\[ P_1 = 1600 \text{ psia} \]
\[ T_1 = 1100^\circ\text{F} \]
\[ m = 1.4 \times 10^6 \text{ lbm/hr} \]

\[ P_2 = 1 \text{ psia} \]

\[ T_6 = 80^\circ\text{F} \]
\[ T_5 = 60^\circ\text{F} \]

\[ \dot{Q}_{\text{in}} \]
\[ \dot{Q}_{\text{out}} \]

\[ \dot{W}_t \]
\[ \dot{W}_p \]

Boiler

Turbine

Cooling water

Condenser
"GIVEN:  An ideal Rankine Cycle with superheat as shown"
"This analysis will be performed using array variables in EES. Array variables are printed out in an Array Table. This table is very helpful in cycle analysis because you can form a table of properties for quick reference."

```python
s$ = 'steam_iapws'
P[1] = 1600[psia]
T[1] = 1100[F]
P[2] = 1[psia]
x[3] = 0
T_5 = 60[F]
T_6 = 80[F]
m_dot = 1.4E6[lbm/hr]
```

"FIND: (a) The net power developed (hp) 
(b) The thermal efficiency of the cycle 
(c) The heat rate of the cycle 
(d) The back work ratio of the cycle 
(e) The mass flow rate of the cooling water (lbm/hr)"

"SOLUTION:"
"Net power delivery from the cycle"
"The net power delivered by the cycle is,"

```
W_dot_net = W_dot_t - W_dot_p
```

"Applying the First Law to the turbine,"
```
W_dot_t*convert(hp, Btu/hr) = m_dot*(h[1] - h[2])
h[1] = enthalpy(s$, P=P[1], T=T[1])
```

"At the turbine exit, the pressure and entropy are known (in the Rankine Cycle, the turbine and pump are isentropic!"
```
h[2] = enthalpy(s$, P=P[2], s=s[2])
T[2] = temperature(s$, P=P[2], h=h[2])
x[2] = quality(s$, P=P[2], s=s[2])
s[2] = s[1]
s[1] = entropy(s$, P=P[1], T=T[1])
```

"Applying the First law to the pump,"
```
W_dot_p*convert(hp, Btu/hr) = m_dot*(h[4] - h[3])
h[3] = enthalpy(s$, P=P[3], x=x[3])
T[3] = temperature(s$, P=P[3], x=x[3])
```

"At the pump exit, the pressure and entropy are known,"
```
h[4] = enthalpy(s$, P=P[4], s=s[4])
```
s[3] = entropy(s$, P=P[3], x=x[3])
T[4] = temperature(s$, P=P[4], h=h[4])

"!Thermal efficiency of the cycle"
"The thermal efficiency of the cycle is defined as,"
eta_th = W_dot_net*convert(hp,Btu/hr)/Q_dot_in

"The heat transfer rate at the boiler is,"
Q_dot_in = m_dot*(h[1] - h[4])

"!Heat rate of the cycle"
"The heat rate (HR) is defined as,"
HR = Q_dot_in / (W_dot_net*convert(hp,kW))

"!Back work ratio of the cycle,"
"The back work ratio (bwr) is defined as,"
bwr = W_dot_p/W_dot_t

"!Mass flow rate of the cooling water"
"To determine the cooling water flow rate, draw a system boundary that keeps the heat transferred between the condensing steam and the cooling water all internal. The First Law applied to this system is,"
m_dot*(h[2] - h[3]) = m_dot_w*cp_w*(T_6 - T_5)

"The heat capacity of the liquid can be estimated as the saturated liquid value at the average temperature"
T_avg = (T_5 + T_6)/2

cp_w = cp(s$, T=T_avg, x=0)

