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VAPORIZING AND ENDOOTHERMIC 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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Shell Development Company,
A Division of Shell Oil Company

TECHNICAL REPORT AFAPL-TR-67-114, Part III, Volume II
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APPENDIX (Cont'd)

Descriptions of the 1/4-in. OD Flow Reactor .......................... 323

Figures
81 Secondary Furnace Liner for 1/4-in. OD Reactor Tube .......... 324
82 Reactor Temperature Profile: 1/4-in. OD Reactor Tube .... 325

Micro Catalyst Test Reactor Data ...................................... 326

Tables
130 MCH Dehydrogenation With Various Catalysts in MICTR:
Runs 677-813 ......................................................... 327
131 MCH Dehydrogenation With Various Catalysts in MICTR:
Runs 814-862 ......................................................... 330
132 MCH Dehydrogenation With Various Catalysts in MICTR:
Runs 863-905 ......................................................... 331
133 MCH Dehydrogenation With Various Catalysts in MICTR:
Runs 906-1060 ......................................................... 332

Measurement of Deposits on Coker Tubes With Nuclear Radiation .... 336
Thin Film Measurement With Nuclear Radiation General Principles .. 336
Table 134. Methods of Utilizing Nuclear Radiation .................... 336

Electron Backscatter Theory ............................................. 337
Table 135. Low Energy Beta Sources .................................. 338

Preliminary Experiments ............................................... 338
Trial Apparatus and Results ........................................... 338

Table 136. Results on Five Coker Tubes ............................... 341
Figure 83. Coker Tube Deposit Profile ................................. 342
Figure 84. Comparison of Deposit Tube Profiles ..................... 343

Proposed Instrument Design ........................................... 344

-286-
APPENDIX (Contd)

<table>
<thead>
<tr>
<th>Properties of Decalin (50% cis, 50% trans)</th>
<th>345</th>
</tr>
</thead>
<tbody>
<tr>
<td>Characteristic Properties of Decalin</td>
<td>345</td>
</tr>
<tr>
<td>Liquid Properties of Decalin at Saturation</td>
<td>345</td>
</tr>
<tr>
<td>Gas Properties of Decalin at Saturation</td>
<td>346</td>
</tr>
<tr>
<td>Gas Properties of Decalin</td>
<td>347</td>
</tr>
<tr>
<td>Properties of JP-5</td>
<td>373</td>
</tr>
<tr>
<td>Characteristic Properties of JP-5</td>
<td>373</td>
</tr>
<tr>
<td>Liquid Properties of JP-5 at Saturation</td>
<td>373</td>
</tr>
<tr>
<td>Gas Properties of JP-5 at Saturation</td>
<td>374</td>
</tr>
<tr>
<td>Gas Properties of JP-5</td>
<td>375</td>
</tr>
<tr>
<td>SHELLDYNE-H (RJ-5)</td>
<td>389</td>
</tr>
<tr>
<td>Preliminary Chemical and Physical Property Data</td>
<td>389</td>
</tr>
<tr>
<td>Preliminary Chemical and Physical Properties and Test Methods of SHELLDYNE-H (RJ-5)</td>
<td>390</td>
</tr>
<tr>
<td>Liquid Properties of SHELLDYNE-H at Saturation Pressure</td>
<td>391</td>
</tr>
<tr>
<td>Gas Properties of SHELLDYNE-H</td>
<td>392</td>
</tr>
</tbody>
</table>
Calculation Procedure for Mach 8 Engine

Station 1.

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

\[
I_f = \frac{n_a(H_f)}{V_1}
\]

\[
W_f = \frac{m(F_g)}{I_f}
\]

\[
A_1 = \frac{W_f}{(F/A)(\rho_1(V_1))}
\]

Assume:

\[
n_a = 0.412
\]

\[
n_g = 0.95
\]

\[
H_f = 1889.4 \text{ Btu/lbm fuel}
\]

At 100,000 ft and \(M = 8\)

\[
T_1 = 420.1^\circ R
\]

\[
P_1 = 22.32 \text{ lb/ft}^2
\]

\[
\rho_1 = 0.00996 \text{ lbm/ft}^3
\]

\[
V_1 = 8050.96 \text{ ft/sec}
\]

\[
I_f = \frac{0.412(1889.4)(778)}{8051}
\]

\[
I_f = 752.23 \text{ sec}
\]

Assume:

L/D = 6

L = 450,000 lb

D = F_g = 75000 lb

Therefore:

\[
W_f = \frac{0.95(75000)}{752.23}
\]

\[
W_f = 94.72 \text{ lbm/sec fuel}
\]

To Calculate the stoichiometric fuel-air ratio \((F/A)\) assume the fuel is MCH converted to \(H_2\) and \(C_7H_8\):

\[
0.75 H_2 + 0.25 C_7H_8 + 2.625 O_2 + 2.625(3.76)N_2 \rightarrow
\]

\[
1.75 H_2O + 1.75 O_2 + 9.87 N_2
\]

The average molecular weight of the fuel: 25.25
\[ F/A = \frac{(1 \text{ mole of fuel})(25.25 \text{ lbm molecular weight})}{(9.81 + 2.025 \text{ moles air})(25.95 \text{ lbm molecular weight})} \]

\[ F/A = .0698 \text{ Assuming E.R.} = 1.0 \]

\[ A_1 = \frac{94.72}{(.0698)(.000996)(5051)} \]

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

Station 3.

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

\[ n_d = 1 - \frac{(\frac{P_{t_1}}{P_{t_2}})^{7/2}}{(\frac{P_{t_1}}{P_{t_2}})^{7/2} - 1} \]

Assume: \( n_d = .959 \)

\[ \frac{7}{2} - 1 = 1.4 - 1 = .286 \]

\[ \frac{(P_{t_1}/P_{t_2})^{2/3}}{(1.4 - 1/2)(8)} = 1 - .959 \]

\[ (P_{t_1}/P_{t_2})^{2/3} = 1.5248 \]

\[ (P_{t_1}/P_{t_2}) = 4.36 \]

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

\[ P_{t_2}/P_{t_1} = .000102 \]

\[ P_{t_1} = \frac{22.72 \text{ lb/ft}^2}{(.000102)(144 \text{ in}^2/\text{ft}^2)} \]

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

-299-
\[ P_{l3} = \frac{1512 \text{ lb/in}^2}{4.30} \]
\[ P_{l3} = 348 \text{ lb/in}^2 \]

Assume:
\[ M_3 = 2.5 \]

From the isentropic flow tables at \( M = 2.5 \)
\[ P_3/P_{l3} = 0.05853 \]

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

Assume the enthalpy at 1 and 3 are equal:

\[ h_3 = h_{l3} = h_3 + \frac{(M_3 h_{2.1})\sqrt{T_3}}{2} \]

\[ h_3 = 100.32 + \frac{(8)(49.1)\sqrt{20.1}}{(2)(32.2)(773)} \]
\[ h_3 = 1394 \text{ Btu/lbm} \]

By trial and error \[ T_3 = 2500^\circ\text{R} \]

\[ h_3 = 732.33 + \frac{(2.5 h_{2.1})\sqrt{2500}}{(2)(32.2)(773)} \]
\[ h_3 = 1395 \text{ close enough} \]

\[ T_3 = \frac{(20.4)(144)}{(55.34)(2500)} \]
\[ T_3 = 0.0220 \text{ lbm/ft}^3 \]

Station 5.

