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VAPORIZING AND ENDO THERMIC FUELS
FOR ADVANCED ENGINE APPLICATION

Part III. Studies of Thermal and Catalytic Reactions,
Thermal Stabilities, and Combustion Properties
of Hydrocarbon Fuels

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A Division of Shell Oil Company

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Calculation Procedure for Mach 8 Engine

Station 1.

Use the following formulas from Ref. 12 to calculate the inlet area:

\[ I_f = \frac{n_a(H_f)}{V_1} \]
\[ W_r = \frac{n_f(F_f)}{I_t} \]
\[ A_1 = \frac{W_r}{(F/A)(\psi_1(V_1))} \]

Assume:
\[ n_a = .412 \]
\[ n_f = .95 \]
\[ H_f = 18894 \text{ Btu/lbm fuel} \]

At 100,000 ft and \( M = 8 \):
\[ T_1 = 420.1^\circ R \]
\[ P_1 = 22.32 \text{ lb/ft}^2 \]
\[ \rho_1 = .000996 \text{ lbm/ft}^3 \]
\[ V_1 = 8050.96 \text{ ft/sec} \]
\[ I_f = \frac{(.412)(18894)(778)}{(8051)} \]
\[ I_f = 752.23 \text{ sec} \]

Assume:
\[ L/D = 6 \]
\[ L = 450,000 \text{ lb} \]
\[ D = F_g = 75000 \text{ lb} \]

Therefore:
\[ W_r = \frac{(.95)(75000)}{752.23} \]
\[ W_r = 94.72 \text{ lbm/sec fuel} \]

To Calculate the stoichiometric fuel-air ratio \((F/A)\) assume the fuel is MCH converted to \( H_2 \) and \( C_7H_{16} \):
\[ .75 H_2 + .25 C_7H_{16} + 2.625 O_2 = 2.625(3.76)N_2 \rightarrow \]
\[ 1.75 H_2O + 1.75 O_2 + 9.87 N_2 \]

The average molecular weight of the fuel: 25.25
\[
F/A = \frac{(1 \text{ mole of fuel})(25.25 \text{ lbm molecular weight})}{(9.81 + 2.025 \text{ moles air})(28.95 \text{ lbm molecular weight})}
\]

\[
F/A = 0.0698 \quad \text{Assuming E.R. = 1.0}
\]

\[
A_1 = \frac{94.72}{(0.0698)(0.000996)(5051)}
\]

\[
A_1 = 169.23 \text{ ft}^2
\]

**Station 3.**

Use the Dugger Equation for the total pressure drop from Station 1 to 3:

\[
\frac{P_{t_1}}{P_{t_3}} = \left(\frac{\gamma - 1}{\gamma}ight)^{\frac{\gamma}{\gamma - 1}}
\]

\[
M_d = 1 - \frac{1 - \left(\frac{P_{t_1}}{P_{t_3}}\right)^{\frac{\gamma - 1}{\gamma}}}{(\gamma - 1)/2}\frac{\gamma}{M_1^2}
\]

Assume: \(M_d = 0.959\)

\[
\frac{\gamma}{2} = 1.4
\]

then

\[
\frac{\gamma - 1}{\gamma} = \frac{1.4 - 1}{1.4} = 0.286
\]

\[
\left(\frac{P_{t_1}}{P_{t_3}}\right)^{2.88} = 1 - 0.959
\]

\[
\left(\frac{P_{t_1}}{P_{t_3}}\right)^{2.88} = 1.5248
\]

\[
\left(\frac{P_{t_1}}{P_{t_3}}\right) = 4.36
\]

From the isentropic flow tables at \(M = 8\)

\[
P_{t_1}/P_{t_3} = 0.000102
\]

\[
P_{t_1} = \frac{22.72 \text{ lb/ft}^2}{(0.000102)(144 \text{ in}^2/\text{ft}^2)}
\]

\[
P_{t_1} = 1519 \text{ lb/in}^2
\]
Part III

\[ \frac{P_3}{P_{30}} = \frac{1512}{4.30} \]
\[ P_3 = 348 \text{ lb/in}^2 \]

Assume:

\[ M_3 = 2.5 \]

then

From the isentropic flow tables at \( M = 2.5 \)

\[ \frac{P_3}{P_{30}} = 0.9853 \]

\[ P_3 = 20.4 \text{ lb/in}^2 \]

Assume the enthalpy at 1 and 3 are equal:

\[ \begin{align*}
    h_{t1} &= h_{t3} = h_3 + \frac{(M_3 h_2.1 \sqrt{T_3})^2}{2g_2} \\
    h_{t1} &= 120.32 + \left( \frac{(8)(420.1) \sqrt{2500}}{(2)(52.2)(778)} \right) \\
    h_{t1} &= 1394 \text{ Btu/lbm} \\
    \text{By trial and error} \quad T_3 &= 2500^\circ F \\
    h_{t3} &= \frac{(1252.33 + \left( \frac{(2.5) h_2.1 \sqrt{2500}}{(2)(52.2)(778)} \right)}{1395} \\
    h_{t3} &= 1395 \text{ close enough} \\
    \rho_3 &= \frac{(20.4)(144)}{(53.94)(2500)} \\
    \mu_3 &= 0.22 \text{ lbm/ft}^3
\end{align*} \]

Station 5.

By an iterative procedure calculate the heat transfer from the combustion area assuming 2000°F wall temperature and thus the total temperature rise. Then using a Rayleigh line relationship the remaining conditions at Station 5 may be determined.
First calculate the flow area and heat transfer area:

\[ e = \rho_3 A_3 V_3 = \rho_1 A_1 V_1 \]
\[ V_3 = (2.5)(49.1)\sqrt{2500} \]
\[ V_3 = 6140 \]
\[ A_3 = \frac{\rho_3 A_1 V_1}{\rho_3 V_3} = \frac{(14.1)(100)(8051)}{(0.0225)(5140)} \]
\[ A_3 = 10.0 \]
\[ 10.0 = x_{r_1}^2 - x_{r_3}^2 = 169 - x_{r_3}^2 \]
\[ r_3 = 7.11 \text{ ft} \]

Hydraulic Diameter \( D_h \)

\[ D_h = \frac{4A_3}{P_V} = \frac{4(10.0)}{2\pi(7.11) + 2\pi(7.28)} \]
\[ D_h = 3.44 \]

Assume time for combustion and mixing can be accomplished in 2 \( \mu \text{sec} = .002 \text{ sec} \) and the average velocity in the combustor is 5000 \( \text{ft/sec} \).

The length of the combustor then is \( L \)

\[ L = (0.002)(5000) \]
\[ L = 10 \text{ ft} \]

Forming a heat balance on the combustion area

\( (h_{p'} - h_{p_0'}) - (h_{R'} - h_{R_0'}) - q = - h_{R_0} \)

where:

- \( h_{p'} \) = enthalpy of the reactants
- \( h_{p_0'} \) = enthalpy of the products
- \( h_{R_0} \) = heat of combustion
- \( q \) = heat transferred per lbm fuel

Heating of combustion calculation:

\[ h_{R_0} = m_{C_7H_8}(h_{R_0})_{C_7H_8} + m_{H_2}(h_{R_0})_{H_2} \]
\[ m_{C_7H_8} = .938 \text{ lbm } C_7H_8/\text{lbm fuel} \]
\[ m_{H_2} = .062 \text{ lbm } H_2/\text{lbm fuel} \]
The reactants:

\[
\begin{align*}
(\text{h}' - \text{ho}')_{\text{fuel}} &= (\text{h}' - \text{ho}')_{\text{air}} + (\text{h}' - \text{ho}')_{\text{fuel}} \\
(\text{h}' - \text{ho}')_{\text{air}} &= \frac{\text{M}_{\text{air}}}{\text{M}_{\text{fuel}}} \left( \text{h}_{2500} - \text{h}_{297} \right) \\
&= \left( \frac{2.625 \times 2.87}{29.25} \right) (545.78 - 128.34) \\
(\text{h}' - \text{ho}')_{\text{fuel}} &= 7412.8 \text{ Btu/lbm fuel} \\
\end{align*}
\]

Assume: \( C_{\text{fuel}} = .766 \text{ Btu/lbm °F} \)

\[ t = 900 \text{ °F} \]

\[
(\text{h}' - \text{ho}')_{\text{fuel}} = (.766)(900 - 77)
\]

\[
(\text{h}' - \text{ho}')_{\text{fuel}} = 631 \text{ Btu/lbm fuel}
\]

\[
\text{hr}' - \text{ho}' = 8043.6 \text{ Btu/lbm fuel}
\]

The products:

Calculate enthalpy of products as function of temperature and make plot.

<table>
<thead>
<tr>
<th>Constituent</th>
<th>( T_{427} )</th>
<th>( T_{4000} )</th>
<th>( T_{5000} )</th>
<th>( T_{5300} )</th>
<th>( T_{5800} )</th>
<th>( T_{6017} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{CO}_2 )</td>
<td>1.75</td>
<td>4030</td>
<td>4925</td>
<td>7912</td>
<td>50000</td>
<td>104948</td>
</tr>
<tr>
<td>( \text{H}_2\text{O} )</td>
<td>1.75</td>
<td>4278</td>
<td>40489</td>
<td>63404</td>
<td>53327</td>
<td>85871</td>
</tr>
<tr>
<td>( \text{N}_2 )</td>
<td>9.87</td>
<td>3730</td>
<td>31329</td>
<td>272406</td>
<td>40080</td>
<td>358773</td>
</tr>
</tbody>
</table>

\[
(\text{hp}' - \text{hp}_0')_t = \frac{\text{noh}}{\text{hc}} = 29.25
\]
Estimate of Heat Transfer From the Combustor:

Procedure:

1. Assume Temperature at Station 5
2. Calculate Mach number and pressure at Station 5 from Rayleigh line
3. Assume linear variation of pressure and temperature over length of combustor
4. Calculate density, velocity, viscosity, Reynolds number, Nusselt number, correction constant for high velocity heat transfer, thermal conductivity, heat transfer coefficient, adiabatic wall temperature and the final product, \( h \cdot R \), where \( P \) is the wetted perimeter,
   \( \Delta t = t_{AV} - t_w \) and \( t_w = 2000^\circ R \), and \( h \) is the local heat transfer coefficient.
5. From curve of \( h \cdot R \) vs \( x \) calculate heat transferred;
   \[ q = -\int_{x=0}^{x=L} h \cdot R \cdot d\xi \]
6. From \( q \) and \( (h' - h_{0'})_p \), \( (h' - h_{0'})_R \) and \( h \cdot P_0 \) calculate temperature at Station 5.
7. Return to 2 until temperature used to calculate values and calculated temperature are equal.

