Potassium-Rankine Power Conversion Subsystem Modeling for Nuclear Electric Propulsion (Task Order 18)

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NASA
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
FOREWORD

Systems engineering efforts initiated by NASA's Lewis Research Center (LeRC) in FY92 under RTOP 593-72, for Nuclear Electric Propulsion (NEP), have enabled the development of detailed mathematical (computer) models to predict NEP subsystem performance and mass. The computer models are intended to help provide greater depth to NEP subsystem (and system) modeling, required for more accurately verifying performance projections and assessing the impact of specific technology developments.

The following subsystem models have been developed:
1) liquid-metal-cooled pin-type, and
2) gas-cooled NERVA (Nuclear Engine for Rocket Vehicle Applications)-derived for reactor/shield;
3) Potassium-Rankine, and
4) Brayton for power conversion;
5) heat rejection general model (includes direct Brayton, pumped loop Brayton, and shear flow condenser (Potassium-Rankine);
6) power management and distribution (PMAD) general model; and
7) ion electric engine, and
8) magnetoplasmadynamic thruster for the electric propulsion subsystem.

These subsystem models for NEP were authored by the Oak Ridge National Laboratory (ORNL) for the reactor (NASA CR-191133), by the Rocketdyne Division of Rockwell International for Potassium-Rankine (NASA CR-191134) and Brayton (NASA CR-191135) power conversion, heat rejection (NASA CR-191132), and power management and distribution (NASA CR-191136), and by Sverdrup Technology for the thrusters (NASA CR-191137).

At the time of this writing, these eight VAX/FORTRAN source and executable codes are resident on one of LeRC’s Scientific VAX computers.

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</table>
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1.0 SUMMARY

NASA LeRC is currently developing a Fortran based model of a complete nuclear electric propulsion (NEP) vehicle that would be used for piloted and cargo missions to the Moon or Mars. The proposed vehicle design will use either a Brayton or K-Rankine power conversion cycle to generate electric power. Two thruster types are also being studied, ion and MPD. In support of this NEP model, Rocketdyne is developing power conversion, heat rejection, and power management and distribution models. These models will be incorporated into the NEP vehicle model and be driven by a master module to be written by NASA LeRC. The purpose of this report is to document the K-Rankine Power Conversion Subsystem (PCS) model and component models.

The K-Rankine PCS model is designed to provide performance characteristics based on externally defined parameters such as turbine inlet temperature, condensing temperature, etc. These characteristics will then be used by the master NEP module to determine the NEP vehicle performance characteristics and to conduct system level trades. It is intended that the models developed during this study be used only for conceptual design studies requiring "ballpark" performance estimates.
2.0 INTRODUCTION

The potassium-Rankine power conversion subsystem model presented in this report was developed to evaluate potential NEP concepts which utilize a potassium-Rankine PCS. The model is valid for turbine inlet temperatures ranging from 1200 K to 1600 K, turbine inlet to condenser temperature ratios ranging from 1.25 to 1.6, power levels ranging from 100 kWe to 10 MWe, and lifetimes ranging from 2 to 10 years. The subsystem modeled is shown in Figure 1. This configuration was chosen based on past experience developed during the Multimegawatt program and the Ultra High Power System study. Inherent assumptions contained in this model are that the heat source is a lithium cooled reactor and that a heat pipe radiator is available for heat rejection. It should be noted, that this model has its roots with the ALKASYS program presented in reference 1, but is many generations removed. Rocketdyne has extensively modified its version of this code that only mild similarities, if any, exists between this code and the one presented in Reference 1.

The potassium-Rankine model subroutines are encoded in Fortran 77 and located on the accompanying computer disk. Table 1 lists all files contained on the disk and Figure 2 shows how they interrelate. These include eleven fortran source code files which can be distinguished by the file extension "FOR", one object file titled "CORELATE.OBJ", one input file entitled "KRANK.IN", and the executable file "KRANK.EXE". The fortran source code "CORELATE.FOR" has not been included since it contains proprietary information as will be further explained later.

Generally, the user runs a case in the following way; (1) the user creates an input file with the desired input data, (2) KRANK is typed to run the case, (3) the generated output is examined. It is best to create a new input file by editing an existing input file. This can be accomplished with any ASCII editor. The input file "KRANK.IN" is available for this purpose. The user may wish to view the input file "KRANK.IN" and note its form. After creating an input file, the user types KRANK to start a run. "KRANK.EXE" is an executable file that reads the input file KRANK.IN, directs the ensuing computations, then directs the output to KRANK.OUT. This file is temporary; the NEP system driver to be written by NASA LeRC will replace it.
The program structure is illustrated in Figures 2 and 3. The K- Rankine submodule, "KRANK.FOR", receives the input data, directs the ensuing computations, then directs the output data back to the data processor. The temporary files "MNRANK.FOR", "PRINP.FOR", and "PROUT.FOR" act as the NEP system driver to be written by NASA LeRC. These files read the data from "KRANK.IN", send it to "KRANK.FOR", then receive the output data from "KRANK.FOR" and send it to the output file "KRANK.OUT".

The input data is contained in a 61 element array entitled "PRIN", and the output data is contained in a 526 element array entitled "PROUT". Element definitions and cross references for the input and output arrays are given in the appendices.

3.0 GENERAL DESCRIPTION OF POWER SYSTEM MODEL

The KRANK program calculates performance and design characteristics and mass estimates for the major components which make up the potassium-Rankine power conversion subsystem. Design and performance characteristics are determined by
detailed engineering procedures rather than by empirical algorithms. Mass estimates are developed using basic design principles augmented in some cases by empirical coefficients.

Table 1. Files Included on Enclosed Diskette

<table>
<thead>
<tr>
<th>File Name</th>
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<tbody>
<tr>
<td>BOILER.FOR</td>
</tr>
<tr>
<td>KRANK.FOR</td>
</tr>
<tr>
<td>KTAGEN.FOR</td>
</tr>
<tr>
<td>KTHRMO.FOR</td>
</tr>
<tr>
<td>MNRANK.FOR</td>
</tr>
<tr>
<td>PIPING.FOR</td>
</tr>
<tr>
<td>PRINP.FOR</td>
</tr>
<tr>
<td>PROP.FOR</td>
</tr>
<tr>
<td>PROUT.FOR</td>
</tr>
<tr>
<td>PUMP.FOR</td>
</tr>
<tr>
<td>STRENGTH.FOR</td>
</tr>
<tr>
<td>SYSTEM.FOR</td>
</tr>
<tr>
<td>CORELATE.OBJ</td>
</tr>
<tr>
<td>KRANK.IN</td>
</tr>
<tr>
<td>KRANK.EXE</td>
</tr>
</tbody>
</table>

In the potassium-Rankine power conversion subsystem, shown in Figure 1, the
The principal flow of potassium vapor leaving the boiler is to the main turbine. A relatively small stream is diverted to the turbine of the turbo feed pump. The main turbine is divided into high-pressure stages and low-pressure stages. Upon exhausting the high-pressure stages, the wet potassium vapor is routed through a reheater to re-vaporize entrained moisture and re-superheat the vapor stream, upon which the vapor stream leaving the reheater is routed to the low-pressure turbine. Upon exhausting from the low-pressure turbine stages, the vapor is condensed in a shear flow controlled condenser. Latent heat of vaporization is rejected by the condenser to the heat rejection subsystem. Condensate leaving the condenser is directed to a Rotary Fluid Management Device (RFMD). The RFMD provides two phase fluid management and pressurizes the condensate to ensure that sufficient net positive suction head (NPSH) is provided to the main turbo-feed pump. The turbo-feed pump re-pressurizes the liquid potassium received from the RFMD and directs it to the boiler.

The thermodynamic analysis of the potassium-Rankine cycle consists of determining energy and mass balances of the working fluid around each of the cycle components and the entire cycle by using specifications for equipment per-
formance and thermodynamic and transport properties for the working fluid. These properties are calculated in subroutines developed from data presented in Reference 2. The energy and mass balances are first calculated on a per mass basis of prime vapor and are subsequently adjusted to the full size system.

3.1 BOILER AND REHEATER

Boiler and Reheater mass and performance are calculated using essentially the same algorithms. The boiler/reheater algorithm is based on a shell and tube once through boiler with liquid lithium on the shell side and potassium on the tube side. For simplicity, straight tubes are assumed. The tubes contain twisted tape inserts, with a 3:1 pitch to diameter ratio, for improved boiling characteristics. In order to keep boiler/reheater mass to a minimum and still retain good heat transfer, the tube to tube pitch to diameter ratio was set to a low value of 1.375 thus eliminating unnecessary lithium inventory.

For calculational purposes, the boiler/reheater is divided into three sections; preheater, boiling, and superheater. The preheater is where liquid potassium entering the boiler is heated to saturation conditions. Note that the reheater does not have a preheating section. The boiling section is the section of the tube in which the liquid is transformed into a vapor. The superheater is where additional thermal energy is added to the saturated vapor.

The boiler/reheater computation is accomplished as follows. Based on an assumed number of tubes and a user input tube diameter, the tube sections are sized (length) based on heat transfer considerations. Next, pressure losses are determined and compared to a user defined maximum allowed pressure loss. If the pressure losses deviate too greatly from the maximum allowed, then the number of tubes is adjusted accordingly and the computation is repeated.

Shell side heat transfer is based on Dwyer's equation for liquid metals flowing parallel through equilateral triangular tube bundles (Ref. 3). Preheater heat transfer is based on Dwyer's equation for liquid metals in circular pipes (Ref. 3). Boiling heat transfer is based on single tube boiler, boiling potassium experiments (Ref. 4). While superheater heat transfer is based on Petukhov's equation for circular pipes (Ref. 5).
Pressure losses for the shell side and the tube side of the preheater and the superheater are based on Darcy's friction equation (Ref. 6). Pressure losses in the boiling section of the tubes is based on procedures outlined in Reference 7.

Boiler/Reheater weights are determined by querying the materials strength algorithm for the creep strength and density of the appropriate material. The materials strength algorithm determines the correct material to use based on user inputs and primary coolant temperatures. From these parameters, the Boiler/Reheater algorithm sizes and determines the weights of the various components which make up the Boiler/Reheater.

Application note: The potential for a temperature cross occurs when the user attempts to use too close of an approach temperature. A temperature cross will cause a run time error and terminate the program. If a temperature cross should occur, decreasing the turbine inlet temperature should alleviate the problem.

Furthermore, the potential for a run time error will occur if too large a boiler and/or reheater pressure loss(es) are specified by the user. If too large a pressure loss is specified, a negative pressure will be tabulated for tube pressure. This usually cause an error in the KTHRMO subroutine. To remedy this, the specified pressure losses should be decreased.

3.2 TURBINES

The main power turbine is a multi-stage axial reaction turbine. The stages are divided roughly in half to form a high-pressure and a low-pressure turbine on the same shaft. Vapor reheat is implemented between the high-pressure and low-pressure turbines to maintain a minimum vapor quality within the turbine stages. The algorithm for determining number of turbine stages and conditions at each stage are very similar to those used in Reference 1. It has been found by Rocketdyne experience that these algorithms produce results which agree reasonably well with more detailed turbine calculations.

The input values affecting the turbine model along with their recommended values are given in the appendices. From these parameters, number of stages,
efficiency and thermodynamic conditions at each stage, and turbine mass are developed.

A basic assumption in determining the number of turbine stages required is that equal temperature drops occur across each stage. The turbine stage computation begins by first determining the last-stage enthalpy drop to produce the given spouting velocity. The number of turbine stages is set equal to the integer nearest to 1.1 times the isentropic enthalpy difference between turbine inlet saturation temperature and condenser temperature divided by the last-stage enthalpy drop. This accounts for the fact that the enthalpy drop is greater for the last stage than for the average stage in a turbine having equal temperature drops across all stages.

Each stage of the turbine is assumed to have an aerodynamic efficiency equal to the input value for dry-stage efficiency. As the mass and energy balance analysis progresses, the actual efficiency for each stage is then assumed to be the aerodynamic efficiency degraded by one percentage point per percent of average moisture in the stage. In addition, a value for turbine exhaust losses, caused by the last stage leaving velocity, is specified in the input. This exhaust loss is applied to both the high-pressure turbine and the low-pressure turbine.

Turbine weight is based on a Rocketdyne correlation modified to correspond with the Multimegawatt turbines. Weight scaling for cases where different materials are used is based on a creep strength to density scaling factor. Materials properties are obtained from the materials strength routine.

**Application note:** Varying input parameters beyond their recommended values or ranges without prior detailed knowledge of turbo-machinery design and limitations may give erroneous results.

3.3 ALTERNATOR

This section discusses the development of the generator design algorithms, KTAGEN.FOR, in support of the power conversion systems code development. Specifically, numerous point design studies have been completed and algorithms
developed to support generator sizing in the full-up system evaluation code.

3.3.1 Study Guidelines

All generator designs studied are high performance, high reliability TPTL [two-pole toothless] PM [permanent magnet] type. Both ring wound [RW]/variable cross-section conductor [VCSC] and conventionally wound TPTL configurations were investigated. Specific operating requirements imposed are summarized in Table 2, below.

The TPTL machines were designed to the achieve maximum rotor speed consistent with high-reliability (.99+) and 2 to 10 year life. Some advances beyond the state-of-the-art could reasonably be assumed since the use dates range form 2000 to 2015. Although the determination of design speed for a turbo-generator is probably dictated by the generator, the generator speed was also limited to the maximum turbine design speed profile shown in Table 2. No overspeed allowance was included.

<table>
<thead>
<tr>
<th>Table 2. Generator Design Requirements</th>
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</thead>
<tbody>
<tr>
<td>Generator Power Output (kVA)</td>
</tr>
<tr>
<td>Generator Type</td>
</tr>
<tr>
<td>Maximum Speed (krpm)</td>
</tr>
<tr>
<td>Voltage (RMSv 1-1)</td>
</tr>
<tr>
<td>Power Factor</td>
</tr>
<tr>
<td>Gap Conditions:</td>
</tr>
<tr>
<td>Viscosity (lb/ft-hr)</td>
</tr>
<tr>
<td>Temp. (°F)</td>
</tr>
<tr>
<td>Press. (psia)</td>
</tr>
<tr>
<td>Density (lb_m/ft^3)</td>
</tr>
<tr>
<td>Voltage Regulation</td>
</tr>
<tr>
<td>Insulation Class</td>
</tr>
<tr>
<td>Rotor Magnet L/D</td>
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</table>

The generator designs are primarily intended for use in a Potassium turbo-generator power system. The rotor/wire-support gap is assumed filled with Potassium vapor at the conditions listed in Table 2.
A 220 deg C insulation system was selected as the reference system. Some
deration of the operating temperature may be required to achieve the more
ambitious reliability and life goals. Generator sizing, however, can be
accomplished at the nominal 220 deg C for hot-spot temperature. Insulation
thickness was based on a potential of 50 volts/mil.

Two generator cooling assumes direct stator cooling with an organic coolant
(e.g. n-Heptane, Dowtherm, etc.).

The generator designs considered produce 3-phase alternating current at an
RMS line-to-line voltage of either 1400 or 8000. The relationship of desired
voltage to generator power level is shown in Table 2.

The generator designs evaluated were optimized for an assumed transformer
interface. The projected power factor for all cases is 0.90 lagging. This
interface is more likely than a rectifier interface for an NEP application. The
power factors for use in design are included in Table 2.

Overall generator conversion efficiency (including windage) is the salient
parameter affecting system optimization. The TPTL designs were
optimized to maximum efficiency with a mass/efficiency trade ratio of approximately 0.2
pounds/kWe generator mass/% generator efficiency.

3.3.2 Generator Design Results

A total of twenty-one point designs were completed using an AiResearch Los
Angeles Division [ALAD] proprietary design code. From the results of these
studies the VCSC-RW PMG configuration was selected for inclusion in the
deliverable generator sizing code. The point designs were reduced to algorithm
form to predict performance, mass, and size as a function of design kVA, rotor
surface speed and desired output voltage.

a) A maximum allowable generator rotor surface speed of 700 ft/sec was
established by ALAD. Above this speed, the primary flux gap widens
rapidly due to the hoop thickness required to retain the rotor magnet.
b) A reference rotor L/D of 2.5 was selected for the study. The algorithms developed are assumed valid in the range of $2 \leq L/D \leq 3$ when corrected for L/D not equal 2.5.

c) The algorithms are assumed valid in the range of output voltage from 1 to 10 kV, RMS and the range of power factor from 0.7 to 1.0.

d) The design analyses were completed assuming 500 °F operating temperature for both rotor and stator. These assumptions effect magnet aging design margin, electrical insulation life, and conductor resistivity.

e) The alternator will be integrated for use with direct stator cooling using an organic coolant such a Dowtherm A, N-Heptane, etc.

The cases run represent three separate data sets run at the power levels defined in Table 2 and the configuration below:

Set A - Conventionally Wound TPTL PMG at 700 ft/sec surface speed

Set B - Ring Wound/Variable Cross-section Conductor TPTL PMG at 700 ft/sec surface speed

Set C - Ring Wound/Variable Cross-section Conductor TPTL PMG at 500 ft/sec surface speed

Data sets A and B were run concurrently with common groundrules to establish the preferred configuration [ring wound or conventional] for continued study.

Tables 3 and 4 summarize the geometries and performance which resulted from the comparison. It can readily be seen that the VCSC-RW TPTL PM machine is the preferred choice for all power ratings studied. The higher efficiency, lower mass, and higher operating speed are made possible by the higher machine air gap flux density resulting from the VCSC-RW design. In addition, better winding space utilization and higher reliability are achieved since the concentrated individual phase windings are located in physically separate 60 degree phase
sectors. The borders of these phase sectors are insulated phase-to-phase, while within the sector only turn-to-turn and winding-to-ground insulation is required.

In contrast, stator windings using conventional slotted configurations use two coil sides per slot. These coil sides are associated with different phase windings. Full phase-to-phase voltage potential exists between the coil sides as well as between the phase windings which cross over each other in the end turns. Even though fully insulated, areas of phase windings in contact still exist. This condition limits stator robustness, particularly in severe environments and high voltage designs, and reduces stator reliability.

Table 3. Design Summary for Conventionaly Wound TPTL Generators Operating at 700 ft/sec Surface Speed

<table>
<thead>
<tr>
<th>Power (kW)</th>
<th>50</th>
<th>100</th>
<th>200</th>
<th>500</th>
<th>1,000</th>
<th>2,000</th>
<th>5,000</th>
</tr>
</thead>
<tbody>
<tr>
<td>kVA (kVA)</td>
<td>56</td>
<td>111</td>
<td>222</td>
<td>556</td>
<td>1,111</td>
<td>2,222</td>
<td>5,556</td>
</tr>
<tr>
<td>N (rpm)</td>
<td>54,500</td>
<td>48,200</td>
<td>34,200</td>
<td>25,000</td>
<td>18,400</td>
<td>13,700</td>
<td>10,240</td>
</tr>
<tr>
<td>V&lt;sub&gt;rms&lt;/sub&gt; (l-n RMS)</td>
<td>808</td>
<td>808</td>
<td>808</td>
<td>808</td>
<td>4,620</td>
<td>4,620</td>
<td>4,620</td>
</tr>
<tr>
<td>Rotor Dia. (in)</td>
<td>2.94</td>
<td>3.55</td>
<td>4.69</td>
<td>6.42</td>
<td>8.72</td>
<td>11.71</td>
<td>15.67</td>
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<tr>
<td>Stator OD (in)</td>
<td>5.75</td>
<td>6.52</td>
<td>8.53</td>
<td>11.05</td>
<td>13.51</td>
<td>17.7</td>
<td>22.7</td>
</tr>
<tr>
<td>Length (in)</td>
<td>12.37</td>
<td>14.20</td>
<td>18.60</td>
<td>24.30</td>
<td>33.60</td>
<td>44.30</td>
<td>59.50</td>
</tr>
<tr>
<td>Magnet L/D</td>
<td>2.57</td>
<td>2.51</td>
<td>2.5</td>
<td>2.45</td>
<td>2.53</td>
<td>2.5</td>
<td>2.58</td>
</tr>
<tr>
<td>X&lt;sub&gt;con&lt;/sub&gt; (P.U.)</td>
<td>0.121</td>
<td>0.119</td>
<td>0.129</td>
<td>0.114</td>
<td>0.131</td>
<td>0.130</td>
<td>0.137</td>
</tr>
<tr>
<td>EM Mass (lb&lt;sub&gt;m&lt;/sub&gt;)</td>
<td>38.48</td>
<td>65.03</td>
<td>146.3</td>
<td>358.2</td>
<td>724</td>
<td>1682</td>
<td>4101</td>
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<tr>
<td>Rotor Mass (lb&lt;sub&gt;m&lt;/sub&gt;)</td>
<td>15.58</td>
<td>26.52</td>
<td>61</td>
<td>152</td>
<td>395</td>
<td>940</td>
<td>2314</td>
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<tr>
<td>Efficiency (%)</td>
<td>95.08</td>
<td>95.88</td>
<td>96.14</td>
<td>96.65</td>
<td>95.4</td>
<td>95.8</td>
<td>96.35</td>
</tr>
<tr>
<td>Losses (kW)</td>
<td>2.56</td>
<td>4.3</td>
<td>8.03</td>
<td>17.3</td>
<td>48.3</td>
<td>88.2</td>
<td>189.3</td>
</tr>
<tr>
<td>Tip Speed (ft/s)</td>
<td>700</td>
<td>700</td>
<td>700</td>
<td>700</td>
<td>700</td>
<td>700</td>
<td>700</td>
</tr>
<tr>
<td>B&lt;sub&gt;core&lt;/sub&gt; (kL/in&lt;sup&gt;2&lt;/sup&gt;)</td>
<td>80</td>
<td>80</td>
<td>80</td>
<td>80</td>
<td>140</td>
<td>140</td>
<td>140</td>
</tr>
</tbody>
</table>

The ring wound stator configuration that uses single-layer variable cross-section conductors readily lends itself the optimization of the winding to achieve high machine air gap flux density, efficient cooling, and maximum reliability. The most valuable space for an electrical machine [motor or generator] is the area between the surface of the rotor magnet and the ID of the
laminated iron flux return path. The smallest possible distance between them yields the highest air gap flux density which leads to the smallest machine mass and size. For the ring wound configuration, the space around the ends of the OD of the flux collector ring is available for much larger conductor segments. Using a high current density Litz wire conductor in the air gap area that is connected to a much larger conductor used for the remainder of the winding results in an enhanced electromagnetic and thermal design. The large cross-section, low current density conductor segment can provide a heat sink and more thermal mass for the winding and thus more effective cooling of the higher current density Litz conductor segment. Lower total winding resistance will result in lower $I^2R$ losses and higher efficiency.