By an iterative procedure calculate the heat transfer from the combustion area assuming 2000°R 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:

\[ A_3 = \frac{\rho_1 A_1 V_1}{\rho_3 V_3} = \frac{(2.5)(49.1)\sqrt{2500}}{6140} \]

\[ V_3 = 6140 \]

\[ A_3 = \frac{2.5}{6140} \cdot \frac{49.1}{\sqrt{2500}} \]

\[ A_3 = 0.00096 \cdot \frac{169}{0.0225} \cdot \frac{1}{6140} \]

\[ A_3 = 10.0 \]

10.0 = \pi r_1^2 - \pi r_3^2 = 169 - \pi r_3^2

\[ r_3 = 7.11 \text{ ft} \]

Hydraulic Diameter \( D_h \)

\[ D_h = \frac{4A_3}{\pi V_3} = \frac{4(10.0)}{\pi(2x(7.11) + 2x(7.26))} \]

\[ D_h = 0.654 \]

Assume time for combustion and mixing can be accomplished in 2 \( \mu \text{sec} = 0.002 \text{ sec} \) 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

\[ (h_{p'} - h_{p0'}) - (h_{R'} - h_{R0'}) = q = -h_{RP0} \]

where:

- \( h_{R'} \) = enthalpy of the reactants
- \( h_{p'} \) = enthalpy of the products
- \( h_{RP0} \) = heat of combustion
- \( q \) = heat transferred per lbm fuel

Heat of combustion calculation:

\[ h_{RP0} = m_{C_7H_8}(h_{RP0}C_7H_8) + m_{H_2}(h_{RP0}H_2) \]

\[ m_{C_7H_8} = 0.938 \text{ lbm } C_7H_8/\text{lbm fuel} \]

\[ m_{H_2} = 0.062 \text{ lbm } H_2/\text{lbm fuel} \]
The products:

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

\[
\begin{align*}
\text{Constituent} & \quad \text{F} & \quad \text{F} & \quad \text{mB} & \quad \text{mB} & \quad \text{mB} & \quad \text{mB} \\
\text{CO}_2 & \quad 1.75 & \quad 40.39 & \quad 4203.7 & \quad 76102 & \quad 54000 & \quad 104848 & \quad 69174 & \quad 113481 \\
\text{H}_2\text{O} & \quad 1.75 & \quad 4258 & \quad 4048.9 & \quad 63404 & \quad 53327 & \quad 85871 & \quad 58339 & \quad 94991 \\
\text{N}_2 & \quad 9.87 & \quad 3730 & \quad 3229.9 & \quad 272406 & \quad 40680 & \quad 358773 & \quad 34336 & \quad 291598 \\
\end{align*}
\]

\[
\left(\text{hp}' - \text{hP}_0'\right)_t = \frac{\text{mB}}{M_c} = \text{num
}
\]

\[
-22
\]
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, $hRt$, 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 $hRt$ vs $x$ calculate heat transferred;

$$q = -\int_{x=0}^{x=L} hRdt$$

6. From $q$ and $(h' - h_0')_P$, $(h' - h_0')_T$ and $h_{R0}$ calculate temperature at Station 5.

7. Return to 2 until temperature used to calculate values and calculated temperature are equal.

Example:
Station 3:

- $M = 2.5$
- $P = 20.1$
- $T = 2500^\circ R$
- $(P/P_0) = .24616$
- $(T/T_0) = .3787$
- Assume $T_0 = 5637.5^\circ R$
\[(T/T_{e})_g = (T/T_{e})_3 \frac{T_3/T_3}{(1/T_{23})} \]

\[(T/T_{e})_s = .85k_0\]

From Rayleigh Line:

\[M_s = 1.31\]

\[(P/P_e)_s = .70535\]

\[P_s = (P/P_e)_s/(P/P_e)_3 \]

\[P_3 = 58.45 \text{ lb/in}^2\]

---

<table>
<thead>
<tr>
<th>(x)</th>
<th>(P)</th>
<th>(T)</th>
<th>(\rho)</th>
<th>(V)</th>
<th>(u)</th>
<th>(Re)</th>
<th>(N_{1/1})</th>
<th>(M)</th>
<th>(c)</th>
<th>(N_{1/2})</th>
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<td>1110</td>
<td>1.31</td>
<td>.89</td>
<td>987.9</td>
<td>.079</td>
</tr>
</tbody>
</table>

* Extrapolated (based on air at low pressures)*

---

\[\frac{\rho}{RT} \quad \text{where } R = 53.54\]

\[V = \frac{c_1}{\sqrt{T_1}} = 135.2/c\]

\[Re = \frac{V D_h c}{\mu}\]

\[N_{1/1} = f(Re, Pr) \quad \text{from Kays}^{14}\]

expression for turbulent flow inside

concentric annuli at \(r_1/r_0 = 1.0\) (See Figure 73)

\[M = \frac{V}{(0.91\sqrt{T})}\]

\[C = \text{From Kays page 13.38 for affect of high velocity on Stanton No.}\]
\[ h = \frac{\text{h}_{\text{in}}}{\ln\frac{T_{\text{aw}}}{T}} \]

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

where \( \gamma = 1.4 \)

\[ \Delta t = (T_{\text{aw}} - T) = (T_{\text{aw}} - 2000) \]

\[ P = 2 \pi r_1 + 2 \pi r_0 = 90.5 \text{ ft} \]

Then:
\[ q' = -\int_{x=0}^{x=L} (hP_0) \, dx \]

This is expression is integrated graphically from Figure 76.

\[ q' = -5.575 \times 10^2 \text{ Btu/hr} \]

\[ m_{\text{air}} = \rho_1 A_1 V_1 = 4.879 \times 10^8 \text{ lbm/hr} \]

\[ q = -\frac{5.575 \times 10^2}{4.879 \times 10^8} \]

\[ q = -1.1426 \times 10^2 \text{ Btu/1bm air} \]

\[ q' = -\frac{1.1426 \times 10^2}{0.0698} \]

\[ q' = -1637 \text{ Btu/1bm fuel} \]

Now to calculate the combustion temperature:

\[ (h' - h_0')_p = (h' - h_0')_R = q' = -hR_0 \]

\[ (h' - h_0')_p = 8043.8 + 1637 = -19708.5 \]

\[ (h' - h_0')_p = 26115.3 \text{ Btu/1bm fuel} \]

From curve in Figure 75 this gives a temperature:

\[ T_s = 5900^\circ R \]

which does not agree with assumed temp., we re-calculate.

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:

\[ T_s = 5791^\circ R \]

\[ q' = 1727 \text{ Btu/1bm fuel} \]
Then \((T/T_0)_s = (0.5787)^{(5791)} (2500)\)

\((T/T_0)_s = 0.877\) from Rayleigh line we get

\[
M_s = 1.265
\]

\((P/P_0)_s = 0.740\)

\[
P_s = \frac{(0.740)}{(240)} (20.4)
\]

\[
P_s = 61.3 \text{ lb/in}^2
\]

**Station 6.**

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

\[
(A/A_s)_s = (A/A_s)_0 \frac{A_s}{A_0} = \frac{(1.052)(313.58)}{10.0}
\]

\((A/A_s)_e = 32.89\)

\[
M_e = 5.28
\]

\((P/P_0)_e = 0.001538\)

\[
P_e = \frac{(0.001538)(61.3)}{377}
\]

\[
P_e = 0.250 \text{ lb/in}^2
\]

\[
T_e = \frac{(T/T_0)_s T_s}{(T/T_0)_s}
\]

\[
T_e = \frac{(1.5415)(5791)}{798}
\]

\[
T_e = 1177.88^\circ R
\]

\[
V = (5.28)(49.1)\sqrt{1177.88}
\]

\[
V_e = 8897.48 \text{ ft/sec}
\]
\[
\rho e = \frac{96.05}{(53.54)(1177.88)}
\]
\[
\rho e = .000574 \text{ lbm/ft}^3
\]

Calculate Thrust, Specific Impulse, and Overall Efficiency:

\[
\text{Thrust} = Fg = f_e - f_1 = P_1(A_e - A_1)
\]
\[
f_e = A_e \left( P_e + \frac{n_0 e V_e^2}{c} \right)
\]
\[
f_1 = A_1 \left( P_e + \frac{e V_e^2}{c} \right)
\]

\[n_0 = .95\]
\[f_1 = 169 \left( 72.32 + \frac{(-.000996)(8051)^2}{32.2} \right)\]
\[f_e = 342644.1 \text{ lb}\]
\[f_e = 313.58 \left( 36.05 + .95(-.000574)(8897.48)^2 \right)\]
\[f_e = 431703.9 \text{ lb}\]
\[Fg = 431703.9 - 342644.1 - 22.32(313.58 - 169.0)\]
\[Fg = 85833.22 \text{ lb}\]

Specific Impulse:
\[I_f = \frac{n_0(Fg)}{W_f}\]
\[W_f = f_0 V_1 A_1 = (.0698)(.000996)(169.0)(8051)\]
\[W_f = 94.6 \text{ lbm/sec fuel}\]
\[I_f = \frac{(95)(85833.22)}{94.6}\]
\[I_f = 861.96 \text{ sec}\]

