ASEE 2003-1703 for Energy Conversion and Conservation Division

"Twenty Years of Experiences in Computer Modeling of Thermodynamic Cycles"

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Mechanical Engineering Department, Union College

Abstract

What we are told we easily forget, but the things we do we understand! Engineering education works best when the students are not overly subjected to listening, but have ample opportunity to do. Computer use in education provides a more subtle example of this principle. Students, like current engineers in industry, now run a variety of commercial application software to perform various calculations and simulations. The danger is that too often they do not understand the underlying principles, mathematical modeling and assumptions.

The author's first experience was twenty years ago. It was an era when mainframe, timeshare and what was then called minicomputers were used for academic research, but personal computers were not yet available. There was no computer use in an undergraduate classroom. The author decided to do some pioneering course development by programming various thermodynamic and nuclear power plant simulations on a time share computer for the benefit of his students in these courses.

During the development he realized that he was enhancing his own understanding of cycles and power plant dynamics. This was because of the long hours and intense concentration that was required for the project. Models were developed of Carnot, Otto, Diesel, Brayton and Rankine cycles. The piston cylinder cycles showed a piston moving up and down with simultaneous display of properties, work and heat and the development of a 1st law process and cycle table and resulting efficiency.

The nuclear power plant simulation displayed the components and response to throttle, control rod motion, change in flow and a scram. Separately the reactor kinetics were programmed in Basic on an Atari 400 game computer with time responses of input and output responses traced on a TV screen.

The next step was to take the students to the computer room to execute the simulations. It was discouraging, but then understandable, to realize that the students were not learning much. Asteroids was the hugely popular video game at the time. Students executed the programs like they were playing such a video game.

The lesson learned was that the professor had learned by developing the programs, but the students were deprived of the development experience. It was 20 years later when that the author revived computer based simulations, by having students do their own development on their personal computers. While the result is less sophisticated, the

educational process and experience has been favorable.

1. Introduction

The author's first experience at modeling thermodynamic processes was twenty years ago when he served as Supervisor of the Thermodynamics and Nuclear Operations Curriculums at Rensselaer Polytechnic Institute. Personal computers were not yet available, but a CAD system with remote time share access had been recently installed. I developed a set of interactive programs named CAT for Computer Aided Thermodynamics.

Recent experiences are teaching at Union College. Personal computers and/or laptops are available to all students. Thus, the students can do the programming rather than the Professor. This paper will describe the computer simulations, experiences with students and educational conclusions from twenty years ago and from now.

2. Early Computer Based Simulation Models

Once the author learned how to draw a line and to make it move and rotate in 1981 versions of Computer Aided Drafting (CAD), he programmed a piston moving up and down in a cylinder while turning a crank. A CAD based FORTRAN allowed for a thermodynamic data base and the calculation of the changing thermodynamic properties such as pressure, temperature, specific volume, internal energy and enthalpy within the piston cylinder. It could also be programmed to display the work and heat during each process. These values were calculated and displayed beside the cylinder.

CAD could also be programmed to graph the dynamic process taking place inside the piston cylinder on a pressure vs volume and a temperature vs entropy graph. It was programmed so that the user could choose a third combination of properties such as pressure vs temperature to be displayed on a third graph.

Finally in a form consistent with the text book at the time, the 1st Law Energy Balance of Heat in plus Work in is equal to the Change of Internal Energy Change was displayed for each process and for the entire cycle.

Process Models

Since cycles are comprised of a set of processes, the first programs were to simulate well defined processes using air as an ideal gas, a common starting point and a final parameter such as pressure, volume or temperature to define the end point. The working fluid was air as an ideal gas.

From a menu the student can choose a constant pressure, constant volume, constant temperature or reversible adiabatic process from point "1" to point "2" and then input the final condition. The simulation responds with piston motion, changing property values and the 1st law energy balance for the defined process.

Figures 1, 2, 3 and 4 show constant pressure, volume, temperature and adiabatic processes respectively. Note the optional graph for the figure 1 is pressure vs entropy, for figure 2 it is volume vs entropy, for figure 3 it is pressure vs entropy and for figure 4 it is pressure vs temperature. The graphs of pressure vs volume and temperature vs entropy is provided for each process.

Cycles

The next endeavor was to program various air standard power cycles that could be selected from a menu. These cycles were the Diesel, Otto, Non Flow Brayton, Carnot and a hypothetical cycle that is a rectangle on a pressure vs volume diagram. Along with the simulation and tables the cycle efficiency is calculated and displayed for each.

Figures 5, 6 and 7 are at various points in the Diesel cycle. The user specified a compression ratio and expansion ratio during fuel injection. Figure 5 is during compression, Figure 6 is during the fuel injection part of the expansion and Figure 7 is for the complete cycle. Note the optional graph is volume vs temperature.

Figure 8 shows a completed Otto Cycle with compression ratio and heat added as the specifications. The optional graph is pressure vs entropy.

Figure 9 shows a Carnot cycle with the high side temperature and heat added specified. The optional graph is pressure vs entropy.

Figure 10 shows the hypothetical cycle that is a rectangle on a pressure vs volume diagram. The optional graph displays pressure vs temperature.

Nuclear Reactor and Power Plant Simulations

The vital starting point for a nuclear power plant simulation is to model the relationship between reactivity, control rod position neutron source strength, and the resulting total neutron population and power along with response to a sudden insertion of control rods which is called a SCRAM.