Table 4. Design Summary for Ring-Wound TPTL Generators Operating at 700 ft/sec Surface Speed

<table>
<thead>
<tr>
<th>Power (kW)</th>
<th>50</th>
<th>100</th>
<th>200</th>
<th>500</th>
<th>1,000</th>
<th>2,000</th>
<th>5,000</th>
</tr>
</thead>
<tbody>
<tr>
<td>kVA (kVA)</td>
<td>56</td>
<td>111</td>
<td>222</td>
<td>556</td>
<td>1,111</td>
<td>2,222</td>
<td>5,556</td>
</tr>
<tr>
<td>N (rpm)</td>
<td>80,000</td>
<td>62,000</td>
<td>47,500</td>
<td>32,500</td>
<td>23,000</td>
<td>16,500</td>
<td>11,400</td>
</tr>
<tr>
<td>$V_{rms}$ (l-n RMS)</td>
<td>808</td>
<td>808</td>
<td>808</td>
<td>808</td>
<td>4,620</td>
<td>4,620</td>
<td>4,620</td>
</tr>
<tr>
<td>Rotor Dia. (in)</td>
<td>2.01</td>
<td>2.59</td>
<td>3.38</td>
<td>4.92</td>
<td>6.98</td>
<td>9.72</td>
<td>14.07</td>
</tr>
<tr>
<td>Stator OD (in)</td>
<td>3.82</td>
<td>4.80</td>
<td>6.10</td>
<td>8.60</td>
<td>10.80</td>
<td>14.50</td>
<td>20.00</td>
</tr>
<tr>
<td>Length (in)</td>
<td>6.20</td>
<td>7.40</td>
<td>9.80</td>
<td>14.30</td>
<td>19.00</td>
<td>27.20</td>
<td>38.00</td>
</tr>
<tr>
<td>Magnet L/D</td>
<td>2.49</td>
<td>2.49</td>
<td>2.5</td>
<td>2.5</td>
<td>2.49</td>
<td>2.5</td>
<td>2.51</td>
</tr>
<tr>
<td>$X_{com}$ (P.U.)</td>
<td>0.120</td>
<td>0.120</td>
<td>0.130</td>
<td>0.130</td>
<td>0.130</td>
<td>0.120</td>
<td>0.130</td>
</tr>
<tr>
<td>EM Mass (Ibm)</td>
<td>14.08</td>
<td>29.40</td>
<td>62.00</td>
<td>182.7</td>
<td>375.0</td>
<td>993.0</td>
<td>3105.0</td>
</tr>
<tr>
<td>Rotor Mass (Ibm)</td>
<td>4.82</td>
<td>10.32</td>
<td>23.00</td>
<td>71.0</td>
<td>198.0</td>
<td>536.0</td>
<td>1630.0</td>
</tr>
<tr>
<td>Efficiency (%)</td>
<td>96.80</td>
<td>96.68</td>
<td>96.80</td>
<td>96.97</td>
<td>96.44</td>
<td>96.3</td>
<td>96.97</td>
</tr>
<tr>
<td>Losses (kW)</td>
<td>1.86</td>
<td>3.44</td>
<td>6.60</td>
<td>15.6</td>
<td>36.9</td>
<td>77.0</td>
<td>156.0</td>
</tr>
<tr>
<td>Tip Speed (ft/s)</td>
<td>700</td>
<td>700</td>
<td>700</td>
<td>700</td>
<td>700</td>
<td>700</td>
<td>700</td>
</tr>
<tr>
<td>$B_{com}$ (kL/in²)</td>
<td>80</td>
<td>80</td>
<td>80</td>
<td>80</td>
<td>80</td>
<td>140</td>
<td>140</td>
</tr>
</tbody>
</table>

Table 5 contains design specifics for a series of VCSC-RW TPTL designs operating at 500 ft/sec surface speed. The units are surprisingly low in mass and exhibit small rotor sizes as well. This excellent result at 500 ft/sec is attributed to the much reduced thickness required for the magnet retaining hoop.
and the resulting large increase in gap flux density. In most cases, rotor sizes are comparable to their 700 ft/sec counterparts and total masses are generally lower.

Table 6 contains a summary of the materials of construction assumed in the point design study and performance algorithm. Table 6 also comments on assumed technology levels relative to today's attainable values.

No technology advancement beyond properties available today were assumed for the point design study or in the resulting algorithm.

| Table 5. Design Summary for Ring-Wound TPTL Generators Operating at 500 ft/sec Surface Speed |
|---|---|---|---|---|---|---|---|
| Power (kW<sub>p</sub>) | 50 | 100 | 200 | 500 | 1,000 | 2,000 | 5,000 |
| kVA (kVA) | 56 | 111 | 222 | 556 | 1,111 | 2,222 | 5,556 |
| N (rpm) | 61,200 | 47,300 | 36,800 | 25,700 | 18,000 | 14,050 | 9,700 |
| \(V_{w,n} \) (l-n RMS) | 808 | 808 | 808 | 808 | 4,620 | 4,620 | 4,620 |
| Rotor Dia. (in) | 1.87 | 2.42 | 3.11 | 4.46 | 6.37 | 8.16 | 11.81 |
| Stator OD (in) | 4.00 | 5.60 | 6.50 | 9.10 | 10.80 | 13.30 | 18.70 |
| Length (in) | 5.60 | 7.20 | 9.00 | 13.00 | 17.70 | 22.70 | 32.80 |
| Magnet L/D | 2.51 | 2.50 | 2.50 | 2.50 | 2.50 | 2.50 | 2.50 |
| \(X_{com} \) (P.U.) | 0.130 | 0.130 | 0.130 | 0.130 | 0.120 | 0.130 | 0.130 |
| EM Mass (lb<sub>m</sub>) | 14.56 | 29.63 | 60.12 | 168.0 | 348.9 | 729.7 | 2131.0 |
| Rotor Mass (lb<sub>m</sub>) | 3.89 | 8.40 | 17.70 | 51.9 | 152.0 | 316.0 | 960.0 |
| Efficiency (%) | 96.55 | 96.71 | 96.76 | 96.88 | 96.29 | 96.49 | 96.69 |
| Losses (kW<sub>l</sub>) | 1.77 | 3.40 | 6.69 | 16.1 | 38.6 | 72.7 | 171.4 |
| Tip Speed (ft/s) | 500 | 500 | 500 | 500 | 500 | 500 | 500 |
| \(B_{com} \) \((kL/in^2)\) | 80 | 80 | 80 | 80 | 140 | 140 | 140 |

3.3.3 Algorithm Development

With the selection of the VCSC-RW TPTL configuration, fourteen valid point designs remained from which to formulate a conceptual design algorithm GENSIZE for turbo-generator systems. This data is contained in Tables 4 and 5 and
represents seven power levels and two rotor surface speeds.

<table>
<thead>
<tr>
<th>Component</th>
<th>Material</th>
<th>Salient Info.</th>
<th>Technology Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotor Magnet</td>
<td>Samarium-Cobalt</td>
<td>30 MGO</td>
<td>Comm. Avail., Select Mat'l</td>
</tr>
<tr>
<td>Rotor Hoop</td>
<td>Inconel</td>
<td>180 ksi</td>
<td>Comm. Avail., Special Order</td>
</tr>
<tr>
<td>Outer condctrs</td>
<td>Copper</td>
<td></td>
<td>Comm. Available</td>
</tr>
<tr>
<td>Inner Condctrs</td>
<td>Litz Wire</td>
<td></td>
<td>Comm. Available</td>
</tr>
<tr>
<td>Stator Insultn</td>
<td>Pyre-ML</td>
<td>Organic</td>
<td>Comm. Available</td>
</tr>
<tr>
<td>Flux Ret. Path</td>
<td>Si-steel [3.5%]</td>
<td>80 kL/in²</td>
<td>Comm. Available</td>
</tr>
<tr>
<td>50-750 kWe</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flux Ret. Path</td>
<td>Hyperco</td>
<td>140 kL/in²</td>
<td>Comm. Available</td>
</tr>
<tr>
<td>750-5000 kWe</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Support Struct</td>
<td>Polyamide</td>
<td></td>
<td>Comm. Available</td>
</tr>
</tbody>
</table>

In order to develop the appropriate algorithms for size, mass and dimension, classical generator/motor scaling laws were applied to compute appropriate sizing coefficients. All algorithms considered design kVA, design voltage and rotor surface speed as the salient independent parameters. By applying the classical ND²L [proportional to kVA] law the rotor diameter sizing coefficient could be determined. Overall dimensions [overall length and OD] were similarly converted to algorithm form. The four relevant equations contained in the generator sizing routine are as follows:

\[
D_{\text{rotor}} = \left[\frac{(U_{sp}/700)^{0.468} \times (40.65 + 6.6E-4 \times V \times (U_{sp}/700)^{2.5}) \times \text{kVA}^{0.75}}{\text{kVA}/(N \times (L/D)_{\text{rotor}})^{1/3}}\right]^{1/3} \quad [1]
\]

\[
M_{\text{mm}} = 1.938 \times (U_{sp}/700)^{0.591} \times (1.0467 - 3.3E-5 \times V \times D_{\text{rotor}}^{2.95}) \times ((L/D)_{\text{rotor}} + 0.48)/2.98 \quad [2]
\]

\[
D_{\text{stator}} = (U_{sp}/700)^{2.4} \times (2.14 - 0.12 \times \text{kVA}^{0.175} - 2.25E-5 \times V \times D_{\text{rotor}}) \quad [3]
\]

\[
L_{\text{al}} = (2.98 - 0.02 \times D_{\text{rotor}}) \times D_{\text{rotor}} \times ((L/D)_{\text{rotor}} + 0.48)/2.98 \quad [4]
\]

Where;

- \(D_{\text{rotor}}\) = Rotor Outside Diameter [including sleeve], inches
- \((L/D)_{\text{rotor}}\) = Rotor L/D; Magnet Length/Sleeve OD
M_{ew} = Generator Electro-magnetic Weight, lb_m
* Copper and insulation
* Magnet and Sleeve
* Polyamide Structure
* Complete Flux Return Path Laminant

D_{stt} = Generator Stator Outside Diameter, inches

L_{oea} = Generator Overall Length, inches
* allowance for end turns/connections included

V = Generator Output Voltage, RMSv, line-to-line

kVA = Generator kilovolt-Amperes as defined by Power and PF

U_{tp} = Design Generator Surface Speed, ft/sec

Tables 4 and 5 also contain mass and dimensional data computed from the equations above. The values computed from the developed algorithms generally agree within a few percent with the point design values and represent attainable designs which can be built with today's technology.

Details of routine function and assumptions are available from the code annotation contained in Appendix I in the subroutine KTAGEN.FOR.

3.4 TURBO-FEEDPUMP

The turbo-feedpump algorithm models a single centrifugal stage with an inducer, and a partial admission axial impulse turbine. It was determined early on in this program that detailed turbine modeling would be too prohibitive for the intended purposes of the program. Therefore, based on Rocketdyne's experience with turbopumps, it was assumed that the turbine would have 10% partial admission and would be 45% efficient.

Pump modeling begins by calculating the pump speed. The pump speed is determined through iteration between the NPSH margin and inducer flow coefficient. Iteration is continued until a design is found which has a tip speed equal to or less than the maximum set by life or material tip speed considerations. The multi-megawatt design had an inducer tip speed limit of 170 ft/sec and this is currently implemented in this program. Within the inducer tip
speed limit loop, the NPSH margin and flow coefficient are varied to meet the tip speed constraint. An inducer tip diameter limit of 0.5 inches is set as an absolute minimum based on the minimum inlet pipe diameter which would be used in the system.

Standard design practices are used in the speed selection loop to determine the operating speed. Thermodynamic suppression head is accounted for through the use of the potassium properties routines. The breakdown suction specific speed which is dependent on the inducer flow coefficient is also varied according to Rocketdyne’s suction specific speed versus flow coefficient correlation. Upon reaching a suitable operating speed the inducer size and state properties at the inlet and discharge are calculated.

The centrifugal stage is sized using the speed and pump discharge pressure with an assumed impeller head coefficient of 0.35. Efficiency is calculated using Rocketdyne’s efficiency versus specific speed correlation and accounts for pump size and seal clearance effects.

The turbopump weight correlation is based on a Rocketdyne correlation and modified to account for the increase in weight due to material density variation and configuration requirements for this type of turbopump. Weight scaling for cases where different materials are used is based on a creep strength to density scaling factor.

Application note: The pump program uses many proprietary correlations developed by Rocketdyne. The source code for these correlations has not been included. These correlations are contained in the object code CORELATE.OBJ. When linking the various object modules together to form the main program, this object code must be included.

3.5 RFMD AND VOLUME ACCUMULATOR

The RFMD and volume accumulator are located at the condenser outlet. These two components provide two-phase fluid inventory management for the potassium Rankine cycle in a microgravity environment. The RFMD also provides NPSH to the boiler feedpump.
Both the RFMD and volume accumulator performance and mass characteristics models are tied to the Multimegawatt design (Ref. 11). Weights for cases where different materials are used are adjusted with a creep strength to density ratio scaling factor obtained from the materials properties routine. The RFMD model uses the same head and flow coefficients and efficiency as the multimegawatt RFMD design. RFMD mass is estimated by using a simple D²L law while the accumulator mass is scaled linearly with potassium inventory. Input values for the RFMD are flow coefficient, head coefficient, and efficiency. There are no input values for the volume accumulator.

Application note: Since pitot pump behavior is uncertain with a change of flow and head coefficients, it is strongly recommended that the user not change these values.

3.6 PIPING

Size and weight is calculated for each run of pipe represented in the potassium-Rankine flow diagram, Figure 1. Pipe inside diameters are calculated from volumetric flow rates and input values for design velocities for lines carrying vapor, wet mixture, or liquid. Wall thickness for each pipe is then calculated from pressure within the pipe, the inside diameter, and the design allowable stress for the pipe. Four alloys, Nb-1%Zr, ASTAR 811C, TZM, and 316SS, are included in the model as available piping materials. For the appropriate alloy and temperature for each pipe run, design-allowable stress is calculated in a subroutine based on available creep data for the alloys as described later in section 3.8.

3.7 THERMODYNAMIC AND TRANSPORT PROPERTIES

The heart of the potassium-Rankine system model is the potassium thermodynamic properties routines. The potassium vapor thermodynamic properties routines for saturated and superheated vapor uses a four coefficient Virial equation based on extensive pressure, volume, temperature (PVT) data (Ref. 2). Additional potassium thermodynamic properties routines were also obtained from Reference 2. Furthermore, potassium transport properties and lithium thermodynamic and transport properties were obtained from Reference 3.
3.8 MATERIALS STRENGTH PROPERTIES

Creep strength algorithms are available for the tantalum based alloy ASTAR 811C, Nb-1%Zr, the molybdenum based alloy TZM, and for 316 stainless steel. Algorithms for ASTAR 811C and Nb-1%Zr were obtained from Reference 8, while the TZM creep strength algorithm was deduced from data obtained from Reference 9. The creep strength algorithm for 316SS was obtained from Reference 11. Above 1350 K, ASTAR 811C has superior creep strength to density characteristics with respect to the other three materials. Below 1350 K TZM is the material of choice based on its creep strength to density ratio. Nb-1%Zr has excellent properties at lower temperatures although its creep strength to density ratio is not as good as TZM. Its ease of fabricability and compatibility with alkali metals may make it the material of choice in situations where creep concerns are not too great. 316SS is included for low temperature operating regimes where a familiar material with vast amounts of experience is desired. In general, for the potassium-Rankine operating temperature ranges, 316SS has poor creep strength characteristics.

Application note: The algorithm for Nb-1%Zr creep is based on experimental data in the temperature range of 1250 K to 1450 K with no guarantee of creep predictions outside this temperature range (Ref. 8). The recommended temperature range for the ASTAR 811C creep strength algorithm is 1300 K to 1800 K (Ref. 8). The TZM algorithm was developed from data ranging in temperature from 1075 K to 1475 K. Results cannot be guaranteed when this algorithm is used outside this range. The recommended temperature range of the 316SS creep strength algorithm is 645 K to 865 K (Ref. 10).

4.0 CONCLUSIONS AND RECOMMENDATIONS

The potassium-Rankine power conversion subsystem model presented in this report will give reasonable predictions of subsystem performance when the input parameters are kept within their recommended ranges. These ranges are 1200 K to 1600 K for turbine inlet temperature, 1.25 to 1.6 for turbine inlet/condenser temperature ratios, 100 kW to 10 MW for power level, 2 to 10 years for lifetime, plus any other parameter values which have been mentioned in this report.
The potassium-Rankine power conversion subsystem model was designed to be as user friendly as possible given the development time allowed. There are some difficult areas in the code which can cause run time errors if the user is not careful. These are in the boiler/reheater module, and the piping module. If too close of an approach temperature is used between reactor outlet temperature and boiler outlet temperature, then a temperature cross may occur in the boiler/reheater module causing a run time error. This can be remedied by either raising the reactor outlet temperature or lowering the boiler outlet temperature. Also, when computing pressure losses in low pressure piping runs the potential for calculating a negative pressure exists which will also cause a runtime error. This can be resolved by either increasing the condensor temperature or decreasing the pipe flow velocity. Furthermore, negative pressures may be calculated if too large a pressure drop is specified for the boiler or the reheater resulting in run time errors. Run time errors caused by negative pressures usually show up in the KTHRMO subroutine, making it difficult to track the cause of the error. The potassium-Rankine code would be vastly improved if error trapping procedures were added to detect and point to the cause of the error allowing corrections to be made with ease. Follow-on work should include development of error trapping procedures to be added to the potassium-Rankine code.
5.0 REFERENCES


## Input Parameter

### General Parameters

<table>
<thead>
<tr>
<th>Input Parameter</th>
<th>Recommended Value/Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>System full power life (years)</td>
<td>1 - 10</td>
</tr>
<tr>
<td>Flow velocity in vapor lines (m/sec)</td>
<td>140.0</td>
</tr>
<tr>
<td>Flow velocity in wet vapor lines (m/sec)</td>
<td>50.0</td>
</tr>
<tr>
<td>Flow velocity in liquid lines (m/sec)</td>
<td>3.5</td>
</tr>
<tr>
<td>Temperature for material switch (K)</td>
<td>1350.0</td>
</tr>
<tr>
<td>High Temperature material</td>
<td>I - ASTAR 811C</td>
</tr>
<tr>
<td>Low Temperature material</td>
<td>2 - Nb-1%Zr</td>
</tr>
<tr>
<td></td>
<td>3 - TZM</td>
</tr>
<tr>
<td></td>
<td>4 - 316SS</td>
</tr>
<tr>
<td>Thermal cond., high temp. alloy (W/m-K)</td>
<td>53.6</td>
</tr>
<tr>
<td>Thermal cond., low temp. alloy (W/m-K)</td>
<td>53.6</td>
</tr>
<tr>
<td># operating units</td>
<td>3.0</td>
</tr>
<tr>
<td># total units</td>
<td>4.0</td>
</tr>
</tbody>
</table>

### Reactor Parameters

<table>
<thead>
<tr>
<th>Input Parameter</th>
<th>Recommended Value/Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor outlet temperature (K)</td>
<td>1550.0</td>
</tr>
<tr>
<td>Reactor inlet temperature (K)</td>
<td>1450.0</td>
</tr>
</tbody>
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### Electrical Parameters

<table>
<thead>
<tr>
<th>Input Parameter</th>
<th>Recommended Value/Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>System net power output (kWe)</td>
<td>10 - 10,000</td>
</tr>
<tr>
<td>Alternator efficiency</td>
<td>0.97</td>
</tr>
<tr>
<td>Fraction of alternator gross output used for - lithium</td>
<td>NA</td>
</tr>
<tr>
<td>pumps</td>
<td>NA</td>
</tr>
<tr>
<td>potassium feed pumps</td>
<td>NA</td>
</tr>
<tr>
<td>other loads</td>
<td>NA</td>
</tr>
</tbody>
</table>

### Alternator Parameters

<table>
<thead>
<tr>
<th>Input Parameter</th>
<th>Recommended Value/Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power factor</td>
<td>0.7 - 0.9</td>
</tr>
<tr>
<td>Voltage (volts)</td>
<td>1000 - 10,000</td>
</tr>
<tr>
<td>Aspect ratio (L/D)</td>
<td>2 - 3</td>
</tr>
<tr>
<td>Coolant inlet temperature (K)</td>
<td>511.1</td>
</tr>
<tr>
<td>Coolant outlet temperature (K)</td>
<td>522.2</td>
</tr>
<tr>
<td>Coolant heat capacity (kJ/kg-K)</td>
<td>2.1</td>
</tr>
</tbody>
</table>
**Turbine Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbine inlet saturation temp. (K)</td>
<td>1000 - 1600</td>
</tr>
<tr>
<td>Turbine inlet - quality if &lt;= 1 superheat, K, if &gt; 1</td>
<td>1 - 100</td>
</tr>
<tr>
<td>Condensing temperature (K)</td>
<td>750 - 1300</td>
</tr>
<tr>
<td>Turbine dry stage efficiency</td>
<td>.85</td>
</tr>
<tr>
<td>Turbine exhaust losses (kJ/kg)</td>
<td>11.63</td>
</tr>
<tr>
<td>Turbine last stage tip velocity (m/sec)</td>
<td>366.0</td>
</tr>
<tr>
<td>Condenser subcooling (K)</td>
<td>2.0</td>
</tr>
<tr>
<td>Turbine inlet stator angle</td>
<td>14.0</td>
</tr>
<tr>
<td>Spouting velocity (m/sec)</td>
<td>389.0</td>
</tr>
<tr>
<td>Layers of Multifoil Insulation</td>
<td>20</td>
</tr>
<tr>
<td>Condenser pressure drop (kPa)</td>
<td>0 - 35</td>
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</table>

**Feed Pump Parameters**

<table>
<thead>
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<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pump turbine efficiency</td>
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**RFMD Parameters**

<table>
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<tr>
<th>Parameter</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure rise through RFMD (kPa)</td>
<td>3.5 - 140</td>
</tr>
<tr>
<td>RFMD pump efficiency</td>
<td>.32</td>
</tr>
<tr>
<td>RFMD motor efficiency</td>
<td>.45</td>
</tr>
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</table>

**Boiler Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum K side pressure drop (kPa)</td>
<td>3.5 - 140</td>
</tr>
<tr>
<td>Boiler tube diameter (cm)</td>
<td>1.27</td>
</tr>
<tr>
<td>Number of boiler tubes</td>
<td>100.0</td>
</tr>
</tbody>
</table>

**Reheat Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum re heater pressure loss (kPa)</td>
<td>3.5 - 140</td>
</tr>
<tr>
<td>Superheat after reheat K</td>
<td>25 - 100</td>
</tr>
<tr>
<td>Reheater tube diameter (cm)</td>
<td>1.27</td>
</tr>
<tr>
<td># tubes in reheater</td>
<td>100.0</td>
</tr>
</tbody>
</table>
Line Parameters

<table>
<thead>
<tr>
<th>Line Label</th>
<th>Length (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boiler Outlet</td>
<td>1.0</td>
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## APPENDIX B
### INPUT PARAMETER DEFINITIONS