Overall Efficiency:
\[n_e = \frac{I_f V_\frac{1}{2}}{H_f + V_\frac{1}{2}^2/2g_0}\]
Estimate of Heat Transfer From Nozzle:

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

\[ r_e = \frac{(861.26(8050.65))}{(19708.5 + (8500.65)^2)} \]

\[ r_e = 9.75 \]

Flow Area:

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

\[ \tan e_2 = \frac{2.47}{40} = 0.06175 \]

\[ \tan e_1 = \frac{7.11}{30.0} = 0.237 \]

\[ e_2 = 3.1^\circ \]

From \( x = 0 \) to \( x = 10 \) where \( r_t = r_e - x \tan e_2 = 9.75 - x (0.06175) \)

From \( x = 10 \) to \( x = 40 \) \( A_x = \frac{x r_e^2 - x r_b^2}{A_t - A_b} \)

\( r_b = (x - 10) \tan e_1 = \frac{(x - 10).237}{(x - 10)} \)

\( x' = 40 - x \)

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<tr>
<th>( x' )</th>
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<th>( r_t )</th>
<th>( A_t )</th>
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<td>6.64</td>
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<td>33.9</td>
</tr>
<tr>
<td>1</td>
<td>39</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:

\[(A/A_0)_x = \frac{(A/A_0)_x A_x}{A_0} = \frac{1.1}{10} \times 3 = 0.10967 \text{ ft}^2\]

This yields a Mach Number from Isentropic Flow Tables.

\[T_x = \frac{(T/T_0)_x}{(T/T_0)_0} = 5.465 \times 0.328 = 7527.5 \text{ (T/T_0)_x} \text{ (°R)}\]

\[P_x = \frac{(P/P_0)_x}{(P/P_0)_0} = 5.465 \times 0.328 = 167 \text{ (P/P_0)_x} \text{ (lb/ft}^2\text{)}\]

\[V_x = M_x \sqrt{\frac{T_x}{P_x}} \text{ (ft/sec)}\]

\[\rho_x = \frac{P_x}{V_x^2} \text{ (lbm/ft}^3\text{)}\]

<table>
<thead>
<tr>
<th>(x)</th>
<th>((A/A_0)_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>4.75</td>
<td>3525</td>
<td>6851</td>
<td>.00948</td>
<td>4.4 \times 10^{-5}</td>
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<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>3.95</td>
</tr>
<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>
</tr>
<tr>
<td>4</td>
<td>6.44</td>
<td>3.45</td>
<td>.014</td>
<td>2.54</td>
<td>.290</td>
<td>2150</td>
<td>7855</td>
<td>.00294</td>
<td>3.47</td>
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<tr>
<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>
</tr>
<tr>
<td>10</td>
<td>13.74</td>
<td>4.28</td>
<td>.0050</td>
<td>.836</td>
<td>.220</td>
<td>1656</td>
<td>8552</td>
<td>.00136</td>
<td>3.07</td>
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<tr>
<td>20</td>
<td>23.05</td>
<td>4.90</td>
<td>.00213</td>
<td>.356</td>
<td>.172</td>
<td>1291</td>
<td>8654</td>
<td>.00074</td>
<td>2.75</td>
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<tr>
<td>30</td>
<td>28.73</td>
<td>5.10</td>
<td>.00165</td>
<td>.276</td>
<td>.160</td>
<td>1200</td>
<td>8674</td>
<td>.00062</td>
<td>2.66</td>
</tr>
<tr>
<td>40</td>
<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.

\[\text{Nu}_x = c(0.332(Pr)^{1/3}(Re_x)^{1/2}) = c\mu_x\]

\[\text{Re}_x = \frac{\rho x V}{\mu} \quad c = \text{correction constant for high speed flow (Kays,}^{14}\text{) p. 13.28}\]

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

<table>
<thead>
<tr>
<th>(x)</th>
<th>(Re)</th>
<th>(Re^{1/2})</th>
<th>(Pr)</th>
<th>(Pr^{1/3})</th>
<th>(\text{Nu}_x)</th>
<th>(c)</th>
<th>(\mu_x)</th>
<th>(k)</th>
<th>(h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.475 \times 10^8</td>
<td>1.214 \times 10^3</td>
<td>.83</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>2.54</td>
<td>1.530</td>
<td>.74</td>
<td>.90</td>
<td>456.2</td>
<td>.62</td>
<td>285</td>
<td>.054</td>
<td>8.8</td>
</tr>
</tbody>
</table>

(Continued)
<table>
<thead>
<tr>
<th>x'</th>
<th>Re</th>
<th>Re^{1/2}</th>
<th>Pr</th>
<th>Pr^{1/3}</th>
<th>Nu'</th>
<th>c</th>
<th>Nu'x</th>
<th>k</th>
<th>h</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.66</td>
<td>1.63</td>
<td>.73</td>
<td>.90</td>
<td>487.0</td>
<td>.55</td>
<td>268</td>
<td>.05</td>
<td>3.4</td>
</tr>
<tr>
<td>5</td>
<td>2.82</td>
<td>1.68</td>
<td>.73</td>
<td>.90</td>
<td>502.0</td>
<td>.54</td>
<td>271</td>
<td>.04</td>
<td>2.7</td>
</tr>
<tr>
<td>10</td>
<td>3.79</td>
<td>1.946</td>
<td>.71</td>
<td>.89</td>
<td>575.0</td>
<td>.45</td>
<td>259</td>
<td>.04</td>
<td>1.1</td>
</tr>
<tr>
<td>20</td>
<td>4.66</td>
<td>2.16</td>
<td>.70</td>
<td>.89</td>
<td>638.2</td>
<td>.38</td>
<td>243</td>
<td>.03</td>
<td>.46</td>
</tr>
<tr>
<td>30</td>
<td>6.06</td>
<td>2.46</td>
<td>.70</td>
<td>.89</td>
<td>726.9</td>
<td>.37</td>
<td>269</td>
<td>.03</td>
<td>.33</td>
</tr>
<tr>
<td>40</td>
<td>8.06</td>
<td>2.84</td>
<td>.696</td>
<td>.89</td>
<td>836.2</td>
<td>.36</td>
<td>302</td>
<td>.03</td>
<td>.27</td>
</tr>
</tbody>
</table>

\[ T_{AW} = T_x \left(1 + \frac{rc}{2}(y - 1)h^2\right) \]

\[ \gamma = 1.4 \]

\[ r_e = Pr^{1/3} \]

\[ \Delta t = T_{AW} - T_W = (T_{AW} - 2000^\circ R) \]

\[ P = 2\pi r_t + 2\pi r_D \]

<table>
<thead>
<tr>
<th>x'</th>
<th>T_{AW}</th>
<th>\Delta t</th>
<th>P</th>
<th>h\Delta t</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7184.8</td>
<td>5184.8</td>
<td>89.3</td>
<td>7.96 x 10^6</td>
</tr>
<tr>
<td>2</td>
<td>6959.6</td>
<td>4959.6</td>
<td>88.2</td>
<td>3.46</td>
</tr>
<tr>
<td>3</td>
<td>6909.0</td>
<td>4909.0</td>
<td>87.1</td>
<td>2.05</td>
</tr>
<tr>
<td>4</td>
<td>6756.3</td>
<td>4756.3</td>
<td>86.0</td>
<td>1.39</td>
</tr>
<tr>
<td>5</td>
<td>6983.1</td>
<td>4983.1</td>
<td>84.9</td>
<td>1.14</td>
</tr>
<tr>
<td>10</td>
<td>7116.3</td>
<td>5116.3</td>
<td>79.4</td>
<td>4.47</td>
</tr>
<tr>
<td>20</td>
<td>6886.4</td>
<td>4886.4</td>
<td>68.4</td>
<td>.158</td>
</tr>
<tr>
<td>30</td>
<td>6618.2</td>
<td>4618.2</td>
<td>57.4</td>
<td>.091</td>
</tr>
<tr>
<td>40</td>
<td>6981.0</td>
<td>4981.0</td>
<td>61.3</td>
<td>.082</td>
</tr>
</tbody>
</table>

Then:

\[ q_N = \int_{x'=0}^{x'=40} (h\Delta t)x'dx' \]

