Thermodynamics:

Theory & Practice

The science of energy and power.

...just the color figures for those who got the B&W printed book...

by D. James Benton

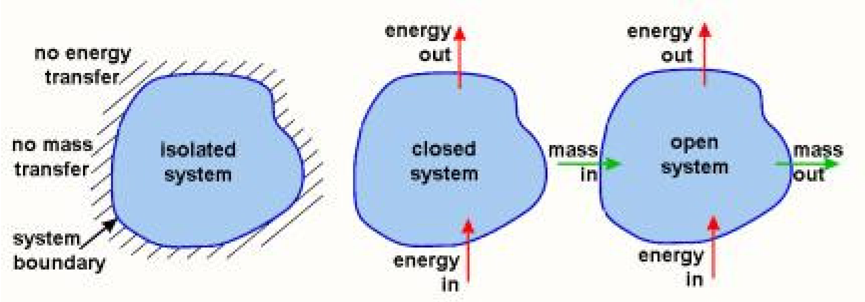
Foreword

Thermodynamics is the branch of physical science that deals with energy in its various forms, including heat and work. Energy is a property of systems that can be stored and transferred to other systems. Energy is not the "ability to perform work." This is a misnomer. A system may contain considerable energy without having the capacity to perform any work. Thermodynamics is the key to understanding how things work. In this text we will explore classical (or macroscopic) as well as statistical (microscopic) thermodynamics, properties, processes, and heat engines. A variety of applications will be presented and all software is included.

This book is not intended to be a textbook on thermodynamics or to replace any of the excellent textbooks that are already available. I hope you will find this to be a helpful companion to such texts. I cover several topics (e.g., microscopic point of view, speed distributions, and probability) that are never covered in textbooks on classical (i.e., macroscopic) thermodynamics and are often reserved for graduate courses. I consider these topics to be essential to understanding the whole of thermodynamics and many practical applications in particular. I hope this presentation will inspire you to dig deeper into this fascinating field.

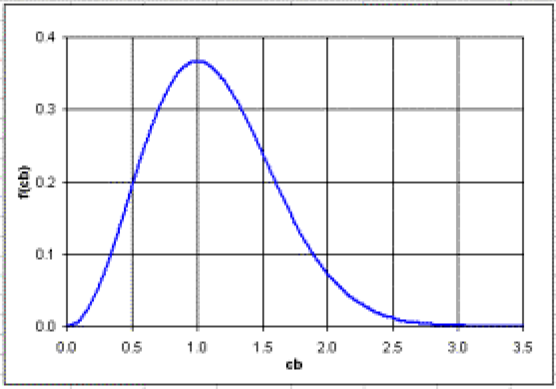
All of the examples contained in this book,
(as well as a lot of free programs) are available at…

http://www.dudleybenton.altervista.org/software/index.html


no energy
transfer
no mass
transfer
system
boundary
isolated
system
energy
out
closed
system
energy
in
mass
in
energy
out
open
system
mass
out
energy
in

Maxwell-Boltzmann Speed Distribution

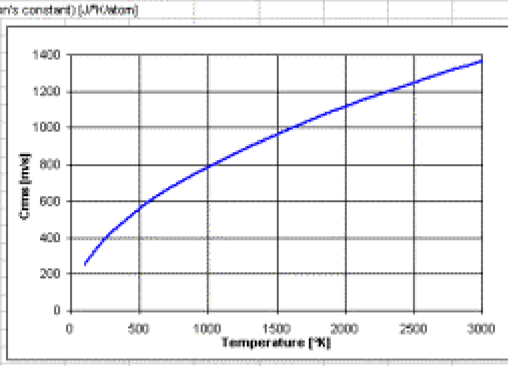
c,β	f(c,β)
0.0	0.0000
0.1	0.0099
0.2	0.0384
0.3	0.0823
0.4	0.1363
0.5	0.1947
0.6	0.2512
0.7	0.3002
0.8	0.3375
0.9	0.3603
1.0	0.3679
1.1	0.3608
1.2	0.3412
1.3	0.3118
1.4	0.2761
1.5	0.2371
1.6	0.1979
1.7	0.1606
1.8	0.1269

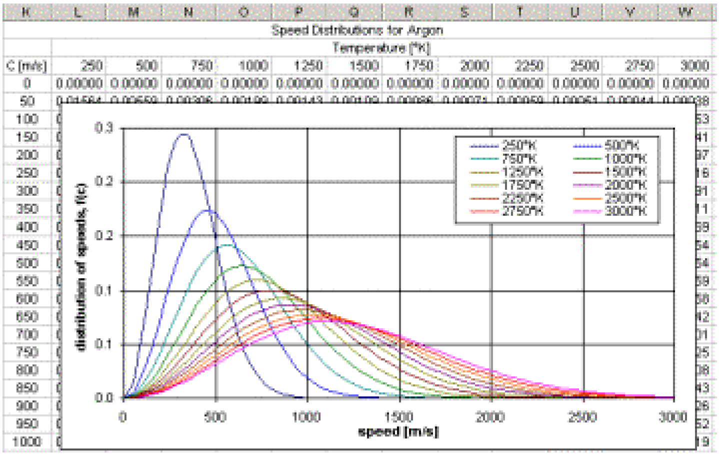


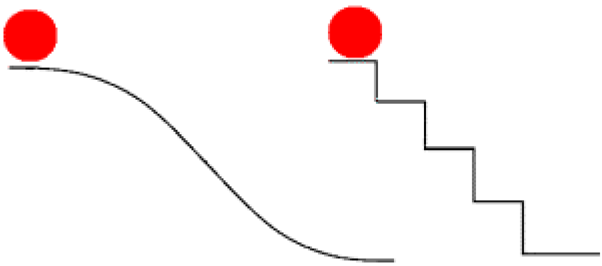
Speed Distributions for Argon

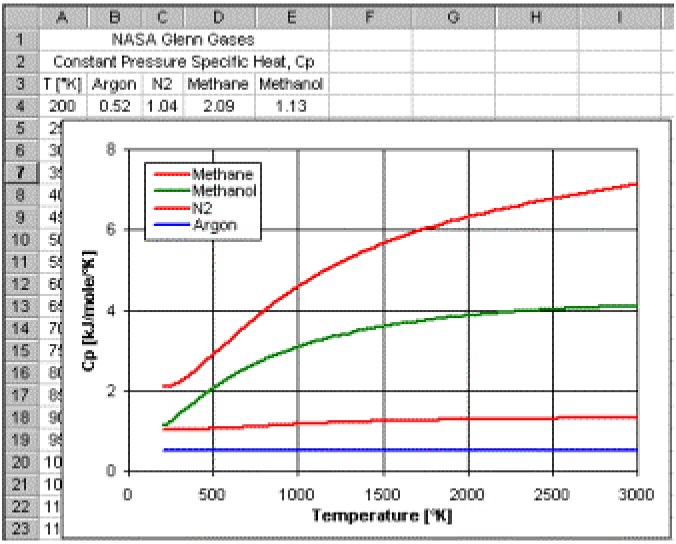
39.948	MW [gm/mole]
6.02E+23	N (Avogadro's number) [atoms/mole]
6.63E-23	μ (mass of one atom) [gm]
1.38E-23	k (Boltzmann's constant) [J/°K/atom]