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<td>Power for lithium pumps (kWe)</td>
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<td>CPCLNT</td>
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<td>Turbine dry stage efficiency</td>
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<td>Reheater tube diameter (cm)</td>
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<td>Condenser pressure losses (kPa)</td>
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<td>DPMAXB</td>
<td>Max. K side pressure losses (kPa)</td>
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<tr>
<td>DPMAXR</td>
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<td>DPRFMD</td>
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<td>Turbine exhaust losses (kJ/kg)</td>
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<td>Generator Length/Diameter aspect ratio</td>
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# APPENDIX E
## OUTPUT PARAMETER DEFINITIONS

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<td>Alternator cooling load (kWt)</td>
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<td>Cycle efficiency</td>
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<td>Diameter of alternator rotor (cm)</td>
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<td>Diameter of alternator stator (cm)</td>
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<td>Boiler lithium side pressure loss (kPa)</td>
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<td>Pressure drop across boiler (kPa)</td>
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DGENSTR PR(520)
DLPBB  PR(432)
DLPBR  PR(435)
DOUTEB PR(439)
DOUTER PR(462)
DPTOTB PR(285)
DPTOTR PR(289)
DTSB   PR(440)
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DT(NSTG) PR(324 - 338)
EFFGRS PR(487)
EFFNET PR(486)
EFF(0:15) PR(416 - 431)
FMDEL PR(305)
GNLOSS PR(491)
HKBOIB PR(451)
HKBOIL PR(474)
HKPHB  PR(450)
HKPHR  PR(473)
HKSHB  PR(452)
HKSHR  PR(475)
HLE(11) PR(153 - 163)
HLILIB PR(449)
HLILIR PR(472)
HLI(11) PR(142 - 152)
HRH   PR(499)
HTBB  PR(438)
HTBR  PR(461)
H(0:15) PR(34 - 49)
ID(11) PR(274 - 284)
KVA   PR(519)
KWOUT PR(406)
LBOILR PR(444)
LBOILR PR(467)
LGENTOT PR(521)
LPHB  PR(443)
LPHR  PR(466)
LSHB  PR(445)
LSHR  PR(468)
LTOTB PR(446)
LTOTR PR(469)
MASSGEN PR(522)
MFITOT PR(302)
MFINTB PR(458)
MFINTR PR(481)
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MQADD   PROUT(410)
MQREJ   PROUT(411)
NS      PROUT(290)
NSTAGE  PROUT(369)
PAB      PROUT(448)
PAR      PROUT(471)
PCSACM  PROUT(409)
PDIS     PROUT(306)
PENG     PROUT(303)
PHI(NSTG) PROUT(354 - 368)
PLE(11)  PROUT(131 - 141)
PLI(11)  PROUT(120 - 130)
PLNTEF  PROUT(490)
PP(0:15) PROUT(18 - 33)
PRSTAG  PROUT(412)
PSI(NSTG) PROUT(370 - 384)
PUMPEFF  PROUT(387)
RPM      PROUT(496)
SLE(11)  PROUT(175 - 185)
SLI(11)  PROUT(164 - 174)
SPMASS   PROUT(485)
SRH      PROUT(500)
SSMARG   PROUT(388)
SVRH     PROUT(497)
SVVLE(11) PROUT(219 - 229)
SVVL(11) PROUT(208 - 218)
SVV(0:15) PROUT(82 - 97)
S(0:15)  PROUT(50 - 65)
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THSB     PROUT(441)
THSR     PROUT(464)
TIPSPDG  PROUT(523)
TITCON   PROUT(489)
TKTUBB   PROUT(447)
TKTUBR   PROUT(470)
TLE(11)  PROUT(109 - 119)
TLI(11)  PROUT(98 - 108)
TORQ     PROUT(405)
TORQUE   PROUT(492)
TOHP     PROUT(386)
TOTWT    PROUT(287)
TRBPWR   PROUT(493)
TSATRH   PROUT(498)
TSAT(0:15) PROUT(501 - 516)
TTP(NSTG) PROUT(308 - 322)
TTRH     PROUT(288)
TT(0:15) PROUT(2 - 17)
TURBWT   PROUT(495)
UTLIM    PROUT(307)
UT(NSTG) PROUT(339 - 353)
VTIP     PROUT(517)
WALL(11) PROUT(241 - 251)
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## APPENDIX H
## KRANK SAMPLE CASE

5 MWe K-Rankine Electric Power System, 7 Year Life, Sept. 8, 1993

### General Parameters

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<th>Parameter</th>
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<td>Flow velocity in wet vapor lines (m/sec)</td>
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<tr>
<td>Flow velocity in liquid lines (m/sec)</td>
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<td>3 - TZM</td>
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<td>4 - 316SS</td>
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<td>Reactor inlet temperature (K)</td>
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<td>Lithium pumps</td>
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<td>Potassium feed pumps</td>
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### Alternator Parameters

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### Turbine Parameters

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<td>- superheat, K, if &gt; 1</td>
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</table>
### POWER CONVERSION CYCLE PARAMETERS

- **Turbine inlet temp**: 1500.0 K
- **Superheat/Quality**: 50.00 K
- **Tip velocity**: 366.0 m/sec
- **No. of stages**: 8
- **Generator efficiency**: 96.6%
- **Saturation temp**: 1450.0 K
- **Condenser temp**: 1050.0 K
- **Dry stage eff**: 85.0%
- **Pump turbine eff**: 45.0%
- **Condenser subcooling**: 2.0 K

### TURBINE CONDITIONS AT EACH STAGE

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<th>Pres (kPa)</th>
<th>Quality</th>
<th>Enthalpy (kJ/kg)</th>
<th>Entropy (kJ/kg-K)</th>
<th>Sp Vol (m3/kg)</th>
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### POWER CONVERSION CYCLE CHARACTERISTICS

- **Generator output**: 5112.95 kWe
- **Thermal input**: 27557.22 kWt
- **Condenser reject**: 22259.96 kWt
- **Generator losses**: 59.62 kWe
- **Cycle efficiency**: 19.20%
- **Plant efficiency**: 18.55%
- **Main vapor flow**: 4.15 kg/sec

### SCHEDULE OF PIPING RUNS

#### Thermodynamic Properties

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<td>0.13</td>
<td>1.00</td>
<td>3.78</td>
<td>0.051</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Reheater Inlet</td>
<td>4.15</td>
<td>1.00</td>
<td>12.35</td>
<td>0.051</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Reheater Outlet</td>
<td>4.15</td>
<td>1.00</td>
<td>13.56</td>
<td>0.051</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Condenser Inlet</td>
<td>4.15</td>
<td>1.00</td>
<td>24.23</td>
<td>0.051</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Condenser Outlet</td>
<td>4.15</td>
<td>1.00</td>
<td>4.77</td>
<td>0.051</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Feed Pump Inlet</td>
<td>4.15</td>
<td>1.00</td>
<td>4.77</td>
<td>0.051</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Feed Pump Outlet</td>
<td>4.15</td>
<td>1.00</td>
<td>4.78</td>
<td>0.051</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Weights**

<table>
<thead>
<tr>
<th>No.</th>
<th>Description</th>
<th>Pipe Wt (kg)</th>
<th>K Wt (kg)</th>
<th>MFI Wt (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Boiler Outlet</td>
<td>4.84</td>
<td>0.030</td>
<td>0.015</td>
</tr>
<tr>
<td>2</td>
<td>Turbine Inlet</td>
<td>4.65</td>
<td>0.029</td>
<td>0.015</td>
</tr>
<tr>
<td>3</td>
<td>Pump Turbine Inlet</td>
<td>0.65</td>
<td>0.003</td>
<td>0.005</td>
</tr>
<tr>
<td>4</td>
<td>HP Turbine Outlet</td>
<td>3.25</td>
<td>0.029</td>
<td>0.022</td>
</tr>
<tr>
<td>5</td>
<td>Pump Turbine Outlet</td>
<td>1.02</td>
<td>0.003</td>
<td>0.007</td>
</tr>
<tr>
<td>6</td>
<td>Reheater Inlet</td>
<td>3.31</td>
<td>0.030</td>
<td>0.023</td>
</tr>
<tr>
<td>7</td>
<td>Reheater Outlet</td>
<td>3.63</td>
<td>0.030</td>
<td>0.025</td>
</tr>
<tr>
<td>8</td>
<td>Condenser Inlet</td>
<td>6.47</td>
<td>0.030</td>
<td>0.044</td>
</tr>
<tr>
<td>9</td>
<td>Condenser Outlet</td>
<td>1.29</td>
<td>1.185</td>
<td>0.009</td>
</tr>
<tr>
<td>10</td>
<td>Feed Pump Inlet</td>
<td>1.29</td>
<td>1.185</td>
<td>0.009</td>
</tr>
<tr>
<td>11</td>
<td>Feed Pump Outlet</td>
<td>1.29</td>
<td>1.185</td>
<td>0.009</td>
</tr>
</tbody>
</table>

**Totals**

|              | 126.73 | 14.947 | 0.730 |

40
CHARACTERISTICS OF ALTERNATOR

RING WOUND TPTL PMG

Voltage = 1000.0 Volts
Power = 1704.3 kWe
Rotor Diameter = 19.1 cm
Weight = 349.4 kg
Total Length = 54.1 cm
Sizing Coef. = 22.9
Cooling Load = 59.6 kWt
Clnt inlet Temp. = 511.1 K
Design Life = 7.0 yrs

DOWTHERM

Volt-Amperes = 1794.0 kVA
Speed = 20054.4 rpm
Tip Speed = 200.9 m/s
Stator Diameter = 32.8 cm
Aspect Ratio = 2.5
Efficiency = 96.6 \%
Coolant Flow = 2.6 kg/s
Clnt outlet Temp. = 522.2 K

CHARACTERISTICS OF TURBINE

Constant xxl = 176.89
Power = 1762.3 kW
Speed = 20054.4 rpm
Stator angle = 13.6 deg

Tip velocity = 363.4 m/sec
Torque = 840.1 Nt-m
Spouting velocity = 389.0 m/sec
Turbine weight = 382.6 kg

TURBO-FEEDPUMP CHARACTERISTICS

Mass flow rate = 4.15 kg/sec
Discharge pressure = 1662.6 kPa
Discharge temp = 1037.4 K
Horsepower = 15.1 kW
Efficiency = 60.3 \%
Specific speed = 2635.4
Stage number = 2
NPSH = 16.1 m
Inducer head coef = 0.1000
Inducer tip speed = 51.7 m/sec
Impeller flow coef = 0.1000
Impeller tip speed = 77.8 m/sec

Inlet pressure = 1034.6 K
Inlet temp = 51.8 m/sec
Tip speed limit = 4.3 Nt-m
Speed = 33801.5 rpm
Weight = 79.5 kg
NPSH margin = 220.0 \%
Inducer flow coef = 0.1990
Inducer tip diameter = 2.92 cm
Impeller tip diameter = 4.39 cm
Impeller head coef = 0.3500

BOILER CHARACTERISTICS

General Dimensions

Height = 596.9 cm
Tube sheet diameter = 67.3 cm
Tube sheet thickness = 11.3 cm
Diameter = 70.4 cm
Shell thickness = 1.6 cm

Tube dimensions

Number of boiler tubes = 849.0
Boiling length = 355.6 cm
Total tube length = 510.5 cm
Tube wall thickness = 0.057 cm
Preheat length = 30.5 cm
Superheat length = 124.5 cm
Tube inside diameter = 1.27 cm
Tube pitch = 1.904 cm
### Summary of Heat Transfer Coefficients

<table>
<thead>
<tr>
<th>Side</th>
<th>Coefficient (kW/m²-K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Li side</td>
<td>4.6</td>
</tr>
<tr>
<td>K boiling</td>
<td>39.7</td>
</tr>
<tr>
<td>K preheat</td>
<td>14.2</td>
</tr>
<tr>
<td>K superheat</td>
<td>0.3</td>
</tr>
</tbody>
</table>

### Summary of Pressures

<table>
<thead>
<tr>
<th>Pressure Drop</th>
<th>Value (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Li side</td>
<td>1.55</td>
</tr>
<tr>
<td>Boiler inlet</td>
<td>1661.6</td>
</tr>
<tr>
<td>Boiler outlet</td>
<td>1591.5</td>
</tr>
<tr>
<td>Boiler pressure drop</td>
<td>70.05</td>
</tr>
</tbody>
</table>

### Summary of boiler weights

<table>
<thead>
<tr>
<th>Component</th>
<th>Weight (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shell</td>
<td>3416.3</td>
</tr>
<tr>
<td>Twisted tapes</td>
<td>722.6</td>
</tr>
<tr>
<td>Heads</td>
<td>206.2</td>
</tr>
<tr>
<td>Total dry weight</td>
<td>7461.3</td>
</tr>
<tr>
<td>Weight of lithium</td>
<td>401.8</td>
</tr>
</tbody>
</table>

### REHEATER CHARACTERISTICS

#### General Dimensions

- **Height**: 111.8 cm
- **Diameter**: 53.1 cm
- **Shell thickness**: 0.2 cm
- **Tube sheet diameter**: 52.7 cm
- **Tube sheet thickness**: 3.4 cm

#### Tube dimensions

- **Number of re heater tubes**: 531.0
- **Boiling length**: 5.1 cm
- **Total tube length**: 55.9 cm
- **Tube wall thickness**: 0.051 cm
- **Preheat length**: 0.0 cm
- **Superheat length**: 50.8 cm
- **Tube inside diameter**: 1.27 cm
- **Tube pitch**: 1.886 cm

### Summary of Heat Transfer Coefficients

<table>
<thead>
<tr>
<th>Side</th>
<th>Coefficient (kW/m²-K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Li side</td>
<td>5.9</td>
</tr>
<tr>
<td>K boiling</td>
<td>39.7</td>
</tr>
<tr>
<td>K preheat</td>
<td>14.8</td>
</tr>
<tr>
<td>K superheat</td>
<td>0.4</td>
</tr>
</tbody>
</table>

### Summary of Pressures

<table>
<thead>
<tr>
<th>Pressure Drop</th>
<th>Value (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Li side</td>
<td>0.96</td>
</tr>
<tr>
<td>Reheater inlet</td>
<td>537.8</td>
</tr>
<tr>
<td>Reheater outlet</td>
<td>502.8</td>
</tr>
<tr>
<td>Reheater pressure drop</td>
<td>35.06</td>
</tr>
</tbody>
</table>

### Summary of reheater weights

<table>
<thead>
<tr>
<th>Component</th>
<th>Weight (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shell</td>
<td>57.4</td>
</tr>
<tr>
<td>Twisted tapes</td>
<td>47.0</td>
</tr>
<tr>
<td>Heads</td>
<td>13.7</td>
</tr>
<tr>
<td>Total dry weight</td>
<td>406.5</td>
</tr>
<tr>
<td>Weight of lithium</td>
<td>27.2</td>
</tr>
<tr>
<td>Reheater tubes</td>
<td>156.6</td>
</tr>
<tr>
<td>Tube sheets</td>
<td>130.9</td>
</tr>
<tr>
<td>Multifoil insulation</td>
<td>0.9</td>
</tr>
<tr>
<td>Weight of Potassium</td>
<td>1.0</td>
</tr>
<tr>
<td>Wet weight of reheater</td>
<td>434.7</td>
</tr>
</tbody>
</table>
## MASS OF POWER CONVERSION SUBSYSTEM

<table>
<thead>
<tr>
<th>Component</th>
<th>Mass (KG)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boiler (wet)</td>
<td>8035.6</td>
</tr>
<tr>
<td>Reheater (wet)</td>
<td>434.7</td>
</tr>
<tr>
<td>Turbines</td>
<td>1530.4</td>
</tr>
<tr>
<td>Alternator</td>
<td>1397.6</td>
</tr>
<tr>
<td>Feed Turbo-pumps</td>
<td>317.9</td>
</tr>
<tr>
<td>RFMDs</td>
<td>766.0</td>
</tr>
<tr>
<td>K piping</td>
<td>126.7</td>
</tr>
<tr>
<td>K inventory</td>
<td>14.9</td>
</tr>
<tr>
<td>Accumulators</td>
<td>217.9</td>
</tr>
</tbody>
</table>

Total: 12842.5

## SYSTEM PERFORMANCE CHARACTERISTICS

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific Mass (kg/kWe)</td>
<td>2.568</td>
</tr>
<tr>
<td>Net Efficiency (%)</td>
<td>17.998</td>
</tr>
<tr>
<td>Gross Efficiency (%)</td>
<td>18.405</td>
</tr>
<tr>
<td>TIT/TCON</td>
<td>1.381</td>
</tr>
</tbody>
</table>
APPENDIX I
SOURCE CODE LISTINGS

PROGRAM MNRANK

IMPLICIT DOUBLE PRECISION (A-H,O-Z)

CHARACTER TITLE(13)*80,LLBL(11)*25,FNAME(50)*50,CLNTYPE*10,
&
   GENTYPE*20,INTTYPE*20,ERRORG*64,WARNINGG*64

*******************************************************************************
OPEN (I,FILE='KRANK.IN',STATUS='OLD')
OPEN (6,FILE='KRANK.OUT',STATUS='UNKNOWN',FORM='FORMATTED')
CALL PRINP(TITLE,LLBL,FNAME)
CALL KRANK
CALL PROUTP(TITLE,LLBL,FNAME)
ENDFILE (6)
CLOSE (1,STATUS='KEEP')
CLOSE (6,STATUS='KEEP')
END
SUBROUTINE PRINP(TITLE,LLBL,FNAME)
IMPLICIT DOUBLE PRECISION (A-H,O-Z)

CHARACTER TITLE(13)*80,LLBL(II)*25,FNAME(50)*50
COMMON /INPUT/ PRIN(61)

READ (1,5) TITLE(1),TITLE(2)
5 FORMAT(/,A80,///ASO,/) DO 10 I = 1,7
10 READ (1,*) FNAME(I),PRIN(I) DO 11 I = 8,9
11 READ (1,*) FNAME(I) DO 12 I = 10,13
12 READ (1,*) FNAME(I),PRIN(I)

C read reactor parameters

READ (1,20) TITLE(3)
20 FORMAT(/,A80,/) DO 25 I = 14,15
25 READ(1,* FNAME(I),PRIN(I)

C READ ELECTRICAL PARAMETERS

READ (1,40) TITLE(4)
40 FORMAT(/,A80,/) DO 45 I = 16,17
45 READ(1,* FNAME(I),PRIN(I) READ(1,* FNAME(18)
46 READ(1,* FNAME(I),PRIN(I)

C READ ALTERNATOR PARAMETERS

READ(1,60) TITLE(5)
60 FORMAT(/,A80,/) DO 65 I = 22,27
65 READ(1,* FNAME(I),PRIN(I)

C READ TURBINE PARAMETERS

READ (1,70) TITLE(6)
70 FORMAT(/,A80,/) DO 75 I = 28,29
75 READ(1,* FNAME(I),PRIN(I) READ(1,* FNAME(30)
76 READ(1,* FNAME(I),PRIN(I)

C READ FEED PUMP PARAMETERS

READ (1,85) TITLE(7)
85 FORMAT(/,A80,/)
READ(1,*) FNAME(40), PRIN(40)

C read RFMD parameters

READ (1,90) TITLE(8)
90 FORMAT(//,A80,/
READ(1,*) (FNAME(I), PRIN(I), I=41,43)

C READ BOILER PARAMETERS

READ (1,100) TITLE(9)
100 FORMAT(//,A80,/
READ(1,*) (FNAME(I), PRIN(I), I=44,46)

C READ REHEAT PARAMETERS

READ (1,110) TITLE(10)
110 FORMAT(//,A80,/
READ(1,*) (FNAME(I), PRIN(I), I=47,50)

C READ LINE PARAMETERS

READ (1,120) TITLE(11), TITLE(12), TITLE(13)
120 FORMAT(//,A80,/,A80,/,A80/
READ(1,*) (LLBL(I), PRIN(I+50), I=1,11)

RETURN
END
SUBROUTINE PROUTP (TITLE, LLBL, FNAME)

IMPLICIT DOUBLE PRECISION (A-H,O-Z)

DOUBLE PRECISION LGENTOT, MASSGEN, KVA, KWOUT, KA, KB, NUMOP, NUMTOT, &
KNET, NOTUBB, NOTUBR, LG, MMAIN, MF, ID, MFITOT, &
MQADD, MQREJ, LPHB, LBOILB, LSHB, LTOTB, MFIWTB, LPHR, &
LBOILR, LSHR, LTOTR, MFIWR, MFLOPT

CHARACTER TITLE(13)*80, LLBL(II)*25, FNAME(50)*50, CLNTYPE*10, &
GENTYPE*20, INTTYPE*20, ERRORG*64, WARNINGG*64

INTEGER REHEAT, RSTAGE

DIMENSION PRIN(61), PROUT(526)

***** ***********************************************

PARAMETER (NSTG=15)

COMMON /INPUT/ FPL, VELV, VELL, TMAT, XMATH, XMATC, DUM1, DUM2, KA, &
KB, NUMOP, NUMTOT, TOUT, TRIN, KNET, GEFF, DUM3, BPP, BFP, &
PBL, PWRFCR, VOLTAGE, GENASP, TINCLNT, TOUTCLNT, &
CPCLNT, TBOIL, XBOIL, DUM4, TCON, DEFF, EXLOSS, VTIPO, &
SCCON, ALPHAT, RSTT, XMFI, DPCON, PTEFF, DPFMD, EFRFMD, &
EHRFMD, DPMAXB, DIATB, NOTUB, DPMAXR, DTRH, DIARH, &
NOTUBR, LG(11)

COMMON /OUTPUT/ MMAIN, TT(0:15), PP(0:15), H(0:15), S(0:15), X(0:15), &
SVV(0:15), TLI(11), TLE(11), PLI(11), PLE(11), HLI(11), &
HLE(11), SLI(11), SLE(11), XLI(11), XLE(11), SVVLI(11), &
SVVLE(11), MF(11), WALL(11), WT(11), WTKINV(11), ID(11), &
DPTOTB, WTKTOT, TOTWT, TTRH, DPTOTR, NS, WTMFI(11), &
MFITOT, PENG, TENG, FMDEL, PDIS, ULTIM, TTP(NSTG), XNPSHA, &
DT(NSTG), UT(NSTG), PHI(NSTG), NSTAGE, PSI(NSTG), XN, &
TOTHP, PUMPEFF, SSMARG, XNSSTG(NSTG), WFPUMP, TORQ, &
KWOUT, ALTWT, CYCEF, PCSCAM, MQADD, MQREJ, PRSTAG, &
WTRFMD, WTURBN, XRH, EFF(0:15), DLPPB, WBOILB, WMTWEB, &
DLPRB, WRHT, WTWER, HTBB, DOUTEB, DTSB, THSB, XTHKB, LPHB, &
LBOILB, LSHB, LTOTB, TKTUBB, PAB, HLIB, HKBPHB, HKBBOB, &
HKSHB, WSHELH, WTUBEH, WTPEBH, WTSSB, WTCLOB, MWIWTB, &
WTPOTB, WTLIB, HTBB, DOUTEB, DTSR, THSR, XTHKR, LPHR, &
LBOILR, LSHR, LTOTR, TKTURB, PAR, HLIBR, HKBPHR, HKBBOIR, &
HKSHR, WSHELH, WTUBER, WTAPER, WTTSR, WTCLOB, MWIWTB, &
WTPOTR, WTLIR, WTPCS, SPMASS, EFFNET, EFFGRS, WTPUMP, &
WTCON, PLNTEF, GNLOSS, TORQUE, TRBPWR, XXI, TURBWT, RPM, &
SVRH, TSATRH, HHR, SRH, TSAT(0:15), VTI, DGENRTR, KVA, &
DGENSTR, LGENTOT, MASSGEN, TIPSPDG, COE, COOLING, WCLNT

