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Thermo Electron Corporation

**December 1983**

Prepared for
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Lewis Research Center
Cleveland, Ohio
Under Contract DEN 3-302

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## Dedication to Grover C. Kinsman

Those of us who worked on Bottoming Cycle Systems at Thermo Electron Corporation have long recognized Grover Kinsman as one of the leading designers, for his contributions were many and significant. More than a valued and competent employee, he was a person who could be counted upon for help when needed. His reasoned judgment and willing manner made working with him both pleasant and productive. It is difficult to do justice to the magnitude of his contribution.

We are all saddened and humbled by his untimely death and he will be greatly missed. The memory of our good friend – his warmth and humanity – will be with us forever.

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# SUMMARY

The major effort and work accomplished in this contract with NASA Lewis Research Center, as part of their Waste-Heat Utilization Programs, are highlighted below.

- A total of 1627 hours of RC-1 testing was completed in the dynamic loop at the following operating temperatures:

  - 442 hours at 700°F
  - 653 hours at 800°F
  - 532 hours at 900°F

  The methods of sample analysis included:

  - Neutralization Number by Color-Indicator Titration (performed in-house)
  - Gas Chromatography (performed in-house)
  - Mass Spectral Analysis (performed by an outside laboratory)

  Static capsule tests up to 900°F temperatures were also performed in a parallel effort. The results of all tests performed, both dynamic and capsule, showed no thermal degradation or changes in RC-1 fluid constituents.

- A system analysis was performed. Data on adiabatic diesels in configurations both with and without aftercooling were supplied by NASA Lewis, and the performance of an RC-1 Rankine bottoming cycle system was computed for these engines.

  The analysis showed that the bottoming cycle effectively utilizes the relatively higher exhaust energy of non-aftercooled diesels to the extent that increased bottoming cycle power output more than compensates for a slight diesel performance penalty associated with non-aftercooling. Bottoming cycle power output reaches 56 horsepower, which represents a 17.6-percent increase in the 317 horsepower of a turbocharged non-aftercooled diesel engine (TC) to yield a compound power output of 373 horsepower. The calculated brake specific fuel consumption (BSFC) for this diesel with a bottoming cycle system is 0.268 lb/bhp-hr, or 8.5-percent better than the comparable turbocompound-aftercooled engine used as the diesel performance reference. Application of the bottoming cycle to a turbocompound engine produced a BSFC result of 0.258 lb/hp-hr, or 12-percent better than the turbocompound-aftercooled diesel.

- A system design for a typical truck installation was prepared and incorporates all components of the RC-1 Rankine-cycle system into three (3) subsystems: the power conversion unit (PCU), which includes the turbine, gearbox, and feedpump; the vapor-generator module; and the condenser-regenerator module. The condenser-regenerator module consists of a regenerator that has been integrated with the cylindrical air-cooled condenser. The cooling module also contains an electric motor with a double-ended through-shaft that drives the booster pump, gerotor lubrication pump, and the clutched fan.

- A life-cycle cost analysis was performed for the RC-1 system design and the potential capital cost of the unit was estimated at $8400 (selling price). Using the NASA reference data provided (i.e., selling price/manufacturing price = 2.0, fuel price = $1.20/gallon), the simple payback period of a turbocharged diesel plus bottoming cycle (without taxes or maintenance) was calculated to be just under 3 years, when compared to the reference turbocompound-aftercooled diesel. The payback interval decreases as fuel price increases.

- Areas of technical development that have been defined as a result of this program, and need to be addressed are:

  - Heat exchanger fouling
  - RC-1 working fluid thermal stability at elevated temperatures up to and exceeding 1000°F
  - High-temperature seal development.

# 1. INTRODUCTION

The steep increases in the price of transportation fuels over the last decade have spurred research and development of more efficient prime movers for heavy-duty transport equipment. A major thrust of this work has been the improvement of the direct injection diesel engine - the most efficient and ubiquitous power source for heavy-duty mobile applications. Incremental improvements in engine efficiency have been brought about through refinements of conventional diesel engine technology to improve thermodynamic performance and combustion phenomena and reduce engine friction. A more innovative approach to improved diesel engine efficiency - one that offers a substantial improvement in efficiency - is the adiabatic engine concept. Through the use of high-temperature materials (mainly ceramic compounds with exceptional mechanical properties at elevated temperatures) in those parts of the engine exposed to the combustion process, heat loss from the engine is greatly diminished and there is a resultant increase in engine efficiency. An increase in exhaust gas temperature is characteristic of the adiabatic engine. Only a part of the extra heat energy contained by the adiabatic engine can be converted to work. The balance of the heat is carried from the engine in the higher temperature exhaust gas.

The other approach to improving prime mover efficiency is the concept of engine compounding wherein a second prime mover is employed to recover power from the reject heat of the fuel-consuming prime mover - in this case the exhaust gas of the diesel engine. Over the past decade, Thermo Electron Corporation has been at the forefront of Bottoming Cycle Technology. We have developed and tested a fully operational diesel/organic Rankine-cycle compound engine for heavy-duty transport that has shown fuel savings of more than 14 percent over the baseline diesel engine alone in dynamometer tests, and over 13 percent in on-highway vehicle tests (ref. 1). These results have been obtained by bottoming present heavy-duty diesel engines that have exhaust temperatures in the range of 650° to 900°F (depending upon their size, fuel air ratio, degree of turbocharging, and whether they are two cycle or four cycle). For this temperature, Fluorinol, a mixture of trifluoroethanol and water, has been shown to produce the greatest power recovery of any working fluid. However, because the practical upper temperature limit for Fluorinol is about 600°F (with conditioning), due to thermal decomposition, it is not the optimum organic working fluid for the higher temperature exhaust gas of the adiabatic diesel engine. These higher temperature heat sources call for a working fluid with higher temperature capability.

In this waste-heat utilization program to design a Rankine-cycle system to bottom an adiabatic diesel engine, the organic fluid designated RC-1 was chosen as the working fluid. The program included tasks to conduct a system analysis, preliminary design, and cost analysis of an RC-1 organic Rankine bottoming cycle system for heavy-duty transport applications. The other major effort was the high-temperature stability testing of the RC-1 organic fluid.

A full description of the work accomplished in the past year is given in the following sections of this report.

## 2. WORK EFFORTS AND ACCOMPLISHMENTS

Thermo Electron Corporation under contract with NASA Lewis Research Center has participated in their Waste-Heat Utilization Program. During the past year, work efforts were directed towards the following major task areas.

- Thermal Stability Testing of RC-1 Organic Fluid - The major goal of these tests is to ascertain the highest operating temperature level of RC-1 through the performance of stability life testing of the organic fluid in a dynamic fluid test loop that simulates the operation of a Rankine-cycle.

- Cycle Analysis - This task consists of performing a parametric analysis of a simple organic Rankine bottoming cycle for an adiabatic diesel engine employing a single vapor-generator and RC-1 working fluid. The objective is to identify system design point criteria based on a combination of factors including cycle efficiency, utilization efficiency of the available exhaust gas heat, heat exchanger design, and turbine design. The schedule of exhaust gas conditions versus diesel engine power was provided by NASA Lewis.

- Preliminary System Design - Based on the selected design point, this task entailed the preliminary baseline design of the RC-1 organic Rankine bottoming cycle system for the reference 300-horsepower diesel engine.

- Life-Cycle Cost Analysis - This final task effort is to evaluate the potential capital cost, maintenance cost and, thus, the simple payback and return on investment generated by the fuel savings capability of the baseline bottoming cycle system design defined by the above analysis and design tasks.

### 2.1 WORKING FLUID STUDIES

The organic fluid RC-1 is a mixture of 60 mole percent pentafluorobenzene (PFB) and 40 mole percent hexafluorobenzene (HFB). Key features of this working fluid for waste-heat utilization from prime movers are:

- Thermally stable at high temperatures

- High chemical stability (resistant to $O_2$ and $H_2O$ contamination and compatible with materials of construction)

- Excellent thermodynamic characteristics (for power generation from high-temperature gaseous waste-heat sources)
- Nonflammable in air
- Low toxicity (acute and subacute exposures)
- Low freezing point (flow point of -44°F)
- Excellent turbine expansion characteristics (particularly for low power applications)

The initial program work consisted of modifying an existing dynamic fluid test loop to provide capability to test RC-1 organic fluid up to 1000°F for periods up to 1000 hours. Subsequently, the test program was initiated by operating the loop containing the RC-1 fluid at various temperature levels from 700° to 1000°F. In addition to loop testing, static glass capsule tests are being carried out.

### 2.1.1 Dynamic Loop

The dynamic test loop has been designed to expose the RC-1 working fluid to the conditions that are encountered in operating systems. Samples of the fluid can be chemically examined to determine any degradation that may occur. The idea of the loop is to expose the fluid to very prescribed conditions over fixed periods of time, and chemically measure any changes in the fluid composition.

The loop schematic is presented in Figure 1. The main considerations in the loop design have been: (1) high reliability and leak tightness, (2) loop control for long-term stable operation with a minimum of attention, and (3) key temperature and pressure measurements.

The fluid flow circuit is identical with that of a Rankine power system except that the turbine expander is replaced by a pressure letdown valve. Instrumentation and controls are incorporated to permit unattended round-the-clock operation of the dynamic loop shown in Figure 2.

The fluid loop used for the thermal stability testing of the RC-1 organic working fluid is similar to those used in prior fluid testing at Thermo Electron (i.e., thermal stability testing of Fluorinol). Because the upper temperature limit of RC-1 is higher than ever encountered with organic fluids (greater than 700°F), it was necessary to modify the method of heating the RC-1 to these high temperature levels. Prior testing with Fluorinol utilized a boiler that was electrically heated and used vapor-phase heat transfer to the boiler tube carrying the test fluid. Electrical

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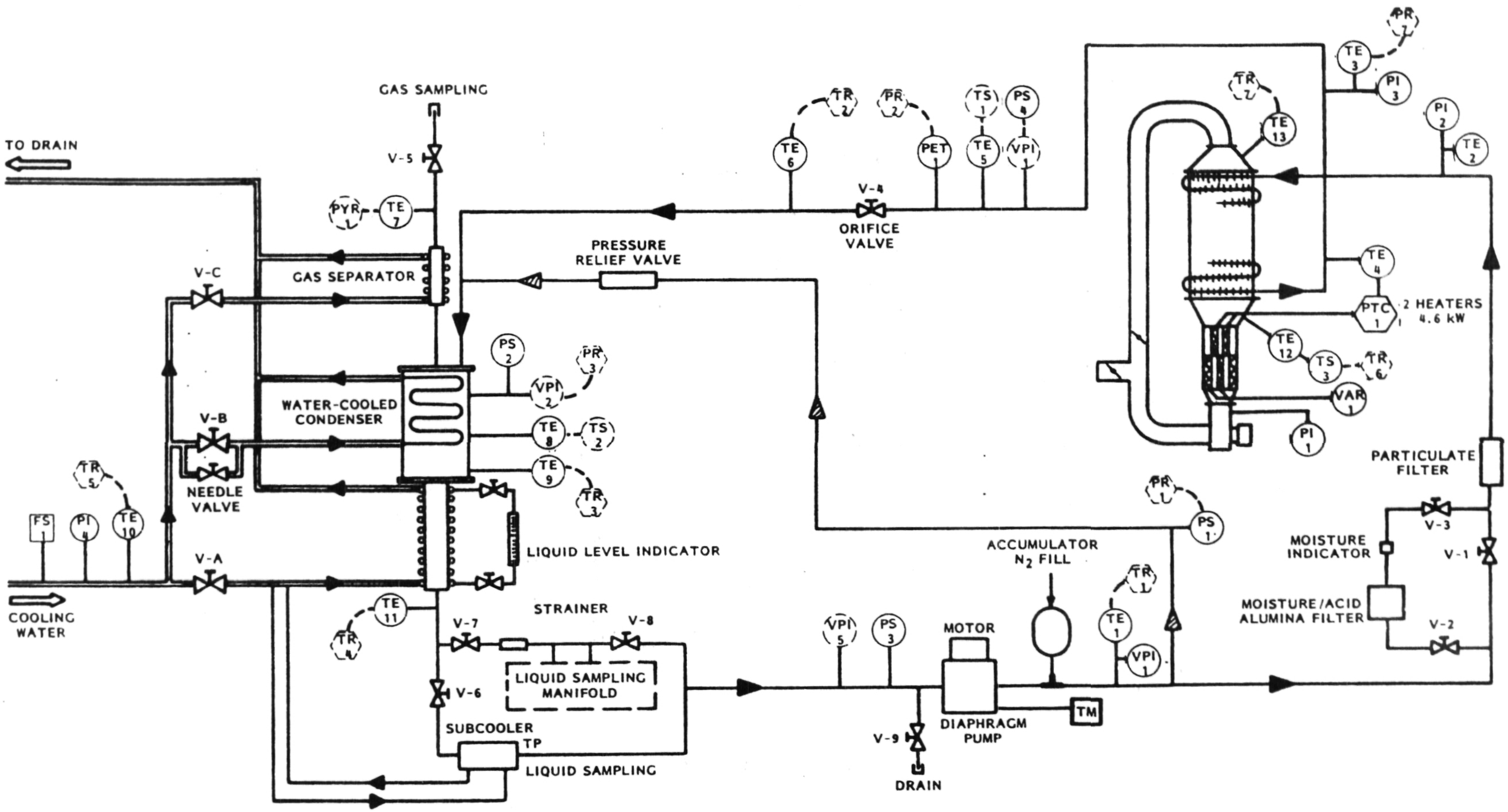



LEGEND:

- INSTRUMENTATION

| | |
|---|---|
| VAR | VARIAC |
| TE | TEMPERATURE ELEMENT |
| TR | DATA LOGGER RECORDER |
| VPI | VACUUM PRESSURE INDICATOR |
| PS | PRESSURE SWITCH |
| TS | TEMPERATURE SWITCH |
| PET | PRESSURE TRANSDUCER |
| PR | DATA LOGGER RECORDER |
| PYR | PYROMETER |
| FS | FLOW SWITCH |
| PI | PRESSURE INDICATOR |
| VI | VOLTAGE INDICATOR |
| TM | ELAPSED TIME INDICATOR |
| PTC | PROPORTIONAL TEMPERATURE CONTROLLER |

- PANEL MOUNT

- PLUMBING FLUID
  - WORKING FLUID
  - V VALVE

- PLUMBING WATER
  - WATER
  - V VALVE

Figure 1. RC-1 Organic Working Fluid Loop

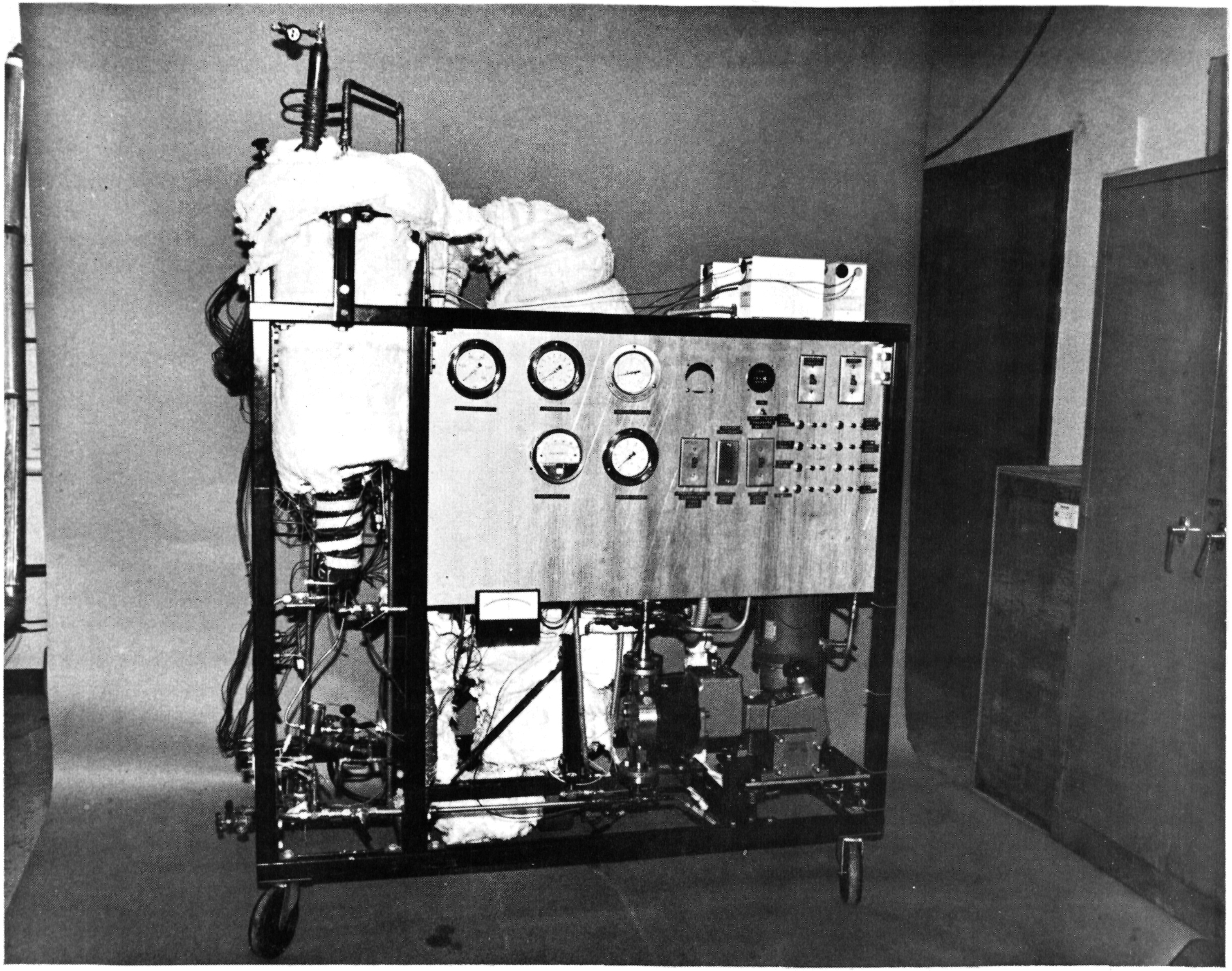


Figure 2. Front View of RC-1 Dynamic Fluid Loop

heaters were immersed in the heat transfer fluid (Dowtherm A with a temperature limit of 720°F), with the boiler tube located in the vapor space above the heat transfer fluid surface.

This RC-1 loop uses a finned-tube heat exchanger for the vapor-generator and a forced convection hot air system to heat the RC-1 organic fluid to temperatures up to 1000°F. Figure 3 is a view of the exposed electrical heating elements that heat the air passing over them to the desired temperature levels.

### 2.1.2 Test Results

More than 1600 hours of testing was completed on the dynamic fluid test loop. Testing was performed at 700°, 800°, and 900°F operating temperature levels. Table 1 summarizes the tests, showing the operating hours and other highlights at each test condition. The three (3) major methods of fluid analysis employed during these tests and their results are:

- Neutralization Number by Color-Indicator Titration (ref. 2)

  This process is performed in-house and measures the acidity of the fluid, expressed in milligrams of potassium hydroxide necessary to neutralize one (1) gram of the fluid sample. The allowable acid level established for the former Fluorinol-85 Rankine-cycle system was a neutralization number of 0.040. All samples taken in these RC-1 loop tests showed no acid formation. Only the initial sample at about the 90-hour mark of Test No. 1 (700°F) registered a neutralization number of 0.0178, which is well below the 0.040 limit. All other samples for testing performed showed neutralization numbers of zero (0) or very close to it (another sample had a 0.006 neutralization number).

- Gas Chromatography (GC)

  A Shimadzu Model 6AM gas chromatograph with an integral thermal conductivity detector was used for this analysis, which is also performed in-house. The samples analyzed during the tests and compared to the pretest stock sample GC of the RC-1 organic fluid show identical constituent peaks in the same proportion. Figures 4 and 5 are GC's of the pretest sample and a sample of the RC-1 fluid at the 606-hour mark of Test No. 2 (800°F operating temperature). Figure 4 is at an attenuation factor of 64 and shows the 606-hour sample to contain the same proportion of RC-1 constituents (PFB and HFB) as the stock working fluid. Figure 5 at an attenuation factor of 8 again shows similar traces with the peak pentafluorochlorobenzene (PFCB) identified with other trace constituents that were already present in the pretest sample.

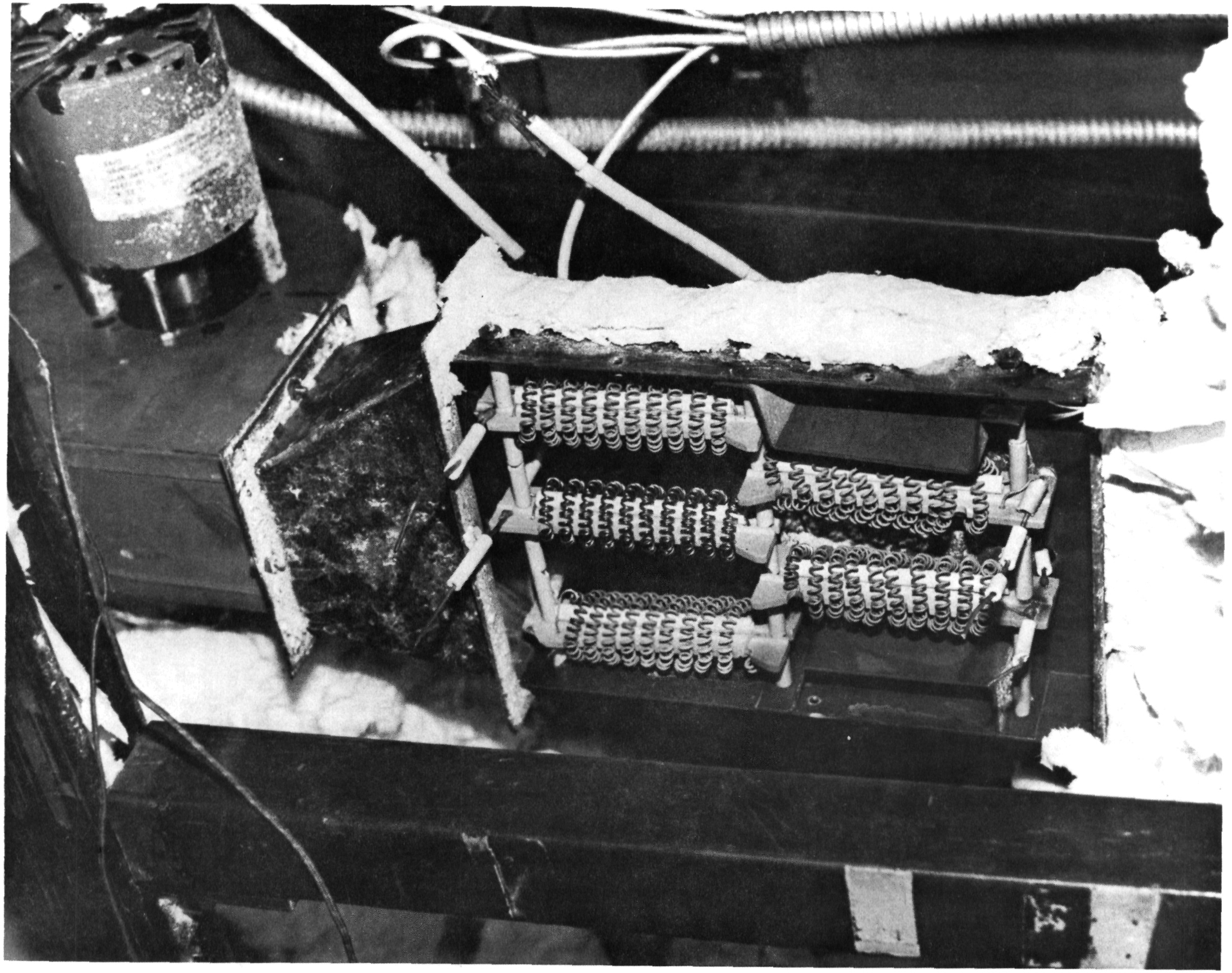


**Figure 3.** View of Heating Elements and Hot Air Source for RC-1 Dynamic Fluid Loop

TABLE 1

SUMMARY OF RC-1 TESTS IN DYNAMIC FLUID LOOP

| Test No. | Boiler Outlet Temp. (°F) | Test Hours | Method of Sample Analysis: Neutralization Number | Method of Sample Analysis: Gas Chromatography (GC) | Method of Sample Analysis: Mass Spectral Analysis (MS) | Remarks |
|---|---|---|---|---|---|---|
| 1 | 700 | 442 | (5) Samples analyzed with no acid formation detected | No degradation products detected. Traces match pretest RC-1 sample. | Not performed at this operating condition | Test terminated due to rupture of pump diaphragm. Since there was no evidence of thermal degradation at this condition, test was considered complete. |
| 2 | 800 | 653 | (5) Samples analyzed with no acid formation detected | No degradation products detected. Traces at 606 hr match pretest RC-1 sample. | This analysis performed by outside lab with no degradation or changes in RC-1 fluid constituents | All results showed no fluid degradation. Test complete at this condition. |
| 3 | 900 | 532 | (2) Samples analyzed with no acid formation detected | Samples ok with proper concentration of major fluid constituents. Trace peaks observed. | Sample at 417 hours analyzed and shows (2) minor constituent peaks at level of 100 ppm. | Tests conducted through last day of contract period of performance. |
| | Total | 1627 | | | | |

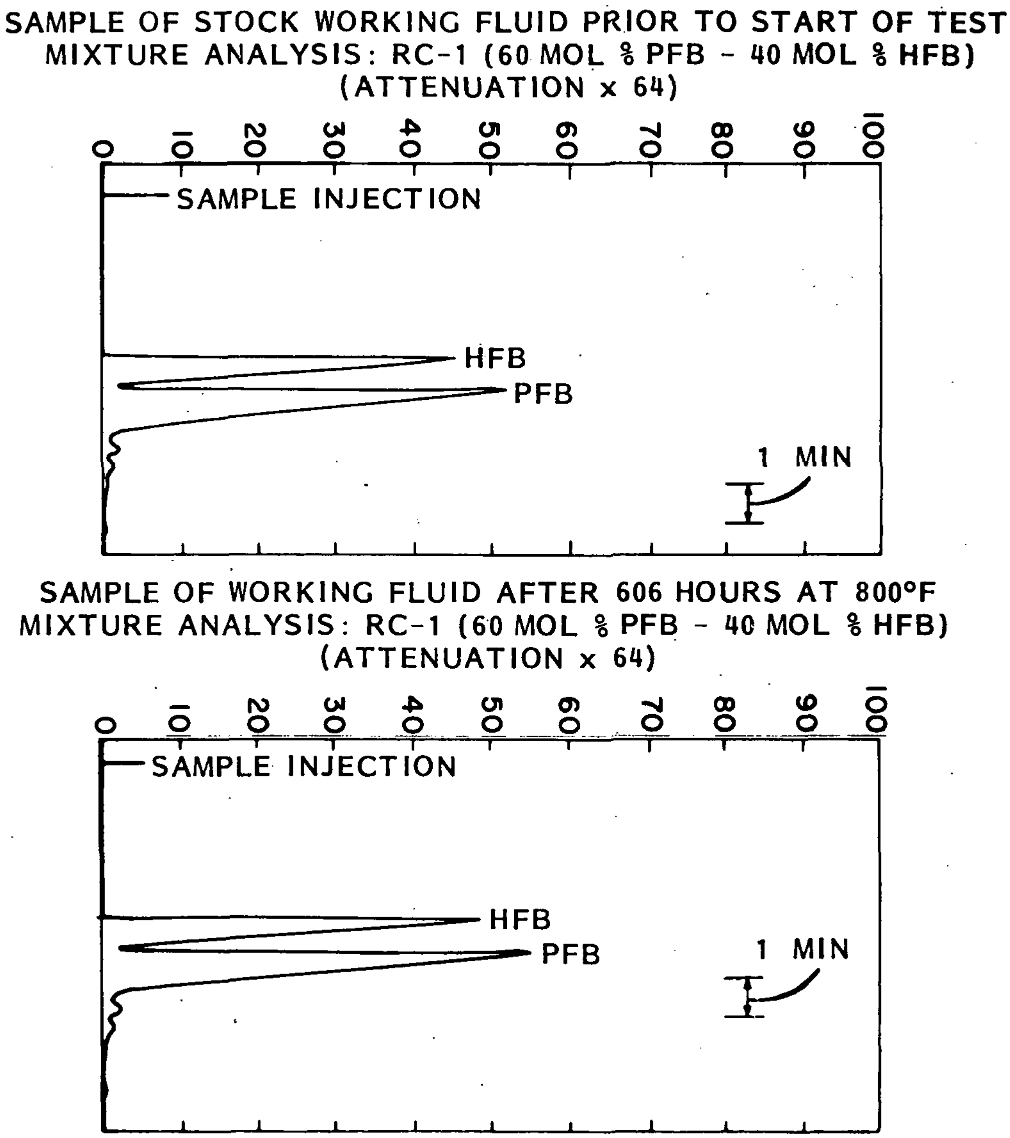



Figure 4. Gas Chromatographs of Dynamic Loop RC-1 Working Fluid Samples - Test No. 2 at Attenuation x 64

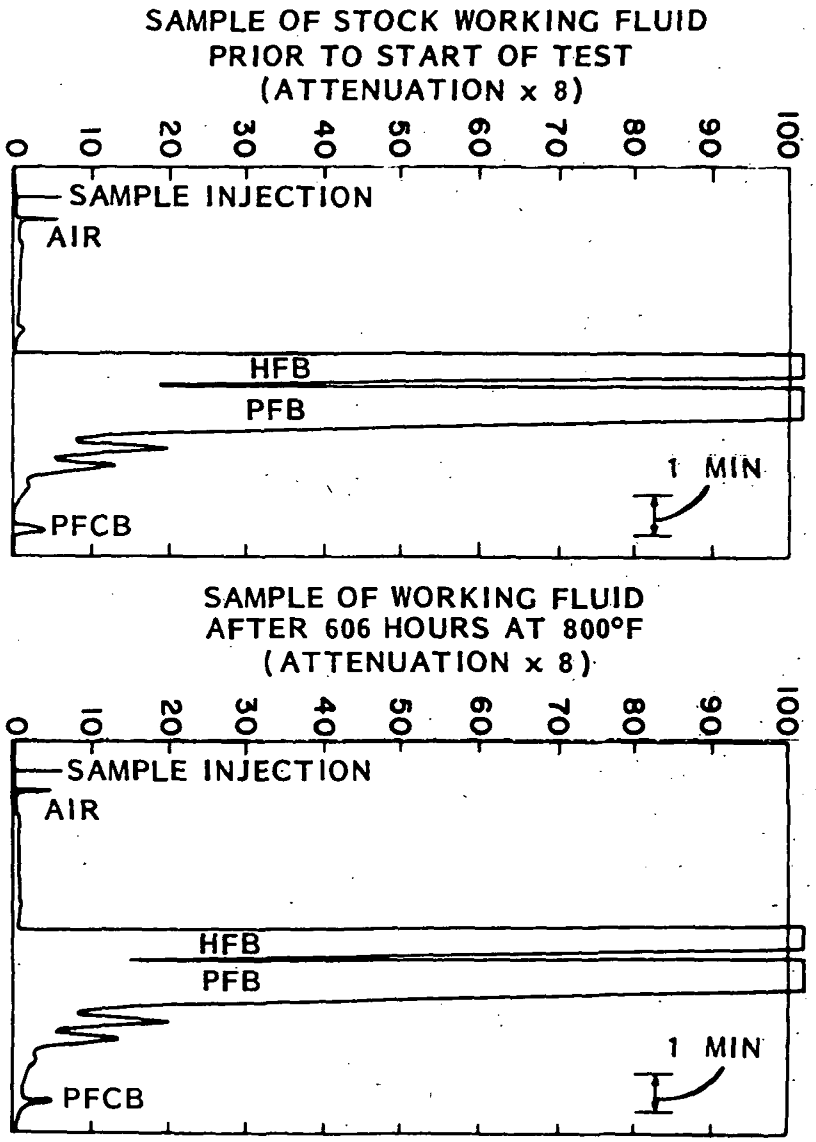



Figure 5. Gas Chromatographs of Dynamic Loop

At the 141-hour mark of Test 3 at the operating temperature of 900°F, an RC-1 sample was taken and analyzed. Figures 6 and 7 are the GC's for this sample and also the corresponding pre-test sample. Again, Figure 6 shows the proper and similar proportions of the PFB and HFB constituents of the RC-1 fluid. At an attenuation factor of 4 which magnifies the constituent peaks, Figure 7 shows no degradation, but the formation of trace constituents which are extremely minute at the 141-hour mark of the test and not quantitatively determinable. GC's of samples at the conclusion of this 900°F test (532 hours) show similar trace peaks with no major growth to contaminant peaks.

- Mass Spectral Analysis (MS)

This method of analysis provides one of the most stringent and exacting methods for the determination of organic compounds. This analysis method is being carried out by an independent outside testing laboratory. Two (2) samples of RC-1 working fluid were sent out for analysis. One of the samples was taken at the 364-hour mark of Test No. 2 at the operating temperature of 800°F. The second sample was the stock fluid that had been loaded into the loop prior to the test.

The written report (see Appendix A) has been received and the outside laboratory (Cambridge Analytical Associates) indicates that inspection of the Reconstructed Gas Chromatograph (RGC) of the Mass Spectra (MS) yielded identical traces for both samples. In conclusion, no impurities were found in the sample that were not detected in the standard indicating no change in the working fluid at the 800°F temperature after 364 hours.

A gas sample and a liquid sample at the 417-hour mark of the 900°F test were sent to Cambridge Analytical Associates for mass spectral analysis. The gas was analyzed and yielded just one minute peak that is probably a rearranged hexafluorobenzene (HFB) molecule. The analysis of the liquid sample showed no breakdown or changes in the major RC-1 constituents, but did indicate two (2) peaks with molecular weights of 330 and 348. These constitutents were present with concentrations of approximately 100 ppm and are identified as fluoroalkanes. The written report on this 417-hour sample at 900°F operating temperature is presented in Appendix B.

- Static Capsule Tests

As a means of further assessing loop results a number of static capsule tests are also being performed. Fluid samples together

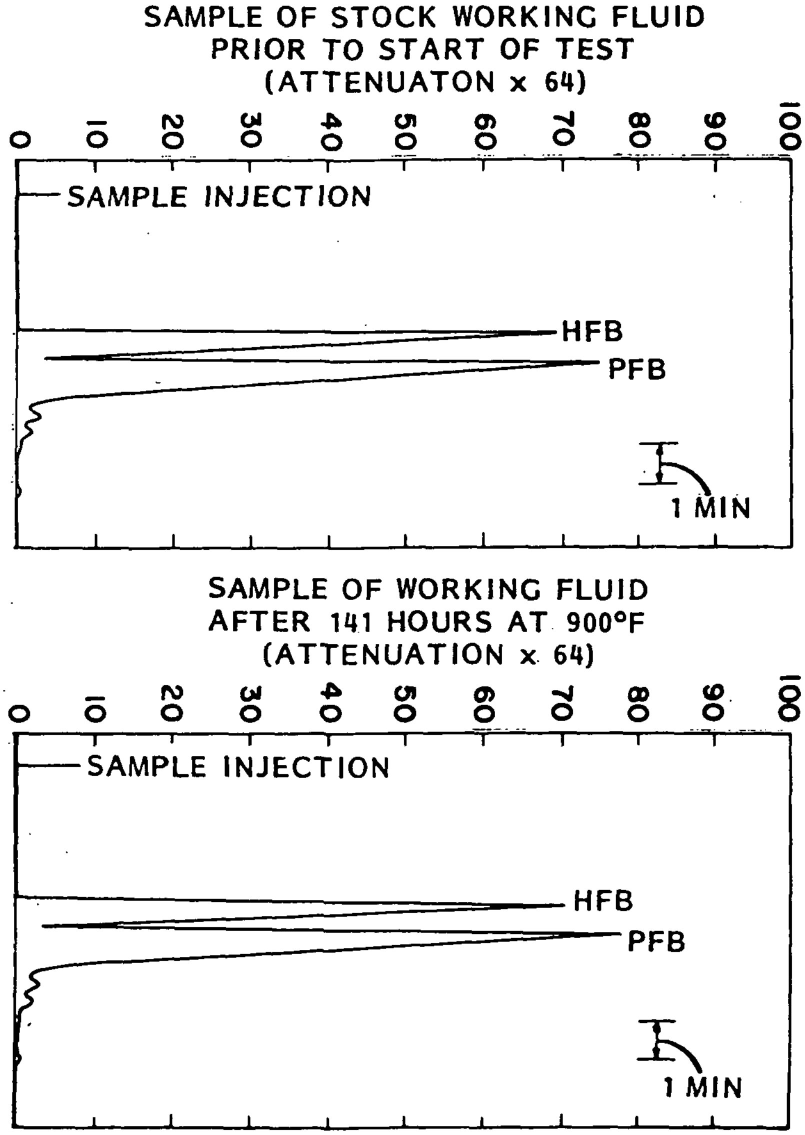



Figure 6. Gas Chromatographs of Dynamic Loop RC-1 Working Fluid Samples - Test No. 3 at Attenuation x 64

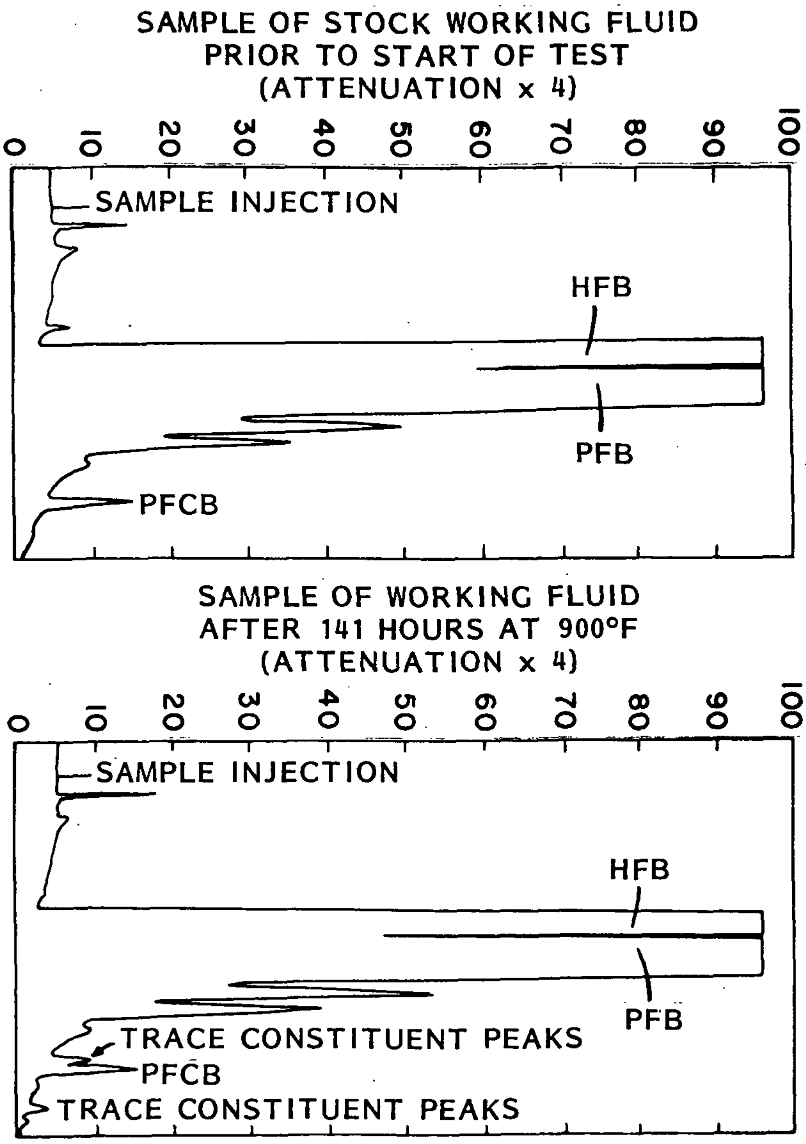



Figure 7. Gas Chromatographs of Dynamic Loop RC-1 Working Fluid Samples - Test No. 3 at Attenuation x 4

with metal coupons are placed in glass capsules, sealed, placed in pressurization manifolds (metal containers for the glass capsules), and heated in an oven at various temperatures for a 14-day period. Each test series consists of testing a total of 10 capsules containing one (1) milliliter of RC-1 with the following metal coupons:

- 2 tubes with no metal coupons
- 2 tubes with 304 stainless steel coupons
- 2 tubes with 316 stainless steel coupons
- 2 tubes with 1010 carbon steel coupons
- 2 tubes with 6061 aluminum coupons

Static capsule tests were performed at 650°, 800°, and 900°F temperature levels and the results of these tests are presented in Tables 2, 3, and 4, respectively. Table 2, which shows the results of the 650°F test, indicates no change in the metal coupon weights. Physical observations of the metal coupons showed a very slight dulling of the St. St. 304 and Aluminum 6061. The St. St. 316 became slightly browned and the Carbon Steel 1010 turned black. The glass tubes remained clear and the RC-1 fluid water white. GC analysis of the samples indicated no change in the RC-1 fluid.

