Basic and applied research have continued on the thermodynamic properties of currently used high density/high energy fuels and of pure chemical compounds that may be constituents of high energy fuels of the future. Enthalpy of combustion was measured for three compounds that are constituents of current ramjet fuels—hexacyclic exo, exo-dihydrodienorbornadiene, hexacyclic endo, endo-dihydrodienorbornadiene and exo-tetrahydrodicyclopentadiene (JP-10). Heat capacities of exo-tetrahydrodicyclopentadiene (JP-10) and RJ-6, a blend of JP-10 and the hydrogenated dimers of norbornadiene, were measured by differential scanning calorimetry. Enthalpy of combustion was measured for two pure hydrocarbons, 1,7-dimethylindan and 1,4-dimethyl-2-isobutylbenzene, that are expected to have high steric interaction energies of alkyl substituents in the ring structure, and measurements are in progress on 1-ethyl-8-methylnaphtalene and 1,6-dimethylindan. Results of present and earlier research sponsored by AFOSR were reported both orally and in journal articles.
FINAL TECHNICAL SUMMARY REPORT

for the period

1 October 1979 - 30 September 1980

THERMODYNAMICS OF ORGANIC COMPOUNDS

Bartlesville Energy Technology Center
Department of Energy
Bartlesville, Oklahoma

Research sponsored by:

Air Force Office of Scientific Research (NA)
Department of the Air Force

Contract No. AFOSR-ISSA-80-00004
Project No. 2308/B1

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH (AFOSR)

Dr. R. F. HENDRY
Research Director

Griffiss Air Force Base
Griffiss AFB 13404

OCT 1980

"This report was prepared under contract for the Air Force Office of Scientific Research, Department of the Air Force, under Contract No. AFOSR-ISSA-80-00004.

The report is subject to public disclosure under 32 CFR 199.12.

F. M. STAFFORD
Office of the Chief, Technical Information Division
FINAL TECHNICAL SUMMARY REPORT
for the period
1 October 1979 - 30 September 1980

THERMODYNAMICS OF ORGANIC COMPOUNDS

Bartlesville Energy Technology Center
Department of Energy
Bartlesville, Oklahoma

Research sponsored by:
Air Force Office of Scientific Research (NA)
Department of the Air Force

Contract No. AFSR-ISSA-80-00004
Project No. 2308/B1

- Approved for public release;
distribution unlimited.
FINAL TECHNICAL SUMMARY REPORT

THERMODYNAMICS OF ORGANIC COMPOUNDS

* * * * * * * * * * *

Bartlesville Energy Technology Center
Department of Energy
Bartlesville, Oklahoma

Project Director: W. D. Good

Report* prepared by:

N. K. Smith
R. H. P. Thomas
B. E. Gammon
S. Lee-Bechtold
J. E. Callanan
W. D. Good

C. J. Thompson, Division Director
H. R. Johnson, Director

* Synthesis and purification of research samples were provided by Professor E. J. Eisenbraun, Oklahoma State University. Samples were produced by purchase agreement for this project.

Qualified requestors may obtain additional copies from the Defense Documentation Center, all others should apply to the National Technical Information Service.

Approved for public release; distribution unlimited.

Conditions of Reproduction

Reproduction, translation, publication, use and disposal in whole or in part by or for the United States Government is permitted.
TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>FOREWORD</th>
<th>..........</th>
<th>i</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>..........</td>
<td>ii</td>
</tr>
<tr>
<td>RESEARCH PROGRESS</td>
<td>...........</td>
<td>1</td>
</tr>
<tr>
<td>1. NOMENCLATURE</td>
<td>...........</td>
<td>1</td>
</tr>
<tr>
<td>2. ENTHALPY OF COMBUSTION</td>
<td>...........</td>
<td>2</td>
</tr>
<tr>
<td>3. HEAT CAPACITIES OF RJ-6 AND JP-10</td>
<td>..........</td>
<td>15</td>
</tr>
<tr>
<td>4. PUBLICATIONS AND PRESENTATIONS</td>
<td>..........</td>
<td>19</td>
</tr>
<tr>
<td>5. MANUSCRIPTS ACCEPTED FOR PUBLICATION</td>
<td>..........</td>
<td>19</td>
</tr>
</tbody>
</table>

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH (AFSC)
NOTICE OF TRANSMITTAL TO DDC
This technical report has been reviewed and is approved for public release IAW AFR 190-12 (7b).
Distribution is unlimited.
A. D. BLOSH
technical information Officer
This research program consists of an integrated and interrelated effort of basic and applied research in chemical thermodynamics and thermochemistry. Knowledge of variation of physical and thermodynamic properties with molecular structure is used to select compounds for study that because of high ring strain or unusual steric effects may have good energy characteristics per unit volume or per unit mass and thus be useful in the synthesis of high energy fuels. These materials are synthesized, and their thermodynamic properties are evaluated. In cooperation with researchers at Wright-Patterson Air Force Base, ramjet fuels currently in use are subjected to careful thermodynamic evaluation by measurements of heat capacity, enthalpy of combustion, and vapor pressure.
ABSTRACT

Basic and applied research have continued on the thermodynamic properties of currently used high density/high energy fuels and of pure chemical compounds that may be constituents of high energy fuels of the future.

Enthalpy of combustion was measured for three compounds that are constituents of current ramjet fuels—hexacyclic exo,exo-dihyrdodinorbornadiene, hexacyclic endo,endo-dihyrdodinorbornadiene and exo-tetrahydodicyclopentadiene (JP-10).

Heat capacities of exo-tetrahydodicyclopentadiene (JP-10) and RJ-6, a blend of JP-10 and the hydrogenated dimers of norbornadiene, were measured by differential scanning calorimetry.

Enthalpy of combustion was measured for two pure hydrocarbons, 1,7-diethylindand and 1,4-dimethyl-2-isobutylbenzene, that are expected to have high steric interaction energies of alkyl substituents in the ring structure, and measurements are in progress on 1-ethyl-8-methylnaphthalene and 1,6-dimethylindand.

Results of present and earlier research sponsored by AFOSR were reported both orally and in journal articles.
1. NOMENCLATURE

This report describes research on the thermodynamic properties of several fuels and compounds of considerable molecular complexity. In an effort to facilitate understanding, the nomenclature and carbon skeletons of these materials follow in Table 1.