COMMON /SYSTM/ MFLOPT, CFSLI(11), CFSLE(11), DELPL(11), DELHL(11), MFI, &
TPUMP, HPUMP, SFSPUMP, VFPUMP, WKFMD, PI, G, TO, XLMIN, &
XLMOUT, EFFIND, HCIND, XKLOSS, PT(NSTG), PS(NSTG), &
HT(NSTG), XIHT(NSTG), HSP(NSTG), ST(NSTG), TS(NSTG), &
RHO(NSTG), CM(NSTG), XNSS, DH(NSTG), B2(NSTG), &
F3S(NSTG), XMARG, XNPSHA, XNPSHOP, HD(NSTG),
**WRITE REACTOR INPUT PARAMETERS**

```fortran
WRITE (6,10) TITLE(1),TITLE(2),(FNAME(I),PRIN(I),I=1,7),
               (FNAME(I),I=8,9),(FNAME(I),PRIN(I),I=10,13)
10 FORMAT(/,A80,///,7(T6,A50,T60,F10.1
               ,/),2(T6,A50,/,4(T6,A50,T60,F10.1
```

**WRITE ELECTRICAL PARAMETERS**

```fortran
WRITE (6,30) TITLE(4),(FNAME(I),PRIN(I),I=14,15)
30 FORMAT(/,A80,///,2(T6,ASO,T60,FIO.I,/) )
```

**WRITE ALTERNATOR PARAMETERS**

```fortran
WRITE (6,35) TITLE(5),(FNAME(I),PRIN(I),I=22,27)
35 FORMAT(/,A80,///,6(T6,A50,T60,F10.1,/) )
```

**WRITE TURBINE PARAMETERS**

```fortran
WRITE (6,40) TITLE(6),(FNAME(I),PRIN(I),I=28,29),FNAME(30),
               (FNAME(J),PRIN(J),J=31,39)
40 FORMAT(/,A80,///,2(T6,A50,T60,F10.1,/,T6,A50,/
               & T6,A50,T60,F10.1,/,T6,A50,T60,F10.2,/,7(T6,A50,T60,F10.1,/) )
```

**WRITE FEED PUMP PARAMETERS**

```fortran
WRITE (6,50) TITLE(7),FNAME(40),PRIN(40)
50 FORMAT(/,A80,///,T6,A50,T60,F10.2,/) 
```

**WRITE RFMD PARAMETERS**

```fortran
WRITE (6,60) TITLE(8),(FNAME(I),PRIN(I),I=41,43)
60 FORMAT(/,A80,///,T6,A50,T60,F10.1,/,2(T6,A50,T60,F10.2,/) )
```

**WRITE BOILER PARAMETERS**

```fortran
```

```fortran
```
WRITE (6,70) TITLE(9),(FNAME(I),PRIN(I),I=44,46)
.70 FORMAT(/,A80,//,T6,A50,T60,F10.1,/,T6,A50,T60,F10.2,/, & T6,A50,T60,F10.1,/)

C WRITE REHEAT PARAMETERS

WRITE (6,80) TITLE(10),(FNAME(I),PRIN(I),I=47,50)
80 FORMAT(/,A80,//,2(T6,A50,T60,FIO.I,/),T6,A50,T60,FIO.2,/, & T6,ASO,T60,FIO.I,/)  

C WRITE LINE PARAMETERS

WRITE (6,90) TITLE(11),TITLE(12),TITLE(13), & (LLBL(I),PRIN(I+50),I=I,11)
90 FORMAT(/,A80,//,A80,/A80,//,II(T6,A25,T66,FIO.1,/))

C WRITE OUTPUT FILE

WRITE(6,100) TT(O),TBOIL,XBOIL,TCON,VTIPO,DEFF*IOO.,NS, & PTEFF*IOO.,GEFF*IOO.,SCCON
100 FORMAT(/,T35,'POWER CONVERSION CYCLE PARAMETERS',//, & T10,'Turbine inlet temp  = ','F8.1,' K',T55, & 'Saturation temp   = ','F8.1,' K',/,, & T10,'Superheat/Quality = ','F8.2,' K',T55, & 'Condensor temp    = ','F8.1,' K',/,, & T10,'Tip velocity    = ','F8.1,' m/sec',T55, & 'Dry stage eff     = ','F8.1,' %',/,, & T10,'No. of stages   = ','I8,T55, & 'Pump turbine eff  = ','F8.1,' %',/,, & T10,'Generator efficiency = ','F8.1,' %',T55, & 'Condenser subcooling = ','F8.1,' K',//)  

WRITE(6,110) TT(O),TBOIL,PP(O),X(O),H(O),S(O),SVV(O)
110 FORMAT(/,T35,'TURBINE CONDITIONS AT EACH STAGE',//, & T5, 'ns',T12,'Temp',T22,'Tsat',T32,'Pres',T41,'Quality',T50, & 'Enthalpy',T61,'Entropy',T72,'Sp Vol',T84,'Eff',/,, & T12,'(K)',T22,'(K)',T31,'(kPa)',T50, '(kJ/kg)',T60, & '(kJ/kg-K)',T72,'(m3/kg)',//,T5, 'O',2FIO.I,1FIO.2,1FIO.4, & 1F10.1,1F10.4,1F10.2,1F10.4)

DO 130 N = I,RSTAGE
WRITE(6,120) N,TT(N),TSAT(N),PP(N),X(N),H(N),S(N),SVV(N),EFF(N)
120 FORMAT(T5,I2,2F10.1,1F10.2,1F10.4,1F10.1,1F10.4,1F10.2,1F10.4)
130 CONTINUE

WRITE (6,140) TTRH,TSATRH,PRSTAG,XRH,HRH,SRH,SVRH
140 FORMAT(T5,'RH',2F10.1,1F10.2,1F10.4,1F10.1,1F10.4,1F10.2,1F10.4)

DO 160 N = RSTAGE+1,NS
WRITE(6,150) N,TT(N),TSAT(N),PP(N),X(N),H(N),S(N),SVV(N),EFF(N)
150 FORMAT(T5,I2,2F10.1,1F10.2,1F10.4,1F10.1,1F10.4,1F10.2,1F10.4)

49
CONTINUE

WRITE(6,170)
170 FORMAT(/,T32,'POWER CONVERSION CYCLE CHARACTERISTICS'/)

WRITE(6,180) KWOUT,CYCEFF*100.,MQADD,PLNTEF*100.,MQREJ,
& MMAIN,GNLOSS
180 FORMAT(TIO, 'Generator output = ',FI0.2,' kWe',T55,
& 'Cycle efficiency = ',F7.2,' %'/
& TIO, 'Thermal input = ',FI0.2,' kWt',T55,
& 'Plant efficiency = ',F7.2,' %'/
& TIO, 'Condenser reject = ',FI0.2,' kWt',T55,
& 'Main vapor flow = ',F7.2,' kg/sec'/
& TIO, 'Generator losses = ',FI0.2,' kWe',//)

WRITE(6,190)
190 FORMAT(/,T39,'SCHEDULE OF PIPING RUNS',/,T39,
& 'Thermodynamic Properties',//,
& T33,'Temp',T42,'Press',T51,'Enthalpy',
& T62,'Entropy',T72,'Quality',T82,'Sp Vol '/
& ' No.',T9,'Description',T33,'(K)',T42,'(kPa)',T51,
& ' (kJ/kg)',T61,'(kJ/kg-K)',T82,'(m3/kg)',//)

DO 220 I = 1,11
WRITE(6,200) I, LLBL(I), TLI(I),PLI(I),HLI(I),SLI(I),XLI(I),SVVLI(I)

200 FORMAT(13,T8,A19,T28,1F10.I,1F10.2,1F10.I,2F10.4,IF10.3)
WRITE(6,210) TLE(I),PLE(I),HLE(I),SLE(I),XLE(I),SVVLE(I)

210 FORMAT(T4,T28,1F10.I,IF10.2,1F10.I,2F10.4,1F10.3)
220 CONTINUE

WRITE(6,230)
230 FORMAT(/,T37,'Flows & Dimensions',//,
& T44,'Flow',T53,'Length',T65,'ID',T74,'Wall',//,
& TIO, ' No.',T9,'Description',T41,'(kg/sec)',T54,
& '(m)',T64,'(cm)',T74,'(cm)',//)

WRITE(6,240) (I,LLBL(I),MF(I),LG(I),ID(I),WALL(I),I=I,11)

240 FORMAT(11(TIO, 13,T8,AI9,T38,3F10.2,1F10.3,//))

WRITE(6,250)
250 FORMAT(/,T47,'Weights',//,
& T52,'Pipe Wt',T64,'K Wt',T73,'MFI Wt',//
& TIO, ' No.',T9,'Description',T53,'(kg)',T64,'(kg)',
& T74,'(kg)',//)

WRITE(6,260) (I,LLBL(I),WT(I),WTKINV(I),WTMFI(I),I=I,11)

260 FORMAT(11(TIO, 13,T8,A19,T48,1F10.2,2F10.3,//),T8,72('_'))

WRITE(6,270) TOTWT, WTKTOT, MFITOT

270 FORMAT(/,T10, 'Totals', T48,1F10.2,2F10.3,//)

WRITE (6,275) ERRORG,WARNINGG,GENTYPE,INTTYPE,CLNTTYPE,VOLTAGE,
& KVA,KWOUT/NUMOP,RPMA,DGENRTR,TIPSPDG,MASSGEN,DGENSTR,LGENTOT,
& GENASP,COE,100.0*GEFF,COOLING,WCLNT,TINCLNT,TOUTCLNT,FPL

275 FORMAT (/,T37,'CHARACTERISTICS OF ALTERNATOR',//,
 2(T10,A64,/,T10,A20,1 IX,A20,12X,A10,//,
  T10,'Voltage'    =',F8.1,' Volts',T55,
  'Volt-Amperes'  =',F8.1,' kVA','/,
  T10,'Power      =',F8.1,' kWe',T55,
  'Speed'        =',F8.1,' rpm','/,
  T10,'Rotor Diameter' =',F8.1,' cm',T55,
  'Tip Speed'    =',F8.1,' m/s','/,
  T10,'Weight'    =',F8.1,' kg',T55,
  'Stator Diameter' =',F8.1,' cm','/,
  T10,'Total Length' =',F8.1,' cm',T55,
  'Aspect Ratio' =',F8.1',/,
  T10,'Sizing Coef.' =',F8.1,T55,
  'Efficiency'   =',F8.1,' %','/,
  T10,'Cooling Load' =',F8.1,' kWT',T55,
  'Coolant Flow' =',F8.1,' kg/s','/,
  T10,'Clnt inlet Temp.' =',F8.1,' K',T55,
  'Clnt outlet Temp.' =',F8.1,' K',/,
  T10,'Design Life' =',F8.1,' yrs')

WRITE(6,280) XX1,VTIP,TRBPWR, TORQUE, RPM, RSTT, ALPHAT, TURBW

280 FORMAT(/,T38,'CHARACTERISTICS OF TURBINE' //,
 & T10,'Constant xxl' =',F8.2,T55,
 & 'Tip velocity'    =',F8.1,' m/sec','/,
 & T10,'Power'       =',F8.1,' kW',T55,
 & 'Torque'         =',F8.1,' Nt-m','/,
 & T10,'Speed'       =',F8.1,' rpm',T55,
 & 'Spouting velocity' =',F8.1,' m/sec',/,
 & T10,'Stator angle' =',F8.1,' deg',T55,
 & 'Turbine weight' =',F8.1,' kg',/)

write(6,290) fmdel,peng,pdis,teng,ttp(2),utlim,tothp,torq,
 & pumpeff*100., xn,xnsstg(2), wf pump, nstage, ssmarg*100.,
 & xnpsha,phi(1),psi(1),dt(1),ut(1),dt(2),phi(2),
 & psi(2),ut(2)

290 format(/T36,'TURBO-FEEDPUMP CHARACTERISTICS',//,
 & T10,'Mass flow rate'    =',F8.2,' kg/sec',T55,
 & 'Inlet pressure'       =',F8.1,' kPa',/,
 & T10,'Discharge pressure' =',F8.1,' kPa',T55,
 & 'Inlet temp'           =',F8.1,' K',/,
 & T10,'Discharge temp'    =',F8.1,' K',T55,
 & 'Tip speed limit'      =',F8.1,' m/sec',/,
 & T10,'Horsepower'       =',F8.1,' kW',T55,
 & 'Torque'               =',F8.1,' Nt-m',/,
 & T10,'Efficiency'       =',F8.1,' %',T55,
 & 'Speed'                =',F8.1,' rpm',/,
 & T10,'Specific speed'    =',F8.1,T55,
 & 'Weight'               =',F8.1,' kg',/,
 & T10,'Stage number'      =',I8,T55,
 & 'NPSH margin'          =',F8.1,' %',/,
& T10,'NPSH' = ',F8.1,' m',T55,
& 'Inducer flow coef' = ',F8.4,/,T55,
& T10,'Inducer head coef' = ',F8.4,T55,
& 'Inducer tip diameter' = ',F8.2,' cm',/,'T55,
& T10,'Inducer tip speed' = ',F8.1,' m/sec',T55,
& 'Impeller tip diameter' = ',F8.2,' cm',/,'T55,
& T10,'Impeller flow coef' = ',F8.4,T55,
& 'Impeller head coef' = ',F8.4,/,T55,
& T10,'Impeller tip speed' = ',F8.1,' m/sec',/)

WRITE(6,300) HTBB,DOUTEB,DTSB,THSB,XTHKB

300 FORMAT(//,T40,'BOILER CHARACTERISTICS',/,T42,'General Dimensions',
& //,T10,'Height' = ',F8.1,' cm',T55,
& 'Diameter' = ',F8.1,' cm',/,
& T10,'Tube sheet diameter' = ',F8.1,' cm',T55,
& 'Shell thickness' = ',F8.1,' cm',/,'T55,
& T10,'Tube sheet thickness' = ',F8.1,' cm'

WRITE(6,310) NOTUBB,LPHB,LBOILB,LSHB,LTOTB,DIATB,TKTUBB,PAB

310 FORMAT(//,T43,'Tube dimensions',//,
& T10,'Number of boiler tubes' = ',F8.1,T55,
& 'Preheat length' = ',F8.1,' cm',/,'T55,
& T10,'Boiling length' = ',F8.1,' cm',T55,
& 'Superheat length' = ',F8.1,' cm',/,'T55,
& T10,'Total tube length' = ',F8.1,' cm',T55,
& 'Tube inside diameter' = ',F8.2,' cm',/,'T55,
& T10,'Tube wall thickness' = ',F8.3,' cm',T55,
& 'Tube pitch' = ',F8.3,' cm',/)

WRITE(6,320) HLILIB,HKPHB,HKBOIB,HKSHB

320 FORMAT(/,T32,'Summary of Heat Transfer Coefficients',//,
& T10,'Li side' = ',F8.1,' kW/m2-K',T55,
& 'K preheat' = ',F8.1,' kW/m2-K',/,
& T10,'K boiling' = ',F8.1,' kW/m2-K',T55,
& 'K superheat' = ',F8.1,' kW/m2-K',/)

WRITE(6,330) DLPBB,PLE(II),PLI(1),DPTOTB

330 FORMAT(/,T41,'Summary of Pressures',//,
& T10,'Li side pressure drop' = ',F8.2,' kPa',T55,
& 'Boiler inlet pressure' = ',F8.1,' kPa',/,
& T10,'Boiler outlet pressure' = ',F8.1,' kPa',T55,
& 'Boiler pressure drop' = ',F8.2,' kPa',/)

WRITE(6,340) WSHELB,WTUBEW,WTAPEB,WTTSB,
& WTCLOB,MIWTB,WBOILB,WPTOTB,WTLIB,WTWETB

340 FORMAT(/,T38,'Summary of boiler weights',//,
& T10,'Shell' = ',F8.1,' kg',T55,
& 'Boiler tubes' = ',F8.1,' kg',/,
& T10,'Twisted tapes' = ',F8.1,' kg',T55,
& 'Tube sheets' = ',F8.1,' kg',/,
& T10,'Heads' = ',F8.1,' kg',T55,
& 'Multifoil insulation' = ',F8.1,' kg',/,
& T10,'Total dry weight' = ',F8.1,' kg',T55,
& 'Weight of Potassium' = ',F8.1,' kg',/,
& T10,'Weight of lithium = ',F8.1,' kg',T55,
& 'Wet weight of boiler = ',F8.1,' kg')

C Now for the reheater

WRITE(6,350) HTBR,DOUTER,DTSR,THSR,XTHKR
350 FORMAT(/,T39,'REHEATER CHARACTERISTICS',/,,
& T42,'General Dimensions',/,,
& T10,'Height = ',F8.1,' cm',T55,
& 'Diameter = ',F8.1,' cm',/,,
& T10,'Tube sheet diameter = ',F8.1,' cm',T55,
& 'Shell thickness = ',F8.1,' cm',/,,
& T10,'Tube sheet thickness = ',F8.1,' cm')

WRITE(6,360) NOTUBR,LPHR,LBOILR,LSHR,LTOTR,DIARH,TKTUBR,PAR
360 FORMAT(/,T43,'Tube dimensions',/,,
& T10,'Number of reheater tubes = ',F8.1,T55,
& 'Preheat length = ',F8.1,' cm',/,,
& T10,'Boiling length = ',F8.1,' cm',T55,
& 'Superheat length = ',F8.1,' cm',/,,
& T10,'Total tube length = ',F8.1,' cm',T55,
& 'Tube inside diameter = ',F8.2,' cm',/,,
& T10,'Tube wall thickness = ',F8.3,' cm',/,,
& 'Tube pitch = ',F8.3,' cm')

WRITE(6,370) HLILIR,HKPHR,HKBOIR,HKSHR
370 FORMAT(/,T32,'Summary of Heat Transfer Coefficients',//,,
& T10,'Li side - ',F8.1,' kW/m2-K',T55,
& 'K preheat = ',F8.1,' kW/m2-K',/,,
& T10,'K boiling - ',F8.1,' kW/m2-K',T55,
& 'K superheat = ',F8.1,' kW/m2-K')

WRITE(6,380) DLPBR,PLE(6),PLI(7),DPTOTR
380 FORMAT(/,T41,'Summary of Pressures',/,,
& T10,'Li side pressure drop = ',F8.2,' kPa',T55,
& 'Reheater inlet pressure = ',F8.1,' kPa',/,,
& T10,'Reheater outlet pressure = ',F8.1,' kPa',T55,
& 'Reheater pressure drop = ',F8.2,' kPa')

WRITE(6,390) WSHELR,WTUBER,WTAPER,WTTSR,
& WTCOR,MTWTR,WRHT,WTPOTR,WTLIR,WTWETR
390 FORMAT(/,T37,'Summary of reheater weights',/,,
& T10,'Shell = ',F8.1,' kg',T55,
& 'Reheater tubes = ',F8.1,' kg',/,,
& T10,'Twisted tapes = ',F8.1,' kg',T55,
& 'Tube sheets = ',F8.1,' kg',/,,
& T10,'Heads = ',F8.1,' kg',T55,
& 'Multifoil insulation = ',F8.1,' kg',/,,
& T10,'Total dry weight = ',F8.1,' kg',T55,
& 'Weight of Potassium = ',F8.1,' kg',/,,
& T10,'Weight of lithium = ',F8.1,' kg',T55,
& 'Wet weight of reheater = ',F8.1,' kg')

C SYSTEM OUTPUT
WRITE (6,400) WTWETB, WTWETR, WTURBN, ALTWT, WTPUMP, 
&WTRFMD, TOTWT, WTKTOT, PCSACM, WTPCS

400 FORMAT(/, T34, 'MASS OF POWER CONVERSION SUBSYSTEM', //,
& T29, 'Component ', T64, 'Mass (KG)', //,
& T29, 'Boiler (wet) ', T64, F8.1, //,
& T29, 'Reheater (wet) ', T64, F8.1, //,
2 T29, 'Turbines ', T64, F8.1, //,
& T29, 'Alternator ', T64, F8.1, //,
& T29, 'Feed Turbo-pumps ', T64, F8.1, //,
& T29, 'RFMDs ', T64, F8.1, //,
& T29, 'K piping ', T64, F8.1, //,
& T29, 'K inventory ', T64, F8.1, //,
& T29, 'Accumulators ', T64, F8.1, //; T27, 45('_'), //,
& T29, 'Total ', T64, F8.1, //)

WRITE(6,410) SPMASS, EFFNET, EFFGRS, TITCON

410 FORMAT(/, T34, 'SYSTEM PERFORMANCE CHARACTERISTICS', //,
& T29, 'Specific Mass (kg/kWe)', T64, F8.3, /,
& T29, 'Net Efficiency (%)', T64, F8.3, /,
& T29, 'Gross Efficiency (%)', T64, F8.3, /,
& T29, 'TIT/TCON', T64, F8.3, /)

RETURN
END
SUBROUTINE KRANK
IMPLICIT DOUBLE PRECISION (A-H,O-Z)

DOUBLE PRECISION LGENTOT,MASSGEN,KVA,KWOUT,KA,NUMOP,NUMTOT,
& KNET,NOTUBB,NOTUBR, LG,MMAIN, MF, ID, MFIOT,
& MQADD, MQREJ, LPHB, LBOILB, LSHB, LTOTB, MFIWTB, LPHR,
& LBOILR, LSHR, LTOTR, MFIWTR, MFIOPT

CHARACTER CLNTYPE*1O, GENTYPE*20, INTTYPE*20, ERRORG*64, WARNINGG*64

INTEGER REHEAT,RSTAGE

PARAMETER (NSTG=15)

COMMON /INPUT/ FPL, VELV, VELM, VELL, TMAT, XMATH, XMATC, DUM1, DUM2, KA,
& KB, NUMOP, NUMTOT, TROUT, TRIN, KNET, GEFF, DUM3, BPP, BFP,
& BPL, PWRCTR, VOLTAGE, GENASP, TINCLNT, TOUTCLNT,
& CPCNLT, TBOIL, XBOIL, DUM4, TCON, DEFF, ELSS, VTIPO,
& SCCON, ALPHAT, RSTT, XMFI, DCON, PTEFF, DPRFMD, EFFRFD,
& EMRFMD, DPMAXB, DIATB, NOTUBB, DPMAXR, DTRH, DIARH,
& NOTUBR, LG(11)