The 800°F test results are summarized in Table 3 and again show no change in the weights of the metal coupons. All metal coupons were generally blackened as were the glass tubes. The RC-1 fluid turned a yellow brown but no change in fluid constituents occurred as determined by the GC analysis, except for trace peaks with one of the Aluminum 6061 samples.

The 900°F results (Table 4) also show no change in the metal weights except for a 3-percent loss from its original weight in the St. St. 304 coupon. All the metal coupons and glass tubes became blackened. The RC-1 fluid without metal in the capsule was brown in appearance, as was the fluid with the Aluminum 6061 samples. The GC of the Aluminum 6061 fluid had three (3) small, late peaks similar to the Aluminum 6061 sample at 800°F. The fluid from the St. St. 304 samples was yellowish in color with evidence of gas evolution. It had the same chromatographic output as the 900°F Aluminum 6061 samples with the addition of two (2) small peaks on the downside shoulder of the PFB peak. The fluid from the Carbon Steel 1010 capsules was yellowish brown and appeared on the chromatograph with the same three (3) peaks as the Aluminum 6061 samples. The St. St. 316 gave results similar to those of the Carbon Steel 1010.

## TABLE 2

## SUMMARY OF RESULTS STATIC CAPSULE TESTS AT 650°F

| No. | Temp. (°F) | Metal | Weight (g) | | Condition | Test Time (Days) | Observations | | | Gas Chromatograph (GC) Analysis |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Before | After | | | RC-1 Solution | Metal | Glass | |
| 1 | 650 | --- | --- | --- | Liquid filled Vac < 20 microns | 14 | Water White | --- | Clear | No Change |
| 2 | 650 | --- | --- | --- | Liquid filled Vac < 20 microns | 14 | Water White | --- | Clear | No Change |
| 3 | 650 | Al 6061 | 0.1023 | 0.1026 | Liquid filled Vac < 20 microns | 14 | Water White | Slightly dulled | Clear | No Change |
| 4 | 650 | Al 6061 | 0.1182 | 0.1187 | Liquid filled Vac < 20 microns | 14 | No fluid rupture | Slightly dulled | Clear | No Change |
| 5 | 650 | St. St. 304 | 0.1679 | 0.1681 | Liquid filled Vac < 20 microns | 14 | Water White | Very slightly dulled "Silver tarnish" brown | Clear | No Change |
| 6 | 650 | St. St. 304 | 0.2047 | 0.2046 | Liquid filled Vac < 20 microns | 14 | Water White | Very slightly dulled, still grey | Clear | No Change |
| 7 | 650 | C.S. 1010 | 0.1497 | 0.1476 | Liquid filled Vac < 20 microns | 14 | Water White | Black, still shiny on cut surfaces | Clear | No Change |
| 8 | 650 | C.S. 1010 | 0.1423 | 0.1422 | Liquid filled Vac < 20 microns | 14 | Water White | Black, still shiny on cut surfaces | Clear | No Change |
| 9 | 650 | St. St. 316 | 0.1926 | 0.1924 | Liquid filled Vac < 20 microns | 14 | Water White | Slightly brownish | Clear | No Change |
| 10 | 650 | St. St. 316 | 0.1962 | 0.1961 | Liquid filled Vac < 20 microns | 14 | Water White | Slightly brownish | Clear | No Change |

## TABLE 3

## SUMMARY OF RESULTS STATIC CAPSULE TESTS AT 800°F

| No. | Temp. (°F) | Metal | Weight (g) | | Condition | Test Time (Days) | Observations | | | Gas Chromatograph (GC) Analysis |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Before | After | | | RC-1 Solution | Metal | Glass | |
| 1 | 800 | --- | --- | --- | Liquid filled Vac < 20 microns | 14 | Brown | --- | Black | No Change |
| 2 | 800 | --- | --- | --- | Liquid filled Vac < 20 microns | 14 | Brown | --- | Black | No Change |
| 3 | 800 | Al 6061 | 0.0975 | 0.0983 | Liquid filled Vac < 20 microns | 14 | Brown | Black | Black | No Change |
| 4 | 800 | Al 6061 | 0.0726 | 0.0733 | Liquid filled Vac < 20 microns | 14 | Brown | Black | Black | Few small late peaks |
| 5 | 800 | St. St. 304 | 0.2418 | 0.2417 | Liquid filled Vac < 20 microns | 14 | Tube ruptured | Brown-Blue | Tube ruptured | No Change |
| 6 | 800 | St. St. 304 | 0.2444 | 0.2444 | Liquid filled Vac < 20 microns | 14 | Brown | Black | Black | No Change |
| 7 | 800 | C.S. 1010 | 0.1911 | 0.1917 | Liquid filled Vac < 20 microns | 14 | Brown | Black | Black | No Change |
| 8 | 800 | C.S. 1010 | 0.1662 | 0.1667 | Liquid filled Vac < 20 microns | 14 | Brown | Black | Black | No Change |
| 9 | 800 | St. St. 316 | 0.2074 | 0.2077 | Liquid filled Vac < 20 microns | 14 | Brown | Black | Black | No Change |
| 10 | 800 | St. St. 316 | 0.1939 | 0.1940 | Liquid filled Vac < 20 microns | 14 | Brown | Black | Black | No Change |

## TABLE 4

## SUMMARY OF RESULTS STATIC CAPSULE TESTS AT 900°F

| No. | Temp. (°F) | Metal | Weight (g) | | Condition | Test Time (Days) | Observations | | | Gas Chromatograph (GC) Analysis |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Before | After | | | RC-1 Solution | Metal | Glass | |
| 1 | 900 | --- | --- | --- | Liquid filled Vac < 20 microns | 14 | Tube ruptured | --- | --- | --- |
| 2 | 900 | --- | --- | --- | Liquid filled Vac < 20 microns | 14 | Very little and brown | --- | Black | Not enough to analyze |
| 3 | 900 | Al 6061 | 0.0765 | 0.0832 | Liquid filled Vac < 20 microns | 14 | Brown | Black | Black | Formed three, small, late peaks |
| 4 | 900 | Al 6061 | 0.1063 | 0.1129 | Liquid filled Vac < 20 microns | 14 | Brown | Black | Black | Formed three, small, late peaks |
| 5 | 900 | St. St. 304 | 0.2141 | 0.2072 | Liquid filled Vac < 20 microns | 14 | Yellow gas evolved | Black | Black | Formed small peaks on shoulder of PFB peak |
| 6 | 900 | St. St. 304 | 0.1859 | 0.179 | Liquid filled Vac < 20 microns | 14 | Yellow gas evolved | Black | Black | Formed small peaks on shoulder of PFB peak |
| 7 | 900 | C.S. 1010 | 0.1557 | 0.1578 | Liquid filled Vac < 20 microns | 14 | Yellow brown | Black | Black | Formed three, small, late peaks |
| 8 | 900 | C.S. 1010 | 0.1486 | 0.1499 | Liquid filled Vac < 20 microns | 14 | Yellow brown | Black | Black | Formed three, small, late peaks |
| 9 | 900 | St. St. 316 | 0.2189 | 0.2193 | Liquid filled Vac < 20 microns | 14 | Yellow brown | Black | Black | Formed three, small, late peaks |
| 10 | 900 | St. St. 316 | 0.2212 | 0.2214 | Liquid filled Vac < 20 microns | 14 | Yellow brown | Black | Black | Formed three, small, late peaks |

GC's of the stock RC-1 sample prior to the tests and GC's of all the capsule samples at the conclusion of the static tests were taken for all RC-1 fluid-metal combinations and for all temperature conditions (650°, 800°, and 900°F).

## 2.2 SYSTEM ANALYSIS

The initial efforts of this task consisted of the acquisition of the RC-1 thermodynamic properties from Monsanto with subsequent storage and formating of the tables for use in Thermo Electron's computer programs. The thermodynamic properties of RC-1 are tabulated in Appendix C.

Studies were made of the effect on performance by varying system component sizes and other variables. Many iterations and computations were undertaken to optimize the system before the design point was chosen.

Data on an adiabatic engine in four (4) different configurations were supplied by NASA Lewis, and the performance of an RC-1 Rankine bottoming cycle system was computed for these engines.

### 2.2.1 RC-1 Parametric Analysis

To determine the most efficient RC-1 operating cycle for this application, a parametric analysis was undertaken. By varying the system operating pressures and temperatures as well as the component efficiencies, it was possible to determine these effects on the overall system performance and the sizes required for the system's heat exchangers. Using this information, a system design point, including the cycle state points and component designs, could be specified.

The parametric analysis proceeded by first identifying a "baseline cycle" state point condition. Then each parameter, whose effect on the system's performance was to be measured, was varied (in turn) and the results of this change to the Rankine-cycle operating conditions were recorded. The baseline condition selected for this RC-1 parametric study is shown in Table 5. Also identified in Table 5 is the range of exhaust gas temperatures of interest as well as the imposed limits of turbine inlet temperature and pressure used in the study. The desired result of any cycle calculation was: the overall cycle conversion efficiency, the identification of component sizes, and the efficiency of the component. The conversion efficiency is not the same as Rankine-cycle efficiency. Conversion efficiency is defined as the ratio of the net cycle power to the maximum power available in the exhaust referenced to 300°F. The imposed

## TABLE 5
## $RC_1$ PARAMETRIC ANALYSIS

Baseline Case:

$\Delta P_{VG} = 70$ psid
$\Delta P_{Cond.} = 0.5$ psid
$\Delta P_{Regn.\ Liq.} = 10$ psid
$\Delta P_{Regn.\ Vap.} = 0.5$ psid
$\Delta T_{VG}$ (Min.) = 35°F
Regenerator Eff. = 90%
Pump Eff. = 50%
$T_{Cond.} = 170°F$
Turbine Thermal Eff. = 75%
Turbine Mech. Eff. = 95%

$T_{Exh.\ Gas\ Range}$: 1000°F $\leq T \leq$ 1400°F
$T_{Turbine\ Inlet\ Range}$: 600°F $\leq T \leq$ 900°F
$P_{Turbine\ Inlet\ Range}$: 300°F $\leq p \leq$ 1000 psia
$P_{Critical}$ = 411 psia
$T_{Critical}$ = 456°F
Exhaust Gas Flow Rate = 4000 lb/hr

$$\left(Cp_{Gas} = 0.26 \frac{Btu}{lbm\text{-}°F}\right)$$

$T_{Exhaust\ Min.\ Stack\ Temp.}$ = 300°F

$$\text{Conversion Eff.} = \frac{bhp}{m \times Cp \times (T_{Exh.\ In} - 300°F)}$$

limit of 300°F was selected as the minimum exhaust temperature, below which particulates could condense out of the exhaust stream to cause corrosion problems on the heat exchanger surfaces. The conversion efficiency equation is defined at the bottom of Table 5.

Five (5) different cases were studied in this parametric analysis. Each case studied the effect of changes of one parameter on the overall cycle performance. A complete list of the parametric variations performed in each case is shown in Table 6. These five (5) limited cases by no means represent all the parametric variations that could be considered in a very detailed Rankine-cycle study. However, they do represent the major parametric variables that have the most effect on the selection of a design point for a waste-heat recovery system. For example, a parametric study could also involve verifying the pressure drops of the system's components. In fact, if the pressure drops were varied from zero (i.e., no pressure drop at all) to the values shown in Table 5, a variation of only 1 to 3 percent in overall conversion efficiency would result. A full summary of the effect of component drop on conversion efficiency is given in Table 7.

The results of each case study were arranged in both graphical and tabular form. This arrangement provided the best representation of the data and facilitated the observation of component size or system performance trends. The graphical results for the Case I study are presented in Figures 8 through 11. By referring to these figures it is possible to quickly determine the conversion efficiency as a function of RC-1 system operating temperature and pressure and exhaust gas inlet temperature. Of equal importance is the effect of these parameter changes on the overall sizes of the heat exchanger equipment needed to obtain that particular system performance. By utilizing this graphical representation of the results, the trends of increasing or decreasing component sizes become more readily apparent.

The tabular data compiled for Cases I, II, III, and V are presented in Tables 8, 9, 10, and 11, respectively. The study data were tabulated as shown in these tables to quickly quantify the effect of changes in the various parameters. By observing Table 8 (parameter summary for Case I), it is possible to quickly determine the magnitude of change in the conversion efficiency as a function of the RC-1 operating temperature and pressure and exhaust temperature.

From Table 8 it is also possible to quantify the effect of this parametric variation on the condenser, regenerator, and vapor-generator. Similarly, Tables 9, 10, and 11 summarize the parametric studies for Cases II, III, and V.*

*Case IV is the effect of turbine efficiency and all the tables and figures shown here were repeated for a tubine efficiency of 0.65.

TABLE 6

PARAMETRIC STUDY VARIATIONS

CASE I: BASELINE CASE

WITH $P_{TURBINE\ INLET}$ = 300, 400, 500, 700, 1000 PSIA

AND $T_{EXH.\ GAS}$ = 1000°, 1200°, 1400°F

CASE II: VARIATION OF CONDENSING TEMPERATURE

$T_{COND.}$ = 140°, 160°F

CASE III: VARIATION OF REGENERATION TEMPERATURE

$N_{REGN.}$ = 0, 0.5, 0.75

CASE IV: VARIATION OF TURBINE EFFICIENCY

$N_{TN.}$ = 0.65, 0.75

CASE V: VARIATION IN MINIMUM APPROACH TEMPERATURE IN VAPOR GENERATOR

$\Delta T_{MIN.}$ = 70°, 100°F

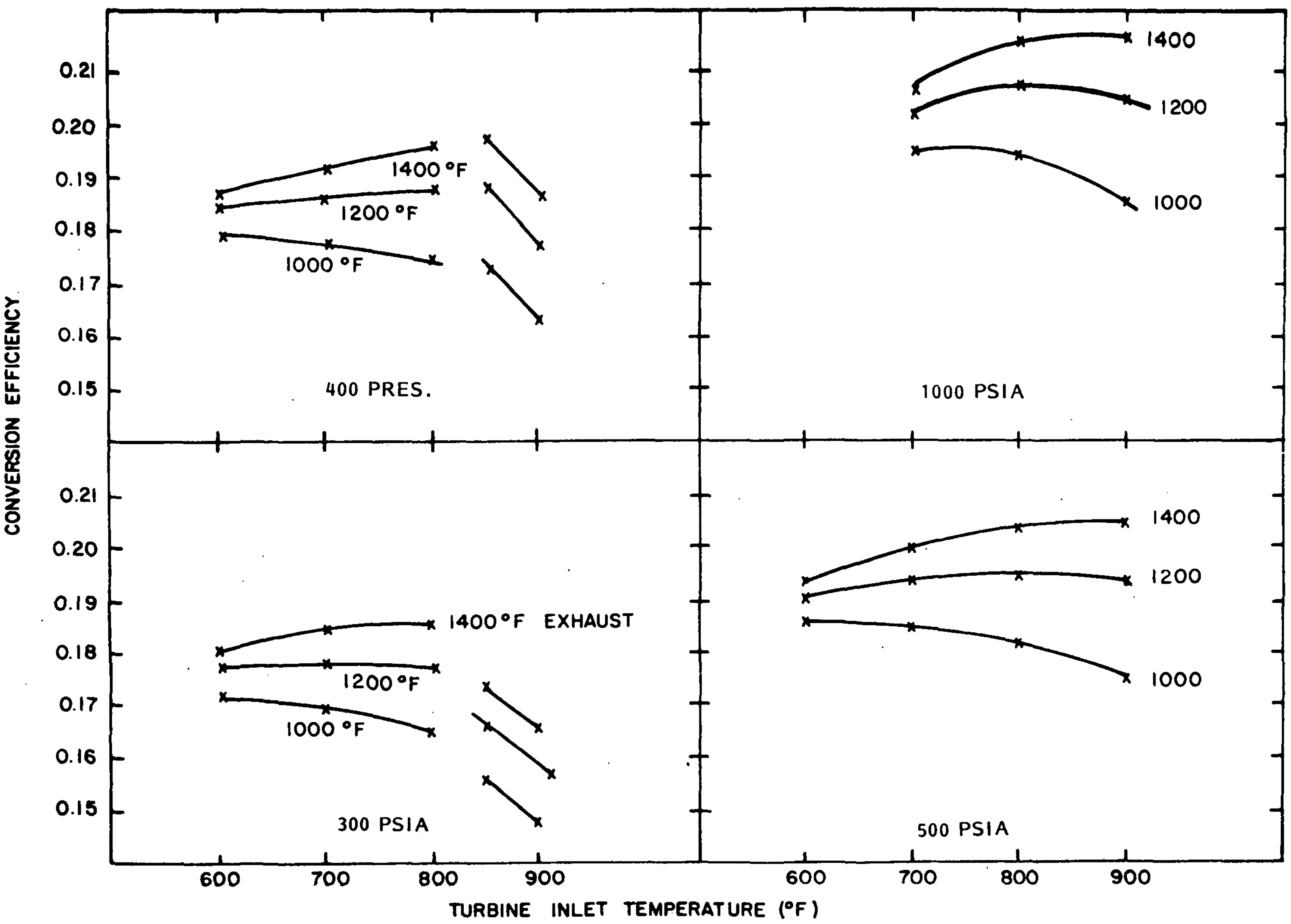
# TABLE 7

## EFFECT OF COMPONENT PRESSURE DROP ON CONVERSION EFFICIENCY

| Exhaust Temperature | 1000°F | | | | | | | | 1200°F | | | | | | | | 1400°F | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Turbine Pressure | 300 | | 400 | | 500 | | 1000 | | 300 | | 400 | | 500 | | 1000 | | 300 | | 400 | | 500 | | 1000 | |
| Turbine Temperature | 700 | 900 | 700 | 900 | 700 | 900 | 700 | 900 | 700 | 900 | 700 | 900 | 700 | 900 | 700 | 900 | 700 | 900 | 700 | 900 | 700 | 900 | 700 | 900 |
| $\frac{\eta_{conv.}}{\eta_{conv.\ ideal}}$ | 0.97 | 0.99 | 0.97 | 0.98 | 0.97 | 0.96 | 0.97 | 0.97 | 0.97 | 0.99 | 0.96 | 0.98 | 0.97 | x | 0.97 | 0.97 | 0.96 | 0.99 | 0.97 | 0.99 | 0.97 | x | 0.96 | 0.97 |

$\eta_{conv.}$ = Conversion Efficiency with Component Pressure Drops Shown for Case I

$\eta_{conv.\ ideal}$ = Conversion Efficiency with Component Pressure Drops Equal to Zero (0)




$\Delta T_{MIN}$ = 35 $\quad$ $\eta_{REGEN}$ = 0.9 $\quad$ $\Delta P \neq 0$ FOR COMPONENTS

$T_{COND}$ = 170°F $\quad$ $\eta_{TUR}$ = 0.75 $\quad$ $\eta_{MECH}$ = 0.95

Figure 8. Case I - Graphical Results of Pressure and Temperature Effect on Conversion Efficiency

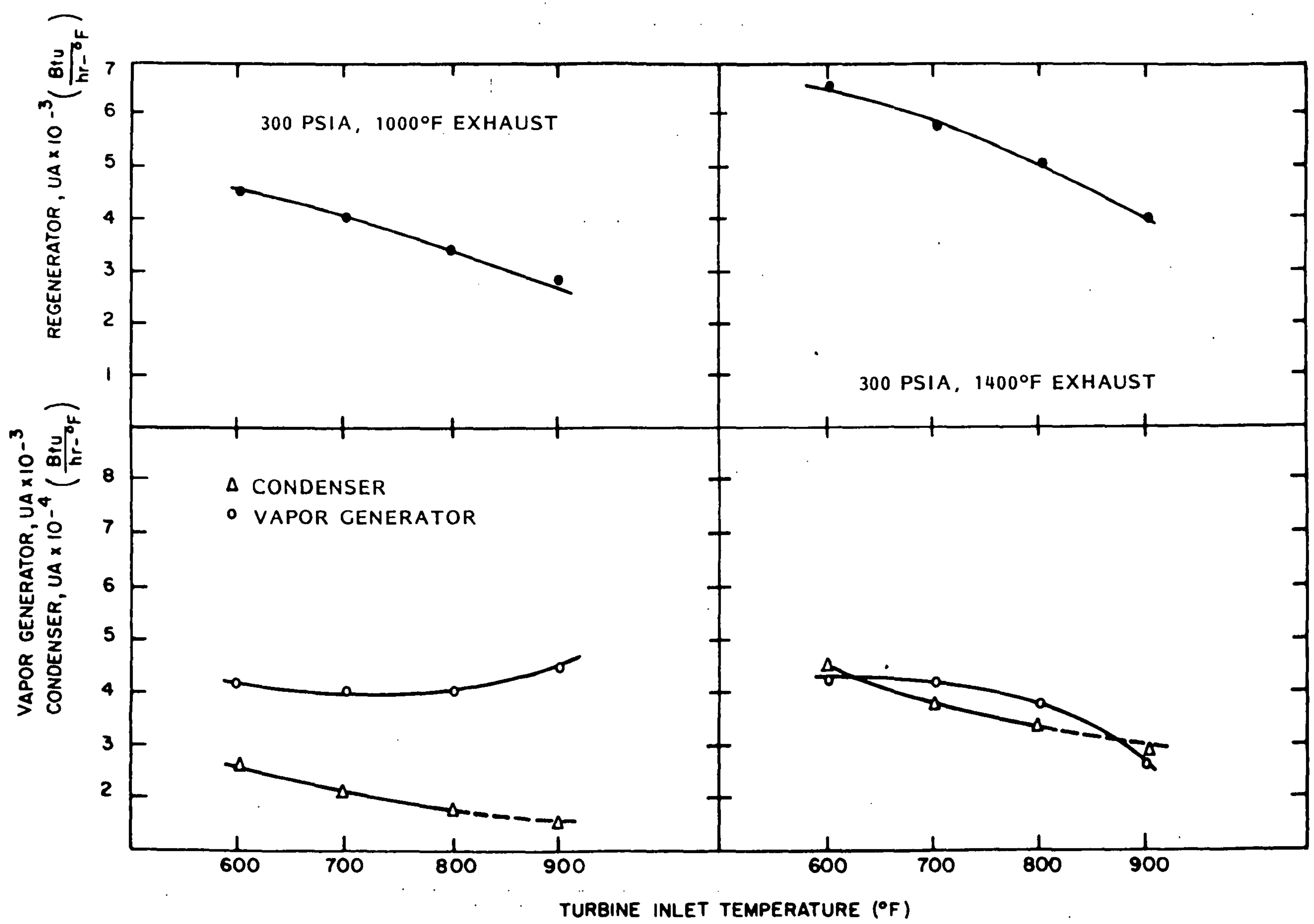



Figure 9. Case I - Graphical Results of RC-1 Pressure (300 psia) and Exhaust Temperature on Heat Exchanger Sizes

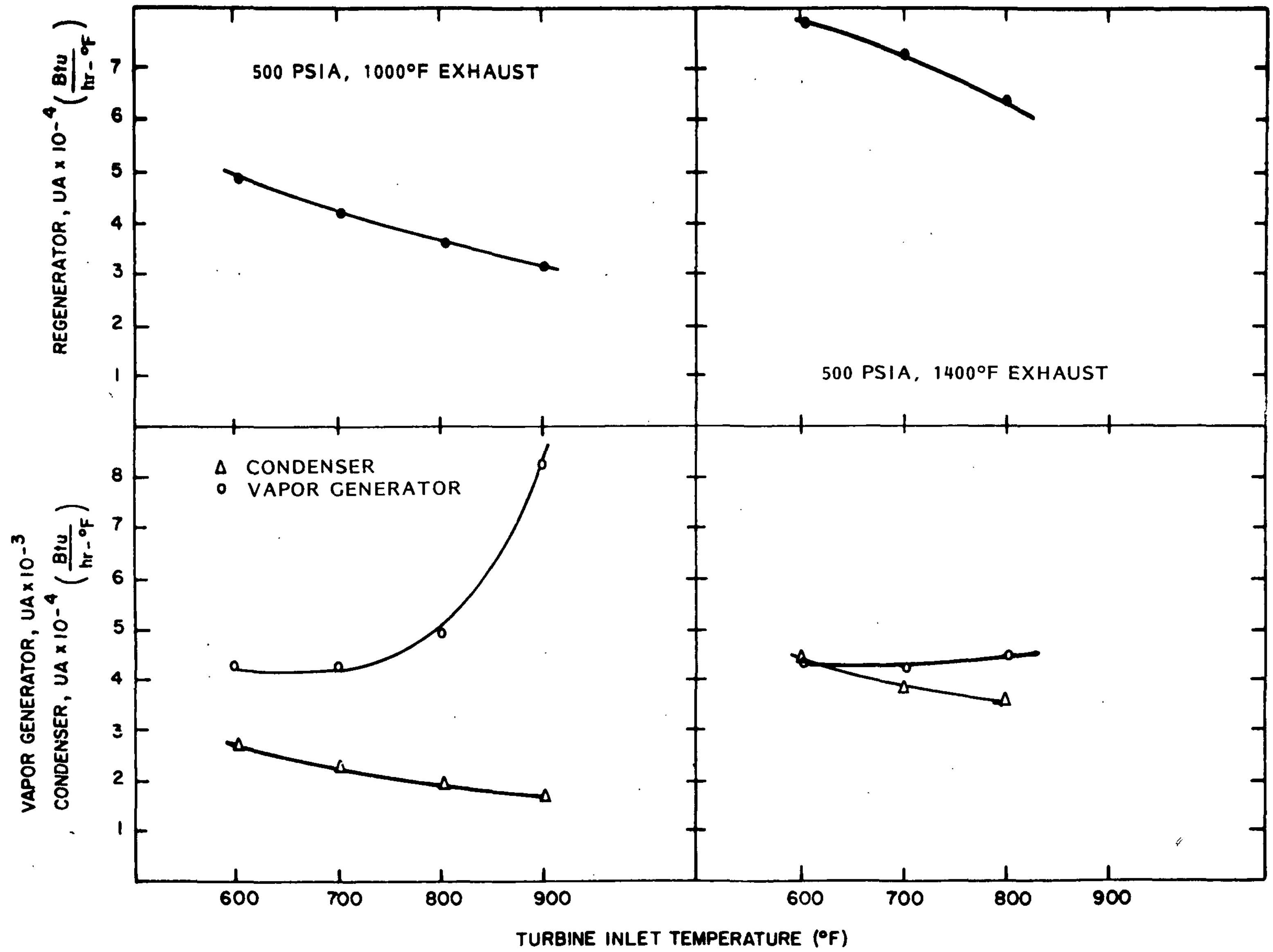



Figure 10. Case I - Graphical Results of RC-1 Pressure (500 psia) and Exhaust Temperature on Heat Exchanger Sizes

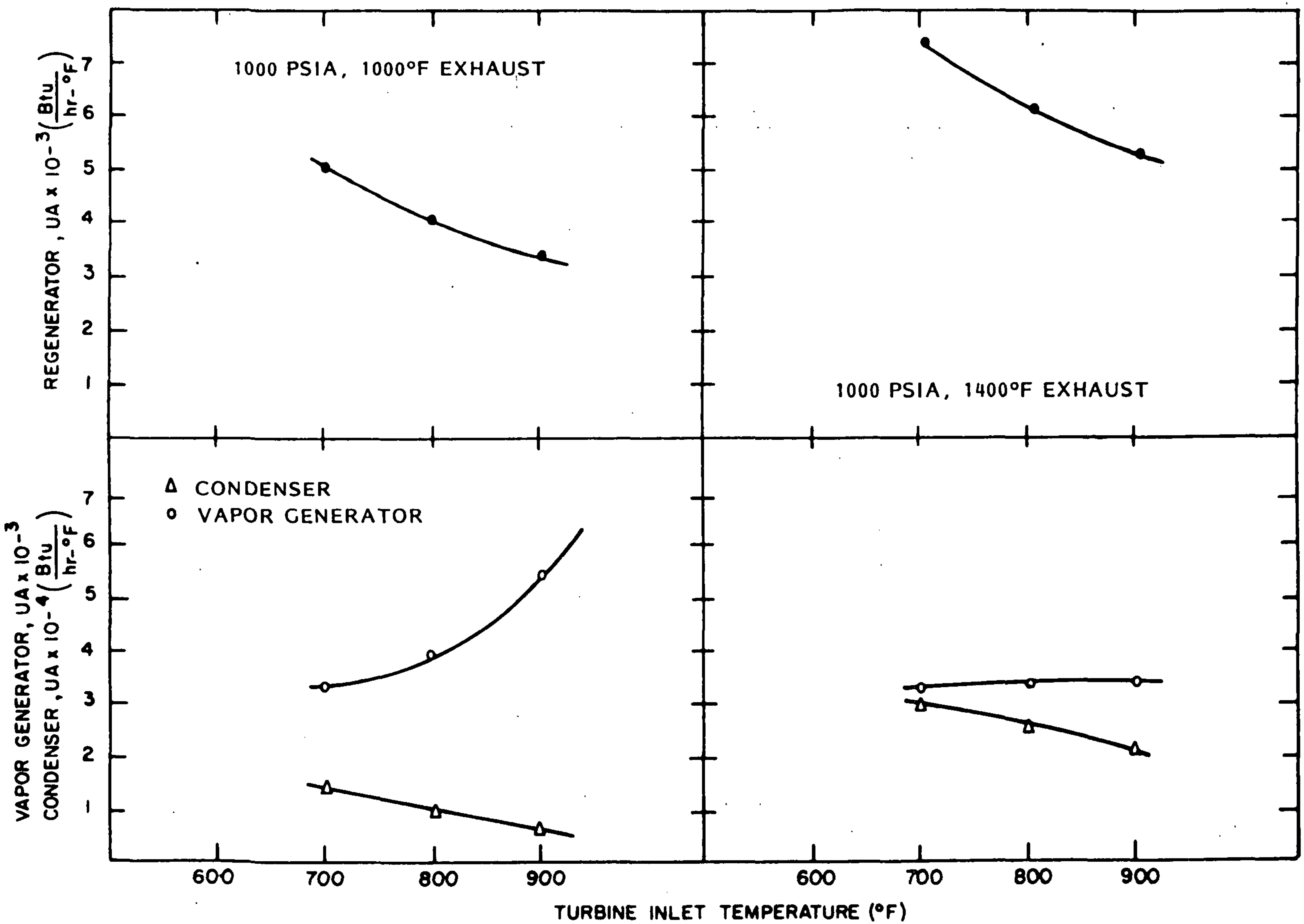



Figure 11. Case I - Graphical Results of RC-1 Pressure (1000 psia) and Exhaust Temperature on Heat Exchanger Sizes

# TABLE 8

## CASE I - BASELINE PERFORMANCE

| Exhaust Temperature In | 1000°F | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Turbine Pressure | 300 | | 400 | | 500 | | 1000 | |
| Turbine Temperature | 700 | 900 | 700 | 900 | 700 | 900 | 700 | 900 |
| $\frac{(\eta_{conv.})}{(\eta_{conv.})_o}$ | 1 | 0.87 | 1.047 | 0.967 | 1.095 | 1.041 | 1.151 | 1.098 |
| $UA_{regen.}$ | 1 | 0.708 | | | 1.011 | 0.775 | 1.275 | 0.850 |
| $(UA/HP)_{regen.}$ | 83.1 | 66.9 | | | 79.7 | 62.2 | 90.6 | 65.0 |
| $UA_{cond.}$ | 1 | 0.738 | | | 1.048 | 0.810 | 1.143 | 0.810 |
| $(UA/HP)_{cond.}$ | 468.0 | 379.8 | | | 433.8 | 343.7 | 435.5 | 322.4 |
| $UA_{vg}$ | 1 | 1.125 | | | 1.063 | 2.08 | 1.10 | 1.6 |
| $(UA/HP)_{vg}$ | 83.0 | 107.9 | | | 80.8 | 165.1 | 78.3 | 120.5 |

| Exhaust Temperature In | 1200°F | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Turbine Pressure | 300 | | 400 | | 500 | | 1000 | |
| Turbine Temperature | 700 | 900 | 700 | 900 | 700 | 900 | 700 | 900 |
| $\frac{(\eta_{conv.})}{(\eta_{conv.})_o}$ | 1.05 | 0.938 | 1.101 | 1.047 | 1.148 | 1.145 | 1.192 | 1.207 |
| $UA_{regen.}$ | 1.364 | | | | 1.421 | 1.108 | 1.683 | 1.22 |
| $(UA/HP)_{regen.}$ | 83.0 | 66.9 | | | 79.6 | 62.3 | 90.6 | 65.0 |
| $UA_{cond.}$ | 1.464 | 1.054 | | | 1.474 | 1.166 | 1.541 | 1.155 |
| $(UA/HP)_{cond.}$ | 467.9 | 379.5 | | | 433.5 | 343.9 | 435.5 | 322.5 |
| $UA_{vg}$ | 1.013 | 0.765 | | | 1.054 | 1.483 | 1.072 | 1.183 |
| $(UA/HP)_{vg}$ | 61.7 | 52.5 | | | 59.1 | 83.3 | 57.7 | 62.9 |

| Exhaust Temperature In | 1400°F | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Turbine Pressure | 300 | | 400 | | 500 | | 1000 | |
| Turbine Temperature | 700 | 900 | 700 | 900 | 700 | 900 | 700 | 900 |
| $\frac{(\eta_{conv.})}{(\eta_{conv.})_o}$ | 1.089 | 0.979 | 1.136 | 1.101 | 1.183 | 1.213 | 1.219 | 1.278 |
| $UA_{regen.}$ | 1.45 | 1.225 | | | 1.80 | 1.300 | 1.838 | 1.325 |
| $(UA/HP)_{regen.}$ | 83.1 | 66.9 | | | 79.7 | 62.3 | 90.6 | 65.1 |
| $UA_{cond.}$ | 1.76 | 1.333 | | | 1.81 | 1.667 | 1.905 | 1.476 |
| $(UA/HP)_{cond.}$ | 468.4 | 379.8 | | | 433.8 | 343.9 | 435.5 | 322.6 |
| $UA_{vg}$ | 1.038 | 0.65 | | | 1.075 | 1.188 | 1.075 | 1.100 |
| $(UA/HP)_{vg}$ | 49.9 | 35.6 | | | 47.4 | | 46.5 | 45.0 |

## TABLE 9

## CASE II - EFFECT OF CONDENSER TEMPERATURE ON TOTAL PERFORMANCE

| Exhaust Gas Temperature | 1000°F | | | | | | | | 1200°F | | | | | | | | 1400°F | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Turbine Pressure | 300 | | 400 | | 500 | | 1000 | | 300 | | 400 | | 500 | | 1000 | | 300 | | 400 | | 500 | | 1000 | |
| Turbine Temperature | 700 | 900 | 700 | 900 | 700 | 900 | 700 | 900 | 700 | 900 | 700 | 900 | 700 | 900 | 700 | 900 | 700 | 900 | 700 | 900 | 700 | 900 | 700 | 900 |
| $UA_{cond.}$ ($T_c$ = 170°F) | 1 | 0.738 | | | 1.048 | 0.81 | 1.143 | 0.810 | 1.46 | 1.054 | | | 1.474 | 1.166 | 1.541 | 1.155 | 1.76 | 1.333 | | | 1.81 | 1.667 | 1.905 | 1.476 |
| (UA/HP) | 468 | 380 | | | 434 | 344 | 436 | 322 | | | | | | | | | 468 | 380 | | | 434 | 344 | 436 | 323 |
| $UA_{cond.}$ ($T_c$ = 160°F) | 1.72 | 1.19 | | | 1.75 | 1.28 | 1.86 | 1.28 | | | | | | | | | 2.9 | 2.1 | | | 2.96 | 2.34 | 3.1 | 2.34 |
| (UA/HP) | 724 | 573 | | | 674 | 523 | 683 | 494 | | | | | | | | | 723 | 573 | | | 675 | 522 | 683 | 494 |
| $\frac{\eta_{conv.}}{\eta_{conv.,o}}$ | 1.03 | 0.90 | | | 1.12 | 1.07 | 1.18 | 1.13 | | | | | | | | | 1.12 | 1.02 | | | 1.21 | 1.24 | 1.25 | 1.31 |
| $UA_{cond.}$ ($T_c$ = 140°F) | 1.37 | 0.997 | | | 1.39 | 1.05 | 1.47 | 1.09 | | | | | | | | | 2.32 | 1.76 | | | 2.33 | 1.9 | 2.43 | 1.93 |
| (UA/HP) | 529 | 432 | | | 497 | 396 | 501 | 375 | | | | | | | | | 530 | 431 | | | 497 | 396 | 501 | 375 |
| $\frac{\eta_{conv.}}{\eta_{conv.,o}}$ | 1.12 | 1 | | | 1.22 | 1.15 | 1.28 | 1.26 | | | | | | | | | 1.21 | 1.13 | | | 1.3 | 1.34 | 1.34 | 1.42 |

## TABLE 10

## CASE III - EFFECT OF REGENERATOR EFFICIENCY ON TOTAL PERFORMANCE

| Exhaust Gas Temperature | 1000°F | | | | | | 1400°F | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Turbine Pressure | 300 | | 500 | | 1000 | | 300 | | 500 | | 1000 | |
| Turbine Temperature | 700 | 900 | 700 | 900 | 700 | 900 | 700 | 900 | 700 | 900 | 700 | 900 |
| at Regn. Eff. = 0.90 | | | | | | | | | | | | |
| $\eta_{conv.}/\eta_{conv.,o}$ | 1 | 0.87 | 1.1 | 1.04 | 1.15 | 1.1 | 1.1 | 0.98 | 1.18 | 1.21 | 1.22 | 1.28 |
| $UA_{regn.}/UA_{regn.,o}$ | 1 | 0.71 | 1.01 | 0.78 | 1.28 | 0.85 | 1.45 | 1.23 | 1.80 | 1.30 | 1.84 | 1.33 |
| (UA/HP) | 83 | 67 | 80 | 62 | 91 | 65 | 83 | 67 | 80 | 62 | 91 | 65 |
| at Regn. Eff. = 0.75 | | | | | | | | | | | | |
| $\eta_{conv.}/\eta_{conv.,o}$ | 0.953 | | 1.05 | 0.98 | 1.11 | 1.07 | 1.02 | | 1.11 | 1.11 | 1.16 | 1.20 |
| $UA_{regn.}/UA_{regn.,o}$ | 0.50 | | 0.51 | 0.39 | 0.58 | 0.41 | 0.83 | | 0.85 | 0.69 | 0.94 | 0.72 |
| (UA/HP) | 43.2 | | 40.6 | 32.8 | 42.9 | 31.9 | 43.3 | | 40.5 | 32.9 | 42.8 | 31.9 |
| at Regn. Eff. = 0.50 | | | | | | | | | | | | |
| $\eta_{conv.}/\eta_{conv.,o}$ | 0.91 | 0.817 | 0.99 | 0.91 | 1.07 | 1.01 | 0.93 | 0.88 | 1.02 | 0.98 | 1.08 | 1.07 |
| $UA_{regn.}/UA_{regn.,o}$ | 0.20 | 0.16 | 0.21 | 0.16 | 0.23 | 0.17 | 0.33 | 0.27 | 0.33 | 0.27 | 0.36 | 0.28 |
| (UA/HP) | 18.5 | 16.1 | 17.2 | 14.6 | 17.6 | 13.8 | 18.5 | 16.2 | 17.1 | 14.6 | 17.6 | 13.8 |
| $UA/UA_o$ Vapor. Gen. | | | | | | | | | | | | |
| at $\eta_{regn.}$ = 0.90 | 1 | 1.125 | 1.06 | 2.1 | 1.1 | 1.6 | 1.04 | 0.65 | 1.08 | 1.19 | 1.08 | 1.10 |
| at $\eta_{regn.}$ = 0.75 | 1.10 | 1.36 | 1.14 | 1.85 | 1.15 | 1.75 | 1.19 | 1.24 | 1.1 | 1.24 | 1.12 | 1.22 |
| at $\eta_{regn.}$ = 0.50 | 1.27 | 1.63 | 1.27 | 1.83 | 1.26 | 1.81 | 1.19 | 1.24 | 1.19 | 1.29 | 1.18 | 1.29 |

## TABLE 11

### CASE V - EFFECT OF VAPOR GENERATOR PINCH POINT TEMPERATURE ON TOTAL PERFORMANCE

| Exhaust Temperature | 1000°F | | | | | | 1400°F | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Turbine Pressure | 300 | | 500 | | 1000 | | 300 | | 500 | | 1000 | |
| Turbine Temperature | 700 | 900 | 700 | 900 | 700 | 900 | 700 | 900 | 700 | 900 | 700 | 900 |
| $\Delta T_{vg}$ = 35 | | | | | | | | | | | | |
| $UA/UA_{vg,o}$ | 1 | 1.125 | 1.06 | 2.08 | 1.1 | 1.6 | 1.04 | 0.65 | 1.08 | 1.19 | 1.08 | 1.1 |
| $\eta_{conv.}/\eta_{conv.,o}$ | 1 | 0.87 | 1.10 | 1.04 | 1.15 | 1.1 | 1.09 | 0.98 | 1.18 | 1.21 | 1.22 | 1.28 |
| UA/HP | 83 | 108 | 81 | 165 | 78 | 121 | 50 | 36 | 47 | | 47 | 45 |
| $\Delta T_{vg}$ = 70 | | | | | | | | | | | | |
| $UA/UA_{vg,o}$ | 0.75 | 0.93 | 0.80 | 1.40 | 0.82 | 1.19 | 0.81 | 0.60 | 0.84 | 1.02 | 0.85 | 0.90 |
| $\eta_{conv.}/\eta_{conv.,o}$ | 0.94 | 0.817 | 1.03 | 0.96 | 1.08 | 1.02 | 1.05 | 0.94 | 1.14 | 1.166 | 1.18 | 1.23 |
| UA/HP | 66 | 94.6 | 64.6 | 119.9 | 62.7 | 96.8 | 40.7 | 33.3 | 38.9 | 46.1 | 38.2 | 38.5 |
| $\Delta T_{vg}$ = 100 | | | | | | | | | | | | |
| $UA/UA_{vg,o}$ | 0.62 | 0.79 | 0.67 | 1.09 | 0.68 | 0.97 | 0.70 | 0.55 | 0.73 | 0.86 | 0.74 | 0.78 |
| $\eta_{conv.}/\eta_{conv.,o}$ | 0.89 | 0.76 | 0.97 | 0.90 | 1.03 | 0.95 | 1.02 | 0.91 | 1.10 | 1.12 | 1.14 | 1.18 |
| UA/HP | 58.0 | 86.3 | 56.9 | 100.4 | 55.2 | 84.2 | 36.3 | 31.6 | 34.7 | 40.4 | 34.1 | 34.7 |

The detailed study and evaluation of all the tabular and graphical results compiled from this parametric study led to the selection of the system design point. This selection, although not necessarily providing the highest conversion efficiency, does consider the tangible consequences of component size and packaging requirements for installation as an integrated system on a heavy-duty vehicle. A detailed state point summary of the design point selected is shown in Figure 12. These particular results and system operating conditions consider the use of a water-cooled condenser. An improvement in performance can be demonstrated by the use of a direct air-cooled condenser. The design point results and conditions for the air-cooled system are shown in Figure 13. Based upon this improved performance and the elimination of water cooling loops in the Bottoming Cycle System, as is accomplished with the adiabatic diesel engine, the RC-1 system utilizing the air-cooled condenser was selected for final component sizing and specification.