A one delayed neutron group and one node mathematical model was developed. It was then programmed on an Atari 400 game computer in BASIC. A television set was the monitor. Moving the joystick up or down raised or lowered control rods. Moving it sideways moved the neutron source in or out or the reactor core. Pushing the red button resulted in a SCRAM. Strip chart like time traces were displayed on the screen.

The reactor kinetics model was extended to an entire Pressurized Water Nuclear Power Plant with reactor, steam generators and turbines (reference 1). The various energy, flow and neutronic equations were developed and programmed on the same CAD system with the thermodynamic cycles. The inputs were control rod motion, the steam valve to the turbine and the reactor circulating pump speed. The nuclear power plant at full power and steady state condition is shown in figure 11. The response 16 seconds into a ramped insertion of the control rods is shown in figure 12. The response to a ramp closing of the steam valve after 31 seconds is shown in figure 13. The response to a ramped change of coolant pump speeds after 11 seconds is shown in figure 14.

Since the dynamic response of a nuclear power plant to these inputs may take several minutes, this simulation was programmed with a FAST option that simulates at 10 times real time, along with the normal speed option.

3. Contemporary Thermodynamic Cycle Simulations

Students now have their own personal computers and lap tops. This means they can develop their own engine cycles. They are given the assignment to develop equations to analyze various cycles, and display the resulting property and process tables.

The cycles they are assigned are the Otto, Diesel, Carnot and a flow Brayton cycle. It is noted that the gas turbine is now called a Brayton cycle. However, the internal combustion engine that Boston engineer George Brayton patented in 1873 used separate pistons for compression and expansion.

From the class room we developed the pedagogical technique of inputting constants to the data base such as the specific heat at constant pressure for air, the ratio of constant pressure and constant volume heat capacities and the work equivalent of heat of 778 ft lbf per Btu. Students then calculate constants from constants such as ideal gas constant for air in heat and work units.

We next develop a toolbox of thermodynamic relationships, and a description of each cycle. Figure 15 is a student's property and 1st law process and cycle table summary for a Diesel engine. Figure 16 is another student's results for an Otto cycle.

4. Conclusion

The exercise of years ago of the professor developing thermodynamic programs for the student use was an educational failure. The subsequent advent of individual computers for each student has allowed each student to develop the and program the cycle equations. This has been educationally effective.

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Reference: 1) Frank Wicks, “Formulation and Application of an Equation for Low Power Reactor Operations and Experiments”, Transactions of the American Nuclear Society, 1983 Winter Annual Meeting, Volume 45, San Francisco, California.

Frank Wicks
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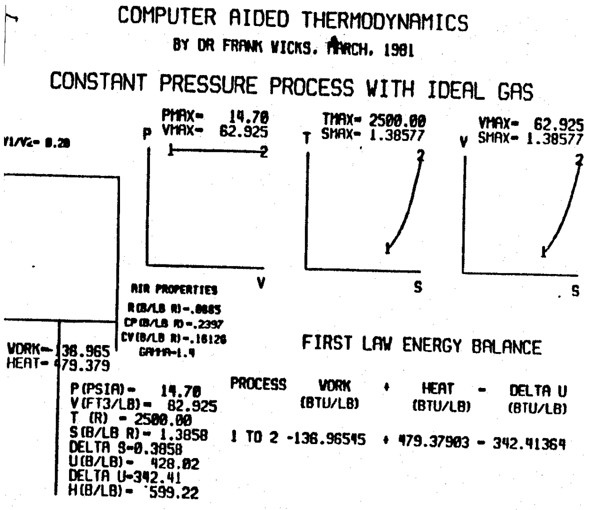
New York Maritime College, MSEE from Union College and PhD in Nuclear Engineering from Rensselaer. He has served as a shipboard engineering officer, General Electric engineer and as a member of Nuclear Engineering Department at Rensselaer.



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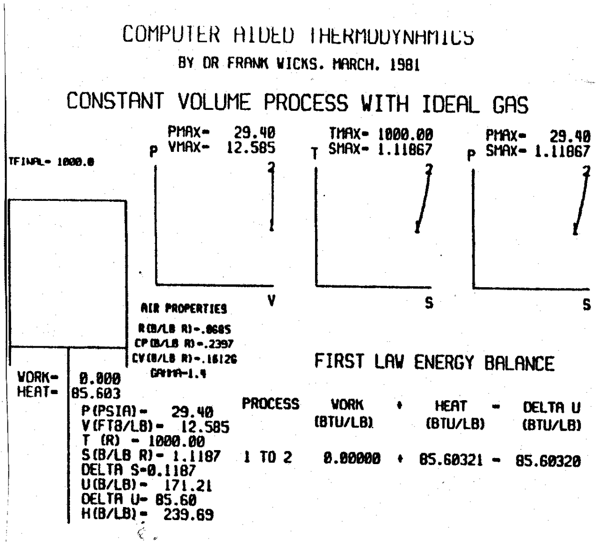
COMPUTER AIDED THERMODYNAMICS
BY DR FRANK VICKS. MARCH. 1981

CONSTANT PRESSURE PROCESS WITH IDEAL GAS
                 PMAX=  14.70     TMAX= 2500.00    VMAX=  62.925
                 VMAX=  82.925    SMAX= 1.38577    SMAX= 1.38577
V1/V2= 0.20