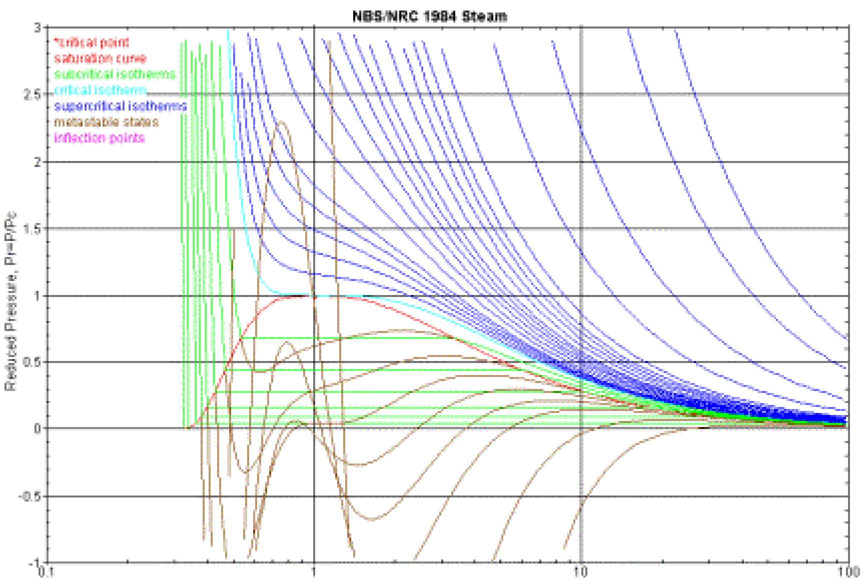
T	Crms
°K	m/s
100	250
200	353
300	433
400	500
500	559
600	612
700	661
800	707
900	750
1000	790
1100	829
1200	866
1300	901
1400	935
1500	968
1600	1000
1700	1030
1800	1060

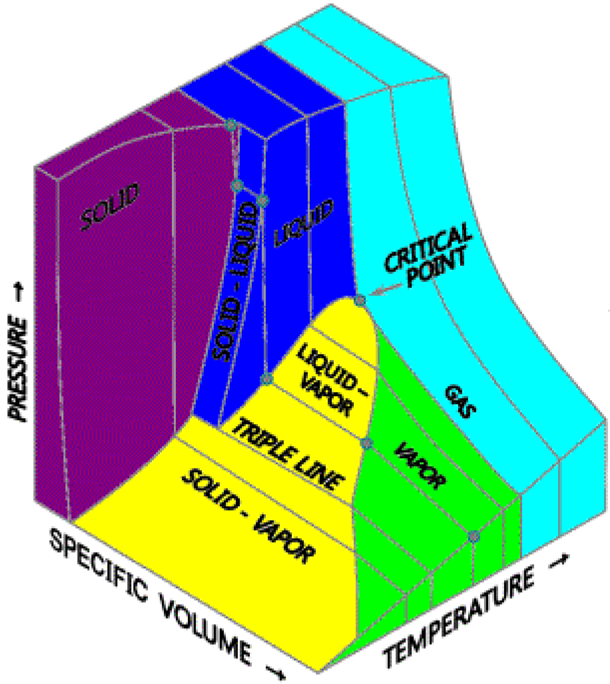


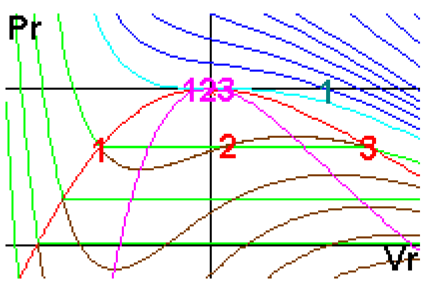

Speed Distributions for Argon
Temperature [°K]
C [m/s]
distribution of speeds, f(c)
speed [m/s]
250°K
500°K
750°K
1000°K
1250°K
1500°K
1750°K
2000°K
2250°K
2500°K
2750°K
3000°K

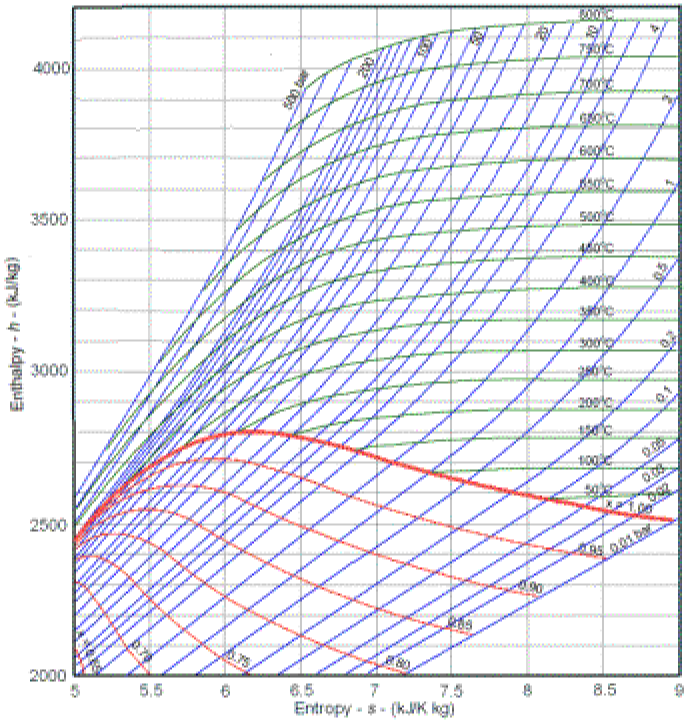



NASA Glenn Gases
Constant Pressure Specific Heat, Cp
T [°K] Argon N2 Methane Methanol
200 0.52 1.04 2.09 1.13
Methane
Methanol
N2
Argon
Cp [kJ/mole/°K]
Temperature [°K]