Integrating graphically from curve of \( x' \) vs \( h\Delta t \) in Figure 76 we get,

\[ q_N = 47.8 \times 10^6 \text{ Btu/hr} \]

\[ q_N = 47.8 \times 10^6 \text{ Btu/hr} \]

\[ 4.879 \times 10^8 \text{ lbm air/hr} \]

-300-
q'\(_N\) = 9.797 Btu/lbm air

q'\(_N\) = \frac{9.797}{0.0698} \text{ lbm fuel/lbm air}

q'\(_N\) = 140.4 Btu/lbm fuel

q'\(_T\) = q'\(_N\) + q'\(_c\)

q'\(_T\) = 1867.4 Btu/lbm fuel
Figure 72. ENTHALPY OF PRODUCTS OF COMBUSTION

\[ \frac{n(\text{moles})}{\text{Btu/lbm fuel}} \]

- \( \text{CO}_2 \): 1.75
- \( \text{H}_2\text{O} \): 1.75
- \( \text{N}_2 \): 9.87
Figure 73: Turbulent Annular Flow
From Kay, Table 9-1
### Table III. UNSTABILIZATION OF BENZENED ANISOLE IN \( \text{HNO}_3 \) SOLUTION

**Temperature:** 1 atm  
**Catalyst Volume:** 7 ml  
**Blank Temperature:** 290°F  
**Reaction Time:** 30 Minutes

<table>
<thead>
<tr>
<th>Run Number</th>
<th>5</th>
<th>10</th>
<th>20</th>
<th>30</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>5</td>
<td>15</td>
<td>30</td>
<td>50</td>
</tr>
</tbody>
</table>

**Catalyst Used**

<table>
<thead>
<tr>
<th>Product</th>
<th>5%</th>
<th>10%</th>
<th>20%</th>
<th>30%</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Catalyst</strong></td>
<td>685-60</td>
<td>682-77</td>
<td>622-35</td>
<td></td>
</tr>
<tr>
<td><strong>Profile, °F</strong></td>
<td>660-75</td>
<td>540-70</td>
<td>580-76</td>
<td></td>
</tr>
<tr>
<td><strong>Reactor Exit Temperature, °F</strong></td>
<td>825-25</td>
<td>693-41</td>
<td>513-55</td>
<td></td>
</tr>
<tr>
<td><strong>Catalyst</strong></td>
<td>735-33</td>
<td>772-66</td>
<td>694-77</td>
<td></td>
</tr>
<tr>
<td><strong>Product Analysis, %</strong></td>
<td>708-35</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Unidentified</strong></td>
<td>74-59</td>
<td>750-94</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Product Analysis</strong></td>
<td>82-42</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Unidentified</strong></td>
<td>74-59</td>
<td>750-94</td>
<td></td>
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<tr>
<td><strong>Product Analysis</strong></td>
<td>82-42</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Notes:**

- a) Unidentified; emerged after 10 minutes.
- b) Unidentified; emerged after 20 minutes.
- c) Unidentified; emerged after 30 minutes.
- d) Catalyst almost completely deactivated after 10 minutes.
### Table 120: CONTRIBUTION OF WET OXIDE CAT.

Pressure: 1 atm  
Catalyst Volume: 7 ml  
Blank Temperature: 882°F  
Reaction Time: 30 Minutes  
Catalyst No.: 10280-45  

<table>
<thead>
<tr>
<th>Time (min):</th>
<th>5</th>
<th>15</th>
<th>30</th>
<th>50</th>
<th>80(*)</th>
<th>100(*)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHSV</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Catalyst Bed</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Profiles, 'F</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>750-250</td>
<td>671-67</td>
<td>645-62</td>
<td>610</td>
<td>620-30</td>
<td>685-42</td>
<td></td>
</tr>
<tr>
<td>725-325</td>
<td>635-28</td>
<td>610</td>
<td>603</td>
<td>663-15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>850-325</td>
<td>581-48</td>
<td>617</td>
<td>603</td>
<td>663-15</td>
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<td></td>
</tr>
<tr>
<td>Reactor Wall Temperature, 'F</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>890</td>
<td>774-70</td>
<td>725-20</td>
<td>705</td>
<td>698</td>
<td>573-31</td>
<td></td>
</tr>
<tr>
<td>H max</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0(*)</td>
<td>7(*)</td>
</tr>
<tr>
<td>Product Analysis, %</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Benzenes</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>
</tr>
<tr>
<td>Methanes</td>
<td>1.1</td>
<td>0.5</td>
<td>19.3</td>
<td>41.3</td>
<td>34.6</td>
<td>52.3</td>
</tr>
<tr>
<td>Toluene</td>
<td>89.0</td>
<td>98.6</td>
<td>80.6</td>
<td>58.1</td>
<td>45.4</td>
<td>59.5</td>
</tr>
<tr>
<td>PCH Conversion, %</td>
<td>98.9</td>
<td>99.5</td>
<td>88.7</td>
<td>58.8</td>
<td>47.7</td>
<td>41.3</td>
</tr>
</tbody>
</table>

(*) Back pressure was about 15 psi during this run.
Table 12.1: CATALYSIS OF MCH OVER 5% Pt-Mn

<table>
<thead>
<tr>
<th>Run Number</th>
<th>Unit</th>
<th>5</th>
<th>15</th>
<th>30</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHSV</td>
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<td>7.5</td>
<td>7.5</td>
<td>7.5</td>
</tr>
<tr>
<td>Catalyst Bed</td>
<td></td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Profile, °F</td>
<td></td>
<td>778-78</td>
<td>779-80</td>
<td>780-81</td>
</tr>
<tr>
<td>Reactor Wall Temperature, °F</td>
<td></td>
<td>615-62</td>
<td>775</td>
<td>785-85</td>
</tr>
<tr>
<td>AX max, %</td>
<td></td>
<td>8</td>
<td>2</td>
<td>180</td>
</tr>
<tr>
<td>Product Analysis, %</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Benzena</td>
<td></td>
<td>3.5</td>
<td>0.5</td>
<td>0.0</td>
</tr>
<tr>
<td>u(b)</td>
<td></td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
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<td>MCH</td>
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<td>1.3</td>
<td>6.1</td>
<td>34.7</td>
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<tr>
<td>u(c)</td>
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<td>0.0</td>
<td>0.0</td>
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<tr>
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<td>95.5</td>
<td>12.5</td>
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<tr>
<td>u(d)</td>
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<tr>
<td>MCH Conversion, %</td>
<td></td>
<td>98.1</td>
<td>95.9</td>
<td>15.3</td>
</tr>
</tbody>
</table>

- a) Unidentified; carried after benzene.
- b) Unidentified; emerged after MCH.
- c) Unidentified; emerged after toluene.
- d) AX max = 160 after 17 minutes; catalyst completely deactivated at end of run.
Table 22: DECOMPOSITION OF THE NH-FERREDOX CATALYST

<table>
<thead>
<tr>
<th>Run Number</th>
<th>11-22</th>
<th>12-22</th>
<th>13-22</th>
<th>14-22</th>
</tr>
</thead>
<tbody>
<tr>
<td>Catalyst Bed</td>
<td>779</td>
<td>724-16</td>
<td>725-76</td>
<td>813-57</td>
</tr>
<tr>
<td>Profile, °F</td>
<td>778</td>
<td>749</td>
<td>725-68</td>
<td>797-813</td>
</tr>
<tr>
<td></td>
<td>890</td>
<td>785</td>
<td>734-54</td>
<td>769-833</td>
</tr>
<tr>
<td></td>
<td>837-35</td>
<td>738-36</td>
<td>748-69</td>
<td>777-830</td>
</tr>
<tr>
<td>Reactor Wall Temperature, °F</td>
<td>826</td>
<td>732</td>
<td>793-97</td>
<td>815-96</td>
</tr>
<tr>
<td>C% wax</td>
<td>0</td>
<td>2</td>
<td>50</td>
<td>52b)</td>
</tr>
<tr>
<td>Product Analysis, %</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Benzene</td>
<td>1.7</td>
<td>0.4</td>
<td>0.2</td>
<td>0.1</td>
</tr>
<tr>
<td>MIB</td>
<td>1.7</td>
<td>19.9</td>
<td>62.8</td>
<td>35.2</td>
</tr>
<tr>
<td>Toluene</td>
<td>97.2</td>
<td>73.7</td>
<td>37.0</td>
<td>5.6</td>
</tr>
<tr>
<td>Ua)</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>1.2</td>
</tr>
<tr>
<td>MIB Conversion, %</td>
<td>99.9</td>
<td>80.1</td>
<td>37.2</td>
<td>6.3</td>
</tr>
</tbody>
</table>

a) Unidentified; recovered after toluene.
b) Catalyst almost completely deactivated at end of run.
### Table 12A. DEHYDROGENATION OF MEH OVER SHELL 108