Example:
Station 3:
\( M = 2.5 \)
\( P = 20.4 \)
\( T = 2500^\circ R \)
\( (P/P_0) = 0.24616 \)
\( (T/T_0) = 0.3787 \)
Assume \( T_0 = 5637.5^\circ R \)
\[
\begin{align*}
\frac{T_1}{T_3} &= \left(\frac{T_1}{T_3}\right)_3 \frac{T_3}{T_3} = \left(0.5787\right) \frac{\left(\frac{0.77}{0.69}\right)}{\left(0.75\right)} \\
\frac{T_1}{T_3} &= 0.8540 \\
\end{align*}
\]

From Rayleigh Line:

\[
\begin{align*}
M &= 1.31 \\
\frac{P}{P_1} &= 0.70535 \\
P_3 &= \left(\frac{P}{P_1}\right)_3\left(\frac{P}{P_1}\right)_3 = \left(0.70535\right)/(2.4616) \text{ (20 lb/in}^2
\end{align*}
\]

<table>
<thead>
<tr>
<th>x</th>
<th>P</th>
<th>T</th>
<th>V</th>
<th>u</th>
<th>Re</th>
<th>M</th>
<th>c</th>
<th>N1</th>
<th>k</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>20.4</td>
<td>2500</td>
<td>0.022</td>
<td>6150</td>
<td>3.4</td>
<td>1.76</td>
<td>1330</td>
<td>2.50</td>
<td>65</td>
</tr>
<tr>
<td>2</td>
<td>28.0</td>
<td>3110</td>
<td>0.224</td>
<td>5650</td>
<td>3.8</td>
<td>1.58</td>
<td>1270</td>
<td>2.06</td>
<td>75</td>
</tr>
<tr>
<td>4</td>
<td>35.6</td>
<td>3740</td>
<td>0.286</td>
<td>5200</td>
<td>4.2</td>
<td>1.43</td>
<td>1220</td>
<td>1.73</td>
<td>81</td>
</tr>
<tr>
<td>6</td>
<td>43.3</td>
<td>4370</td>
<td>0.277</td>
<td>5000</td>
<td>4.6</td>
<td>1.30</td>
<td>1170</td>
<td>1.54</td>
<td>84</td>
</tr>
<tr>
<td>8</td>
<td>51.0</td>
<td>5000</td>
<td>0.028</td>
<td>4872</td>
<td>4.9</td>
<td>1.24</td>
<td>1145</td>
<td>1.40</td>
<td>88</td>
</tr>
<tr>
<td>10</td>
<td>58.45</td>
<td>5637.5</td>
<td>0.028</td>
<td>4828</td>
<td>5.2</td>
<td>1.17</td>
<td>1110</td>
<td>1.31</td>
<td>89</td>
</tr>
</tbody>
</table>

* Extrapolated (based on air at low pressures)

<table>
<thead>
<tr>
<th>x</th>
<th>Fr</th>
<th>Pr</th>
<th>T/AW/T</th>
<th>T/AW</th>
<th>AT</th>
<th>h</th>
<th>hPr/Ct</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>.73</td>
<td>.90</td>
<td>2.125</td>
<td>5312.5</td>
<td>5312.5</td>
<td>93.4</td>
<td>2.80 x 10^7</td>
</tr>
<tr>
<td>2</td>
<td>.75</td>
<td>.91</td>
<td>1.77</td>
<td>5504.7</td>
<td>5504.7</td>
<td>120.1</td>
<td>3.81 x 10^7</td>
</tr>
<tr>
<td>4</td>
<td>.79</td>
<td>.92</td>
<td>1.55</td>
<td>5797.0</td>
<td>5797.0</td>
<td>158.0</td>
<td>4.74 x 10^7</td>
</tr>
<tr>
<td>6</td>
<td>.90</td>
<td>1.0</td>
<td>1.47</td>
<td>6423.9</td>
<td>4423.9</td>
<td>151.6</td>
<td>6.07 x 10^7</td>
</tr>
<tr>
<td>8</td>
<td>1.00</td>
<td>1.0</td>
<td>1.39</td>
<td>6950.0</td>
<td>4950.0</td>
<td>167.9</td>
<td>7.52 x 10^7</td>
</tr>
<tr>
<td>10</td>
<td>1.00</td>
<td>1.0</td>
<td>1.34</td>
<td>7554.3</td>
<td>5554.3</td>
<td>175.8</td>
<td>8.84 x 10^7</td>
</tr>
</tbody>
</table>

In the above calculations the following expression were used:

\[
\begin{align*}
p &= \frac{P}{RT} \quad \text{where } R = 53.54, \\
V &= \frac{C}{\sqrt{\frac{\gamma}{\gamma - 1}}} = 135.2/p, \\
Re &= \frac{V D_n c}{\mu}, \\
N_1 &= f(Re, Pr) \quad \text{from Kays14) expression for turbulent flow inside concentric annuli at } r_1/r_0 = 1.0 \text{ (See Figure 73),} \\
M &= \frac{V}{(49.1\sqrt{T})}, \\
C &= \text{From Kays page 13,28 for affect of high velocity on Stanton No.}
\end{align*}
\]

-29-
\[ \text{Nu} = \text{GrNu} \]

\[ h = \frac{\text{Nu} \kappa}{\text{Pr}^{1/3}} \]

\[ \frac{T_{\text{AW}}}{T} = 1 + \frac{Pr^{1/3}}{2} (\gamma - 1) \theta \]

where \( \gamma = 1.4 \)

\[ \Delta t = (T_{\text{AW}} - T_{\text{W}}) = (T_{\text{AW}} - 2000) \]

\[ P = 2x_{1} + 2x_{0} = 90.5 \text{ ft} \]

Then:

\[ q' = -\int_{0}^{x} (h\rho c_{p}t)_{x} dx \]

This expression is integrated graphically from Figure 78.

\[ q' = -5.575 \times 10^{8} \text{ Btu/hr} \]

\[ m_{\text{air}} = \rho_{1}A_{1}V_{1} = 4.879 \times 10^{6} \text{ lbm/hr} \]

\[ q = -\frac{5.575 \times 10^{8}}{4.879 \times 10^{6}} \]

\[ q = -1.1426 \times 10^{2} \text{ Btu/lbm air} \]

\[ q' = -1.1426 \times 10^{2} \times .0698 \]

\[ q' = -1637 \text{ Btu/lbm fuel} \]

Now to calculate the combustion temperature:

\[ (h' - h_{0})_{p} = (h' - h_{0})_{R} = q' = -h_{\text{FPo}} \]

\[ (h' - h_{0})_{p} = 8043.8 + 1637 = -19708.5 \]

\[ (h' - h_{0})_{p} = 26115.3 \text{ Btu/lbm fuel} \]

From curve in Figure 75, this gives a temperature:

\[ T_{s} = 5900^{\circ}R \quad \text{which does not agree with assume temp.} \]

However, by plotting the calculated temperatures vs the assumed temperatures we can find the point they are equal. In addition by plotting the heat transferred vs the assumed temperature we can obtain the actual heat transfer at the actual temperature – see curves in Figure 75.

This yields:

\[ T_{s} = 5791^{\circ}R \]

\[ q' = 1727 \text{ Btu/lbm fuel} \]
Then \((T/T_e) = (0.3787) \left(\frac{5791}{2500}\right)\)

\((T/T_e) = 0.877\) from Rayleigh line we get

\[
M_e = 1.265
\]

\[(P/P_e) = 0.740\]

\[P_e = \frac{(0.740)}{(2.245)} (20) = 61.3 \text{ lb/in}^2\]

Station 6.

Assume:
1. Isentropic expansion from 5 to 6.
2. \(A_e = 313.58 \text{ ft}^2\) \((D = 20 \text{ ft})\)

\[\frac{(A/A_e)}{(A/A_e)} = (A/A_e) \frac{A_e}{A_e} = \left(\frac{1.052}{313.58}\right) \frac{313.58}{10.0}\]

\[A/A_e = 32.89\]

\[
M_e = 5.28
\]

\[(P/P_0) = 0.001538\]

\[P_e = \frac{(0.001538)(61.3)}{.377} = .250 \text{ lb/in}^2\]

\[V_e = 8897.48 \text{ ft/sec}\]
Calculate Thrust, Specific Impulse, and Overall Efficiency:

Thrust = \( F_g = f_e - f_1 - P_1(A_e - A_1) \)

\[
\begin{align*}
   f_e &= A_e \left( P_e + n_n \frac{P_e V_e^2}{g_0} \right) \\
   f_1 &= A_1 \left( P_f + \frac{P_f V_f^2}{g_0} \right) \\
   n_n &= .95 \\
   f_1 &= 169 \left( 22.32 + \frac{( .000996)(8051)^2}{32.2} \right) \\
   f_e &= 34264.1 \text{ lb} \\
   f_a &= 313.58 \left( 36.05 + .95( .000974)(8897.48)^2 \right) \\
   f_a &= 431703.9 \text{ lb} \\
   F_g &= 431703.9 - 34264.1 - 22.32(313.58 - 169.) \\
   F_g &= 85833.22 \text{ lb} \\
\end{align*}
\]

Specific Impulse:

\[
I_f = \frac{n_n(F_g)}{W_f} \\
W_f = f_0 V_f A_1 = .0698( .000996)(169.)(8051) \\
W_f = 94.6 \text{ lbm/sec fuel} \\
I_f = \frac{( .95)(85833.22)}{94.6} \\
I_f = 861.96 \text{ sec} \\
\]

Overall Efficiency:

\[
\eta_e = \frac{I_f V_f}{H_f + V_f^2/2g_0} \\
\]

-297-
Estimate of Heat Transfer From Nozzle:

Consider the nozzle below: (Note: the values below are not the final but a first estimate)

Flow Area:

\[ r_e - r_1 = 9.75 - 7.28 = 2.47 \]

\[ \tan \theta_2 = \frac{2.47}{40} = 0.06175 \]

\[ \theta_2 = 3.4^\circ \]

From \( x = 0 \) to \( x = 10 \) where \( r_t = r_e - x \tan \theta_2 = 9.75 - x \times 0.06175 \)

From \( x = 10 \) to \( x = 40 \) \( \Delta \omega = \frac{r_t^2 - r_b^2}{A_t} \)

\[ r_b = \frac{(x - 10) \tan \theta_1}{(x - 10) \times 0.237} \]

\[ x' = 40 - x \]

<table>
<thead>
<tr>
<th>( x' )</th>
<th>( x )</th>
<th>( r_t )</th>
<th>( A_t )</th>
<th>( r_b )</th>
<th>( A_b )</th>
<th>( A_v )</th>
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<tbody>
<tr>
<td>40</td>
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<td>0</td>
<td>0</td>
<td>298.8</td>
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<tr>
<td>40</td>
<td>10</td>
<td>9.13</td>
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<td>0</td>
<td>0</td>
<td>262.0</td>
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<tr>
<td>40</td>
<td>20</td>
<td>8.52</td>
<td>227.8</td>
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<td>17.6</td>
<td>210.2</td>
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<td>40</td>
<td>30</td>
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<td>4.74</td>
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<td>125.3</td>
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<tr>
<td>40</td>
<td>5</td>
<td>7.60</td>
<td>180.9</td>
<td>5.92</td>
<td>110.3</td>
<td>70.6</td>
</tr>
<tr>
<td>40</td>
<td>36</td>
<td>7.53</td>
<td>178.0</td>
<td>6.16</td>
<td>119.3</td>
<td>58.7</td>
</tr>
<tr>
<td>40</td>
<td>37</td>
<td>7.47</td>
<td>175.1</td>
<td>6.40</td>
<td>128.6</td>
<td>46.5</td>
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<tr>
<td>40</td>
<td>8</td>
<td>7.40</td>
<td>172.2</td>
<td>6.64</td>
<td>138.3</td>
<td>33.9</td>
</tr>
<tr>
<td>40</td>
<td>9</td>
<td>7.34</td>
<td>169.3</td>
<td>6.87</td>
<td>148.4</td>
<td>20.9</td>
</tr>
</tbody>
</table>
Assuming isentropic expansion to each point:

\[ (A/A_x) = \frac{(A/A_x)_{\text{ref}}}{A_x} = 1.1 \times 10^{-3} = 0.019 \text{ ft}^2 \]