                 AIR PROPERTIES
                 R(B/LB R)=.0685
                 CP(B/LB R)=.2397
                 CV(B/LB R)=.16126        FIRST LAW ENERGY BALANCE
VORK=-136.965       GAMA=1.4
HEAT= 479.379
   P(PSIA)=   14.70   PROCESS   VORK    +    HEAT    -   DELTA U
   V(FT3/LB)=  82.925          (BTU/LB)     (BTU/LB)     (BTU/LB)
   T  (R)  = 2500.00
   S(B/LB R)= 1.3858  1 TO 2 -136.96545 + 479.37903 - 342.41364
   DELTA S=0.3858
   U(B/LB)=  428.02
   DELTA U=342.41
   H(B/LB)=  599.22
```

Figure 1 Constant Pressure Process



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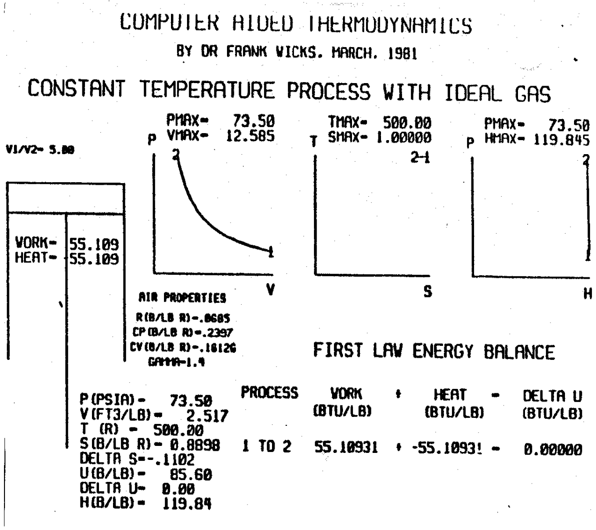
COMPUTER AIDED THERMODYNAMICS
BY DR FRANK VICKS. MARCH. 1981

CONSTANT VOLUME PROCESS WITH IDEAL GAS
                 PMAX=   29.40    TMAX= 1000.00    PMAX=   29.40
                 VMAX=  12.585    SMAX= 1.11867    SMAX= 1.11867
TFINAL= 1000.0

                 AIR PROPERTIES
                 R(B/LB R)=.0685
                 CP(B/LB R)=.2397
                 CV(B/LB R)=.16126        FIRST LAW ENERGY BALANCE
VORK=   0.000       GAMA=1.4
HEAT=  85.603
   P(PSIA)=   29.40   PROCESS   VORK    +    HEAT    -   DELTA U
   V(FT8/LB)=  12.585          (BTU/LB)     (BTU/LB)     (BTU/LB)
   T  (R)  = 1000.00
   S(B/LB R)= 1.1187  1 TO 2   0.00000 +  85.60321 -  85.60320
   DELTA S=0.1187
   U(B/LB)=  171.21
   DELTA U= 85.60
   H(B/LB)=  239.69
```

Figure 2 Constant Volume Process



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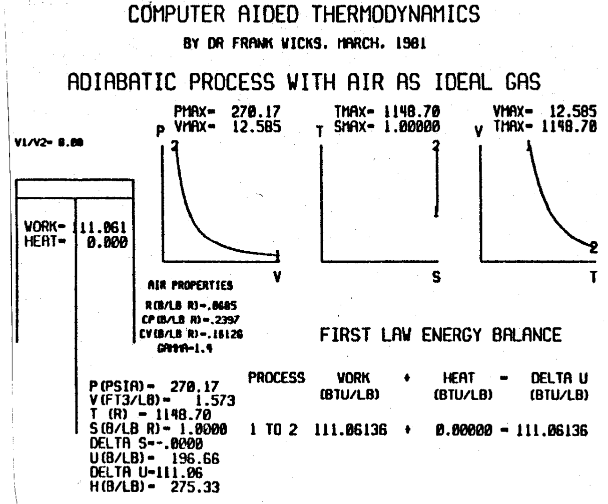
COMPUTER AIDED THERMODYNAMICS
BY DR FRANK VICKS. MARCH. 1981

CONSTANT TEMPERATURE PROCESS WITH IDEAL GAS
                 PMAX=   73.50    TMAX=  500.00    PMAX=   73.50
                 VMAX=  12.585    SMAX= 1.00000    HMAX= 119.845
V1/V2= 5.00

VORK=  55.109
HEAT= -55.109
                 AIR PROPERTIES
                 R(B/LB R)=.0685
                 CP(B/LB R)=.2397
                 CV(B/LB R)=.16126        FIRST LAW ENERGY BALANCE
                    GAMA=1.4