### 2.2.2 Diesel/RC-1 Bottoming Cycle Power Summary

The baseline diesel engine data supplied by NASA Lewis are shown in Table 12. Four (4) diesel configurations with performance and exhaust gas conditions were provided for the waste-heat recovery performance evaluation.

Using the waste-heat energy from these base diesel engines, an RC-1 bottoming cycle system performance was calculated for each diesel engine configuration. Performance was determined for RC-1 systems using both the water-cooled and air-cooled condenser options. The operating state point conditions used in this analysis were those determined to be optimum from the parametric study. A typical RC-1 state point and thermodynamic process diagram is shown on the temperature-entropy plot in Figure 14. Table 13 contains the performance data for the RC-1 bottoming cycle system matched to each diesel engine configuration. Bottoming cycle power as high as 56 horsepower for the air-cooled condenser option and 53 horsepower for the water-cooled condenser option are possible. In all instances, the performance calculations did not consider engine fan power parasitics. This rationale is consistent with the performance presentation of the base diesel engines given in Table 12.

The compound engine (diesel plus bottoming cycle) performance is shown in Table 14. The analysis indicates that a minimum compound engine BSFC of 0.258 lb/hp-hr can be obtained if an RC-1 Bottoming Cycle System (with the air-cooled condenser option) is used to bottom the turbocharged, turbocompounded air after cooled diesel engine (TCPD/A). For the simple turbocharged diesel engine (TC), a maximum fuel savings and power improvement of 15 and 18 percent, respectively, is possible with the RC-1 Bottoming Cycle System.

| | | T | P | H | | DT | DP | DH |
|---|---|---|---|---|---|---|---|---|
| 14 | BOIL IN | 327.65 | 870.00 | 82.25 | BOIL | 422.352 | 70.000 | 150.423 |
| 1 | OUT | 750.00 | 800.00 | 232.67 | LINE | .000 | .000 | .000 |
| 2 | ENG IN | 750.00 | 800.00 | 232.67 | ENG | 198.423 | 789.910 | 36.815 |
| 3 | OUT | 551.58 | 10.09 | 195.86 | LINE | .000 | .000 | .000 |
| 4 | REGU IN | 551.58 | 10.09 | 195.86 | REGU | 220.419 | .500 | 49.996 |
| 5 | OUT | 331.16 | 9.59 | 145.86 | LINE | .000 | .000 | .000 |
| 6 | COND IN | 331.16 | 9.59 | 145.86 | COND | 182.910 | .500 | 117.314 |
| 9 | OUT | 148.25 | 9.09 | 28.55 | LINE | .000 | .000 | .000 |
| 10 | PUMP IN | 148.25 | 9.09 | 28.55 | PUMP | 13.547 | -870.910 | 3.705 |
| 11 | OUT | 161.80 | 880.00 | 32.25 | LINE | .000 | .000 | .000 |
| 12 | REGL IN | 161.80 | 880.00 | 32.25 | REGL | 165.853 | 10.000 | 49.996 |
| 13 | OUT | 327.65 | 870.00 | 82.25 | LINE | .000 | .000 | .000 |

SYSTEM

FLOWRATE = 4401. HP = 52.55 EFF = 20.20

EXPANDER Q = .1620E 06 HP = 58.96

EFFTH = .7650 EFFME = .9260 EFFALL = .7084

WES = 48.12 WSHAFT = 34.09 WNET = 30.39

EXHAUST QUALITY = 1.000

REGENERATOR EFF = .6000 Q = .2201E 06

UA = 1126.

CONDENSER Q = .5164E 06 UATOTAL = 42771.

HSUB = 1.41 HDESUP = 33.84 HLATENT = 82.06

UASUB = 592. UACOND = 39298. UADESUP = 2881.

TWATER IN = 140.0 TWATER OUT = 150.0 WATERFLOW = 51635.

BOILER Q = .6621E 06 UATOTAL = 3635.

HSENS = 59.75 HLATENT = .00 HSUPER = 90.67

TBSUP = 178.91

UASENS = 2520. UALAT = 0. UASUPER = 1115.

PUMP

EFF = .5000 GPM = 6.47 HP = 6.41

GAS

FLOWRATE = 2886 TGASI = 1240.0 TGASO = 357.6

TPINCH = 708.1 DTPINCH = 30.0

Figure 12. Computer Output of Design Point for Water-Cooled RC-1 System

| | | T | P | H | | DT | DP | DH |
|---|---|---|---|---|---|---|---|---|
| 14 | BOIL IN | 316.76 | 870.00 | 78.59 | BOIL | 433.236 | 70.000 | 154.081 |
| 1 | OUT | 750.00 | 800.00 | 232.67 | LINE | .000 | .000 | .000 |
| 2 | ENG IN | 750.00 | 800.00 | 232.67 | ENG | 208.212 | 791.990 | 39.147 |
| 3 | OUT | 541.79 | 8.01 | 193.52 | LINE | .000 | .000 | .000 |
| 4 | REGV IN | 541.79 | 8.01 | 193.52 | REGV | 221.528 | .500 | 49.868 |
| 5 | OUT | 320.26 | 7.51 | 143.66 | LINE | .000 | .000 | .000 |
| 6 | COND IN | 320.26 | 7.51 | 143.66 | COND | 185.260 | .500 | 118.570 |
| 9 | OUT | 135.00 | 7.01 | 25.08 | LINE | .000 | .000 | .000 |
| 10 | PUMP IN | 135.00 | 7.01 | 25.08 | PUMP | 13.615 | -872.990 | 3.635 |
| 11 | OUT | 148.62 | 880.00 | 28.72 | LINE | .000 | .000 | .000 |
| 12 | REGL IN | 148.62 | 880.00 | 28.72 | REGL | 168.149 | 10.000 | 49.868 |
| 13 | OUT | 316.76 | 870.00 | 78.59 | LINE | .000 | .000 | .000 |

SYSTEM

FLOWRATE = 4350. HP = 55.75 EFF = 21.17

EXPANDER Q = .1703E 06 HP = 61.96

EFFTH = .7650 EFFME = .9260 EFFALL = .7084

WES = 51.17 WSHAFT = 36.25 WNET = 32.61

EXHAUST QUALITY = 1.000

REGENERATOR EFF = .6000 Q = .2169E 06

UA = 1100.

CONDENSER Q = .5158E 06 UATOTAL = 9970.

HSUB * 1.34 HDESUP = 33.76 HLATENT = 83.48

UASUB = 101. UACOND = 8258. UADESUP = 1611.

TWATER IN = 80.0 TWATER OUT = 120.0 WATERFLOW = 53727.

BOILER Q = .6702E 06 UATOTAL = 3691.

HSENS = .00 HLATENT = .00 HSUPER = .00

TBSUP = 178.91

UASENS = 2601. UALAT = 0. UASUPER = 1090.

PUMP

EFF = .5000 GPM = 6.25 HP = 6.21

GAS

FLOWRATE = 2886 TGASI = 1240.0 TGASO = 346.8

TPINCH = 714.4 DTPINCH = 30.0

Figure 13. Computer Output Design Point for Air-Cooled RC-1 System

TABLE 12

DIESEL ENGINE DATA

| DIESEL CONFIGURATION | BHP | BSFC (LB/BHP-HR) | EXHAUST (°F) | EXHAUST (LB/MIN) |
|---|---|---|---|---|
| TURBOCHARGED-NONAFTERCOOLED (TC) | 317 | 0.315 | 1240 | 48.1 |
| TURBOCHARGED-AFTERCOOLED (TC/A) | 320 | 0.310 | 1120 | 47.6 |
| TURBOCOMPOUND-NONAFTERCOOLED (TCPD) | 335 | 0.297 | 1140 | 47.8 |
| TURBOCOMPOUND-AFTERCOOLED (TCPD/A) | 340 | 0.293 | 1060 | 48.4 |

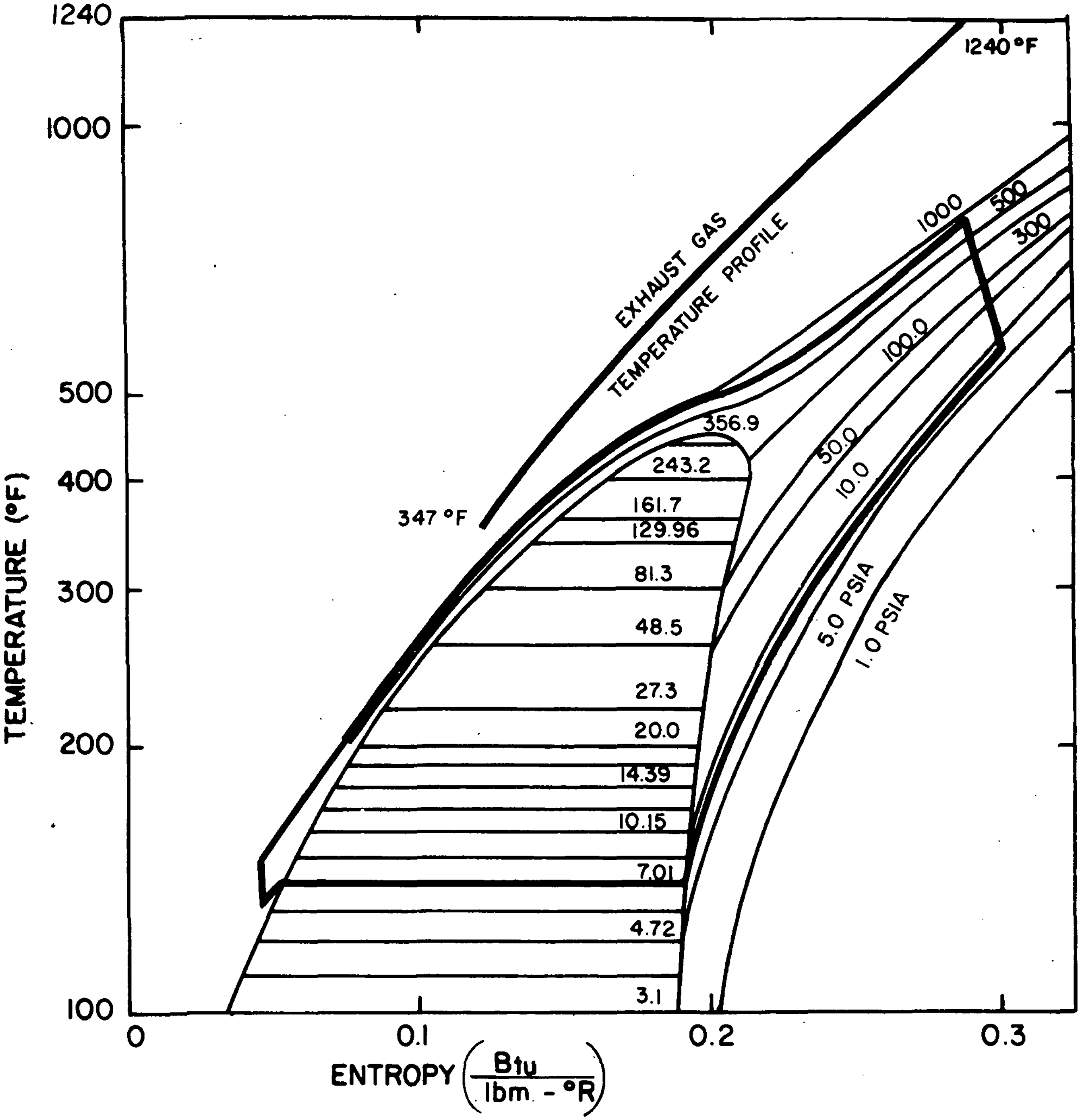



Figure 14. RC-1 State Point Diagram for Design Point Thermodynamic Process

# TABLE 13
## BOTTOMING CYCLE DATA

| DIESEL CONFIGURATION | TURBINE EFFICIENCY | | WATER-COOLED CONDENSER | | | | AIR-COOLED CONDENSER | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | $\eta_{th}$ (1) | $\eta_{OA}$ (2) | $\eta_{CYCLE}$ (3) | $\eta_{CONV.}$ (4) | BHP | EXHAUST TEMPERATURE (5) (°F) | $\eta_{CYCLE}$ (3) | $\eta_{CONV.}$ (4) | BHP | EXHAUST TEMPERATURE (5) (°F) |
| TC | 0.765 | 0.708 | 0.202 | 0.19 | 52.6 | 358 | 0.212 | 0.201 | 55.8 | 347 |
| TC/A | 0.788 | 0.728 | 0.211 | 0.198 | 47.5 | 349 | 0.229 | 0.215 | 51.5 | 348 |
| TCPD | 0.765 | 0.706 | 0.201 | 0.187 | 46.1 | 358 | 0.218 | 0.204 | 50.3 | 352 |
| TCPD/A | 0.765 | 0.708 | 0.197 | 0.188 | 42.5 | 334 | 0.222 | 0.206 | 46.4 | 355 |

NOTES:

(1) $\eta_{EXPANDER} = \frac{\text{TURBINE THERMAL POWER OUTPUT}}{\text{ISENTROPIC IDEAL POWER}} \frac{(\Delta H)}{(\Delta H_s)}$

(2) TGU = TURBINE GEARBOX UNIT OVERALL EFFICIENCY

(3) $\eta_{CYCLE} = \frac{BHP}{\dot{m} \times c_p \times (\Delta T)_{ACTUAL}}$; $c_p$ = 0.26 BTU/LBM-°F

(4) $\eta_{CONVERSION} = \frac{BHP}{\dot{m} \times c_p \times (T_{GAS\ IN} - 300)}$

(5) EXHAUST GAS STACK TEMPERATURE (OUT OF VAPOR GENERATOR)

## TABLE 14
## COMPOUND ENGINE SYSTEM DATA

| DIESEL CONFIGURATION | WATER-COOLED CONDENSER | | | | AIR-COOLED CONDENSER | | | | $\Delta HP_{FL85}$ (3) (%) |
|---|---|---|---|---|---|---|---|---|---|
| | BHP | BSFC (LB/HP-HR) | ΔBSFC (1) (%) | ΔHP (2) (%) | BHP | BSFC (LB/HP-HR) | ΔBSFC (1) (%) | ΔHP (2) (%) | |
| TC | 369.6 | 0.270 | 14.2 | 16.6 | 372.8 | 0.268 | 14.9 | 17.6 | 14.8 |
| TC/A | 367.5 | 0.270 | 12.9 | 14.8 | 371.5 | 0.267 | 13.9 | 16.1 | 13.0 |
| TCPD | 381.1 | 0.261 | 12.1 | 13.8 | 385.3 | 0.258 | 13.1 | 15.0 | 12.8 |
| TCPD/A | 382.5 | 0.260 | 11.1 | 12.5 | 386.4 | 0.258 | 11.9 | 13.6 | 11.6 |

NOTES:

(1) $$\Delta BSFC\ (\%) = \left(1 - \frac{(BSFC)_{COMPOUND}}{(BSFC)_{WITHOUT\ COMPOUND}}\right) \times 100$$

(2) $$\Delta HP\ (\%) = \left(\frac{HP_{COMPOUND}}{HP_{WITHOUT\ COMPOUND}} - 1\right) \times 100$$

(3) $$\Delta HP_{FL85}\ (\%) = \left(\frac{HP_{FL85\ ORCS}}{HP_{WITHOUT\ COMPOUND}} - 1\right) \times 100$$

An analysis to determine the performance sensitivity with respect to exhaust gas temperature was also conducted, and the results of this study are shown in Table 15. The table shows that a compound engine BSFC as low as 0.251 lb/hp-hr is possible if the exhaust temperature from the adiabatic diesel engine reaches 1600°F. This represents a fuel savings potential of 19 percent and a bottoming cycle power delivery of 75 horsepower.

## 2.3 PRELIMINARY SYSTEM DESIGN

All of the power performance calculations presented in the previous section for the diesel bottoming cycle system compound engine were performed with fixed Organic Rankine-Cycle System (ORCS) component sizes. These component sizes were chosen because they could be realistically packaged and installed in a heavy-duty transport vehicle equipped with an adiabatic diesel engine.

Thermo Electron's prior experience with the Fluorinol-based truck bottoming cycle system was of considerable advantage in the design of each component for the RC-1 system. These advantages also included the general packaging arrangement for an effective vehicle installation. Because of the properties of the RC-1 organic fluid, it was necessary to redesign or modify the four (4) principal Rankine-cycle components: the vapor-generator, feedpump, turbine-gearbox unit, and integrated air-cooled condenser-regenerator heat exchangers. The bottoming system schematic showing the relative location of each component and the operating conditions for this RC-1 system at the design point is shown in Figure 15. A description of the major components and their design features are presented below.

- Vapor-Generator

  The vapor-generator for this system has a core area which is only 11 percent larger than the one for the Fluorinol-85 truck ORCS. For the same diameter unit, this translates into a 4-inch increase in the overall length of the finned-tube core. However, at this increased length the core will fit inside the 48-inch-long vapor-generator shroud, thus maintaining the same package size for the vapor-generator module. The core consists of finned tubing spirally wound in "pancake" sections as in the VGIII design for the Fluorinol system. All other features, such as the diverter valve and internal bypass stack, also remain the same. Figure 16 shows the basic design of the vapor-generator.

- Feedpump Design

  The RC-1 feedpump design is identical with the Fluorinol truck system design except for an increase in the cylinder displacement.

## TABLE 15

## TEMPERATURE SENSITIVITY FOR TC/A DIESEL CONFIGURATION

| DIESEL TEMPERATURE (°F) | WATER-COOLED CONDENSER | | | AIR-COOLED CONDENSER | | |
|---|---|---|---|---|---|---|
| | ORCS (BHP) | COMPOUND BSFC (LB/HP-HR) | ΔBSFC (%) | ORCS (BHP) | COMPOUND BSFC (LB/HP-HR) | ΔBSFC (%) |
| 1000 | 38.9 | 0.276 | 11.0 | 44.3 | 0.272 | 12.3 |
| 1200 | 50.8 | 0.268 | 13.5 | 56.1 | 0.264 | 14.8 |
| 1400 | 60.7 | 0.261 | 15.8 | 66.6 | 0.257 | 17.1 |
| 1600 | 70.7 | 0.254 | 18.1 | 75.2 | 0.251 | 19.0 |

*BASELINE DIESEL (TC/A)

BHP = 320
BSFC = 0.310 LB/HP-HR
EXHAUST TEMPERATURE = 1120°F
EXHAUST FLOW RATE = 2856 LB/HR

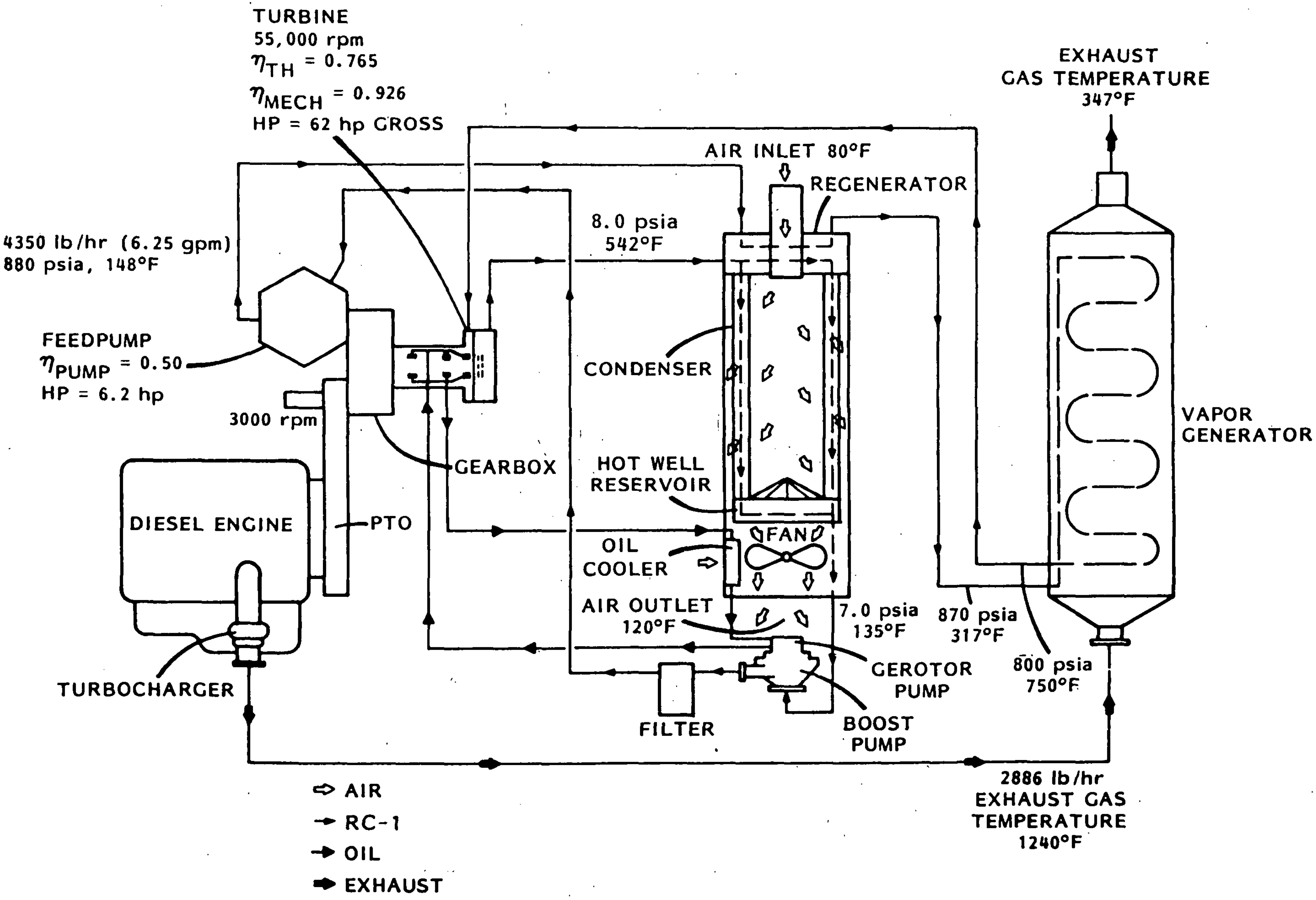



Figure 15. Bottoming System Schematic

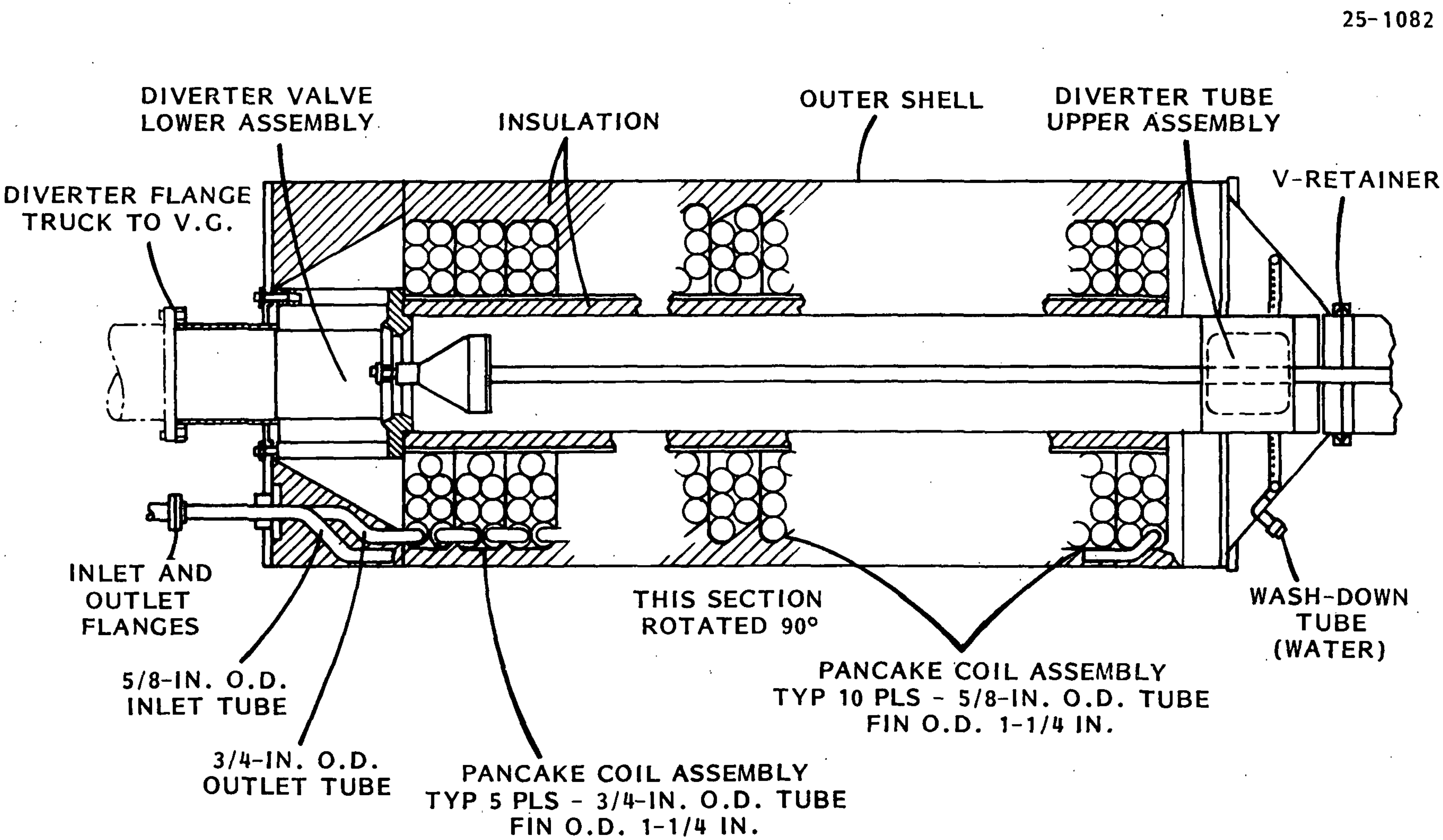



**Figure 16. RC-1 Vapor Generator Design**

Basically, it is a three (3) cylinder, variable positive displacement pump with a flow rate capability from 0 to 6½ gpm at 1000 psia design pressure. It has a cylinder base of 1.1 inches and a maximum stroke of 0.315 inch.

The change in pump displacement is accomplished by using a small electric screw-motor that axially moves a Z-bar camshaft which changes the eccentricity of a rotating cam follower. The net effect is the capability to vary the piston stroke from 0 to 0.315 inch.

The pump is integrated with a feedpump drive unit and installed as a package as part of the PCU.

- Turbine-Gearbox Unit

The RC-1 turbine and gearbox requirements were reviewed very carefully. The RC-1 turbine operating conditions were sufficiently different from the Fluorinol-85 conditions to warrant a new turbine design analysis. Using several organic fluid-turbine design computer programs and inputting the new RC-1 operating conditions (i.e., 750°F and 800 psia turbine inlet conditions), certain turbine specifications were identified that were used in finalizing a turbine design. The turbine design is defined in the computer output of Figure 17 and shown in Figure 18. The turbine rotor is 3½ inches in diameter and will turn at a speed of 55,000 rpm. The shaft seal is a double-faced carbon seal with a single mating ring and a buffer oil zone between the seals to prevent leakage of RC-1 fluid out of the system and at the same time prevent air leakage into the subatmospheric system. Hydraulic bearings are used in this design instead of roller bearing elements, and the turbine housing and rotor are expected to be cast for cost effectiveness.

The turbine gearbox reduces the speed of the turbine (55,000 rpm) to 3000 rpm at the Power Take Off (PTO) input gear. This speed reduction is accomplished by a planetary gear train that is contained in a small compact housing. The turbine output power is transmitted to the diesel driveline through an overrunning (Sprague-type) or one-way clutch. Thus, the turbine-gearbox unit is not a parasitic and cannot be turned by the diesel engine. Only when the Bottoming Cycle System is putting out power will the clutch engage and deliver positive power to the diesel driveline.

The turbine, gearbox, feedpump, and feedpump drive assembly are installed on the PTO as a single assembly. There is a single

```
!START $
?800.,750.,4408.,10.09,10.,10000.,3000.,1
 STEAM CALC.S TRUE OR FALSE
?.FALSE.
 P1 = 800.000
T1 = 750.000
FLOW = 4408.00
PE = 10.0900
VERSP = 10.0000
 RLIFE = 10000.0
ARPM = 3000.00
INPUT NTNF (FIRST STAGE TO BE RUN)
?1
 INPUT NTNL (LAST STAGE TO BE RUN)
?1
 INPUT NOPT=1 FOR OPT. RUNS...NOPT=0 IF NO
?0
  1STAGES                               STAGE NUMBERS
         1        2         3          4          5          6        7
 PIN
   800.00
TIN
   749.37
 PEST
     9.84
HSTAGE                          OVERALL   PERFORMANCE
    48.42                        GBR(1-7)
 STNS                                .18372E 02
    56.26                       GBN
 SD                                    .30000E 01
     1.46                       SHAFT
 D                                     .44017E 00
     3.47                       THRUST
 BHEIGHT                               .12031E 01
      .23                        ROTWT
 VRM                                   .25120E 00
      .50                        BRGNO
 TIPVEL                                .20200E 03
   835.67                       BRGSHAFT
 REACTION                            .59055E 00
      .00                       BLIFE
 VU                                    .17213E 06
   779.83                        AVGLIFE
ALPHA2                               .36067E 06
    16.00                       SEALD
BETA2                                  .89055E 00
    31.54                       SEALSP
W2                                     .21417E 03
   802.21                       SEALHP
 RELMC2                                .72790E 00
     1.76                       THEFF
ALPHA3                                 .76503E 00
    90.00                        HPTHERM
BETA3                                .63717E 02
    15.20                       GBEF
W3                                     .94929E 00
   808.09                       MECHEF
RELMC3                                 .97572E 00
     1.77                       TGVEF
PTHH                                   .70861E 00
   498.23                       TRPMM
VTHH                                   .55117E 05
      .12                       TGVHPNET
HWORK                                .59017E 02
    36.82                       *STOP* 0
 TTE
      .86
STE
      .76
```



Figure 17. RC-1 Turbine Design Computer Output

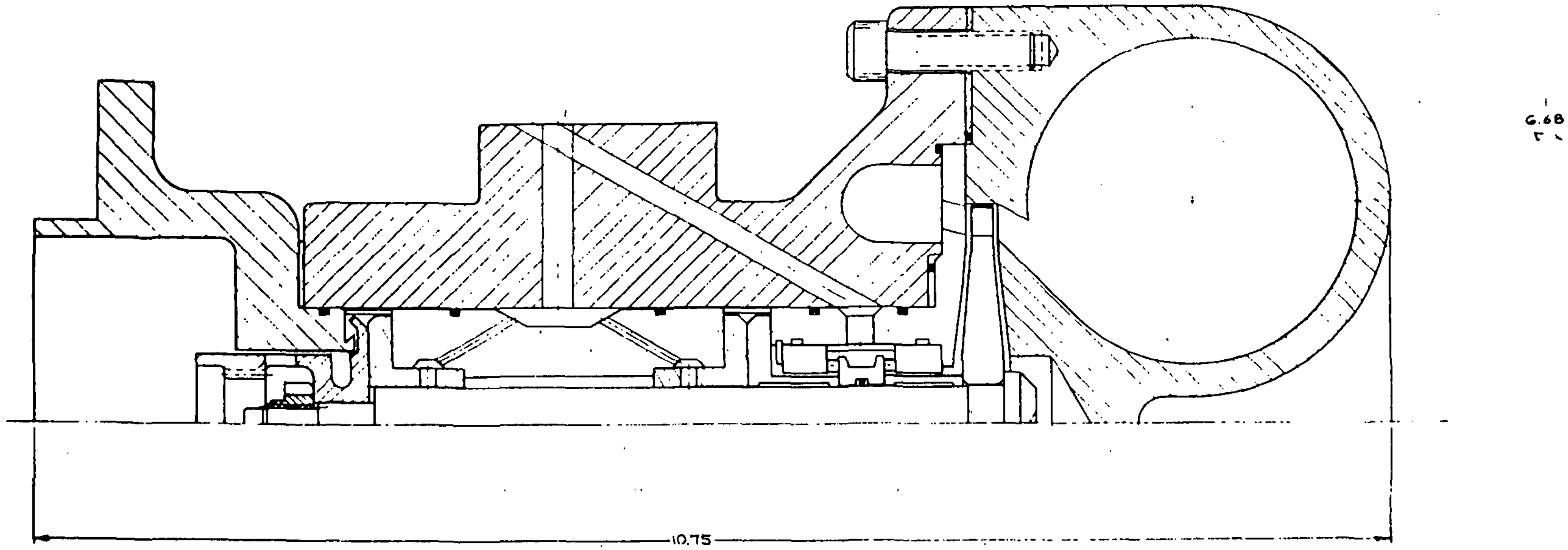



Figure 18. Turbine Design

mechanical interface between the RC-1 bottoming cycle PCU and the vehicle PTO. With this new arrangement, only one (1) gear in the PTO must be engaged, which not only reduces the complexity but also allows the bottoming cycle system to be more universally applied to various engine systems. The PCU module containing the turbine, gearbox, and feedpump assembly is shown in Figure 19.

- Condenser-Regenerator Module

  The integrated air-cooled condenser-regenerator is the most unique subsystem in the RC-1 bottoming cycle system design. The existing Fluorinol-85 Truck Bottoming Cycle System consists of a water-cooled condenser and an air-cooled radiator heat exchanger cooling loop. With the arrival of the adiabatic engine, there is now considerable incentive to eliminate any and all radiators in front of the diesel engine. The air-cooled condenser design for this system eliminates the need for a water-cooling loop and the module is located to the rear of the engine and vehicle cab (as is the vapor-generator). The regenerator in this design is integrated into the top header of the condenser. This arrangement eliminates the pipe connections that would otherwise be required of two (2) separate heat exchangers and also minimizes the installation space required for the heat exchanger. The condenser-regenerator module, shown in Figure 20, consists of a unique condenser design. The air-cooled condenser is cylindrically shaped permitting cooling air to flow radially across the condenser from the inside to the outside diameter surface. The heated air is then rejected to the ambient after passing through a small induction fan. The fan is sized to provide sufficient air flow only when the vehicles ram air intake is reduced.

  A small dc motor with a double-output through-shaft drives the fan on one end, and the boost pump and gerotor turbine lubrication pump on the other end. The assembly, as shown in Figure 20, also provides for an air-scoop device that could be used to supply condenser heated air (120°F.) to the cab interior for passenger comfort heating and for window defrosting. The overall length of the integrated condenser-regenerator unit is approximately the same as the vapor-generator (4 feet) and is installed in a similar manner - to the rear of the vehicle on the opposite side to the vapor-generator.

Figure 21 shows the RC-1 bottoming cycle system installed on a heavy-duty vehicle.