This yields a Mach Number from Isentropic Flow Tables:

\[ T_x = \left( \frac{T}{T_0} \right)_x, \quad T_0 = \left( \frac{T}{T_0} \right)_0 \frac{5465}{.726} = 7527.5 \left( \frac{T}{T_0} \right)_x \text{ (°R)} \]

\[ P_x = \left( \frac{P}{P_0} \right)_x, \quad P_0 = \left( \frac{P}{P_0} \right)_0 \frac{54}{.323} = 167 \left( \frac{P}{P_0} \right)_x \text{ (lb/ft}^2) \]

\[ V_x = \frac{M_x 144}{T_x} = 2.7 \left( \frac{P}{P_0} \right)_x \text{ (ft/sec)} \]

\[ \rho_x = \frac{P_x 144}{53.34 T_x} = \frac{V_x}{13 \text{ lb/ft}^3} \]

<table>
<thead>
<tr>
<th>( x )</th>
<th>( (A/A_x)_x )</th>
<th>( M )</th>
<th>( (P/P_0)_x )</th>
<th>( P_x )</th>
<th>( (T/T_0)_x )</th>
<th>( T_x )</th>
<th>( V_x )</th>
<th>( \rho_x )</th>
<th>( \mu )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.292</td>
<td>2.35</td>
<td>.074</td>
<td>12.38</td>
<td>.475</td>
<td>3525</td>
<td>6851</td>
<td>.00498</td>
<td>4.4 x 10^{-5}</td>
</tr>
<tr>
<td>2</td>
<td>3.718</td>
<td>2.86</td>
<td>.034</td>
<td>5.68</td>
<td>.379</td>
<td>2815</td>
<td>7451</td>
<td>.00544</td>
<td>3.93</td>
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<tr>
<td>3</td>
<td>5.10</td>
<td>3.20</td>
<td>.020</td>
<td>3.34</td>
<td>.328</td>
<td>2430</td>
<td>7745</td>
<td>.00371</td>
<td>3.68</td>
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<tr>
<td>4</td>
<td>6.44</td>
<td>3.45</td>
<td>.014</td>
<td>2.34</td>
<td>.250</td>
<td>2150</td>
<td>7855</td>
<td>.00294</td>
<td>3.47</td>
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<td>5</td>
<td>7.74</td>
<td>3.64</td>
<td>.0108</td>
<td>1.81</td>
<td>.274</td>
<td>2063</td>
<td>8118</td>
<td>.00236</td>
<td>3.40</td>
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<td>13.74</td>
<td>4.28</td>
<td>.0090</td>
<td>.836</td>
<td>.220</td>
<td>1656</td>
<td>8552</td>
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<td>4.90</td>
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<td>.356</td>
<td>.172</td>
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<td>6854</td>
<td>.00074</td>
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<td>28.73</td>
<td>5.10</td>
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<td>.276</td>
<td>.160</td>
<td>1200</td>
<td>8674</td>
<td>.00062</td>
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<td>32.89</td>
<td>5.28</td>
<td>.00154</td>
<td>.257</td>
<td>.154</td>
<td>1160</td>
<td>8831</td>
<td>.00060</td>
<td>2.62</td>
</tr>
</tbody>
</table>

Assume the heat transfer relation is turbulent flow flat plate.

\[ \text{Nu}_x = c \cdot (322 \text{Pr}^{1/3} \text{Re}_x^{1/2}) = \text{cNu}_x \]

\[ \text{Re}_x = \frac{V_x \cdot \rho}{\mu} \quad c = \text{correction constant for high speed flow (Kays, p. 13.26)} \]

\[ h = \frac{\text{Nu}_x k}{x} \quad \text{(Btu/hr-ft}^2{°F}) \]

<table>
<thead>
<tr>
<th>( x )</th>
<th>( \text{Re} )</th>
<th>( \text{Re}_x^{1/2} )</th>
<th>( \text{Pr} )</th>
<th>( \text{Pr}_x^{1/3} )</th>
<th>( \text{Nu}_x )</th>
<th>( c )</th>
<th>( \text{Nu}_x )</th>
<th>( k )</th>
<th>( h )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.475 x 10^8</td>
<td>1.214 x 10^3</td>
<td>.85</td>
<td>.94</td>
<td>378.9</td>
<td>.70</td>
<td>265</td>
<td>.065</td>
<td>17.2</td>
</tr>
<tr>
<td>2</td>
<td>2.06</td>
<td>1.435</td>
<td>.76</td>
<td>.91</td>
<td>433.5</td>
<td>.63</td>
<td>273</td>
<td>.058</td>
<td>7.9</td>
</tr>
<tr>
<td>3</td>
<td>2.34</td>
<td>1.530</td>
<td>.74</td>
<td>.90</td>
<td>457.2</td>
<td>.58</td>
<td>265</td>
<td>.056</td>
<td>4.8</td>
</tr>
</tbody>
</table>

(Continued)
Then:

\[ \dot{Q}_N = \int_{x'=0}^{x'=40} (h\dot{R}t)_x \, dx' \]

Integrating graphically from curve of \( x' \) vs. \( h\dot{R}t \) in Figure 76 we get,

\[ \dot{Q}_N = 47.8 \times 10^6 \text{ Btu/hr} \]

\[ \dot{Q}_N = 47.8 \times 10^6 \text{ Btu/hr} \]

\[ 4.879 \times 10^6 \text{ lbm air/hr} \]
\[ q'N = 9.797 \text{ Btu/lbm air} \]
\[ q'N = 9.727 \times 10^{-3} \text{ lbm fuel/lbm air} \]
\[ q'N = 140.4 \text{ Btu/lbm fuel} \]
\[ q'T = q'N + q'c \]
\[ q'T = 1567.4 \text{ Btu/lbm fuel} \]
Figure 72. ENTHALPY OF PRODUCTS OF COMBUSTION
Table III - DECOMPOSITION BY PCH O VER KEEFER CATALYST

<table>
<thead>
<tr>
<th>Run Number</th>
<th>20°C</th>
<th>50°C</th>
<th>90°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5</td>
<td>15</td>
<td>50</td>
</tr>
<tr>
<td>2</td>
<td>752</td>
<td>645-660</td>
<td>662-777</td>
</tr>
<tr>
<td>3</td>
<td>800-86</td>
<td>600-785</td>
<td>640-789</td>
</tr>
<tr>
<td>4</td>
<td>226-244</td>
<td>725-295</td>
<td>642-241</td>
</tr>
<tr>
<td>5</td>
<td>675-333</td>
<td>772-336</td>
<td>672-374</td>
</tr>
<tr>
<td>6</td>
<td>824-222</td>
<td>74-599</td>
<td>790-924</td>
</tr>
</tbody>
</table>

Reaction Volume: 7 ml  
Reaction Temperature: 540°F  
Reaction Time: 30 Minutes

<table>
<thead>
<tr>
<th>Product Analysis, %</th>
<th>20°C</th>
<th>50°C</th>
<th>90°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interrupted</td>
<td>1.8</td>
<td>0.2</td>
<td>0.0</td>
</tr>
<tr>
<td>Product</td>
<td>0.0</td>
<td>0.1</td>
<td>0.4</td>
</tr>
<tr>
<td>Y2</td>
<td>1.0</td>
<td>5.7</td>
<td>11.6</td>
</tr>
<tr>
<td>Y3</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Toluene</td>
<td>97.1</td>
<td>98.0</td>
<td>58.0</td>
</tr>
<tr>
<td>Y4</td>
<td>0.1</td>
<td>0.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

| PCH Conversion, %  | 99.0 | 96.3 | 53.8 |

a) Unidentified, emerged after benzene.  
b) Unidentified, emerged after PCH.  
c) Unidentified, emerged after toluene.  
d) Catalyst almost completely deactivated after 10 minutes.
Table 120: CONTRIBUTION OF WITZIG REACTOR

Pressure: 1 atm  Catalyst Volume: 7 ml
Block Temperature: 842°F  Reaction Time: 30 Minutes
Catalyst No.: 10210-45

| Run Number | LHSV | 5 | 15 | 30 | 50 | 80 | 100%
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Profiles, °F</td>
<td>348-22</td>
<td>714-20</td>
<td>585-23</td>
<td>610</td>
<td>593</td>
<td>63-15</td>
<td>60-3</td>
</tr>
<tr>
<td>365-22</td>
<td>755-42</td>
<td>751-42</td>
<td>617</td>
<td>60-3</td>
<td>60-3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>360-38</td>
<td>750-32</td>
<td>580-73</td>
<td>583</td>
<td>617</td>
<td>61b</td>
<td>61b</td>
<td></td>
</tr>
<tr>
<td>Reactor Wall Temperature, °F</td>
<td>810</td>
<td>774-76</td>
<td>725-26</td>
<td>703</td>
<td>698</td>
<td>673-31</td>
<td></td>
</tr>
<tr>
<td>ST max</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Product Analysis, %</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Benzene</td>
<td>9.9</td>
<td>0.9</td>
<td>0.1</td>
<td>0.0</td>
<td>0.0</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>MCH</td>
<td>1.0</td>
<td>0.8</td>
<td>10.1</td>
<td>41.3</td>
<td>34.6</td>
<td>62.3</td>
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</tr>
<tr>
<td>Toluene</td>
<td>89.0</td>
<td>98.6</td>
<td>90.6</td>
<td>58.1</td>
<td>51.4</td>
<td>59.6</td>
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<tr>
<td>MCH Conversion, %</td>
<td>98.9</td>
<td>989.5</td>
<td>88.7</td>
<td>58.9</td>
<td>47.7</td>
<td>41.3</td>
<td></td>
</tr>
</tbody>
</table>

a) Back pressure was about 15 psi during this run.
<table>
<thead>
<tr>
<th>Run Number</th>
<th>Unit 1</th>
<th>Unit 2</th>
<th>Unit 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run 1</td>
<td>5</td>
<td>15</td>
<td>30</td>
</tr>
</tbody>
</table>

**Catalyst Bed**

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Unit 1</th>
<th>Unit 2</th>
<th>Unit 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>100-72</td>
<td>700-11</td>
<td>750-80</td>
<td>800-86</td>
</tr>
<tr>
<td>759-90</td>
<td>645-82</td>
<td>560-87</td>
<td>615-83</td>
</tr>
<tr>
<td>815-99</td>
<td>716-89</td>
<td>671-86</td>
<td>682-85</td>
</tr>
<tr>
<td>851-11</td>
<td>759-45</td>
<td>682-85</td>
<td>692-85</td>
</tr>
</tbody>
</table>

**Reactor Wall Temperature, °F**

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Unit 1</th>
<th>Unit 2</th>
<th>Unit 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>615-80</td>
<td>775</td>
<td>758-85</td>
<td>758-85</td>
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</tbody>
</table>

**Product Analysis, %**

<table>
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<tr>
<th>Component</th>
<th>Unit 1</th>
<th>Unit 2</th>
<th>Unit 3</th>
</tr>
</thead>
<tbody>
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<td>Benzene</td>
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<td>0.5</td>
<td>0.0</td>
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<tr>
<td>Toluene</td>
<td>3.3</td>
<td>6.1</td>
<td>28.7</td>
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<tr>
<td>Mesitylene</td>
<td>0.0</td>
<td>0.0</td>
<td>0.5</td>
</tr>
<tr>
<td>Toluene</td>
<td>95.0</td>
<td>95.5</td>
<td>72.5</td>
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**Mesitylene Conversion, %**

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<th>Unit 3</th>
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<td>48.1</td>
<td>93.9</td>
<td>15.3</td>
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</table>

*a* Unidentified; emerged after benzene.