**TABLE 1. Nomenclature of Materials**

<table>
<thead>
<tr>
<th>No.</th>
<th>Nomenclature</th>
<th>Structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Hexacyclic exo,exo-dihydro-dinorbornadiene</td>
<td><img src="image1.png" alt="Structure 1" /></td>
</tr>
<tr>
<td>2.</td>
<td>Hexacyclic endo,endo-dihydro-dinorbornadiene</td>
<td><img src="image2.png" alt="Structure 2" /></td>
</tr>
<tr>
<td>3.</td>
<td>exo-Tetrahydro-dicyclopentadiene</td>
<td><img src="image3.png" alt="Structure 3" /></td>
</tr>
<tr>
<td>4.</td>
<td>1,7-Dimethyl-indan</td>
<td><img src="image4.png" alt="Structure 4" /></td>
</tr>
<tr>
<td>5.</td>
<td>1,4-Dimethyl-2-isobutylbenzene</td>
<td><img src="image5.png" alt="Structure 5" /></td>
</tr>
</tbody>
</table>
2. ENTHALPY OF COMBUSTION

Material and Techniques

Two series of combustion experiments were performed. In the first series hexacyclic \( \text{exo,exo-di}- \)hydrodinorbornadiene, hexacyclic \( \text{endo,endo-di}- \)hydrodinorbornadiene, and \( \text{exo-tetra-} \)hydrodicyclopentadiene were studied. These materials were supplied by Professor C. T. Moynihan of the Catholic University of America. They were prepared from concentrates obtained from Suntech, Incorporated, by triple recrystallization at \(-65^\circ\) C from acetone and subsequent vacuum distillation. Gas chromatography of the two substances indicated the \( \text{exo,exo-} \) isomer to be 99.9 mole percent pure and the \( \text{endo,endo-} \) isomer to be 99.7 mole percent pure. Professor Moynihan also supplied a sample of \( \text{exo-tetra-} \)hydrodicyclopentadiene, also obtained from Suntech, Incorporated, of 99.9 mole percent purity. These materials were used as received without further drying.

A second series of combustion calorimetric experiments involved 1,4-dimethyl-2-isobutylbenzene and 1,7-dimethylindan. The alkylbenzene was purified by the American Petroleum Institute Research Project 58 at Carnegie-Mellon University, A. J. Streiff, Director. The sample description given by API Project 58 lists the purity as 99.96 ± 0.01 mole percent. The alkylindan was prepared in the laboratories of Professor E. J. Eisenbraun at Oklahoma State University.

Carbon dioxide was recovered from the combustion products of most combustion experiments. Quantitative carbon dioxide recovery is an excellent indication that the materials are dry and free of all but isomeric impurity. Carbon dioxide recoveries for the two series of experiments and their companion benzoic acid calibration experiments are given in Table 2.

Fragile flexible ampoules\(^1,\)\(^2\) of borosilicate glass confined the liquid samples for combustion calorimetry; auxiliary oil (laboratory designation TKL 66) was used to initiate the combustion. Rotating-bomb calorimeter BMR II\(^3\) and platinum-lined bomb PT-3b\(^4\) were used without bomb rotation. For each experiment, 1 cm\(^3\) of water was added to the bomb, and the

TABLE 2. Carbon Dioxide Recovery

<table>
<thead>
<tr>
<th>Compound</th>
<th>Percent Recovery(^a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hexacyclic (\text{exc,exo-dihydro-dinorbornadiene}) (6)</td>
<td>99.96 ± 0.01</td>
</tr>
<tr>
<td>Hexacyclic (\text{endo,endo-dihydro-dinorbornadiene}) (7)</td>
<td>99.95 ± 0.01</td>
</tr>
<tr>
<td>(\text{exo-Tetrahydrodicyclopentadiene}) (4)</td>
<td>99.98 ± 0.03</td>
</tr>
<tr>
<td>Benzoic acid (8)</td>
<td>99.96 ± 0.02</td>
</tr>
<tr>
<td>1,7-Dimethylindan (8)</td>
<td>99.99 ± 0.01</td>
</tr>
<tr>
<td>1,4-Dimethyl-2-isobutylbenzene (6)</td>
<td>99.98 ± 0.02</td>
</tr>
<tr>
<td>Benzoic acid (8)</td>
<td>99.99 ± 0.00</td>
</tr>
</tbody>
</table>

\(^a\) Mean and standard deviation of the mean.

\(^b\) Number of experiments.
bomb was flushed and charged to 30 atm with oxygen. Each experiment was started at 296.15 K, and because the masses of combustibles were properly chosen, the final temperatures were very nearly 298.15 K. Temperatures were measured by quartz crystal thermometry; the quartz thermometer was calibrated with a platinum resistance thermometer. A programmable desktop calculator was used to control the combustion experiments and record the results. Readings were taken at 100-second intervals throughout the experiment; integration of the time-temperature curve is inherent in the quartz thermometer reading.

The experimental results are based on 1961 atomic weights. For reducing weights in air to masses, converting the energy of the actual bomb process to that of the isothermal bomb process, and reducing to standard states, the values of physical properties listed in Table 3 were used. The values of the densities of the hydrogenated dinorbornadienes and hydrogenated dicyclopentadiene are those of Moynihan. The densities of 1,7-dimethylindan and 1,4-dimethyl-2-isobutylbenzene were derived from the masses of sample contained by ampoules of known volume. All values in parentheses are estimates.

National Bureau of Standards sample 39i benzoic acid was used for the two calibration series. The result of eight calibration experiments interspersed with the hydrogenated dibornadiene and dicyclopentadiene experiments was ε(calor) = 4007.28 ± 0.08 cal deg⁻¹ (mean and standard deviation of the mean). The result of nine calibration experiments interspersed with the experiments with 1,7-dimethylindan and 1,4-dimethyl-2-isobutylbenzene was ε(calor) = 4007.40 ± 0.07 cal deg⁻¹ (mean and standard deviation of the mean).