311-1083

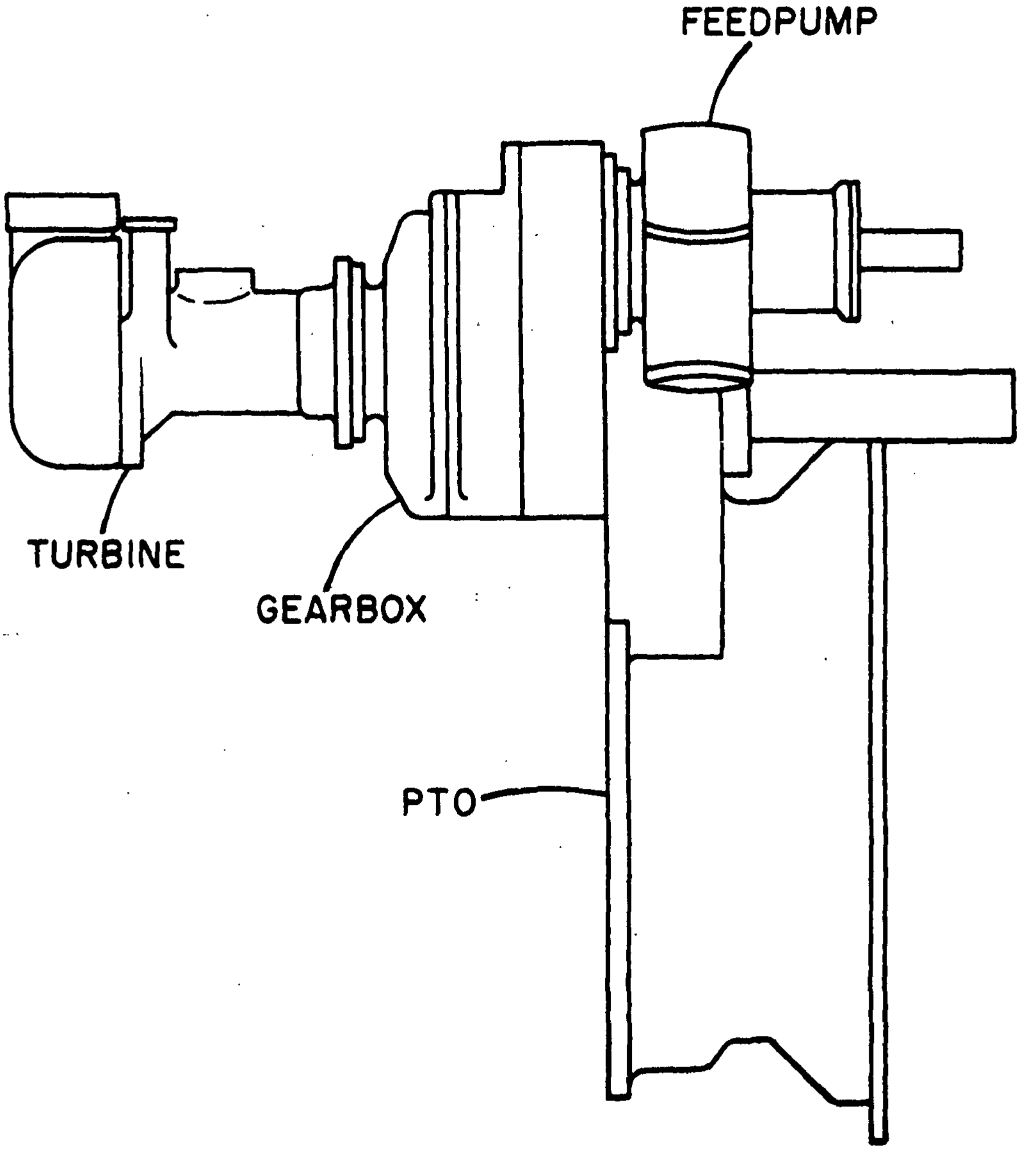



Figure 19. Power Conversion Unit (PCU)

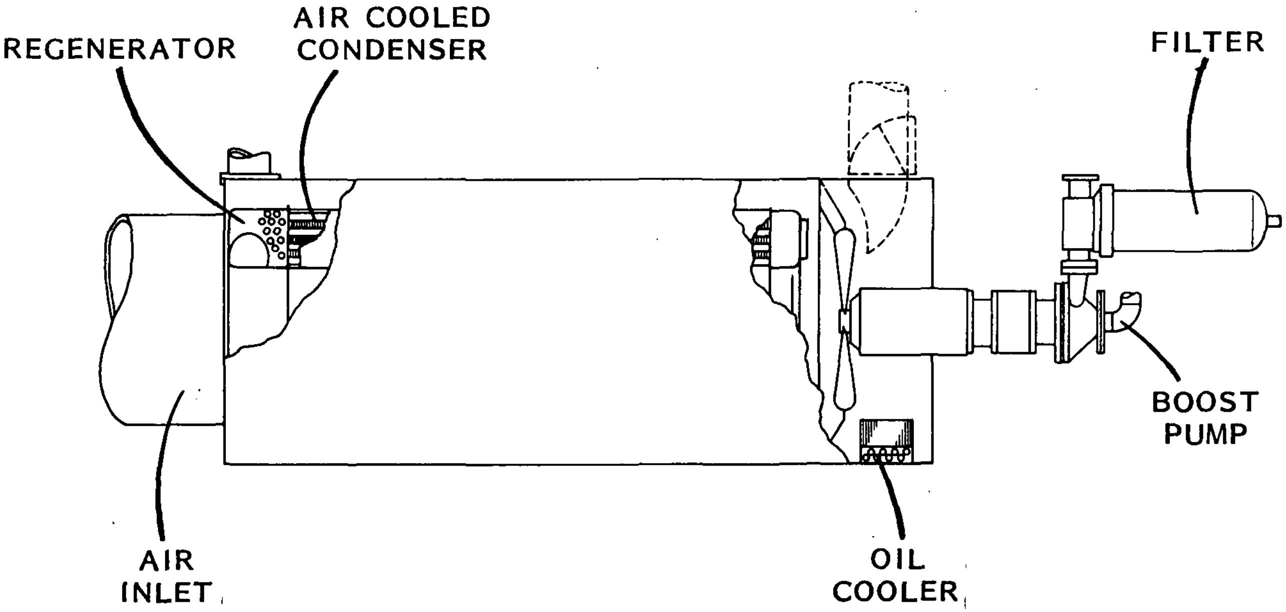



Figure 20. Condenser-Regenerator Module

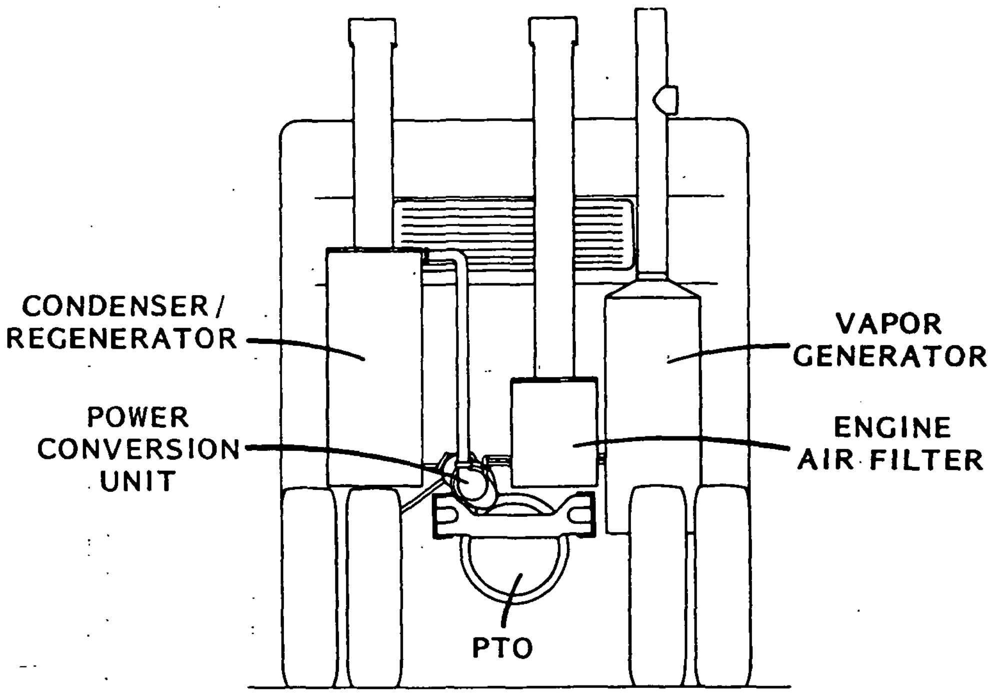



Figure 21. Typical Truck Installation

A parts list for the RC-1 system is presented in Table 16, listing the major assemblies and part breakdown for each assembly. This table also lists the estimated weight of the various components of the system. The total weight (692 lb) given here does not consider the plumbing, control system, and RC-1 organic fluid inventory. Table 17 organizes the RC-1 Bottoming Cycle System weight into the three (3) basic modules and also includes the plumbing, control system, and RC-1 fluid inventory in the estimate. The net ORCS weight of 740 lb is 300 lb lighter than the 1039-lb Fluorinol Truck Bottoming Cycle System.

## 2.4 LIFE-CYCLE COST ANALYSIS

After selection of the design point establishing the system performance and definition of the components by the system design, a cost analysis was conducted for this RC-1 Organic Rankine Bottoming Cycle System.

Efforts in the cost evaluation for the RC-1 Bottoming Cycle included:

- Potential Capital Cost
- Maintenance Cost
- Simple Payback Period
- Return on Investment

The following sections describe the evaluations and estimates made, including methodology and the economic and operational reference data provided by NASA Lewis in arriving at the final results.

### 2.4.1 Bottoming Cycle Manufacturing Cost

In 1980 Thermo Electron Corporation contracted Rath & Strong, Inc., under PO #42646, to develop the manufacturing costs to produce a diesel-organic Rankine compound engine for long-haul trucks. At that time the manufacturing costs were developed for three (3) different annual production rates and are shown in the following table.

| Annual Production Rate (units/yr) | Total Manufacturing ($/unit) |
|---|---|
| 5,000 | 5619 |
| 50,000 | 3045 |
| 150,000 | 1934 |

TABLE 16

PARTS LIST FOR RC-1 ORGANIC RANKINE-CYCLE SYSTEM

| Item | Description | Drawing No. | Req. | Est. Weight (lb) | | Remarks |
|---|---|---|---|---|---|---|
| | | | | Part | Ass'y. | |
| 1 | Turbine Ass'y. | 048-01-000 | 1 | | 33.53 | |
| | Exhaust Housing | | | 5.69 | | |
| | Inlet/Seal Housing | | | 19.30 | | |
| | Rotor | | | 0.55 | | |
| | Shaft | | | 0.48 | | |
| | Bearings | | | 0.27 | | |
| | Seal Ass'y. | | | 0.12 | | |
| | Preload Spacer | | | 1.47 | | |
| | Mounting Flange | | | 5.65 | | |
| 2 | Turbine Gearbox | 048-02-000 | 1 | | 36 | Actual weight of similar gearbox |
| | Housing | | | | | |
| | Gears | | | | | |
| | Coupling | | | | | |
| | Quill-Shaft | | | | | |
| | Bearings | | | | | |
| 3 | Feedpump Drive | 048-03-000 | 1 | | 36 | |
| | Housing | | | - | | Housing weight included in turbine gearbox |
| | Over-Running Clutch | | | 25 | | |
| | Flex-Shaft | | | | | |
| | Bearings | | | | | |
| | Pulleys | | | 9 | | |
| | Belt | | | | | |

TABLE 16 (Cont'd)

PARTS LIST FOR RC-1 ORGANIC RANKINE-CYCLE SYSTEM

| Item | Description | Drawing No. | Req. | Est. Weight (lb) | | Remarks |
|---|---|---|---|---|---|---|
| | | | | Part | Ass'y. | |
| 4 | Feedpump Ass'y.<br>Housing<br>Roll-Nut<br>Pistons<br>Bearings<br>Potentiometer<br>Motor | 048-04-000 | 1 | | 17.3 | Actual weight of Fl-85 feedpump |
| 5 | Vapor Generator<br>Shell<br>Baseplate<br>Top<br>Exhaust Pipe<br>Core (Finned Tube)<br>Diverter Valve | 048-05-000 | 1 | | 450 | Actual weight |
| 6 | Cond./Regen. Ass'y.<br>Shell<br>Top Plate<br>Regen. Ass'y.<br>Tubes<br>Core (Finned Tube) | 048-06-000 | 1 | 22<br>13<br>40 | 75 | |
| 7 | Fan Ass'y. | 048-07-000 | 1 | | 1.5 | |

TABLE 16 (Cont'd)

PARTS LIST FOR RC-1 ORGANIC RANKINE-CYCLE SYSTEM

| Item | Description | Drawing No. | Req. | Est. Weight (lb) Part | Est. Weight (lb) Ass'y. | Remarks |
|---|---|---|---|---|---|---|
| 8 | Filter Ass'y.<br>Shell<br>Flanges<br>Element | 048-08-000 | 1 | | 5 | Actual weight |
| 9 | Boost/Lube Pump<br>Motor<br>Housing<br>Shaft<br>Empellar<br>Bearings<br>Gerotor<br>Seal Ass'y. | 048-09-000 | 1 | | 23.8 | Actual weight |
| 10 | Oil Cooler<br>Frame<br>Core (Finned Tube) | 048-10-000 | 1 | | 2.5 | |
| 11 | Regen. Support Brkt. | 048-00-011 | 1 | | 9.5 | |
| 12 | Filter/Boost Pump Brkt. | 048-00-11 | 1 | | 2.0 | |
| | | | | | 692.13 | Total Weight |

TABLE 17

RC-1 BOTTOMING CYCLE SYSTEM WEIGHT

| | |
|---|---|
| • Vapor-Generator Module | 450 lb |
| • Power Conversion Unit (PCU) | 135 lb |
| – Turbine | |
| – Gearbox | |
| – Feedpump | |
| – Feedpump Drive | |
| – Plumbing and Hardware | |
| • Condenser-Regenerator Module | 119 lb |
| – Condenser | |
| – Regenerator | |
| – Fan | |
| – Filter Assembly | |
| – Boost/Lube Pump | |
| – Oil Cooler | |
| – Regenerator Support Bracket | |
| – Filter/Boost Pump Bracket | |
| • Control System | 7 lb |
| • RC-1 Fluid Inventory (4 gal at 13.4 lb/gal) | 54 lb |
| Gross ORCS Weight | 765 lb |
| Deduct for Muffler | -25 lb |
| Net ORCS Weight | 740 lb |

The factors and concepts applied in the calculation of the above unit costs are summarized as follows.

- Material Cost

  The material cost per unit applies to the 5000 per year volume level with a 0.9 learning curve concept applied for the other production levels. That is, for every doubled quantity, the cost is reduced by 10 percent.

- Direct Labor Cost

  A labor rate of $8.00 per hour was used for each man-hour.

- Indirect Labor Cost

  40 percent of direct labor unit cost was used.

- Tools Cost

  These costs were amortized over 3 years.

- Equipment Cost

  - Machine Utilization - For the 5000 units per year volume level, it was estimated that the machines would be 30 percent loaded on an ideal basis. Industry experience indicates that only about 75 percent of ideal utilization is attained; therefore, a combined factor of 40 percent (30% ÷ 75%) has been applied. A multiplication factor of 0.90 was used for 50,000 units/year and 0.95 was used for 150,000 units/year.

  - The resultant estimates were amortized over 12 years.

A manufacturing cost of $4189 for the RC-1 Bottoming Cycle System has been developed for an annual production rate of 10,000 units (Table 18). For all similar components in the RC-1 system design, the same methodology was used as described above for the Rath & Strong, Inc. cost development. New cost estimates or vendor quoted costs (noted items in Table 18) for components that are unique or different for the RC-1 system design have been incorporated. Factors for the 10,000 units/year production level have been calculated or extrapolated from those used in the Rath & Strong cost estimates. Those costs shown in Table 18 have also been escalated by 20.4 percent to bring the estimates in line with the current dollar value. This 20.4-percent factor was obtained from the "Survey of Current Business," United States Department of Commerce/ Bureau of Economic Analysis and is the inflation index for Transportation Motor Vehicles and Equipment.

TABLE 18

MANUFACTURING COST ESTIMATE FOR RC-1 BOTTOMING CYCLE SYSTEM AT AN ANNUAL PRODUCTION RATE OF 10,000 UNITS

| Assembly | Dollars Per Unit |
|---|---|
| Feedpump | $ 402 |
| Turbine/Gearbox | 827 |
| Condenser/Regenerator | 490 |
| Vapor Generator | 1500* |
| Feedpump Drive | 102 |
| Boost/Lube Pump and Fan | 205 |
| Filter Assembly | 36 |
| Oil Cooler | 11 |
| Rupture Disc Assembly | 85 |
| Bracket Support Regenerator | 17 |
| Flanges, Condenser | 6 |
| Miscellaneous Equipment and Hardware<br>- Corrugated Metal Hose<br>- "O"-Rings<br>- Tubing<br>- Pipe<br>- Hardware | 27 |
| Control System | 305 |
| RC-1 Organic Working Fluid | 176** |
| Total Cost | $4189 |

Notes:

*This cost is an actual quote from Cannon Boiler Works of Pennsylvania. The recalculated cost for this heat exchanger performed by the Rath & Strong method yielded a cost of $1405 for this production level. This adds another degree of confidence to the Rath & Strong method.

**The fluid inventory required for the RC-1 bottoming cycle system is 4 gallons at an estimated manufacturing cost of $44 per gallon.

The cost estimate of $44 per gallon for the RC-1 fluid is based on an annual production rate of 100,000 gallons. This RC-1 manufacturing cost has been developed utilizing both in-house experience and a Monsanto study (ref. 3). One input for this cost estimate was the experience of an actual pilot plant built and operated by Thermo Electron Corporation with production rate of 66 gallons per year. The total manufacturing cost at this small production capacity was $1208 per gallon. Estimates of the manufacturing cost for a plant with a production capacity 100 times greater (6600 gallons per year) resulted in a cost at $86 per gallon. Recent verbal communication with Imperial Smelting of England indicates that RC-1 fluid can be purchased from them at approximately $1000 per gallon in single gallon quantities.

The other major source and basis for the RC-1 manufacturing cost developed for this system is the previously mentioned Monsanto study. A manufacturing and economic evaluation indicated a plant selling price of $1.40/lb of RC-1 for a large plant producing 50,000,000 lb/hr. With a liquid density of 13 lb/gal, these values are equivalent to $18/gal RC-1 and 3,900,000 gal/year.

### 2.4.2 Bottoming Cycle Maintenance Cost

A maintenance expense for the RC-1 Bottoming Cycle System has been estimated at $0.011 per mile. This maintenance cost has been derived from prior evaluation and studies performed for the Fluorinol Truck Bottoming Cycle System ($0.01/mile in 1980 dollars), and the actual service contract price for maintenance that Thermo Electron offers for its TECOGEN™ Cogeneration Module.

The TECOGEN is an automatic cogeneration module manufactured by Thermo Electron. The module simultaneously produces hot water and 60 kW of electricity. This powerplant, although a stationary system, can be compared to the bottoming cycle with similar components. The cogeneration module, which is designed to operate 24 hours a day, continuously, contains the following major components.

- Modified V-8 Engine for Industrial Use (Not in Bottoming Cycle System)
- Engine Coolant Heat Exchanger (Coolant to Water)
- Exhaust Heat Exchanger (Gas to Water)
- Water-Cooled Exhaust Manifolds
- Oil Cooler
- Induction Generator (Not in Bottoming Cycle System)

- Microprocessor Control System
  - Automatically starts and stops the unit
  - Connects or disconnects the module with the electric utility
  - Provides diagnostic capability

Thermo Electron offers a service maintenance contract at a cost of \$0.015/kWh. The maintenance price includes:

- Personnel travel to and from the site.
- Preventive maintenance schedule that includes engine oil changes every 500 hours.
- Repairs and parts replacement, both scheduled and unscheduled.
- Complete engine replacement after 12,000 hours (if required).

Personnel travel to and from the site is one-third the maintenance cost. Because this cost does not apply for the bottoming cycle where maintenance is performed in a service area, then the comparable maintenance cost for the bottoming cycle can be based on two-thirds the module maintenance cost (2/3 x \$0.015/kWh), or \$0.010/kWh. For continuous operation of the module the total maintenance cost for the year then becomes:

$$\$0.01/\text{kWh} \times 60 \text{ kW} \times 8760 \text{ hr/yr} = \$5256/\text{yr}.$$

For steady-state operation this translates to an equivalent yearly mileage of:

$$8760 \text{ hr/yr} \times 55 \text{ miles/hr} = 481{,}800 \text{ miles/yr}.$$

Thus, the maintenance cost calculated on a mileage basis becomes:

$$\frac{\$5256/\text{yr}}{481{,}800 \text{ miles/yr}} = \$0.0109/\text{mile}.$$

The 1980 \$0.01/mile maintenance cost for the Truck Bottoming Cycle System considered the following factors.

- Scheduled Maintenance
  - Vapor-generator cleaning (water wash) at same interval as diesel engine oil change (Mack recommends oil change every 16,000 miles).
  - Gearbox oil changes at same interval as diesel engine oil change.
  - Organic fluid filter cartridge change at same interval as diesel engine oil change.

- One (1) burst disc replacement per year
- One-half organic fluid inventory replacement per year (2 to 2½ gallons)

- Unscheduled Maintenance
  - One (1) fan belt replacement
  - Control system repair (i.e., card replacement).
  - Other failures (i.e., organic fluid flexline leak, turbine seal leak, and feedpump feedback pot)

Time estimates for the normal maintenance schedule were determined from actual operating experience with the Test Bed Vehicles (over 55,000 miles) and also with the laboratory system (over 2000 hours of operation). These times together, with allowance for some unscheduled maintenance, were used to determine the prior 1980 maintenance cost of $0.01/mile. Of this $0.01/mile maintenance burden for the ORCS, just over half ($0.006/mile) is for the normal maintenance schedule, while the balance of the $0.01/mile cost is allocated for unscheduled maintenance or failures. These maintenance costs are based on a truck annual mileage of 100,000 miles.

Considering the above mentioned service contract for the TECOGEN and prior studies done on the Truck Bottoming Cycle System to determine maintenance requirements both scheduled and unscheduled, a maintenance cost of $0.011 per mile was established for this study.

### 2.4.3 Bottoming Cycle System Economic Incentives

The economic benefits of an RC-1 Bottoming Cycle System are based on the fuel savings potential of the system, system cost, and economic conditions that exist at the time. The fuel savings potential has been established by the analysis task of this program and the unit and other associated costs have been developed in the preceding paragraphs. The economic conditions for this study have been established by the NASA Lewis Research Center. Table 19 shows the NASA Reference Diesel Engine Data with respect to the mission fuel economy and selling price for each of the four (4) base diesel engine configurations. The other pertinent economic and operational data, such as fuel price and annual vehicle mileage, are presented in Table 20.

The simple payback period was then calculated for the Bottoming Cycle versus the Turbocompound Engine System by the procedure designated by NASA and shown in Table 21. This example calculates the payback period of the bottoming cycle compound engine only in reference to

TABLE 19

NASA REFERENCE DIESEL ENGINE DATA

| DIESEL CONFIGURATION | BHP* | BSFC (LB/BHP-HR) | MISSION (MPG) | SELLING PRICE ($) |
|---|---|---|---|---|
| TC | 317 | 0.315 | 5.66 | 14,000 |
| TC/A | 320 | 0.310 | 5.75 | 14,500 |
| TCPD | 335 | 0.297 | 6.00 | 16,000 |
| TCPD/A | 340 | 0.293 | 6.08 | 16,500 |

*FOR ENGINE RATINGS ABOVE THOSE LISTED IN THE TABLE, ADD $30 PER HORSEPOWER.

TABLE 20

NASA REFERENCE
ECONOMIC/OPERATIONAL DATA

- COST OF MONEY (INTEREST)........... 12%
- CORPORATE TAX RATE ................. 46%
- INVESTMENT TAX CREDIT.............. 7%
- ESCALATION RATE...................... 0%
- DIESEL FUEL PRICE PER GALLON....... $1.20
- ANNUAL MILEAGE PER TRUCK.......... 100,000
- HARDWARE USEFUL LIFE ............... 7 YEARS
- ANNUAL PRODUCTION RATE ........... 10,000*
- SELLING PRICE/MFG COST ............. 2.0

*10% PENETRATION ON A MARKET OF 100,000 CLASS-8 TRUCKS SOLD PER YEAR

TABLE 21

NASA REFERENCE SIMPLE PAYBACK PERIOD
(BOTTOMING CYCLE VS TURBOCOMPOUND)

- BOTTOMING CYCLE PARAMETERS:
  - OUTPUT AS APPLIED TO TC ENGINE - 56 HP
  - BOTTOMING CYCLE SELLING PRICE - $8378
- COMPOUND ENGINE PARAMETERS:
  - RATED BHP - 317 + 56 = 373
  - BSFC/MPG - 0.268/6.65
  - ANNUAL FUEL - 15,037 GAL/$18,044
  - ENGINE SYSTEM PRICE - $14,000 + $8378 = $22,378
- COMPARABLE TCPD/A ENGINE PARAMETERS:
  - RATED BHP - 373
  - BSFC/MPG - 0.293/6.08
  - ANNUAL FUEL - 16,447 GAL/$19,737
  - ENGINE SYSTEM PRICE - $16,500 + (33 x 30) = $17,490)
- SIMPLE PAYBACK:
  - ANNUAL FUEL SAVINGS - 1410 GAL/$1692
  - ENGINE CAPITAL COST DIFFERENCE - $4888
  - PAYBACK PERIOD - 2.89 YEARS

the turbocompound (TCPD/A) engine and does not consider the payback period requirements of the TCPD/A engine with reference to the TC engine configuration, for example. A set of calculations for payback period was made for both the TCPD/A engine and the bottoming cycle compound engine versus each reference diesel engine configuration. The examples for each case are presented in Tables 22 (a) through 22(d). The last item in each table shows the difference in payback period between the Bottoming Cycle Compound Engine and the TCPD/A Engine Systems.

A summary for the simple payback period for the option choice versus each base engine configuration is shown in Table 23. Besides the payback periods for the TCPD/A, ORCS, and the difference between them, the payback periods for the other engine options versus the reference base engine configuration has also been calculated where applicable. If a potential buyer is weighing the options against the base TC engine, consideration should be given to the payback period of each option for the fuel economy benefits derived and the capital cost difference required. For instance, if one chooses the TC/A engine over the TC engine, the simple payback period is 1.22 years for the fuel saving benefit of the TC/A over the TC engine for the $500 cost difference between them. Similarly, if one decides to spend $8400 for the ORCS option, it will take only 2.12 years to pay back considering the fuel savings potential of this system.

A nomogram was developed to graphically determine the simple payback period of any Bottoming Cycle System compared to any of the four (4) reference diesel engine configurations knowing only the compound engine BSFC and the additional power output provided by the bottoming system. The nomogram and expressions for the development of this payback period nomogram are presented in Appendix D.

The simple payback period examples shown above were based on a fuel price of $1.20/gal and an annual truck mileage of 100,000 miles (defined by NASA reference data). Figure 22 shows the payback period sensitivity to fuel price for the vehicle mileage "window" from 100,000 to 150,000 miles per year. As vehicle annual mileage approaches 150,000 miles and fuel prices advance towards the $2.00 per gallon figure, this $8400 RC-1 Bottoming Cycle System will pay back in less than one (1) year.

A cash flow projection was executed for the RC-1 Bottoming Cycle System utilizing the Table 20 economic reference data furnished by NASA. Table 24 shows the cash flow subset of a potential fleet or other vehicle owner for the 7-year hardware useful life with cumulative profits of over $6600 and cash flow exceeding $5500. This example shows an internal rate of return of 45 percent for this "up front" capital investment, even after introducing a maintenance cost of $0.011 per mile.

## TABLE 22a

## SIMPLE PAYBACK EXAMPLE
## FOR BOTTOMING TC ENGINE

| | | |
|---|---|---|
| (1) BOTTOMING CYCLE PARAMETERS | | |
| - Output as Applied to TC Engine | - | 56 hp |
| - Bottoming Cycle Selling Price | - | $8378 |
| (2) COMPOUND ENGINE PARAMETERS (BOTTOMING CYCLE) | | |
| - Rated bhp | - | 317 + 56 = 373 hp |
| - bsfc/mpg | - | 0.268/6.65 |
| - Annual Fuel | - | 15,037 gal/$18,044 |
| - Engine System Price | - | $14,000 + $8,378 = $22,378 |
| (3) SIMPLE PAYBACK (BOTTOMING CYCLE) | | |
| - Annual Fuel Savings | - | 2631 gal/$3157 |
| - Engine Capital Cost Difference | - | $6698 |
| - Payback Period | - | 2.12 years |
| (4) DIESEL ENGINE PARAMETERS | | |
| - Output of TC Engine | - | 317 + 56 = 373 hp |
| - bsfc/mpg | - | 0.315/5.66 |
| - Annual Fuel | - | 17,668 gal/$21,201 |
| - Engine Selling Price | - | $14,000 + (56 x 30) = $15,680 |
| (5) TCPD/A ENGINE PARAMETERS | | |
| - Rated bhp | - | 340 + 33 = 373 hp |
| - bsfc/mpg | - | 0.293/6.08 |
| - Annual Fuel | - | 16,447 gal/$19,737 |
| - Engine System Price | - | $16,500 + (33 x 30) = $17,490 |
| (6) SIMPLE PAYBACK (TURBOCOMPOUND) | | |
| - Annual Fuel Savings | - | 1221 gal/$1465 |
| - Engine Capital Cost Difference | - | $1810 |
| - Payback Period | - | 1.24 years |
| (7) DIFFERENCE IN PAYBACK PERIOD | | |
| (3) (6)<br>2.12 - 1.24 = 0.88 year | | |

## TABLE 22b

## SIMPLE PAYBACK EXAMPLE FOR BOTTOMING TC/A ENGINE

(1) BOTTOMING CYCLE PARAMETERS

| | | |
|---|---|---|
| - Output as Applied to TC/A Engine | - | 52 |
| - Bottoming Cycle Selling Price | - | \$8378 |

(2) COMPOUND ENGINE PARAMETERS (BOTTOMING CYCLE)

| | | |
|---|---|---|
| - Rated bhp | - | 320 + 52 = 372 hp |
| - bsfc/mpg | - | 0.267/6.68 |
| - Annual Fuel | - | \$14,970 gal/\$17,965 |
| - Engine System Price | - | \$14,500 + \$8,378 = \$22,878 |

(3) SIMPLE PAYBACK (BOTTOMING CYCLE)

| | | |
|---|---|---|
| - Annual Fuel Savings | - | 2421 gal/\$2905 |
| - Engine Capital Cost Difference | - | \$6818 |
| - Payback Period | - | 2.35 years |

(4) DIESEL ENGINE PARAMETERS

| | | |
|---|---|---|
| - Output of TC/A Engine | - | 320 + 52 = 372 hp |
| - bsfc/mpg | - | 0.310/5.75 |
| - Annual Fuel | - | 17,391 gal/\$20,870 |
| - Engine Selling Price | - | \$14,500 + (52 x 30) = \$16,060 |

(5) TCPD/A ENGINE PARAMETERS

| | | |
|---|---|---|
| - Rated bhp | - | 340 + 32 = 372 hp |
| - bsfc/mpg | - | 0.293/6.08 |
| - Annual Fuel | - | 16,447 gal/\$19,737 |
| - Engine System Price | - | \$16,500 + (32 x 30) = \$17,460 |

(6) SIMPLE PAYBACK (TURBOCOMPOUND)

| | | |
|---|---|---|
| - Annual Fuel Savings | - | 944 gal/\$1133 |
| - Engine Capital Cost Difference | - | \$1400 |
| - Payback Period | - | 1.24 years |

(7) DIFFERENCE IN PAYBACK PERIOD

(3) (6)

2.35 - 1.24 = 1.11 years

## TABLE 22c

## SIMPLE PAYBACK EXAMPLE FOR BOTTOMING TCPD ENGINE

(1) BOTTOMING CYCLE PARAMETERS

| | | |
|---|---|---|
| - Output as Applied to TCPD Engine | - | 50 hp |
| - Bottoming Cycle Selling Price | - | $8378 |

(2) COMPOUND ENGINE PARAMETERS (BOTTOMING CYCLE)

| | | |
|---|---|---|
| - Rated bhp | - | 335 + 50 = 383 hp |
| - bsfc/mpg | - | 0.258/6.91 |
| - Annual Fuel | - | 14,472 gal/$17,366 |
| - Engine System Price | - | $16,000 + $8,378 = $24,378 |

(3) SIMPLE PAYBACK (BOTTOMING CYCLE)

| | | |
|---|---|---|
| - Annual Fuel Savings | - | 2195 gal/$2634 |
| - Engine Capital Cost Difference | - | $6878 |
| - Payback Period | - | 2.61 years |

(4) DIESEL ENGINE PARAMETERS

| | | |
|---|---|---|
| - Output of TCPD Engine | - | 335 + 50 = 385 hp |
| - bsfc/mpg | - | 0.297/6.00 |
| - Annual Fuel | - | 16,667 gal/$20,000 |
| - Engine Selling Price | - | $16,000 + (50 x 30) = $17,500 |

(5) TCPD/A ENGINE PARAMETERS

| | | |
|---|---|---|
| - Rated bhp | - | 340 + 45 = 385 hp |
| - bsfc/mpg | - | 0.293/6.08 |
| - Annual Fuel | - | 16,447 gal/$19,737 |
| - Engine System Price | - | $16,500 + (45 x 30) = $17,850 |

(6) SIMPLE PAYBACK (TURBOCOMPOUND)

| | | |
|---|---|---|
| - Annual Fuel Savings | - | 220 gal/$264 |
| - Engine Capital Cost Difference | - | $350 |
| - Payback Period | - | 1.33 years |

(7) DIFFERENCE IN PAYBACK PERIOD

(3) (6)

2.61 - 1.33 = 1.28 years

TABLE 22d

SIMPLE PAYBACK EXAMPLE
FOR BOTTOMING TCPD/A ENGINE

(1) BOTTOMING CYCLE PARAMETERS

| | | |
|---|---|---|
| - Output as Applied to TCPD/A Engine | - | 46 hp |
| - Bottoming Cycle Selling Price | - | $8378 |

(2) COMPOUND ENGINE PARAMETERS (BOTTOMING CYCLE)

| | | |
|---|---|---|
| - Rated bhp | - | 340 + 46 = 386 hp |
| - bsfc/mpg | - | 0.258/6.91 |
| - Annual Fuel | - | 14,472 gal/$17,366 |
| - Engine System Price | - | $16,500 + $8,378 = $24,878 |

(3) SIMPLE PAYBACK (BOTTOMING CYCLE)

| | | |
|---|---|---|
| - Annual Fuel Savings | - | 1975 gal/$2370 |
| - Engine Capital Cost Difference | - | $6998 |
| - Payback Period | - | 2.95 years |

(4) DIESEL ENGINE PARAMETERS

| | | |
|---|---|---|
| - Output of TCPD/A Engine | - | 340 + 46 = 386 hp |
| - bsfc/mpg | - | 0.293/6.08 |
| - Annual Fuel | - | 16,447 gal/$19,737 |
| - Engine Selling Price | - | $16,500 + (46 x 30) = $17,880 |

(5) TCPD/A ENGINE PARAMETERS

| | | |
|---|---|---|
| - Rated bhp | - | 340 + 46 = 386 hp |
| - bsfc/mpg | - | 0.293/6.08 |
| - Annual Fuel | - | 16,447 gal/$19,737 |
| - Engine System Price | - | $16,500 + (46 x 30) = $17,880 |

(6) SIMPLE PAYBACK (TURBOCOMPOUND)

- Annual Fuel Savings
- Engine Capital Cost Difference
- Payback Period

(7) DIFFERENCE IN PAYBACK PERIOD

TABLE 23

SIMPLE PAYBACK PERIOD FOR OPTION CHOICE (YEARS)

| BASE ENGINE CONFIGURATION | OPTION | | | | | ΔPAYBACK PERIOD |
|---|---|---|---|---|---|---|
| | TC | TC/A | TCPD | TCPD/A | ORCS | ORCS-TCPD/A |
| TC | - | 1.22 | 1.20 | 1.24 | 2.12 | 0.88 |
| TC/A | - | - | 1.20 | 1.24 | 2.35 | 1.11 |
| TCPD | - | - | - | 1.33 | 2.61 | 1.28 |
| TCPD/A | - | - | - | - | 2.95 | 2.95 |

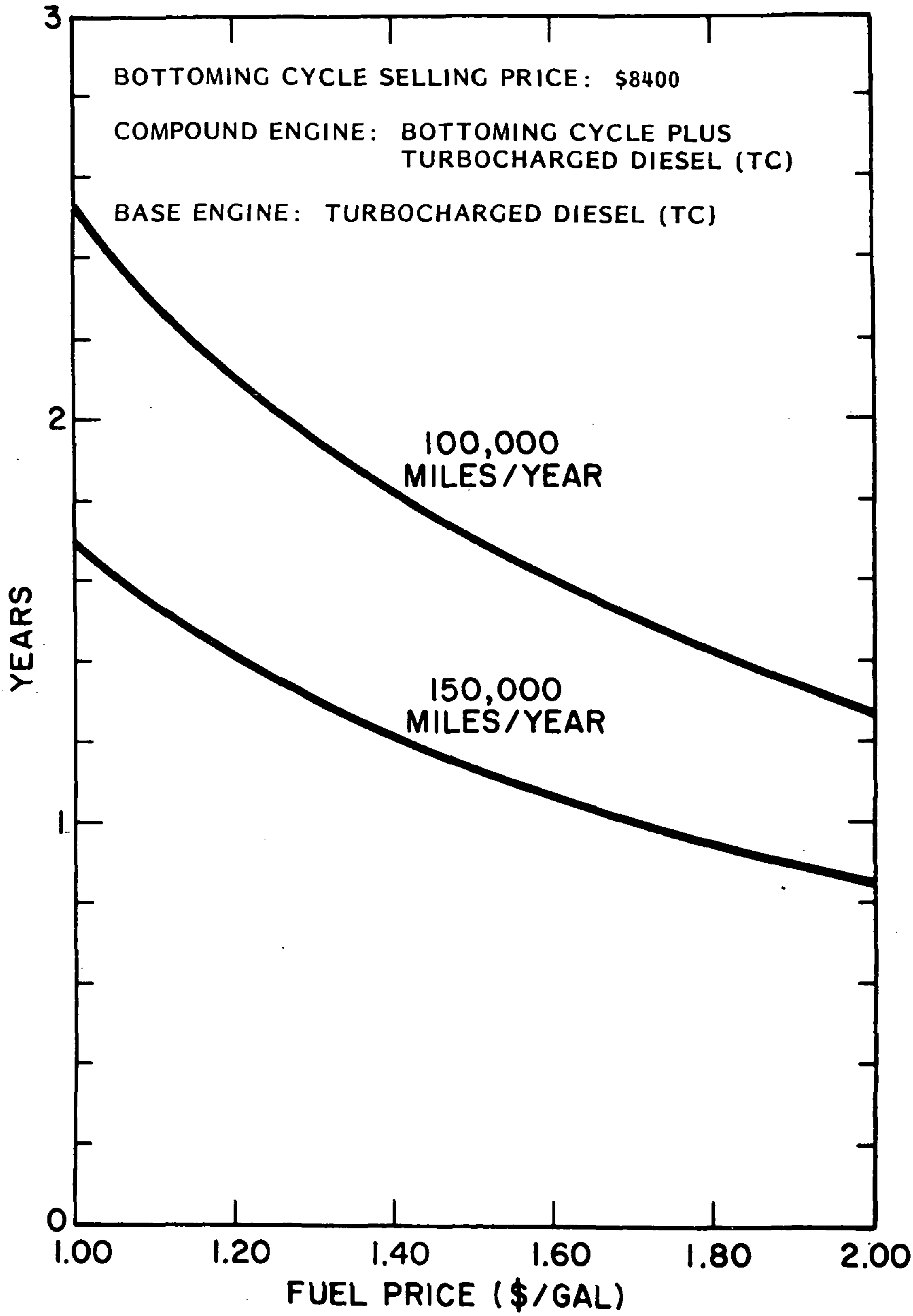



Figure 22. RC-1 Bottoming Cycle System Simple Payback Period without Maintenance Burden

# TABLE 24

## RC-1 BOTTOMING CYCLE SYSTEM - CASH FLOW PROJECTION

| | |
|---|---|
| COST OF MONEY | 12% |
| CORPORATE TAX RATE | 46% |
| INVESTMENT TAX CREDIT | 7% |
| ESCALATION RATE | 0% |
| DIESEL FUEL PRICE/GAL | $1.20 |
| ANNUAL MILEAGE/TRUCK | 100,000 |
| HARDWARE USEFUL LIFE (YR) | 7 |
| OPERATION AND MAINTENANCE COST/MIL | $0.011 |
| ORCS COST | $8378.00 |
| ORCS COST DIFFERENTIAL | $6698.00 |
| ORCS POWER OUTPUT (HP) | 56 |
| COST/HP ABOVE BASE ENGINE POWER | $30.00 |
| MPG BASE DIESEL | 5.66 |
| MPG ORCS/DIESEL | 6.65 |
| DEPRECIATION RATE/YR | 3% |
| DEBT | 0% |
| LOAN TERM (MON) | 0 |

| YEAR | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|
| ORCS COST | 8378 | 0 | 0 | 0 | 0 | 0 | 0 |
| ORCS COST DIFFERENTIAL | 6698 | 0 | 0 | 0 | 0 | 0 | 0 |
| INVESTMENT TAX CREDIT | 586 | 0 | 0 | 0 | 0 | 0 | 0 |
| DEPRECIATION | 2793 | 2793 | 2793 | 0 | 0 | 0 | 0 |
| FUEL SAVINGS | 3156 | 3156 | 3156 | 3156 | 3156 | 3156 | 3156 |
| OPERATION AND MAINTENANCE COST | 1100 | 1100 | 1100 | 1100 | 1100 | 1100 | 1100 |
| OPERATING SAVINGS | 2056 | 2056 | 2056 | 2056 | 2056 | 2056 | 2056 |
| LOAN PRINCIPAL/END | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| MONTHS ON NOTE | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| PRINCIPAL PAYMENT | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| INTEREST PAYMENT | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| TOTAL: PRINCIPAL AND INTEREST | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| PRETAX PROFITS | -736 | -736 | -736 | 2056 | 2056 | 2056 | 2056 |
| TAXES | -925 | -339 | -339 | 946 | 946 | 946 | 946 |
| AFTERTAX PROFITS | 189 | -398 | -398 | 1110 | 1110 | 1110 | 1110 |
| CASH FLOW | -3717 | 2395 | 2395 | 1110 | 1110 | 1110 | 1110 |
| CUMULATIVE PROFITS | 189 | -209 | 2186 | 3297 | 4407 | 5517 | 6628 |
| CUMULATIVE CASH FLOW | -3717 | -1321 | 1074 | 2184 | 3294 | 4405 | 5515 |

| | |
|---|---|
| SIMPLE PAYBACK (YR) | 3.26 |
| INTERNAL RATE OF RETURN (%) | 45 |

Similar cash flow projections are presented in Tables 25 and 26. A 50-percent loan for 5 years (60 months) is carried in the Table 25 example, while the full capital cost (100 percent debt) is carried for 60 months in the example of Table 26. The internal rate of return for the 50-percent debt of Table 25 exceeds 200 percent while the 100-percent debt cash flow projection of Table 26 indicates a rate of return that approaches infinity. The reason for this high rate of return in Table 26 is that the cash flow is never negative. By definition the rate of return equates the equivalent value of positive cash flow to the negative cash flow over the number of years (N) in the study period and determines the interest rate value (i).