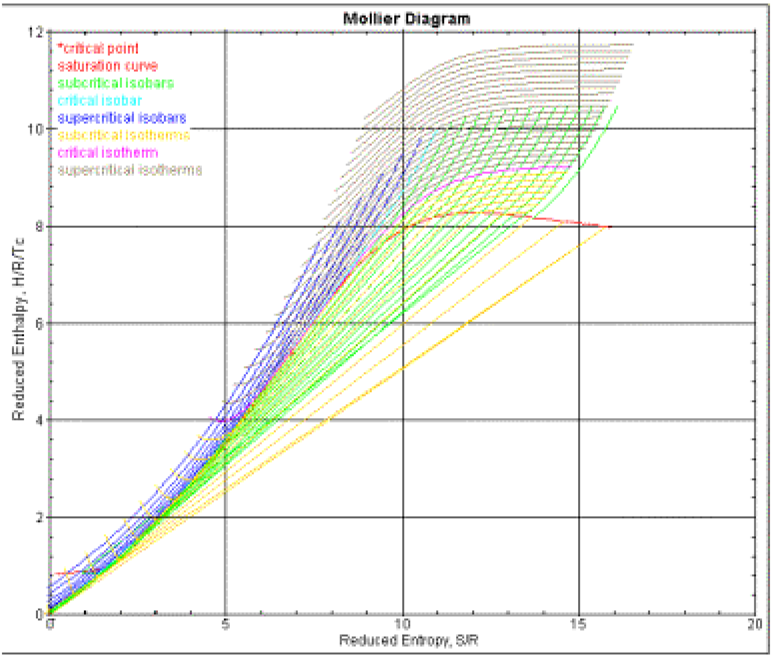

NBS/NRC 1984 Steam
*critical point
saturation curve
subcritical isotherms
critical isotherm
supercritical isotherms
metastable states
inflection points
Reduced Pressure, Pr=P/Pc
Reduced Volume, Vr=V/Vc


SOLID
SOLID - LIQUID
LIQUID
CRITICAL POINT
LIQUID - VAPOR
TRIPLE LINE
SOLID - VAPOR
VAPOR
GAS
PRESSURE →
SPECIFIC VOLUME →
TEMPERATURE →

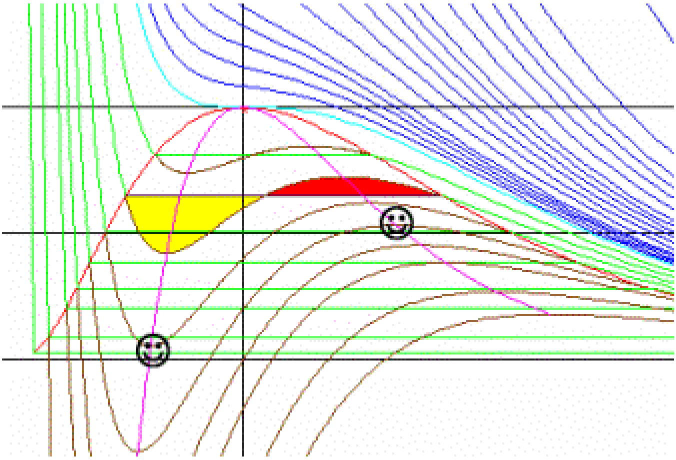

Pr
Vr
123
1
1
2
3

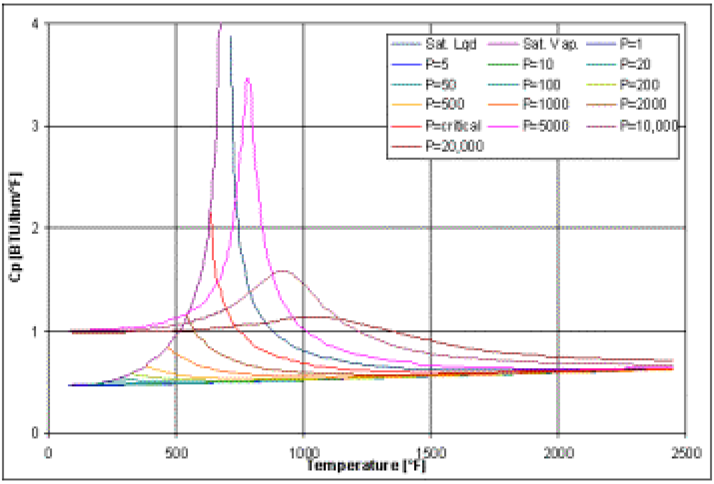


Enthalpy - h - (kJ/kg)
Entropy - s - (kJ/K kg)
2000
2500
3000
3500
4000
5
5.5
6
6.5
7
7.5
8
8.5
9
800°C
750°C
700°C
650°C
600°C
550°C
500°C
450°C
400°C
350°C
300°C
250°C
200°C
150°C
100°C
50°C
500 bar
200
100
50
20
10
4
2
1
0.5
0.2
0.1
0.05
0.03
0.02
0.01 bar
x = 1.00
0.95
0.90
0.85
0.80
0.75
0.70

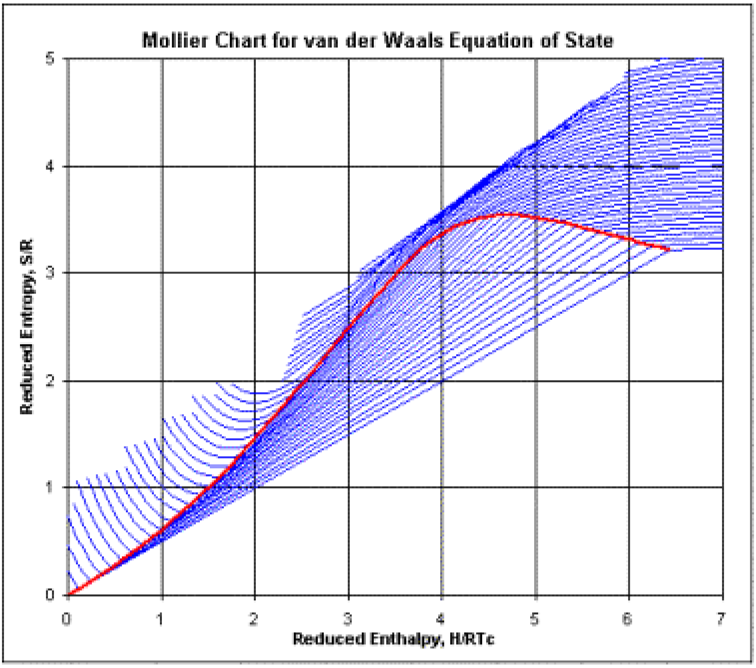


Mollier Diagram
*critical point
saturation curve
subcritical isobars
critical isobar
supercritical isobars
subcritical isotherms
critical isotherm
supercritical isotherms
Reduced Enthalpy, H/R/Tc
Reduced Entropy, S/R
0
2
4
6
8
10
12
0
5
10
15
20