<table>
<thead>
<tr>
<th>Run Number, 11018-</th>
<th>50-1</th>
<th>50-2</th>
<th>50-3</th>
<th>50-4</th>
<th>50-5</th>
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<tr>
<td>Catalyst Bed</td>
<td>5</td>
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<td>30</td>
<td>50</td>
<td>80</td>
<td>100</td>
</tr>
<tr>
<td>Profile, °F</td>
<td>873-72</td>
<td>874-63</td>
<td>855-35</td>
<td>842-53</td>
<td>869-75</td>
<td>887-94</td>
</tr>
<tr>
<td>Reactor Wall Temp., °F</td>
<td>826-77</td>
<td>761</td>
<td>727-25</td>
<td>715-16</td>
<td>716</td>
<td>725-29</td>
</tr>
<tr>
<td>Of max</td>
<td>0</td>
<td>0</td>
<td>4</td>
<td>11</td>
<td>6</td>
<td>7</td>
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<td>Product Analysis, %</td>
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<td></td>
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<td>50.8</td>
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<td>68.3</td>
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<td>94.9</td>
<td>69.5</td>
<td>69.2</td>
<td>35.7</td>
<td>37.7</td>
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<td>98.6</td>
<td>95.1</td>
<td>69.6</td>
<td>69.5</td>
<td>56.9</td>
<td>3.9</td>
</tr>
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</table>
Table 124: \textit{INFORMATION OF MTH \& 3MT REACTIONS}

Pressure: 1 atm  \quad \text{Catalyst Volume: 7 ml}
Block Temperature: 840°F  \quad \text{Reaction Time: 90 Minutes}

<table>
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<tr>
<th>Run Number: 124</th>
<th>124-1</th>
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<th>124-3</th>
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<th>124-5</th>
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<td>669-85</td>
<td>657-71</td>
<td>700-75</td>
<td>800-75</td>
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<tr>
<td>\text{Profile, °F}</td>
<td>806-62</td>
<td>691-87</td>
<td>691-84</td>
<td>642-75</td>
<td>620-75</td>
</tr>
<tr>
<td>\text{Reactor Wall Temperature, °F}</td>
<td>606-72</td>
<td>729-73</td>
<td>693-55</td>
<td>644-71</td>
<td>560-55</td>
</tr>
<tr>
<td>( \Delta T \text{ max} )</td>
<td>325-20</td>
<td>763-61</td>
<td>727-29</td>
<td>725-28</td>
<td>824-35</td>
</tr>
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<td>\text{Product Analysis, %}</td>
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<td></td>
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<td></td>
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<tr>
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<td>97.5</td>
<td>85.7</td>
<td>1.6</td>
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<td>97.3</td>
<td>92.5</td>
<td>45.9</td>
<td>5.1(4)</td>
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</tbody>
</table>

\text{a) \text{Identified; emerged after Benzene.}}
\text{b) \text{Identified; emerged after MTH.}}
\text{c) \text{Identified; emerged after Toluene.}}
\text{d) \text{Catalyst almost completely deactivated at end of run.}}
<table>
<thead>
<tr>
<th>Run No.</th>
<th>85-1</th>
<th>85-2</th>
<th>86-1</th>
<th>86-2</th>
<th>87-1</th>
<th>87-2</th>
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<td>30</td>
<td>50</td>
<td>80</td>
<td>100</td>
</tr>
<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>646-57</td>
<td>640-657</td>
<td>673-761</td>
<td>734-822</td>
</tr>
<tr>
<td></td>
<td>831-29</td>
<td>752-50</td>
<td>668-67</td>
<td>644-51</td>
<td>550-89</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>688-66a</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>862-28</td>
</tr>
<tr>
<td>ΔT_{max}, °F</td>
<td>-4</td>
<td>-5</td>
<td>11</td>
<td>43</td>
<td>86a</td>
<td>31a</td>
</tr>
<tr>
<td>Product Analysis, %</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
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<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>MCH</td>
<td>7.4</td>
<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>
<td>Toluene</td>
<td>92.4</td>
<td>95.2</td>
<td>66.8</td>
<td>45.1</td>
<td>29.0</td>
<td>18.0</td>
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<tr>
<td>Othersb)</td>
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<td>0.0</td>
<td>0.0</td>
<td>0.1</td>
<td>0.5</td>
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<tr>
<td>MCH Conversion, %</td>
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<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. 1325-</th>
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<th>82-1</th>
<th>82-2</th>
<th>83-1</th>
<th>83-2</th>
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</thead>
<tbody>
<tr>
<td>LHSV</td>
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<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>Reactor Wall Temp, °F</td>
<td>831-28</td>
<td>781-76</td>
<td>750-52</td>
<td>747-61</td>
<td>770-810</td>
<td>817-831</td>
</tr>
<tr>
<td>Λmax, °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, 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>0.3</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
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<td>12.8</td>
<td>44.5</td>
<td>63.7</td>
<td>82.4</td>
<td>92.5</td>
</tr>
<tr>
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<td>95.7</td>
<td>86.9</td>
<td>55.2</td>
<td>35.8</td>
<td>16.7</td>
<td>4.9</td>
</tr>
<tr>
<td>Othersa)</td>
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<td>0.0</td>
<td>0.2</td>
<td>0.4</td>
<td>0.8</td>
<td>2.5</td>
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<tr>
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<td>87.2</td>
<td>55.5</td>
<td>36.3</td>
<td>17.6</td>
<td>7.5</td>
</tr>
<tr>
<td>Selectivity for Toluene, w</td>
<td>97.9</td>
<td>99.7</td>
<td>99.4</td>
<td>99.4</td>
<td>94.5</td>
<td>65.3</td>
</tr>
</tbody>
</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

| Pressure: 1 atm |
| Block Temperature: 842°F |
| Catalyst Volume: 7 ml |
| Reaction Time: 30 minutes |

<table>
<thead>
<tr>
<th>Run No. 11325-</th>
<th>74-1</th>
<th>74-2</th>
<th>75-1</th>
<th>75-2</th>
<th>76-1</th>
<th>76-2</th>
</tr>
</thead>
<tbody>
<tr>
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<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></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>759-61</td>
<td>640-35</td>
<td>619</td>
<td>621-26</td>
<td>635-37</td>
<td>644-50</td>
<td></td>
</tr>
<tr>
<td>815</td>
<td>689-82</td>
<td>632-30</td>
<td>621</td>
<td>619-21</td>
<td>621-23</td>
<td></td>
</tr>
<tr>
<td>833</td>
<td>750-43</td>
<td>660-57</td>
<td>635</td>
<td>626</td>
<td>626</td>
<td></td>
</tr>
<tr>
<td>837-35</td>
<td>792-84</td>
<td>691-89</td>
<td>698</td>
<td>644</td>
<td>657-35</td>
<td></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>ΔTmax, °F</td>
<td>-2</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></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Benzene</td>
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<td>0.1</td>
<td>0.0</td>
<td>0.0</td>
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<td>1.7</td>
<td>26.8</td>
<td>47.2</td>
<td>59.6</td>
<td>65.0</td>
</tr>
<tr>
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<td>73.1</td>
<td>52.8</td>
<td>40.4</td>
<td>35.0</td>
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<td>98.3</td>
<td>73.2</td>
<td>52.8</td>
<td>40.4</td>
<td>35.0</td>
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</table>
Table 172. DEHYDROGENATION OF MCP OVER 10589-1148 CATALYST