COMMON /OUTPUT/MMAIN, TT(0:15), PP(0:15), H(0:15), S(0:15), X(0:15),
& SVV(0:15), TLI(11), TLE(11), P1(11), PLE(11), HLI(11),
& HLE(11), SLI(11), SLE(11), XLI(11), XLE(11), SWVL(11),
& SVVLE(11), MF(11), WALL(11), WT(11), WTKINV(11), ID(11),
& DPTOTB, WTKTB, TOTWI, TTRH, DPTOTR, NS, WTMFI(11),
& MFIOT, PENG, TENG, FMDEL, PDIS, UTLIM, TTP(NSTG), XNPSHA,
& DT(NSTG), UT(NSTG), PHI(NSTG), NSTAGE, PSI(NSTG), XN,
& TOTHP, PUMPEFF, SSMARG, XNSSTG(NSTG), WFPUMP, TORQ,
& KWOUT, ALTWT, CYCEFF, PCSACM, MQADD, MQREJ, PRSTAG,
& WTRMD, WTRBN, XRH, EFF(0:15), DLPBB, WBOILB, WTWEB,
& DLPBR, WRHT, WTRR, HTBB, DOUTE, DTSB, THSB, XTHKB, LPBB,
& LBOILB, LSHB, LTOTB, TKTUB, PAB, HLILB, HKPHB, HKBOIB,
& HKSHB, WSHLB, WTUBE, WTAPEB, WTTSB, WTCLOB, MFIWTB,
& WTPOTB, WTLIB, HTBR, DOUTER, DTSR, THSR, XTHKB, LPHR,
& LBOILR, LSHR, LTOTR, TKTUBR, PAR, HLILR, HKPHR, HKBOIR,
& HKSHR, WSHLB, WTUBER, WTAPER, WTTSR, WTCLOR, MFIWTR,
& WTPOTR, WTLIR, WTPCS, SPMASS, EFFNET, EFFGRS, WTPUMP,
& TITCON, PLNTEF, GNLOSS, TORQUE, TRBPWR, XX1, TURBWT, RPM,
& SVRH, TSATRH, HRH, SRH, TSAT(0:15), VTIP, DGENRTR, KVA,
& DGENSTR, LGENTOT, MASSGEN, TIPSPDG, COE, COOLING, WCLNT

COMMON /SYSTM/ MFLOPT, CFSLI(11), CFSLE(11), DELPL(11), DELHL(11), MFI,
& TPUMP, HPUMP, SFPU, WFPUMP, WKRFD, PI, G, TOL, XLAMIN,
& XLAMOUT, EFFIND, HCIND, XLASS, PT(NSTG), PS(NSTG),
& HT(NSTG), XIH(NSTG), HSP(NSTG), ST(NSTG), TS(NSTG),
& RHO(NSTG), CM(NSTG), XNSS, DH(NSTG), B2(NSTG),
& F3S(NSTG), XMARG, XNPSHA, XNPSHOP, HD(NSTG),
& EFFP(0:NSTG), HP(NSTG), XIMPSS, XNSSIP, QBOILL,
& QRLS, PEFF, RPM, VPOTSB, VPOTS, XRHEAT, PTI, FRACRH,
& RSTAGE, TTI, TFW, FLOC, TBOUT, TBLIN, TRHOUT, TRHIN,
& REHEAT, MATH, MATC, RPM

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COMMON/CONFIG/GENTYPE,INTTYPE,CLNTTYPE
COMMON/DIAGNOS/ERRORG,WARNINGG

*****  **********************************************************************************************************************

C CONVERT UNITS OF GENERAL INPUT PARAMETERS

VELV = VELV*3.281DO
VELM = VELM*3.281DO
VELL = VELL*3.281DO
TMAT = TMAT*1.8DO
KA = KA/1.73DO
KB = KB/1.73DO
MATH = IDINT(XMATH)
MATC = IDINT(XMATC)

C CONVERT UNITS OF REACTOR INPUT PARAMETERS

TROUT = 1.8DO*TROUT
TRIN = 1.8DO*TRIN
KWOUT = (KWNET + BPP + BFP + BPL)*1.02DO

C CONVERT UNITS OF ALTERNATOR INPUT PARAMETERS

TINCLNT = 1.8DO*TINCLNT
TOUTCLNT = 1.8DO*TOUTCLNT
CPCLNT = CPCLNT/4.185DO

C CONVERT UNITS OF TURBINE INPUT PARAMETERS

TBOIL = TBOIL*1.8DO
IF (XBOIL .GT. 1) XBOIL = XBOIL*1.8DO
TCON = TCON*1.8DO
SCCON = SCCON*1.8DO
MFI = IDINT(XMFI)
EXLOSS = 0.43*EXLOSS
VTIPO = 3.28*VTIPO
RSTT = 3.28*RSTT
DPCON = 0.145*DPCON

C CONVERT UNITS OF RFMD INPUT PARAMETERS

DPRFMD = 0.145*DPRFMD

C CONVERT UNITS

DPMAXB = 0.145*DPMAXB
DPBOIL = DPMAXB
DIATB = 0.3937*DIATB

C CONVERT UNITS

DPMAXR = 0.145*DPMAXR

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DPRH = DPMAXR  
DTRH = DTRH*1.8  
DIARH = 0.3937*DIARH  

C convert units  

DO 10 I = 1,11  
10 LG(I) = 3.28*LG(I)  

****** ************  

C CALL PROCESS SUBROUTINES  

DO 20 J = 1,10  

CALL SYSTEM  
CALL GENRTR  

TAVLI = (TRIN + TROUT)/2.DO  
CALL LIPORT (TAVLI,MULI,KLI,CPLI,RHOLI,P)  
PMIN = P*14.696DO  
FLOC = (MQADD + QBOILL + QRHLSS)/(CPLI*(TROUT - TRIN))  
KWOUT = (KWNET + BPP + BFP + BPL)*1.02DO  

****** ************  

TBLIN = TROUT  
TBLOUT = TROUT*FRACRH + (1.DO - FRACRH)*TRIN  
REHEAT = 0  
CALL BOILER  

TRHOUT = TRIN  
TRHIN = TBLOUT  
REHEAT = 1  

CALL BOILER  

20 CONTINUE  

****** ************  

C CONVERT MASS UNITS  

WTWETB = WTWETB/2.205DO  
WTURBN = WTRUBN/2.205DO  
WTPUMP = WTPUMP/2.205DO  
TOTWT = TOTWT/2.205DO  
WTKTOT = WTKTOT/2.205DO  
MFITOT = MFITOT/2.205DO  
ALTWT = ALTWT/2.205DO  
WTWETR = WTWETR/2.205DO  
WTRFMD = WTRFMD/2.205DO  
PCSACM = PCSACM/2.205DO  

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C TOTAL MASS

\[ WTPCS = WTURBN + ALTWT + WTPUMP + TOTWT + WTKTOT + MFITOT + \]
\[ & PCSACM + WTRFMD + WTWETB + WTWETR \]

C Compute system performance characteristics

\[ PWRT = (MQADD + QBOILL + QRHLSS) \times 3.6D0/3.413D0 \]
\[ SPMASS = WTPCS/KWNET \]
\[ EFFNET = KWNET/PWRT*1.2 \]
\[ EFFGRS = KWOUT/PWRT*1.2 \]
\[ TITCON = TBOIL/TCON \]

***** ****************************

C CONVERT UNITS OF GENERAL INPUT PARAMETERS

\[ VELV = VELV/3.281D0 \]
\[ VELM = VELM/3.281D0 \]
\[ VELL = VELL/3.281D0 \]
\[ TMAT = TMAT/1.8D0 \]
\[ KA = KA*1.73D0 \]
\[ KB = KB*1.73D0 \]

C CONVERT UNITS OF REACTOR INPUT PARAMETERS

\[ TROUT = TROUT/1.8D0 \]
\[ TRIN = TRIN/1.8D0 \]

C CONVERT UNITS OF ALTERNATOR INPUT PARAMETERS

\[ TINCLNT = TINCLNT/1.8D0 \]
\[ TOUTCLNT = TOUTCLNT/1.8D0 \]
\[ CPCLNT = CPCLNT*4.185D0 \]

C CONVERT UNITS OF TURBINE INPUT PARAMETERS

\[ TBOIL = TBOIL/1.8D0 \]
\[ IF (XBOIL .GT. 1) XBOIL = XBOIL/1.8D0 \]
\[ TCON = TCON/1.8D0 \]
\[ SCCON = SCCON/1.8D0 \]
\[ EXLOSS = EXLOSS/0.43 \]
\[ VTIPO = VTIPO/3.28 \]
\[ VTIP = VTIP/3.28 \]
\[ RSTT = RSTT/3.28 \]
\[ DPCON = DPCON/0.145 \]

C CONVERT UNITS OF RFMD INPUT PARAMETERS

\[ DPRFMD = DPRFMD/0.145 \]

C CONVERT UNITS

\[ DPMAXB = DPMAXB/0.145 \]

58
DPBOIL = DPMAXB
DIATB = DIATB/0.3937

C CONVERT UNITS

DPMAXR = DPMAXR/0.145
DPRH = DPMAXR
DTRH = DTRH/1.8
DIARH = DIARH/0.3937

C convert units

DO 30 I = 1,11
30 LG(I) = LG(I)/3.28

C CONVERT OUTPUT UNITS TO SI

MMAIN = MMAIN/2.205

DO 40 I = 0,15
TT(I) = TT(I)/1.8
TSAT(I) = TSAT(I)/1.8
PP(I) = PP(I)/0.145
H(I) = H(I)*2.325
S(I) = S(I)*4.185
SVV(I) = SVV(I)*0.0624
40 CONTINUE

DO 50 I = 1,11
TLI(I) = TLI(I)/1.8
TLE(I) = TLE(I)/1.8
PLI(I) = PLI(I)/0.145
PLE(I) = PLE(I)/0.145
HLI(I) = HLI(I)*2.325
HLE(I) = HLE(I)*2.325
SLI(I) = SLI(I)*4.185
SLE(I) = SLE(I)*4.185
SVVLI(I) = SVVLI(I)*0.0624
SVVLE(I) = SVVLE(I)*0.0624
MF(I) = MF(I)/2.205
WALL(I) = WALL(I)*2.54
WT(I) = WT(I)/2.205
WTINV(I) = WTINV(I)/2.205
ID(I) = ID(I)*2.54
WTMFI(I) = WTMFI(I)/2.205
50 CONTINUE

DO 60 I = 1,NSTG
TTP(I) = TTP(I)/1.8
DT(I) = DT(I)*2.54
UT(I) = UT(I)*0.3048
60 CONTINUE

DPTOTB = DPTOTB/0.145
TTRH = TTRH/1.8
DPTOTR = DPTOTR/0.145
PENG = PENG/0.145
TENG = TENG/1.8
FMDEL = FMDEL/2.205
PDIS = PDIS/0.145
UTLIM = UTLIM*0.3048
XNPSHA = XNPSHA*0.3048
TOTHP = TOTHP*0.745
TORQ = TORQ*1.356
MQADD = MQADD*1.0545
MQREJ = MQREJ*1.0545
PRSTAG = PRSTAG/0.145
DLPBB = DLPBB/0.145
WBOILB = WBOILB/2.205
DLPBR = DLPBR/0.145
WRHT = WRHT/2.205
HTBB = HTBB*2.54
DOUTEB = DOUTEB*2.54
DTSB = DTSB*2.54
THSB = THSB*2.54
XTHKB = XTHKB*2.54
LPHB = LPHB*2.54
LBOILB = LBOILB*2.54
LSHB = LSHB*2.54
LTOTB = LTOTB*2.54
TKTUBB = TKTUBB*2.54
PAB = PAB*2.54
HLILIB = HLILIB*2942.0
HKPHB = HKPHB*2942.0
HKBOIB = HKBOIB*2942.0
HKSHB = HKSHB*2942.0
WSHELB = WSHELB/2.205
WTUEB = WTUEB/2.205
WTAPEB = WTAPEB/2.205
WTTSB = WTTSB/2.205
WTTCLOB = WTTCLOB/2.205
MIWITB = MIWITB/2.205
WTPOTB = WTPOTB/2.205
WTLIB = WTLIB/2.205
HTBR = HTBR*2.54
DOUTER = DOUTER*2.54
DTSR = DTSR*2.54
THSR = THSR*2.54
XTHKR = XTHKR*2.54
LPHR = LPHR*2.54
LBOILR = LBOILR*2.54
LSHR = LSHR*2.54
LTOTR = LTOTR*2.54
TKTUBR = TKTUBR*2.54
PAR = PAR*2.54
HLILIR = HLILIR*2942.0
HKPHR = HKPHR*2942.0
HKBOIR = HKBOIR*2942.0
HKSHR  =  HKSHR*2942.0
WSHEL =  WSHELR/2.205
WTUBER =  WTUBER/2.205
WTAPER =  WTAPER/2.205
WTTSR =  WTTSR/2.205
WTCLOR =  WTCLOR/2.205
MFIWTR =  MFIWTR/2.205
WTPOTR =  WTPOTR/2.205
WTLIR =  WTLIR/2.205
TORQUE =  TORQUE*1.356
TRBPWR =  TRBPWR*0.745
TURBWT =  TURBWT/2.205
MASSGEN =  MASSGEN/2.205
WFPUMP =  WFPUMP/2.205
SVRH  =  SVRH*0.0624
TSATRH =  TSATRH/1.8
HRH   =  HRH*2.325
SRH   =  SRH*4.185
DGENVTR =  DGENVTR*2.54
TIPSPDG =  TIPSPDG*0.3048
DGENVST =  DGENVST*2.54
LGENTOT =  LGENTOT*2.54
WCLNT =  WCLNT/2.205

RETURN
END
SUBROUTINE SYSTEM
C TYPE STATEMENTS BY COMMON BLOCKS

IMPLICIT DOUBLE PRECISION (A-Y)

INTEGER I,J,K,M,N,RSTAGE,NP,NS,MFI,KRH,KSH,NSRH,NSTG,NSTAGE,
& REHEAT,MATH,MATC,NMATH,NMATC

*****=================================================================================

C DIMENSIONS BY COMMON BLOCKS

DIMENSION TY(II),DELHT(O:IS),FLOW(O:IS),MFL0(O:IS),WORKS(15)

*****=================================================================================

PARAMETER (NSTG=15)

COMMON /INPUT/ FPL,VELV,VELM,VELL,TMAT,XMATH,XMATC,DUM1,DUM2,KA,
& KB,NUMOP,NUMTOT,TROUT,TRIN,KWNET,GEFF,DUM3,BPP,BFP,
& BPL,PWRFCTR,VOLTAGE,GENASP,TINCLN,TOUTCLN,
& CPCLN,TBOIL,DBOIL,DUM4,TCON,DEFF,EXLOSS,VTIP0,
& SCCON,ALPHAT,RSTT,XMFI,DPF0,PTEFF,DERFMD,ERFM0D,
& EMRFMD,DPMAXB,DIA0B,NOTUBB,DPMAXR,DTHR,DIA0R,
& NOTUBR,KG(11)

COMMON /OUTPUT/MMAIN,TT(O:I5),PP(O:IS),H(O:IS),S(O:IS),X(0:15),
& SVV(O:IS),TLI(II),TLE(II),PLI(II),PLE(II),HLI(II),
& HLE(II),SLI(II),SLE(II),XLI(II),XLE(II),SVVLI(II),
& SVVLE(II),MF(II),WALL(II),WT(II),WTKINV(II),ID(II),
& DPTOTB,WTKTOT,TOTW,DFOTR,NS,WMTFI(II),
& MFIT0T,PENG,TENG,FMD0L,PD0L,UTL0M,TPP(NSTG),XNPSHA,
& DT(NSTG),UT(NSTG),PHI(NSTG),NSTAGE,PSI(NSTG),XN,
& TOTHP,PUMPEFF,SSM0RG,XNSSTG(NSTG),WFPUMP,TORQ,
& KWOUT,ALTWT,CYEFF,PCSACM,MQADD,MQREJ,PRSTAG,
& WTRFM0D,WTURBN,XRH,EFF(O:15),DLPBB,WBOILB,WTWETB,
& DLPBB,WRHT,WTWETR,HBB,DOUTEB,DTSR,HTSR,XTHKR,LPRH,
& LBOILR,LSHR,LTOR,TKTRB,PAR,HLILB,HPHBR,HPKBOI,
& HKSHR,WSHBE,WUT0B,WT9AB,WTCS0B,MFIWBT,
& WTP0TB,WT0BL,HT0BR,DOUTER,DTSR,HTSR,XTHKR,LPRH,
& LBOILR,LSHR,LT0R,TKTRB,PAR,HLILR,HPHHR,HPKHIR,
& HKSHR,WSHLR,WTUR0R,WTAC0R,WTCS0R,MFIWTR,
& WTP0TR,WT0LR,WT0CS,SPMASS,EFFNET,EFFG0S,WPUMP,
& TITCON,PLTNF,E0L0SS,T0RQ,TRBPWR,X1,TURBWT,RP0M,
& SVRH,TSATRH,HRH,SRH,TSAT(O:15),VTIP,DGEN0TR,KVA,
& DGENSTR,LT0T0NT,MASS0G,TIPSPDG,COE,COOLING,WCLNT

COMMON /SYST0M/ MFL0PT,CFSLI(II),CFSLE(II),DELPL(II),DELHL(II),MFI,
& T0PUMP,H0PUMP,SPF0MP,VPF0MP,W0RFMD,PT,IG,TOL,XLAMIN,
& XLAM0UT,EFFIND,HCIND,KXLOSS,PT(NSTG),PS(NSTG),
& HT(NSTG),XIHT(NSTG),HSP(NSTG),ST(NSTG),TS(NSTG),
& RH0(NSTG),CM(NSTG),XNSS,DX(NSTG),B2(NSTG),
& F3S(NSTG),XMARG,XNP0SHA,XNP0SHOP,HD(NSTG),
PI = 3.141592654
KRH = 0

C TEST FOR SUPERHEAT

T = TBOIL
KSH = 0
CALL KTHRMO(KSH,T,P,VF,VG,HF,HG,HFG,SF,SG,SFG)
TT(0) = T
PP(0) = 14.696*P
H(0) = HF + XBOIL*HFG
S(0) = SF + XBOIL*SFG
X(0) = XBOIL
SVV(0) = VF + X(0)*(VG - VF)

IF (XBOIL .GT. 1.D0) THEN
T = TBOIL + XBOIL
KSH = 1
CALL KTHRMO(KSH,T,P,VF,VG,HF,HG,HFG,SF,SG,SFG)
TT(0) = T
H(0) = HG
S(0) = SG
X(0) = 1.D0
SVV(0) = VG
ENDIF

TTI = TT(0)
PTI = PP(0)

T = TCON
KSH = 0
CALL KTHRMO(KSH,T,P,VF,VG,HF,HG,HFG,SF,SG,SFG)

SFCON = SF
SFGCON = SFG
HFCON = HF
HFGCON = HFG

XX = (S(0) - SFCON)/SFGCON
HH = HFCON + XX*HFGCON
D = H(0) - HH - DRISD1 + DRISD2

L = RSTT**2.DO/(64.348*778.16) - 1.25
XNS = 1.1DO*D/L
NS = NINT(XNS)
XRHEAT = DFLOAT(NS)/2.DO

160 DELTS = (TBOIL - TCON)/NS
   TEMP = TBOIL

   DO 170 N=1,NS
   TEMP = TEMP - DELTS
   T = TEMP
   KSH = 0
   CALL KTHRMO(KSH,T,P,VF,VG,HG,HFG,SG,SFG)
   PP(N) = 14.696*P

170 CONTINUE

   DO 295 N = 1,NS
   P = PP(N)/14.696
   CALL TFROMP(P,TSAT(N))
   KSH = 0
   CALL KTHRMO(KSH,TSAT(N),P,VF,VG,HG,HFG,SG,SFG)

C TEST FOR SUPERHEAT

   HIN = H(N-I)
   SIN = S(N-I)

173 IF(SIN .GT. SG) THEN
   CALL TFRMSG(SIN,P,T,HG,VG,VF)
   EFF(N) = DEFF
   H(N) = HIN - (HIN - HG)*EFF(N)
   CALL TFRMHG(H(N),P,T,SG,VG,VF)
   TT(N) = T
   X(N) = 1.0
   S(N) = SG
   SVV(N) = VG
   ELSE

180 XS = (SIN - SF)/SFG
   HS = HF + XS*HFG
   H(N) = (HIN - (HIN - HS)*(DEFF - 1.0 + X(N-I)/2.0 -
   & HF/(2.0*HFG))/1.0 + (HIN - HS)/(2.0*HFG))

   IF (H(N) .GE. HG) THEN
   EFF(N) = DEFF
   X(N) = 1.0
   H(N) = HIN - EFF(N)*(HIN - HS)
   CALL TFRMHG(H(N),P,T,SG,VG,VF)
   S(N) = SG
   TT(N) = T
   SVV(N) = VG
   ELSE

ELSE
\[
X(N) = \frac{(H(N) - HF)}{HFG}
\]
\[
EFF(N) = DEFF - 1.0 + \frac{(X(N-1) + X(N))}{2.0}
\]
\[
TT(N) = TSAT(N)
\]
\[
S(N) = SF + X(N)*SFG
\]
\[
SVV(N) = VF + X(N)*(VG - VF)
\]

ENDIF
ENDIF

IF (N .EQ. RSTAGE) THEN
    \[
    H(N) = H(N) + EXLOSS
    \]
    \[
    X(N) = \frac{(H(N) - HF)}{HFG}
    \]
    \[
    SVV(N) = VF + X(N)*(VG-VF)
    \]
    \[
    S(N) = SF + X(N)*SFG
    \]
ENDIF

181
\[
DELHT(N) = H(N-1) - H(N)
\]

IF ((DFLOAT(N) .GE. XRHEAT) .AND. (KRH .EQ. 0)) THEN
    KRH = 1
    RSTAGE = N
    PLI(4) = PP(N)
    TLI(4) = TT(N)
    HLI(4) = H(N)
    SLI(4) = S(N)
    XLI(4) = X(N)
    SVVLI(4) = SVV(N)
    XQUAL = (S(O) - SF)/SFG
    HHQUAL = HF + XQUAL*HFG
    DRI(S) = HHQUAL - HH
    IF (PLE(7) .EQ. 0.0) PLE(7) = PP(N)
    PRSTAG = PP(N) - DELPL(4) - DELPL(6) - DELPL(7) - DPTOTR
    P = PRSTAG/14.696
    CALL TFROMP(P,T)
    TSATRH = T
    TTRH = T + DTRH
    KSH = 1
    CALL KTHRMO(KSH,TTRH,P,VF,VG,HF,HG,HFG,SF,SG,SFG)
    IF (HLI(7) .EQ. 0.0) HLI(7) = HG
    IF (HLE(6) .EQ. 0.0) HLE(6) = H(N)
    DELRH = HLI(7) - HLE(6)
    HRH = HG
    SRH = SG
    XRH = 1.0
    SVRH = VG
    GOTO 300
ENDIF
295 CONTINUE