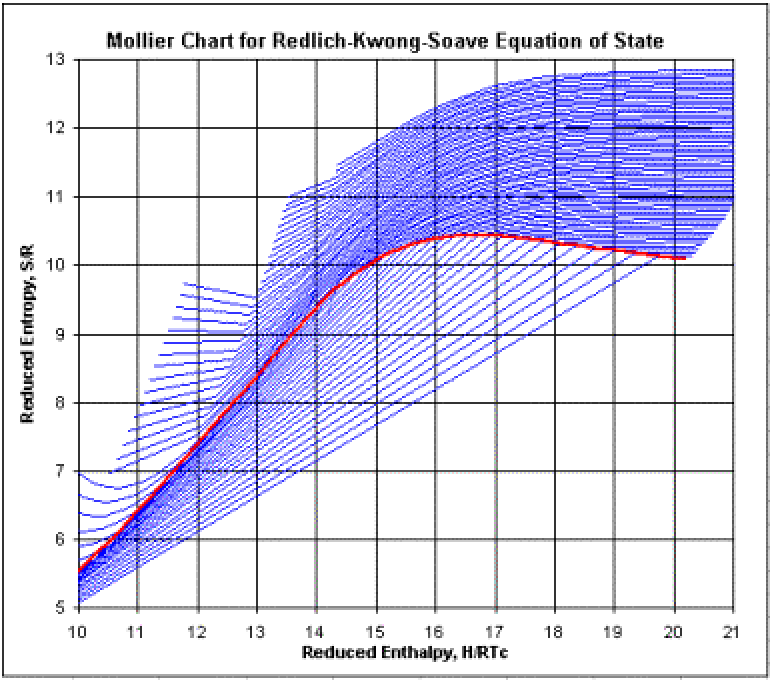


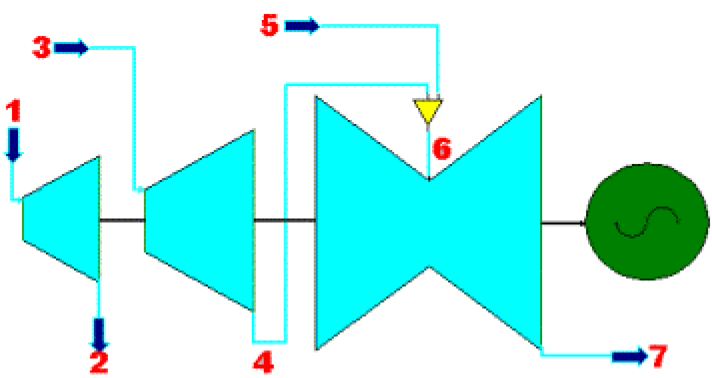


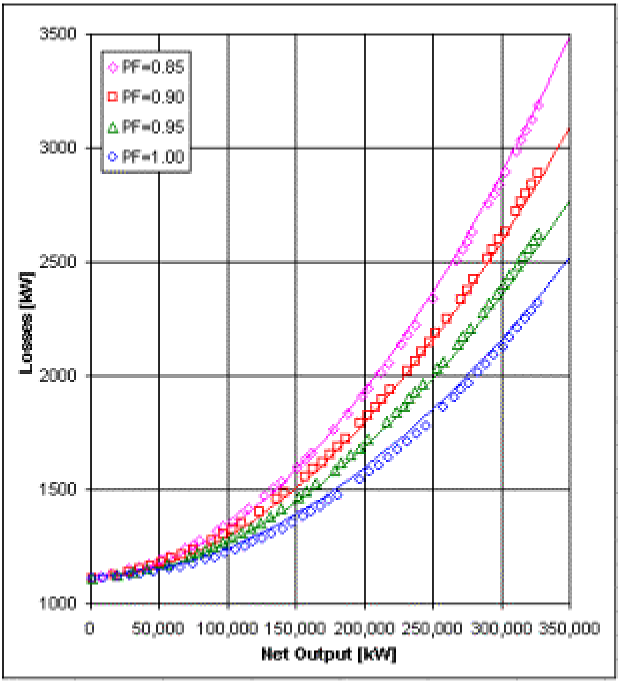
Sat. Lqd
Sat. Vap.
P=1
P=5
P=10
P=20
P=50
P=100
P=200
P=500
P=1000
P=2000
P=critical
P=5000
P=10,000
P=20,000
Cp [BTU/lbm/°F]
Temperature [°F]
0
1
2
3
4
0
500
1000
1500
2000
2500



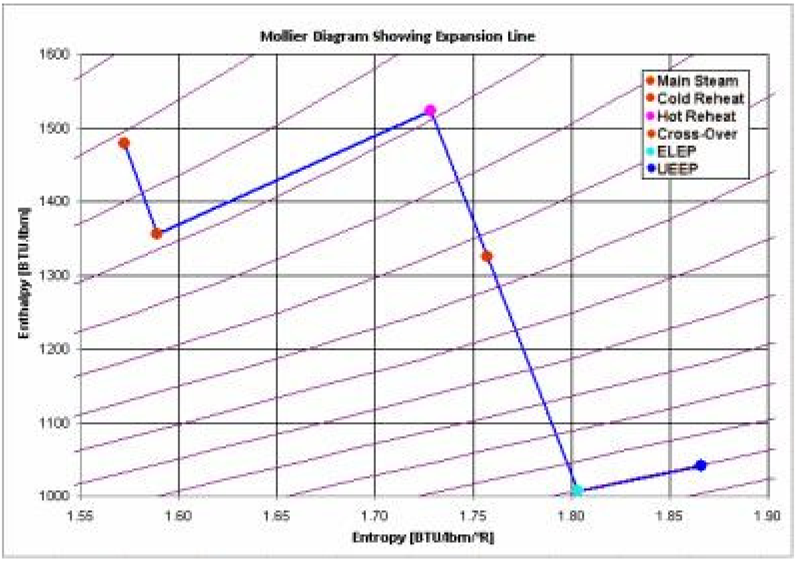
Mollier Chart for van der Waals Equation of State
Reduced Entropy, S/R
Reduced Enthalpy, H/RTc
0
1
2
3
4
5
0
1
2
3
4
5
6
7


Mollier Chart for Redlich-Kwong-Soave Equation of State
Reduced Entropy, S/R
Reduced Enthalpy, H/RTc
13
12
11
10
9
8
7
6
5
10
11
12
13
14
15
16
17
18
19
20
21