---

<table>
<thead>
<tr>
<th>Compound</th>
<th>$\rho$ (g cm$^{-3}$)</th>
<th>$(\Delta E/\Delta p)_T$ (cal atm$^{-1}$ g$^{-1}$)</th>
<th>$c_p$ (cal K$^{-1}$ g$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hexacyclic exo, exo-dihydro-dinorbornadiene</td>
<td>1.073</td>
<td>(-0.0029)</td>
<td>(0.3)</td>
</tr>
<tr>
<td>Hexacyclic endo, endo-dihydro-dinorbornadiene</td>
<td>1.085</td>
<td>(-0.0029)</td>
<td>(0.3)</td>
</tr>
<tr>
<td>exo-Tetrahydrodicyclopentadiene</td>
<td>0.931</td>
<td>(-0.0029)</td>
<td>(0.3)</td>
</tr>
<tr>
<td>1,7-Dimethylindan</td>
<td>0.93</td>
<td>(-0.0029)</td>
<td>(0.3)</td>
</tr>
<tr>
<td>1,4-Dimethyl-2-isobutylbenzene</td>
<td>0.836</td>
<td>(-0.0029)</td>
<td>(0.3)</td>
</tr>
<tr>
<td>Benzoic acid</td>
<td>1.32</td>
<td>-0.0028</td>
<td>0.289</td>
</tr>
</tbody>
</table>
Combustion Calorimetry Results

The following equations represent the combustion reaction for the compounds:

Hexacyclic exo,exo-dihydrodinorbornadiene and hexacyclic endo,endo-dihydrodinorbornadiene

\[ \text{C}_{14}\text{H}_{18}(l) + \frac{37}{2} \text{O}_2(g) = 14 \text{CO}_2(g) + 9 \text{H}_2\text{O}(l) \]  \( (1) \)

exo-Tetrahydrodicyclopentadiene

\[ \text{C}_{10}\text{H}_{16}(l) + 14 \text{O}_2(g) = 10 \text{CO}_2(g) + 8 \text{H}_2\text{O}(l) \]  \( (2) \)

1,7-Dimethylindan

\[ \text{C}_{11}\text{H}_{14}(l) + \frac{29}{2} \text{O}_2(g) = 11 \text{CO}_2(g) + 7 \text{H}_2\text{O}(l) \]  \( (3) \)

1,4-Dimethyl-2-isobutylbenzene

\[ \text{C}_{12}\text{H}_{18}(l) + \frac{33}{2} \text{O}_2(g) = 12 \text{CO}_2(g) + 9 \text{H}_2\text{O}(l) \]  \( (4) \)

Values of \( \Delta E^0/m \) for all five compounds are given in Tables 4 through 8. All values of \( \Delta E^0/m \) refer to the reaction of one gram of sample at 25° C. Derived molar values of the standard molar energy of the combustion reactions, \( \Delta E^0 \), and the standard molar enthalpy of combustion, \( \Delta H^0 \), are given in Table 9.

Uncertainty values are the "uncertainty interval" equal to twice the final overall standard deviation of the mean.

The formation reactions for the compounds from the elements follow.

Hexacyclic exo,exo-dihydrodinorbornadiene and hexacyclic endo,endo-dihydrodinorbornadiene

\[ 14 \text{C(c, graphite)} + 9 \text{H}_2(g) = \text{C}_{14}\text{H}_{18}(l \text{ or } g) \]  \( (5) \)

exo-Tetrahydrodicyclopentadiene

\[ 10 \text{C(c, graphite)} + 8 \text{H}_2(g) = \text{C}_{10}\text{H}_{16}(l) \]  \( (6) \)
### Table 4. Summary of Calorimetric Experiments With Hexacyclic \( \text{ex}, \text{ex} \)-Dihydrodinorbornadiene

\( (\text{cal}_{\text{th}} = 4.184 \text{ J}) \)

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>( m' ) (compound)/g</td>
<td>0.692566</td>
<td>0.632900</td>
<td>0.680725</td>
<td>0.643644</td>
<td>0.663355</td>
<td>0.636626</td>
</tr>
<tr>
<td>( m'' ) (auxiliary oil)/g</td>
<td>0.076106</td>
<td>0.129905</td>
<td>0.084764</td>
<td>0.121109</td>
<td>0.100928</td>
<td>0.132413</td>
</tr>
<tr>
<td>( m''' ) (fusel)/g</td>
<td>0.000937</td>
<td>0.001390</td>
<td>0.000946</td>
<td>0.001114</td>
<td>0.000806</td>
<td>0.000938</td>
</tr>
<tr>
<td>( n ) ( (\text{H}_2\text{O}) )/mol</td>
<td>0.05535</td>
<td>0.05535</td>
<td>0.05535</td>
<td>0.05535</td>
<td>0.05535</td>
<td>0.05535</td>
</tr>
<tr>
<td>( \Delta t_c/K = (t_f - t_i + \Delta t_{corr})/K )</td>
<td>2.007103</td>
<td>2.000166</td>
<td>1.999089</td>
<td>2.003034</td>
<td>1.998326</td>
<td>2.002806</td>
</tr>
<tr>
<td>( \varepsilon (\text{calor}) (\Delta t_c)/\text{cal}_{\text{th}} )</td>
<td>-884.302</td>
<td>-8015.22</td>
<td>-8010.91</td>
<td>-8026.72</td>
<td>-8007.85</td>
<td>-8025.80</td>
</tr>
<tr>
<td>( \varepsilon (\text{cont}) (\Delta t_c)/\text{cal}_{\text{th}} )</td>
<td>-10.03</td>
<td>-10.07</td>
<td>-9.99</td>
<td>-9.95</td>
<td>-10.04</td>
<td>-10.14</td>
</tr>
<tr>
<td>( \Delta E_{\text{ign}}/\text{cal}_{\text{th}} )</td>
<td>0.18</td>
<td>0.18</td>
<td>0.18</td>
<td>0.18</td>
<td>0.18</td>
<td>0.18</td>
</tr>
<tr>
<td>( \Delta E_{\text{dec}}(\text{HNO}<em>3)/\text{cal}</em>{\text{th}} )</td>
<td>0.17</td>
<td>0.38</td>
<td>0.07</td>
<td>0.08</td>
<td>0.10</td>
<td>0.11</td>
</tr>
<tr>
<td>( \Delta E_{\text{corr to std states}}/\text{cal}_{\text{th}} )</td>
<td>3.49</td>
<td>3.40</td>
<td>3.47</td>
<td>3.42</td>
<td>3.44</td>
<td>3.40</td>
</tr>
<tr>
<td>( \left( -m'' (\Delta E_c/m) \right) (auxiliary oil))/\text{cal}_{\text{th}} )</td>
<td>883.50</td>
<td>1429.53</td>
<td>932.77</td>
<td>1332.73</td>
<td>1110.65</td>
<td>1468.13</td>
</tr>
<tr>
<td>( \left( -m''' (\Delta E_c/m) \right) (fusel))/\text{cal}_{\text{th}} )</td>
<td>3.79</td>
<td>5.63</td>
<td>3.83</td>
<td>4.51</td>
<td>3.67</td>
<td>3.80</td>
</tr>
<tr>
<td>( \left( m' (\Delta E_c/m) \right) (compound))/\text{cal}_{\text{th}} )</td>
<td>-7207.92</td>
<td>-6586.17</td>
<td>-7080.58</td>
<td>-6695.75</td>
<td>-6899.85</td>
<td>-5560.32</td>
</tr>
<tr>
<td>( (\Delta E_c/m) (compound))/\text{cal}_{\text{th}} ) g(^{-1})</td>
<td>-10407.56</td>
<td>-10406.34</td>
<td>-10401.53</td>
<td>-10402.88</td>
<td>-10401.44</td>
<td>-10402.87</td>
</tr>
<tr>
<td>( (\Delta E_c/m) (compound))/\text{cal}_{\text{th}} ) g(^{-1})</td>
<td>-10403.77 ± 1.05 (mean and standard deviation of the mean)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