300 CONTINUE

XX = (SRH - SFCON)/SFGCON
HH = HFCON + XX*HFGCON
D = HRH - HH
DRISD2 = D
L = RSTT**2.DO/(64.348*778.16) - 1.25
XNSRH = 1.1*D/L
NSRH = NINT(XNSRH)
NS = RSTAGE + NSRH

310 DELTS = (TSATRH - TCON)/NSRH
TEMP = TSATRH

DO 320 N = RSTAGE+1,NS
TEMP = TEMP - DELTS
T = TEMP
KSH = 0
CALL KTHRMO(KSH,T,P,VF,VG,HF,HG,HFG,SG,SFG)
PP(N) = 14.696*P
320 CONTINUE

DO 330 N = RSTAGE+1,NS
P = PP(N)/14.696
CALL TFROMP(P,TSAT(N))
KSH = 0
CALL KTHRMO(KSH,TSAT(N),P,VF,VG,HF,HG,HFG,SG,SFG)

C Test for Superheat

HIN = H(N-1)
SIN = S(N-1)
XIN = X(N-1)

IF ((N-1).EQ. RSTAGE) THEN
HIN = HRH
SIN = SRH
XIN = XRH
ENDIF

340 IF(SIN .GT. SG) THEN
CALL TFRMSG (SIN,P,T,HG,VG,VF)
EFF(N) = DEFF
H(N) = HIN - (HIN - HG)*EFF(N)
CALL TFRMHG (H(N),P,T,SG,VG,VF)
TT(N) = T
X(N) = 1.0
S(N) = SG
SVV(N) = VG
ELSE
XS = (SIN - SF)/SFG
HS = HF + XS*HFG
H(N) = (HIN - (HIN - HS)*(DEFF - 1.0 + XIN/2.0 -
& HF/(2.0*HFG))/(1.0 + (HIN - HS)/(2.0*HFG)))

IF (H(N) .GE. HG) THEN
EFF(N) = DEFF
X(N) = 1.0
H(N) = HIN - EFF(N)*(HIN - HS)
CALL TFRMHG (H(N),P,T,SG,VG,VF)
S(N) = SG
TT(N) = T
SVV(N) = VG

ELSE

X(N) = (H(N) - HF)/HFG
EFF(N) = DEFF - 1.0 + (XIN + X(N))/2.0
TT(N) = TSAT(N)
S(N) = SF + X(N)*SFG
SVV(N) = VF + X(N)*(VG - VF)
ENDIF
ENDIF

IF (N .EQ. NS) THEN
H(N) = H(N) + EXLOSS
X(N) = (H(N) - HF)/HFG
SVV(N) = VF + X(N)*(VG-VF)
S(N) = SF + X(N)*SFG
ENDIF

360 DELHT(N) = HIN - H(N)
330 CONTINUE

IF (PLI(5) .EQ. 0.0) PLI(5) = PLI(4)
390 PTOUT = PLI(5)
IF (PLE(3) .EQ. 0.0) PLE(3) = PP(0)
PTIN = PLE(3)
IF (TLE(3) .EQ. 0.0) TLE(3) = TT(0)
TIN = TLE(3)
IF (HLE(3) .EQ. 0.0) HLE(3) = H(0)
HIN = HLE(3)
IF (SLE(3) .EQ. 0.0) SLE(3) = S(0)
SIN = SLE(3)
P = PTOUT/14.696
CALL TFROMP(P,T)
KSH = 0
CALL KTHRMO(KSH,T,P,VF,VG,HF,HG,HFG,SF,SG,SFG)
TLI(5) = T
XS = (SIN - SF)/SFG
HS = HF + XS*HFG
HLI(5) = HIN - (HIN - HS)*PTEFF
XLI(5) = (HLI(5) - HF)/HFG
SLI(5) = SF + XLI(5)*SFG
SVVLI(5) = VF + XLI(5)*(VG - VF)
IF (TLE(IO) .EQ. 0.0) TLE(IO) = TCON - SCCON
T = TLE(IO)
THW = T
IF (PLE(IO) .EQ. 0.0) PLE(IO) = PP(NS) + DPRFMD
\[ PHW = PLE(10) \]
\[ P = PHW/14.696 \]
\[ \text{CALL KTHRML (T,P,VF,HF,SF)} \]
\[ VFHW = VF \]
\[ HHW = HF \]
\[ SHW = SF \]

\[ \text{IF (PLI(11) .EQ. 0.0) PLI(11) = PP(0)} \]
\[ \text{FMDEL = MF(10)} \]
\[ \text{IF (FMDEL .EQ. 0.0) FMDEL = 5.0D0} \]
\[ \text{PENG = PLE(10)} \]
\[ \text{TENG = TLE(10)} \]
\[ \text{PDIS = PLI(11)} \]
\[ \text{CALL PSIZE} \]
\[ \text{TREF = 2.7D3} \]
\[ \text{NMATH = 1} \]
\[ \text{NMATC = 2} \]
\[ \text{CALL STRNTH (TREF, TMAT, NMATH, NMATC, FPL, SIGPV, RHOAST)} \]
\[ \text{STRHO = SIGPV/RHOAST} \]
\[ \text{CALL STRNTH (TT(0), TMAT, MATH, MATC, FPL, SIGPV, RHOAST)} \]
\[ \text{WFPUMP = WFPUMP*SIGPV/(RHOAST*STRHO)} \]

\[ \text{WORKP} = \text{TOTH∀*550.DO}/(778.DO*FMDEL) \]
\[ \text{WRKSHT} = \text{WORKP} \]
\[ \text{HPUMP} = \text{HHW} + \text{WRKSHT} \]
\[ \text{HH} = \text{HPUMP} \]
\[ \text{T} = \text{THW} \]
\[ \text{P} = \text{PLI(11)/14.696} \]
\[ \text{CALL TFRMHF(HH,T,P,VF,SF)} \]
\[ \text{TPUMP} = \text{T} \]
\[ \text{TFW} = \text{TPUMP} \]
\[ \text{VFPUMP} = \text{VF} \]
\[ \text{SFPUMP} = \text{SF} \]
\[ \text{FLOWPT} = \text{WRKSHT}/(\text{HIN} - \text{HLI(5)}) \]
\[ \text{FLOW(0)} = 1.0 - \text{FLOWPT} \]
\[ \text{WORK} = 0.0 \]

\[ \text{DO} 545 \text{ I = 1,NS} \]
\[ \text{FLOW(I)} = \text{FLOW(I-1)} \]
\[ \text{IF (I .EQ. (RSTAGE + 1)) FLOW(I) = FLOW(I-1) + FLOWPT} \]
\[ \text{WORKS(I)} = \text{FLOW(I)*DELHT(I)} \]
\[ \text{WORK} = \text{WORK} + \text{WORKS(I)} \]

\[ \text{545 CONTINUE} \]

\[ \text{IF (HLI(1) .EQ. 0.0) HLI(1) = H(0)} \]
\[ \text{IF (HLE(11) .EQ. 0.0) HLE(11) = HPUMP} \]

\[ \text{555 QADD = HLI(1) - HLE(11) + DELRH} \]
\[ \text{IF (HLE(8) .EQ. 0.0) HLE(8) = H(NS)} \]
\[ \text{IF (HLI(9) .EQ. 0.0) HLI(9) = HHW} \]
\[ \text{QREJ = FLOW(NS)*(HLE(8) - HLI(9))} \]
\[ \text{CYCEFF = WORK/QADD} \]

\[ \text{C} \quad \text{'SIZE TURBINE CYCLE FOR DESIRED OUTPUT} \]
FACTOR LB/SEC

1230 MMAIN = KWOUT*3413.0/(WORK*GEFF*3600.0*NUMOP)
MFLOPT = MMAIN*FLOWPT

DO 1250 I = 1,NS
MFL0(I) = FLOW(I)*MMAIN
1250 CONTINUE

MQADD = QADD*MMAIN
MQREJ = QREJ*MMAIN

'**** PIPING DESIGN ****
CALL PIPER
1450 CONTINUE

PCSACM = (WTKTOT*SVVLE(9) + VPOTSB + VPOTSR)*2.5DO*13.5DO

CFSRFM = (CFSLE(9) + CFSLI(10))/2.DO
HEAD = 32.174DO*1.44D2*DPRFMD*(SVVLE(9) + SVVLI(10))/2.DO
PWRFMD = HEAD*MF(10)*3.6D3/(32.174DO*778.DO*3.414D3*EFRFMD*EMRFMD)
RPRFMD = 4.5DO*HEAD**0.75DO/DSQRT(PI*CFSRFM)
WTRFMD = 6.01D4*2.205D0*PWRFMD/RPRFMD
TREF = 1.89D3
NMATH = 1
NMATC = 2
CALL STRNTH (TREF, TMAT, NMATH, NMATC, FPL, SIGPV, RHOAST)
STRHO = SIGPV/RHOAST
CALL STRNTH (TCON, TMAT, MATH, MATC, FPL, SIGPV, RHOAST)
WTRFMD = WTRFMD*SIGPV/(RHOAST*STRHO)

' SIZE TURBINE

VTIP = VTIPO
DO 2050 DJINT = 1,100
ALPHAR = PI*ALPHAT/I.SD2
XXI = RSTT*(DSIN(ALPHAR))*(PI/4.DO)*0.75DO
DTIP = 1.2DI*DSQRT(CFSLI(8)/XXI)
RPMT = 2.2918D2*VTIP/DTIP
ALPHAO = ALPHAT
ALPHAT = 77.6234/RPMT**0.175736
ERROR = DABS(ALPHAT - ALPHAO)
IF (ERROR.LT.1.D-2) GOTO 2060
2050 CONTINUE
2060 CONTINUE

IF (RPM.EQ.0.0DO) GOTO 2070
IF (RPMT.GT. RPM) THEN
ALPHAT = 77.6234/RPMT**0.175736
ALPHAR = PI*ALPHAT/1.8D2
VTIP = RPM/15.DO*DSQRT(PI*CFSLI(8)/(3.DO*RSTT*DSIN(ALPHAR)))
XX1 = RSTT*(DSIN(ALPHAR))*(PI/4.DO)*0.75DO
DTIP = 1.2D1*DSQRT(CFSLI(8)/XX1)
RPM = RPM
ENDIF

2070 TORQUE = WORK*MMAIN*778.DO*30.DO/(RPMT*PI)
TRBPWR = TORQUE*(RPMT*PI)/(3.DO*5.DO)
TURBWT = 17.82DO*TORQUE**0.6DO
TREF = 2.7D3
NMATH = 1
NMATC = 2
CALL STRNTH (TREF, TMAT, NMATH, NMATC, FPL, SIGPV, RHOAST)
STRHO = SIGPV/RHOAST
CALL STRNTH (T0, TMAT, MATH, MATC, FPL, SIGPV, RHOAST)
TURBWT = TURBWT*SIGPV/(RHOAST*STRHO)

FRACHR = (MMAIN*NUMOP*DELRH + QRHLSS)/(MQADD*NUMOP + QRHLSS + QBOILL)
PLNTEF = CYCEFF*GEFF
GNLOSS = KWOUT*(1./GEFF-1.)/NUMOP

TOTWT = NUMTOT*TOTWT
WTKTOT = NUMTOT*WTKTOT
MFITOT = NUMTOT*MFITOT
WTURBN = NUMTOT*TURBWT
WTPUMP = NUMTOT*WFPUMP
TOTHTR = NUMTOT*TOTHTR
PCSCAM = NUMTOT*PCSCAM
WTTRFM = NUMTOT*WTTRFM
MQADD = NUMOP*MQADD
MQREJ = NUMOP*MQREJ

RETURN
END
SUBROUTINE BOILER

IMPLICIT DOUBLE PRECISION (A-H,O-Z)
DOUBLE PRECISION LGENTOT, MASSGEN, KVA, KWOUT, KA, KB, NUMOP, NUMTOT,
& KNET, NOTUBB, NOTUBR, LG, MAIN, MF, ID, MFI, TOB,
& MQADD, MQR, LLPB, LBOILB, LSHB, LTOTB, MFIWTR, LPHR,
& LBOILR, LSHR, LTOTR, MFIWTR, MFIOT, MULI, MUF1, MUF2,
& MUG1, MUG2, MUPH, MUSH, KKPH, KKSH, IDTUBE, KLI, KTUBE,
& NLI, KK, NUPH, NUSH, NOTUBI, NOTUBO

CHARACTER TITLE(13)*80, LLBL(11)*25, FNAME(50)*50, CLNTYPE*10,
& GENTYPE*20, INTTYPE*20, ERRORG*64, WARNINGG*64

INTEGER REHEAT, RSTAGE

C DIMENSIONS BY COMMON BLOCKS

*****  ***********************************************************************

PARAMETER (NSTG=15)

COMMON /INPUT/ FPL, VELV, VELM, VELL, TMAT, XMATH, XMATC, DUM1, DUM2, KA,
& KB, NUMOP, NUMTOT, TROUT, TRIN, KNET, GEFF, DUM3, BPP, BFP,
& BPL, PWRFCTR, VOLTAGE, GENASP, TINCLNT, TOUTCLNT,
& CPCLNT, TBOIL, XBOIL, DUM4, TCON, DEFF, EXLOSS, VTIPO,
& SCCON, ALPHAT, RSTT, XMFI, DP, PTEFF, DPFMD, ERFMD,
& EMRFMD, DMAXB, DIAT, NOTUBB, DMAXR, DTRH, DIARH,
& NOTUBR, LG(II)

COMMON /OUTPUT/ MMAIN, TT(0:15), PP(0:15), H(0:15), S(0:15), X(0:15),
& SVV(0:15), TLI(11), TLE(11), PII(11), HLE(11), SLI(11), SLE(11),
& SVVLE(11), MF(11), WALL(11), WT(11), WTKINV(11), ID(II),
& DPTOB, WTKOT, TOTW, TTRH, DPTOTR, NS, WTMF(II),
& MFIOT, PENG, TENG, FMDEL, PDIS, UTILIM, TGP(NSTG), XNSHA,
& DT(NSTG), UT(NSTG), PHI(NSTG), NTS, PS(NSTG), XN,
& TOTHP, PUMPEFF, SSMA, XNS(STG), WFPUP, TORQ,
& KWOUT, ALTWT, CYCCEF, PCSACM, MQADD, MQR, PRSTAG,
& WTRFMD, WTRB, XRH, EFF(0:15), DLPB, WBOIL, WTRTB,
& DLPR, WRT, WTRER, HTBB, DOUTE, DTSB, THSB, XTHKBB, LPHB,
& LBOILB, LSHB, LTOB, KTUBB, PAB, HLIIL, HKB, KBBOIB,
& HKSH, WSHEL, WTUBE, WTAEB, WTCB, WTIWBT, WTB, WLB, HTBB, DOUTE, DTSR, THSR, XTHKR, LPRH,
& LBOILR, LSHR, LTOTR, KTUBER, PAR, HLIILR, HKB, HKBOIR,
& HKSHR, WSHEL, WTUBER, WTAPER, WTTSR, WTCLR, WFIWT,
& WTPOR, WTLB, HTBR, DOUTR, DTSR, THSR, XTHKR, LPRH,
& LBOILR, LSHR, LTOTR, KTUBER, PAR, HLIILR, HKB, HKBOIR,
& HKSHR, WSHEL, WTUBER, WTAPER, WTTSR, WTCLR, WFIWT,
& WTPOR, WTLIR, WTPCS, SPMASS, EFFNET, EFGRS, WTPUMP,
& TITCON, PLNTEF, GNLOSS, TORQUE, TRPWR, XXI, TURBWT, RPM,
& SVR, TSATRH, HRH, SHR, TSAT(0:15), VTI, DGENTR, KVA,
& DGENSTR, LGENTOT, MASSGEN, TIPS, COE, COOLING, WClN

COMMON /SYSTM/ MFIOT, CFSLI(11), CFSL(11), DELPL(11), DELHR(11), MFI,
& TPUMP, HPUMP, SFPUMP, VPUMP, WKRFD, PI, G, TOL, XLAMIN,
& XMOUT, EFFIND, HCIND, XKLOSS, PT(NSTG), PS(NSTG),
& HT(NSTG), XIHT(NSTG), HSP(NSTG), ST(NSTG), TS(NSTG),
& RHO(NSTG), CM(NSTG), XNS, DH(NSTG), B2(NSTG),
**F3S(NSTG), XMARG, XNPHSA, XNPISH, HD(NSTG),**

**EFFP(0:NSTG), HP(NSTG), XIMPNS, XNNSIMP, QBOILL,**

**QRHLSS, PEFF, RPMT, VPS, VPSR, XRHEAT, PTI, FRACRH,**

**RSTAGE, TTI, TFW, FLOC, TBLOUT, TBLIN, TRHOUT, TRHIN,**

**COMMON/CONFIG/GENTYPE, INTTY, CLNTTYPE**

**COMMON/DIAGNOS/ERRORG, WARNINGG**

DATA LTOT /1.44D2/
PI = 3.141592654D0

IF (REHEAT .EQ. 0) THEN

TLIOUT = TBLOUT
TLIIN = TBLIN
TIN = TLE(11)
TOUT = TLI(1)
POUT = PLI(1)
IDTUBE = DIATB
NOTUB1 = NOTUBB
HIN = HLE(11)
HOUT = HLI(1)
PIN = PLE(11)
XIN = XLE(11)
XOUT = XLI(1)
DPMAX = DPMAXB

ELSE

TLIOUT = TRHOUT
TLIIN = TRHIN
TIN = TLE(6)
TOUT = TLI(7)
POUT = PLI(7)
IDTUBE = DIARH
NOTUB1 = NOTUBR
HIN = HLE(6)
HOUT = HLI(7)
PIN = PLE(6)
XIN = XLE(6)
XOUT = XLI(7)
DPMAX = DPMAXR

ENDIF

NOTUBO = 0.DO
WXOT = MMAIN*NUMOP
WXOC = FLOC
CALL STRNTH (TLIIN, TMAT, MATH, MATC, FPL, SVP, RHOAST)
C INITIAL GUESS OF TUBE LENGTH (IN)

\[ T_{KTUB} = \frac{P_{OUT} \times ID_{TUBE}}{SIG_{PV}} \]

IF (\( T_{KTUB} < 2 \times 10^{-2} \)) \( T_{KTUB} = 2 \times 10^{-2} \)

\[ NOTUB = NOTUB1 \times NUMTOT/NUMOP \]

\[ OD_{TUBE} = (ID_{TUBE} + 2 \times 10^{-2} \times T_{KTUB}) \]

C INITIALIZE TUBE DIA, PITCH(PA), AVG HELIX DIA(\( DC \)),
C NUMBER OF TUBES PER CIRCLE(\( NTC \)), NUMBER OF CIRCLES(\( NC \))

\[ PA = 1.375 \times OD_{TUBE} \]

C LITHIUM SIDE

\[ T_{AVL} = \frac{T_{LIOUT} + T_{LIIN}}{2} \]

CALL LIPORT(\( T_{AVL} \),\( MULI \),\( KLI \),\( CPLI \),\( RHOLI \),\( P \))

IF (\( T_{LIIN} > TMAT \)) \( KTUBE = KA/(1.21 \times 3.63) \)

IF (\( T_{LIIN} \leq TMAT \)) \( KTUBE = KB/(1.21 \times 3.63) \)

DO 90 I = 1, 1, 100

C TUBE PITCH IS A FUNCTION OF DELTA P, LENGTH & HELIX ANGLE
C USE HTRI CROSS FLOW CORRELATIONS DM C2.2

\[ V_{LI} = WXOC \times 1.442/(RHOLI \times NOTUB \times OD_{TUBE} \times 1.2 \times 0.51931 - 1) \]

\[ RELI = 1.0847 \times 3.82 \times OD_{TUBE} \times V_{LI} \times RHOLI / MULI \]

\[ FEL_{L} = (1.62 \times DLOG10(RELI) - 1.64) \times (-2) \]

IF (\( RELI \leq 2.03 \)) \( FEL_{L} = 6.41 / RELI \)

\[ PRL_{L} = CPLI \times MULI / KLI \]

\[ EDDY = - 7.2767D-1 + 1.5054D-1 \times DLOG10(RELI) + \]

\[ 7.2749D-2 \times DLOG10(RELI)^{2} \]

\[ EDDY = 10.0D ** EDDY \]

\[ PSIBAR = 1.0 - 1.82D0/(PRL_{L} \times EDDY \times 1.4D0) \]

IF (\( PSIBAR \leq 0.0D0 \)) \( PSIBAR = 0.0D0 \)

\[ NUL_{I} = 1.19936D1 + 2.74889D-2 \times (PSIBAR \times RELI \times PRL_{L}) \times 0.8D0 \]

IF (\( NUL_{I} \leq 12.266D0 \)) \( NUL_{I} = 12.266D0 \)

IF (\( RELI \leq 2.03 \)) \( NUL_{I} = 4.81 \times 1.1D1 \)

\[ HL_{LI} = 0.15 \times NUL_{I} \times KLI / (OD_{TUBE} \times 1.21 \times 3.63) \]

\[ DLP_{B} = (FEL_{L} \times LTOT / (1.0847 \times OD_{TUBE}) + 1.5D0) \]

\[ DLP_{B} = DLP_{B} / 1.44D2 \]

C CALCULATE TUBE SPACING, MUST BE GREATER THAN TWICE THE TUBE DIA
C potassium side; boiler

\[ PBOIL_{L} = PBI1 \times 14.696D0 \]

CALL TFROMP(\( P \),\( PBOIL_{L} \))

\[ KSH = 0 \]

CALL KTHRMO(\( KSH \),\( TBOIL_{L} \),\( P \),\( VF \),\( VG \),\( HF \),\( HG \),\( HFG \),\( SF \),\( SG \),\( SFG \))

\[ PBOIL_{L} = 14.696D0 \times P \]

\[ HBOIL_{L} = HF + XIN \times HFG \]

\[ RHOBFI = 1.0D0 / VF \]
RHOBGI = 1.DO/VG
CALL KXPORT (TBOIL1,MUF1,KK,CP,RHOFL)
CALL KVPORT (KSH,TBOIL1,P,MUGI,KK,CP,RHOFL)
VF1 = WXOT*1.44D2/(PI*IDTUBE**2.DO*NOTUB1*RHOBF1/4.DO)
RELI = IDTUBE*VF1*RHOBF1*3.D2/MUF1
VG1 = WXOT*1.44D2/(PI*IDTUBE**2.DO*NOTUB1*RHOBG1/4.DO)
REG1 = IDTUBE*VG1*RHOBG1*3.D2/MUG1

PBOIL2 = PBOIL1 - DPBOIL
P = PBOIL2/14.696DO
CALL TFROMP (P,TBOIL2)
KSH = 0
CALL KTHRMO(KSH,TBOIL2,P,VF,VG,HF,HG,HFG,SF,SG,SFG)
PBOIL2 = P*14.696DO
HBOIL2 = HF + XOUT*HFG
RHOBF2 = 1.DO/VF
RHOBG2 = 1.DO/VG
CALL KXPORT (TBOIL2,MUF2,KK,CP,RHOFL)
CALL KVPORT (KSH,TBOIL2,P,MUG2,KK,CP,RHOFL)
VF2 = WXOT*1.44D2/(PI*IDTUBE**2.DO*NOTUB1*RHOBF2/4.DO)
REL2 = IDTUBE*VF2*RHOBF2*3.D2/MUF2
VG2 = WXOT*1.44D2/(PI*IDTUBE**2.DO*NOTUB1*RHOBG2/4.DO)
REG2 = IDTUBE*VG2*RHOBG2*3.D2/MUG2