1
2
3
4
5
6
7

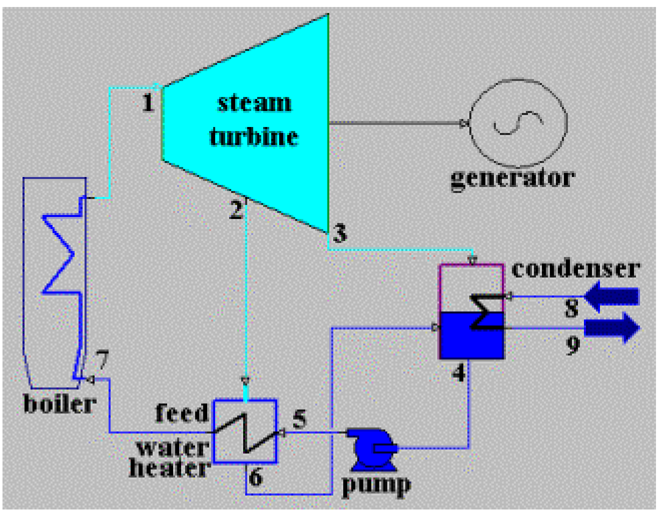


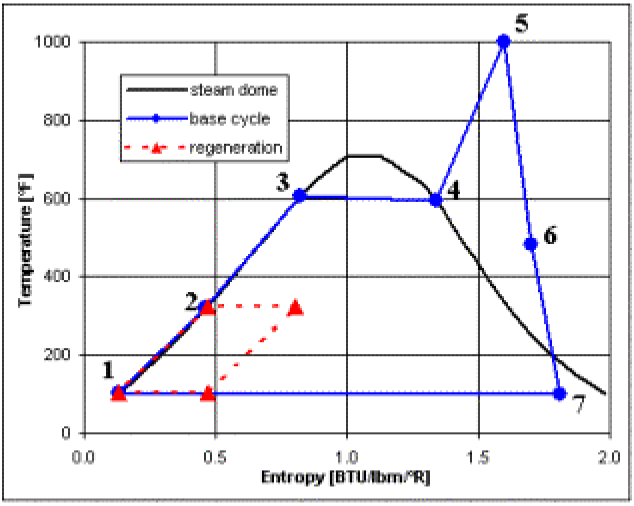
PF=0.85
PF=0.90
PF=0.95
PF=1.00
Losses [kW]
Net Output [kW]
3500
3000
2500
2000
1500
1000
0
50,000
100,000
150,000
200,000
250,000
300,000
350,000



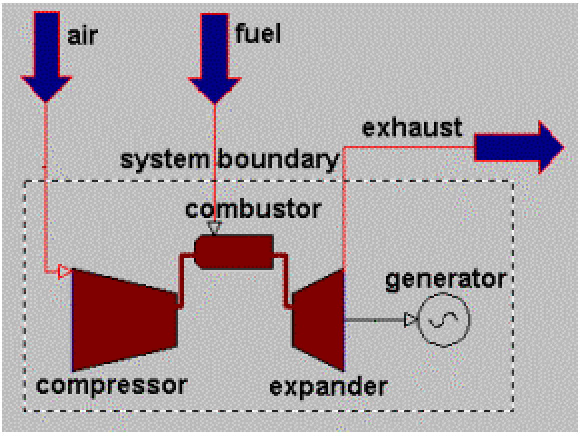
Mollier Diagram Showing Expansion Line
Main Steam
Cold Reheat
Hot Reheat
Cross-Over
ELEP
UEEP
Enthalpy [BTU/lbm]
Entropy [BTU/lbm/°R]
1600
1500
1400
1300
1200
1100
1000
1.55
1.60
1.65
1.70
1.75
1.80
1.85
1.90

	A	B	C	D	E	F	G	H	I	J	K
1	design					Area [sq.ft.]	66.14				
2	measured					Vg	342.2952				
3	calculated					x	0.938523				
4	iterative					Van	1284.862				
5	solve					loss	42.17177	35.22332			
6	description	main steam	cold reheat	hot reheat	IPT exit	LPT inlet	exp.lin.end	used energ	IPT isentr.	LP admis.	LPT isentr.
7	point	1	2	3	4	6	ELEP	UEEP	4s	5	7s
8	flow		1778199		1812039	1874969				62930	
9	pressure	1820.9	618.6	551.7	97.32	97.32	0.9728	0.9728	97.32	97.32	0.97
10	temperatur	997.1	710.5	1006.2	590.5	589.5			531.3	558.2	100.8
11	enthalpy	1478.8	1356.0	1522.8	1324.9	1324.4	1006.1	1041.3	1295.3	1308.8	979.9
12	entropy	1.5727	1.5888	1.7282	1.7573	1.7567	1.8034	1.8663	1.7282	1.7417	1.7567
13	kW		84021.9		105082.1			155532.3			
14				slope, dh/ds	-6815	-6815	shaft	324636.4			
15				for method 1 adjust until this is zero		0	PF	0.999224			
16				efficiency	86.98%	92.40%	loss	2318			
17				for method 2 adjust until this is zero		5.42%	net calc	322318			
18							net meas	322318			
19						adjust until this is zero for either method		0			