# TABLE 25

## RC-1 BOTTOMING CYCLE SYSTEM - CASH FLOW PROJECTION

| | |
|---|---|
| COST OF MONEY | 12% |
| CORPORATE TAX RATE | 46% |
| INVESTMENT TAX CREDIT | 7% |
| ESCALATION RATE | 0% |
| DIESEL FUEL PRICE/GAL | $1.20 |
| ANNUAL MILEAGE/TRUCK | 100,000 |
| HARDWARE USEFUL LIFE (YR) | 7 |
| OPERATION AND MAINTENANCE COST/MIL | $0.011 |
| ORCS COST | $8378.00 |
| ORCS COST DIFFERENTIAL | $6698.00 |
| ORCS POWER OUTPUT (HP) | 56 |
| COST/HP ABOVE BASE ENGINE POWER | $30.00 |
| MPG BASE DIESEL | 5.66 |
| MPG ORCS/DIESEL | 6.65 |
| DEPRECIATION RATE/YR | 3% |
| DEBT | 50% |
| LOAN TERM (MON) | 60 |

| YEAR | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|
| ORCS COST | 4189 | 0 | 0 | 0 | 0 | 0 | 0 |
| ORCS COST DIFFERENTIAL | 3349 | 0 | 0 | 0 | 0 | 0 | 0 |
| INVESTMENT TAX CREDIT | 586 | 0 | 0 | 0 | 0 | 0 | 0 |
| DEPRECIATION | 2793 | 2793 | 2793 | 0 | 0 | 0 | 0 |
| FUEL SAVINGS | 3156 | 3156 | 3156 | 3156 | 3156 | 3156 | 3156 |
| OPERATION AND MAINTENANCE COST | 1100 | 1100 | 1100 | 1100 | 1100 | 1100 | 1100 |
| OPERATING SAVINGS | 2056 | 2056 | 2056 | 2056 | 2056 | 2056 | 2056 |
| LOAN PRINCIPAL/END | 2829 | 2243 | 1583 | 838 | 0 | 0 | 0 |
| MONTHS ON NOTE | 48 | 36 | 24 | 12 | 0 | 0 | 0 |
| PRINCIPAL PAYMENT | 520 | 586 | 660 | 744 | 838 | 0 | 0 |
| INTEREST PAYMENT | 374 | 308 | 234 | 150 | 55 | 0 | 0 |
| TOTAL: PRINCIPAL AND INTEREST | 894 | 894 | 894 | 894 | 894 | 0 | 0 |
| PRETAX PROFITS | -1110 | -1630 | -1630 | 1162 | 1162 | 2056 | 2056 |
| TAXES | -1269 | - 892 | - 857 | 466 | 509 | 946 | 946 |
| AFTERTAX PROFITS | 159 | - 739 | - 773 | 697 | 653 | 1110 | 1110 |
| CASH FLOW | - 917 | 2054 | 2020 | 697 | 653 | 1110 | 1110 |
| CUMULATIVE PROFITS | 159 | - 580 | 1440 | 2137 | 2790 | 3900 | 5011 |
| CUMULATIVE CASH FLOW | - 917 | 1136 | 3156 | 3853 | 4506 | 5616 | 6727 |

| | |
|---|---|
| SIMPLE PAYBACK (YR) | 3.26 |
| INTERNAL RATE OF RETURN (%) | 208 |

# TABLE 26

## RC-1 BOTTOMING CYCLE SYSTEM - CASH FLOW PROJECTION

| | |
|---|---|
| COST OF MONEY | 12% |
| CORPORATE TAX RATE | 46% |
| INVESTMENT TAX CREDIT | 7% |
| ESCALATION RATE | 0% |
| DIESEL FUEL PRICE/GAL | $1.20 |
| ANNUAL MILEAGE/TRUCK | 100,000 |
| HARDWARE USEFUL LIFE (YR) | 7 |
| OPERATION AND MAINTENANCE COST/MIL | $0.011 |
| ORCS COST | $8378.00 |
| ORCS COST DIFFERENTIAL | $6698.00 |
| ORCS POWER OUTPUT (HP) | 56 |
| COST/HP ABOVE BASE ENGINE POWER | $30.00 |
| MPG BASE DIESEL | 5.66 |
| MPG ORCS/DIESEL | 6.65 |
| DEPRECIATION RATE/YR | 3% |
| DEBT | 100% |
| LOAN TERM (MON) | 60 |

| YEAR | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|
| ORCS COST | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| ORCS COST DIFFERENTIAL | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| INVESTMENT TAX CREDIT | 586 | 0 | 0 | 0 | 0 | 0 | 0 |
| DEPRECIATION | 2793 | 2793 | 2793 | 0 | 0 | 0 | 0 |
| FUEL SAVINGS | 3156 | 3156 | 3156 | 3156 | 3156 | 3156 | 3156 |
| OPERATION AND MAINTENANCE COST | 1100 | 1100 | 1100 | 1100 | 1100 | 1100 | 1100 |
| OPERATING SAVINGS | 2056 | 2056 | 2056 | 2056 | 2056 | 2056 | 2056 |
| LOAN PRINCIPAL/END | 5658 | 4486 | 3165 | 1677 | 0 | 0 | 0 |
| MONTHS ON NOTE | 48 | 36 | 24 | 12 | 0 | 0 | 0 |
| PRINCIPAL PAYMENT | 1040 | 1172 | 1321 | 1488 | 1677 | 0 | 0 |
| INTEREST PAYMENT | 748 | 616 | 467 | 300 | 111 | 0 | 0 |
| TOTAL: PRINCIPAL AND INTEREST | 1788 | 1788 | 1788 | 1788 | 1788 | 0 | 0 |
| PRETAX PROFITS | -1484 | -2524 | -2524 | 268 | 268 | 2056 | 2056 |
| TAXES | -1613 | -1444 | -1376 | -14 | 72 | 946 | 946 |
| AFTERTAX PROFITS | 129 | -1080 | -1148 | 283 | 196 | 1110 | 1110 |
| CASH FLOW | 1882 | 1713 | 1644 | 283 | 196 | 1110 | 1110 |
| CUMULATIVE PROFITS | 129 | - 951 | 694 | 976 | 1172 | 2283 | 3393 |
| CUMULATIVE CASH FLOW | 1882 | 3594 | 5239 | 5522 | 5718 | 6828 | 7938 |

SIMPLE PAYBACK (YR) 3.26

INTERNAL RATE OF RETURN (%) N/A

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# 3. FUTURE PLANS

With the increased efforts to improve the efficiency of diesel engine prime movers, especially with the adiabatic engine concept, parallel efforts for the development of waste-heat recovery systems must be continued.

As the high-temperature problems (i.e., high-strength ceramic engine components) and other technical barriers are solved, the high-efficiency adiabatic diesel engine will become an accepted reality. With that reality comes the characteristic of increased exhaust-gas temperatures of the adiabatic engine. All advanced bottoming cycle systems and associated technology problems should, therefore, be addressed with the same urgency as those barriers facing the adiabatic engine.

Investigations of high-temperature, advanced, waste-heat utilization systems should include those that have the potential for even greater fuel savings than those already considered. The high-performance RC-1 Rankine bottoming cycle is one such system.

## 3.1 RC-1 HIGH-PERFORMANCE CYCLE

Waste-heat recovery from the higher temperature exhaust gas of the adiabatic diesel engine and conversion to useful power can be maximized by implementing the RC-1 High-Performance Cycle (RC-1 HPC). The operation of the RC-1 HPC is a modified version of the simple Rankine-cycle and is diagrammed in Figure 23. The modifications include: the use of two (2) turbines instead of one (1) or, alternatively, a two-stage, single turbine expander; a second vapor-generator in place of the regenerator located after the first turbine expander; and a working fluid flow split from the system's feedpump into two (2) paths (see state points 5 and 7 in Figure 23). The cycle modifications also include regeneration using the hot vapor from the second turbine expander to preheat the liquid working fluid entering the primary vapor-generator. These modifications are practical with the RC-1 working fluid because it has the ability to operate at a high system (turbine inlet) temperature of 850°F (potentially up to 1000°F), and because of the thermodynamic characteristic of the fluid to maintain a high vapor temperature after expansion through a turbine. Temperature drops of only 125° to 150°F are typical. Thus, the (first) turbine's vapor exhaust can be used as a heat source for a second Rankine-cycle. With the substitution of a vapor-generator heat exchanger for the regenerator of the simple cycle and the division of the feedpump fluid flow rate, a second closed loop (identified by state points 7, 8, 9, and 10 in Figure 23) can be accommodated.

The high-performance cycle (HPC) has not been evaluated in the depth indicated by the simple cycle (SC) conceptual design study results

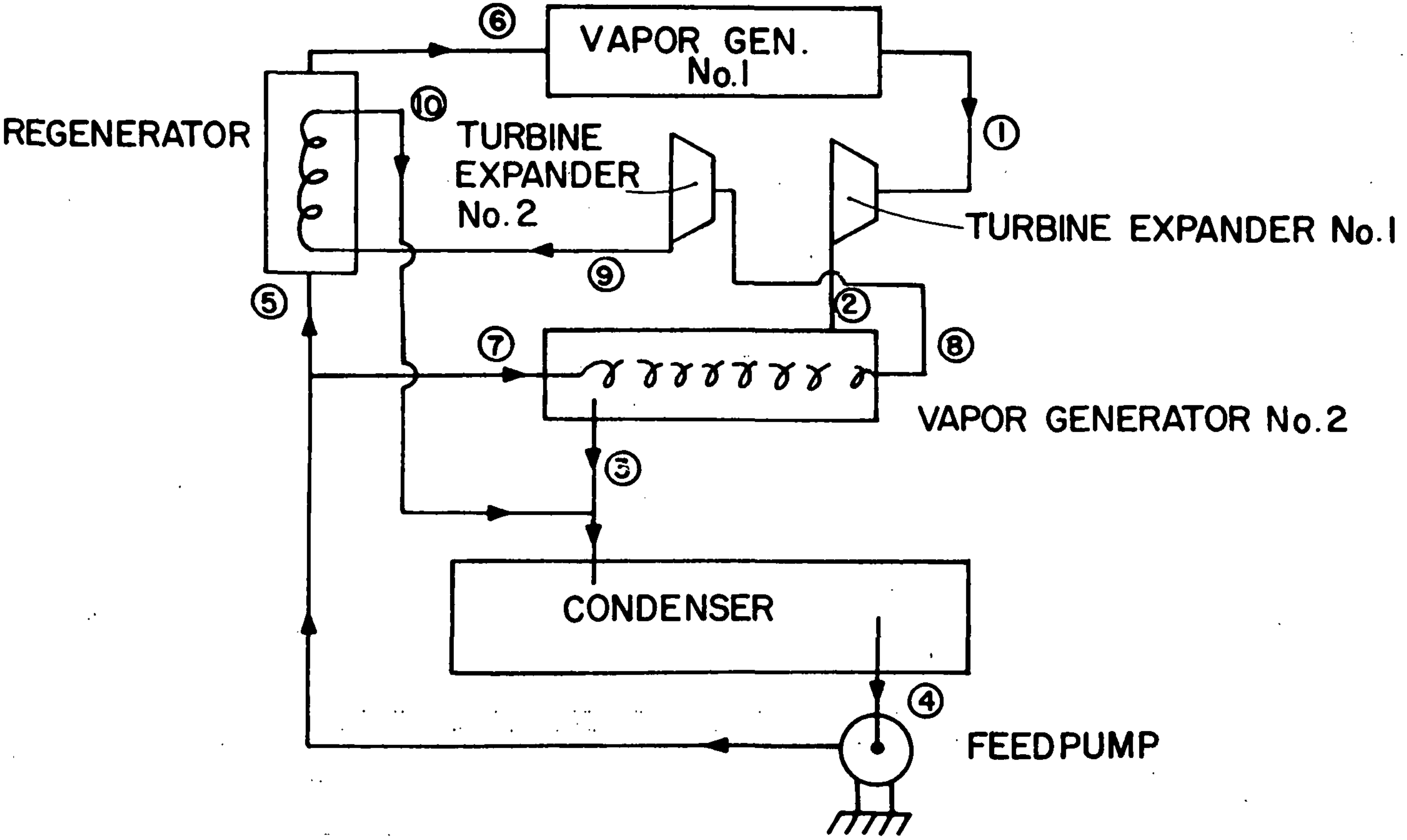


Figure 23. Schematic of an Organic Rankine High Performance Cycle (HPC) System with Internal Heat Regeneration

which are the subject of this report. However, preliminary comparison of performance estimates for the two (2) cycle configurations indicates (under idealized cycle conditions) the HPC has a potential to produce a compound engine BSFC that is 3 to 3½ percent lower than that produced by the SC over a diesel engine exhaust temperature range from 1000° to 1600°F. This BSFC potential for the HPC translates into power improvements from 15 to 25 percent over the SC. While both systems are operating at 1000 psia, the organic operating temperature for the HPC is 900°F compared to the SC at 750°F.

## 3.2 TECHNOLOGY DEVELOPMENT AREAS

The majority of the technology barriers associated with Rankine-cycle systems used to bottom diesel engines with moderate exhaust gas temperatures between 650° to 1000°F (i.e., Fluorinol Truck ORCS) have been identified and dealt with for the most part. Except for the problem of heat exchanger fouling from the exhaust gas of diesel engines that burn No. 2 fuel oil, the majority of development work required on these systems, such as improvement in reliability, are solvable engineering problems.

These higher temperature, Rankine, bottoming systems, especially the RC-1 HPC at organic fluid operating temperatures approaching 1000°F, introduce new areas for technology development, as does any higher temperature operating system (e.g., adiabatic diesel engine, gas turbine). Some of the technology barriers that must be addressed for successful development of these high-temperature, high-performance Rankine bottoming cycle systems are identified below.

- Heat Exchanger Fouling - This problem, as mentioned above, is one that applies to any bottoming cycle system that requires a heat exchanger to capture the exhaust gas waste heat of the diesel engine. As with the conventional diesel engine, this technology barrier is also common to the adiabatic diesel engine applications.

- Organic Working Fluid Thermal Stability - This report has described the tests performed on the RC-1 and the results that show this fluid is capable of operating at temperatures up to 900°F. If systems such as the RC-1 HPC are to be considered as viable waste-heat recovery systems, then more organic fluid studies and testing must be accomplished for temperatures in excess of 1000°F. Systems and methods of fluid conditioning must also be investigated and developed if fluid degradation occurs at these elevated temperature levels.

- High-Temperature Seal Development - Seals presently used on the turbine shaft (Fluorinol Truck ORCS) are of a double-faced, buffered chamber design with a lubricating oil as the buffer fluid. These seals prevent the entry of air into the working fluid, but do permit a small amount of the buffer fluid to pass into the working fluid space. The use of oil in the buffer chamber cools and lubricates the seal rubbing faces. There is no problem with the small amount of oil getting into the system because it is chemically compatible with the Fluorinol working fluid and thermally stable at the working fluid temperatures.

  The same scheme cannot be used with RC-1 working fluid because the lubricating oil would decompose at RC-1 working fluid temperatures. Therefore, high-temperature seal cooling and lubrication, proper seal materials, and seal life with RC-1 are areas that require further technical investigation and development.

## REFERENCES

(1) DiBella, F., DiNanno, L., and Koplow, M.: Laboratory and On-Highway Testing of Diesel Organic Rankine Compound Long-Haul Vehicle Engine. SAE Publication: 830122.

(2) Standard Method of Test for Neutralization Number by Color-Indicator Titration. ASTM Designation: D974-64 (Reapproved 1968).

(3) Miller, D.R. et al.: Optimum Working Fluids for Automotive Rankine Engines. Volumes I, II, III, and IV, Report Nos. APTD-1563 through APTD-1566, Monsanto Research Corporation. St. Louis, Missouri, June 1973.

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# APPENDIX A

## ANALYSIS REPORT OF RC-1 FLUID SAMPLE (800°F) BY CAMBRIDGE ANALYTICAL ASSOCIATES

## 1. INTRODUCTION

On September 14, 1983 sample IV-L-9/13/83-2L (CAA ID 83-8105) was submitted for GC/MS analysis of possible contaminants. A standard sample of RC-1 (CAA ID 83-8106) was also analyzed for comparison.

## 2. EXPERIMENTAL

The analytical conditions employed are summarized in Table 1.

## 3. RESULTS AND DISCUSSION

Figure 1 shows the reconstructed gas chromatogram (RGC) for both samples. As can be seen, they are identical. The large, saturated peak is due to pentafluorobenzene and hexaflourobenzene, the two major components.

The peak appearing at scan 60 is due to pentafluorochlorobenzene. The mass spectrum of this compound is given in Figure 2A. This peak was present in both samples at the same approximate concentrations. Four other minor components were also detected in both the sample and the standard. Figures 2B and 3 give the mass spectra of two of these peaks. A manual search of the NBS reference library spectra of 32,000 compounds gave no matches. The mass spectra of the peaks indicate that they are fluorinated compounds (characterized by an ($M^+$ - 19) ion), and both aromatic and aliphatic in nature, as the molecular ion is of medium intensity. Alkanes would give a much weaker molecular ion, and aromatics would give a much more intense one. The four minor components had molecular weights of 212, 218, 236 and 262.

In conclusion, no impurities were found in the sample that were not detected in the standard.

Table 1

ANALYTICAL CONDITIONS

| | |
|---|---|
| SAMPLE TYPE: | Liquid |
| INTRODUCTION: | on column injection |
| INSTRUMENT: | Finnigan 9500GC/3200MS/6000DS |
| GC COLUMN: | 6ft x 1/4" OD OV-101 packed column |
| INJECTOR TEMPERATURE: | 220°C |
| INITIAL TEMPERATURE: | 35°C |
| INITIAL TIME: | 2 minutes |
| TEMPERATURE PROGRAM: | 35°C to 300°C at 12°C/minute |
| FINAL TEMPERATURE: | 300°C |
| FINAL TIME: | 12 minutes |
| MASS RANGE SCANNED: | 41 to 350 amu |
| SCAN RATE: | 3 seconds per scan |

082303 830-8106, STANDARD RC-1

RGC AMP.: 00251264

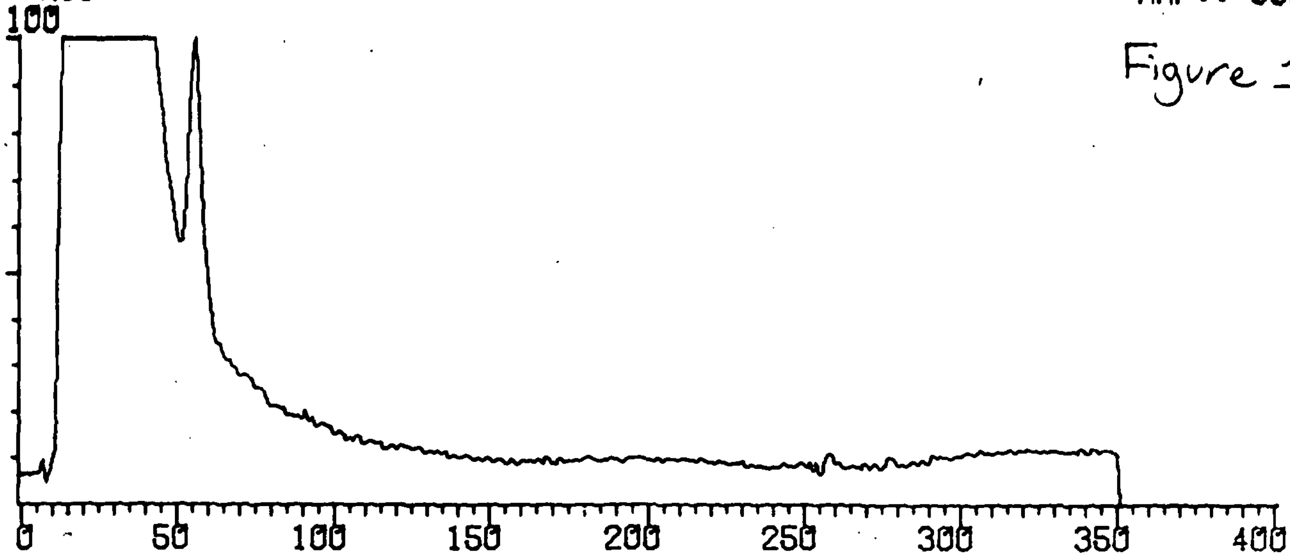
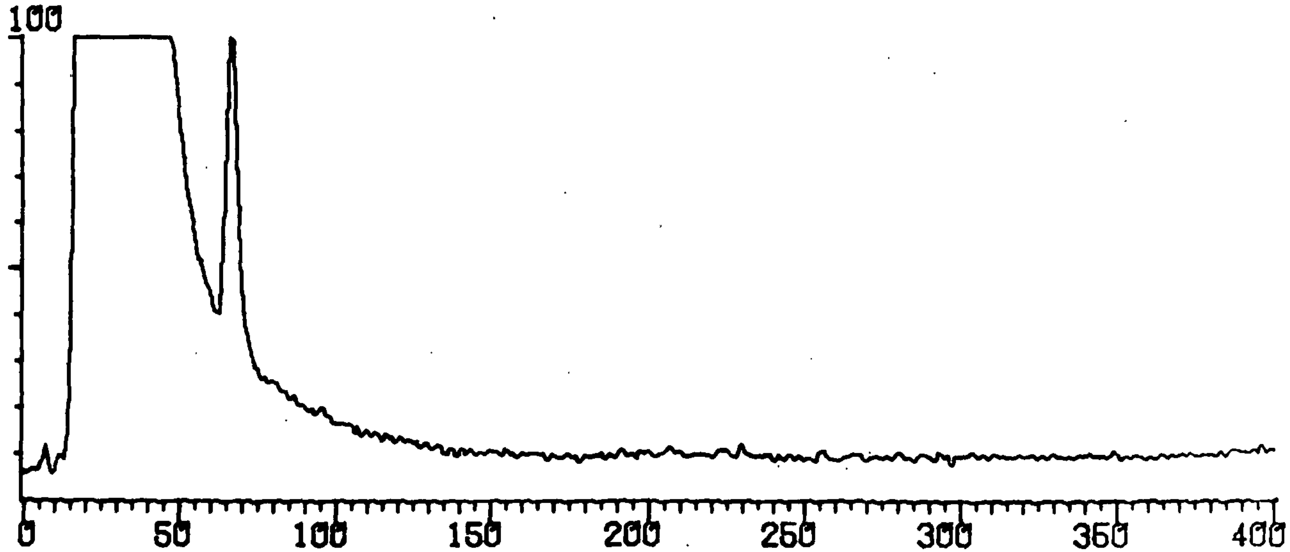



Figure 1

92302 830-8105, I/-L-9/13/83-2L

RGC AMP.: 00217824



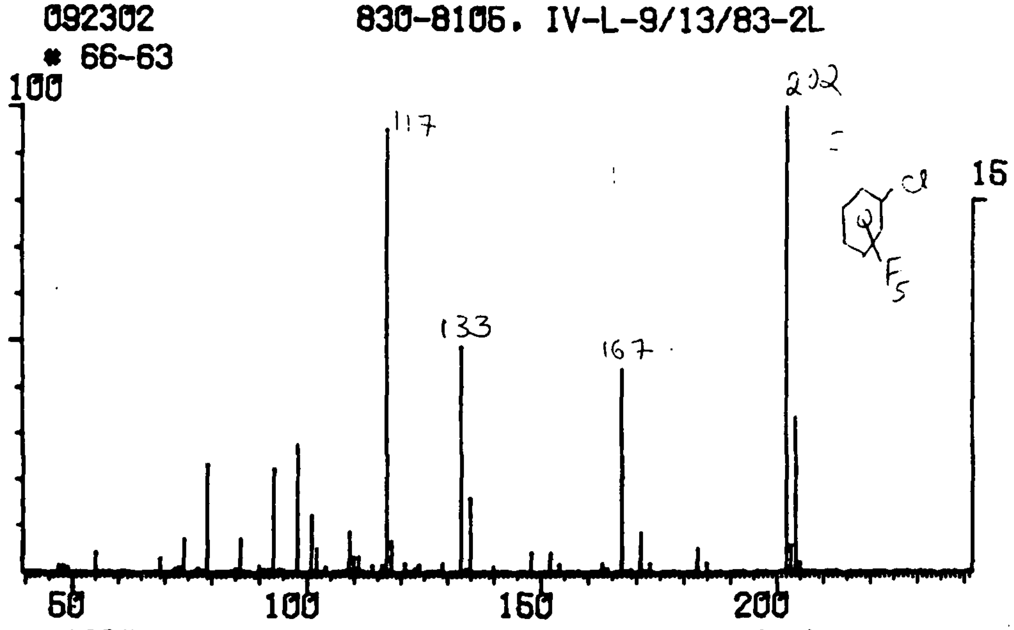



Figure 2A
pentafluorochlorobenzene

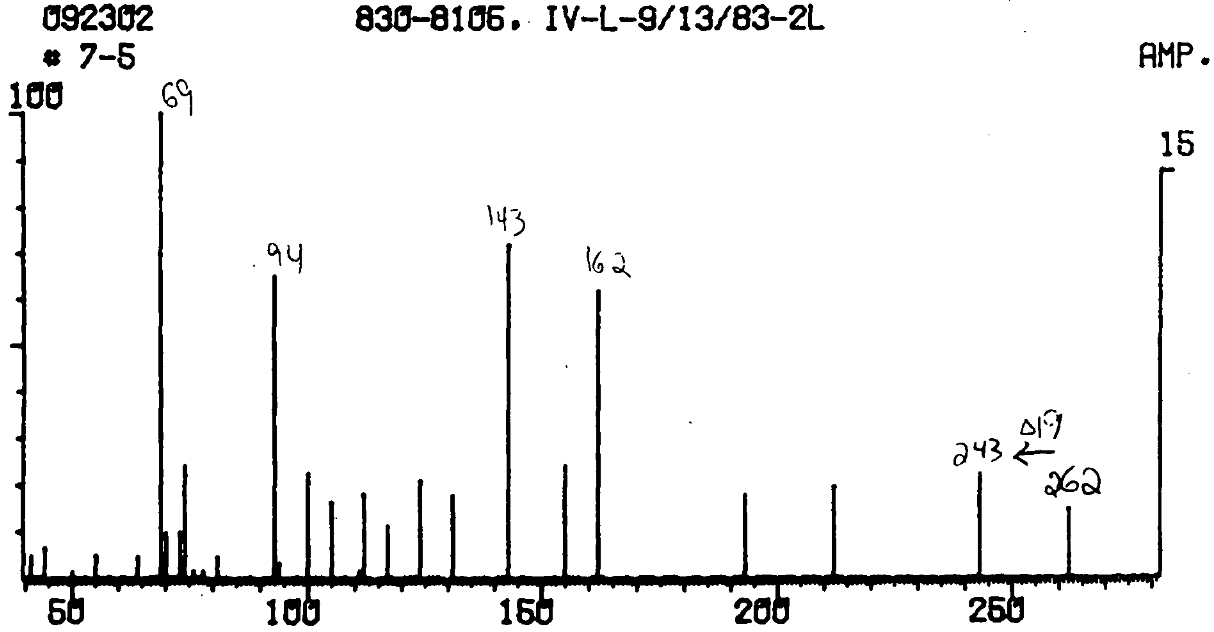
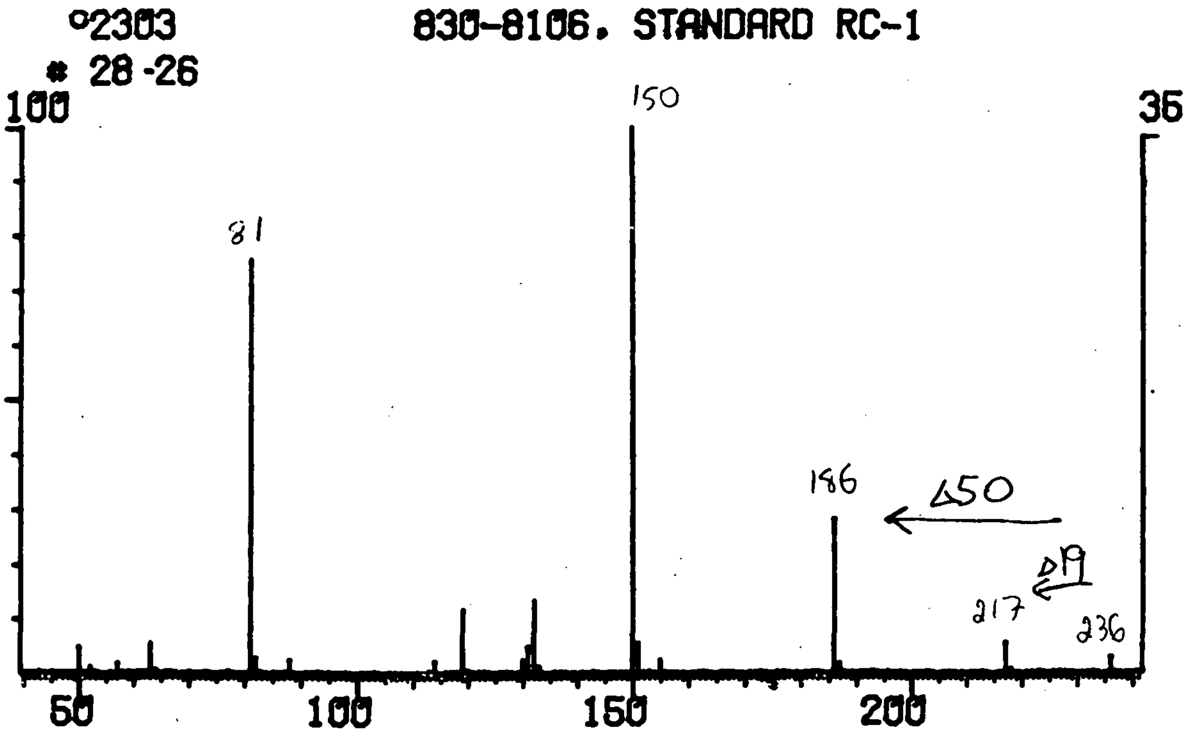



Figure 2B
unidentified compound
mw 262




AMP.: 00036864

Figure 3
unidentified compound
mw 236

# APPENDIX B

## ANALYSIS REPORT OF RC-1 FLUID SAMPLE (900°F) BY CAMBRIDGE ANALYTICAL ASSOCIATES

## INTRODUCTION

On September 29 and November 9, 1983 the following samples were submitted for GC/MS analysis of possible contaminants.

| Thermoelectron ID | CAA ID | Sample Type |
| --- | --- | --- |
| IV-G-9/29/83-1G | 8308428 | gas |
| III-L-11/16/83-1L | 8309123 | liquid |
| IV-L-11/7/83-1L | 8309124 | gas |

## EXPERIMENTAL

The analytical conditions employed are summarized in Table 1.

## RESULTS AND DISCUSSION

Comparisons were made between this analysis and previous analyses done at CAA (see CAA Report 83-788). Sample IV-G-9/29/83-1G was of insufficient pressure to get an intense chromatogram. Only pentafluorobenzene and hexafluorobenzene were detected in this sample.

Sample IV-L-11/7/83-1L had a large peak that eluted before the fluorinated benzenes, (see Figure 2). The compound had no matches against the NBS library of reference compounds. It was tentatively identified as molecular weight 186 with a possible structure of perfluoro-n-propanol (see Figure 3). Sample II-L-11/16/83-1L had pentafluorochlorobenzene, as seen in previous analyses of the liquid (see Figure 4). This compound was not present in the gas samples. Two other major peaks were detected (see Figure 5 and 6). They appear to be fluoroalkanes of molecular weights 348 and 338. Fluoroalkanes of molecular weight 316 and 334 were also detected. Sample IV-L-9/13/83-2L was reanalyzed to make sure that these compounds weren't missed in previous analyses due to altered chromatographic condition. They were not detected (see Figure 7).

All compounds were present at low levels (estimated to be parts per million) except for the perfluoro-n-propanol in sample III-L-11/16/83-1L. This compound is estimated to be present at low percent levels. Hydrofluoroic acid would not be detected in this analysis.