RHOBFA = (RHOBF1 + RHOBF2)/2.DO
RHOBGA = (RHOBG1 + RHOBG2)/2.DO
REL = (RELI + REL2)/2.DO*(1.DO - XOUT/2.DO - XIN/2.DO)
REG = (REG1 + REG2)/2.DO*(XOUT/2.DO + XIN/2.DO)

C PREHEAT

TAVEPR = (TIN + TBOIL1)/2.DO
CALL KXPORT(TAVEPR,MUPH,KKPH,CPPH,RHOPH)
VPH = WXOT*1.44D2/(PI*IDTUBE**2.DO*NOTUB1*RHOPH/4.DO)
REPH = IDTUBE*VPH*RHOPH*3.D2/MUPH
FEPH = (1.82DO*DLOGIO(REPH) - 1.64DO)**(-2.DO)
IF (REPH .LT. 2.D3) FEPH = 6.4D1/REPH
PRPH = CPPH*MUPH/KKPH
EDDY = - 6.115D-1 + 2.7792D-1*DLOG10(RELI) +
& 6.4292D-2*(DLOG10(RELI))**2.DO
EDDY = 10.DO**EDDY
PSIBAR = 1.DO - 1.82DO/(PRPH*EDDY**1.4DO)

IF (PSIBAR.LT.0.DO) PSIBAR = 0.DO

NUPH = 7.DO + 2.5D-2*(PSIBAR*REPH*PRPH)**0.8DO
IF (REPH .LT. 2.D3) NUPH = 4.8D1/1.1D1
HKPH = NUPH*KKPH/(IDTUBE**1.2D1*3.6D3)

C BOILING

HKBOIL = 1.35D-2

C SUPERHEAT
TAVESH = (TOUT + TBOIL2)/2.DO
PAVESH = POUT + DPSH/2.DO
P = PAVESH/14.696DO
KSH = 1
CALL KVPORT (KSH, TAVESH, P, MUSH, KKSH, CPSH, RHOSH)
VSH = WXOT*1.44D2/(PI*IDTUBE**2.DO*NOTUBI*RHOSH/4.DO)
RESH = IDTUBE*VSH*RHOSH*3.D2/MUSH
FESH = (1.82D0*DLOG10(RESH) - 1.64D0)**(-2.DO)
IF (RESH .LT. 2.D3) FESH = 6.4D1/RESH
PRSH = CPSH*MUSH/KKSH
NUSH = ((FESH/8.DO)*RESH*PRSH)/+(1.07D0 + 1.27D1*DSQRT(FESH/8.DO)*(PRSH**(2.DO/3.DO) - 1.DO))
IF (RESH .LT. 2.D3) NUSH = 1.1D1/3.DO
HKSH = NUSH*KKSH/(IDTUBE*1.2D1*3.6D3)

C Compute overall heat transfer coefficients

UIPH = 1.DO/(1.DO/HKPH + IDTUBE*DLOG(ODTUBE/IDTUBE)/(2.DO*KTUBE)
+ IDTUBE/(HLILI*ODTUBE))
UIBOIL = 1.DO/(1.DO/HKBOIL + IDTUBE*DLOG(ODTUBE/IDTUBE)
+ (2.DO*KTUBE) + IDTUBE/(HLILI*ODTUBE))
UISH = 1.DO/(1.DO/HKSH + IDTUBE*DLOG(ODTUBE/IDTUBE)/(2.DO*KTUBE)
+ IDTUBE/(HLILI*ODTUBE))
QPH = WXOT*(HBOILI - HIN)
QBOIL = WXOT*(HBOIL2 - HBOILI)
QSH = WXOT*(HOUT - HBOIL2)

C Compute log mean temperature differences

T2 = TLIIN - QSH/(WXOC*CPLI)
T1 = T2 - QBOIL/(WXOC*CPLI)
DTLMPH = ((T1-TBOIL1)-(TLIOUT-TIN))/DLOG((T1-TBOIL1)/(TLIOUT-TIN))
DTLMBL = ((T2-TBOIL2)-(T1-TBOIL1))/DLOG((T2-TBOIL2)/(T1-TBOIL1))

IF (TOUT .GT. TBOIL2) THEN
DTLMSH = ((TLIIN-TOUT)-(T2-TBOIL2))/DLOG((TLIIN-TOUT)/(T2-TBOIL2))
ELSE
DTLMSH = 0.DO
ENDIF

C Compute tube lengths & number of reheater tubes required

LPH = QPH/(UIPH*DTLMPH*PI*IDTUBE*NOTUBI)
LBOIL = QBOIL/(UIBOIL*DTLMBL*PI*IDTUBE*NOTUBI)

IF (TOUT .GT. TBOIL2) THEN
LSH = QSH/(UISH*DTLMSH*PI*IDTUBE*NOTUBI)
ELSE
LSH = 0.DO
ENDIF
LTOT = LPH + LBOIL + LSH

c compute pressure drops in boiler tubes
c first the superheater

***** *****************************************************

DPSH = (FESH*(LSH/IDTUBE) + 1.0)*(VSH**2.DO*RHOSH/6.4348D1)
DPSH = DPSH/1.44D2

***** *****************************************************

c next the boiling section

PARAM = DSQRT(RHOBFA/RHOBGA)
R1 = (1.0 + PARAM*XOUT)**2.DO - 1.0
DPINRT = R1*VPH**2.DO*RHOPH/3.2174D1
DPINRT = DPINRT/1.44D2

R2 = (1.0/PARAM - 1.0)/(PARAM - 1.0) +
& (PARAM - 1.0/PARAM)/(XOUT*(PARAM - 1.0)**2.DO) +
& DLOG(1.0 + XOUT*(PARAM - 1.0))

DPGRAV = R2*RHOPH*LBOIL*1.65D-1/1.44D2
FEBOIL = (6.667D-1 + 1.28D-3*DSQRT(REL))/REG**2.D-1
DPDRAG = FEBOIL*(LBOIL/IDTUBE)*(VPH**2.DO*RHOPH/3.2174D1)*
& (R1 + 2.0)
DPDRAG = DPDRAG/1.44D2

DPBOIL = DPINRT + DPDRAG

c Now compute pressure drop in the preheater

DPH = (FEPH*(LPH/IDTUBE) + 0.5DO)*(VPH**2.DO*RHOPH/6.4348D1)
DPH = DPH/1.44D2

DPTOT = DPBOIL + DPH + DPSH
PIN = POUT + DPTOT

FUNC2 = DPTOT - DPMAX
CHECK = -0.7DO*DPMAX

IF ((FUNC2 .GT. 1.D1) .OR. (FUNC2 .LT. CHECK)) THEN
NOTUB1 = NOTUB1*DSQRT(DPTOT/DPMAX)
NOTUB = NOTUB1*NUMTOT/NUMOP
PIN = POUT
DPBOIL = 0.DO
DPH = 0.DO
DPSH = 0.DO
GOTO 90
ENDIF
IF (NOTUB0.EQ.0.DO) THEN
   FUNCT1 = FUNC2
   NOTUB0 = NOTUB1
   NOTUB1 = NOTUB1*DSQRT(DPTOT/DPMAX)
   NOTUB = NOTUB1*NUMTOT/NUMOP
   GOTO 90
ENDIF

IF (JTUBE .EQ. 1) GOTO 75
IF (DABS(FUNC2).GE.1.D-6) THEN
   DELTA = FUNC2*(NOTUBI - NOTUB0)/(FUNC2 - FUNCT1)
   IF (DELTA .GT. NOTUB0) DELTA = DELTA/2.DO
   NOTUB0 = NOTUB1
   NOTUB1 = NOTUB1 - DELTA
   FUNCT1 = FUNC2
   NOTUB = NOTUB1*NUMTOT/NUMOP
   GOTO 80
ENDIF

IF (JTUBE .EQ. 0) THEN
   J = NINT(NOTUBI/NUMOP)
   NOTUB1 = DFLOAT(J)*NUMOP
   NOTUB = NOTUB1*NUMTOT/NUMOP
   JTUBE = 0
   GOTO 80
ENDIF

75 IF (ABS(LTOT - HTTUB).LT.0.5D0) GO TO 99
80 HTTUB = LTOT
90 CONTINUE
99 JTUBE = 0

C **************************
C ****************** MODIFIED 8-16-88 **************
C volume of the tube sheets

   XNOTUB = DFLOAT(NOTUB)
   DTS = 1.444D0*ODTUBE*DSQRT(XNOTUB)

C Routine for determining tube sheet thickness

   A1 = (DTS - ODTUBE)/2.DO
   A2 = DSQRT(NOTUB*PA**2.DO*DSIN(PI/3.DO)/PI) +
       (ODTUBE - PA)/2.DO
   ASHEET = DMINI(A1,A2)
   BSHEET = DTS/2.DO
   KSHEET = BSHEET/ASHEET
   PPRIME = ASHEET*DSQRT(P/(NOTUB*DSIN(PI/3.DO)))
   ETASHT = (PPRIME - ODTUBE)/PPRIME
   FSTAR = 0.556D0*KSHEET**(0.39D0*DLOG(ETASHT))
   OMEGA1 = 1.5/ETASHT
   OMEGA2 = 2.0
OMEGA = DMINI(OMEGA1,OMEGA2)
H1SHT = DTS*FSTAR*DSQRT(PIN/(OMEGA*SIGPV*ETASHT))
H2SHT = PIN*ASHEET/(1.6DO*SIGPV*(PA - ODTUBE)/PA)
XTHK = DMAXI(H1SHT,H2SHT)
VTS = (DTS**2.DO - NOTUB*ODTUBE**2.DO)*PI*XTHK/2.DO

C calculate the length of the boiler, lcl=3" + dia of tube sheet
LCL = DTS/2.DO + XTHK
HTB = LTOT + 2.DO*LCL

C CALCULATE THE VOLUME OF METAL PARTS - DENSITY = 0.31 lb/in3
C volume of the shell
THS = PIN*DTS/(2.DO*SIGPV)
SIXTENH = 1.DO/16.DO
IF (THS.LT.SIXTENH) THS = SIXTENH
DOUTER = DTS + 2.DO*THS

C assume 18 inches added to accomodate reheat tubes
VSHELL = (PI/4.DO)*(DOUTER**2.DO - DTS**2.DO)*HTB

C volume of the tubes
VTUBE = NOTUB*(LTOT + 2.DO*XTHK)*(PI/4.DO)*
& (ODTUBE**2.DO - IDTUBE**2.DO)

C volume of closure, assume spherical end caps
C assume a flat end plate closure
VCLO = (PI/2.DO)*(DOUTER**2.DO)*THS

VMFI = PI/4.DO*(((DOUTER + 1.06D-2*MFI)**2.DO - DOUTER**2.DO)*
& (LTOT + XTHK)
VMFI = VMFI + PI/6.DO*(((DOUTER + 1.06D-2*MFI)**3.DO -
& DOUTER**3.DO)

WT SHELL = VSHELL*RHOAST
WTUBE = VTUBE*RHOAST
WTape = WTUBE*0.3DO
WTTS = VTS*RHOAST
WTCL0 = VCLO*RHOAST
MFIWT = VMFI*9.2D-3

WBOIL = WT SHELL + WTUBE + WTape + WTTS + WTCL0 + MFIWT
VTOT = VSHELL + VTUBE + VTS + VCLO

C calculate the volume of the Lithium
VCYL = (PI/4.DO)*DTS**2.DO*LTOT

C take out primary helix tubes and shroud and reheater tubes
V2 = NOTUB*LTOT*(PI/4.DO)*ODTUBE**2.DO
VLI = VCYL - V2

compute weight of potassium in the boiler

FACTOR = 1.DO - (XIN + XOUT)/2.DO
V2 = V2*(((LPH + LBOIL*FACTOR)/LTOT)*(IDTUBE/ODTUBE)**2.DO
VHEAD = PI*DTS**3.DO*FACTOR/6.DO
VPOTAS = (VHEAD + V2)/(12.DO**3.DO*NUMTOT)
WTPOTS = VPOTAS*RHOPH*NUMOP

WTLI = VLI*RHOLI/1.2D1**3.DO
WTWET = WBOIL + WTLI + WTPOTS

compute heat losses

TRADAV = ((TLIN**5.DO - TLIOUT**5.DO)/(TLIN - TLIOUT))
QLOSS = PI*DOUTER*HTB*0.2DO*3.305D-15*TRADAV
QLOSS = QLOSS/DFLOAT(MFI)
TRADAV = TRADAV**0.25DO

parameter transformation

IF (REHEAT .EQ. 0) THEN
NOTUBB = NOTUBI
QBOILL = QLOSS
PLE(11) = PIN
DLPBB = DLPB
DPTOTB = DPTOT
WBOILB = WBOIL
WTWETB = WTWET
VPOTSB = VPOTAS
HTBB = HTB
DOUTEB = DOUTER
DTSB = DTS
THSB = THS
XTHKB = XTHK
LPHB = LPH
LBOILB = LBOIL
LSHB = LSH
LTDUB = LTOT
TKTUBB = TKTUB
PAB = PA
HLILIB = HLILI
HKPHB = HKPH
HKBOIB = HKBOIL
HKSHB = HKSH
WSHELB = WSHHELL
WTUBEB = WTUBE
WTAPEB = WTAPE
WTTSB = WTTS
WTCLOB = WTCLO
MFINTB = MFINT
WTPOTB = WTPOTS
WTLIB = WTLI

ELSE

NOTUBR = NOTUB1
QRHLSS = QLOSS
PLE(6) = PIN
DLPBR = DLBP
DPTOTR = DPTOT
WRHT = WBOIL
WTWETR = WTWET
VPOTSR = VPOTAS
HTBR = HTB
DTSR = DTS
THSR = THS
XTHKR = XTHK
LPHR = LPH
LBOILR = LBOIL
LSHR = LSH
LTOTR = LTOT
TKTUBR = TKTUB
PAR = PA
HLILIR = HLILI
HKPHR = HKPH
HKBOIR = HKBOIL
HKSHR = HKSH
WSHELR = WTSHELL
WTUVER = WTUBE
WTAPER = WTAPE
WTTSR = WTTS
WTCLOR = WTCL0
MFIWTR = MFIWT
WTPOTR = WTPOTS
WTLIR = WTLI

ENDIF

RETURN
END
subroutine psize

********************************************************************
* this program is a generalized conceptual design program
* for a centrifugal stage + inducer are sized
* ghf 2/92
********************************************************************

implicit double precision (a-h,o-z)

DOUBLE PRECISION KA,KB,NUMOP,NUMTOT,KWNET,NOTUBB,
& NOTUBR,LG,MMAIN,MFLOPT,MF,ID,MFITOT,KWOUT,
& MQADD,MQREJ,LPHB,LBOILB,LSHB,LTOTB,MFIWTB,LPHR,
& LBOILR,LSHR,LTOTR,MFIWTR

INTEGER REHEAT,RSTAGE

PARAMETER (NSTG=15)

COMMON /INPUT/ FPL,VELV,VELM,VELL,TMAT,XMATH,XMATC,DUM1,DUM2,KA,
& KB,NUMOP,NUMTOT,TROUT,TRIN,KWNET,GEFF,DUM3,BPP,BFP,
& BPL,PNRFCTR,VOLTAGE,GENASP,TINCLNT,TOUTCLNT,
& CPCLNT,TBOIL,XBOIL,DUM4,TCON,DEFF,EXLOSS,VTIPO,
& SCCON,ALPHAT,RSTT,XMFI,DPCON,PTEFF,DPRFMD,EFRFMD,
& EMRFMD,DFWAX,DIA TB,NOTUBB,DFMAXR, DTHR, DIARH,
& NOTUBR, LG(II)

COMMON /OUTPUT/MMAIN,TT(0:15),PP(0:15),H(0:15),S(0:15),X(0:15),
& SVV(0:15),TLI(II),TLE(II),PLI(II),PLE(II),HLI(II),
& HLE(II),SLE(II),XLI(II),XLE(II),SVVL(II),
& SVVL(II),MF(II),WALL(II),WT(II),WTKINV(II),ID(II),
& DPTOTB,WKTOTB,TOTWT,TTRH,DPTOTR,NS, WTMF(II),
& MFITOT,PENG,TENG,FMDEL,PDIS,UTLIM,TPP(NSTG),XNPSHA,
& DT(NSTG),UT(NSTG), PHI(NSTG), NSTATE, PSI(NSTG), XN,
& TOTHP,PUMFEF,SMARG,XNSTGT(NSTG), WFPUMP, TORQ,
& KWOUT, ALTWT, CYCEFF, PCSACM, MQADD, MQREJ, PRSTAG,
& WTRFMD, WTRB MN, XRH, EFF(0:15), DLPB B, WBOILB, WTWEB,
& DLPBR,WRHT,WTWTR,HTBB,DOUTEB,DTSB,THSB,XTHKB,LPHB,
& LBOILB,LSHB,LTOTB,TKTUBB,PAB,HLILIB,HKP HB,KHOOB,
& HKSHB,WSHELB,WTUBEB,WTAPEB,WTTSB,WTCLOB,MFIWTB,
& WTPOTB,WTLIB,HTBR,DOUTEB,DTSR,THSR,XTHKR,LPHR,
& LBOILR,LSHR,LTOTR,TKTUBR,PAR,HLILIR,HKP HR, HKBOIR,
& HKSHR,WSHEL R,WTUEBB,WTUPER,WTTSR,WTCLOB,MFIWTR,
& WTPOTR,WTLIR,WTPCS,SPMASS,EFFNET,EFFGRS, WFPUMP,
& TITCON,PLNTEF,GLOSS, TORQUE, TRBWR, XXI, TURBW, RPM,
& SVRH,TSA T RH, HRH, SRH, T SAT(0:15), VTI, DGENRTR, KVA,
& DGENST, LGE Y, MESSN, TIPS, W, COE, COOLING, WCLNT

COMMON /SYSTM/ MFLOPT,CFSLI(II),CFSLE(II),DELP(II),DEH(II),MFI,
& TPUMP,HPUMP,SPFUMP,VFPUMP,WPUMP,FPRM,PI,G,TOL,XLAMIN,
& XLAMOUT,EFFIND,HCIND,XKLOSS,PT(NSTG),PS(NSTG),
& HT(NSTG),Xi(T)H(NSTG),HSP(NSTG),ST(NSTG),TS(NSTG),
set constants
g = 32.174
tol = 0.0000001

set default values
ssmarg = 2.00
psi(1) = 0.10
phi(1) = 0.14
efpp(1) = 0.848
utlim = 170.0

begin pump sizing
 call indsize
torq = 5252.*tothp/xn
call corelate(5,torq,wf pump)

return
end
subroutine indsize

************************************************************************************
*  This subroutine evaluates the size and state conditions *
*  on and around the inducer.  ghp 2/92                                           *
*  ************************************************************************************

implicit double precision (a-h,o-z)

DOUBLE PRECISION KA,KB,NUMOP,NUMTOT,KWNET,NOTUBB,
  NOTUBR,LM,MAIN,MFLOPT,MF,ID,MFITOT,KWOUT,
  MQADD,MQREQ,LPHB,LBOILB.LSHB,LTOTB,MIWTB,LPHR,
  LBOILR,LSHR,LTOR,MFIWTR

INTEGER REHEAT,RSTAGE

PARAMETER (NSTG=15)

COMMON /INPUT/ FPL,VELV,VELL,TMAT,XMATC,DUM1,DUM2,KA,
  KB,NUMOP,NUMTOT,TROUT,TRIN,KWNET,GHEF,DUM3,BFP,
  BPL,PWRECFR,VOLGAGE,GENASP,TINCLNT,TOUTCLNT,
  CPCLNT,BOIL,BOIL,BOIL,BOIL,CON,DFF,EXLSS,VTIPO,
  SCCON,ALPHAT,RSTT,XMFI,DPCON,PEFF,DPFMD,EFDFMD,
  EMRFMD,DMXMB,DIATB,NOTUBB,DMXMR,DTRH,DIARH,
  NOTUBR,LG(I)

COMMON /OUTPUT/MMAIN,TT(I:15),PP(I:15),H(I:15),S(I:15),X(I:15),
  SVV(I:15),TIL(I:11),SLI(I:11),PLI(I:11),PLE(I:11),HLI(I:11),
  HLE(I:11),SLI(I:11),SLI(I:11),SLI(I:11),SLI(I:11),SLI(I:11),
  SLI(I:11),MF(I:11),WALL(I:11),WT(I:11),WTINV(I:11),ID(I:11),
  DPTOTB,WTOKT,WTOKT,WTOKT,WTOKT,WTOKT,WTOKT,WTOKT,WTOKT,
  MFITOT,PENG,TENG,FMDLF,DISLIT,TPP(NSTG),XNPSHA,
  DT(NSTG),UT(NSTG),PHI(NSTG),NSTAGE,PSI(NSTG),XN,
  TOTHP,PUMPEFF,SSMARG,XNSSTG(NSTG),WPUMP,TORQ,
  KWOUT,ALTWT,CYCEFF,PCSACM,MQADD,MQREQ,PRSTAG,
  WTRFMD,WTRBNS,RRR,EFDF(0:15),DLPB,BOILB,WTWETB,
  DLBR,WRHT,WTWET,HTBB,DOUTB,DTSB,THBB,THKBB,LPBB,
  LBOILB,LSHB,LTOTB,TKTUBB,PAB,HLILB,HKPHB,HKBOIB,
  HKSHB,WSHELB,WTUDB,WTAEQP,WTTSB,WTCLB,MIWTB,
  WPOTB,WTLIB,HTBR,DOUTL,DTSL,TSHR,XTHKR,LPHR,
  LBOILR,LSHR,LTOTR,TKTURR,PAR,HLILR,HKPHR,HKBOIR,
  HKSHR,WSHELR,WTUBER,WTAPER,WTTSR,WTCLR,MIWR,
  WPOTR,WTLR,WTPLS,SPWSS,EFNDF,EFGRS,WTMPU,
  TTICON,PLNTEF,GNLOSS,TOUR,TPRBPR,XXI,TURNBWR,PMR,
  SVRH,TSMRHR,HSHR,SRH,TSAT(0:15),VTIP,DEGENTR,KVA,
  DGENSTR,LENOCT,MASSGEN,TIPSDD,COE,COOLLE,WCLNT