---


**b** \( \varepsilon (\text{cont}) (t_f - 298.15 \text{ K}) = \varepsilon (\text{cont}) (298.15 \text{ K} - t_f + \Delta t_{corr}) \).

**c** Items 81 to 85, 87 to 90, 93 and 94 of the computation form of Hubbard et al (footnote a).
### TABLE 5. Summary of Calorimetric Experiments With Hexacyclic endo,endo-Dihydrodinorbornadiene<sup>a</sup>

(cal<sub>th</sub> = 4.184 J)

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>n&lt;sup&gt;-1&lt;/sup&gt;(compound)/g</td>
<td>0.652947</td>
<td>0.661060</td>
<td>0.677778</td>
<td>0.685595</td>
<td>0.683514</td>
<td>0.682014</td>
<td>0.682267</td>
</tr>
<tr>
<td>n&lt;sup&gt;-1&lt;/sup&gt;(auxiliary oil)/g</td>
<td>0.109059</td>
<td>0.100517</td>
<td>0.085842</td>
<td>0.078907</td>
<td>0.080562</td>
<td>0.081030</td>
<td>0.081858</td>
</tr>
<tr>
<td>n&lt;sup&gt;-1&lt;/sup&gt;(fuse)/g</td>
<td>0.001346</td>
<td>0.000884</td>
<td>0.001429</td>
<td>0.001104</td>
<td>0.000829</td>
<td>0.000883</td>
<td>0.000954</td>
</tr>
<tr>
<td>n&lt;sup&gt;1&lt;/sup&gt;(H&lt;sub&gt;2&lt;/sub&gt;O)/mol</td>
<td>0.05535</td>
<td>0.05535</td>
<td>0.05535</td>
<td>0.05535</td>
<td>0.05535</td>
<td>0.05535</td>
<td>0.05535</td>
</tr>
<tr>
<td>ε&lt;sub&gt;C&lt;/sub&gt;/θ = (t&lt;sub&gt;f&lt;/sub&gt; - t&lt;sub&gt;i&lt;/sub&gt; + ε&lt;sub&gt;corr&lt;/sub&gt;)&lt;sup&gt;b&lt;/sup&gt;</td>
<td>2.001078</td>
<td>1.997969</td>
<td>2.002148</td>
<td>2.002391</td>
<td>2.001245</td>
<td>1.999382</td>
<td>2.002284</td>
</tr>
<tr>
<td>r(calor) - ε&lt;sub&gt;C&lt;/sub&gt;/θ&lt;sub&gt;th&lt;/sub&gt;</td>
<td>-8018.88</td>
<td>-8006.42</td>
<td>-8023.16</td>
<td>-8024.14</td>
<td>-8019.55</td>
<td>-8012.08</td>
<td>-8023.71</td>
</tr>
<tr>
<td>t(cont) - ε&lt;sub&gt;C&lt;/sub&gt;/θ&lt;sub&gt;th&lt;/sub&gt;</td>
<td>-10.08</td>
<td>-10.07</td>
<td>-9.93</td>
<td>-10.00</td>
<td>-10.00</td>
<td>-10.04</td>
<td>-9.99</td>
</tr>
<tr>
<td>ΔE&lt;sub&gt;ign&lt;/sub&gt;/θ&lt;sub&gt;th&lt;/sub&gt;</td>
<td>0.10</td>
<td>0.10</td>
<td>0.10</td>
<td>0.18</td>
<td>0.18</td>
<td>0.18</td>
<td>0.18</td>
</tr>
<tr>
<td>ΔE&lt;sub&gt;dec&lt;/sub&gt;(HNO&lt;sub&gt;3&lt;/sub&gt;)&lt;sup&gt;c&lt;/sup&gt;/θ&lt;sub&gt;th&lt;/sub&gt;</td>
<td>0.15</td>
<td>0.16</td>
<td>0.24</td>
<td>0.18</td>
<td>0.08</td>
<td>0.13</td>
<td>0.14</td>
</tr>
<tr>
<td>ΔE&lt;sub&gt;corr to std states&lt;/sub&gt;/θ&lt;sub&gt;th&lt;/sub&gt;</td>
<td>3.42</td>
<td>3.43</td>
<td>3.46</td>
<td>3.47</td>
<td>3.46</td>
<td>3.46</td>
<td>3.46</td>
</tr>
<tr>
<td>(-m&lt;sup&gt;-1&lt;/sup&gt;(ΔE&lt;sub&gt;C&lt;/sub&gt;/m)(auxiliary oil))/θ&lt;sub&gt;th&lt;/sub&gt;</td>
<td>1200.12</td>
<td>1106.13</td>
<td>944.64</td>
<td>868.32</td>
<td>886.5</td>
<td>891.69</td>
<td>900.80</td>
</tr>
<tr>
<td>(-m&lt;sup&gt;-1&lt;/sup&gt;(ΔE&lt;sub&gt;C&lt;/sub&gt;/m)(fuse))/θ&lt;sub&gt;th&lt;/sub&gt;</td>
<td>5.45</td>
<td>3.98</td>
<td>5.79</td>
<td>4.47</td>
<td>3.16</td>
<td>3.57</td>
<td>3.86</td>
</tr>
<tr>
<td>(-m&lt;sup&gt;-1&lt;/sup&gt;(ΔE&lt;sub&gt;C&lt;/sub&gt;/m)(compound))/θ&lt;sub&gt;th&lt;/sub&gt;</td>
<td>-6819.64</td>
<td>-6902.61</td>
<td>-7078.78</td>
<td>-7157.52</td>
<td>-7135.94</td>
<td>-7123.09</td>
<td>-7125.26</td>
</tr>
<tr>
<td>(-m&lt;sup&gt;-1&lt;/sup&gt;(ΔE&lt;sub&gt;C&lt;/sub&gt;/m)(compound)/q&lt;sup&gt;-1&lt;/sup&gt;)&lt;sup&gt;c&lt;/sup&gt;/θ&lt;sub&gt;th&lt;/sub&gt;</td>
<td>-10444.40</td>
<td>-10441.73</td>
<td>-10444.10</td>
<td>-10435.87</td>
<td>-10440.08</td>
<td>-10444.20</td>
<td>-10443.51</td>
</tr>
<tr>
<td>(-m&lt;sup&gt;-1&lt;/sup&gt;(ΔE&lt;sub&gt;C&lt;/sub&gt;/m)(compound)/q&lt;sup&gt;-1&lt;/sup&gt;)&lt;sup&gt;c&lt;/sup&gt;</td>
<td>-10442.56 ± 0.75 (mean and standard deviation of the mean)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<sup>a</sup> The symbols and abbreviations of this table are those of M. N. Hubbard et al, *Experimental Thermochimistry*, Chap. 5, Ph. 75-128. F. D. Rossini, editor. Interscience: 1956.