Table 1

ANALYTICAL CONDITIONS

| | |
|---|---|
| SAMPLE TYPE: | liquid/gas |
| INTRODUCTION: | liquid - direct injection/gas - loop injection |
| INSTRUMENT: | Finnigan 3200 GC/MS |
| GC COLUMN: | 6 ft x 1/4" OD OV-101 packed column |
| INJECTOR TEMPERATURE: | $220^{o}C$ |
| INITIAL TEMPERATURE: | $35^{o}C$ |
| INITIAL TIME: | 2 minutes |
| TEMPERATURE PROGRAM: | $35^{o}C$ to $300^{o}C$ at $12^{o}C$/minute |
| FINAL TEMPERATURE: | $300^{o}C$ |
| FINAL TIME: | 12 minutes |
| MASS RANGE SCANNED: | 41 to 350 amu |
| SCAN RATE: | 3 seconds per scan |

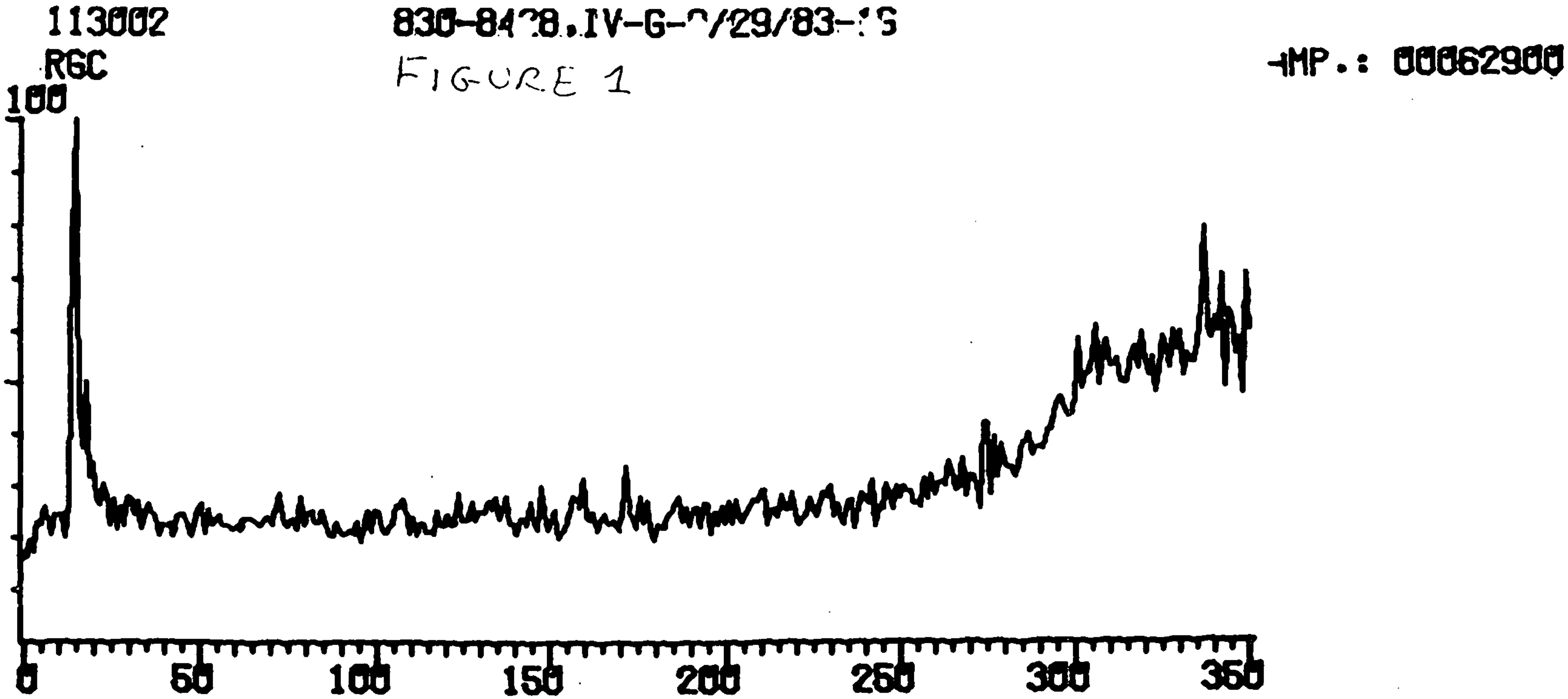
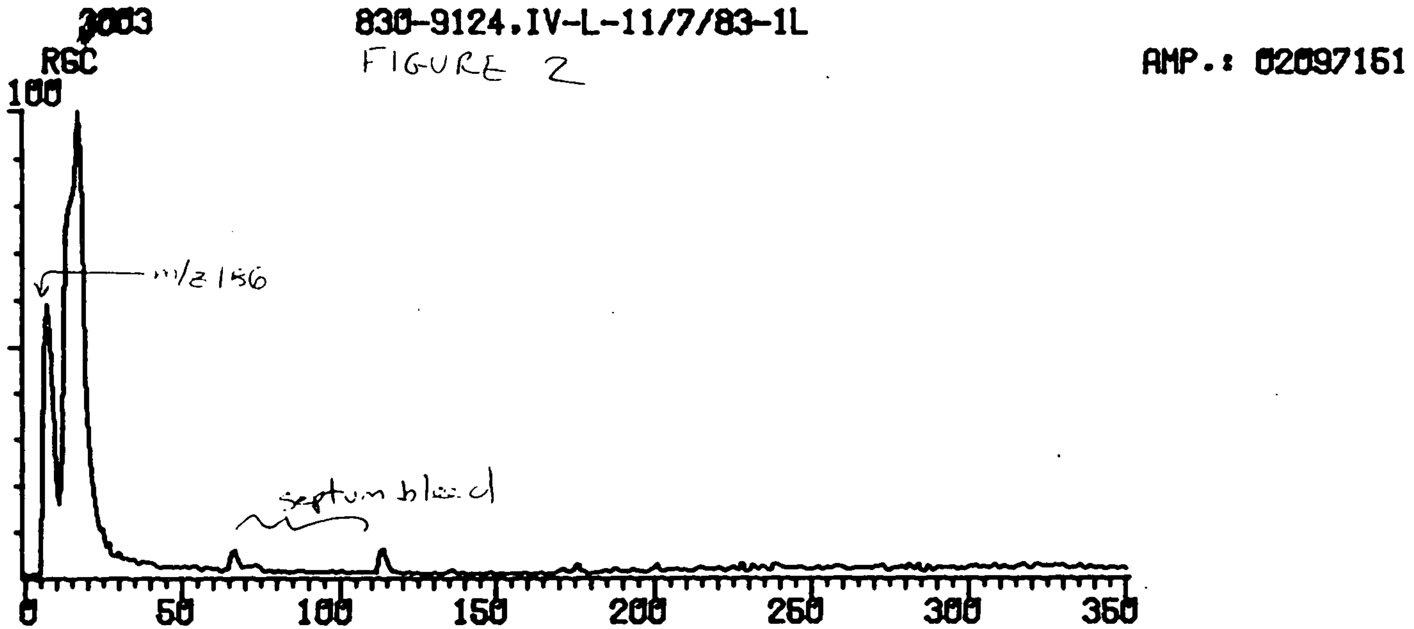
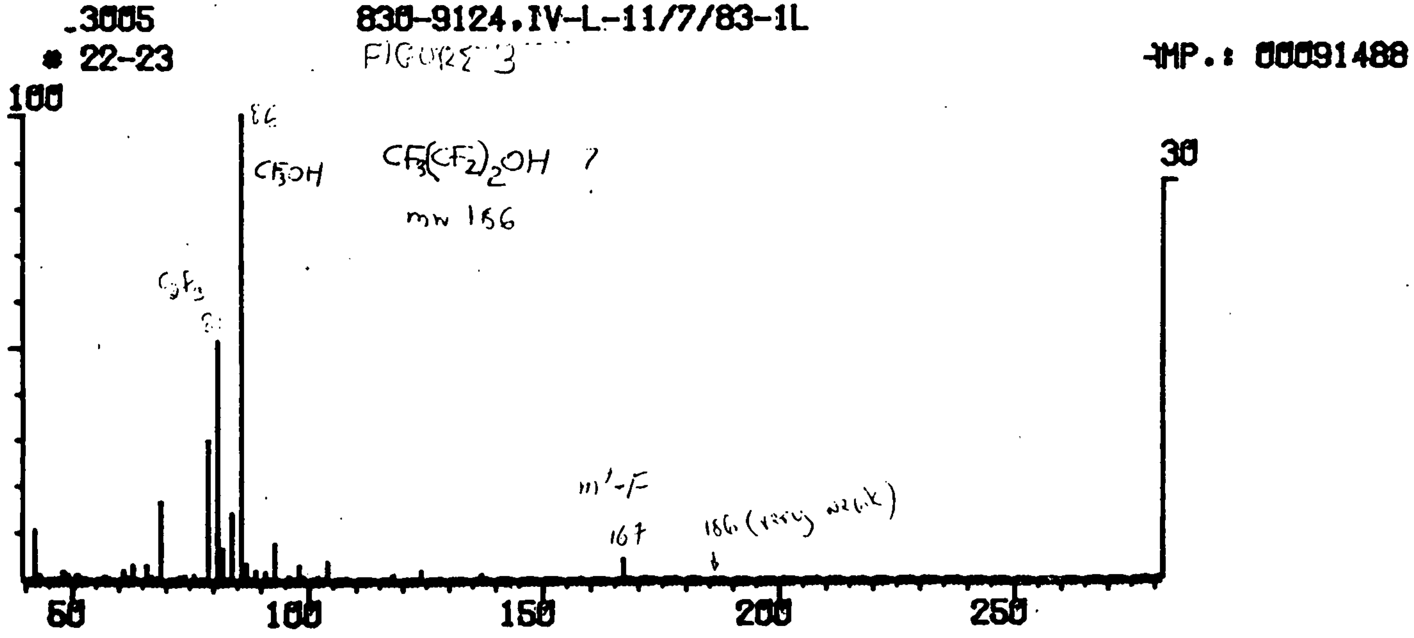
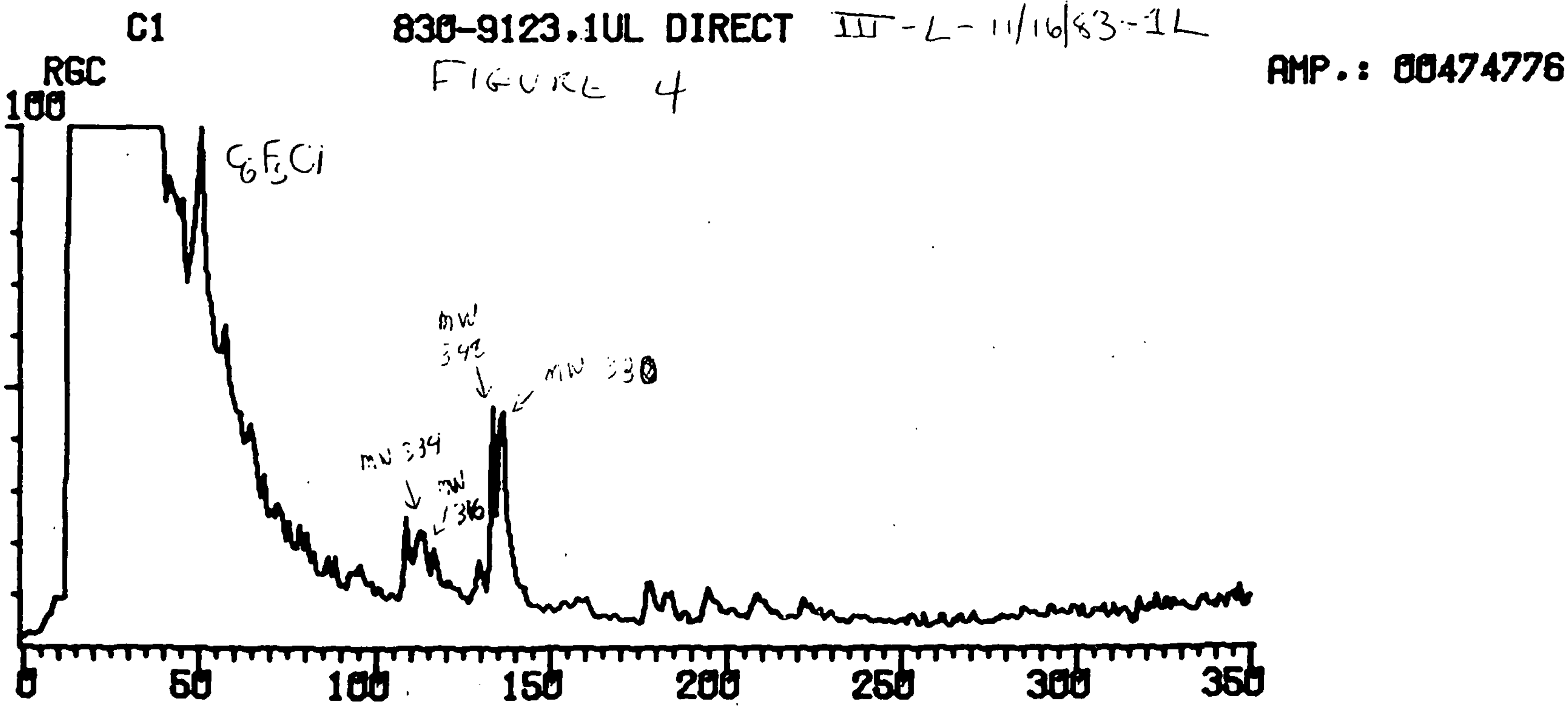
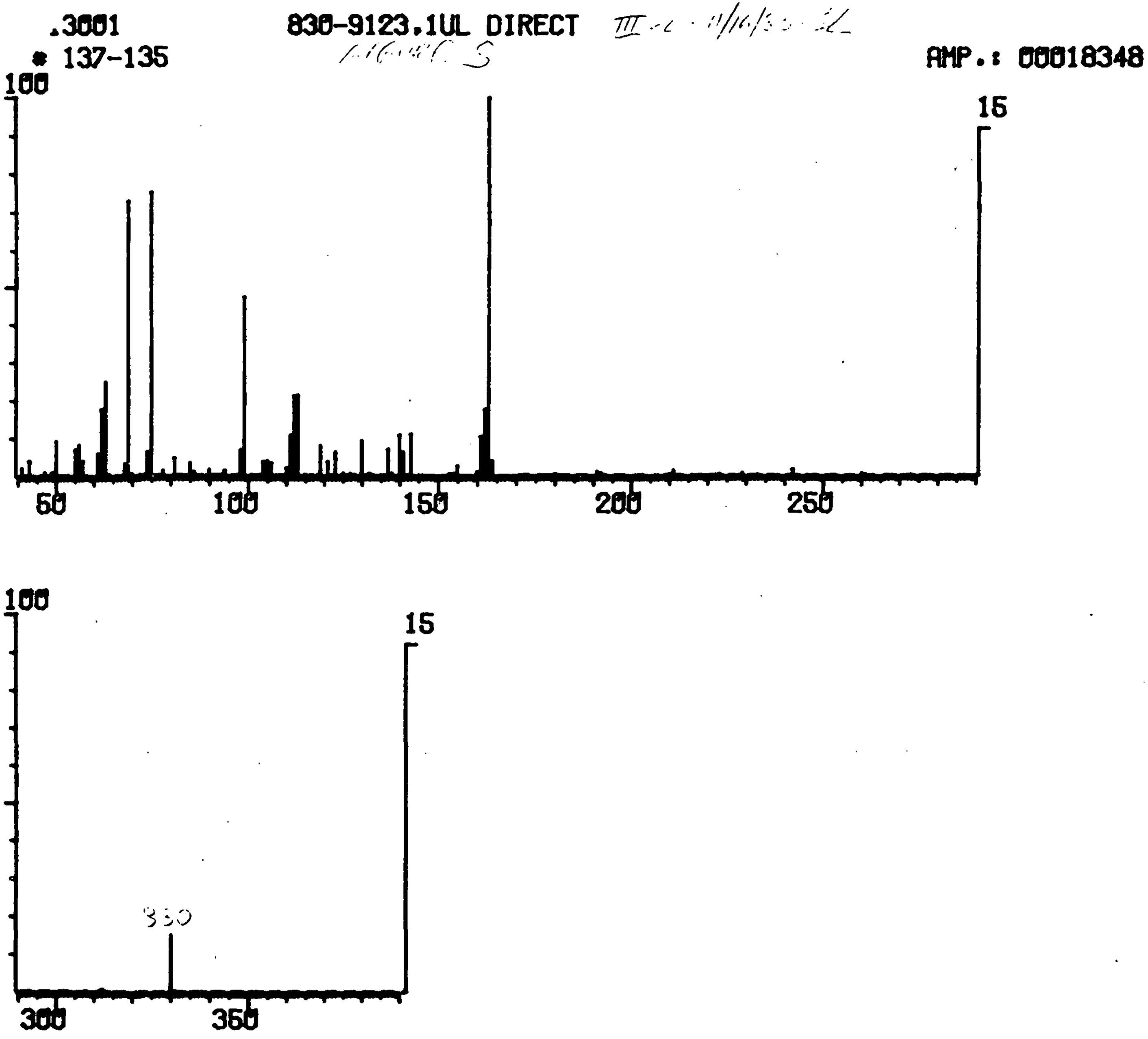

113002
RGC
830-84?8.IV-G-?/29/83-?S
-IMP.: 00062900
100
0
50
100
150
200
250
300
350

FIGURE 1


3003
RGC
830-9124.IV-L-11/7/83-1L
FIGURE 2
AMP.: 02097151
100
m/z 186
septum bleed
0
50
100
150
200
250
300
350

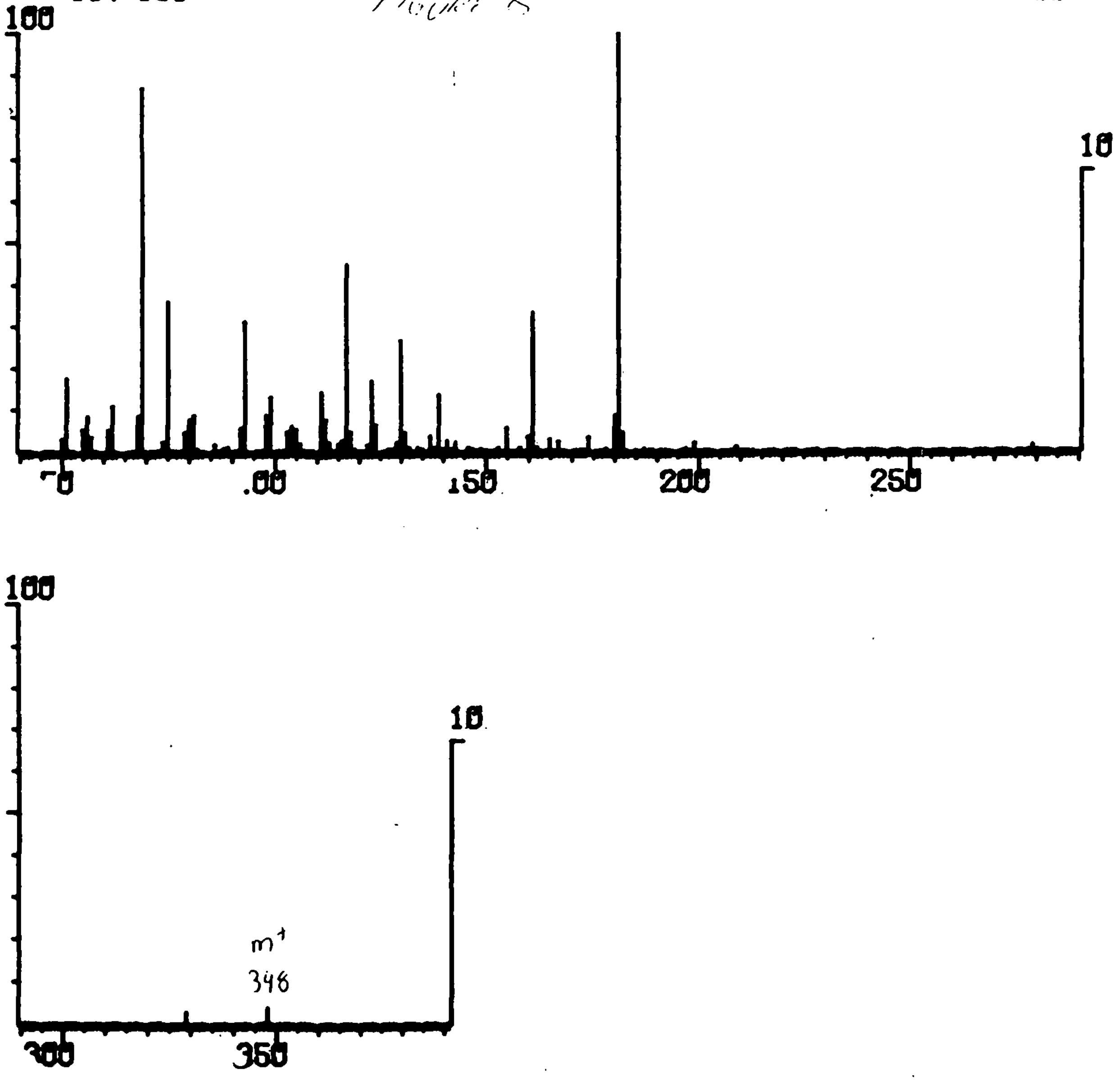

.3005
# 22-23
830-9124.IV-L-11/7/83-1L
FIGURE 3
AMP.: 00091488
100
30
CF3OH
CF3(CF2)2OH ?
mw 186
m+-F
167
186 (very weak)
50
100
150
200
250


C1
830-9123.1UL DIRECT
III-L-11/16/83-1L
FIGURE 4
AMP.: 00474776
RGC
100
0
50
100
150
200
250
300
350


.3001
830-9123.1UL DIRECT
* 137-135
AMP.: 00018348
100
15
50
100
150
200
250
100
15
330
300
350

.13001 830-9123.1UL DIRECT
# 134-133 MP.: 00022656

Figure 6



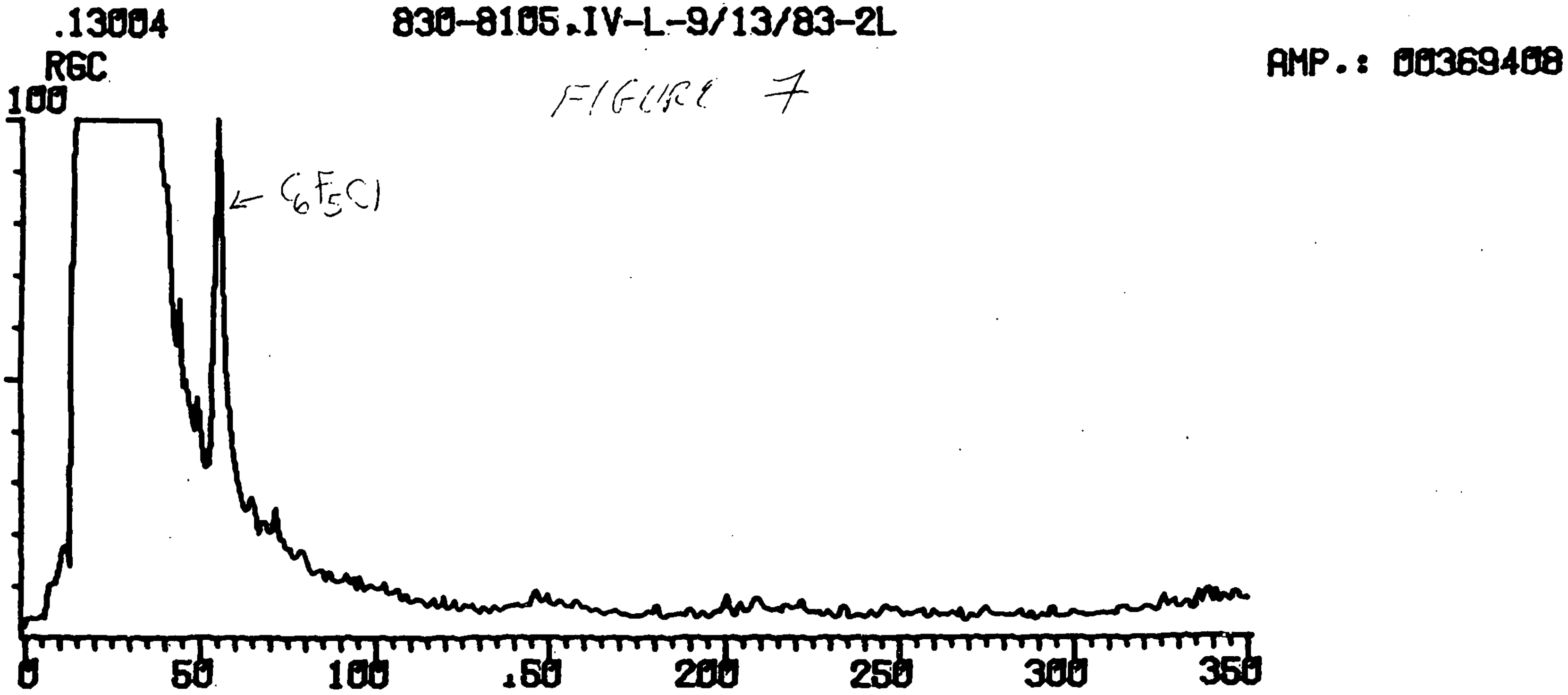

.13004
830-8105.IV-L-9/13/83-2L
AMP.: 00369408
RGC
100
$C_6F_5Cl$
0
50
100
150
200
250
300
350

FIGURE 7

# APPENDIX C

# RC-1 THERMODYNAMIC PROPERTIES

## SATURATION

| P (PSIA) | T (°F) | VL (FT³/LB) | VV (FT³/LB) | HL (BTU/LB) | HV (BTU/LB) |
|---|---|---|---|---|---|
| .23 | .00 | .9217E-02 | .1228E 03 | -.7054E 01 | .8896E 02 |
| .19 | 5.00 | .9269E-02 | .9163E 02 | -.6067E 01 | .8957E 02 |
| .27 | 10.00 | .9336E-02 | .8454E 02 | -.4940E 01 | .9027E 02 |
| .34 | 15.00 | .9403E-02 | .7746E 02 | -.3814E 01 | .9098E 02 |
| .42 | 20.00 | .9470E-02 | .7037E 02 | -.2687E 01 | .9169E 02 |
| .36 | 25.00 | .9526E-02 | .5402E 02 | -.1665E 01 | .9234E 02 |
| .48 | 30.00 | .9597E-02 | .5002E 02 | -.5035E 00 | .9307E 02 |
| .61 | 35.00 | .9667E-02 | .4603E 02 | .6578E 00 | .9379E 02 |
| .73 | 40.00 | .9737E-02 | .4203E 02 | .1819E 01 | .9452E 02 |
| .67 | 45.00 | .9792E-02 | .3308E 02 | .2875E 01 | .9520E 02 |
| .85 | 50.00 | .9868E-02 | .3074E 02 | .4071E 01 | .9594E 02 |
| 1.04 | 55.00 | .9943E-02 | .2840E 02 | .5267E 01 | .9669E 02 |
| 1.23 | 60.00 | .1002E-01 | .2606E 02 | .6464E 01 | .9743E 02 |
| 1.14 | 65.00 | .1008E-01 | .2095E 02 | .7560E 01 | .9807E 02 |
| 1.42 | 70.00 | .1016E-01 | .1953E 02 | .8790E 01 | .9885E 02 |
| 1.70 | 75.00 | .1024E-01 | .1811E 02 | .1002E 02 | .9962E 02 |
| 1.98 | 80.00 | .1032E-01 | .1669E 02 | .1125E 02 | .1004E 03 |
| 1.89 | 85.00 | .1038E-01 | .1368E 02 | .1238E 02 | .1011E 03 |
| 2.29 | 90.00 | .1047E-01 | .1279E 02 | .1364E 02 | .1019E 03 |
| 2.69 | 95.00 | .1055E-01 | .1190E 02 | .1490E 02 | .1027E 03 |
| 3.10 | 100.00 | .1064E-01 | .1101E 02 | .1617E 02 | .1035E 03 |
| 3.00 | 105.00 | .1071E-01 | .9170E 01 | .1734E 02 | .1043E 03 |
| 3.58 | 110.00 | .1080E-01 | .8599E 01 | .1863E 02 | .1051E 03 |
| 4.15 | 115.00 | .1089E-01 | .8028E 01 | .1993E 02 | .1059E 03 |
| 4.72 | 120.00 | .1098E-01 | .7457E 01 | .2123E 02 | .1067E 03 |
| 4.66 | 125.00 | .1105E-01 | .6305E 01 | .2241E 02 | .1075E 03 |
| 5.44 | 130.00 | .1115E-01 | .5928E 01 | .2375E 02 | .1083E 03 |
| 6.23 | 135.00 | .1125E-01 | .5551E 01 | .2508E 02 | .1091E 03 |
| 7.01 | 140.00 | .1135E-01 | .5173E 01 | .2642E 02 | .1099E 03 |
| 6.97 | 145.00 | .1142E-01 | .4429E 01 | .2766E 02 | .1106E 03 |
| 8.03 | 150.00 | .1153E-01 | .4174E 01 | .2902E 02 | .1115E 03 |
| 9.09 | 155.00 | .1164E-01 | .3919E 01 | .3039E 02 | .1123E 03 |
| 10.15 | 160.00 | .1174E-01 | .3664E 01 | .3176E 02 | .1131E 03 |
| 10.18 | 165.00 | .1182E-01 | .3172E 01 | .3303E 02 | .1138E 03 |
| 11.59 | 170.00 | .1194E-01 | .2997E 01 | .3443E 02 | .1147E 03 |
| 12.99 | 175.00 | .1206E-01 | .2821E 01 | .3583E 02 | .1155E 03 |
| 14.39 | 180.00 | .1217E-01 | .2645E 01 | .3723E 02 | .1164E 03 |
| 14.52 | 185.00 | .1225E-01 | .2313E 01 | .3852E 02 | .1173E 03 |
| 16.35 | 190.00 | .1238E-01 | .2189E 01 | .3996E 02 | .1181E 03 |
| 18.17 | 195.00 | .1251E-01 | .2065E 01 | .4139E 02 | .1189E 03 |
| 20.00 | 200.00 | .1264E-01 | .1941E 01 | .4283E 02 | .1198E 03 |
| 20.30 | 205.00 | .1273E-01 | .1712E 01 | .4416E 02 | .1206E 03 |
| 22.63 | 210.00 | .1287E-01 | .1624E 01 | .4563E 02 | .1215E 03 |
| 24.97 | 215.00 | .1301E-01 | .1535E 01 | .4711E 02 | .1223E 03 |
| 27.31 | 220.00 | .1315E-01 | .1446E 01 | .4858E 02 | .1232E 03 |
| 27.79 | 225.00 | .1324E-01 | .1285E 01 | .4994E 02 | .1241E 03 |
| 30.75 | 230.00 | .1339E-01 | .1221E 01 | .5145E 02 | .1249E 03 |
| 33.71 | 235.00 | .1355E-01 | .1156E 01 | .5296E 02 | .1258E 03 |
| 36.66 | 240.00 | .1371E-01 | .1092E 01 | .5447E 02 | .1266E 03 |
| 37.44 | 245.00 | .1381E-01 | .9772E 00 | .5586E 02 | .1275E 03 |
| 41.12 | 250.00 | .1398E-01 | .9295E 00 | .5741E 02 | .1283E 03 |
| 44.80 | 255.00 | .1415E-01 | .8818E 00 | .5896E 02 | .1292E 03 |
| 48.48 | 260.00 | .1433E-01 | .8340E 00 | .6051E 02 | .1300E 03 |
| 49.61 | 265.00 | .1443E-01 | .7506E 00 | .6193E 02 | .1308E 03 |
| 54.14 | 270.00 | .1463E-01 | .7148E 00 | .6352E 02 | .1316E 03 |
| 58.67 | 275.00 | .1483E-01 | .6789E 00 | .6512E 02 | .1324E 03 |
| 63.20 | 280.00 | .1503E-01 | .6431E 00 | .6671E 02 | .1333E 03 |
| 64.78 | 285.00 | .1514E-01 | .5814E 00 | .6817E 02 | .1342E 03 |
| 70.29 | 290.00 | .1537E-01 | .5542E 00 | .6981E 02 | .1350E 03 |
| 75.81 | 295.00 | .1559E-01 | .5270E 00 | .7145E 02 | .1359E 03 |

## SATURATION

| P (PSIA) | T (°F) | VL (FT³/LB) | VV (FT³/LB) | HL (BTU/LB) | HV (BTU/LB) |
|---|---|---|---|---|---|
| 81.32 | 300.00 | .1582E-01 | .4998E 00 | .7309E 02 | .1367E 03 |
| 83.45 | 305.00 | .1593E-01 | .4539E 00 | .7456E 02 | .1377E 03 |
| 90.09 | 310.00 | .1620E-01 | .4329E 00 | .7625E 02 | .1384E 03 |
| 96.74 | 315.00 | .1646E-01 | .4119E 00 | .7795E 02 | .1392E 03 |
| 103.38 | 320.00 | .1673E-01 | .3909E 00 | .7965E 02 | .1400E 03 |
| 106.19 | 325.00 | .1684E-01 | .3562E 00 | .8114E 02 | .1408E 03 |
| 114.11 | 330.00 | .1716E-01 | .3398E 00 | .8290E 02 | .1416E 03 |
| 122.04 | 335.00 | .1748E-01 | .3234E 00 | .8467E 02 | .1423E 03 |
| 129.96 | 340.00 | .1780E-01 | .3070E 00 | .8644E 02 | .1431E 03 |
| 133.53 | 345.00 | .1789E-01 | .2805E 00 | .8797E 02 | .1441E 03 |
| 142.91 | 350.00 | .1829E-01 | .2675E 00 | .8981E 02 | .1448E 03 |
| 152.28 | 355.00 | .1868E-01 | .2545E 00 | .9166E 02 | .1455E 03 |
| 161.66 | 360.00 | .1908E-01 | .2415E 00 | .9351E 02 | .1462E 03 |
| 166.14 | 365.00 | .1912E-01 | .2210E 00 | .9490E 02 | .1471E 03 |
| 177.15 | 370.00 | .1964E-01 | .2105E 00 | .9690E 02 | .1478E 03 |
| 188.16 | 375.00 | .2015E-01 | .2000E 00 | .9890E 02 | .1484E 03 |
| 199.17 | 380.00 | .2067E-01 | .1895E 00 | .1009E 03 | .1490E 03 |
| 204.59 | 385.00 | .2054E-01 | .1738E 00 | .1022E 03 | .1500E 03 |
| 217.46 | 390.00 | .2127E-01 | .1650E 00 | .1044E 03 | .1505E 03 |
| 230.34 | 395.00 | .2199E-01 | .1562E 00 | .1067E 03 | .1510E 03 |
| 243.21 | 400.00 | .2272E-01 | .1475E 00 | .1089E 03 | .1515E 03 |
| 248.05 | 405.00 | .2178E-01 | .1373E 00 | .1096E 03 | .1533E 03 |
| 263.60 | 410.00 | .2307E-01 | .1290E 00 | .1123E 03 | .1533E 03 |
| 279.16 | 415.00 | .2435E-01 | .1207E 00 | .1151E 03 | .1534E 03 |
| 294.71 | 420.00 | .2563E-01 | .1124E 00 | .1178E 03 | .1535E 03 |
| 306.22 | 425.00 | .2226E-01 | .1159E 00 | .1164E 03 | .1649E 03 |
| 323.12 | 430.00 | .2510E-01 | .1037E 00 | .1206E 03 | .1612E 03 |
| 340.02 | 435.00 | .2793E-01 | .9139E-01 | .1247E 03 | .1575E 03 |
| 356.92 | 440.00 | .3077E-01 | .7911E-01 | .1288E 03 | .1538E 03 |
| 402.73 | 445.00 | .3984E-01 | .3984E-01 | .1420E 03 | .1420E 03 |

*STOP* 0

## SUPERHEATED VAPOR

| P (PSIA) | T (°F) | H (BTU/LB) | S (BTU/LB-°F) | V (FT³/LB) | CP (BTU/LB-°F) |
|---|---|---|---|---|---|
| 5.00 | 60.00 | .6464E 01 | .1461E-01 | .1002E-01 | .957 |
| 5.00 | 80.00 | .1125E 02 | .2465E-01 | .1032E-01 | .984 |
| 5.00 | 100.00 | .1617E 02 | .3440E-01 | .1064E-01 | 1.012 |
| 5.00 | 120.00 | .2123E 02 | .4389E-01 | .1098E-01 | 1.038 |
| 5.00 | 140.00 | .1098E 03 | .1963E 00 | .7239E 01 | .172 |
| 5.00 | 160.00 | .1134E 03 | .2018E 00 | .7491E 01 | .175 |
| 5.00 | 180.00 | .1169E 03 | .2073E 00 | .7742E 01 | .178 |
| 5.00 | 200.00 | .1205E 03 | .2128E 00 | .7994E 01 | .180 |
| 5.00 | 220.00 | .1242E 03 | .2183E 00 | .8241E 01 | .185 |
| 5.00 | 240.00 | .1279E 03 | .2238E 00 | .8489E 01 | .190 |
| 5.00 | 260.00 | .1318E 03 | .2291E 00 | .8737E 01 | .195 |
| 5.00 | 280.00 | .1356E 03 | .2345E 00 | .8985E 01 | .200 |
| 5.00 | 300.00 | .1396E 03 | .2398E 00 | .9236E 01 | .203 |
| 5.00 | 320.00 | .1437E 03 | .2451E 00 | .9488E 01 | .205 |
| 5.00 | 340.00 | .1479E 03 | .2503E 00 | .9734E 01 | .208 |
| 5.00 | 360.00 | .1521E 03 | .2556E 00 | .9980E 01 | .210 |
| 5.00 | 380.00 | .1564E 03 | .2607E 00 | .1023E 02 | .215 |
| 5.00 | 400.00 | .1607E 03 | .2659E 00 | .1047E 02 | .220 |
| 5.00 | 420.00 | .1651E 03 | .2710E 00 | .1072E 02 | .225 |
| 5.00 | 440.00 | .1696E 03 | .2760E 00 | .1097E 02 | .230 |
| 5.00 | 460.00 | .1742E 03 | .2810E 00 | .1122E 02 | .232 |
| 5.00 | 480.00 | .1788E 03 | .2860E 00 | .1146E 02 | .235 |
| 5.00 | 500.00 | .1836E 03 | .2910E 00 | .1171E 02 | .237 |
| 5.00 | 520.00 | .1883E 03 | .2959E 00 | .1196E 02 | .240 |
| 5.00 | 540.00 | .1931E 03 | .3007E 00 | .1220E 02 | .242 |
| 5.00 | 560.00 | .1980E 03 | .3056E 00 | .1245E 02 | .245 |
| 5.00 | 580.00 | .2029E 03 | .3104E 00 | .1270E 02 | .250 |
| 5.00 | 600.00 | .2079E 03 | .3151E 00 | .1294E 02 | .255 |
| 5.00 | 620.00 | .2130E 03 | .3198E 00 | .1319E 02 | .255 |
| 5.00 | 640.00 | .2181E 03 | .3246E 00 | .1343E 02 | .255 |
| 5.00 | 660.00 | .2233E 03 | .3292E 00 | .1368E 02 | .257 |
| 5.00 | 680.00 | .2285E 03 | .3338E 00 | .1393E 02 | .260 |
| 5.00 | 700.00 | .2338E 03 | .3384E 00 | .1417E 02 | .262 |
| 5.00 | 720.00 | .2391E 03 | .3430E 00 | .1442E 02 | .265 |
| 5.00 | 740.00 | .2445E 03 | .3475E 00 | .1466E 02 | .267 |
| 5.00 | 760.00 | .2499E 03 | .3520E 00 | .1491E 02 | .270 |
| 5.00 | 780.00 | .2554E 03 | .3564E 00 | .1516E 02 | .275 |
| 5.00 | 800.00 | .2608E 03 | .3608E 00 | .1540E 02 | .280 |
| 5.00 | 820.00 | .2664E 03 | .3652E 00 | .1565E 02 | .282 |
| 5.00 | 840.00 | .2720E 03 | .3696E 00 | .1589E 02 | .285 |
| 5.00 | 860.00 | .2777E 03 | .3739E 00 | .1614E 02 | .285 |
| 5.00 | 880.00 | .2834E 03 | .3782E 00 | .1639E 02 | .285 |
| 5.00 | 900.00 | .2891E 03 | .3824E 00 | .1663E 02 | .288 |
| 5.00 | 920.00 | .2949E 03 | .3866E 00 | .1687E 02 | .290 |
| 5.00 | 940.00 | .3008E 03 | .3908E 00 | .1712E 02 | .292 |
| 5.00 | 960.00 | .3066E 03 | .3950E 00 | .1737E 02 | .295 |
| 5.00 | 980.00 | .3125E 03 | .3991E 00 | .1761E 02 | .297 |
| 5.00 | 1000.00 | .3184E 03 | .4032E 00 | .1786E 02 | .300 |
| 5.00 | 1020.00 | .3244E 03 | .4072E 00 | .1810E 02 | .300 |
| 5.00 | 1040.00 | .3304E 03 | .4113E 00 | .1835E 02 | .300 |

## SUPERHEATED VAPOR

| P (PSIA) | T (°F) | H (BTU/LB) | S (BTU/LB-°F) | V (FT³/LB) | CP (BTU/LB-°F) |
|---|---|---|---|---|---|
| 10.00 | 60.00 | .6464E 01 | .1461E-01 | .1002E-01 | .957 |
| 10.00 | 80.00 | .1125E 02 | .2465E-01 | .1032E-01 | .984 |
| 10.00 | 100.00 | .1617E 02 | .3440E-01 | .1064E-01 | 1.012 |
| 10.00 | 120.00 | .2123E 02 | .4389E-01 | .1098E-01 | 1.033 |
| 10.00 | 140.00 | .2642E 02 | .5316E-01 | .1135E-01 | 1.068 |
| 10.00 | 160.00 | .1131E 03 | .1937E 00 | .3698E 01 | .180 |
| 10.00 | 180.00 | .1166E 03 | .1992E 00 | .3825E 01 | .182 |
| 10.00 | 200.00 | .1202E 03 | .2048E 00 | .3953E 01 | .185 |
| 10.00 | 220.00 | .1239E 03 | .2102E 00 | .4080E 01 | .187 |
| 10.00 | 240.00 | .1277E 03 | .2157E 00 | .4207E 01 | .190 |
| 10.00 | 260.00 | .1316E 03 | .2211E 00 | .4333E 01 | .195 |
| 10.00 | 280.00 | .1355E 03 | .2265E 00 | .4458E 01 | .200 |
| 10.00 | 300.00 | .1395E 03 | .2318E 00 | .4584E 01 | .205 |
| 10.00 | 320.00 | .1435E 03 | .2371E 00 | .4710E 01 | .210 |
| 10.00 | 340.00 | .1477E 03 | .2423E 00 | .4835E 01 | .212 |
| 10.00 | 360.00 | .1519E 03 | .2476E 00 | .4960E 01 | .215 |
| 10.00 | 380.00 | .1563E 03 | .2527E 00 | .5086E 01 | .217 |
| 10.00 | 400.00 | .1606E 03 | .2579E 00 | .5211E 01 | .220 |
| 10.00 | 420.00 | .1651E 03 | .2630E 00 | .5335E 01 | .225 |
| 10.00 | 440.00 | .1695E 03 | .2681E 00 | .5459E 01 | .230 |
| 10.00 | 460.00 | .1741E 03 | .2731E 00 | .5583E 01 | .233 |
| 10.00 | 480.00 | .1787E 03 | .2781E 00 | .5708E 01 | .235 |
| 10.00 | 500.00 | .1834E 03 | .2830E 00 | .5832E 01 | .237 |
| 10.00 | 520.00 | .1882E 03 | .2879E 00 | .5956E 01 | .240 |
| 10.00 | 540.00 | .1930E 03 | .2928E 00 | .6080E 01 | .243 |
| 10.00 | 560.00 | .1979E 03 | .2977E 00 | .6203E 01 | .245 |
| 10.00 | 580.00 | .2028E 03 | .3025E 00 | .6328E 01 | .250 |
| 10.00 | 600.00 | .2078E 03 | .3072E 00 | .6452E 01 | .255 |
| 10.00 | 620.00 | .2129E 03 | .3119E 00 | .6577E 01 | .257 |
| 10.00 | 640.00 | .2180E 03 | .3166E 00 | .6702E 01 | .260 |
| 10.00 | 660.00 | .2232E 03 | .3213E 00 | .6826E 01 | .260 |
| 10.00 | 680.00 | .2284E 03 | .3259E 00 | .6949E 01 | .260 |
| 10.00 | 700.00 | .2337E 03 | .3305E 00 | .7072E 01 | .265 |
| 10.00 | 720.00 | .2390E 03 | .3351E 00 | .7194E 01 | .270 |
| 10.00 | 740.00 | .2444E 03 | .3396E 00 | .7317E 01 | .270 |
| 10.00 | 760.00 | .2498E 03 | .3441E 00 | .7440E 01 | .279 |
| 10.00 | 780.00 | .2553E 03 | .3485E 00 | .7563E 01 | .272 |
| 10.00 | 800.00 | .2608E 03 | .3529E 00 | .7686E 01 | .275 |
| 10.00 | 820.00 | .2663E 03 | .3573E 00 | .7811E 01 | .280 |
| 10.00 | 840.00 | .2719E 03 | .3617E 00 | .7937E 01 | .285 |
| 10.00 | 860.00 | .2776E 03 | .3660E 00 | .8060E 01 | .285 |
| 10.00 | 880.00 | .2833E 03 | .3703E 00 | .8183E 01 | .285 |
| 10.00 | 900.00 | .2891E 03 | .3745E 00 | .8304E 01 | .287 |
| 10.00 | 920.00 | .2948E 03 | .3788E 00 | .8425E 01 | .290 |
| 10.00 | 940.00 | .3006E 03 | .3829E 00 | .8549E 01 | .292 |
| 10.00 | 960.00 | .3065E 03 | .3871E 00 | .8673E 01 | .295 |
| 10.00 | 980.00 | .3124E 03 | .3912E 00 | .8797E 01 | .297 |
| 10.00 | 1000.00 | .3183E 03 | .3953E 00 | .8921E 01 | .300 |
| 10.00 | 1020.00 | .3243E 03 | .3993E 00 | .9043E 01 | .300 |
| 10.00 | 1040.00 | .3303E 03 | .4034E 00 | .9166E 01 | .300 |