   P(PSIA)=   73.50   PROCESS   VORK    +    HEAT    -   DELTA U
   V(FT3/LB)=   2.517          (BTU/LB)     (BTU/LB)     (BTU/LB)
   T  (R)  =  500.00
   S(B/LB R)= 0.8898  1 TO 2  55.10931 + -55.1093! -   0.00000
   DELTA S=-.1102
   U(B/LB)=   85.60
   DELTA U=  0.00
   H(B/LB)=  119.84
```

Figure 3 Constant Temperature Process



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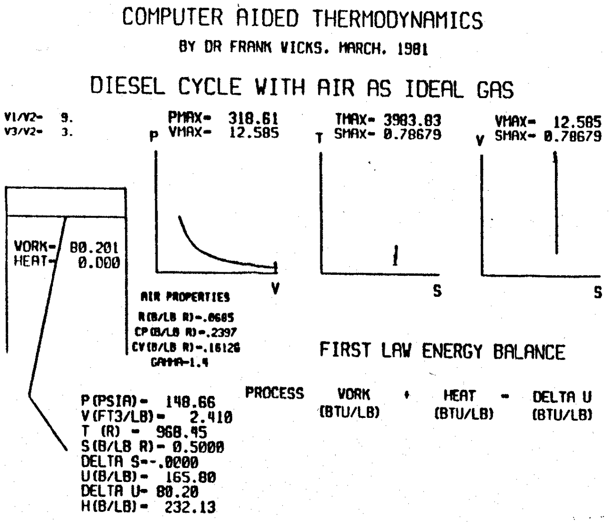
COMPUTER AIDED THERMODYNAMICS
BY DR FRANK VICKS. MARCH. 1981

ADIABATIC PROCESS WITH AIR AS IDEAL GAS
                 PMAX=  270.17    TMAX= 1148.70    VMAX=  12.585
                 VMAX=  12.585    SMAX= 1.00000    TMAX= 1148.70
V1/V2= 8.00

VORK= 111.061
HEAT=   0.000
                 AIR PROPERTIES
                 R(B/LB R)=.0685
                 CP(B/LB R)=.2397
                 CV(B/LB R)=.16126        FIRST LAW ENERGY BALANCE
                    GAMA=1.4

   P(PSIA)=  270.17   PROCESS   VORK    +    HEAT    -   DELTA U
   V(FT3/LB)=   1.573          (BTU/LB)     (BTU/LB)     (BTU/LB)
   T  (R)  = 1148.70
   S(B/LB R)= 1.0000  1 TO 2 111.06136 +   0.00000 - 111.06136
   DELTA S=-.0000
   U(B/LB)=  196.66
   DELTA U=111.06
   H(B/LB)=  275.33
```

Figure 4 Adiabatic Process



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            COMPUTER AIDED THERMODYNAMICS
            BY DR FRANK VICKS. MARCH. 1981

          DIESEL CYCLE WITH AIR AS IDEAL GAS

V1/V2-   9.          PMAX-  318.61     TMAX- 3983.83     VMAX-  12.585
V3/V2-   3.          VMAX-  12.585     SMAX- 0.78679     SMAX- 0.78679

VORK-  80.201
HEAT-   0.000
                     AIR PROPERTIES
                     R(B/LB R)-.0685
                     CP(B/LB R)-.2397
                     CV(B/LB R)-.16126
                     GAMMA-1.4
                                   FIRST LAW ENERGY BALANCE

P(PSIA)-  140.66     PROCESS   VORK     +    HEAT    -   DELTA U
V(FT3/LB)-   2.410            (BTU/LB)      (BTU/LB)     (BTU/LB)
T (R) -  968.45
S(B/LB R)- 0.5000
DELTA S--.0000
U(B/LB)-  165.80
DELTA U- 80.20
H(B/LB)-  232.13
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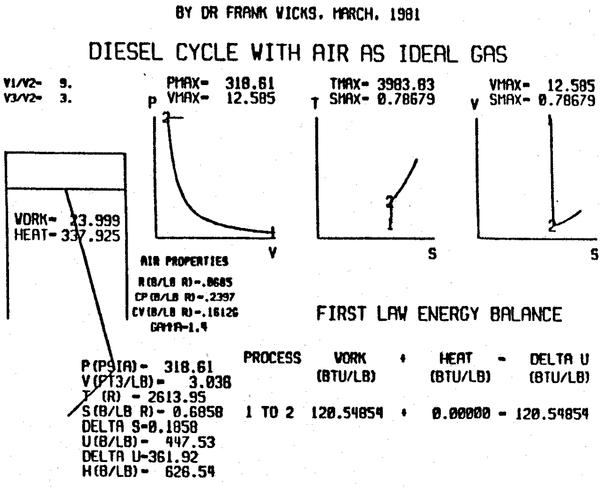
Figure 5 Diesel During Compression



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            BY DR FRANK VICKS. MARCH. 1981

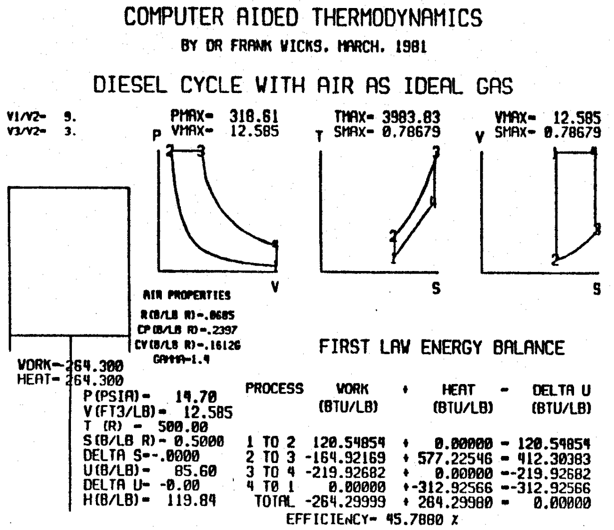
          DIESEL CYCLE WITH AIR AS IDEAL GAS

V1/V2-   9.          PMAX-  318.61     TMAX- 3983.83     VMAX-  12.585
V3/V2-   3.          VMAX-  12.585     SMAX- 0.78679     SMAX- 0.78679

VORK-  23.999
HEAT- 337.925
                     AIR PROPERTIES
                     R(B/LB R)-.0685
                     CP(B/LB R)-.2397
                     CV(B/LB R)-.16126
                     GAMMA-1.4
                                 FIRST LAW ENERGY BALANCE