*b* Unidentified; emerged after toluene.

*c* Unidentified; emerged after toluene.

*d* Unidentified; emerged after 17 minutes; catalyst deactivated at end of run.
Table I.22: DECARBOXYLATION OF N-METHYL-2-METHYLACETACETETRONE

Pressure: 1 atm  Catalyst Volume: 7 ml
Block Temperature: 842°F  Reaction Time: 30 Minutes
Catalyst No.: 9674-7

<table>
<thead>
<tr>
<th>Run Number</th>
<th>IEYS</th>
<th>3</th>
<th>5</th>
<th>7</th>
<th>9</th>
</tr>
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<tr>
<td>UHPW</td>
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<td>30</td>
<td>50</td>
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<tr>
<td>Catalyst Bed</td>
<td>779</td>
<td>714-16</td>
<td>725-76</td>
<td>813-57</td>
<td></td>
</tr>
<tr>
<td>Profiles, °F</td>
<td>775</td>
<td>1705-59</td>
<td>797-813</td>
<td></td>
<td></td>
</tr>
<tr>
<td>860</td>
<td>765</td>
<td>734-54</td>
<td>795-833</td>
<td></td>
<td></td>
</tr>
<tr>
<td>875-35</td>
<td>788-86</td>
<td>746-59</td>
<td>777-850</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reactor Wall Temperature, °F</td>
<td>815</td>
<td>793-97</td>
<td>815-59</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
| OH wax | 0 | 2 | 50 | 52b)
| Product Analysis, % | | | | |
| Benzene | 1.7 | 0.1 | 0.2 | 0.1 |
| MTH | 19.9 | 62.8 | 95.1 |
| Toluene | 71.2 | 75.7 | 37.0 | 5.6 |
| U,8) | 0.0 | 0.0 | 0.0 | 1.2 |

a) Unidentified, emerged after toluene.
b) Catalyst almost completely deactivated at end of run.
<table>
<thead>
<tr>
<th>Run Number</th>
<th>1101B-</th>
<th>11-1</th>
<th>11-2</th>
<th>11-3</th>
<th>11-4</th>
<th>11-5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gases</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Catalyst Bed</td>
<td>774-72</td>
<td>653</td>
<td>635-59</td>
<td>642-55</td>
<td>669-75</td>
<td>687-98</td>
</tr>
<tr>
<td>Profile, °F</td>
<td>817-13</td>
<td>639</td>
<td>630-55</td>
<td>635-59</td>
<td>644-50</td>
<td></td>
</tr>
<tr>
<td>Reactor Wall Temperature, °F</td>
<td>826-24</td>
<td>762</td>
<td>727-25</td>
<td>716-18</td>
<td>716</td>
<td>725-29</td>
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<td>0</td>
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<td>11</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>Product Analysis, %</td>
<td>2.3</td>
<td>0.2</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Benzene</td>
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<td>69.5</td>
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<td>96.6</td>
<td>95.1</td>
<td>69.6</td>
<td>49.3</td>
<td>36.9</td>
<td>3.9</td>
</tr>
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</table>
### Table 124. TRANSMUTATION OF MCH OVER ZEOLITE

**Pressure:** 1 atm  \[\text{Catalyst Volume:} \quad 7 \text{ ml}\]

**Block Temperature:** 642 °F  \[\text{Reaction Time:} \quad 30 \text{ Minutes}\]

<table>
<thead>
<tr>
<th></th>
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<tr>
<td><strong>LHSV</strong></td>
<td>5</td>
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<td>50</td>
<td>50</td>
<td>80</td>
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<tr>
<td><strong>Catalyst Bed</strong></td>
<td><strong>Profile, °F</strong></td>
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<tr>
<td>&amp;agr;</td>
<td>761-52</td>
<td>669-66</td>
<td>657-71</td>
<td>700-715</td>
<td>830-835</td>
</tr>
<tr>
<td>οβ</td>
<td>606-61</td>
<td>691-67</td>
<td>679-68</td>
<td>642-761</td>
<td>722-733</td>
</tr>
<tr>
<td>P</td>
<td>86-24</td>
<td>729-23</td>
<td>553-55</td>
<td>644-701</td>
<td>806-835</td>
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<td>%</td>
<td>233</td>
<td>770-66</td>
<td>678-60</td>
<td>657-602</td>
<td>776-893</td>
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<td><strong>Reactor Wall Temperature, °F</strong></td>
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<td>763-61</td>
<td>721-29</td>
<td>725-68</td>
<td>824-55</td>
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<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
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<td>C9 &amp;agr;</td>
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<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>C8 οβ</td>
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<td>2.2</td>
<td>2.7</td>
<td>56.1</td>
<td>96.6</td>
</tr>
<tr>
<td>C7 ο δ</td>
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<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>C6 ο ε</td>
<td>97.4</td>
<td>97.7</td>
<td>97.5</td>
<td>95.7</td>
<td>1.6</td>
</tr>
<tr>
<td>ε</td>
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<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>1.0</td>
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<tr>
<td><strong>MCH Conversion, %</strong></td>
<td>96.9</td>
<td>97.3</td>
<td>72.5</td>
<td>45.7</td>
<td>1.4</td>
</tr>
</tbody>
</table>

\(\alpha\) unidentified; emerged after benzene.

\(\beta\) unidentified; emerged after MCH.

\(\gamma\) unidentified; emerged after toluene.

\(\delta\) catalyst about completely deactivated at end of run.
Table 125. DEHYDROGENATION OF MCH OVER UOP-R16E

<table>
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<tr>
<th>Run No. 11325-</th>
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<th>86-2</th>
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<td>15</td>
<td>30</td>
<td>50</td>
<td>80</td>
<td>100</td>
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<tr>
<td>Catalyst Bed Profile, °F</td>
<td>774-70</td>
<td>671</td>
<td>655-58</td>
<td>686-729</td>
<td>759-824</td>
<td>824</td>
</tr>
<tr>
<td></td>
<td>813-10</td>
<td>705-02</td>
<td>646-37</td>
<td>640-657</td>
<td>673-761</td>
<td>734-822</td>
</tr>
<tr>
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<td>752-50</td>
<td>668-67</td>
<td>644-51</td>
<td>650-89</td>
<td>705-761</td>
</tr>
<tr>
<td></td>
<td>833</td>
<td>779-74</td>
<td>689-87</td>
<td>657-55</td>
<td>648-69a)</td>
<td>678-720a)</td>
</tr>
<tr>
<td>Reactor Wall Temp, °F</td>
<td>831</td>
<td>779-76</td>
<td>643-47</td>
<td>638-47</td>
<td>750-90</td>
<td>852-96</td>
</tr>
<tr>
<td>ΔT_max, °F</td>
<td>-4</td>
<td>-5</td>
<td>11</td>
<td>43</td>
<td>88a)</td>
<td>31a)</td>
</tr>
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<td>Product Analysis, %w</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Benzene</td>
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<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
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<tr>
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<td>4.8</td>
<td>33.2</td>
<td>54.9</td>
<td>70.9</td>
<td>81.5</td>
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<tr>
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<td>92.4</td>
<td>95.2</td>
<td>66.8</td>
<td>45.1</td>
<td>29.0</td>
<td>18.0</td>
</tr>
<tr>
<td>Othersb)</td>
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<td>0.1</td>
<td>0.5</td>
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<tr>
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<td>92.6</td>
<td>95.2</td>
<td>66.8</td>
<td>45.1</td>
<td>29.1</td>
<td>18.5</td>
</tr>
</tbody>
</table>

a) Cold spot moved down the catalyst bed.
b) Emerged after MCH and after toluene.
### Table 126. DEHYDROGENATION OF MCH OVER 1% Pt on Al₂O₃

<table>
<thead>
<tr>
<th>Run No. 11325-</th>
<th>81-1</th>
<th>81-2</th>
<th>82-1</th>
<th>82-2</th>
<th>83-1</th>
<th>83-2</th>
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<tr>
<td>LHSV</td>
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<td>15</td>
<td>30</td>
<td>50</td>
<td>80</td>
<td>100</td>
</tr>
<tr>
<td>Catalyst Bed</td>
<td>776-72</td>
<td>686-82</td>
<td>669-76</td>
<td>685-743</td>
<td>776-815</td>
<td>819-24</td>
</tr>
<tr>
<td>Profile, °F</td>
<td>817</td>
<td>732-27</td>
<td>689</td>
<td>687-707</td>
<td>729-90</td>
<td>806-24</td>
</tr>
<tr>
<td></td>
<td>833</td>
<td>765-61</td>
<td>711-99</td>
<td>696-707</td>
<td>716-66</td>
<td>786-819</td>
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<tr>
<td></td>
<td>837</td>
<td>795-92</td>
<td>741-59</td>
<td>718-22</td>
<td>720-54</td>
<td>772-812</td>
</tr>
<tr>
<td>Reactor Wall Temp, °F</td>
<td>831-26</td>
<td>781-76</td>
<td>750-52</td>
<td>747-61</td>
<td>770-810</td>
<td>817-831</td>
</tr>
<tr>
<td>ΔT_max, °F</td>
<td>-4</td>
<td>-5</td>
<td>+7</td>
<td>52</td>
<td>61b)</td>
<td>40b)</td>
</tr>
<tr>
<td>Product Analysis, %</td>
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<td></td>
</tr>
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<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
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<td>12.8</td>
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<tr>
<td>MCH Conversion, %</td>
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<td>17.6</td>
<td>7.5</td>
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<td>99.7</td>
<td>99.4</td>
<td>99.4</td>
<td>94.5</td>
<td>65.3</td>
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</table>

a) Emerged after MCH and after toluene.
b) Cold spot moved down the catalyst bed.
Table 127. DEHYDROGENATION OF MCH OVER 10860-114C CATALYST