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<th>72-1</th>
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<td>60</td>
<td>100</td>
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<td>671.80</td>
<td>689.27</td>
<td>727.48</td>
<td>781.806</td>
</tr>
<tr>
<td>Profile, °F</td>
<td>818.64</td>
<td>713.07</td>
<td>676.6</td>
<td>653.82</td>
<td>687.759</td>
<td>723.63</td>
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<td>811.5-29</td>
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<td>681.26</td>
<td>656.87</td>
<td>687.714</td>
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<td></td>
<td>835.3</td>
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<td>27.23</td>
<td>705.72</td>
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<td>705.72</td>
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<tr>
<td>ΔTmax, °F</td>
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<td>+9</td>
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<td>41</td>
<td>40a</td>
</tr>
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<td>0.1</td>
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<td>0.1</td>
</tr>
<tr>
<td>Benzene</td>
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<td>37.8</td>
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</table>

MCH Conversion, %

a) Cold spot moved down the catalyst bed.
Table 129. DEHYDROGENATION OF MCH OVER 10660-115A AND HODAY 200 SR CATALYSTS

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<th>89-2</th>
<th>78-1</th>
<th>78-2</th>
<th>79</th>
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<tbody>
<tr>
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<td>5</td>
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<td>5</td>
<td>15</td>
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</tr>
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<td>LHSV</td>
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</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>801-759</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>824-17</td>
<td>761-58</td>
<td>774-826</td>
</tr>
<tr>
<td></td>
<td>833</td>
<td>770-826</td>
<td>831-28</td>
<td>784-779</td>
<td>770-817</td>
</tr>
<tr>
<td>Reactor Wall Temp, °F</td>
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<td>783-838</td>
<td>824-21</td>
<td>788-97</td>
<td>820-837</td>
</tr>
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<td>-2</td>
<td>131</td>
<td>-7</td>
<td>23</td>
<td>b)</td>
</tr>
<tr>
<td>Product Analysis, %</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Benzene</td>
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<td>1.7</td>
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<td>0.1</td>
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<tr>
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<td>4.8</td>
<td>55.6</td>
<td>88.3</td>
</tr>
<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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<td>6.2</td>
<td>0.0</td>
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<td>0.8</td>
</tr>
<tr>
<td>MCH Conversion, %</td>
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<td>40.6</td>
<td>95.2</td>
<td>65.0</td>
<td>11.7</td>
</tr>
<tr>
<td>Selectivity for 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 above that of reactor wall temperature.
Description of the Pulse Reactor

The pulse reactor was a 1/8-in. OD stainless steel tube (No. 304) 9-1/4 in. long and 0.025 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 wall 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 71.

All lines were 1/8-in. OD stainless steel tubing (No. 304). About 28 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 302° to 356°F. The injection port temperature was about 5°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 73 shows the pulse reactor system with the secondary furnace liner in place; Figure 86 shows the GLC analysis system.
Figure 7.1 PULSE REACTOR SCHEMATIC
Figure 72. SECONDARY FURNACE LINER FOR PULSE 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 6", 8", 8", 6" 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 Mehanite liner with a groove down the center to hold the reactor tube. Then 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 Mehanite 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.
Micro Catalyst Test Reactor Data

The micro catalyst test reactor (MCTR) 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 847, 752, and 842°F, at 10 atm pressure without added hydrogen. Figures 67 through 69, 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 150. MCH DEHYDROGENATION WITH VARIOUS CATALYSTS IN MICR: RNS 677-915

**Period:** June-August 1968  
**Condition:** 10 atm pressure; catalysts reduced in H₂ for 20 minutes at 750°F; GLC samples normally taken at 3-, 9-, and 15-minute operation at each block temperature.  
**Catalyst Volume:** 0.9 ml catalyst diluted with 1.1 ml quartz chips; LHSV 100 (catalyst and quartz particles 10-20 mesh unless otherwise noted).

<table>
<thead>
<tr>
<th>No.</th>
<th>Temperature</th>
<th>Product A (%)</th>
<th>Product B (%)</th>
<th>Product C (%)</th>
<th>Product D (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<td>60</td>
<td>30</td>
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<td>0</td>
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<td>600°F</td>
<td>80</td>
<td>10</td>
<td>10</td>
<td>0</td>
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... (additional rows as shown in the image)
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<th>Column 4</th>
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<tr>
<td>Data 57</td>
<td>Data 58</td>
<td>Data 59</td>
<td>Data 60</td>
</tr>
</tbody>
</table>
### Table III: Gel Reactivation Using Various Catalysts in Water

**Period:** September-November 1969

**Conditions:** 10 atm pressure; catalysts refluxed in Hz for 20 minutes at 76°C; A1 samples normally taken at 2, 3, and 4 minute operation at each block temperature.

**Catalyst Volume:** 0.9 ml catalyst diluted with 1.1 ml quartz chips; 12.5 vol.

(Catalyst and quartz 10-30 mesh unless otherwise noted)

<table>
<thead>
<tr>
<th>Period</th>
<th>Conditions</th>
<th>Catalyst Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>September-November 1969</td>
<td>10 atm pressure; catalysts refluxed in Hz for 20 minutes at 76°C</td>
<td>0.9 ml catalyst diluted with 1.1 ml quartz chips; 12.5 vol.</td>
</tr>
</tbody>
</table>
### Table III. CATALYTIC CONVERTER WITH VARIOUS CATALYSTS

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Description</th>
<th>HCP Conversion, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Metal type 1</td>
<td>60</td>
</tr>
<tr>
<td>2</td>
<td>Metal type 2</td>
<td>63</td>
</tr>
<tr>
<td>3</td>
<td>Metal type 3</td>
<td>66</td>
</tr>
<tr>
<td>4</td>
<td>Metal type 4</td>
<td>69</td>
</tr>
</tbody>
</table>

### Conditions:
- **Period:** December, 1968 - February, 1969
- **Conditions:** 10 atm pressure; catalysts reduced in hydrogen at 796°F. CEC samples taken normally at 3-, 6-, and 15-minute operation at each temperature.
- **Volume:** 0.9 ml catalyst diluted with 1.1 ml quartz chips (10-20 mesh). LEY 100 with MCH

### Notes:
1. **HCP:** Hydrocarbon conversion percentage.
2. **Metal Type:** Type of metal used in the catalyst.
3. **Support:** Type of support material used.
4. **Kinds:** Number of kinds of catalyst used in the experiment.
5. **Type:** Type of catalyst used in the experiment.
6. **Type 1:** Type 1 of catalyst used in the experiment.
7. **Type 2:** Type 2 of catalyst used in the experiment.
8. **Type 3:** Type 3 of catalyst used in the experiment.
9. **Type 4:** Type 4 of catalyst used in the experiment.

---

**Legend:**
- **HCP:** Hydrocarbon conversion percentage.
- **Metal Type:** Type of metal used in the catalyst.
- **Support:** Type of support material used.
- **Kinds:** Number of kinds of catalyst used in the experiment.
- **Type:** Type of catalyst used in the experiment.
- **Type 1:** Type 1 of catalyst used in the experiment.
- **Type 2:** Type 2 of catalyst used in the experiment.
- **Type 3:** Type 3 of catalyst used in the experiment.
- **Type 4:** Type 4 of catalyst used in the experiment.
<table>
<thead>
<tr>
<th>Conditions:</th>
<th>Volume:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Press</td>
<td>PC</td>
</tr>
<tr>
<td>70</td>
<td>III</td>
</tr>
</tbody>
</table>

Conditions: PC at pressure; Ajusts: just-in-time; at temperature; 012; 04 stapes; taken; respectively; at a-aw; A4-Mn-ide; operation at 04ct tpra. -v; Child (11,20 meshi). UV; 100; VIA; MCHi.
### Table 11 (Cont'd). \( \frac{\text{MCP}}{\text{Commercial with Various Catalysts}} \)