                      PROCESS   VORK      +    HEAT    -   DELTA U
P(PSIA)-  318.61               (BTU/LB)       (BTU/LB)     (BTU/LB)
V(FT3/LB)-   3.036
T (R) - 2613.95
S(B/LB R)- 0.6858     1 TO 2  120.54854  +   0.00000 - 120.54854
DELTA S-0.1858
U(B/LB)-  447.53
DELTA U-361.92
H(B/LB)-  626.54
```

Figure 6 Diesel During Fuel Injection



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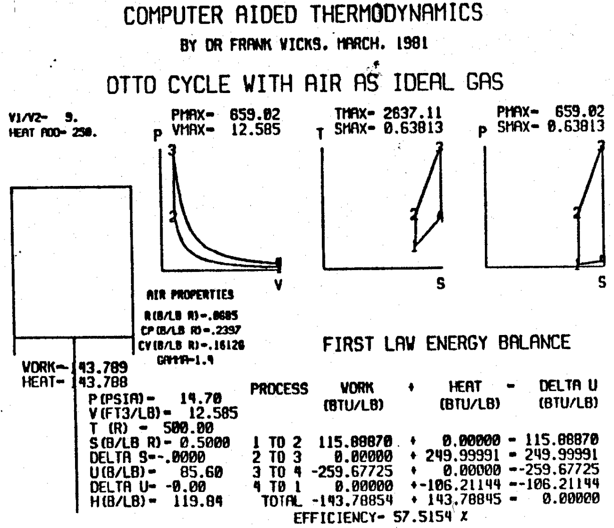
            COMPUTER AIDED THERMODYNAMICS
            BY DR FRANK VICKS. MARCH. 1981

          DIESEL CYCLE WITH AIR AS IDEAL GAS

V1/V2-   9.          PMAX-  318.61     TMAX- 3983.83     VMAX-  12.585
V3/V2-   3.          VMAX-  12.585     SMAX- 0.78679     SMAX- 0.78679

                     AIR PROPERTIES
                     R(B/LB R)-.0685
                     CP(B/LB R)-.2397
                     CV(B/LB R)-.16126
                     GAMMA-1.4
                                   FIRST LAW ENERGY BALANCE
VORK--264.300
HEAT- 264.300        PROCESS   VORK      +    HEAT    -   DELTA U
   P(PSIA)-   14.70           (BTU/LB)       (BTU/LB)     (BTU/LB)
   V(FT3/LB)-  12.585
   T (R) -  500.00
   S(B/LB R)- 0.5000   1 TO 2  120.54854  +   0.00000 - 120.54854
   DELTA S--.0000      2 TO 3 -164.92169  + 577.22546 - 412.30383
   U(B/LB)-   85.60    3 TO 4 -219.92682  +   0.00000 --219.92682
   DELTA U- -0.00      4 TO 1    0.00000  +-312.92566 --312.92566
   H(B/LB)-  119.84     TOTAL -264.29999  + 264.29980 -   0.00000
                            EFFICIENCY- 45.7880 %
```

Figure 7 Complete Diesel Cycle



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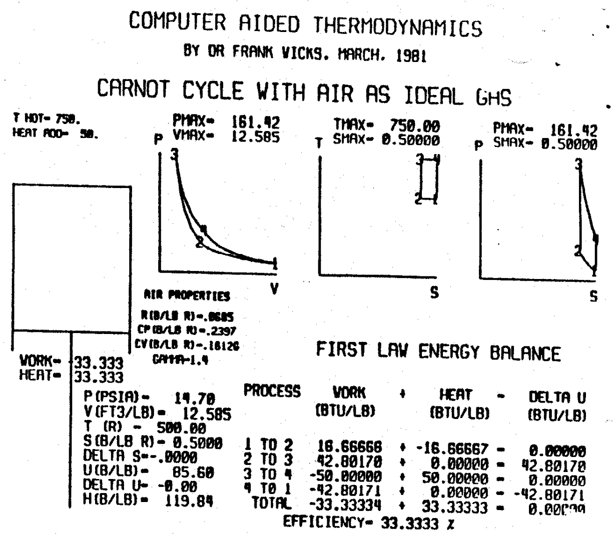
            COMPUTER AIDED THERMODYNAMICS
            BY DR FRANK VICKS. MARCH. 1981

          OTTO CYCLE WITH AIR AS IDEAL GAS

V1/V2-   9.          PMAX-  659.02     TMAX- 2637.11     PMAX-  659.02
HEAT ADD- 250.       VMAX-  12.585     SMAX- 0.63813     SMAX- 0.63813

