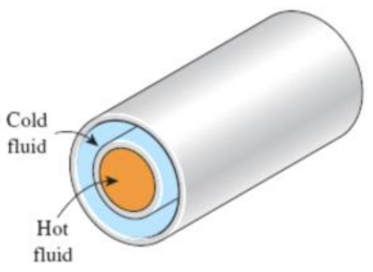
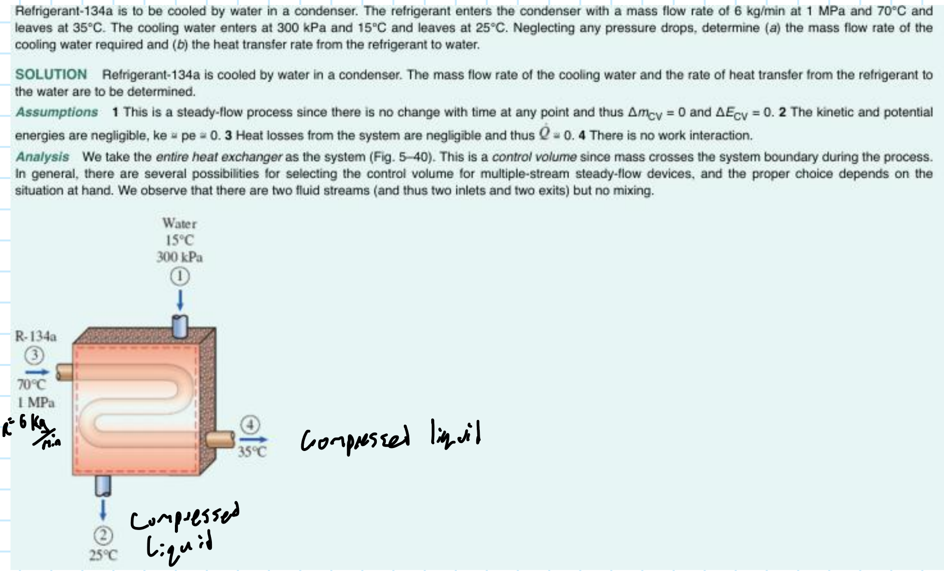


FIGURE 5–38
A heat exchanger can be as simple as two concentric pipes.

- Heat exchangers are devices where two moving fluid streams exchange heat without mixing
- When the entire heat exchanger is selected as the control volume, Q = 0, since the boundary for this case lies just beneath the insulation and little or no heat crosses the boundary
- Typically involve no work interactions
- Negligible kinetic and potential energy changes (Δke ≅ 0, Δpe ≅ 0) for each fluid stream
- Under steady operation, the mass flow rate of each fluid stream flowing through a heat exchanger remains constant.



Refrigerant-134a is to be cooled by water in a condenser. The refrigerant enters the condenser with a mass flow rate of 6 kg/min at 1 MPa and 70°C and leaves at 35°C. The cooling water enters at 300 kPa and 15°C and leaves at 25°C. Neglecting any pressure drops, determine (*a*) the mass flow rate of the cooling water required and (*b*) the heat transfer rate from the refrigerant to water.

SOLUTION Refrigerant-134a is cooled by water in a condenser. The mass flow rate of the cooling water and the rate of heat transfer from the refrigerant to the water are to be determined.

Assumptions **1** This is a steady-flow process since there is no change with time at any point and thus $\Delta m_{CV} = 0$ and $\Delta E_{CV} = 0$. **2** The kinetic and potential energies are negligible, ke ≅ pe ≅ 0. **3** Heat losses from the system are negligible and thus $\dot{Q} \cong 0$. **4** There is no work interaction.

Analysis We take the *entire heat exchanger* as the system (Fig. 5–40). This is a *control volume* since mass crosses the system boundary during the process. In general, there are several possibilities for selecting the control volume for multiple-stream steady-flow devices, and the proper choice depends on the situation at hand. We observe that there are two fluid streams (and thus two inlets and two exits) but no mixing.

$\dot{m}_R = 6\ kg/min$

Compressed liquid

Compressed liquid

a Energy balance:

$$\dot{m}_R h_{1R} + \dot{m}_w h_{1w} = \dot{m}_R h_{2R} + \dot{m} h_{2w}$$

$$\dot{m}_R (h_{2R} - h_{1R}) = \dot{m}_w (h_{2w} - h_{1w})$$

$$\dot{m}_w = \frac{\dot{m}_R (h_{2R} - h_{1R})}{h_{2w} - h_{1w}}$$

$h_{1R} = 303.87$

$h_{1w} = 62\ 982$

$h_{2R} = 100.88$

$h_{2w} = 104.83$

$$\boxed{\dot{m}_w = 29.1\ kg/min}$$