<sup>b</sup> t<sub>1</sub>(cont) = 298.15 K + ε<sub>corr</sub>.

<sup>c</sup> Items 81 to 85, 87 to 90, 91 and 94 of the computation form of Hubbard et al (footnote a).
<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>m'(compound)/g</td>
<td>0.709651</td>
<td>0.695413</td>
<td>0.683246</td>
<td>0.665336</td>
<td>0.660817</td>
<td>0.582034</td>
</tr>
<tr>
<td>m''(auxiliary oil)/g</td>
<td>0.040632</td>
<td>0.054945</td>
<td>0.065372</td>
<td>0.082981</td>
<td>0.086661</td>
<td>0.164243</td>
</tr>
<tr>
<td>m'''(fuse)/g</td>
<td>0.000998</td>
<td>0.001380</td>
<td>0.001224</td>
<td>0.001399</td>
<td>0.001474</td>
<td>0.001429</td>
</tr>
<tr>
<td>n(H₂O)/mol</td>
<td>0.05535</td>
<td>0.05535</td>
<td>0.05535</td>
<td>0.05535</td>
<td>0.05535</td>
<td>0.05535</td>
</tr>
<tr>
<td>Δt_c/K = (t_f - t_i + Δt_corr)/K</td>
<td>2.002666</td>
<td>2.004302</td>
<td>2.000068</td>
<td>2.001950</td>
<td>1.999687</td>
<td>2.002634</td>
</tr>
<tr>
<td>c(calor)(-Δt_c)/cal_th</td>
<td>-8025.24</td>
<td>-8031.80</td>
<td>-8014.83</td>
<td>-8022.37</td>
<td>-8013.30</td>
<td>-8025.11</td>
</tr>
<tr>
<td>c(cont)(-Δt_c)/cal_th</td>
<td>-10.00</td>
<td>-10.02</td>
<td>-9.96</td>
<td>-8.63</td>
<td>-10.13</td>
<td>-8.76</td>
</tr>
<tr>
<td>ΔE_ign/cal_th</td>
<td>0.18</td>
<td>0.18</td>
<td>0.18</td>
<td>0.18</td>
<td>0.18</td>
<td>0.18</td>
</tr>
<tr>
<td>ΔE_dec(HNO₃)/cal_th</td>
<td>0.15</td>
<td>0.35</td>
<td>0.18</td>
<td>0.19</td>
<td>0.20</td>
<td>0.26</td>
</tr>
<tr>
<td>ΔE_corr to std states/cal_th</td>
<td>3.03</td>
<td>3.02</td>
<td>3.01</td>
<td>2.99</td>
<td>2.99</td>
<td>2.93</td>
</tr>
<tr>
<td>[m'(ΔE_c/m)(auxiliary oil)]/cal_th</td>
<td>447.13</td>
<td>604.64</td>
<td>719.38</td>
<td>913.16</td>
<td>953.65</td>
<td>1807.40</td>
</tr>
<tr>
<td>[m''(ΔE_c/m)(fuse)]/cal_th</td>
<td>4.04</td>
<td>5.59</td>
<td>4.96</td>
<td>5.67</td>
<td>5.97</td>
<td>5.79</td>
</tr>
<tr>
<td>[m'(ΔE_c/m)(compound)]/cal_th</td>
<td>-7580.71</td>
<td>-7428.04</td>
<td>-7297.08</td>
<td>-7108.81</td>
<td>-7060.44</td>
<td>-6217.31</td>
</tr>
<tr>
<td>(<a href="compound">ΔE_c/m</a>)/cal_th g⁻¹</td>
<td>-10682.31</td>
<td>-10681.48</td>
<td>-10680.02</td>
<td>-10684.54</td>
<td>-10684.41</td>
<td>-10682.04</td>
</tr>
<tr>
<td>(<a href="compound">ΔE_c/m</a>)/cal_th g⁻¹</td>
<td>-10682.47 ± 0.71 (mean and standard deviation of the mean)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The symbols and abbreviations of this table are those of W. N. Hubbard et al., Experimental Thermochemistry, Chap. 5, pp. 75-128. P. D. Rossini, editor. Interscience: 1956.

b c'(cont)(t_j - 298.15 K) + t'(cont)(298.15 K - t_f + 't_corr).