# SUPERHEATED VAPOR

| P (PSIA) | T (°F) | H (BTU/LB) | S (BTU/LB-°F) | $(FT^3/LB)$ | CP (BTU/LB-°F) |
|---|---|---|---|---|---|
| 15.00 | 60.00 | .6464E 01 | .1461E-01 | .1002E-01 | .957 |
| 15.00 | 80.00 | .1125E 02 | .2465E-01 | .1032E-01 | .984 |
| 15.00 | 100.00 | .1617E 02 | .3440E-01 | .1064E-01 | 1.012 |
| 15.00 | 120.00 | .2123E 02 | .4389E-01 | .1098E-01 | 1.038 |
| 15.00 | 140.00 | .2642E 02 | .5316E-01 | .1135E-01 | 1.068 |
| 15.00 | 160.00 | .3176E 02 | .6223E-01 | .1174E-01 | 1.094 |
| 15.00 | 180.00 | .3723E 02 | .7112E-01 | .1217E-01 | 1.120 |
| 15.00 | 200.00 | .1200E 03 | .2000E 00 | .2627E 01 | .185 |
| 15.00 | 220.00 | .1237E 03 | .2055E 00 | .2714E 01 | .190 |
| 15.00 | 240.00 | .1275E 03 | .2110E 00 | .2801E 01 | .195 |
| 15.00 | 260.00 | .1314E 03 | .2164E 00 | .2887E 01 | .197 |
| 15.00 | 280.00 | .1353E 03 | .2218E 00 | .2973E 01 | .200 |
| 15.00 | 300.00 | .1393E 03 | .2271E 00 | .3059E 01 | .203 |
| 15.00 | 320.00 | .1434E 03 | .2324E 00 | .3145E 01 | .205 |
| 15.00 | 340.00 | .1476E 03 | .2377E 00 | .3230E 01 | .210 |
| 15.00 | 360.00 | .1518E 03 | .2429E 00 | .3315E 01 | .215 |
| 15.00 | 380.00 | .1561E 03 | .2481E 00 | .3400E 01 | .220 |
| 15.00 | 400.00 | .1604E 03 | .2533E 00 | .3484E 01 | .225 |
| 15.00 | 420.00 | .1649E 03 | .2584E 00 | .3569E 01 | .225 |
| 15.00 | 440.00 | .1694E 03 | .2634E 00 | .3653E 01 | .225 |
| 15.00 | 460.00 | .1740E 03 | .2684E 00 | .3737E 01 | .230 |
| 15.00 | 480.00 | .1786E 03 | .2734E 00 | .3822E 01 | .235 |
| 15.00 | 500.00 | .1833E 03 | .2784E 00 | .3906E 01 | .240 |
| 15.00 | 520.00 | .1880E 03 | .2833E 00 | .3990E 01 | .245 |
| 15.00 | 540.00 | .1929E 03 | .2882E 00 | .4074E 01 | .245 |
| 15.00 | 560.00 | .1978E 03 | .2930E 00 | .4158E 01 | .245 |
| 15.00 | 580.00 | .2027E 03 | .2978E 00 | .4242E 01 | .250 |
| 15.00 | 600.00 | .2077E 03 | .3026E 00 | .4325E 01 | .255 |
| 15.00 | 620.00 | .2128E 03 | .3073E 00 | .4409E 01 | .258 |
| 15.00 | 640.00 | .2179E 03 | .3120E 00 | .4493E 01 | .260 |
| 15.00 | 660.00 | .2231E 03 | .3167E 00 | .4576E 01 | .263 |
| 15.00 | 680.00 | .2283E 03 | .3213E 00 | .4660E 01 | .265 |
| 15.00 | 700.00 | .2336E 03 | .3259E 00 | .4743E 01 | .268 |
| 15.00 | 720.00 | .2389E 03 | .3305E 00 | .4826E 01 | .270 |
| 15.00 | 740.00 | .2443E 03 | .3350E 00 | .4909E 01 | .273 |
| 15.00 | 760.00 | .2497E 03 | .3395E 00 | .4992E 01 | .275 |
| 15.00 | 780.00 | .2552E 03 | .3439E 00 | .5076E 01 | .278 |
| 15.00 | 800.00 | .2607E 03 | .3483E 00 | .5159E 01 | .280 |
| 15.00 | 820.00 | .2663E 03 | .3527E 00 | .5242E 01 | .280 |
| 15.00 | 840.00 | .2719E 03 | .3571E 00 | .5326E 01 | .280 |
| 15.00 | 860.00 | .2775E 03 | .3614E 00 | .5409E 01 | .285 |
| 15.00 | 880.00 | .2832E 03 | .3657E 00 | .5492E 01 | .290 |
| 15.00 | 900.00 | .2890E 03 | .3700E 00 | .5575E 01 | .290 |
| 15.00 | 920.00 | .2948E 03 | .3742E 00 | .5658E 01 | .290 |
| 15.00 | 940.00 | .3006E 03 | .3784E 00 | .5742E 01 | .293 |
| 15.00 | 960.00 | .3064E 03 | .3825E 00 | .5825E 01 | .295 |
| 15.00 | 980.00 | .3123E 03 | .3866E 00 | .5908E 01 | .295 |
| 15.00 | 1000.00 | .3183E 03 | .3907E 00 | .5991E 01 | .295 |
| 15.00 | 1020.00 | .3243E 03 | .3948E 00 | .6073E 01 | .298 |
| 15.00 | 1040.00 | .3303E 03 | .3988E 00 | .6156E 01 | .300 |

## SUPERHEATED VAPOR

| P (PSIA) | T (°F) | H (BTU/LB) | S (BTU/LB-°F) | V (FT³/LB) | CP (BTU/LB-°F) |
|---|---|---|---|---|---|
| 20.00 | 60.00 | .6464E 01 | .1461E-01 | .1002E-01 | .957 |
| 20.00 | 80.00 | .1125E 02 | .2465E-01 | .1032E-01 | .984 |
| 20.00 | 100.00 | .1617E 02 | .3440E-01 | .1064E-01 | 1.012 |
| 20.00 | 120.00 | .2123E 02 | .4389E-01 | .1098E-01 | 1.038 |
| 20.00 | 140.00 | .2642E 02 | .5316E-01 | .1135E-01 | 1.068 |
| 20.00 | 160.00 | .3176E 02 | .6223E-01 | .1174E-01 | 1.094 |
| 20.00 | 180.00 | .3723E 02 | .7112E-01 | .1217E-01 | 1.120 |
| 20.00 | 200.00 | .1196E 03 | .1970E 00 | .2078E 01 | .182 |
| 20.00 | 220.00 | .1235E 03 | .2025E 00 | .2148E 01 | .187 |
| 20.00 | 240.00 | .1273E 03 | .2079E 00 | .2218E 01 | .192 |
| 20.00 | 260.00 | .1312E 03 | .2133E 00 | .2287E 01 | .196 |
| 20.00 | 280.00 | .1351E 03 | .2187E 00 | .2356E 01 | .200 |
| 20.00 | 300.00 | .1391E 03 | .2240E 00 | .2426E 01 | .204 |
| 20.00 | 320.00 | .1432E 03 | .2294E 00 | .2495E 01 | .208 |
| 20.00 | 340.00 | .1474E 03 | .2346E 00 | .2563E 01 | .211 |
| 20.00 | 360.00 | .1516E 03 | .2399E 00 | .2632E 01 | .215 |
| 20.00 | 380.00 | .1559E 03 | .2451E 00 | .2700E 01 | .220 |
| 20.00 | 400.00 | .1602E 03 | .2503E 00 | .2768E 01 | .225 |
| 20.00 | 420.00 | .1647E 03 | .2553E 00 | .2836E 01 | .226 |
| 20.00 | 440.00 | .1692E 03 | .2604E 00 | .2904E 01 | .228 |
| 20.00 | 460.00 | .1738E 03 | .2654E 00 | .2971E 01 | .231 |
| 20.00 | 480.00 | .1784E 03 | .2704E 00 | .3039E 01 | .235 |
| 20.00 | 500.00 | .1832E 03 | .2754E 00 | .3106E 01 | .239 |
| 20.00 | 520.00 | .1879E 03 | .2803E 00 | .3174E 01 | .242 |
| 20.00 | 540.00 | .1928E 03 | .2852E 00 | .3241E 01 | .245 |
| 20.00 | 560.00 | .1976E 03 | .2901E 00 | .3308E 01 | .248 |
| 20.00 | 580.00 | .2026E 03 | .2948E 00 | .3375E 01 | .251 |
| 20.00 | 600.00 | .2076E 03 | .2996E 00 | .3442E 01 | .255 |
| 20.00 | 620.00 | .2127E 03 | .3043E 00 | .3509E 01 | .258 |
| 20.00 | 640.00 | .2178E 03 | .3091E 00 | .3576E 01 | .260 |
| 20.00 | 660.00 | .2230E 03 | .3137E 00 | .3643E 01 | .262 |
| 20.00 | 680.00 | .2282E 03 | .3184E 00 | .3710E 01 | .265 |
| 20.00 | 700.00 | .2335E 03 | .3229E 00 | .3777E 01 | .268 |
| 20.00 | 720.00 | .2388E 03 | .3275E 00 | .3843E 01 | .270 |
| 20.00 | 740.00 | .2442E 03 | .3320E 00 | .3910E 01 | .273 |
| 20.00 | 760.00 | .2496E 03 | .3366E 00 | .3977E 01 | .275 |
| 20.00 | 780.00 | .2551E 03 | .3410E 00 | .4043E 01 | .278 |
| 20.00 | 800.00 | .2606E 03 | .3454E 00 | .4110E 01 | .280 |
| 20.00 | 820.00 | .2662E 03 | .3498E 00 | .4177E 01 | .281 |
| 20.00 | 840.00 | .2718E 03 | .3542E 00 | .4243E 01 | .283 |
| 20.00 | 860.00 | .2775E 03 | .3585E 00 | .4309E 01 | .285 |
| 20.00 | 880.00 | .2831E 03 | .3628E 00 | .4376E 01 | .287 |
| 20.00 | 900.00 | .2889E 03 | .3670E 00 | .4442E 01 | .290 |
| 20.00 | 920.00 | .2947E 03 | .3713E 00 | .4509E 01 | .293 |
| 20.00 | 940.00 | .3005E 03 | .3754E 00 | .4575E 01 | .293 |
| 20.00 | 960.00 | .3064E 03 | .3796E 00 | .4642E 01 | .292 |
| 20.00 | 980.00 | .3123E 03 | .3837E 00 | .4708E 01 | .294 |
| 20.00 | 1000.00 | .3182E 03 | .3878E 00 | .4774E 01 | .295 |
| 20.00 | 1020.00 | .3242E 03 | .3918E 00 | .4840E 01 | .299 |
| 20.00 | 1040.00 | .3302E 03 | .3959E 00 | .4906E 01 | .303 |

## SUPERHEATED VAPOR

| P (PSIA) | T (°F) | H (BTU/LB) | S (BTU/LB-°F) | V (FT³/LB) | CP (BTU/LB-°F) |
|---|---|---|---|---|---|
| 40.00 | 60.00 | .6464E 01 | .1461E-01 | .1002E-01 | .957 |
| 40.00 | 80.00 | .1125E 02 | .2465E-01 | .1032E-01 | .984 |
| 40.00 | 100.00 | .1617E 02 | .3440E-01 | .1064E-01 | 1.012 |
| 40.00 | 120.00 | .2123E 02 | .4389E-01 | .1098E-01 | 1.038 |
| 40.00 | 140.00 | .2642E 02 | .5316E-01 | .1135E-01 | 1.068 |
| 40.00 | 160.00 | .3176E 02 | .6223E-01 | .1174E-01 | 1.094 |
| 40.00 | 180.00 | .3723E 02 | .7112E-01 | .1217E-01 | 1.120 |
| 40.00 | 200.00 | .4283E 02 | .7986E-01 | .1264E-01 | 1.150 |
| 40.00 | 220.00 | .4858E 02 | .8846E-01 | .1315E-01 | 1.178 |
| 40.00 | 240.00 | .5447E 02 | .9695E-01 | .1371E-01 | 1.208 |
| 40.00 | 260.00 | .1303E 03 | .2050E 00 | .1156E 01 | .200 |
| 40.00 | 280.00 | .1343E 03 | .2104E 00 | .1195E 01 | .203 |
| 40.00 | 300.00 | .1384E 03 | .2158E 00 | .1233E 01 | .206 |
| 40.00 | 320.00 | .1425E 03 | .2211E 00 | .1271E 01 | .210 |
| 40.00 | 340.00 | .1467E 03 | .2264E 00 | .1308E 01 | .214 |
| 40.00 | 360.00 | .1509E 03 | .2317E 00 | .1345E 01 | .218 |
| 40.00 | 380.00 | .1553E 03 | .2369E 00 | .1382E 01 | .221 |
| 40.00 | 400.00 | .1597E 03 | .2422E 00 | .1419E 01 | .225 |
| 40.00 | 420.00 | .1642E 03 | .2473E 00 | .1456E 01 | .227 |
| 40.00 | 440.00 | .1687E 03 | .2524E 00 | .1493E 01 | .230 |
| 40.00 | 460.00 | .1733E 03 | .2574E 00 | .1529E 01 | .232 |
| 40.00 | 480.00 | .1779E 03 | .2624E 00 | .1565E 01 | .235 |
| 40.00 | 500.00 | .1827E 03 | .2674E 00 | .1601E 01 | .239 |
| 40.00 | 520.00 | .1874E 03 | .2724E 00 | .1637E 01 | .243 |
| 40.00 | 540.00 | .1923E 03 | .2772E 00 | .1673E 01 | .247 |
| 40.00 | 560.00 | .1972E 03 | .2821E 00 | .1709E 01 | .250 |
| 40.00 | 580.00 | .2022E 03 | .2869E 00 | .1745E 01 | .253 |
| 40.00 | 600.00 | .2072E 03 | .2917E 00 | .1781E 01 | .255 |
| 40.00 | 620.00 | .2123E 03 | .2965E 00 | .1816E 01 | .258 |
| 40.00 | 640.00 | .2174E 03 | .3012E 00 | .1852E 01 | .260 |
| 40.00 | 660.00 | .2226E 03 | .3059E 00 | .1888E 01 | .262 |
| 40.00 | 680.00 | .2279E 03 | .3105E 00 | .1923E 01 | .265 |
| 40.00 | 700.00 | .2332E 03 | .3151E 00 | .1959E 01 | .267 |
| 40.00 | 720.00 | .2385E 03 | .3196E 00 | .1994E 01 | .270 |
| 40.00 | 740.00 | .2439E 03 | .3242E 00 | .2029E 01 | .272 |
| 40.00 | 760.00 | .2493E 03 | .3287E 00 | .2065E 01 | .275 |
| 40.00 | 780.00 | .2548E 03 | .3332E 00 | .2100E 01 | .278 |
| 40.00 | 800.00 | .2603E 03 | .3376E 00 | .2135E 01 | .280 |
| 40.00 | 820.00 | .2659E 03 | .3420E 00 | .2170E 01 | .283 |
| 40.00 | 840.00 | .2715E 03 | .3463E 00 | .2205E 01 | .285 |
| 40.00 | 860.00 | .2772E 03 | .3507E 00 | .2240E 01 | .285 |
| 40.00 | 880.00 | .2829E 03 | .3550E 00 | .2275E 01 | .285 |
| 40.00 | 900.00 | .2887E 03 | .3592E 00 | .2310E 01 | .288 |
| 40.00 | 920.00 | .2944E 03 | .3634E 00 | .2345E 01 | .292 |
| 40.00 | 940.00 | .3003E 03 | .3676E 00 | .2381E 01 | .292 |
| 40.00 | 960.00 | .3062E 03 | .3718E 00 | .2416E 01 | .293 |
| 40.00 | 980.00 | .3121E 03 | .3759E 00 | .2450E 01 | .294 |
| 40.00 | 1000.00 | .3180E 03 | .3800E 00 | .2485E 01 | .295 |
| 40.00 | 1020.00 | .3240E 03 | .3840E 00 | .2520E 01 | .299 |
| 40.00 | 1040.00 | .3300E 03 | .3881E 00 | .2555E 01 | .302 |

# SUPERHEATED VAPOR

| P (PSIA) | T (°F) | H (BTU/LB) | S (BTU/LB-°F) | V ($FT^3$/LB) | CP (BTU/LB-°F) |
|---|---|---|---|---|---|
| 60.00 | 60.00 | .6464E 01 | .1461E-01 | .1002E-01 | .957 |
| 60.00 | 80.00 | .1125E 02 | .2465E-01 | .1032E-01 | .984 |
| 60.00 | 100.00 | .1617E 02 | .3440E-01 | .1064E-01 | 1.012 |
| 60.00 | 120.00 | .2123E 02 | .4389E-01 | .1098E-01 | 1.038 |
| 60.00 | 140.00 | .2642E 02 | .5316E-01 | .1135E-01 | 1.068 |
| 60.00 | 160.00 | .3176E 02 | .6223E-01 | .1174E-01 | 1.094 |
| 60.00 | 180.00 | .3723E 02 | .7112E-01 | .1217E-01 | 1.120 |
| 60.00 | 200.00 | .4283E 02 | .7986E-01 | .1264E-01 | 1.150 |
| 60.00 | 220.00 | .4858E 02 | .8846E-01 | .1315E-01 | 1.178 |
| 60.00 | 240.00 | .5447E 02 | .9695E-01 | .1371E-01 | 1.208 |
| 60.00 | 260.00 | .6051E 02 | .1053E 00 | .1433E-01 | 1.240 |
| 60.00 | 280.00 | .1334E 03 | .2050E 00 | .7397E 00 | .205 |
| 60.00 | 300.00 | .1375E 03 | .2104E 00 | .7657E 00 | .208 |
| 60.00 | 320.00 | .1417E 03 | .2158E 00 | .7916E 00 | .211 |
| 60.00 | 340.00 | .1460E 03 | .2211E 00 | .8170E 00 | .216 |
| 60.00 | 360.00 | .1502E 03 | .2264E 00 | .8423E 00 | .221 |
| 60.00 | 380.00 | .1547E 03 | .2317E 00 | .8673E 00 | .223 |
| 60.00 | 400.00 | .1591E 03 | .2370E 00 | .8922E 00 | .225 |
| 60.00 | 420.00 | .1636E 03 | .2421E 00 | .9166E 00 | .228 |
| 60.00 | 440.00 | .1681E 03 | .2472E 00 | .9410E 00 | .231 |
| 60.00 | 460.00 | .1728E 03 | .2523E 00 | .9652E 00 | .233 |
| 60.00 | 480.00 | .1774E 03 | .2573E 00 | .9894E 00 | .235 |
| 60.00 | 500.00 | .1822E 03 | .2623E 00 | .1013E 01 | .240 |
| 60.00 | 520.00 | .1870E 03 | .2674E 00 | .1037E 01 | .245 |
| 60.00 | 540.00 | .1919E 03 | .2722E 00 | .1061E 01 | .248 |
| 60.00 | 560.00 | .1968E 03 | .2771E 00 | .1085E 01 | .250 |
| 60.00 | 580.00 | .2018E 03 | .2819E 00 | .1108E 01 | .253 |
| 60.00 | 600.00 | .2068E 03 | .2868E 00 | .1132E 01 | .256 |
| 60.00 | 620.00 | .2119E 03 | .2915E 00 | .1155E 01 | .259 |
| 60.00 | 640.00 | .2170E 03 | .2962E 00 | .1179E 01 | .261 |
| 60.00 | 660.00 | .2222E 03 | .3009E 00 | .1202E 01 | .263 |
| 60.00 | 680.00 | .2275E 03 | .3056E 00 | .1225E 01 | .266 |
| 60.00 | 700.00 | .2328E 03 | .3102E 00 | .1248E 01 | .268 |
| 60.00 | 720.00 | .2381E 03 | .3147E 00 | .1272E 01 | .271 |
| 60.00 | 740.00 | .2435E 03 | .3193E 00 | .1295E 01 | .273 |
| 60.00 | 760.00 | .2489E 03 | .3238E 00 | .1318E 01 | .276 |
| 60.00 | 780.00 | .2545E 03 | .3283E 00 | .1341E 01 | .278 |
| 60.00 | 800.00 | .2600E 03 | .3327E 00 | .1364E 01 | .280 |
| 60.00 | 820.00 | .2656E 03 | .3371E 00 | .1387E 01 | .283 |
| 60.00 | 840.00 | .2713E 03 | .3415E 00 | .1409E 01 | .285 |
| 60.00 | 860.00 | .2770E 03 | .3458E 00 | .1432E 01 | .286 |
| 60.00 | 880.00 | .2827E 03 | .3501E 00 | .1455E 01 | .286 |
| 60.00 | 900.00 | .2884E 03 | .3544E 00 | .1478E 01 | .288 |
| 60.00 | 920.00 | .2942E 03 | .3586E 00 | .1501E 01 | .290 |
| 60.00 | 940.00 | .3000E 03 | .3628E 00 | .1523E 01 | .292 |
| 60.00 | 960.00 | .3059E 03 | .3670E 00 | .1546E 01 | .295 |
| 60.00 | 980.00 | .3118E 03 | .3711E 00 | .1569E 01 | .296 |
| 60.00 | 1000.00 | .3178E 03 | .3752E 00 | .1591E 01 | .296 |
| 60.00 | 1020.00 | .3238E 03 | .3792E 00 | .1614E 01 | .299 |
| 60.00 | 1040.00 | .3298E 03 | .3833E 00 | .1637E 01 | .301 |

## SUPERHEATED VAPOR

| P (PSIA) | T (°F) | H (BTU/LB) | S (BTU/LB-°F) | V (FT³/LB) | CP (BTU/LB-°F) |
|---|---|---|---|---|---|
| 80.00 | 60.00 | .6464E 01 | .1461E-01 | .1002E-01 | .957 |
| 80.00 | 80.00 | .1125E 02 | .2465E-01 | .1032E-01 | .984 |
| 80.00 | 100.00 | .1617E 02 | .3440E-01 | .1064E-01 | 1.012 |
| 80.00 | 120.00 | .2123E 02 | .4389E-01 | .1098E-01 | 1.038 |
| 80.00 | 140.00 | .2642E 02 | .5316E-01 | .1135E-01 | 1.068 |
| 80.00 | 160.00 | .3176E 02 | .6223E-01 | .1174E-01 | 1.094 |
| 80.00 | 180.00 | .3720E 02 | .7112E-01 | .1217E-01 | 1.120 |
| 80.00 | 200.00 | .4283E 02 | .7986E-01 | .1264E-01 | 1.150 |
| 80.00 | 220.00 | .4258E 02 | .8846E-01 | .1315E-01 | 1.178 |
| 80.00 | 240.00 | .5447E 02 | .9695E-01 | .1371E-01 | 1.208 |
| 80.00 | 260.00 | .6051E 02 | .1053E 00 | .1433E-01 | 1.240 |
| 80.00 | 280.00 | .6671E 02 | .1137E 00 | .1503E-01 | 1.276 |
| 80.00 | 300.00 | .1366E 03 | .2065E 00 | .5777E 00 | .209 |
| 80.00 | 320.00 | .1409E 03 | .2119E 00 | .5987E 00 | .213 |
| 80.00 | 340.00 | .1452E 03 | .2173E 00 | .6195E 00 | .218 |
| 80.00 | 360.00 | .1495E 03 | .2227E 00 | .6402E 00 | .223 |
| 80.00 | 380.00 | .1540E 03 | .2280E 00 | .6604E 00 | .224 |
| 80.00 | 400.00 | .1584E 03 | .2333E 00 | .6806E 00 | .225 |
| 80.00 | 420.00 | .1630E 03 | .2385E 00 | .7003E 00 | .229 |
| 80.00 | 440.00 | .1675E 03 | .2437E 00 | .7200E 00 | .233 |
| 80.00 | 460.00 | .1722E 03 | .2487E 00 | .7393E 00 | .234 |
| 80.00 | 480.00 | .1769E 03 | .2538E 00 | .7587E 00 | .235 |
| 80.00 | 500.00 | .1817E 03 | .2588E 00 | .7779E 00 | .240 |
| 80.00 | 520.00 | .1865E 03 | .2639E 00 | .7970E 00 | .245 |
| 80.00 | 540.00 | .1914E 03 | .2688E 00 | .8159E 00 | .247 |
| 80.00 | 560.00 | .1963E 03 | .2736E 00 | .8348E 00 | .250 |
| 80.00 | 580.00 | .2013E 03 | .2785E 00 | .8534E 00 | .254 |
| 80.00 | 600.00 | .2063E 03 | .2833E 00 | .8721E 00 | .258 |
| 80.00 | 620.00 | .2115E 03 | .2881E 00 | .8907E 00 | .261 |
| 80.00 | 640.00 | .2166E 03 | .2929E 00 | .9092E 00 | .263 |
| 80.00 | 660.00 | .2218E 03 | .2975E 00 | .9276E 00 | .266 |
| 80.00 | 680.00 | .2271E 03 | .3022E 00 | .9459E 00 | .268 |
| 80.00 | 700.00 | .2324E 03 | .3068E 00 | .9642E 00 | .271 |
| 80.00 | 720.00 | .2378E 03 | .3114E 00 | .9825E 00 | .273 |
| 80.00 | 740.00 | .2432E 03 | .3160E 00 | .1001E 01 | .275 |
| 80.00 | 760.00 | .2486E 03 | .3205E 00 | .1019E 01 | .278 |
| 80.00 | 780.00 | .2542E 03 | .3250E 00 | .1037E 01 | .279 |
| 80.00 | 800.00 | .2597E 03 | .3294E 00 | .1055E 01 | .280 |
| 80.00 | 820.00 | .2653E 03 | .3338E 00 | .1073E 01 | .283 |
| 80.00 | 840.00 | .2710E 03 | .3382E 00 | .1091E 01 | .285 |
| 80.00 | 860.00 | .2767E 03 | .3425E 00 | .1109E 01 | .286 |
| 80.00 | 880.00 | .2824E 03 | .3468E 00 | .1127E 01 | .288 |
| 80.00 | 900.00 | .2882E 03 | .3511E 00 | .1145E 01 | .289 |
| 80.00 | 920.00 | .2939E 03 | .3553E 00 | .1163E 01 | .290 |
| 80.00 | 940.00 | .2998E 03 | .3595E 00 | .1181E 01 | .293 |
| 80.00 | 960.00 | .3056E 03 | .3637E 00 | .1199E 01 | .295 |
| 80.00 | 980.00 | .3116E 03 | .3678E 00 | .1216E 01 | .297 |
| 80.00 | 1000.00 | .3175E 03 | .3719E 00 | .1234E 01 | .298 |
| 80.00 | 1020.00 | .3235E 03 | .3760E 00 | .1252E 01 | .300 |
| 80.00 | 1040.00 | .3295E 03 | .3800E 00 | .1270E 01 | .303 |

# SUPERHEATED VAPOR

| P (PSIA) | T (°F) | H (BTU/LB) | S (BTU/LB-°F) | V (FT³/LB) | CP (BTU/LB-°F) |
|---|---|---|---|---|---|
| 100.00 | 60.00 | .6464E 01 | .1461E-01 | .1002E-01 | .957 |
| 100.00 | 80.00 | .1125E 02 | .2465E-01 | .1032E-01 | .984 |
| 100.00 | 100.00 | .1617E 02 | .3440E-01 | .1064E-01 | 1.012 |
| 100.00 | 120.00 | .2123E 02 | .4389E-01 | .1098E-01 | 1.038 |
| 100.00 | 140.00 | .2642E 02 | .5316E-01 | .1135E-01 | 1.068 |
| 100.00 | 160.00 | .3176E 02 | .6223E-01 | .1174E-01 | 1.094 |
| 100.00 | 180.00 | .3723E 02 | .7112E-01 | .1217E-01 | 1.120 |
| 100.00 | 200.00 | .4283E 02 | .7986E-01 | .1264E-01 | 1.150 |
| 100.00 | 220.00 | .4858E 02 | .8846E-01 | .1315E-01 | 1.178 |
| 100.00 | 240.00 | .5447E 02 | .9695E-01 | .1371E-01 | 1.208 |
| 100.00 | 260.00 | .6051E 02 | .1053E 00 | .1433E-01 | 1.240 |
| 100.00 | 280.00 | .6671E 02 | .1137E 00 | .1503E-01 | 1.276 |
| 100.00 | 300.00 | .7309E 02 | .1220E 00 | .1582E-01 | 1.312 |
| 100.00 | 320.00 | .1398E 03 | .2084E 00 | .4070E 00 | .225 |
| 100.00 | 340.00 | .1443E 03 | .2137E 00 | .4225E 00 | .225 |
| 100.00 | 360.00 | .1487E 03 | .2191E 00 | .4391E 00 | .215 |
| 100.00 | 380.00 | .1533E 03 | .2243E 00 | .4541E 00 | .220 |
| 100.00 | 400.00 | .1578E 03 | .2296E 00 | .4690E 00 | .225 |
| 100.00 | 420.00 | .1623E 03 | .2348E 00 | .4840E 00 | .230 |
| 100.00 | 440.00 | .1669E 03 | .2401E 00 | .4990E 00 | .235 |
| 100.00 | 460.00 | .1716E 03 | .2452E 00 | .5135E 00 | .235 |
| 100.00 | 480.00 | .1764E 03 | .2503E 00 | .5280E 00 | .235 |
| 100.00 | 500.00 | .1812E 03 | .2553E 00 | .5424E 00 | .240 |
| 100.00 | 520.00 | .1860E 03 | .2604E 00 | .5568E 00 | .245 |
| 100.00 | 540.00 | .1909E 03 | .2653E 00 | .5708E 00 | .247 |
| 100.00 | 560.00 | .1959E 03 | .2702E 00 | .5848E 00 | .250 |
| 100.00 | 580.00 | .2009E 03 | .2750E 00 | .5986E 00 | .255 |
| 100.00 | 600.00 | .2059E 03 | .2799E 00 | .6124E 00 | .260 |
| 100.00 | 620.00 | .2110E 03 | .2847E 00 | .6261E 00 | .263 |
| 100.00 | 640.00 | .2162E 03 | .2895E 00 | .6398E 00 | .265 |
| 100.00 | 660.00 | .2214E 03 | .2941E 00 | .6532E 00 | .268 |
| 100.00 | 680.00 | .2267E 03 | .2988E 00 | .6667E 00 | .270 |
| 100.00 | 700.00 | .2320E 03 | .3034E 00 | .6801E 00 | .273 |
| 100.00 | 720.00 | .2374E 03 | .3081E 00 | .6935E 00 | .275 |
| 100.00 | 740.00 | .2428E 03 | .3126E 00 | .7070E 00 | .277 |
| 100.00 | 760.00 | .2483E 03 | .3172E 00 | .7205E 00 | .280 |
| 100.00 | 780.00 | .2538E 03 | .3216E 00 | .7336E 00 | .280 |
| 100.00 | 800.00 | .2594E 03 | .3261E 00 | .7468E 00 | .280 |
| 100.00 | 820.00 | .2650E 03 | .3305E 00 | .7598E 00 | .283 |
| 100.00 | 840.00 | .2707E 03 | .3349E 00 | .7728E 00 | .285 |
| 100.00 | 860.00 | .2764E 03 | .3392E 00 | .7858E 00 | .287 |
| 100.00 | 880.00 | .2821E 03 | .3435E 00 | .7987E 00 | .290 |
| 100.00 | 900.00 | .2879E 03 | .3478E 00 | .8119E 00 | .290 |
| 100.00 | 920.00 | .2937E 03 | .3521E 00 | .8251E 00 | .290 |
| 100.00 | 940.00 | .2995E 03 | .3562E 00 | .8381E 00 | .293 |
| 100.00 | 960.00 | .3054E 03 | .3604E 00 | .8511E 00 | .295 |
| 100.00 | 980.00 | .3113E 03 | .3645E 00 | .8637E 00 | .298 |
| 100.00 | 1000.00 | .3173E 03 | .3687E 00 | .8764E 00 | .300 |
| 100.00 | 1020.00 | .3233E 03 | .3727E 00 | .8895E 00 | .302 |
| 100.00 | 1040.00 | .3293E 03 | .3768E 00 | .9025E 00 | .305 |

## SUPERHEATED VAPOR

| P (PSIA) | T (°F) | H (BTU/LB) | S (BTU/LB-°F) | V ($FT^3$/LB) | CP (BTU/LB-°F) |
|---|---|---|---|---|---|
| 300.00 | 60.00 | .6464E 01 | .1461E-01 | .1002E-01 | .957 |
| 300.00 | 80.00 | .1125E 02 | .2465E-01 | .1032E-01 | .984 |
| 300.00 | 100.00 | .1617E 02 | .3440E-01 | .1064E-01 | 1.012 |
| 300.00 | 120.00 | .2123E 02 | .4399E-01 | .1098E-01 | 1.038 |
| 300.00 | 140.00 | .2642E 02 | .5316E-01 | .1135E-01 | 1.068 |
| 300.00 | 160.00 | .3176E 02 | .6223E-01 | .1174E-01 | 1.094 |
| 300.00 | 180.00 | .3723E 02 | .7112E-01 | .1217E-01 | 1.120 |
| 300.00 | 200.00 | .4283E 02 | .7986E-01 | .1264E-01 | 1.150 |
| 300.00 | 220.00 | .4858E 02 | .8846E-01 | .1315E-01 | 1.178 |
| 300.00 | 240.00 | .5447E 02 | .9695E-01 | .1371E-01 | 1.208 |
| 300.00 | 260.00 | .6051E 02 | .1053E 00 | .1433E-01 | 1.240 |
| 300.00 | 280.00 | .6671E 02 | .1137E 00 | .1503E-01 | 1.276 |
| 300.00 | 300.00 | .7309E 02 | .1220E 00 | .1582E-01 | 1.312 |
| 300.00 | 320.00 | .7965E 02 | .1302E 00 | .1673E-01 | 1.358 |
| 300.00 | 340.00 | .8644E 02 | .1386E 00 | .1780E-01 | 1.414 |
| 300.00 | 360.00 | .9351E 02 | .1470E 00 | .1908E-01 | 1.478 |
| 300.00 | 380.00 | .1009E 03 | .1556E 00 | .2067E-01 | 1.600 |
| 300.00 | 400.00 | .1089E 03 | .1647E 00 | .2272E-01 | 1.780 |
| 300.00 | 420.00 | .1178E 03 | .1745E 00 | .2563E-01 | 2.200 |
| 300.00 | 440.00 | .1587E 03 | .2208E 00 | .1191E 00 | .275 |
| 300.00 | 460.00 | .1641E 03 | .2267E 00 | .1280E 00 | .270 |
| 300.00 | 480.00 | .1695E 03 | .2326E 00 | .1369E 00 | .265 |
| 300.00 | 500.00 | .1748E 03 | .2381E 00 | .1444E 00 | .262 |
| 300.00 | 520.00 | .1801E 03 | .2436E 00 | .1519E 00 | .260 |
| 300.00 | 540.00 | .1854E 03 | .2488E 00 | .1586E 00 | .262 |
| 300.00 | 560.00 | .1906E 03 | .2541E 00 | .1653E 00 | .265 |
| 300.00 | 580.00 | .1959E 03 | .2592E 00 | .1715E 00 | .265 |
| 300.00 | 600.00 | .2012E 03 | .2643E 00 | .1778E 00 | .265 |
| 300.00 | 620.00 | .2065E 03 | .2692E 00 | .1837E 00 | .268 |
| 300.00 | 640.00 | .2119E 03 | .2742E 00 | .1896E 00 | .270 |
| 300.00 | 660.00 | .2173E 03 | .2790E 00 | .1952E 00 | .273 |
| 300.00 | 680.00 | .2228E 03 | .2839E 00 | .2008E 00 | .275 |
| 300.00 | 700.00 | .2283E 03 | .2886E 00 | .2063E 00 | .275 |
| 300.00 | 720.00 | .2338E 03 | .2934E 00 | .2117E 00 | .275 |
| 300.00 | 740.00 | .2393E 03 | .2980E 00 | .2170E 00 | .280 |
| 300.00 | 760.00 | .2449E 03 | .3027E 00 | .2223E 00 | .285 |
| 300.00 | 780.00 | .2506E 03 | .3072E 00 | .2274E 00 | .285 |
| 300.00 | 800.00 | .2563E 03 | .3118E 00 | .2326E 00 | .285 |
| 300.00 | 820.00 | .2620E 03 | .3163E 00 | .2376E 00 | .287 |
| 300.00 | 840.00 | .2677E 03 | .3208E 00 | .2427E 00 | .290 |
| 300.00 | 860.00 | .2735E 03 | .3252E 00 | .2476E 00 | .292 |
| 300.00 | 880.00 | .2793E 03 | .3296E 00 | .2525E 00 | .295 |
| 300.00 | 900.00 | .2852E 03 | .3339E 00 | .2574E 00 | .295 |
| 300.00 | 920.00 | .2911E 03 | .3382E 00 | .2623E 00 | .295 |
| 300.00 | 940.00 | .2971E 03 | .3424E 00 | .2671E 00 | .295 |
| 300.00 | 960.00 | .3030E 03 | .3467E 00 | .2719E 00 | .295 |
| 300.00 | 980.00 | .3090E 03 | .3509E 00 | .2766E 00 | .297 |
| 300.00 | 1000.00 | .3150E 03 | .3551E 00 | .2814E 00 | .300 |
| 300.00 | 1020.00 | .3211E 03 | .3592E 00 | .2861E 00 | .302 |
| 300.00 | 1040.00 | .3271E 03 | .3633E 00 | .2908E 00 | .305 |