                     AIR PROPERTIES
                     R(B/LB R)-.0685
                     CP(B/LB R)-.2397
                     CV(B/LB R)-.16126
                     GAMMA-1.4
                                   FIRST LAW ENERGY BALANCE
VORK--143.789
HEAT- 143.788        PROCESS   VORK      +    HEAT    -   DELTA U
   P(PSIA)-   14.70           (BTU/LB)       (BTU/LB)     (BTU/LB)
   V(FT3/LB)-  12.585
   T (R) -  500.00
   S(B/LB R)- 0.5000   1 TO 2  115.88870  +   0.00000 - 115.88870
   DELTA S--.0000      2 TO 3    0.00000  + 249.99991 - 249.99991
   U(B/LB)-   85.60    3 TO 4 -259.67725  +   0.00000 --259.67725
   DELTA U- -0.00      4 TO 1    0.00000  +-106.21144 --106.21144
   H(B/LB)-  119.84     TOTAL -143.78854  + 143.78845 -   0.00000
                            EFFICIENCY- 57.5154 %
```

Figure 8 Complete Otto Cycle



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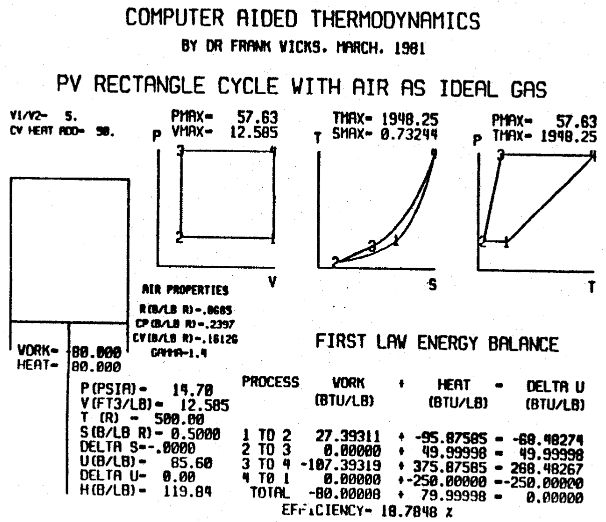
            COMPUTER AIDED THERMODYNAMICS
          BY DR FRANK VICKS. MARCH. 1981

     CARNOT CYCLE WITH AIR AS IDEAL GAS

T HOT- 750.         PMAX-  161.42     TMAX-  750.00      PMAX-  161.42
HEAT ADD-  50.      VMAX-  12.585     SMAX- 0.50000      SMAX- 0.50000

                 AIR PROPERTIES
                 R(B/LB R)-.0685
                 CP(B/LB R)-.2397
                 CV(B/LB R)-.18126       FIRST LAW ENERGY BALANCE
VORK-  33.333      GAMMA-1.4
HEAT-  33.333
       P(PSIA)-    14.70   PROCESS   VORK     +    HEAT    -   DELTA U
       V(FT3/LB)-  12.585            (BTU/LB)      (BTU/LB)    (BTU/LB)
       T (R) -  500.00
       S(B/LB R)- 0.5000   1 TO 2   18.66668  + -16.66667 -    0.00000
       DELTA S--.0000      2 TO 3   42.80170  +   0.00000 -   42.80170
       U(B/LB)-    85.60   3 TO 4  -50.00000  +  50.00000 -    0.00000
       DELTA U- -0.00      4 TO 1  -42.80171  +   0.00000 -  -42.80171
       H(B/LB)-  119.84     TOTAL  -33.33334  +  33.33333 -    0.00099
                               EFFICIENCY- 33.3333 %
```

Figure 9 Complete Carnot Cycle



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            COMPUTER AIDED THERMODYNAMICS
          BY DR FRANK VICKS. MARCH. 1981

     PV RECTANGLE CYCLE WITH AIR AS IDEAL GAS

V1/V2-   5.           PMAX-   57.63    TMAX- 1948.25     PMAX-   57.63
CV HEAT ADD-  50.     VMAX-  12.585    SMAX- 0.73244     TMAX- 1948.25