c Items 81 to 85, 87 to 90, 93 and 94 of the computation form of Hubbard et al (footnote a).
<table>
<thead>
<tr>
<th></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>
</tr>
</thead>
<tbody>
<tr>
<td>m'(compound)/g</td>
<td>0.693120</td>
<td>0.701879</td>
<td>0.702513</td>
<td>0.704488</td>
<td>0.705371</td>
<td>0.704564</td>
<td>0.707447</td>
<td>0.709814</td>
</tr>
<tr>
<td>m''(auxiliary oil)/g</td>
<td>0.083326</td>
<td>0.076565</td>
<td>0.075499</td>
<td>0.073255</td>
<td>0.073403</td>
<td>0.073324</td>
<td>0.071136</td>
<td>0.069150</td>
</tr>
<tr>
<td>m'''(fusce)/g</td>
<td>0.000867</td>
<td>0.001138</td>
<td>0.001563</td>
<td>0.001169</td>
<td>0.001129</td>
<td>0.001385</td>
<td>0.001514</td>
<td>0.001009</td>
</tr>
<tr>
<td>n1(H2O)/mol</td>
<td>0.05535</td>
<td>0.05535</td>
<td>0.05535</td>
<td>0.05535</td>
<td>0.05535</td>
<td>0.05535</td>
<td>0.05535</td>
<td>0.05535</td>
</tr>
<tr>
<td>nt_c/K = (t_f - t_i + ∆t_corr)/K</td>
<td>1.999569</td>
<td>2.003615</td>
<td>2.002673</td>
<td>2.001173</td>
<td>2.003886</td>
<td>2.002150</td>
<td>2.003541</td>
<td>2.003995</td>
</tr>
<tr>
<td>E(calor)(-∆t_c)/cal_th</td>
<td>-8013.08</td>
<td>-8029.29</td>
<td>-8025.51</td>
<td>-8019.50</td>
<td>-8030.38</td>
<td>-8023.42</td>
<td>-8028.99</td>
<td>-8030.81</td>
</tr>
<tr>
<td>E(cont)(-∆t_c)/cal_th</td>
<td>-8.70</td>
<td>-8.76</td>
<td>-8.78</td>
<td>-8.71</td>
<td>-8.78</td>
<td>-8.70</td>
<td>-8.76</td>
<td>-8.78</td>
</tr>
<tr>
<td>E1yon/cal_th</td>
<td>0.18</td>
<td>0.18</td>
<td>0.18</td>
<td>0.18</td>
<td>0.18</td>
<td>0.18</td>
<td>0.18</td>
<td>0.18</td>
</tr>
<tr>
<td>Edec(NH3)/cal_th</td>
<td>0.17</td>
<td>0.21</td>
<td>0.15</td>
<td>0.03</td>
<td>0.07</td>
<td>0.18</td>
<td>0.34</td>
<td>0.24</td>
</tr>
<tr>
<td>E(corr to std states)/cal_th</td>
<td>3.53</td>
<td>3.55</td>
<td>3.55</td>
<td>3.55</td>
<td>3.56</td>
<td>3.56</td>
<td>3.56</td>
<td>3.57</td>
</tr>
<tr>
<td>(-m':(-ΔE/m)(auxiliary oil))/cal_th</td>
<td>916.95</td>
<td>842.56</td>
<td>830.83</td>
<td>806.13</td>
<td>807.76</td>
<td>806.89</td>
<td>782.81</td>
<td>760.95</td>
</tr>
<tr>
<td>(-m'''(-ΔE/m)(fusce))/cal_th</td>
<td>3.51</td>
<td>4.61</td>
<td>6.33</td>
<td>4.73</td>
<td>4.57</td>
<td>5.61</td>
<td>6.13</td>
<td>4.09</td>
</tr>
<tr>
<td>m'(-ΔE/m)(compound))/cal_th</td>
<td>-7097.44</td>
<td>-7186.94</td>
<td>-7193.25</td>
<td>-7213.59</td>
<td>-7223.02</td>
<td>-7215.70</td>
<td>-7244.73</td>
<td>-7270.56</td>
</tr>
<tr>
<td>i(-ΔE/m)(compound))/cal_th g⁻¹</td>
<td>-10239.84</td>
<td>-10239.57</td>
<td>-10239.31</td>
<td>-10239.48</td>
<td>-10240.03</td>
<td>-10241.37</td>
<td>-10240.67</td>
<td>-10242.91</td>
</tr>
<tr>
<td>i(-ΔE/m)(compound))/cal_th g⁻¹</td>
<td>-10240.40 ± 0.43 (mean and standard deviation of the mean)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

---

**Notes:**

- a The symbols and abbreviations of this table are those of W. N. Hubbard et al., *Experimental Thermodynamics*, Chap. 5, pp. 75-128. F. D. Rossini, editor. Interscience: 1956.
- b (t'cont)(t_f - 298.15 K) + (t'cont)(298.15 K - t_i + ∆t_corr).
- c Items 81 to 85, 87 to 90, 93 and 94 of the computation form of Hubbard et al (footnote a).
| m'(compound)/g | m''(auxiliary oil)/g | m'''(fuse)/g | n(H2O)/mol | \( \Delta t_c/K = (t_f - t_i + \Delta t_{corr})/K \) | (calor) \( (-\Delta t_c)/c_{th} \) | ((cont) \( (-\Delta t_c)/c_{th} \) | \( \Delta E_{ign}/c_{th} \) | \( \Delta E_{dec}(HNO_3)/c_{th} \) | \( \Delta E_{(corr to std states)}/c_{th} \) | \( -m''(\Delta E_c/m)(auxiliary oil))/c_{th} \) | \( -m'''(\Delta E_c/m)(fuse))/c_{th} \) | \( -m''(\Delta E_c/m)(compound))/c_{th} \) | \( (\Delta E_c/m)(compound))/c_{th} g^{-1} \) | \( (\Delta E_c/m)(compound))/c_{th} g^{-1} \) |
|----------------|---------------------|-------------|-------------|---------------------------------|-------------------------------|-------------------------------|------------------|-----------------|-----------------|-----------------|------------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 0.683943       | 0.074882            | 0.000984    | 0.05535     | 1.99903                         | -8014.41                      | -9.98                         | 0.18             | 0.29            | 3.16            | 824.03          | 3.98              | -10516.59       | -10518.18       | -10518.18       | 0.37 (mean and standard deviation of the mean) |
| 0.705659       | 0.054872            | 0.001077    | 0.05535     | 2.002601                         | -8025.23                      | -8.79                         | 0.15             | 0.15            | 3.19            | 603.84          | 4.36              | -7422.30        | -10518.18       | -10518.18       |
| 0.701350       | 0.059812            | 0.001552    | 0.05535     | 2.002920                         | -8026.50                      | -8.72                         | 0.16             | 0.16            | 3.18            | 658.20          | 6.29              | -7367.21        | -10518.18       | -10518.18       |
| 0.705518       | 0.055607            | 0.001041    | 0.05535     | 2.004169                         | -8031.51                      | -8.72                         | 0.18             | 0.09            | 3.19            | 611.92          | 4.22              | -7420.63        | -10518.18       | -10518.18       |
| 0.705477       | 0.073525            | 0.000992    | 0.05535     | 2.053260                         | -8228.24                      | -8.72                         | 0.18             | 0.13            | 3.27            | 809.10          | 4.02              | -7420.57        | -10518.18       | -10518.38       |
| 0.706340       | 0.053966            | 0.001248    | 0.05535     | 2.002558                         | -8025.05                      | -8.71                         | 0.18             | 1.94            | 3.18            | 593.86          | 5.05              | -7429.55        | -10518.18       | -10518.38       |

*The symbols and abbreviations of this table are those of W. N. Hubbard et al., *Experimental Thermochimistry*, Chap. 5, pp. 75-128. F. D. Rossini, editor. Interscience: 1956.