# SUPERHEATED VAPOR

| P (PSIA) | T (°F) | H (BTU/LB) | S (BTU/LB-°F) | V (FT³/LB) | CP (BTU/LB-°F) |
|---|---|---|---|---|---|
| 500.00 | 60.00 | .6464E 01 | .1461E-01 | .1002E-01 | .957 |
| 500.00 | 80.00 | .1125E 02 | .2465E-01 | .1032E-01 | .984 |
| 500.00 | 100.00 | .1617E 02 | .3440E-01 | .1064E-01 | 1.012 |
| 500.00 | 120.00 | .2123E 02 | .4389E-01 | .1098E-01 | 1.038 |
| 500.00 | 140.00 | .2642E 02 | .5316E-01 | .1135E-01 | 1.068 |
| 500.00 | 160.00 | .3176E 02 | .6223E-01 | .1174E-01 | 1.094 |
| 500.00 | 180.00 | .3723E 02 | .7112E-01 | .1217E-01 | 1.120 |
| 500.00 | 200.00 | .4283E 02 | .7986E-01 | .1264E-01 | 1.150 |
| 500.00 | 220.00 | .4858E 02 | .8846E-01 | .1315E-01 | 1.178 |
| 500.00 | 240.00 | .5447E 02 | .9695E-01 | .1371E-01 | 1.200 |
| 500.00 | 260.00 | .6051E 02 | .1053E 00 | .1433E-01 | 1.240 |
| 500.00 | 280.00 | .6671E 02 | .1137E 00 | .1503E-01 | 1.276 |
| 500.00 | 300.00 | .7309E 02 | .1220E 00 | .1582E-01 | 1.312 |
| 500.00 | 320.00 | .7965E 02 | .1302E 00 | .1673E-01 | 1.358 |
| 500.00 | 340.00 | .8644E 02 | .1386E 00 | .1780E-01 | 1.414 |
| 500.00 | 360.00 | .9351E 02 | .1470E 00 | .1908E-01 | 1.478 |
| 500.00 | 380.00 | .1009E 03 | .1556E 00 | .2067E-01 | 1.600 |
| 500.00 | 400.00 | .1089E 03 | .1647E 00 | .2272E-01 | 1.780 |
| 500.00 | 420.00 | .1178E 03 | .1745E 00 | .2563E-01 | 2.200 |
| 500.00 | 440.00 | .1288E 03 | .1862E 00 | .3077E-01 | 2.643 |
| 500.00 | 460.00 | -.1445E 49 | -.8296E 48 | -.4006E 45 | ######## |
| 500.00 | 480.00 | -.8672E 49 | -.4978E 49 | -.2404E 46 | ######## |
| 500.00 | 500.00 | .1608E 03 | .2199E 00 | .5074E-01 | .425 |
| 500.00 | 520.00 | .1700E 03 | .2295E 00 | .6246E-01 | .345 |
| 500.00 | 540.00 | .1766E 03 | .2361E 00 | .7002E-01 | .325 |
| 500.00 | 560.00 | .1832E 03 | .2427E 00 | .7758E-01 | .305 |
| 500.00 | 580.00 | .1892E 03 | .2484E 00 | .8327E-01 | .298 |
| 500.00 | 600.00 | .1952E 03 | .2542E 00 | .8897E-01 | .290 |
| 500.00 | 620.00 | .2010E 03 | .2596E 00 | .9379E-01 | .287 |
| 500.00 | 640.00 | .2068E 03 | .2650E 00 | .9862E-01 | .285 |
| 500.00 | 660.00 | .2126E 03 | .2701E 00 | .1030E 00 | .285 |
| 500.00 | 680.00 | .2183E 03 | .2752E 00 | .1073E 00 | .285 |
| 500.00 | 700.00 | .2240E 03 | .2801E 00 | .1114E 00 | .287 |
| 500.00 | 720.00 | .2297E 03 | .2851E 00 | .1154E 00 | .290 |
| 500.00 | 740.00 | .2355E 03 | .2899E 00 | .1192E 00 | .290 |
| 500.00 | 760.00 | .2413E 03 | .2947E 00 | .1230E 00 | .290 |
| 500.00 | 780.00 | .2471E 03 | .2994E 00 | .1266E 00 | .293 |
| 500.00 | 800.00 | .2529E 03 | .3041E 00 | .1302E 00 | .295 |
| 500.00 | 820.00 | .2588E 03 | .3087E 00 | .1336E 00 | .295 |
| 500.00 | 840.00 | .2646E 03 | .3133E 00 | .1371E 00 | .295 |
| 500.00 | 860.00 | .2706E 03 | .3177E 00 | .1405E 00 | .295 |
| 500.00 | 880.00 | .2765E 03 | .3222E 00 | .1438E 00 | .295 |
| 500.00 | 900.00 | .2824E 03 | .3266E 00 | .1471E 00 | .297 |
| 500.00 | 920.00 | .2884E 03 | .3310E 00 | .1504E 00 | .300 |
| 500.00 | 940.00 | .2944E 03 | .3353E 00 | .1535E 00 | .300 |
| 500.00 | 960.00 | .3005E 03 | .3396E 00 | .1567E 00 | .300 |
| 500.00 | 980.00 | .3066E 03 | .3439E 00 | .1599E 00 | .305 |
| 500.00 | 1000.00 | .3126E 03 | .3481E 00 | .1630E 00 | .310 |
| 500.00 | 1020.00 | .3188E 03 | .3522E 00 | .1660E 00 | .310 |
| 500.00 | 1040.00 | .3249E 03 | .3564E 00 | .1691E 00 | .310 |

# SUPERHEATED VAPOR

| P (PSIA) | T (°F) | H (BTU/LB) | S (BTU/LB-°F) | V (FT³/LB) | CP (BTU/LB-°F) |
|---|---|---|---|---|---|
| 700.00 | 60.00 | .6464E 01 | .1461E-01 | .1002E-01 | .957 |
| 700.00 | 80.00 | .1125E 02 | .2465E-01 | .1032E-01 | .984 |
| 700.00 | 100.00 | .1617E 02 | .3440E-01 | .1064E-01 | 1.012 |
| 700.00 | 120.00 | .2123E 02 | .4389E-01 | .1098E-01 | 1.038 |
| 700.00 | 140.00 | .2642E 02 | .5316E-01 | .1135E-01 | 1.068 |
| 700.00 | 160.00 | .3176E 02 | .6223E-01 | .1174E-01 | 1.094 |
| 700.00 | 180.00 | .3723E 02 | .7112E-01 | .1217E-01 | 1.120 |
| 700.00 | 200.00 | .4283E 02 | .7986E-01 | .1264E-01 | 1.150 |
| 700.00 | 220.00 | .4858E 02 | .8846E-01 | .1315E-01 | 1.178 |
| 700.00 | 240.00 | .5447E 02 | .9695E-01 | .1371E-01 | 1.208 |
| 700.00 | 260.00 | .6051E 02 | .1053E 00 | .1433E-01 | 1.240 |
| 700.00 | 280.00 | .6671E 02 | .1137E 00 | .1503E-01 | 1.276 |
| 700.00 | 300.00 | .7309E 02 | .1220E 00 | .1582E-01 | 1.312 |
| 700.00 | 320.00 | .7965E 02 | .1302E 00 | .1673E-01 | 1.358 |
| 700.00 | 340.00 | .8644E 02 | .1386E 00 | .1780E-01 | 1.414 |
| 700.00 | 360.00 | .9351E 02 | .1470E 00 | .1908E-01 | 1.478 |
| 700.00 | 380.00 | .1009E 03 | .1556E 00 | .2067E-01 | 1.600 |
| 700.00 | 400.00 | .1089E 03 | .1647E 00 | .2272E-01 | 1.780 |
| 700.00 | 420.00 | .1178E 03 | .1745E 00 | .2563E-01 | 2.200 |
| 700.00 | 440.00 | .1288E 03 | .1862E 00 | .3077E-01 | 2.640 |
| 700.00 | 460.00 | -.1445E 49 | -.8296E 48 | -.4006E 45 | ######## |
| 700.00 | 480.00 | -.8672E 49 | -.4978E 49 | -.2404E 46 | ######## |
| 700.00 | 500.00 | -.1590E 50 | -.9126E 49 | -.4407E 46 | ######## |
| 700.00 | 520.00 | -.2313E 50 | -.1327E 50 | -.6410E 46 | ######## |
| 700.00 | 540.00 | -.3035E 50 | -.1742E 50 | -.8413E 46 | ######## |
| 700.00 | 560.00 | .1768E 03 | .2349E 00 | .5844E-01 | .313 |
| 700.00 | 580.00 | .1831E 03 | .2409E 00 | .6263E-01 | .310 |
| 700.00 | 600.00 | .1893E 03 | .2468E 00 | .6682E-01 | .306 |
| 700.00 | 620.00 | .1954E 03 | .2525E 00 | .7061E-01 | .305 |
| 700.00 | 640.00 | .2015E 03 | .2582E 00 | .7440E-01 | .303 |
| 700.00 | 660.00 | .2076E 03 | .2636E 00 | .7798E-01 | .301 |
| 700.00 | 680.00 | .2136E 03 | .2690E 00 | .8155E-01 | .299 |
| 700.00 | 700.00 | .2196E 03 | .2741E 00 | .8493E-01 | .299 |
| 700.00 | 720.00 | .2256E 03 | .2793E 00 | .8830E-01 | .300 |
| 700.00 | 740.00 | .2316E 03 | .2843E 00 | .9151E-01 | .300 |
| 700.00 | 760.00 | .2376E 03 | .2893E 00 | .9472E-01 | .300 |
| 700.00 | 780.00 | .2436E 03 | .2941E 00 | .9777E-01 | .301 |
| 700.00 | 800.00 | .2496E 03 | .2990E 00 | .1008E 00 | .301 |
| 700.00 | 820.00 | .2556E 03 | .3037E 00 | .1037E 00 | .301 |
| 700.00 | 840.00 | .2616E 03 | .3084E 00 | .1067E 00 | .301 |
| 700.00 | 860.00 | .2676E 03 | .3130E 00 | .1095E 00 | .302 |
| 700.00 | 880.00 | .2737E 03 | .3175E 00 | .1123E 00 | .303 |
| 700.00 | 900.00 | .2798E 03 | .3220E 00 | .1151E 00 | .304 |
| 700.00 | 920.00 | .2858E 03 | .3265E 00 | .1178E 00 | .306 |
| 700.00 | 940.00 | .2920E 03 | .3308E 00 | .1205E 00 | .305 |
| 700.00 | 960.00 | .2981E 03 | .3352E 00 | .1231E 00 | .304 |
| 700.00 | 980.00 | .3043E 03 | .3395E 00 | .1257E 00 | .309 |
| 700.00 | 1000.00 | .3104E 03 | .3438E 00 | .1283E 00 | .314 |
| 700.00 | 1020.00 | .3166E 03 | .3480E 00 | .1309E 00 | .314 |
| 700.00 | 1040.00 | .3229E 03 | .3522E 00 | .1334E 00 | .314 |

| P (PSIA) | T (°F) | H (BTU/LB) | S (BTU/LB-°F) | V (FT³/LB) | CP (BTU/LB-°F) |
|---|---|---|---|---|---|
| 900.00 | 60.00 | .6464E 01 | .1461E-01 | .1002E-01 | .957 |
| 900.00 | 80.00 | .1125E 02 | .2465E-01 | .1032E-01 | .984 |
| 900.00 | 100.00 | .1617E 02 | .3440E-01 | .1064E-01 | 1.012 |
| 900.00 | 120.00 | .2123E 02 | .4389E-01 | .1099E-01 | 1.038 |
| 900.00 | 140.00 | .2642E 02 | .5316E-01 | .1135E-01 | 1.068 |
| 900.00 | 160.00 | .3176E 02 | .6223E-01 | .1174E-01 | 1.094 |
| 900.00 | 180.00 | .3723E 02 | .7112E-01 | .1217E-01 | 1.120 |
| 900.00 | 200.00 | .4283E 02 | .7986E-01 | .1264E-01 | 1.150 |
| 900.00 | 220.00 | .4858E 02 | .8846E-01 | .1315E-01 | 1.178 |
| 900.00 | 240.00 | .5447E 02 | .9695E-01 | .1371E-01 | 1.208 |
| 900.00 | 260.00 | .6051E 02 | .1053E 00 | .1433E-01 | 1.240 |
| 900.00 | 280.00 | .6671E 02 | .1137E 00 | .1503E-01 | 1.276 |
| 900.00 | 300.00 | .7309E 02 | .1220E 00 | .1582E-01 | 1.312 |
| 900.00 | 320.00 | .7965E 02 | .1302E 00 | .1673E-01 | 1.358 |
| 900.00 | 340.00 | .8644E 02 | .1386E 00 | .1780E-01 | 1.414 |
| 900.00 | 360.00 | .9351E 02 | .1470E 00 | .1908E-01 | 1.478 |
| 900.00 | 380.00 | .1009E 03 | .1556E 00 | .2067E-01 | 1.600 |
| 900.00 | 400.00 | .1089E 03 | .1647E 00 | .2272E-01 | 1.780 |
| 900.00 | 420.00 | .1178E 03 | .1745E 00 | .2563E-01 | 2.200 |
| 900.00 | 440.00 | .1288E 03 | .1862E 00 | .3077E-01 | 2.640 |
| 900.00 | 460.00 | -.1445E 49 | -.8296E 48 | -.4006E 45 | ######## |
| 900.00 | 480.00 | -.8672E 49 | -.4978E 49 | -.2404E 46 | ######## |
| 900.00 | 500.00 | -.1590E 50 | -.9126E 49 | -.4407E 46 | ######## |
| 900.00 | 520.00 | -.2313E 50 | -.1327E 50 | -.6410E 46 | ######## |
| 900.00 | 540.00 | -.3035E 50 | -.1742E 50 | -.8413E 46 | ######## |
| 900.00 | 560.00 | -.3758E 50 | -.2157E 50 | -.1042E 47 | ######## |
| 900.00 | 580.00 | -.4481E 50 | -.2572E 50 | -.1242E 47 | ######## |
| 900.00 | 600.00 | -.5203E 50 | -.2987E 50 | -.1442E 47 | ######## |
| 900.00 | 620.00 | .1898E 03 | .2454E 00 | .4743E-01 | .322 |
| 900.00 | 640.00 | .1962E 03 | .2513E 00 | .5019E-01 | .321 |
| 900.00 | 660.00 | .2026E 03 | .2570E 00 | .5298E-01 | .317 |
| 900.00 | 680.00 | .2089E 03 | .2627E 00 | .5577E-01 | .313 |
| 900.00 | 700.00 | .2152E 03 | .2681E 00 | .5850E-01 | .311 |
| 900.00 | 720.00 | .2215E 03 | .2735E 00 | .6123E-01 | .310 |
| 900.00 | 740.00 | .2277E 03 | .2787E 00 | .6385E-01 | .310 |
| 900.00 | 760.00 | .2339E 03 | .2839E 00 | .6648E-01 | .310 |
| 900.00 | 780.00 | .2401E 03 | .2889E 00 | .6897E-01 | .309 |
| 900.00 | 800.00 | .2463E 03 | .2939E 00 | .7146E-01 | .307 |
| 900.00 | 820.00 | .2524E 03 | .2987E 00 | .7385E-01 | .307 |
| 900.00 | 840.00 | .2586E 03 | .3035E 00 | .7623E-01 | .307 |
| 900.00 | 860.00 | .2648E 03 | .3082E 00 | .7852E-01 | .309 |
| 900.00 | 880.00 | .2709E 03 | .3128E 00 | .8081E-01 | .311 |
| 900.00 | 900.00 | .2771E 03 | .3174E 00 | .8303E-01 | .312 |
| 900.00 | 920.00 | .2833E 03 | .3220E 00 | .8524E-01 | .312 |
| 900.00 | 940.00 | .2895E 03 | .3264E 00 | .8739E-01 | .310 |
| 900.00 | 960.00 | .2958E 03 | .3308E 00 | .8953E-01 | .308 |
| 900.00 | 980.00 | .3020E 03 | .3352E 00 | .9162E-01 | .313 |
| 900.00 | 1000.00 | .3082E 03 | .3395E 00 | .9371E-01 | .318 |
| 900.00 | 1020.00 | .3145E 03 | .3438E 00 | .9574E-01 | .318 |
| 900.00 | 1040.00 | .3208E 03 | .3480E 00 | .9777E-01 | .318 |

# SUPERHEATED VAPOR

| P (PSIA) | T (°F) | H (BTU/LB) | S (BTU/LB-°F) | V (FT³/LB) | CP (BTU/LB-°F) |
|---|---|---|---|---|---|
| 1100.00 | 60.00 | .6464E 01 | .1461E-01 | .1002E-01 | .957 |
| 1100.00 | 80.00 | .1125E 02 | .2465E-01 | .1032E-01 | .984 |
| 1100.00 | 100.00 | .1617E 02 | .3440E-01 | .1064E-01 | 1.012 |
| 1100.00 | 120.00 | .2123E 02 | .4389E-01 | .1098E-01 | 1.038 |
| 1100.00 | 140.00 | .2642E 02 | .5316E-01 | .1135E-01 | 1.068 |
| 1100.00 | 160.00 | .3176E 02 | .6223E-01 | .1174E-01 | 1.094 |
| 1100.00 | 180.00 | .3723E 02 | .7112E-01 | .1217E-01 | 1.120 |
| 1100.00 | 200.00 | .4283E 02 | .7986E-01 | .1264E-01 | 1.150 |
| 1100.00 | 220.00 | .4858E 02 | .8846E-01 | .1315E-01 | 1.178 |
| 1100.00 | 240.00 | .5447E 02 | .9695E-01 | .1371E-01 | 1.208 |
| 1100.00 | 260.00 | .6051E 02 | .1053E 00 | .1433E-01 | 1.240 |
| 1100.00 | 280.00 | .6671E 02 | .1137E 00 | .1503E-01 | 1.276 |
| 1100.00 | 300.00 | .7309E 02 | .1220E 00 | .1582E-01 | 1.312 |
| 1100.00 | 320.00 | .7965E 02 | .1302E 00 | .1673E-01 | 1.358 |
| 1100.00 | 340.00 | .8644E 02 | .1386E 00 | .1780E-01 | 1.414 |
| 1100.00 | 360.00 | .9351E 02 | .1470E 00 | .1908E-01 | 1.478 |
| 1100.00 | 380.00 | .1009E 03 | .1556E 00 | .2067E-01 | 1.600 |
| 1100.00 | 400.00 | .1089E 03 | .1647E 00 | .2272E-01 | 1.780 |
| 1100.00 | 420.00 | .1178E 03 | .1745E 00 | .2563E-01 | 2.200 |
| 1100.00 | 440.00 | .1288E 03 | .1862E 00 | .3077E-01 | 2.640 |
| 1100.00 | 460.00 | -.1445E 49 | -.8296E 48 | -.4006E 45 | ######## |
| 1100.00 | 480.00 | -.8672E 49 | -.4978E 49 | -.2404E 46 | ######## |
| 1100.00 | 500.00 | -.1590E 50 | -.9126E 49 | -.4407E 46 | ######## |
| 1100.00 | 520.00 | -.2313E 50 | -.1327E 50 | -.6410E 46 | ######## |
| 1100.00 | 540.00 | -.3035E 50 | -.1742E 50 | -.8413E 46 | ######## |
| 1100.00 | 560.00 | -.3758E 50 | -.2157E 50 | -.1042E 47 | ######## |
| 1100.00 | 580.00 | -.4481E 50 | -.2572E 50 | -.1242E 47 | ######## |
| 1100.00 | 600.00 | -.5203E 50 | -.2987E 50 | -.1442E 47 | ######## |
| 1100.00 | 620.00 | -.5926E 50 | -.3401E 50 | -.1643E 47 | ######## |
| 1100.00 | 640.00 | -.6649E 50 | -.3816E 50 | -.1843E 47 | ######## |
| 1100.00 | 660.00 | .1990E 03 | .2523E 00 | .3825E-01 | .322 |
| 1100.00 | 680.00 | .2055E 03 | .2581E 00 | .4038E-01 | .319 |
| 1100.00 | 700.00 | .2119E 03 | .2635E 00 | .4254E-01 | .317 |
| 1100.00 | 720.00 | .2183E 03 | .2690E 00 | .4469E-01 | .315 |
| 1100.00 | 740.00 | .2246E 03 | .2743E 00 | .4680E-01 | .315 |
| 1100.00 | 760.00 | .2309E 03 | .2796E 00 | .4891E-01 | .315 |
| 1100.00 | 780.00 | .2372E 03 | .2847E 00 | .5094E-01 | .313 |
| 1100.00 | 800.00 | .2435E 03 | .2897E 00 | .5296E-01 | .311 |
| 1100.00 | 820.00 | .2498E 03 | .2946E 00 | .5491E-01 | .311 |
| 1100.00 | 840.00 | .2560E 03 | .2996E 00 | .5686E-01 | .311 |
| 1100.00 | 860.00 | .2623E 03 | .3043E 00 | .5873E-01 | .314 |
| 1100.00 | 880.00 | .2685E 03 | .3090E 00 | .6060E-01 | .316 |
| 1100.00 | 900.00 | .2748E 03 | .3136E 00 | .6242E-01 | .316 |
| 1100.00 | 920.00 | .2810E 03 | .3183E 00 | .6423E-01 | .316 |
| 1100.00 | 940.00 | .2874E 03 | .3227E 00 | .6599E-01 | .314 |
| 1100.00 | 960.00 | .2937E 03 | .3272E 00 | .6774E-01 | .312 |
| 1100.00 | 980.00 | .3000E 03 | .3316E 00 | .6945E-01 | .316 |
| 1100.00 | 1000.00 | .3062E 03 | .3360E 00 | .7117E-01 | .320 |
| 1100.00 | 1020.00 | .3126E 03 | .3403E 00 | .7282E-01 | .320 |
| 1100.00 | 1040.00 | .3190E 03 | .3446E 00 | .7448E-01 | .321 |

## SUPERHEATED VAPOR

| P (PSIA) | T (°F) | H (BTU/LB) | S (BTU/LB-°F) | V (FT³/LB) | CP (BTU/LB-°F) |
|---|---|---|---|---|---|
| 1300.00 | 60.00 | .6464E 01 | .1461E-01 | .1002E-01 | .957 |
| 1300.00 | 80.00 | .1125E 02 | .2465E-01 | .1032E-01 | .984 |
| 1300.00 | 100.00 | .1617E 02 | .3440E-01 | .1064E-01 | 1.012 |
| 1300.00 | 120.00 | .2123E 02 | .4399E-01 | .1098E-01 | 1.038 |
| 1300.00 | 140.00 | .2642E 02 | .5316E-01 | .1135E-01 | 1.068 |
| 1300.00 | 160.00 | .3176E 02 | .6223E-01 | .1174E-01 | 1.094 |
| 1300.00 | 180.00 | .3723E 02 | .7112E-01 | .1217E-01 | 1.120 |
| 1300.00 | 200.00 | .4283E 02 | .7986E-01 | .1264E-01 | 1.150 |
| 1300.00 | 220.00 | .4858E 02 | .8846E-01 | .1315E-01 | 1.178 |
| 1300.00 | 240.00 | .5447E 02 | .9695E-01 | .1371E-01 | 1.208 |
| 1300.00 | 260.00 | .6051E 02 | .1053E 00 | .1433E-01 | 1.240 |
| 1300.00 | 280.00 | .6671E 02 | .1137E 00 | .1503E-01 | 1.276 |
| 1300.00 | 300.00 | .7309E 02 | .1220E 00 | .1582E-01 | 1.312 |
| 1300.00 | 320.00 | .7965E 02 | .1302E 00 | .1673E-01 | 1.358 |
| 1300.00 | 340.00 | .8644E 02 | .1386E 00 | .1780E-01 | 1.414 |
| 1300.00 | 360.00 | .9351E 02 | .1470E 00 | .1908E-01 | 1.478 |
| 1300.00 | 380.00 | .1009E 03 | .1556E 00 | .2067E-01 | 1.600 |
| 1300.00 | 400.00 | .1089E 03 | .1647E 00 | .2272E-01 | 1.700 |
| 1300.00 | 420.00 | .1178E 03 | .1745E 00 | .2563E-01 | 2.200 |
| 1300.00 | 440.00 | .1288E 03 | .1862E 00 | .3077E-01 | 2.640 |
| 1300.00 | 460.00 | -.1445E 49 | -.8296E 48 | -.4006E 45 | ######## |
| 1300.00 | 480.00 | -.8672E 49 | -.4978E 49 | -.2404E 46 | ######## |
| 1300.00 | 500.00 | -.1590E 50 | -.9126E 49 | -.4407E 46 | ######## |
| 1300.00 | 520.00 | -.2313E 50 | -.1327E 50 | -.6410E 46 | ######## |
| 1300.00 | 540.00 | -.3035E 50 | -.1742E 50 | -.8413E 46 | ######## |
| 1300.00 | 560.00 | -.3758E 50 | -.2157E 50 | -.1042E 47 | ######## |
| 1300.00 | 580.00 | -.4481E 50 | -.2572E 50 | -.1242E 47 | ######## |
| 1300.00 | 600.00 | -.5203E 50 | -.2987E 50 | -.1442E 47 | ######## |
| 1300.00 | 620.00 | -.5926E 50 | -.3401E 50 | -.1643E 47 | ######## |
| 1300.00 | 640.00 | -.6649E 50 | -.3816E 50 | -.1843E 47 | ######## |
| 1300.00 | 660.00 | -.7371E 50 | -.4231E 50 | -.2043E 47 | ######## |
| 1300.00 | 680.00 | -.8094E 50 | -.4646E 50 | -.2244E 47 | ######## |
| 1300.00 | 700.00 | -.8817E 50 | -.5061E 50 | -.2444E 47 | ######## |
| 1300.00 | 720.00 | .2160E 03 | .2659E 00 | .3870E-01 | .315 |
| 1300.00 | 740.00 | .2223E 03 | .2712E 00 | .4037E-01 | .315 |
| 1300.00 | 760.00 | .2286E 03 | .2765E 00 | .4203E-01 | .315 |
| 1300.00 | 780.00 | .2349E 03 | .2815E 00 | .4367E-01 | .314 |
| 1300.00 | 800.00 | .2412E 03 | .2866E 00 | .4531E-01 | .313 |
| 1300.00 | 820.00 | .2476E 03 | .2915E 00 | .4693E-01 | .313 |
| 1300.00 | 840.00 | .2539E 03 | .2965E 00 | .4854E-01 | .313 |
| 1300.00 | 860.00 | .2601E 03 | .3013E 00 | .5011E-01 | .316 |
| 1300.00 | 880.00 | .2664E 03 | .3061E 00 | .5169E-01 | .318 |
| 1300.00 | 900.00 | .2728E 03 | .3107E 00 | .5323E-01 | .318 |
| 1300.00 | 920.00 | .2791E 03 | .3154E 00 | .5477E-01 | .318 |
| 1300.00 | 940.00 | .2855E 03 | .3199E 00 | .5627E-01 | .317 |
| 1300.00 | 960.00 | .2918E 03 | .3244E 00 | .5777E-01 | .316 |
| 1300.00 | 980.00 | .2982E 03 | .3288E 00 | .5924E-01 | .318 |
| 1300.00 | 1000.00 | .3045E 03 | .3333E 00 | .6071E-01 | .320 |
| 1300.00 | 1020.00 | .3109E 03 | .3376E 00 | .6214E-01 | .321 |
| 1300.00 | 1040.00 | .3173E 03 | .3419E 00 | .6357E-01 | .323 |

## SUPERHEATED VAPOR

| P (PSIA) | T (°F) | H (BTU/LB) | S (BTU/LB-°F) | V ($FT^3$/LB) | CP (BTU/LB-°F) |
|---|---|---|---|---|---|
| 1500.00 | 60.00 | .6464E 01 | .1461E-01 | .1002E-01 | .957 |
| 1500.00 | 80.00 | .1125E 02 | .2465E-01 | .1032E-01 | .984 |
| 1500.00 | 100.00 | .1617E 02 | .3440E-01 | .1064E-01 | 1.012 |
| 1500.00 | 120.00 | .2123E 02 | .4389E-01 | .1098E-01 | 1.038 |
| 1500.00 | 140.00 | .2642E 02 | .5316E-01 | .1135E-01 | 1.068 |
| 1500.00 | 160.00 | .3176E 02 | .6223E-01 | .1174E-01 | 1.094 |
| 1500.00 | 180.00 | .3723E 02 | .7112E-01 | .1217E-01 | 1.120 |
| 1500.00 | 200.00 | .4283E 02 | .7986E-01 | .1264E-01 | 1.150 |
| 1500.00 | 220.00 | .4858E 02 | .8846E-01 | .1315E-01 | 1.178 |
| 1500.00 | 240.00 | .5447E 02 | .9695E-01 | .1371E-01 | 1.208 |
| 1500.00 | 260.00 | .6051E 02 | .1053E 00 | .1433E-01 | 1.240 |
| 1500.00 | 280.00 | .6671E 02 | .1137E 00 | .1503E-01 | 1.276 |
| 1500.00 | 300.00 | .7309E 02 | .1220E 00 | .1582E-01 | 1.312 |
| 1500.00 | 320.00 | .7965E 02 | .1302E 00 | .1673E-01 | 1.358 |
| 1500.00 | 340.00 | .8644E 02 | .1386E 00 | .1780E-01 | 1.414 |
| 1500.00 | 360.00 | .9351E 02 | .1470E 00 | .1908E-01 | 1.478 |
| 1500.00 | 380.00 | .1009E 03 | .1556E 00 | .2067E-01 | 1.600 |
| 1500.00 | 400.00 | .1089E 03 | .1647E 00 | .2272E-01 | 1.780 |
| 1500.00 | 420.00 | .1178E 03 | .1745E 00 | .2563E-01 | 2.200 |
| 1500.00 | 440.00 | .1288E 03 | .1862E 00 | .3077E-01 | 2.640 |
| 1500.00 | 460.00 | -.1445E 49 | -.8296E 48 | -.4006E 45 | ######## |
| 1500.00 | 480.00 | -.8672E 49 | -.4978E 49 | -.2404E 46 | ######## |
| 1500.00 | 500.00 | -.1590E 50 | -.9126E 49 | -.4407E 46 | ######## |
| 1500.00 | 520.00 | -.2313E 50 | -.1327E 50 | -.6410E 46 | ######## |
| 1500.00 | 540.00 | -.3035E 50 | -.1742E 50 | -.8413E 46 | ######## |
| 1500.00 | 560.00 | -.3758E 50 | -.2157E 50 | -.1042E 47 | ######## |
| 1500.00 | 580.00 | -.4481E 50 | -.2572E 50 | -.1242E 47 | ######## |
| 1500.00 | 600.00 | -.5203E 50 | -.2987E 50 | -.1442E 47 | ######## |
| 1500.00 | 620.00 | -.5926E 50 | -.3401E 50 | -.1643E 47 | ######## |
| 1500.00 | 640.00 | -.6649E 50 | -.3816E 50 | -.1843E 47 | ######## |
| 1500.00 | 660.00 | -.7371E 50 | -.4231E 50 | -.2043E 47 | ######## |
| 1500.00 | 680.00 | -.8094E 50 | -.4646E 50 | -.2244E 47 | ######## |
| 1500.00 | 700.00 | -.8817E 50 | -.5061E 50 | -.2444E 47 | ######## |
| 1500.00 | 720.00 | -.9539E 50 | -.5475E 50 | -.2644E 47 | ######## |
| 1500.00 | 740.00 | -.1026E 51 | -.5890E 50 | -.2844E 47 | ######## |
| 1500.00 | 760.00 | -.1098E 51 | -.6305E 50 | -.3045E 47 | ######## |
| 1500.00 | 780.00 | .2326E 03 | .2784E 00 | .3641E-01 | .315 |
| 1500.00 | 800.00 | .2390E 03 | .2835E 00 | .3766E-01 | .315 |
| 1500.00 | 820.00 | .2453E 03 | .2885E 00 | .3895E-01 | .315 |
| 1500.00 | 840.00 | .2517E 03 | .2934E 00 | .4023E-01 | .315 |
| 1500.00 | 860.00 | .2580E 03 | .2982E 00 | .4150E-01 | .318 |
| 1500.00 | 880.00 | .2644E 03 | .3031E 00 | .4277E-01 | .320 |
| 1500.00 | 900.00 | .2708E 03 | .3078E 00 | .4404E-01 | .320 |
| 1500.00 | 920.00 | .2772E 03 | .3125E 00 | .4531E-01 | .320 |
| 1500.00 | 940.00 | .2836E 03 | .3170E 00 | .4656E-01 | .320 |
| 1500.00 | 960.00 | .2900E 03 | .3216E 00 | .4780E-01 | .320 |
| 1500.00 | 980.00 | .2964E 03 | .3260E 00 | .4903E-01 | .320 |
| 1500.00 | 1000.00 | .3028E 03 | .3305E 00 | .5025E-01 | .320 |
| 1500.00 | 1020.00 | .3093E 03 | .3349E 00 | .5146E-01 | .322 |
| 1500.00 | 1040.00 | .3157E 03 | .3392E 00 | .5266E-01 | .325 |

## APPENDIX D

## NOMOGRAM FOR SIMPLE PAYBACK PERIOD OF BOTTOMING CYCLE SYSTEM

## EXPRESSIONS FOR DEVELOPMENT OF PAYBACK PERIOD NOMOGRAM

Definitions:

| | | |
|---|---|---|
| DC | = | base diesel engine cost ($) |
| BC | = | bottoming cycle cost ($) |
| BCO | = | bottoming cycle power output (hp) |
| $/hp | = | cost per additional horsepower above base diesel engine rating |
| $BSFC_*$ | = | brake specific fuel consumption of engine (lb/hp-hr) |
| $MPG_*$ | = | fuel economy of engine (mile/gal) |

*Subscript denoting engine configuration as follows:

| | | |
|---|---|---|
| o | = | reference diesel engine (TC/A engine from which others are keyed) |
| D | = | base diesel engine |
| BC | = | compound engine (diesel + bottoming cycle) |
| miles/yr | = | annual vehicle mileage |
| $/gal | = | fuel cost |

Since the BSFC and MPG are keyed to the reference diesel engine (TC/A) where $BSFC_o = 0.310$ lb/hp-hr and $MPG_o = 5.75$ mile/gal, then the fuel usage of any engine configuration can be determined as follows:

- Fuel Usage of Base Diesel Engine (gal/yr) $= \frac{\text{miles/yr}}{MPG_D}$

$$= \frac{\text{miles/yr}}{\left(\frac{BSFC_o}{BSFC_D}\right)(MPG_o)}.$$

Likewise,

- Fuel Usage of Compound Engine (gal/yr) $= \frac{\text{miles/yr}}{MPG_{BC}}$

$$= \frac{\text{miles/yr}}{\left(\frac{BSFC_o}{BSFC_{BC}}\right)(MPG_o)}.$$

In both the above expressions for fuel usage,

$$(BSFC_o)(MPG_o) = (0.310)(5.75) = 1.7825.$$

So:

Fuel Savings (gal/yr) = Fuel Usage of Diesel Engine - Fuel Usage of Compound Engine

$$= \frac{\text{miles/yr}}{\left(\frac{1.7825}{BSFC_D}\right)} - \frac{\text{miles/yr}}{\left(\frac{1.7825}{BSFC_{BC}}\right)}$$

$$= \frac{(\text{miles/yr})(BSFC_D - BSFC_{BC})}{1.7825}.$$

The Annual Fuel Cost Savings ($/yr) then becomes the product of Fuel Savings (gal/yr) and Fuel Cost ($/gal) or,

$$\frac{(\text{miles/yr})(BSFC_D - BSFC_{BC})(\$/\text{gal})}{1.7825}.$$

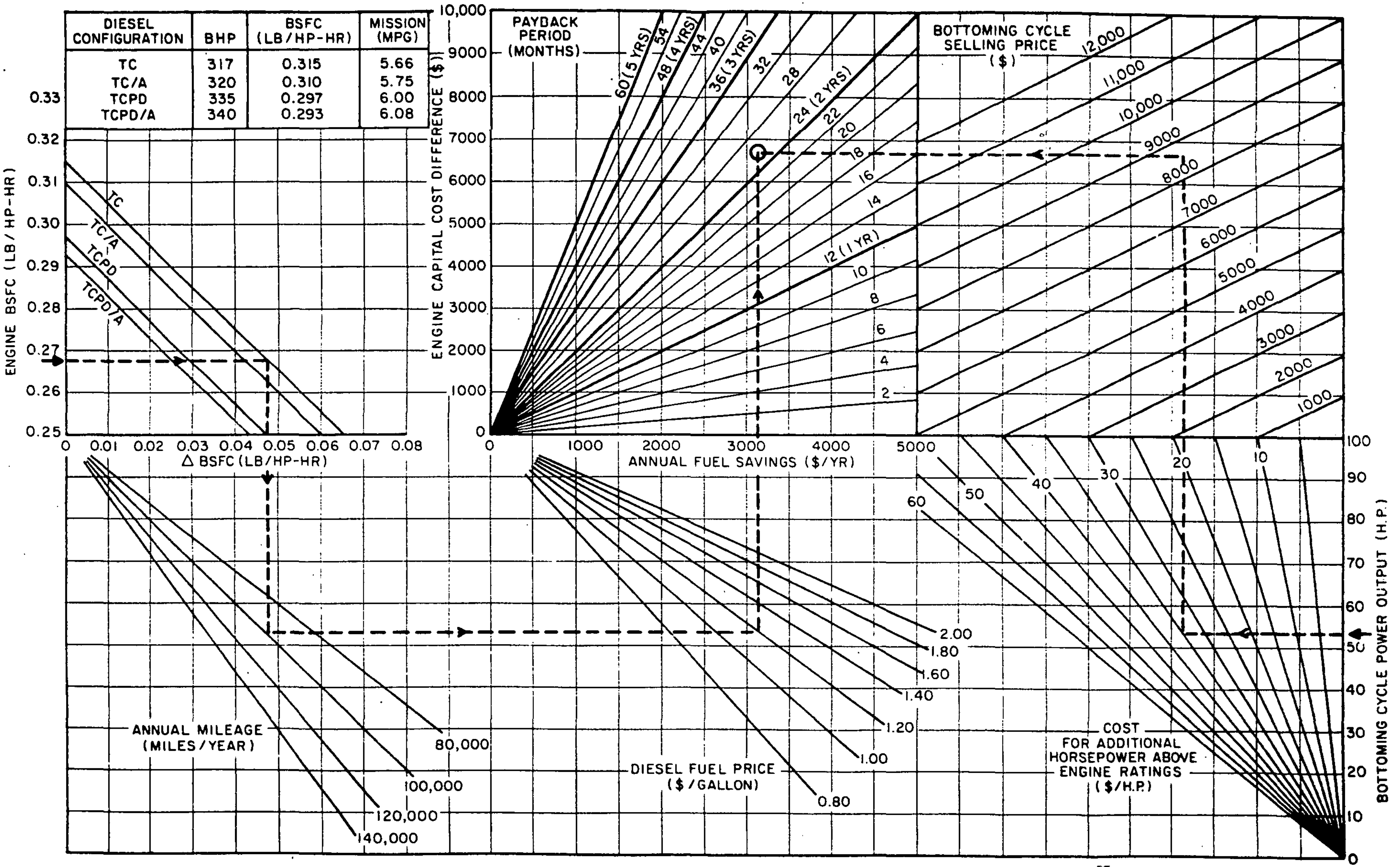
The Engine Capital Cost Difference is the sum of the Base Diesel Engine Cost and the Bottoming Cycle Cost minus the Diesel Engine Cost at the compound engine rating. This is expressed as follows:

Engine Capital Cost Difference ($) = DC + BC - (DC + BCO x $/hp)

= BC - (BCO)($/hp).

The Payback Period is defined as the Engine Capital Cost Difference divided by the Annual Fuel Cost Savings of the compound engine and is expressed as:

$$\text{Payback Period (yr)} = \frac{(BC - BCO \times \$/\text{hp})(1.7825)}{(\text{miles/yr})(\$/\text{gal})(BSFC_D - BSFC_{BC})}.$$




| DIESEL CONFIGURATION | BHP | BSFC (LB/HP-HR) | MISSION (MPG) |
|---|---|---|---|
| TC | 317 | 0.315 | 5.66 |
| TC/A | 320 | 0.310 | 5.75 |
| TCPD | 335 | 0.297 | 6.00 |
| TCPD/A | 340 | 0.293 | 6.08 |

**Nomogram for Determination of Payback Period for a Truck Bottoming Cycle System**

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15. Supplementary Notes

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16. Abstract

A system analysis and preliminary design were conducted for an organic Rankine-cycle system to bottom the high-temperature waste heat of an "adiabatic" diesel engine. The bottoming cycle is a compact package that includes a cylindrical air-cooled condenser-regenerator module and other unique features. The bottoming cycle output is 56 horsepower at design point conditions when compounding the reference 317 horsepower turbocharged (TC) diesel engine with a resulting brake specific fuel consumption of 0.268 lb/hp-hr for the compound engine. The bottoming cycle when applied to a turbocompound (TCPD) diesel delivers a compound engine brake specific fuel consumption of 0.258 lb/hp-hr. This system for heavy-duty transport applications uses the organic working fluid RC-1, which is a mixture of 60 mole percent pentafluorobenzene (PFB) and 40 mole percent hexafluorobenzene (HFB). Included in these 1983 work efforts was the thermal stability testing of the RC-1 organic fluid in a dynamic fluid test loop that simulates the operation of Rankine-cycle. More than 1600 hours of operation were completed with results showing that the RC-1 is thermally stable up to 900°F. This report describes the work performed for one of the multiple contracts awarded under the Department of Energy's Heavy-Duty Transport Technology Program. Related reports in the area of alternative power cycles for waste-heat recovery from the exhaust of adiabatic diesel engines are NASA CR-168255 (Steam Rankine) and NASA CR-168257 (Brayton).

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