<table>
<thead>
<tr>
<th>Run No. 11325-</th>
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<th>75-1</th>
<th>75-2</th>
<th>76-1</th>
<th>76-2</th>
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<tr>
<td>LHSV</td>
<td>5</td>
<td>15</td>
<td>30</td>
<td>50</td>
<td>80</td>
<td>100</td>
</tr>
<tr>
<td>Catalyst Bed Profile, °F</td>
<td>759-61</td>
<td>640-35</td>
<td>619</td>
<td>621-26</td>
<td>635-37</td>
<td>644-50</td>
</tr>
<tr>
<td>Block Temperature: 842°F</td>
<td>815</td>
<td>789-82</td>
<td>632-30</td>
<td>621</td>
<td>619-21</td>
<td>621-23</td>
</tr>
<tr>
<td>Catalyst Volume: 7 ml</td>
<td>833</td>
<td>750-83</td>
<td>660-57</td>
<td>635</td>
<td>626</td>
<td>626</td>
</tr>
<tr>
<td>Reaction Time: 30 minutes</td>
<td>837-35</td>
<td>792-84</td>
<td>691-89</td>
<td>658</td>
<td>644</td>
<td>657-35</td>
</tr>
<tr>
<td>Reactor Wall Temp, °F</td>
<td>831</td>
<td>770-66</td>
<td>750-28</td>
<td>718</td>
<td>711</td>
<td>709</td>
</tr>
<tr>
<td>△T max, °F</td>
<td>42</td>
<td>-8</td>
<td>-3</td>
<td>+5</td>
<td>+2</td>
<td>+6</td>
</tr>
<tr>
<td>Product Analysis, %w</td>
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<td>0.0</td>
<td>0.0</td>
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<tr>
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<td>1.7</td>
<td>26.8</td>
<td>47.2</td>
<td>59.6</td>
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<tr>
<td>Toluene</td>
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<td>97.8</td>
<td>73.1</td>
<td>52.8</td>
<td>40.4</td>
<td>35.0</td>
</tr>
<tr>
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<td>98.3</td>
<td>73.2</td>
<td>52.8</td>
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<td>35.0</td>
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<td>71</td>
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<td>72-2</td>
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<tr>
<td>LHSV</td>
<td>5</td>
<td>15</td>
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<td>50</td>
<td>60</td>
<td>100</td>
</tr>
<tr>
<td>Catalyst Bed Profile, °F</td>
<td>761-72</td>
<td>783-76</td>
<td>671-60</td>
<td>689-72</td>
<td>727-78</td>
<td>781-806</td>
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<td>683-60</td>
<td>687-729</td>
<td>723-63</td>
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<td>727-23</td>
<td>707</td>
<td>696-702</td>
<td>702-16</td>
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<td>Reactor Wall Temp, °F</td>
<td>826-26</td>
<td>779-76</td>
<td>752</td>
<td>743-47</td>
<td>747-63</td>
<td>768-75</td>
</tr>
<tr>
<td>ΔT_max, °F</td>
<td>-9</td>
<td>-7</td>
<td>+9</td>
<td>18</td>
<td>41</td>
<td>40(^a)</td>
</tr>
<tr>
<td>Product Analysis, %</td>
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<td></td>
<td></td>
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<td></td>
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</tr>
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<td>73.3</td>
<td>81.3</td>
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<td>89.0</td>
<td>55.6</td>
<td>37.7</td>
<td>26.6</td>
<td>15.6</td>
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<tr>
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<td>89.2</td>
<td>55.7</td>
<td>37.8</td>
<td>26.7</td>
<td>15.7</td>
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</table>

\(^a\) Cold spot moved down the catalyst bed.
Table 129. DEHYDROGENATION OF MCH OVER 10660-113A AND
HOLAY 200 SR CATALYSTS

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<th>Run No. 11325-</th>
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<td></td>
<td></td>
</tr>
<tr>
<td>Catalyst Bed</td>
<td>758-56</td>
<td>705-833</td>
<td>763-58</td>
<td>725-68</td>
<td>824-37</td>
</tr>
<tr>
<td>Profile,  F</td>
<td>801-799</td>
<td>700-831</td>
<td>804-797</td>
<td>741-50</td>
<td>797-833</td>
</tr>
<tr>
<td></td>
<td>826-24</td>
<td>741-830</td>
<td>624-17</td>
<td>761-58</td>
<td>778-226</td>
</tr>
<tr>
<td></td>
<td>833</td>
<td>770-828</td>
<td>831-28</td>
<td>784-779</td>
<td>770-817</td>
</tr>
<tr>
<td>Reactor Wall Temp,  F</td>
<td>826</td>
<td>783-838</td>
<td>824-21</td>
<td>788-97</td>
<td>820-837</td>
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<td>AT_max,  F</td>
<td>-2</td>
<td>13</td>
<td>-7</td>
<td>43</td>
<td>b)</td>
</tr>
<tr>
<td>Product Analysis, %</td>
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<td></td>
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<td>0.2</td>
<td>1.7</td>
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<td>1.7</td>
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<td>4.8</td>
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<tr>
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<td>34.1</td>
<td>93.5</td>
<td>64.8</td>
<td>10.8</td>
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<tr>
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<td>40.6</td>
<td>95.2</td>
<td>65.0</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Toluene, %</td>
<td>98.6</td>
<td>84.0</td>
<td>92.8</td>
<td>99.7</td>
<td>92.3</td>
</tr>
</tbody>
</table>

a) Emerged after MCH, after benzene, after toluene.
b) Catalyst bed temperature about that of reactor wall temperature.
Description of the Pulsed Reactor

The pulse reactor was a 1/4-in. OD stainless steel tube (No. 304) 9-1/4 in. long and 0.022 in. wall thickness. Swagelok Tees were fastened at each end and one arm of the Tee served as an injection port. A rubber septum (GLC type) was held in place by the fitting nut and the feed was injected through this septum from a syringe. A five inch length of the reactor tube was surrounded by a secondary furnace liner and the whole was heated by an electric furnace. The secondary liner had seven radial drilled holes for thermocouples and the holes were located as shown in Figure 72. A schematic diagram of the pulse reactor is shown in Figure 77.

All lines were 1/4-in. OD stainless steel tubing (No. 304). About 26 in. of line just prior to the reactor was wrapped with heating tape and constituted a gas preheater. About 8 in. of the preheater section was filled with quartz chips (10-20 mesh size).

In the pulse reactor system the carrier gas was metered through a rotameter (Figure 71) and passed through the preheater section and into the reactor. The exit gas passed into a manifold and then into the GLC. The purpose of the manifold was to maintain the exit gas pressure slightly greater than the gas pressure in the GLC. This was done by adjusting the pressure control valve and the vent valve. The manifold was wrapped with heating tape and was maintained at 300° to 350°F. The injection port temperature was about 450°F. The pressure control and the vent valves were needle valves (Hoke No. 1315) and the GLC valve was a lever operated valve (Hoke No. 490).

To carry out an experiment the reactor was brought to temperature and the carrier gas flow rate, reactor pressure and manifold pressure were adjusted by means of the appropriate flow control valves. Then with inert gas flowing to the GLC a pulse was injected through the lower injection port and subsequently analyzed. This gave an analysis of the starting material. A pulse was then injected in the top injection port, passed over the catalyst and analyzed.

In this system the space velocity was obtained from the inert gas flow rate. Figure 78 shows the pulse reactor system with the secondary furnace liner in place; Figure 80 shows the GLC analysis system.
Figure 72. SECONDARY FURNACE LINER FOR PULSE REACTOR
Description of the 1/4-in. OD Flow Reactor

In order to test candidate fuels that are in short supply one section of our laboratory dual reactor system was modified in the following manner, so that 1/4-in. OD reactor tubes could be used.

In our laboratory reactor system the furnace is 26 in. overall length and contains four heating elements of lengths 4", 8", 8", 4" located from top to bottom in that order. The outer shell of the furnace extends one inch beyond the top and bottom of the heating elements. The furnace consists of two hinged halves and opens lengthwise. Each half contains a heavy Meehanite liner with a groove down the center to hold the reactor tube. When closed the grooves form an opening 7/8 inch in diameter.

To modify the apparatus, a secondary furnace liner was fabricated from a 7/8-in. stainless steel rod (No. 416), 13 inches long. A 0.257-in. diameter hole was drilled down the center to accommodate a 1/4-in. OD reactor tube. Seven holes were drilled radially from the outside to the center hole in which thermocouples were cemented. The thermocouples were 1-1/2 inches apart and the top couple was 1-1/2 inches from the top of the liner. The thermocouples were situated so that they just touched the reactor wall. This secondary liner was placed in the Meehanite liners at the very bottom of the furnace and extended one inch below the bottom heating element. Figure 81 shows the construction of the secondary liner and its position in the furnace.

The reactor was a stainless steel tube (No. 304) 30 inches long, 1/4-inch OD with 0.035" wall thickness. Reaction was carried out in the lower part of the tube and the top part served as a feed preheater. The reactor was furnace-heated and a 13" long secondary furnace liner surrounded the reactor tube at the reaction zone. Figure 81 shows the secondary furnace liner and its position in the furnace.

The reactor wall temperature was measured at seven points along the tube. The points were 1-1/2 inches apart and the top point was one inch below the top of the secondary liner (Figure 81). The temperature of the reactor wall varied down the tube and Figure 82 shows the temperature variation for a furnace block temperature of 1202°F.

The maximum reaction rate will occur in the region of maximum temperature. Presumably the rate in that portion of the tube whose temperature was 18°F (10°C) or more below the maximum temperature, did not contribute appreciably to the overall rate. Thus the "effective" volume of the tube was that portion of the tube whose temperature was within 18°F of the maximum wall temperature, and whose volume was determined from a plot such as Figure 82. The "effective" reactor temperature was taken as 9°F below the maximum temperature.
Figure 81. SECONDARY FURNACE LINER FOR \frac{1}{4}" OD REACTOR TUBE

- Hole for Reactor Tube 0.257" Diameter
- Holes for Thermocouples \frac{1}{16}" Diameter
- Slot for Thermocouple Leads \frac{1}{32}" Deep, \frac{1}{8}" Wide

End View

Secondary Furnace Liner

Reactor Furnace with Secondary Furnace Liner in Position

Heating Elements

Secondary Liner
Figure 82. REACTOR TEMPERATURE PROFILE

-64157

-325-
Micro Catalyst Test Reactor Data

The micro catalyst test reactor (MICTR) and the operational techniques used for screening candidate catalysts have been described in the Appendix of the last Annual Report. No further changes have been made. Catalysts are tested with MCH at 100 and 662, 752 and 842°F, at 10 atm pressure without added hydrogen. Figures 87 through 89, of reference 18 show the apparatus in detail, except for the changes noted in reference 16. It has been found that more consistent results are obtained if a fresh loading of the reference catalyst 9874-139 is made each week as a base point for calibration, rather than using the same reference catalyst tube over and over again, since the activity gradually declines. Also prepared catalysts have been rescreened to 10-20 mesh to remove fines after impregnation and drying of the supports, and this gives more reproducible results.
Table 130. MCH DEHYDROGENATION WITH VARIOUS CATALYSTS IN MICH - REG-577-511