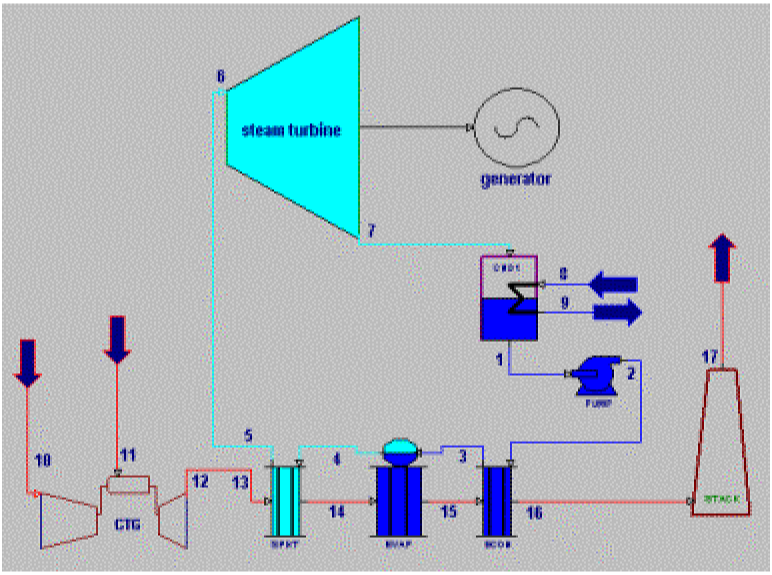


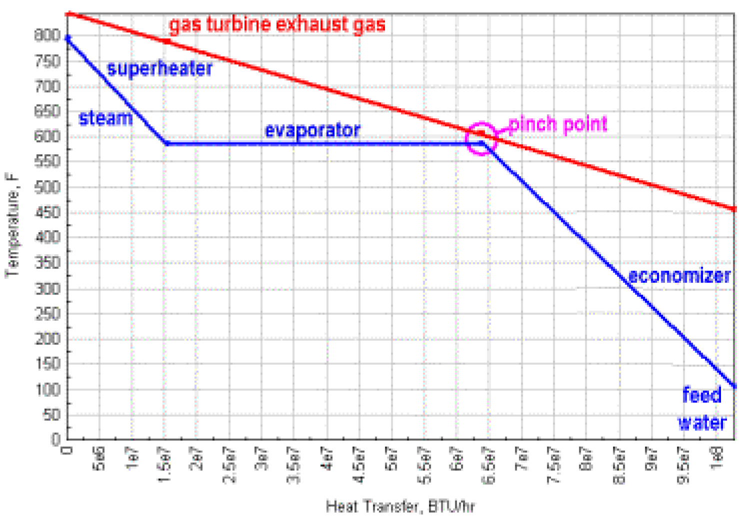


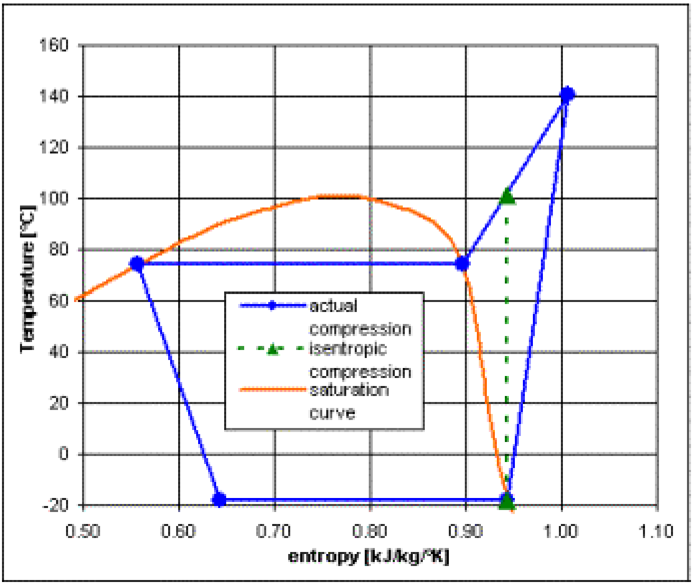
1000
800
600
400
200
0
0.0
0.5
1.0
1.5
2.0
Temperature [°F]
Entropy [BTU/lbm/°R]
steam dome
base cycle
regeneration
1
2
3
4
5
6
7

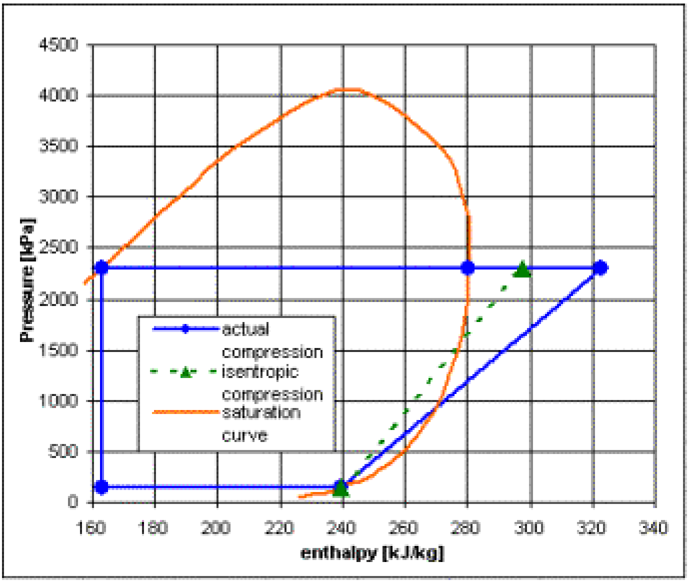


air
fuel
exhaust
system boundary
combustor
generator
compressor
expander


steam turbine
generator
6
7
8
9
1
2
17
5
4
3
10
11
12
13
14
15
16
CTG
STACK


gas turbine exhaust gas
superheater
steam
evaporator
pinch point
economizer
feed
water
Temperature, F
Heat Transfer, BTU/hr
800
750
700
650
600
550
500
450
400
350
300
250
200
150
100
50
0
0
5e6
1e7
1.5e7
2e7
2.5e7
3e7
3.5e7
4e7
4.5e7
5e7
5.5e7
6e7
6.5e7
7e7
7.5e7
8e7
8.5e7
9e7
9.5e7
1e8


160
140
120
100
80
60
40
20
0
-20
0.50
0.60
0.70
0.80
0.90
1.00
1.10
Temperature [°C]
entropy [kJ/kg/°K]
actual compression
isentropic compression
saturation curve

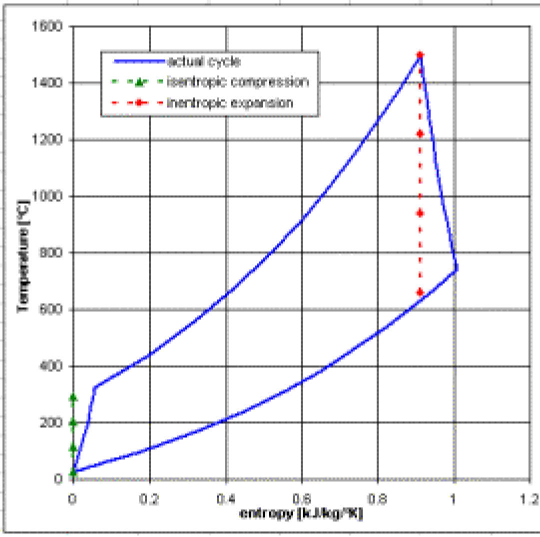

4500
4000
3500
3000
2500
2000
1500
1000
500
0
160
180
200
220
240
260
280
300
320
340
Pressure [kPa]
enthalpy [kJ/kg]
actual compression
isentropic compression
saturation curve

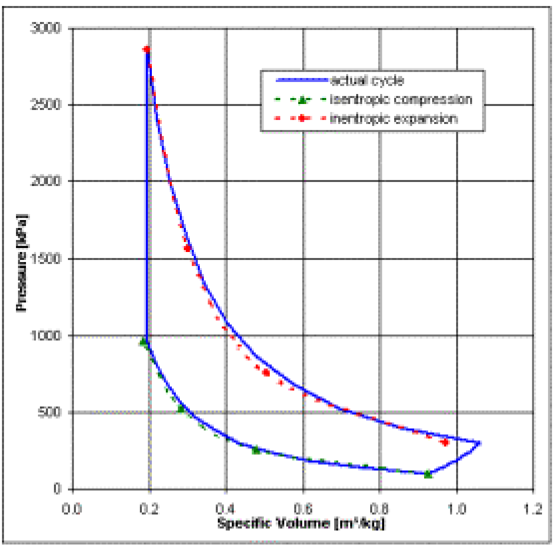
Otto Cycle

User Inputs

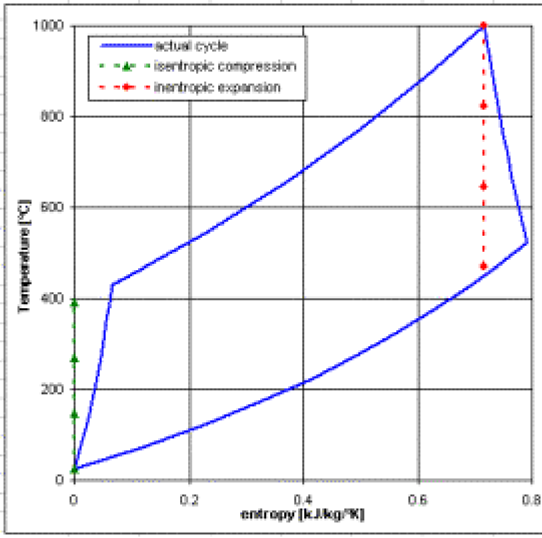
compression ratio	**9.5**	
compression eff.	**90%**	
expansion efficiency	**90%**	
combustion temp.	**1500**	°C
k=Cp/Cv	**1.4**	-
Cp	**1.1**	kJ/kg/°C
R	0.314	kJ/kg/°C