                 AIR PROPERTIES
                 R(B/LB R)-.0685
                 CP(B/LB R)-.2397
                 CV(B/LB R)-.18126       FIRST LAW ENERGY BALANCE
VORK-  80.000      GAMMA-1.4
HEAT-  80.000
       P(PSIA)-    14.70   PROCESS   VORK      +    HEAT     -  DELTA U
       V(FT3/LB)-  12.585            (BTU/LB)       (BTU/LB)    (BTU/LB)
       T (R) -  500.00
       S(B/LB R)- 0.5000   1 TO 2    27.39311  +  -95.87585 -  -68.48274
       DELTA S--.0000      2 TO 3     0.00000  +   49.99998 -   49.99998
       U(B/LB)-    85.60   3 TO 4  -107.39319  +  375.87585 -  268.48267
       DELTA U-  0.00      4 TO 1     0.00000  + -250.00000 - -250.00000
       H(B/LB)-  119.84     TOTAL   -80.00008  +   79.99998 -    0.00000
                               EFFICIENCY- 18.7848 %
```

Figure 10 Complete PV Rectangle Cycle

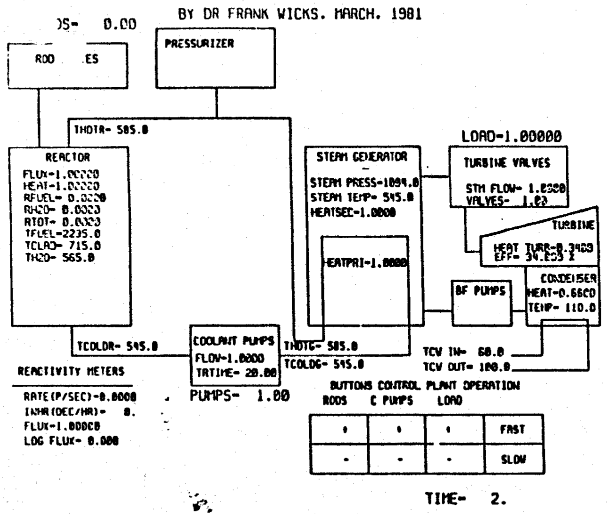


Figure 11 Nuclear Power Plant Steady State

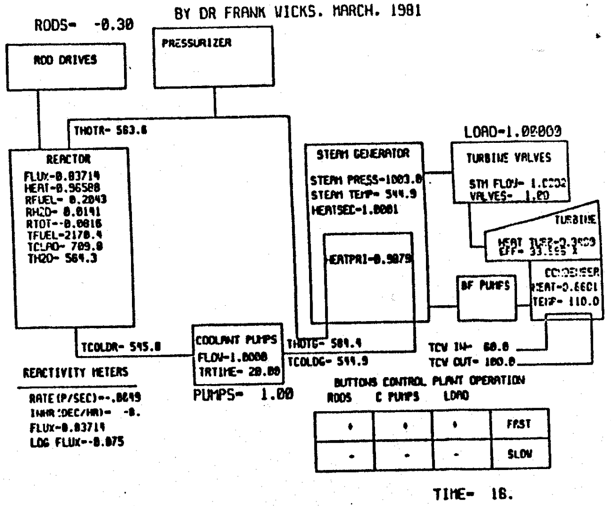


Figure 12 Response to ramped insertion of control rods.

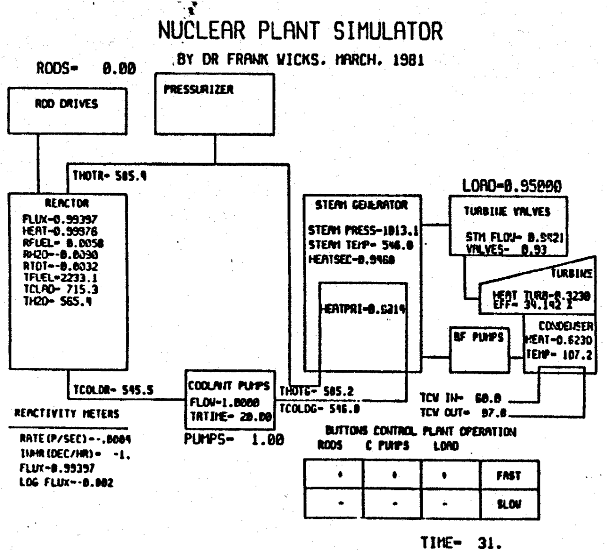


Figure 13 Nuclear Power Plant Ramped Turbine Valve Response

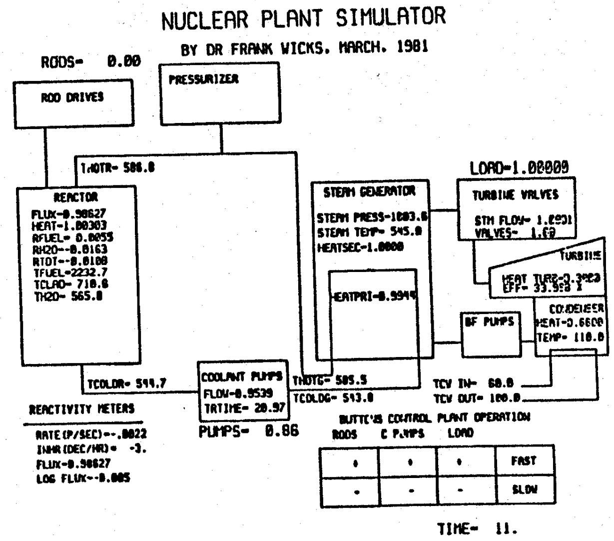
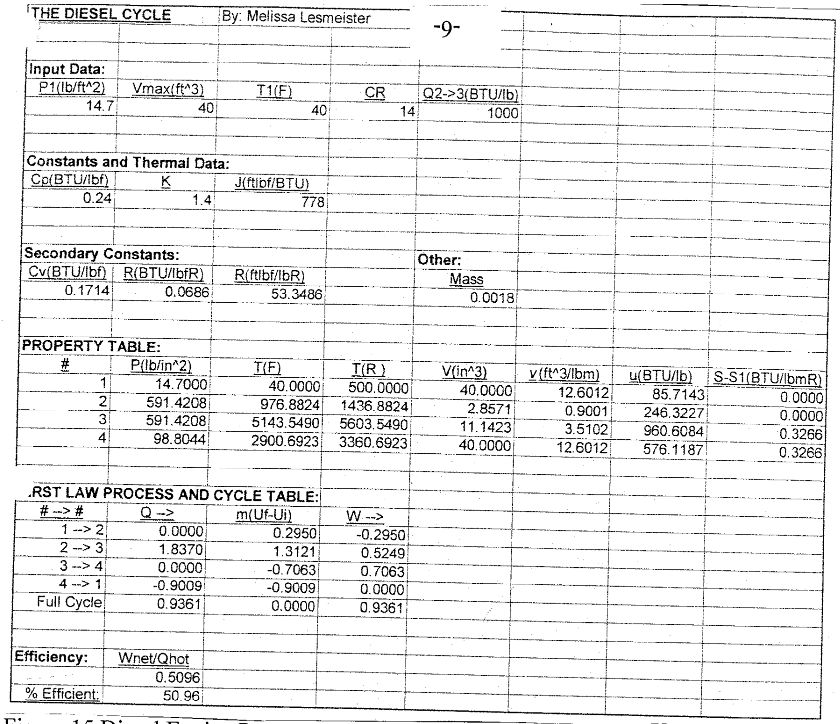


Figure 14 Nuclear Power Plant Coolant Flow Rate Change Response



THE DIESEL CYCLE By: Melissa Lesmeister

Input Data:

P1(lb/ft^2)	Vmax(ft^3)	T1(F)	CR	Q2->3(BTU/lb)
14.7	40	40	14	1000

Constants and Thermal Data:

Cp(BTU/lbf)	K	J(ftlbf/BTU)
0.24	1.4	778

Secondary Constants:

Cv(BTU/lbf)	R(BTU/lbfR)	R(ftlbf/lbR)
0.1714	0.0686	53.3486

Other:

Mass
0.0018

PROPERTY TABLE:

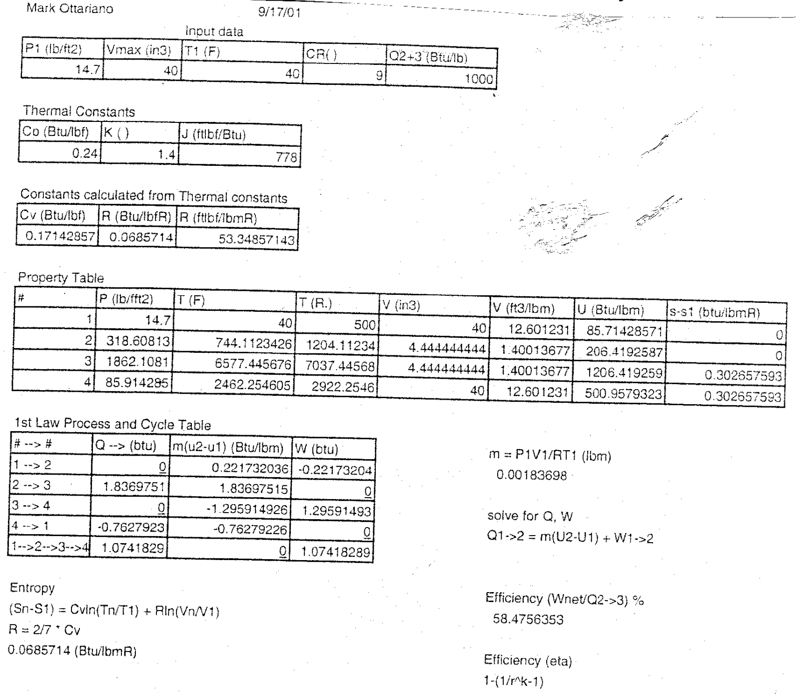
#	P(lb/in^2)	T(F)	T(R)	V(in^3)	v(ft^3/lbm)	u(BTU/lb)	S-S1(BTU/lbmR)
1	14.7000	40.0000	500.0000	40.0000	12.6012	85.7143	0.0000