<table>
<thead>
<tr>
<th>Catalyst Volume</th>
<th>Temperature</th>
<th>Pressure</th>
<th>Reaction Rate</th>
<th>Conversion</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.9 ml catalyst diluted with 1.1 ml quartz chips; LHSV 100 (catalyst and quartz particles 10-20 mesh unless otherwise noted).</td>
<td>10 atm pressure; catalysts reduced in H₂ for 20 minutes at 726°F; GLC samples normally taken at 3-, 6-, and 15-minute operation at each block temperature.</td>
<td>Period: June-August 1968</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Column 1</td>
<td>Column 2</td>
<td>Column 3</td>
<td>Column 4</td>
<td>Column 5</td>
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<td>---------</td>
</tr>
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### Table 4-9 (Continued)

**WATER TEMPERATURE VERSUS VOLTAGE**

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<th>Voltage (V)</th>
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<tr>
<td>4.0</td>
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</table>

- The table continues with similar data points.
Table III.  

| Period: September-November 1968 | Conditions: 10 atm pressure; catalyst refluxed in Hz for 20 minutes at 750°F. All samples normally taken at 3, 6, and 12 minute operation at each block temperature.  
Catalyst Volume: 0.9 ml catalyst diluted with 1.1 ml quartz chips; 500/0 (catalyst and quartz) 10-30 mesh unless otherwise noted. |
## Table III. POLYMERIZATION WITH VARIOUS CATALYSTS

<table>
<thead>
<tr>
<th>No.</th>
<th>Catalyst</th>
<th>Description</th>
<th>HCR Conversion, %</th>
</tr>
</thead>
<tbody>
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<td>Pt 0.1</td>
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### Notes
1. HCR =...
Table III. MTH HYDROCONVERSION WITH VARIOUS CATALYSTS IN BLEND, HCC AND MCH

| Period: March-August, 1969 |
| Conditions: 10 atm pressure; catalysts reduced in hydrogen at 775°F. GLC samples taken normally at 3-, 8- and 13-minute operation at each temperature |
| Volume: 0.9 ml catalyst diluted with 1.1 ml quartz chips (10-20 mesh). LHSV 100 with MCH |

<table>
<thead>
<tr>
<th>Entry</th>
<th>Catalyst</th>
<th>Reaction</th>
<th>T.M. Conversion, %</th>
<th>5 MTH Conversion, %</th>
<th>10 MTH Conversion, %</th>
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</thead>
</table>

Continued...
<table>
<thead>
<tr>
<th>Process</th>
<th>Catalyst</th>
<th>Space Velocity</th>
<th>Reaction Type</th>
<th>% Conversion</th>
<th>% Yield</th>
<th>Time</th>
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<tr>
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<td>Type E</td>
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(continued)
Measurement of Deposits on Coker Tubes With Nuclear Radiation

Presented here is a summary to date of the results and thoughts that have gone into the application of nuclear radiation as a tool for the evaluation of coker tube deposits. Covered are the general principles, electron scattering theory, preliminary experiments, trial apparatus and results, and proposed permanent instrument design. Electron backscatter appears to be the most promising approach and is the method of primary concern in the work presented here.

Thin Film Measurement With Nuclear Radiation General Principles

Thin film measurement with nuclear radiation can be accomplished either by transmission or scatter of the radiation. The problem is to select the best type and energy of radiation and guidelines to such selection that are available. The deposits of interest have a surface density in the neighborhood of $10^{-5}$ g/cm$^2$ equivalent to an air path of only .01 cm. This implies an arrangement based on scattering rather than absorption and the probable need of vacuum operation. Possible types of radiation applicable in the present case are summarized in the table below.

**Table 1**, METHODS OF UTILIZING NUCLEAR RADIATION

<table>
<thead>
<tr>
<th>Type</th>
<th>Source Radiation</th>
<th>Detected Radiation</th>
<th>Operation</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
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<td>$\alpha$</td>
<td>$\alpha$</td>
<td>alpha backscatter</td>
<td>Low scattering coefficient, requires very high intensity source.</td>
</tr>
<tr>
<td>2</td>
<td>$\alpha$</td>
<td>$x$</td>
<td>x-ray fluorescence</td>
<td>Possible method. Efficiency very dependent on tube metal.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>in coker tube</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>$\beta$</td>
<td>$\beta$</td>
<td>beta backscatter</td>
<td>Preferred method.</td>
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<tr>
<td>4</td>
<td>$\beta$</td>
<td>$x$</td>
<td>x-ray fluorescence</td>
<td>Similar to method 2.</td>
</tr>
<tr>
<td>5</td>
<td>$x$</td>
<td>$x$</td>
<td>x-ray backscatter</td>
<td>Low efficiency.</td>
</tr>
<tr>
<td>6</td>
<td>$x$</td>
<td>$x$</td>
<td>x-ray fluorescence</td>
<td>Low efficiency.</td>
</tr>
</tbody>
</table>

The conclusion from this list is that electron scattering is preferred but other factors, not listed, also lead to the same conclusion. Should an alternative method be considered for investigation the use of fluorescence from alpha bombardment is probably the most promising. A transmission type of measurement is possible if radioactivity is introduced, by plating for example, onto the coker tube. This method, suggested by H. Siegel, is

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a) Acknowledgment is made to Dr. R. Curtis of the Analytical Department for this work.
preferable from the point of view of measurement to any of those listed above, but the handling of radioactive tubes is a sufficient deterrent to exclude the method.

**Electron Backscatter Theory**

An approximate description of the relative backscattered electron flux to be expected from a coating of thickness \(x\) (g/cm\(^2\)) on a base of effectively infinite thickness is given by Tittle\(^{58}\) as:

\[
\frac{I}{I_0} = \frac{Z_1}{u_1 + \lambda_1} \left[ 1 - e^{-(u_1 + \lambda_1)x} \right] + \frac{Z_2}{u_1 + \lambda_2} e^{-(u_1 + \lambda_2)x}
\]

(53)

The constants \(u\), \(\lambda\), and \(Z\) depend upon the materials involved and the maximum beta energy, subscripts 1 and 2 referring to the coating and base respectively, and 3 to properties of both. From relations given by Tittle equation (53) in the approximation of small \(x\) can be expressed as:

\[
\frac{I}{I_0} = \left( 1 - e^{-Z_2/40} \right) + \frac{352}{E_1/44} \left[ \left( \frac{Z_1}{A_1} \right) \left( \frac{Z_1 + Z_2}{100 + Z_1} \right) \left( 1 - e^{-Z_1/40} \right) \right]
\]

(54)

\[
= \left( \frac{Z_1}{A_1} + \frac{502}{100} \frac{0.31}{Z_2} \right) \left( 1 - e^{-Z_2/40} \right)
\]

in which \(Z_1\) and \(A_1\) are the atomic number and atomic mass of the coating, \(Z_2\) the atomic number of the substrate, and \(E\) is the maximum beta energy in Mev. Approximating the deposit composition by \(Z_1/A_1 = 0.56\) and \(Z_1 = 5.9\) on an aluminum (\(Z_2 = 13\)) base gives

\[
\frac{I}{I_0} = 0.28 - \frac{4.4x}{E_1/44}
\]

(55)

as the ratio of scattered to incident flux. The statistics of counting and the general level of instrumental variables is such that it is not practical to measure a change \(dI/I_0\) of much less than 1%. Equation (55) then predicts a maximum energy of 1.1 KeV in order to detect a thickness change \(dx\) of \(10^{-8}\) cm, assuming unit density for the deposit. Some idea of the range of thickness measurable with this energy is obtained by equating (55) to zero with the result \(x = 3.10^{-8}\) g/cm\(^2\). This prediction indicates the need of a very low energy source though perhaps not as low as 1 KeV if the expected range of thickness (up to \(10^{-6}\) cm) is to be covered. Possible sources that are available are listed in Table 135. None of these sources is as low in energy as might be desired, but the least energetic sources should provide a usable compromise since even \(^{14}\)C is capable of showing some response to the heavier deposits.
Table 25. LOW ENERGY BETA SOURCES

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Half Life, Years</th>
<th>E_max., Kev</th>
<th>Range in Air, cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{310}$Pb</td>
<td>21</td>
<td>17</td>
<td>0.4</td>
</tr>
<tr>
<td>$^3$H</td>
<td>12</td>
<td>19</td>
<td>0.5</td>
</tr>
<tr>
<td>$^{60}$Ni</td>
<td>85</td>
<td>67</td>
<td>5.5</td>
</tr>
<tr>
<td>$^{14}$C</td>
<td>5-700</td>
<td>155</td>
<td>26.0</td>
</tr>
</tbody>
</table>

Though not immediately apparent, equation (54) dictates that the replacement of aluminum with any metal of higher atomic number will produce an increased response to a given deposit. The method depends on the difference, primarily in atomic number, between coating and base. This difference is not large with aluminum so that a successful measurement in this case assures success with heavier metals.

Preliminary Experiments

Initial tests were aimed at answering three questions: whether operation without a vacuum was feasible, whether to minimize absorption a windowless flow counter was practical, and what magnitude of response would be observed in practice. To this end a small counter was constructed (courtesy A. Telfer) from one inch brass tubing with a wedge shaped end opening approximately one cm wide. As a source $^{60}$Ni, having a reasonable penetration in air, was utilized in the form of the chloride adsorbed on a strip of filter paper mounted near the counter entrance. Tests were made using a 3/16" aluminum rod covered with various thicknesses of mylar film and mounted 1/2 cm from the counter.

This arrangement was unsatisfactory in several respects. One difficulty, not unexpected, was a large dependence of count rate upon counter gas flow rate. This could be controlled, but drift beyond this factor occurred that could not be accounted for. Stability was sufficient to show a count difference for one mill mylar film but was wholly inadequate for the detection of deposit films. In short, it was concluded that vacuum operation, which would require a thin window counter, was necessary and that a lower energy beta source was essential.

Trial Apparatus and Results

The bell jar and cryopump portion of a vacuum deposition apparatus were utilized in the following measurements. Feedthroughs in the base were provided for piping the flow of counter gas, the high voltage lead to the detector, and a slide fitting to which the cover tube could be attached. This slide fitting allowed translation and rotation of the cover tube in front of the source and detector for scanning the deposit area.
A locally constructed thin window flow counter was used as detector. This window is exposed via a 3/32 x 5/8" slot cut in a one inch diameter faceplate. The source was mounted directly on this face about 1/4" from the slot. The source itself was a 1/3 x 1/4" section of a neutron generator target arranged with a rather simple collimator fashioned from aluminum foil. The source-to-scatterer and scatterer-to-detector distance was 2.5 cm.

The associated electronics consisted of a Baird-Atomic Model 530 Spectrometer and Printer which provides the necessary functions of high voltage supply, pulse amplifier, discriminator, counter, and timer. Originally the high voltage was carried into the vacuum to the detector through a shielded cable, but this proved unsatisfactory. Attempts at shielding and insulating were not sufficient to eliminate corona and discharge in the vacuum with resultant spurious counting. A sufficiently hard vacuum to eliminate this problem was not practical. Instead, the high voltage lead and connection to the detector were enclosed in copper tubing and arranged to remain at atmospheric pressure.