<table>
<thead>
<tr>
<th>Temperature</th>
<th>( \text{Volatility} )</th>
<th>( \text{Total Reactivity} )</th>
<th>( \text{Density} )</th>
<th>( \text{Flash Point} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>100°C</td>
<td>1.75</td>
<td>11.48</td>
<td>5.11</td>
<td>77.35</td>
</tr>
<tr>
<td>110°C</td>
<td>1.75</td>
<td>11.48</td>
<td>5.11</td>
<td>77.35</td>
</tr>
<tr>
<td>120°C</td>
<td>1.75</td>
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<td>5.11</td>
<td>77.35</td>
</tr>
<tr>
<td>130°C</td>
<td>1.75</td>
<td>11.48</td>
<td>5.11</td>
<td>77.35</td>
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<tr>
<td>140°C</td>
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<td>5.11</td>
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<tr>
<td>150°C</td>
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<td>11.48</td>
<td>5.11</td>
<td>77.35</td>
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<tr>
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<td>5.11</td>
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<tr>
<td>170°C</td>
<td>1.75</td>
<td>11.48</td>
<td>5.11</td>
<td>77.35</td>
</tr>
<tr>
<td>180°C</td>
<td>1.75</td>
<td>11.48</td>
<td>5.11</td>
<td>77.35</td>
</tr>
<tr>
<td>190°C</td>
<td>1.75</td>
<td>11.48</td>
<td>5.11</td>
<td>77.35</td>
</tr>
<tr>
<td>200°C</td>
<td>1.75</td>
<td>11.48</td>
<td>5.11</td>
<td>77.35</td>
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(continued)
<table>
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<tr>
<th>No.</th>
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<th>10% of Reactant, °C</th>
<th>15% of Reactant, °C</th>
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<td>1</td>
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<td>77.2</td>
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<td>73.2</td>
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<td>7</td>
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<td>103.8</td>
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...
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 0.01 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 I

<table>
<thead>
<tr>
<th>Type</th>
<th>Source Radiation</th>
<th>Detected Radiation</th>
<th>Operation</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<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 in coker tube</td>
<td>Possible method. Efficiency very dependent on tube metal.</td>
</tr>
<tr>
<td>3</td>
<td>$\beta$</td>
<td>$\beta$</td>
<td>beta backscatter</td>
<td>Preferred method.</td>
</tr>
<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

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\(^{28}\) as:

\[
\frac{I}{I_0} = \frac{\beta_1}{\mu_1 + \lambda_1} \left[ 1 - e^{-(\mu_1 + \lambda_1)x} \right] + \frac{\beta_2}{\mu_1 + \lambda_2} e^{-(\mu_1 + \lambda_2)x}
\]

(55)

The constants \( \nu, \lambda_1, \) and \( \beta \) 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 (55) in the approximation of small \( x \) can be expressed as:

\[
\frac{I}{I_0} = \left( 1 - e^{-z_2/40} \right) + \frac{35x}{E^{1.14}} \left[ \left( \frac{Z_1}{A_1} \right) \left( \frac{1.15 + z_1}{106 + z_1} \right) \left( 1 - e^{-z_2/40} \right) \right]
\]

(54)

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

\[
\frac{I}{I_0} = 0.28 - \frac{4.4x}{E^{1.14}}
\]

(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 \( 10^{-6} \) 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 \( x = 3.1 \times 10^{-3} \) 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 useable compromise since even \( ^{14}\)C is capable of showing some response to the heavier deposits.
Table I.5: LOW ENERGY BETA SOURCES

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Half Life, Years</th>
<th>E&lt;sub&gt;max&lt;/sub&gt;, Kev</th>
<th>Range in Air, cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>211Po</td>
<td>21</td>
<td>17</td>
<td>0.4</td>
</tr>
<tr>
<td>3H</td>
<td>12</td>
<td>19</td>
<td>0.5</td>
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<tr>
<td>60Ni</td>
<td>85</td>
<td>67</td>
<td>5.5</td>
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<tr>
<td>14C</td>
<td>5700</td>
<td>155</td>
<td>26.0</td>
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</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 60Ni, 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 cathode tube could be attached. This slide fitting allowed translation and rotation of the cathode tube in front of the source and detector for scanning the deposition 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-β-rays. These contribute to the scattered flux which is detected and produce 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 330 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

\[\text{AFAPL-TR-67-114}\]

\[\text{Part III}\]

deposit profile, the present arrangement viewing about 0.2 cm of tube at a time. The second improvement incorporates a collimator over the detector window the purpose of which is to reduce background scatter from the bell jar. This background involves both x-ray and electron scatter and amounts to about 100 c/s in the absence of a sample tube.

Results with a group of coker tubes are given in Figure 84. 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 3 min. The two curves for each sample are scans along opposite sides of the tubes. The horizontal line to the right of each curve is an adjusted rate of 500 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 500 to 200 c/s. Reasonably consistent results were obtained with 1, 2 and 4000A of film.

Applied to the five tubes in Figure 84 this gives the following results as shown in Table 156.

\[
\frac{I}{I_0} = 1 - e^{-Z_2/40} + \frac{35x}{E^{1.74}} \left( \frac{Z_1}{A_1} \right) \left( \frac{Z_1 + Z_2}{100 + Z_1} \right) \left( 1 - e^{-Z_1/40} \right) - \left( \frac{Z_1}{A_1} + \frac{400 Z_1 Z_2}{100 + Z_2} \right) \left( 1 - e^{-Z_2/40} \right)
\]

For aluminum base \(Z_2 = 13\) \(x = \text{film thickness, g/cm}^2\)

\[
\frac{I}{I_0} = 0.2775 + \frac{35x}{E^{1.74}} \left[ \frac{Z_1}{A_1} \left( \frac{Z_1 + Z_2}{100 + Z_1} \right) \left( 1 - e^{-Z_1/40} \right) - \left( \frac{Z_1}{A_1} + 4.195 Z_1 Z_2 \right) (0.27/4) \right]
\]

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<tr>
<th>Composition</th>
<th>(Z_1)</th>
<th>(Z_2/A_1)</th>
<th>(Z_1 Z_2^{3.1}/40)</th>
<th>(1 - e^{-Z_1/40})</th>
<th>(&lt;0)</th>
<th>% Change (a))</th>
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<tr>
<td>CH</td>
<td>1.74% H</td>
<td>5.613</td>
<td>0.583</td>
<td>1.707</td>
<td>1.1509</td>
<td>1.914</td>
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<tr>
<td>CHg</td>
<td>1.24% H</td>
<td>5.232</td>
<td>0.572</td>
<td>1.675</td>
<td>1.1377</td>
<td>1.858</td>
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<tr>
<td>CHO,25</td>
<td>23.5% O</td>
<td>6.186</td>
<td>0.529</td>
<td>1.758</td>
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<td>CNS,09</td>
<td>11.0% S</td>
<td>6.755</td>
<td>0.534</td>
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<td>1.1553</td>
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<td>CHFe,01</td>
<td>4.12% Fe</td>
<td>6.460</td>
<td>0.535</td>
<td>1.784</td>
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<tr>
<td>CHPb,001</td>
<td>1.44% Pb</td>
<td>6.664</td>
<td>0.519</td>
<td>1.798</td>
<td>1.1530</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 (5) was assumed to be CH₂O₂5. It can approach CH₂O₂₂ 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 CH₂O₂₅ and going to CH₂O₂₂S₂, 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% of the average that does not depend on composition is still far superior to visual estimates.
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 carbon 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>
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<tr>
<th>Temperature (°C)</th>
<th>State</th>
<th>Density (g/cm³)</th>
<th>Specific Heat (J/g°C)</th>
<th>Heat of Fusion (J/g)</th>
<th>Heat of Vaporization (J/g)</th>
<th>Heat of Sublimation (J/g)</th>
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<tr>
<td>0</td>
<td>Solid</td>
<td>1.001</td>
<td>2.14</td>
<td>0.67</td>
<td>24.4</td>
<td>49.6</td>
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<td>10</td>
<td>Liquid</td>
<td>0.997</td>
<td>2.12</td>
<td>0.68</td>
<td>23.9</td>
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<td>0.993</td>
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<td>30</td>
<td>Liquid</td>
<td>0.989</td>
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<td>0.67</td>
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Note: Values are approximate and may vary slightly.
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**Table Footnotes:**
- Footnote 1
- Footnote 2
- Footnote 3
### Table 1: Properties of the Material

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### Table 2: Basic Velocity, Consec.