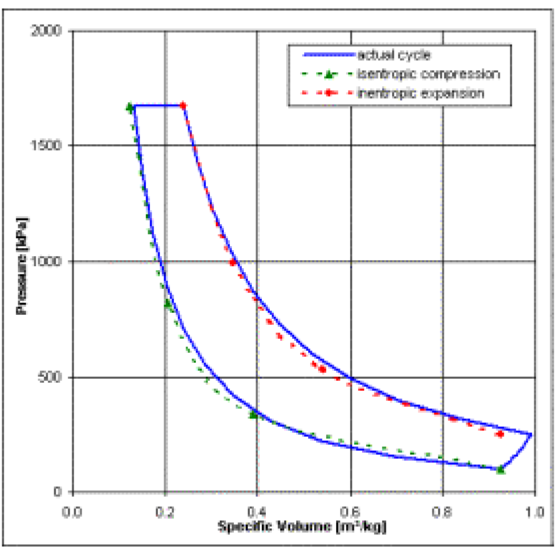
point	P	T	v	h	s
units	kPa	°C	m³/kg	kJ/kg	kJ/kg/°C
1	101	25	0.925	0	0.000
1.1	138	55	0.746	33	0.008
1.2	183	85	0.614	66	0.015
1.3	238	115	0.513	99	0.021
1.4	302	145	0.434	132	0.027
1.5	378	175	0.372	164	0.033
1.6	466	204	0.322	197	0.038
1.7	568	234	0.281	230	0.043
1.8	684	264	0.247	263	0.048
1.9	815	294	0.219	296	0.052
2	963	324	0.195	329	0.057
2.1	1152	442	0.195	458	0.198
2.2	1342	559	0.195	588	0.317
2.3	1531	677	0.195	717	0.421
2.4	1721	794	0.195	846	0.513
2.5	1910	912	0.195	976	0.595
2.6	2100	1030	0.195	1105	0.669
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]





Diesel Cycle					
User Inputs					
compression ratio			16.5		
compression eff.			90%		
expansion efficiency			90%		
combustion temp.			1000	°C	
k=Cp/Cv			1.4	-	
Cp			1.1	kJ/kg/°C	
R			0.314	kJ/kg/°C	
point	P	T	v	h	s
units	kPa	°C	m³/kg	kJ/kg	kJ/kg/°C
1	101	25	0.925	0	0.000
1.1	154	66	0.693	45	0.010
1.2	222	106	0.536	89	0.018
1.3	310	147	0.426	134	0.026
1.4	419	188	0.346	179	0.033
1.5	552	228	0.286	224	0.040
1.6	711	269	0.240	268	0.045
1.7	900	310	0.204	313	0.051
1.8	1121	350	0.175	358	0.056
1.9	1378	391	0.152	403	0.061
2	1672	432	0.133	447	0.065
2.1	1672	489	0.143	510	0.151
2.2	1672	545	0.154	572	0.230
2.3	1672	602	0.165	635	0.304
2.4	1672	659	0.175	697	0.373
2.5	1672	716	0.186	760	0.438
2.6	1672	773	0.197	822	0.499



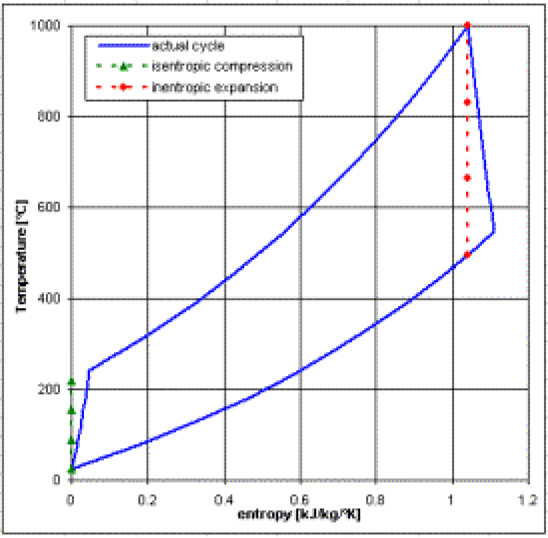


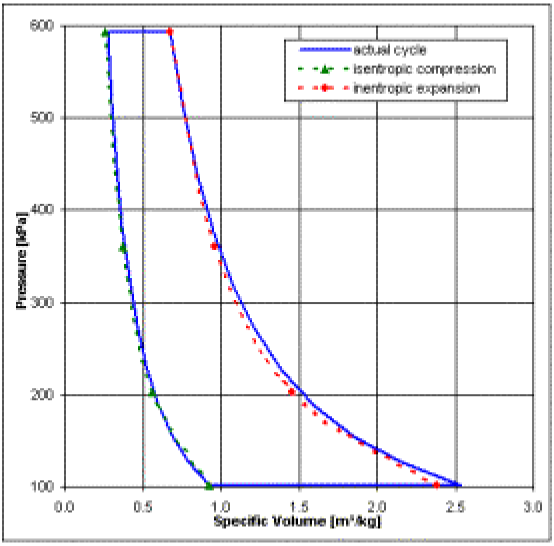
Brayton Cycle

User Inputs

compression ratio	5.9	
compression eff.	90%	
expansion efficiency	90%	
combustion temp.	1000	°C
k=Cp/Cv	1.4	-
Cp	1.1	kJ/kg/°C
R	0.314	kJ/kg/°C

point	P	T	v	h	s
units	kPa	°C	m³/kg	kJ/kg	kJ/kg/°C
1	101	25	0.925	0	0.000
1.1	127	47	0.791	24	0.006
1.2	157	68	0.683	48	0.012
1.3	192	90	0.595	72	0.017
1.4	231	112	0.523	96	0.022
1.5	276	134	0.463	120	0.027
1.6	327	155	0.412	144	0.031
1.7	383	177	0.369	167	0.036
1.8	446	199	0.333	191	0.040
1.9	516	221	0.301	215	0.044
2	593	242	0.273	239	0.047
2.1	593	318	0.314	323	0.198
2.2	593	394	0.354	406	0.331
2.3	593	470	0.394	489	0.449
2.4	593	545	0.434	573	0.556
2.5	593	621	0.474	656	0.653
2.6	593	697	0.514	739	0.743