The beta source used produces as well, super-γ-rays. These contribute to the scattered flux which is detected and provide a background counting rate even at atmospheric pressure. As the air pressure is reduced, a point is reached where the mean free path of the scattered electrons is sufficient for them to reach the detector and be counted. It was anticipated that a maximum count rate would be reached at some pressure and that this rate would remain constant below this pressure where essentially all electrons that could be scattered toward the detector would reach it. Instead, it was found that the count rate reached a maximum and then decreased with increasing vacuum. This maximum occurred at a pressure of approximately 25 torr while below 1/2 torr the count rate was independent of pressure. Apparently, as the pressure is reduced there is a maximum in count rate when the coker tube, bell jar wall, and residual atmosphere all contribute to the scattering and further evacuation diminishes the air scatter more rapidly than the increased scatter from wall and coker tube. As long as the pressure remains under 1/2 torr this presents no difficulty.

The coker tubes used in this study are of a miniature variety, the section of interest being 2-1/2" long and 1/8" diameter between end sections of 3/16" diameter. The deposit generally covers only a portion of the central tube section, being lightest (visually) near one shoulder, increasing in darkness toward the center of the tube and ending fairly abruptly to leave apparently bare metal beyond this point. The scattered intensity measured along such a tube is shown in Figure 83. Each point in the figure represents a 20 second count. The scatter of these points from a smooth curve is primarily due to statistical variations in counting. The rate corresponding to an uncoated tube is about 300 c/s, while on the wider tube section beyond the shoulder it is approximately 350 c/s. While the deposit in this example is a rather heavy one by visual inspection there appears to be ample sensitivity in the backscatter response. This is particularly true considering two simple improvements that could easily be introduced. The first involves better collimation of the incident beta flux to improve resolution of the

Results with a group of coker tubes are given in Figure 86. Again a 20 sec count was made at each point, but with the limited number of points involved a good approximation to the profile is acquired in roughly 5 min. The two curves for each sample are scans along opposite sides of the tube. The horizontal line to the right of each curve is an adjusted rate of 300 c/s. This adjustment was necessary because of an unexplained drift, possibly arising from the electronics, which could be corrected for each scan by returning to the starting position, but which is more difficult to correct for in going from tube to tube.

Calibration points for establishing a thickness scale were obtained using mylar film and by coating a tube with films of solution cast nitrocellulose. The mylar film (1/8 mil) is approaching infinite scattering thickness which simply means that the aluminum rod no longer contributes to the scattering. At this point the count rate has dropped from 300 to 200 c/s. Reasonably consistent results were obtained with 1, 2 and 4000A of film. Applied to the five tubes in Figure 86 this gives the following results as shown in Table 16.

\[
\frac{I}{I_0} = 1 - e^{-Z_2/40} + \frac{35x}{16.174} \left[ \frac{Z_2}{A_1} \left( \frac{351 + Z_1}{100 + Z_1} \right) \left( 1 - e^{-Z_1/40} \right) \right] \\
\left( \frac{Z_2}{A_1} + \frac{400 Z_2^{0.31}}{100 + Z_2} \right) \left( 1 - e^{-Z_2/40} \right)
\]

For Aluminum base \( Z_2 = 13 \)  

\[
\frac{I}{I_0} = 0.2775 + \frac{35x}{16.174} \left[ \frac{Z_2}{A_1} \left( \frac{351 + Z_1}{100 + Z_1} \right) \left( 1 - e^{-Z_1/40} \right) \right] \\
\left( \frac{Z_2}{A_1} + 4.195 Z_2^{0.31} \right) \left( 6.276 \right)
\]

<table>
<thead>
<tr>
<th>Composition</th>
<th>( Z_1 )</th>
<th>( Z_2/A_1 )</th>
<th>( Z_2^{0.31} )</th>
<th>( 1 - e^{-Z_1/40} )</th>
<th>% Change (^{a})</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH</td>
<td>7.74% H</td>
<td>5.613</td>
<td>.5383</td>
<td>1.707</td>
<td>1.914</td>
</tr>
<tr>
<td>CH(_2)</td>
<td>14.3% H</td>
<td>5.23</td>
<td>.572</td>
<td>1.675</td>
<td>1.898</td>
</tr>
<tr>
<td>CH(_2) _25</td>
<td>23.5% O</td>
<td>6.18</td>
<td>.529</td>
<td>1.758</td>
<td>1.965</td>
</tr>
<tr>
<td>CH(_3) _25</td>
<td>11.3% S</td>
<td>6.75</td>
<td>.534</td>
<td>1.806</td>
<td>2.005</td>
</tr>
<tr>
<td>CH(_2)Fe _01</td>
<td>4.13% Fe</td>
<td>6.46</td>
<td>.535</td>
<td>1.784</td>
<td>1.985</td>
</tr>
<tr>
<td>CHF(_2) _001</td>
<td>1.14% Pb</td>
<td>6.64</td>
<td>.519</td>
<td>1.798</td>
<td>1.997</td>
</tr>
</tbody>
</table>

\(^a\) Scaled with CH as reference.
There is little agreement with the visual ratings. The scattering results are, of course, reproducible and independent of operator judgment.

The deposit composition in calculations with equation (54) was assumed to be CH$_3$O$_{25}$. It can approach CH$_3$O and may contain up to 5% sulfur. Again the effects of composition changes in the deposit on the scattered intensity can be estimated at least roughly from this equation. The main effect from composition changes is in the average for Z. Starting with CH$_3$O$_{25}$ and going to CH$_3$O$_{25}$S$_{0.25}$, that is, adding 5% sulfur is equivalent to a 2% change in apparent thickness. The dependence on sulfur or any other heavier element is large, as expected, but film measurement within 2% that does not depend on composition is still far superior to visual estimates.

Table 136. RESULTS ON FIVE COVER TYPES

<table>
<thead>
<tr>
<th>Pred No.</th>
<th>Max Count Rate Decrease</th>
<th>Max Film Thickness, Å</th>
<th>Approx Total Deposit, Å x cm</th>
<th>Visual Ratings</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Max</td>
</tr>
<tr>
<td>1</td>
<td>85 c/s</td>
<td>5000</td>
<td>6000</td>
<td>7.0</td>
</tr>
<tr>
<td>2</td>
<td>70</td>
<td>4500</td>
<td>7000</td>
<td>6.5</td>
</tr>
<tr>
<td>3</td>
<td>20</td>
<td>1200</td>
<td>1500</td>
<td>4.0</td>
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<tr>
<td>4</td>
<td>50</td>
<td>3000</td>
<td>4000</td>
<td>6.5</td>
</tr>
<tr>
<td>5</td>
<td>125</td>
<td>8000</td>
<td>6000</td>
<td>6.5</td>
</tr>
</tbody>
</table>

a) Multiplication by tube circumference (1.0 cm) will give total deposit volume.
Figure 83. COKER TUBE DEPOSIT PROFILE
Figure 84. COMPARISON OF DEPOSIT TUBE PROFILES
Proposed Instrument Design

The results observed above demonstrate the feasibility of electron backscatter as a means of quantitative measurement of coke tube deposits. Several conveniences can, however, be incorporated in a practical instrument. These include automatic scanning and recording of the profile and a convenient vacuum assembly.

In respect to scanning it may be convenient to integrate or average readings around the tube circumference so that a one-dimensional average along the tube length is obtained. This can be achieved in either of two ways. With a point source and detector arrangement and a ratemeter output the tube can be rotated with a period less than the time constant of the ratemeter while being translated along its length. A motor driven screw motion would achieve this. The alternative is to arrange both source and cylinder in the form of rings surrounding the rod. Actually, a triangular array would provide a sufficient approximation to a continuous ring. The main cost increase would be in respect to three detectors. The source and electronics cost increase is trivial. In this way only a linear motion need be applied to the sample tube and eccentricity is averaged out.

For the vacuum assembly it may be most convenient to adapt a commercially available apparatus involving a bell jar. But a smaller volume would allow quicker pumping down and would be more compact. This could be in the form of a tube sufficiently long for sample translation and of perhaps 3" ID. An external motor drive would move the sample placed on a suitable carriage. Source and detector would be mounted in the mid-section wall of the tube with collimation on the source and on the detector to reduce extraneous backscatter. Electrical connections would then all be at atmospheric pressure.
### Table 1A

#### Vapour Pressure of Water at Various Temperatures (1000 Cals. 1000 Tons)

<table>
<thead>
<tr>
<th>Temp (°C)</th>
<th>Vapour Pressure (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>5.00</td>
</tr>
<tr>
<td>10</td>
<td>15.50</td>
</tr>
<tr>
<td>20</td>
<td>40.00</td>
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<tr>
<td>30</td>
<td>85.00</td>
</tr>
<tr>
<td>40</td>
<td>150.00</td>
</tr>
<tr>
<td>50</td>
<td>250.00</td>
</tr>
<tr>
<td>60</td>
<td>420.00</td>
</tr>
<tr>
<td>70</td>
<td>670.00</td>
</tr>
<tr>
<td>80</td>
<td>990.00</td>
</tr>
<tr>
<td>90</td>
<td>1390.00</td>
</tr>
<tr>
<td>100</td>
<td>1990.00</td>
</tr>
</tbody>
</table>

### Table 1B

#### Liquid Properties of Water at Various Temperatures (1000 Cals. 1000 Tons)

<table>
<thead>
<tr>
<th>Temp (°C)</th>
<th>Liquid Volume (cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.000</td>
</tr>
<tr>
<td>10</td>
<td>1.001</td>
</tr>
<tr>
<td>20</td>
<td>1.002</td>
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<tr>
<td>30</td>
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<tr>
<td>40</td>
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<td>50</td>
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<td>80</td>
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<tr>
<td>90</td>
<td>1.009</td>
</tr>
<tr>
<td>100</td>
<td>1.010</td>
</tr>
</tbody>
</table>

### Table 1C

#### Physical Properties of Water

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>0.99707060</td>
</tr>
<tr>
<td>Viscosity</td>
<td>0.01001000</td>
</tr>
<tr>
<td>Heat of Fusion</td>
<td>0.9999000</td>
</tr>
<tr>
<td>Heat of Vaporization</td>
<td>0.99999000</td>
</tr>
<tr>
<td>Heat of Combustion</td>
<td>0.99999990</td>
</tr>
<tr>
<td>Heat of Ignition</td>
<td>0.99999999</td>
</tr>
</tbody>
</table>

-345-
<table>
<thead>
<tr>
<th>Pressure</th>
<th>Specific Heat</th>
<th>Ratio of Specific Heats</th>
<th>Density</th>
<th>Viscosity</th>
<th>Thermal Conductivity</th>
<th>Dynamic Viscosity</th>
<th>Thermal Expansion Coefficient</th>
<th>Specific Heat Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1 atm</td>
<td>1.00</td>
<td>0.68</td>
<td>0.10</td>
<td>0.01</td>
<td>0.00</td>
<td>0.01</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>0.2 atm</td>
<td>1.01</td>
<td>0.67</td>
<td>0.11</td>
<td>0.02</td>
<td>0.01</td>
<td>0.02</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>0.3 atm</td>
<td>1.02</td>
<td>0.66</td>
<td>0.12</td>
<td>0.03</td>
<td>0.02</td>
<td>0.03</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>0.4 atm</td>
<td>1.03</td>
<td>0.65</td>
<td>0.13</td>
<td>0.04</td>
<td>0.03</td>
<td>0.04</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>0.5 atm</td>
<td>1.04</td>
<td>0.64</td>
<td>0.14</td>
<td>0.05</td>
<td>0.04</td>
<td>0.05</td>
<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td>0.6 atm</td>
<td>1.05</td>
<td>0.63</td>
<td>0.15</td>
<td>0.06</td>
<td>0.05</td>
<td>0.06</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>0.7 atm</td>
<td>1.06</td>
<td>0.62</td>
<td>0.16</td>
<td>0.07</td>
<td>0.06</td>
<td>0.07</td>
<td>0.06</td>
<td>0.06</td>
</tr>
</tbody>
</table>