- \( t_i = 298.15 \) K + \( t_f + \Delta t_{corr} \).

- \( t_i = 298.15 \) K.

- Items 81 to 85, 87 to 90, 93 and 94 of the computation form of Hubbard et al. (footnote a).
### TABLE 9. Derived Molar Values at 298.15 K

<table>
<thead>
<tr>
<th>Compound</th>
<th>$\Delta E_C^\circ$ kcal mol$^{-1}$</th>
<th>$\Delta H_C^\circ$ kcal mol$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hexacyclic exo,exo-dihydro-dinorbornadiene</td>
<td>-1938.22 ± 0.46</td>
<td>-1940.88 ± 0.46</td>
</tr>
<tr>
<td>Hexacyclic endo,endo-dihydro-dinorbornadiene</td>
<td>-1945.44 ± 0.36</td>
<td>-1948.11 ± 0.36</td>
</tr>
<tr>
<td>exo-Tetrahydrodicyclopentadiene</td>
<td>-1455.37 ± 0.26</td>
<td>-1457.74 ± 0.26</td>
</tr>
<tr>
<td>1,7-Dimethylindan</td>
<td>-1497.50 ± 0.22</td>
<td>-1499.57 ± 0.22</td>
</tr>
<tr>
<td>1,4-Dimethyl-2-isobutylbenzene</td>
<td>-1706.86 ± 0.24</td>
<td>-1709.53 ± 0.24</td>
</tr>
</tbody>
</table>
1,7-Dimethylindan

\[ 11 \text{C(c, graphite)} + 7 \text{H}_2(g) = \text{C}_{11}\text{H}_{14}(l) \] (7)

1,4-Dimethyl-2-isobutylbenzene

\[ 12 \text{C(c, graphite)} + 9 \text{H}_2(g) = \text{C}_{12}\text{H}_{18}(l) \] (8)

Derived values of the enthalpy of formation for the five compounds are given in Table 10. Values of the enthalpy of vaporization of the two hydrogenated dimers of norbornadiene and of \( \text{exo-tetrahydrodicyclopentadiene} \) were provided by Dr. Margret Månsso of the University of Lund, Lund, Sweden. These values permit derivation of enthalpies of formation in the gaseous state. The enthalpies of formation of \( \text{CO}_2(g) \) and \( \text{H}_2\text{O}(l) \) were taken to be \(-94.051 \) and \(-68.315 \) kcal mol\(^{-1}\), respectively. Uncertainties assigned were \( 0.011 \) kcal mol\(^{-1}\) for \( \text{CO}_2(g) \), and \( 0.010 \) kcal mol\(^{-1}\) for \( \text{H}_2\text{O}(l) \).

The values of uncertainty expressed in Table 10 are also the "uncertainty interval" and reflect uncertainties in the enthalpies of formation of gaseous \( \text{CO}_2 \) and liquid water as well as the combustion calorimetry.

It is of interest to note that the greater value of the enthalpy of formation of the \( \text{end}_2,\text{end}_2 \)-dimer of hydrogenated norbornadiene is at least qualitatively what would be expected from the close proximity of the hydrogen atoms and their repulsions.

The value of the enthalpy of combustion of \( \text{exo-tetrahydrodicyclopentadiene} \) is in excellent agreement with a value obtained earlier in this laboratory on a sample of less certain purity.

Combustion calorimetry of \( 1\text{-ethyl-8-methylnaphthalene} \) and \( 1,6\)-dimethylindan is in progress. When this study is completed, it will be possible to make an assessment of the magnitude of the steric interaction energies in the 1,8-alkyl substituted naphthalenes and the 1,7-alkyl substituted indans.

---

<table>
<thead>
<tr>
<th>Compound</th>
<th>State</th>
<th>$\Delta H_f^\circ$ (kcal mol$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hexacyclic <em>exo,exo</em>-dihydro-</td>
<td>(l)</td>
<td>9.34 ± 0.49</td>
</tr>
<tr>
<td>dinorbornadiene</td>
<td>(g)</td>
<td>24.97 ± 0.50</td>
</tr>
<tr>
<td>Hexacyclic <em>endo,endo</em>-dihydro-</td>
<td>(l)</td>
<td>16.56 ± 0.40</td>
</tr>
<tr>
<td>dinorbornadiene</td>
<td>(g)</td>
<td>32.18 ± 0.41</td>
</tr>
<tr>
<td><em>exo</em>-Tetrahydrodi-</td>
<td>(l)</td>
<td>-29.29 ± 0.29</td>
</tr>
<tr>
<td>cyclopentadiene</td>
<td>(g)</td>
<td>-17.65 ± 0.29</td>
</tr>
<tr>
<td>1,7-Dimethylindan</td>
<td>(l)</td>
<td>-13.20 ± 0.26</td>
</tr>
<tr>
<td>1,4-Dimethyl-2-</td>
<td>(l)</td>
<td>-33.92 ± 0.28</td>
</tr>
<tr>
<td>isobutylbenzene</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
3. HEAT CAPACITIES OF RJ-6 AND JP-10

The heat capacities of JP-10 (exo-tetrahydrodicyclopentadiene) and RJ-6 (a blend of JP-10 and three hydrogenated dimers of norbornadienes) were measured on a Perkin-Elmer DSC-2 differential scanning calorimeter. Measurements had been made previously on these substances; however the results were suspect because Perkin-Elmer volatile sample pans were used. With these pans it is difficult to seal an adequate amount of liquid sample for accurate measurements. Also, results have been obtained with these pans for other liquids that incorrectly show maxima in plots of liquid heat capacities versus temperature. For these reasons new measurements were made in high pressure cells that were designed in part to overcome these problems.

Results were obtained on 25-mg samples from 260 K up to 465 K where the vapor pressure reaches about 2 atmospheres. Two methods of measurement were used with the high pressure cells: (1) the ordinary "displacement" method and (2) a "differential" method suggested by Cassel. The temperature range was covered in two stages, 260-373.3 K and 335-465 K, so that the methods could be compared before the samples were heated to the boiling region. After results were obtained at the highest temperature, repeat measurements by method 2 for the lower temperature range gave results that agreed to within 0.5 percent of those obtained initially. This is believed to be evidence of lack of significant change in the samples during the study. The results from the two methods agreed to within 1 percent. The values selected and given below are those obtained from the differential, or substitution, method because it is inherently more accurate.