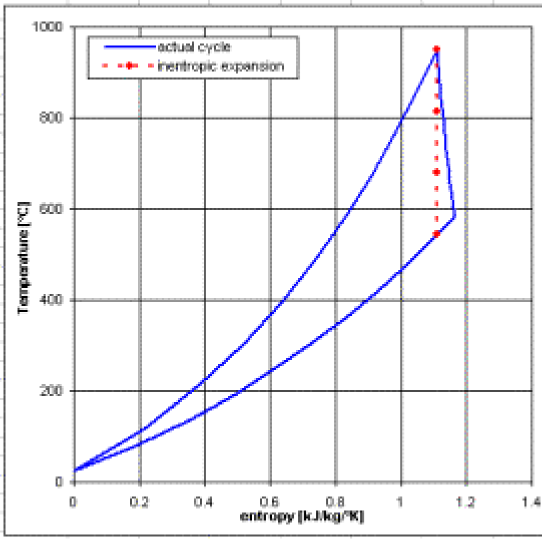


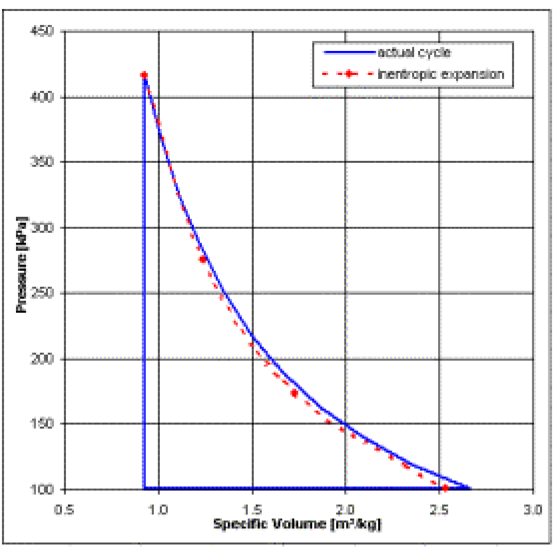


Lenoir Cycle

User Inputs			
expansion efficiency	90%		
combustion temp.	950	°C	
k=Cp/Cv	1.4	-	
Cp	1.1	kJ/kg/°C	
R	0.314	kJ/kg/°C	

point	P	T	v	h	s
units	kPa	°C	m³/kg	kJ/kg	kJ/kg/°C
1	101	25	0.925	0	0.000
1.1	133	118	0.925	102	0.212
1.2	164	210	0.925	204	0.379
1.3	196	303	0.925	305	0.517
1.4	227	395	0.925	407	0.634
1.5	259	488	0.925	509	0.736
1.6	290	580	0.925	611	0.826
1.7	321	673	0.925	712	0.907
1.8	353	765	0.925	814	0.980
1.9	384	858	0.925	916	1.047
2	416	950	0.925	1018	1.109
2.1	368	913	1.012	977	1.114
2.2	325	877	1.111	937	1.118
2.3	286	840	1.223	897	1.123
2.4	251	804	1.351	857	1.128
2.5	218	767	1.497	817	1.133
2.6	189	731	1.665	776	1.139
2.7	163	694	1.860	736	1.144
2.8	140	658	2.086	696	1.150
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

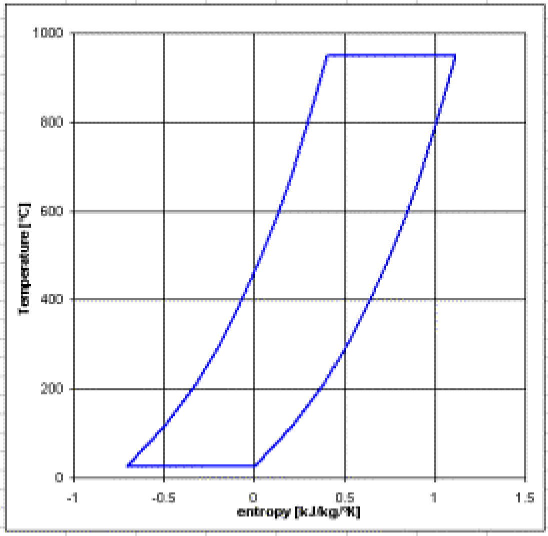


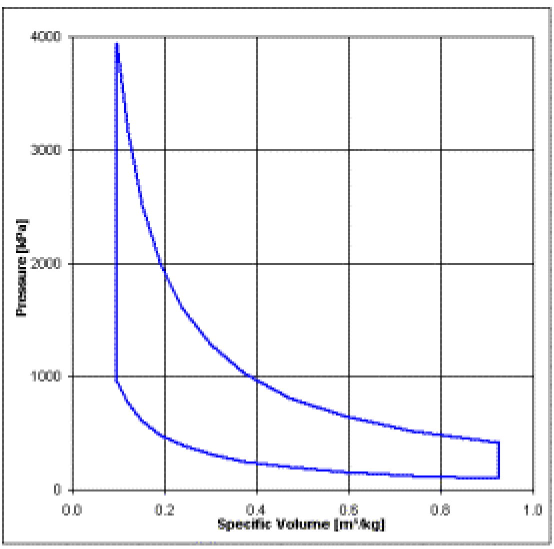


Stirling Cycle

User Inputs		
compression ratio	**9.5**	
combustion temp.	**950**	°C
k=Cp/Cv	**1.4**	-
Cp	**1.1**	kJ/kg/°C
R	0.314	kJ/kg/°C

point	P	T	v	h	s
units	kPa	°C	m³/kg	kJ/kg	kJ/kg/°C
1	101	25	0.926	0	0.000
1.1	127	25	0.738	0	-0.071
1.2	159	25	0.590	0	-0.142
1.3	199	25	0.471	0	-0.212
1.4	249	25	0.376	0	-0.283
1.5	312	25	0.300	0	-0.354
1.6	391	25	0.240	0	-0.425
1.7	490	25	0.191	0	-0.495
1.8	614	25	0.153	0	-0.566
1.9	769	25	0.122	0	-0.637
2	963	25	0.097	0	-0.708
2.1	1261	118	0.097	102	-0.495
2.2	1560	210	0.097	204	-0.326
2.3	1859	303	0.097	305	-0.191
2.4	2157	395	0.097	407	-0.074
2.5	2456	488	0.097	509	0.028
2.6	2754	580	0.097	611	0.119
2.7	3053	673	0.097	712	0.199
2.8	3352	765	0.097	814	0.273
2.9	3650	858	0.097	916	0.340





Ericsson Cycle

User Inputs

compression ratio	**9.5**	
combustion temp.	**950**	°C
k=Cp/Cv	**1.4**	-
Cp	**1.1**	kJ/kg/°C
R	0.314	kJ/kg/°C

point	P	T	v	h	s
units	kPa	°C	m³/kg	kJ/kg	kJ/kg/°C
1	101	25	0.925	0	0.000
1.1	127	25	0.738	0	-0.071
1.2	159	25	0.590	0	-0.142
1.3	199	25	0.471	0	-0.212
1.4	249	25	0.376	0	-0.283
1.5	312	25	0.300	0	-0.354
1.6	391	25	0.240	0	-0.425
1.7	490	25	0.191	0	-0.495
1.8	614	25	0.153	0	-0.566
1.9	769	25	0.122	0	-0.637
2	963	25	0.097	0	-0.708
2.1	963	118	0.128	102	-0.410
2.2	963	210	0.158	204	-0.177
2.3	963	303	0.188	305	0.016
2.4	963	395	0.218	407	0.180
2.5	963	488	0.248	509	0.323
2.6	963	580	0.279	611	0.449
2.7	963	673	0.309	712	0.562
2.8	963	765	0.339	814	0.665
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]