"!Extra stuff for lecture"
"Btu/hr values for comparison"
W_dot_net_2 = W_dot_net*convert(hp,Btu/hr)
W_dot_t2 = W_dot_t*convert(hp,Btu/hr)
W_dot_p2 = W_dot_p*convert(hp,Btu/hr)
Q_dot_out = m_dot*(h[2] - h[3])
CHECK = (Q_dot_in + W_dot_p2) - (W_dot_t2 + Q_dot_out)

"Estimate of the Carnot Efficiency,"
eta_Carnot = 1 - T_L/T_H
T_L = converttemp(F,R,T_sat(s$, P=P[2]))
T_H = converttemp(F,R,T[1])

SOLUTION
Unit Settings: Eng F psia mass deg
bwr = 0.007483 [dim]
cpw = 0.9992 [Btu/lbm-R]
eta = 0.4288 [dim]
CHECK = 1.164E-10 [Btu/hr]
eta_Carnot = 0.6401 [dim]
HR = 7957 [Btu/kW-hr]
\[ \dot{m} = 1.400 \times 10^6 \text{ [lbm/hr]} \]
\[ \dot{Q}_{in} = 2.063 \times 10^9 \text{ [Btu/hr]} \]
\[ s$ = 'steam_lapws' \]
\[ T_6 = 60 \text{ [F]} \]
\[ T_H = 1560 \text{ [R]} \]
\[ W_{net} = 347636 \text{ [hp]} \]
\[ W_p = 2621 \text{ [hp]} \]
\[ W_t = 350257 \text{ [hp]} \]
\[ \dot{m}_w = 5.896 \times 10^7 \text{ [lbm/hr]} \]
\[ \dot{Q}_{out} = 1.178 \times 10^9 \text{ [Btu/hr]} \]
\[ T_5 = 60 \text{ [F]} \]
\[ T_{avg} = 70 \text{ [F]} \]
\[ T_L = 561.4 \text{ [R]} \]
\[ W_{net,2} = 8.845 \times 10^8 \text{ [Btu/hr]} \]
\[ W_p2 = 6.669 \times 10^6 \text{ [Btu/hr]} \]
\[ W_L2 = 8.912 \times 10^7 \text{ [Btu/hr]} \]

No unit problems were detected.

**KEY VARIABLES**

- \( W_t = 350257 \text{ [hp]} \) \quad **Total turbine power delivery**
- \( \dot{m} = 1.400 \times 10^6 \text{ [lbm/hr]} \) \quad **Mass flow rate of steam in the cycle**
- \( W_p = 2621 \text{ [hp]} \) \quad **Pump power required**
- \( W_{net} = 347636 \text{ [hp]} \) \quad **Net power delivery from the cycle**
- \( \dot{Q}_{in} = 2.063 \times 10^9 \text{ [Btu/hr]} \) \quad **Heat transfer rate at the boiler**
- \( \eta_{th} = 0.4288 \text{ [dim]} \) \quad **Thermal efficiency of the cycle**
- \( HR = 7957 \text{ [Btu/kW-hr]} \) \quad **Heat rate of the cycle**
- \( bwr = 0.007483 \text{ [dim]} \) \quad **Back work ratio of the cycle**
- \( \dot{m}_w = 5.896 \times 10^7 \text{ [lbm/hr]} \) \quad **Mass flow rate of cooling water**

**Array Table: Main**

<table>
<thead>
<tr>
<th>( P_i )</th>
<th>( T_i )</th>
<th>( h_i )</th>
<th>( s_i )</th>
<th>( x_i )</th>
</tr>
</thead>
<tbody>
<tr>
<td>[psia]</td>
<td>[F]</td>
<td>[Btu/lbm]</td>
<td>[Btu/lbm-R]</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1600</td>
<td>1100</td>
<td>1548</td>
<td>1.632</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>101.7</td>
<td>911.4</td>
<td>1.632</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>101.7</td>
<td>69.72</td>
<td>0.1326</td>
</tr>
<tr>
<td>4</td>
<td>1600</td>
<td>102.3</td>
<td>74.49</td>
<td>0.1326</td>
</tr>
</tbody>
</table>