2	591.4208	976.8824	1436.8824	2.8571	0.9001	246.3227	0.0000
3	591.4208	5143.5490	5603.5490	11.1423	3.5102	960.6084	0.3266
4	98.8044	2900.6923	3360.6923	40.0000	12.6012	576.1187	0.3266

.RST LAW PROCESS AND CYCLE TABLE:

# --> #	Q -->	m(Uf-Ui)	W -->
1 --> 2	0.0000	0.2950	-0.2950
2 --> 3	1.8370	1.3121	0.5249
3 --> 4	0.0000	-0.7063	0.7063
4 --> 1	-0.9009	-0.9009	0.0000
Full Cycle	0.9361	0.0000	0.9361

Efficiency:	Wnet/Qhot
	0.5096
% Efficient:	50.96

Figure 15 Diesel Engine Properties, Processes, Cycle and Efficiency



Mark Ottariano 9/17/01

Input data

P1 (lb/ft2)	Vmax (in3)	T1 (F)	CR( )	Q2+3 (Btu/lb)
14.7	40	40	9	1000

Thermal Constants

Co (Btu/lbf)	K ( )	J (ftlbf/Btu)
0.24	1.4	778

Constants calculated from Thermal constants

Cv (Btu/lbf)	R (Btu/lbfR)	R (ftlbf/lbmR)
0.17142857	0.0685714	53.34857143

Property Table

#	P (lb/fft2)	T (F)	T (R.)	V (in3)	V (ft3/lbm)	U (Btu/lbm)	s-s1 (btu/lbmR)
1	14.7	40	500	40	12.601231	85.71428571	0
2	318.60813	744.1123426	1204.11234	4.444444444	1.40013677	206.4192587	0
3	1862.1081	6577.445676	7037.44568	4.444444444	1.40013677	1206.419259	0.302657593
4	85.914285	2462.254605	2922.2546	40	12.601231	500.9579323	0.302657593

1st Law Process and Cycle Table

# --> #	Q --> (btu)	m(u2-u1) (Btu/lbm)	W (btu)
1 --> 2	0	0.221732036	-0.22173204
2 --> 3	1.8369751	1.83697515	0
3 --> 4	0	-1.295914926	1.29591493
4 --> 1	-0.7627923	-0.76279226	0
1-->2-->3-->4	1.0741829	0	1.07418289

m = P1V1/RT1 (lbm)
0.00183698

solve for Q, W
Q1->2 = m(U2-U1) + W1->2

Entropy
(Sn-S1) = Cvln(Tn/T1) + Rln(Vn/V1)
R = 2/7 * Cv
0.0685714 (Btu/lbmR)

Efficiency (Wnet/Q2->3) %
58.4756353

Efficiency (eta)
1-(1/r^k-1)
58.4756353

Figure 16 Otto Engine Properties, Processes, Cycle and Efficiency