The heat capacities of the two fuels are represented by the following equations:

JP-10

\[
C_p (\text{cal/g K}) = (0.10423 + 0.76972 \times 10^{-3} T \\
+ 0.46992 \times 10^{-6} T^2) \pm 0.00081
\]

for \( T = 260 \) to \( 465 \) K \hspace{1cm} (9)

\[\text{12} \]

RJ-6

\[ C_p (\text{cal/g K}) = (0.013913 + 0.10963 \times 10^{-2} T) \]

\[ \pm 0.00056 \]

for \( T = 260 \) to \( 465 \) K \hspace{1cm} (10)

where uncertainties are standard deviations at either end of the measurement range.

The new results as well as those obtained previously, in this laboratory and at the Catholic University of America\textsuperscript{7,13} by C. T. Moynihan, are shown in Figures 1 and 2. The new values of heat capacity are believed to be reliable. The results for JP-10 turn upward as they should with increasing temperature. Also, the values of RJ-6 are lower and essentially linear with temperature as would be expected by the modifications produced by introducing the higher molecular weight, hydrogenated dimers of norbornadienes into the JP-10.

\textsuperscript{13} C. T. Moynihan, private communication, March 14, 1978.
FIGURE 1. Comparison with other experimental heat capacities of RJ-6.
FIGURE 2. Comparison with other experimental heat capacities of JP-10.
4. PUBLICATIONS AND PRESENTATIONS


5. MANUSCRIPTS ACCEPTED FOR PUBLICATION


Vapor Heat Capacities and Enthalpies of Vaporization of Six Miscellaneous Organic Compounds by I. A. Hossenlopp and D. W. Scott. Accepted by Journal of Chemical Thermodynamics.
DISTRIBUTION LIST

CONTRACTORS

Aerospace Corporation
The Ivan L Getting Laboratories
Attn: Dr Charles M Randall
P O Box 95085
Los Angeles, CA 90045

CINDAS
Purdue University Research Park
Attn: Dr H H Li
2595 Yeager Road
West Lafayette, IN 47907

Department of Energy
Bartlesville Energy Technology Center
Attn: Mr William D Good
Bartlesville, OK 74003

Dow Chemical Company
Thermal Laboratory, Bldg 1707
Attn: Dr Malcolm Chase
Midland, MI 48640

University of Manchester/UMIST
Department of Metallurgy
Attn: Dr Roy Taylor
Grosvenor Street
Manchester Ml 7HS, ENGLAND

Department of Energy
Pittsburgh Energy Technology Center
Attn: Dr Francis E Spencer, Jr
P. O. Box 10940
Pittsburgh, PA 15236

National Bureau of Standards
Thermophysics Division
Attn: Dr Ared Gezaireliyan
Washington, DC 20234

National Bureau of Standards
Chemical Thermodynamics Division
Attn: Dr Stan Abramowitz
Mr David Ditmars
Washington, DC 20234

University of Nevada
Mackay School of Mines
Attn: Prof Eugene Miller
Reno, NV 89507

Purdue University
School of Mechanical Engineering Properties Research Laboratory
Attn: Dr R E Taylor
2595 Yeager Road
West Lafayette, IN 47907

Space Sciences, Inc
Attn: Mr Milton Farber
135 W Maple
Monrovia, CA 91016

SRI International
Physical Sciences Division
Attn: Dr D L Hildenbrand
Menlo Park, CA 94025

NON-CONTRACTORS

AFML/MXE (L Scott Theibert)
Wright-Patterson AFB, OH 45433

AFML/LP (Dr Merrill L Minges)
Wright-Patterson AFB, OH 45433

AFML/MBC (Dr W C Kessler)
Wright-Patterson AFB, OH 45433

Jet Propulsion Laboratory
Attn: Mr. Theodore W Price
4800 Oak Grove Drive
Pasadena, CA 91103

Johns Hopkins University
Applied Physics Laboratory
Attn: Dr Robert Fristrom
Johns Hopkins Road
Laurel, MD 20810
AFRPL/LKCB (Mr Curtis C Selph)
Edwards AFB, CA 93523

AFRPL/PACP (Dr David Mann)
Edwards AFB, CA 93523

AFWL/ALD (Dr Leroy Wilson)
Kirtland AFB, NM 87117

AFWL/ALD (Major David S Olson)
Kirtland AFB, NM 87117

AFAOL/RJT (Dr F D Stull)
Wright-Patterson AFB, OH 43433

U.S. Army Research Office
Attn: Dr David R Squire
P O Box 12211
Research Triangle Park, NC 27709

Atlantic Research Corporation
Attn: Dr Charles Henderson
5390 Cherokee Avenue
Alexandria, VA 22314

University of California
Department of Chemistry
Attn: Dr Leo Brewer
Berkeley, CA 94700

Cornell University
Department of Chemistry
Attn: Dr S H Bauer
Ithica, NY 14850

NSSC
Department of the Navy
Code NSEA-0331
Attn: Mr John W Murrin
Washington, DC 20360

Naval Ordnance Station
Attn: Mr Al Camp
Indian Head, MD 20640

NASA
Lewis Laboratories (Mail Stop 6-1)
Attn: Mr Sanford Gordon
Cleveland, OH 44135

NAS-NRC
Numerical Data Advisory Board
2101 Constitution Avenue, NW
Washington, DC 20418

National Bureau of Standards
OSRD
Attn: Dr David Lide
Washington, DC 20234

National Bureau of Standards
Chemical Thermodynamics Division
Attn: Mr Donald D Wagman
Washington, DC 20234

National Bureau of Standards
Office of Standard Reference Materials
Attn: Dr Richard Kirby
Washington, DC 20234

National Bureau of Standards
Thermophysical Properties Division
Attn: Dr Jerry Hust
Boulder, CO 80302

Office of Naval Research
Attn: Mr Rudolph Marcus
1030 E Green Street
Pasadena, CA 91101

Office of Naval Research
Power Program, Code 473
Attn: Dr Richard Miller
800 North Quincy Street
Arlington, VA 22217

Rice University
Department of Chemistry
Attn: Dr John Margrave
Houston, TX 77001

United Technologies Corporation
Chemical Systems Division
Attn: Dr R O MacLaren
Sunnyvale, CA 94086

Chemical Propulsion Information Agency
APL/JHU (2 copies)
Johns Hopkins Road
Laurel, MD 20810