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**Note:** The tables contain detailed properties and velocity data relevant to the material under discussion.
| T (°F) | V | b | c | d | e | f | g | h | i | j | k | l | m | n | o | p | q | r | s | t | u | v | w | x | y | z |
| 100    | 1000 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 |
| 200    | 2000 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 |
| 300    | 3000 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 |
| 400    | 4000 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 |
| 500    | 5000 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 |
| 600    | 6000 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 | 32 |

**Gas Properties of Decalin, 1,000 psi, 1,000 lbs**

- **Temp.**
- **V**
- **b**
- **c**
- **d**
- **e**
- **f**
- **g**
- **h**
- **i**
- **j**
- **k**
- **l**
- **m**
- **n**
- **o**
- **p**
- **q**
- **r**
- **s**
- **t**
- **u**
- **v**
- **w**
- **x**
- **y**
- **z**
### Table 1: Tabulated Data

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<td>Item 4</td>
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<td>Value 16</td>
<td></td>
</tr>
<tr>
<td>Item 5</td>
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<td>Value 18</td>
<td>Value 19</td>
<td>Value 20</td>
<td></td>
</tr>
<tr>
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<td>Value 22</td>
<td>Value 23</td>
<td>Value 24</td>
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<tr>
<td>Item 7</td>
<td>Value 25</td>
<td>Value 26</td>
<td>Value 27</td>
<td>Value 28</td>
<td></td>
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<tr>
<td>Item 8</td>
<td>Value 29</td>
<td>Value 30</td>
<td>Value 31</td>
<td>Value 32</td>
<td></td>
</tr>
<tr>
<td>Item 9</td>
<td>Value 33</td>
<td>Value 34</td>
<td>Value 35</td>
<td>Value 36</td>
<td></td>
</tr>
<tr>
<td>Item 10</td>
<td>Value 37</td>
<td>Value 38</td>
<td>Value 39</td>
<td>Value 40</td>
<td></td>
</tr>
</tbody>
</table>

This is a table with ten items, each with four corresponding values.
<table>
<thead>
<tr>
<th>Column 1</th>
<th>Column 2</th>
<th>Column 3</th>
<th>Column 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data 1</td>
<td>Data 2</td>
<td>Data 3</td>
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<tr>
<td>Data 5</td>
<td>Data 6</td>
<td>Data 7</td>
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<td>Data 9</td>
<td>Data 10</td>
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<tr>
<td>Data 17</td>
<td>Data 18</td>
<td>Data 19</td>
<td>Data 20</td>
</tr>
</tbody>
</table>

The table represents data collected from various sources and includes columns for different categories.
Following are typical empirical data and calculated physical property information based on a variety of methods. Since only a limited number of samples of sulphur have been prepared, the consistency of the data from batch to batch has not been established. Also, proving larger scale preparations, we have not independently calculated the effect of temperature, pressure, outside the normal range, on various physical and chemical properties of interest. Instead, we have applied corrections to the results calculated for CODERNE 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.
### Table 3.5: Physical and Chemical Properties of Pd-30

<table>
<thead>
<tr>
<th>Property</th>
<th>Unit 1</th>
<th>Unit 2</th>
<th>Unit 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravity, deg API</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Distillation temperature, °C</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Flash point, °C</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Autoignition, °F</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Ash contents, %</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Copper strip corrodibility</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Viscosity, cs, at 60°F</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Flash point, °C</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Vapor pressure, psi at 100°F</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Thermal stability, hr</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Pressure change, in. Hg</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
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<tr>
<td>Sulfur, %</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
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<tr>
<td>Carbon, %</td>
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<tr>
<td>Critical temperature, °F</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
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<tr>
<td>Critical pressure, psi</td>
<td>0.00</td>
<td>0.00</td>
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<tr>
<td>Density at 60°F, lb</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
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<tr>
<td>Blend weight</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
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</tbody>
</table>

#### Notes:

- All properties are tested under standard conditions.
- Samples have been analyzed at temperatures of about 60°F and 100°F.
- All tests are conducted in accordance with API specifications.
<table>
<thead>
<tr>
<th>Temp, °C</th>
<th>Velocity, ft/min</th>
<th>viscosity, lb/ft-hr</th>
<th>Thermal Conductivity, Btu/ft-hr-°F</th>
<th>Heat Capacity, Btu/lb</th>
<th>Density, lb/ft³</th>
<th>Enthalpy, Btu/lb</th>
<th>Heat of Vaporization, Btu/lb</th>
<th>Specific Heat, Btu/lb °F</th>
<th>sg. Pressure, psia</th>
</tr>
</thead>
<tbody>
<tr>
<td>-60</td>
<td>70.8</td>
<td>22000.0</td>
<td>0.048</td>
<td>0.217</td>
<td>-23.5</td>
<td>151.0</td>
<td>0.000</td>
<td>0.000</td>
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<tr>
<td>0</td>
<td>69.3</td>
<td>552.6</td>
<td>0.096</td>
<td>0.287</td>
<td>0.0</td>
<td>108.5</td>
<td>0.000</td>
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<tr>
<td>100</td>
<td>66.6</td>
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<td>0.093</td>
<td>0.342</td>
<td>0.0</td>
<td>120.3</td>
<td>0.012</td>
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<tr>
<td>200</td>
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<td>0.367</td>
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<tr>
<td>300</td>
<td>60.9</td>
<td>3.12</td>
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<td>0.412</td>
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<td>115.5</td>
<td>0.003</td>
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<tr>
<td>400</td>
<td>57.6</td>
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<td>0.507</td>
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<td>0.003</td>
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<tr>
<td>500</td>
<td>54.5</td>
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<td>0.112</td>
<td>0.559</td>
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<td>600</td>
<td>50.9</td>
<td>0.092</td>
<td>0.124</td>
<td>0.626</td>
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<td>0.142</td>
<td>0.765</td>
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<td>0.003</td>
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<tr>
<td>900</td>
<td>34.2</td>
<td>0.117</td>
<td>0.152</td>
<td>0.848</td>
<td>0.0</td>
<td>111.5</td>
<td>0.003</td>
<td>0.003</td>
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</table>

a) To convert Multiply by Density.
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<td>Data 22</td>
<td>Data 23</td>
<td>Data 24</td>
<td>Data 25</td>
</tr>
</tbody>
</table>

Note: The table contains numerical data and is structured in columns and rows for easy reading and analysis.


*This extends the survey of the literature presented in reference 13.*
AFAP-12-6114
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10. [Text begins here]

11. [Text begins here]

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-539-
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1473. ANALYSIS OF TRACE METALLIC CONTAMINANTS IN KET FUELS BY NUCLEAR ACTIVATION. (AD 831 067)

1474. THE EFFECTS OF HYDROCARBON FUEL VAPOR PHASE DEPOSITS. (AD 833 746)

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1478. FUNDAMENTAL INVESTIGATION OF THE DEGRADATION OF HYDROCARBON FUELS. (AD 825 427)

1479. DETERMINATION OF THE EFFECTS OF COPPER IN STABILITY PROBLEMS ENCOUNTERED WITH GAS TURBINE FUELS. (AD 821 2946)

1480. DEVELOPMENT OF GET FUEL TANK VELOCITIES. (AD 817 9461)

1481. EXPERIMENTAL INVESTIGATION OF HYPERSONIC FLOWS - TRANSLATION. (AD 825 366)

1482. ON THE INFLUENCE OF THE ADDITION OF HEAT TO HYPERSONIC FLOW - TRANSLATION. (AD 825 709)

1483. REAL GAS PROPERTY EFFECTS ON FLOW AND HEAT TRANSFER IN THE ENTRANCE REGION OF A PARALLEL-PLATE CHANNEL. (AD 817 940)

1484. FREE-FLOW CONVECTION HEAT TRANSFER IN A CURVED CHANNEL. (AD 817 991)

1485. THERMIST OF FLOW INCLUDING CHEMICAL REACTION - TEXT IN FRENCH. (AD 821 574)

1486. MICROVOLTS MEASUREMENTS OF NON-EQUILIBRIUM AIR FLAMMABLES BEHIND SHOCK WAVES CONTAINING ELECTROPHOTOIC GASES. (AD 817 650)

1487. SCRAMJET THERMAL PROTECTION PROGRAM. (AD 818 153)

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1489. HEAT TRANSFER IN THE VICINITY OF A 28 DEGREES COMPRESSION CONE AT MACH NUMBERS FROM 0.5 TO 4.4. (AD 823 554)

1490. HEAT TRANSFER TO SUPERCRITICAL KERMA. (AD 824 271)

-558-
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1493. SUPERCRITICAL PRESSURE LIQUID HYDROGEN HEAT TRANSFER DATA COMPILATION. (AD 818 418)

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