The table provides the properties of water at different pressures and densities, including specific heat, ratio of specific heats, density, viscosity, thermal conductivity, dynamic viscosity, thermal expansion coefficient, and specific heat capacity.
### Table 1: Gas Properties of Octanol at 1000°C and 1000 Torr

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
<th>16</th>
</tr>
</thead>
<tbody>
<tr>
<td>250</td>
<td>1.25</td>
<td>1.25</td>
<td>1.25</td>
<td>1.25</td>
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<td>2.5</td>
<td>2.5</td>
<td>2.5</td>
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<tr>
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Units: kcal/mol
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### TABLE I. CONTINUED

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<th>Test</th>
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<th>70</th>
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<td></td>
<td></td>
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</tr>
</tbody>
</table>

**Notes:**

- Data represents average measurements from five trials.
- Error margins are within ±2% of the indicated values.
- Further analysis is required for values below 30.
Following are typical experimental data and calculated physical properties incorporated in a variety of methods. Since only a limited number of samples of TiC2+2 have been prepared, the consistency of the data from batch to batch has not been established. Also, planning larger scale preparations, we have not independently calculated the effect of temperature and pressure, outside the normal range, on various liquid and gaseous properties of interest. Instead we have applied corrections to the values calculated for C2+2 itself, as given in the citation above, as deemed advisable.

The magnitudes of the correction factors involved are generally not large and we believe the data can be used without serious error. Improved information will be supplied as soon as it is available.
### Properties of Material

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
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<tbody>
<tr>
<td>Gravity, deg API</td>
<td>5.0</td>
</tr>
<tr>
<td>Specific Gravity, g/cc</td>
<td>0.700</td>
</tr>
<tr>
<td>Freezing Point, °F</td>
<td>25</td>
</tr>
<tr>
<td>Boiling Point, °F</td>
<td>230</td>
</tr>
<tr>
<td>Melting Point, °F</td>
<td>220</td>
</tr>
<tr>
<td>Acidic Content, %</td>
<td>0.1</td>
</tr>
<tr>
<td>Alkaline Content, %</td>
<td>0.9</td>
</tr>
<tr>
<td>Upper Snubbing Point, °F</td>
<td>168</td>
</tr>
<tr>
<td>Lower Snubbing Point, °F</td>
<td>155</td>
</tr>
<tr>
<td>Distillation, °F, at 100°F</td>
<td>118</td>
</tr>
<tr>
<td>Flash Point, °F</td>
<td>132</td>
</tr>
<tr>
<td>Vapour Pressure, psi at 100°F</td>
<td>25</td>
</tr>
<tr>
<td>Thermal Stability, h</td>
<td>2.5</td>
</tr>
<tr>
<td>Pressure Change, in. Hg</td>
<td>5.9</td>
</tr>
<tr>
<td>Flameproof Impact rating</td>
<td>1.6</td>
</tr>
<tr>
<td>Cold Proof Impact</td>
<td>5.0</td>
</tr>
<tr>
<td>Carbon / Hydrogen Ratio</td>
<td>4.9</td>
</tr>
<tr>
<td>Critical Temperature, °F</td>
<td>245</td>
</tr>
<tr>
<td>Critical Pressure, psi</td>
<td>100</td>
</tr>
<tr>
<td>Water Fraction, %</td>
<td>0.2</td>
</tr>
</tbody>
</table>

* Additional notes:*

a) Samples have formed crystals at temperatures of about 10°C and below.

b) C formaldehyde solution.

c) Add 10% by volume as per API Table 2.
Table 146: I.I.Y. INFERENCE OF V. M. & I. M. AT RAND IN 1918

<table>
<thead>
<tr>
<th>Temp.</th>
<th>Velocity, ft./sec.</th>
<th>Velocity, ft./sec.</th>
<th>Thermal Conductivity, Btu/hr/ft/°F</th>
<th>Heat Capacity, Btu/lb</th>
<th>Density, lb./fdm</th>
<th>Heat of vaporization, Btu/lb</th>
<th>Specific Pressure, psi</th>
</tr>
</thead>
<tbody>
<tr>
<td>-60</td>
<td>70.3</td>
<td>22000.0</td>
<td>0.008</td>
<td>0.237</td>
<td>-14.3</td>
<td>51.0</td>
<td>0.100</td>
</tr>
<tr>
<td>0</td>
<td>69.3</td>
<td>552.0</td>
<td>0.010</td>
<td>0.257</td>
<td>0.0</td>
<td>142.6</td>
<td>0.100</td>
</tr>
<tr>
<td>100</td>
<td>66.6</td>
<td>23.7</td>
<td>0.048</td>
<td>0.312</td>
<td>78.0</td>
<td>141.5</td>
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<tr>
<td>200</td>
<td>67.8</td>
<td>8.78</td>
<td>0.090</td>
<td>0.337</td>
<td>134.7</td>
<td>136.7</td>
<td>0.038</td>
</tr>
<tr>
<td>300</td>
<td>66.9</td>
<td>3.12</td>
<td>0.095</td>
<td>0.345</td>
<td>136.4</td>
<td>138.4</td>
<td>0.040</td>
</tr>
<tr>
<td>400</td>
<td>57.6</td>
<td>1.47</td>
<td>0.079</td>
<td>0.377</td>
<td>120.4</td>
<td>130.4</td>
<td>2.7</td>
</tr>
<tr>
<td>500</td>
<td>56.5</td>
<td>0.74</td>
<td>0.072</td>
<td>0.359</td>
<td>207.7</td>
<td>111.5</td>
<td>11.5</td>
</tr>
<tr>
<td>600</td>
<td>59.6</td>
<td>0.492</td>
<td>0.064</td>
<td>0.352</td>
<td>260.0</td>
<td>101.5</td>
<td>50.0</td>
</tr>
<tr>
<td>700</td>
<td>60.7</td>
<td>0.341</td>
<td>0.071</td>
<td>0.343</td>
<td>260.8</td>
<td>88.9</td>
<td>76.2</td>
</tr>
<tr>
<td>800</td>
<td>61.7</td>
<td>0.290</td>
<td>0.088</td>
<td>0.332</td>
<td>260.3</td>
<td>77.3</td>
<td>153.0</td>
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<tr>
<td>900</td>
<td>54.2</td>
<td>0.155</td>
<td>0.040</td>
<td>0.318</td>
<td>270.9</td>
<td>64.8</td>
<td>273.0</td>
</tr>
</tbody>
</table>

a) To convert to density, multiply by 58.3.


This indicates the survey of the literature presented in reference 10.



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70. Prakash, A. "THEORETICAL THERMODYNAMICS." Munich, Germany, 1962.


73. Prakash, A. "THEORETICAL THERMODYNAMICS." Munich, Germany, 1962.

74. Prakash, A. "THEORETICAL THERMODYNAMICS." Munich, Germany, 1962.

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76. Prakash, A. "THEORETICAL THERMODYNAMICS." Munich, Germany, 1962.

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1490. HEAT TRANSFER TO SUPERCRITICAL KERNELE. (AD 825 272)
BIBLIOGRAPHY (Cont.)

1491. On one-dimensional frictionless compressible gas flow with heat addition and area change under particular consideration of the subsonic regime. (AD 816 786)

1492. On the effect of vibrations on nuclear boiling heat transfer at near saturated conditions. (AD 816 402)

1493. Supercritical pressure liquid hydrogen heat transfer data compilation. (AD 816 438)

1494. Heat transfer in coaxial systems. (AD 820 902)

1495. Offset rectangular plate-fin surfaces -- heat transfer and flow friction characteristics. (AD 822 954)

1496. Oblate flow headers for heat exchangers -- the influence of inlet velocity profiles. (AD 822 955)

1497. Notes on the progress of free-flight trials to measure heat transfer at Mach numbers up to 5. (AD 816 971)

1498. Hypersonic ramjet heat transfer and cooling program. Volume V: control system studies and experiments. (AD 912 770)

1499. Heat transfer from a cylindrical source to liquid in porous media. (AD 819 824)

1500. Transient heat transfer measurement with thin-film resistance thermometers -- data reduction techniques. (AD 823 515)

1501. Study of heat transfer characteristics of hot-gas igniters. (AD 821 540)

1502. The motion of pure acetilene through shock waves -- translation. (AD 816 435)


The feasibility of utilizing hydrogen-rich fuels for high speed air craft depends upon the endothermic and exothermic capacity of the hydrocarbons, and the combustion properties of the products. As Rankin and Carman combustion rates for this type of fuel must be augmented by thermal, and exothermic reactions. These have been studied. The rate of thermolysis can be accelerated by means of additives. The rate of endothermic combustion, in hydrocarbons, can be increased by the use of high pressure catalysts based on platinum and palladium. The stability of such catalysts is inversely proportional to the pore size of the support. The stability of the catalysts is affected by composition. Dispersed catalysts have some advantages over the type catalyst and some indications of possible reaction have been observed at 3/4 of the 80% catalysts. The hydrogen-rich hydrocarbons have been more active than the standard laboratory catalyst, although none is of magnitude better. Wall catalysts have the advantage of low pressure drop and are showing efficiency benefits also. Calculations show that diffusion limitations can be avoided if the stoichiometric is no more than about 3 miles thick. Satisfactory operation with both improved bed catalysts and wall catalysts has been demonstrated in the fuel system simulator with both hydrogen-rich and oxygenated fuels. Recent transfer studies have been carried out with N/C. These 2.12/184 and 2.12/24 fuel in small diameter test sections under mass fluxes up to 6.75 Btu per hour per square foot. Studies on the effect of high temperatures on the thermal stability of various fuels were carried out with emphasis on methods of measuring deposits on the surface. Combustion and electron back scattering are the methods of present choice and an instrument based on the latter principle has been designed. Mathematical models are being devised to represent the various portions of an endothermic fuel system with present emphasis on the development of heat transfer correlations and a model for the dehydrogenation of Decalin. Physics, properties for Decalin and JP-4 are included. Calculation of the rate of evaporation of normal octane and 3.12/184 from these two studies indicate similar rates of reaction and temperature coefficients.
Fuel thermal fuels
Advanced fuel systems
High velocity fuels
Fuel properties
Supercritical combustion
Chemical catalytic reaction
decomposition
Catalysts
Self-catalysts
Reactor kinetics
Kinetic models
Heat with
Thermal reaction
Hydrocarbon fuels
Literature survey
Thermal stability
Deposit measurement