COMMON /SYSTM/ MFLOPT,CFSLI(I:11),CSLE(I:11),DELPL(I:11),DELHL(I:11),MFI,
  TPUMP,HPUMP,SPFUMP,VFSPUMP,WKRFMD,PI,G,TOL,XMLAIN,
  XMAMOUT,EFFIND,HCIND,AKLSS,PT(NSTG),PS(NSTG),
  HT(NSTG),XTHT(NSTG),HSP(NSTG),ST(NSTG),TS(NSTG),
  RHO(NSTG),CM(NSTG),XNSS,DH(NSTG),B2(NSTG),
determine inlet conditions at engine interface

call ept2d(peng,teng,rhoeng,kfluid)
call ept2h(peng,teng,heng,steng,kfluid)

flow rate for pump allows for variation through stages later

\[ f_{3s}(I) = \frac{f_{mdel}}{\rho_{eng}} \]

begin iteration on inducer size

\[ d_{indg} = 0.0 \]
\[ cm(1) = 0.0 \]
\[ tshg = 1000.0 \]
\[ ttp(I) = teng \]
\[ rho(1) = \rho_{eng} \]
\[ ht(I) = heng \]
\[ v_{duct} = 0.0 \]

\[ pt(I) = peng + \left(0.5 \times \kappa_{loss} \times \rho_{(I)} \times v_{duct}^{2.0}\right) \left(\frac{1}{g \times 144.}\right) \]
\[ ps(I) = pt(I) - \left(cm(1)^{2.0} \times \rho_{(I)}\right) \left(\frac{2.0}{g \times 144.}\right) \]
call ept2h(pt(I),ttp(I),ht(I),steng,kfluid)
\[ h_{sp}(I) = ht(I) - \left(cm(1)^{2.0} \times \frac{1}{(1.0 \times 778.26)}\right) \]
call eph2s(pt(I),ht(I),st(I),ttp(I))
call eph2d(ps(I),hsp(I),rho(I),ttp(I))
call et2vap(ttp(I),dum,pvapor,kfluid)

\[ x_{npsha} = \left((pt(I) - pvapor) / \rho_{(I)}\right) \times 144. \]

size inducer given flow coefficient, inlet conditions, and margin

31 call corelate(1,phi(1),xnsstr)

\[ x_{nssh2o} = x_{nsstr} \times dsqrt(1.0 - x_{lamin}^{2.0}) \]
\[ tsh1 = 0.5 \times pvapor / \rho_{(I)} \times 144. \]
\[ tsh2 = (1.0 / (2.0 \times g)) \times cm(1)^{2.0} \]
if (tsh2 .eq. 0.00) tsh2 = tsh1
if (tsh1 .le. tsh2) tsh = tsh1
if (tsh2 .le. tsh1) tsh = tsh2
\[ x_{npshop} = x_{npsha} / (1.0 + ssmarg) \]
\[ x_{n} = (x_{nssh2o} \times ((x_{npshop} + tsh) \times 3.0)) / dsqrt(f_{3s}(1) \times 448.83) \]
\begin{verbatim}
    dt(1) = ((4.*60./pi**2.)*(f3s(1)/(xn*(1-xlamin**2.)*
        phi(1))))**(1./3.)
    if (dt(1) .lt. 0.5/12.) then
        dt(1) = 0.5/12.
    endif

    ut(1) = (pi/60.)*(xn*dt(1))
    cm(1) = phi(1)*ut(1)

    if (dabs(tshg-tsh) .gt. 0.00001 ) then
        tshg = tsh
        goto 31
    endif

    if (ssmarg .gt. 5.00 .and. dt(1) .le. 0.5/12.) then
        dt(1) = 0.5/12.
        xn = (utlim/dt(1))*(60./pi)
        ut(1) = (pi/60.)*(xn*dt(1))
        phi(1) = 0.14
        call corelate(1,phi(1),xnsstar)
        xnssh2o = xnsstar*dsqrt(1.-xlamin**2.)
        xnpshbd = (xn*dsqrt(f3s(1)*448.83)/xnssh2o)**(4./3.)
        if (tsh .gt. xnpshbd) then
            xnpshbd = xnpshbd
        else
            xnpshbd = xnpshbd - tsh
        endif
        ssmarg = (xnpsha/xnpshbd)-1.
    endif

    if (ut(1) .gt. utlim) then
        phi(1) = phi(1) + 0.001
        if (phi(1) .gt. 0.200d0) then
            phi(1) = 0.140d0
            ssmarg = ssmarg + 0.1
        endif
        goto 31
    endif

    xnss = xn*dsqrt(f3s(1)*448.83)/xnpsha**0.75
    pengi = pt(1) + (0.5*xkloss*rho(1)*vduct**2.)*(1./(g*144.))

    suction performance correction for small pumps
    if (dt(1) .lt. 2.778/12.) xnss = xnss*0.48*dsqrt(dt(1)/.64)

    if (dabs(dindg-dt(1)) .gt. .00001) then
        dindg = dt(1)
        go to 30
    endif

    n = 1
    call convrg3(n,peng,pengi,pt(1),tol,k,500)
\end{verbatim}
if (k) 10, 20, 30
  print 11, n
  format(10x, 'error at loop', i3/
  stop
  call eph2t(ps(1), hsp(1), ts(1), ttp(1))
calculate discharge of first inducer
dh(2) = dt(1)*xlamout
pt(2) = (0.25*ut(1)**2.*rho(1))/(g*144.) + pt(1)
if (pt(2) .ge. pdis) then
  psi(1) = (pdis-pt(1))/rho(1)*g*144./ut(1)**2
endif
pt(2) = (psi(1)*ut(1)**2.*rho(1))/(g*144.) + pt(1)
ps(2) = pt(2) - cm(2)**2./(2.*g)*rho(1)/144.
gh = ht(1) + (pt(2)-pt(1))/rho(1)*144./778.26
call isen(pt(2), gh, st(1), 1, tol, xiht(2), ttp(1))
ht(2) = (xiht(2)-ht(1))/effp(1) + ht(1)
hsp(2) = ht(2) - (cm(2)**2./2.*g)/778.26
call eph2t(pt(2), ht(2), ttp(2), ttp(1))
call eph2s(pt(2), ht(2), st(2), ttp(2))
call eph2t(ps(2), hsp(2), ts(2), ttp(2))
call eph2d(ps(2), hsp(2), rho(2), ts(2))

hp(1) = (xiht(2)-ht(1))*778.26/effp(1)*fmdel/550.0
tothp = hp(1)
assume one stage centrifugal with an inducer
if (dabs(pt(2)-pdis) .lt. 1.0) then
  pt(2) = pdis
endif
if (pt(2) .lt. pdis) then
  numstg = 1
  numstg = numstg + 1
  do 60 jstage = 2, numstg
    in = jstage
    i = in + 1
    dtg = 0.0
    continue
  pt(i) = pt(2) + (jstage - 1)*(pdis - pt(2))/(numstg - 1)
  ps(i) = pt(i) - cm(i)**2.)/(2.*g)*rho(i-1)/144.
  gh = ht(i-1) + (pt(i)-pt(i-1))/rho(i-1)*144./778.26
  call isen(pt(i), gh, st(i-1), 0, tol, xiht(i), ttp(i-1))
  ht(i) = (xiht(i)-ht(i-1))/effp(i) + ht(i-1)
  hsp(i) = ht(i) - (cm(i)**2./2.*g))/778.26
  call eph2t(pt(i), ht(i), ttp(i), ttp(i-1))
  call eph2s(pt(i), ht(i), st(i), ttp(i-1))
call eph2t(ps(i),hsp(i),ts(i),ttp(i))
call eph2d(ps(i),hsp(i),rho(i),ts(i))

size centrifugal stage

hd(in) = 1.10*(xiht(i)-ht(i-1))*778.26
dt(in) = (60./(xn*pi))*dsqrt(hd(in)*g/psi(in))
ut(in) = (dt(in)/2.)*(2.*pi/60.)*xn
b2(in) = f3s(1)/(pi*dt(in)*ut(in)*phi(in))
cm(i) = f3s(1)/(pi*dt(in)*b2(in))

re-evaluate efficiency

xnsstg(in) = xn*dsqrt(f3s(1)*448.83)/(hd(in)/1.1)**0.75
if (xnsstg(in) .lt. 300) go to 70
 call corelate(2,xnsstg(in),effp(in))

if (dt(1)/dt(in) .ge. 0.90) then
  dt(in) = dt(1)
ut(in) = (dt(in)/2.)*(2.*pi/60.)*xn
  psi(in) = hd(in)*g/ut(in)**2
  effp(in) = 0.848
endif

if (dr(in) .lt. 5.0/12.0 .and. dt(1) .ne. dt(in)) then
  xks = (5.0/12.)/(dt(in)/0.49)
xkb = 0.0
  call corelate(3,xks,xkb)
  if (xkb .lt. 0) xkb = 0.1
  effp(in) = effp(in)*xkb
endif

if (dt(in) .lt. 5.0/12.0 .and. dt(1) .ne. dt(in)) then
  xks = (0.005/(dt(in)*12.))*(dt(1)/dt(in)/0.49)
xkb = 0.0
  call corelate(4,xks,xkb)
  effp(in) = effp(in)*xkb
endif

loop around stage to correct efficiency

if (dabs(dtg-dt(in)) .gt. 0.0001) then
  dtg = dt(in)
  if (dt(1)/dt(in) .gt. 0.80) then
    psi(in) = psi(in) - 0.01
    goto 50
  endif
endif

calculate pump power requirment

hp(in) = (xiht(i)-ht(i-1))*778.26/effp(in)*fmdel/550.0
60 tothp = tothp + hp(in)
```c
nstage = in

else
    nstage = 1
    effp(in) = 0.848
endif

setup the analysis of the stages

do 100 in = 1, nstage
    dt(in) = dt(in)*12.
    dh(1) = dt(1)*xlamin
    dh(in) = dt(in)*xlamout
100 continue

calculate pump efficiency

in = nstage+1
gh = ht(1) + (pt(in)-pt(1))*144./rho(1)/778.26
call isen(pt(in),gh,st(1),in,tol,xiht(in+1),ttp(in))
pumpeff = (xiht(in+1)-ht(1))/(ht(in)-ht(1))

return
end
```
subroutine isen(pres, gh, strue, n, tol, hout, temp)

*******************************************************************************
* Calculates isentropic enthalpy - ghp 2/92
*******************************************************************************

implicit double precision (a-h,o-z)

tol = 0.0001

10 if (dabs(gh) .lt. 1.0e-10) gh = 1.0e-10*(-1.0*dabs(gh)/gh)
call eph2s(pres, gh, gs, temp)
call convrg3(n, strue, gs, gh, tol, k, 500)
   if (k) 11,13,10
11 print 12, n
12 format(10x,'error at loop ',i3/)
   stop
13 hout = gh

return
end
SUBROUTINE CONVRG3 (L, X, Y, Z, TOL, K, N)
IMPLICIT DOUBLE PRECISION (A-H,O-Z)
DIMENSION DL(0:25), M(0:25), VL(0:25)

C INSTRUCTIONS:
C L IS THE LOOP NUMBER IF USING NESTED LOOPING
C X AND Y ARE THE VARIABLES TO BE COMPARED
C Z IS THE VARIABLE TO BE CHANGED TO CONVERGE X AND Y
C TOL IS THE TOLERANCE LIMIT OF COMPARISON
C K IS A FLAG SET WITHIN THE SUBROUTINE TO DETECT CONVERGENCE
C - ERROR SUCH AS NUMBER OF ITERATIONS EXCEEDED
C 0 CONVERGING COMPLETED
C + GO BACK INTO SUBROUTINE, NOT CONVERGED
C CHECK K IN MAIN PROGRAM COMING OUT OF CONVRG
C N IS MAXIMUM NUMBER OF ITERATIONS TO BE ALLOWED

DATA DL,M,VL/26*0.D0,26*0,26*0.D0/
L1=L
X1=X
Y1=Y
Z1=Z
IF(Z1) 20,30,20
20 W=Z1
GOTO 40
30 W=X1
40 D=X1-Y1
   IF(ABS(D)-ABS(TOL)) 50,50,60
50 K1 = 0
55 M(L1)=0
GOTO 220
60 IF(M(L1)) 70,70,80
70 V=1.01*W
   M(L1)=1
GOTO 190
80 IF(M(L1)-N) 110,110,90
90 PRINT*, ' ',-CONVRG- ITERATIONS EXCEEDED'
   K1 = -1
   GO TO 140
110 M(L1)=M(L1)+1
   B=DL(L1)-D
   IF(B) 160,120,160
120 CONTINUE
K1=-2
140 PRINT*, ' ','LOOP NO.=',L1,' ERROR INDICATOR=',K1
   PRINT*, ' ','ARG. ARE::',X1,Y1,Z1
   DO 155 I=1,25
155 M(I)=0
   GOTO 220
160 C=D*(W-VL(L1))/B
   IF(ABS(C)-.2*ABS(W)) 180,180,170
170 V=W+.2*SIGN(W,C)
   GOTO 190
180 V=W+C

90
program propfunct

*****************************************************************************
*  
*  This program is an interface between the pump sizing
*  program and the properties routines. The correct property
*  routine must be bound along with this program to the main
*  pump sizing program. This method is similar to that used in
*  the gas path program. ghp 2/92
*  
*****************************************************************************

subroutine ept2d(p,t,density,kfluid)

*****************************************************************************
*  
*  This subroutine determines the density from p and t
*  
*****************************************************************************

implicit double precision (a-h,o-z)

call vfromt(t,vf)
density = 1.0/vf

return
end
190 K1=1
  VL(L1)=W
  DL(L1)=D
  IF(Z1) 200,210,200
200 Z=V
  GOTO 220
210 X=V
220 K=K1
  RETURN
  END
subroutine eph2d(p,h,density,temp)

******************************************************************************
* This subroutine determines the density from p and h
******************************************************************************

implicit double precision (a-h,o-z)

    patm = p/14.696
    call tfrmhf(h,temp,patm,vf,sf)
    density = 1.0/vf

return
end
subroutine ept2h(p,t,enthalpy,st,kfluid)

******************************************************************************
*  This subroutine determines the enthalpy from p and t  
******************************************************************************

implicit double precision (a-h,o-z)

patm = p/14.696
call kthrml(t,patm,vf,hf,sf)
enthalpy = hf

return
end
subroutine eph2s(p,h,entropy,temp)

*******************************************************************************
*     This subroutine determines the entropy from p and h                    *
*******************************************************************************
implicit double precision (a-h,o-z)

patm = p/14.696
call tfrmhf(h,temp,patm,vf,entropy)

return
end
subroutine eph2t(p,h,temp,templ)

****************************************************************************************
* This subroutine determines the temperature from p and h *
****************************************************************************************

implicit double precision (a-h,o-z)

patm = p/14.696
call tfrmhf(h,templ,patm,dum,duml)
temp = templ

return
end
subroutine et2vap(t,dum,pvap,kfluid)

*****************************************************************************
* This subroutine determines the vapor pressure for the given t *
*****************************************************************************
implicit double precision (a-h,o-z)

ksh = 0
    call kthrmo(ksh,t,pvap,dum1,dum2,dum3,dum4,dum5,dum6,dum7,
    dum8)
    pvap = pvap*14.696

return
end
SUBROUTINE PIPER
IMPLICIT DOUBLE PRECISION (A-Z)
INTEGER I,J,K,L,M,N,KSH,MFI,NS,MATH,MATC,REHEAT,RSTAGE,NSTG

***** ************************************************************

PARAMETER (NSTG=15)

COMMON /INPUT/ FPL,VELV,VELM,VELL,TMAT,XMATH,XMATC,DUM1,DUM2,KA,
& KB,NUMOP,NUMTOT,TROUT,TRIN,KWNET,GEFF,DUM3,BPP,BFP,
& BPL,PWRFCTR,VOLTAGE,GENASP,TINCLNT,TOUTCLNT,
& CPCNLT,TBOIL,XBOIL,DUM4,TCON,DEFF,EXLOSS,VTIPO,
& SCCON,ALPHAT,RSTT,XMFI,DPCON,PTEFF,DPRFMD,EFFRFMD,
& EMRFMD,DPMAXB,DIATB,NOTUBB,DPMAXR,DTRH,DIARH,
& NOTUBR,KG(11)

COMMON /OUTPUT/MMAIN,TT(O:IS),PP(O:IS),H(O:IS),S(O:IS),X(0:15),
& SVV(O:IS),TLI(I),PLE(I),HLI(I),
& HLE(I),SLI(I),SLE(I),XLI(I),XLE(I),SVVLI(I),
& SVVLE(I),MF(I),WALL(I),HOUT(I),
& DPTOTB,WTOTB,TOTW,TRH,DPTOTR,NS,WTMF(I),
& MFITOT,IPEN,TEM,FDEL,PDIS,UTLIM,TTP(NSTG),XNPSHA,
& DT(NSTG),UT(NSTG),PHI(NSTG),NSTAGE,PSI(NSTG),XN,
& TOFHP,PUMP,SSMARG,XNSSTG(NSTG),WFSPUMP,TOQ,
& KWOUT,ALTW,TYF,PCSACM,MQADD,MRREJ,PRSTAG,
& WTRFMD,WTURBN,XRH,EFF(O:IS),DLPPB,WBOILB,WTWETB,
& DLPBR,WRHT,WTWETR,HTBB,DOUTEB,DTBB,THSB,XTHKB,LPHB,
& LBOILB,LHSB,LTBB,TBB,PTBB,PABB,HLILB,HKPB,HKBOIB,
& HSHB,WSHELB,WTUEB,WTAPEB,WTTS,TWCLOB,MIWETB,
& WTPOTB,WTLIB,HTBR,DOUTER,DTBR,THSR,XTHKB,LPHR,
& LBOIR,LHBR,LTBR,TBB,PAR,HLILIR,HKPHR,HKBOIR,
& HKSHR,WSHELWB,WTUEBR,WTAPEB,WTTSR,TWCLOB,MIWETR,
& WTPOTR,WTLIR,WTPCS,SPMASS,EFNET,EFFGRS,WTPUMP,
& TITCON,PLNTG,GNLOSS,TORQUE,TRBPWR,XXI,TURNRT,RP,
& SVRH,TSAHR,HRR,SRH,TSAO(1:15),VTIP,DGENRTR,KVA,
& DGENSTR,LENTOT,MASSGEN,TIPSPDG,CWCOOL,WMLNT

COMMON /SYSTM/ MFLOPT,CFSLI(I),CFSLIE(I),DELPL(I),DEHL(I),MFI,
& TPUMP,HPUMP,SPUMP,VPUMP,WPUMP,PT(0:IS),G,TOI,XLAMIN,
& XLAMOUT,EFFIND,HCIND,XKLOSS,PT(NSTG),PS(NSTG),
& HT(NSTG),XIHT(NSTG),HSP(NSTG),ST(NSTG),TS(NSTG),
& RH(NSTG),CM(NSTG),XNNS,DH(NSTG),B2(NSTG),
& F3S(NSTG),XNARG,XNPHSA,XNPWH,HD(NSTG),
& EFFP(0:NSTG),HP(NSTG),XIMPNS,XNSSIMP,QBOILL,
& QRHLSS,PEFF,RPMT,VPSTV,VPSTMR,XRHET,PIT,FRACRH,
& RSTAGE,TTI,TFR,FLOC,TBLOUT,TBLIN,TRHOUT,TRHIN,
& REHEAT,MATH,MATC,RPMA

COMMON/CONFIG/GENTYPE,INTTYPE,CLNTYPE
COMMON/DIAGNOS/ERRORG,WARNINGG

***** ************************************************************
MF(1) = MMAIN
MF(2) = MF(1) - MFLOPT
MF(3) = MFLOPT
MF(4) = MF(2)
MF(5) = MF(3)
DO 1455 J = 6, 11
MF(J) = MF(1)
1455 CONTINUE

TLE(2) = TT(O)
PLE(2) = PP(O)
HLE(2) = H(O)
SLE(2) = S(O)
XLE(2) = X(O)
SVWLE(2) = SVV(O)
CFSLE(2) = MF(2)*SVVLE(2)

CALL SIZEPP (CFSLE(2), VELV, TLE(2), TMAT, FPL, PLE(2), LG(2), MF(2),
         & WALL(2), WT(2), WTKINV(2), WTMFI(2), ID(2), MFI)

VISCOS = 1.98227D-2 + 1.36364D-5*TLE(2)
DENSIT = 1.0/SVVLE(2)
CALL HEADLOSS (DENSIT, ID(2), VELV, VISCOS, LG(2), DELPL(2))
CALL QLOSS (TLE(2), LG(2), ID(2), MF(2), MFI, DELHL(2))

PLI(2) = PLE(2) + DELPL(2)
HLI(2) = HLE(2) + DELHL(2)
P = PLI(2)/14.696
CALL TFROMP (P, T)
KSH = 0
CALL KTHRMO (KSH, T, P, VF, VG, HF, HG, HFG, SF, SG, SFG)

IF (HLI(2) .GT. HG) THEN
HH = HLI(2)
CALL TFRMHG (HH, P, T, SG, VG, VF)
TLI(2) = T
SLI(2) = SG
SVVLI(2) = VG
XLI(2) = 1.0
ELSE
XLI(2) = (HLI(2) - HF)/HFG
TLI(2) = T
SLI(2) = SF + SFG*XLI(2)
SVVLI(2) = VF + XLI(2)*(VG - VF)
ENDIF
CFSLI(2) = MF(2)*SVVLI(2)

TLE(1) = TLI(2)
PLE(1) = PLI(2)
HLE(1) = HLI(2)
SLE(1) = SLI(2)
XLE(1) = XLI(2)
SVVLI(1) = SVVLE(2)
CFSLI(1) = MF(1)*SVVLE(1)

CALL SIZEPP (CFSLI(1),VELV,TLE(1),TMAT,FPL,PLE(1),LG(1),MF(1),
            WALL(1),WT(1),WTKINV(1),WTMFI(1),ID(1),MFI)

VISCOS = 1.98227D-2 + 1.36364D-5*TLE(1)
DENSIT = 1.0/SVVLE(1)
CALL HEADLOSS (DENSIT,ID(1),VELV,VISCOS,LG(1),DELPL(1))
CALL QLOSS (TLE(1),LG(1),ID(1),MF(1),MFI,DELHL(1))

PLI(1) = PLE(1) + DELPL(1)
HLI(1) = HLE(1) + DELHL(1)
P = PLI(1)/14.696
CALL TFROMP (P,T)
KSH = 0
CALL KTHRMO (KSH,T,P,VF,VG,HF,HG,HFG,SG,SFG)

IF (HLI(1) .GT. HG) THEN
  HH = HLI(1)
  CALL TFRMHG (HH,P,T,SG,VG,VF)
  TLI(1) = T
  SLI(1) = SG
  SVVLI(1) = VG
  XLI(1) = 1.0
ELSE
  XLI(1) = (HLI(1) - HF)/HFG
  TLI(1) = T
  SLI(1) = SF + SFG*XLI(1)
  SVVLI(1) = VF + XLI(1)*(VG - VF)
ENDIF
CFSLI(1) = MF(1)*SVVLI(1)

TLI(3) = TLE(1)
PLI(3) = PLE(1)
HLI(3) = HLE(1)
SLI(3) = SLE(1)
XLI(3) = XLE(1)
SVVLI(3) = SVVLE(1)
CFSLI(3) = MF(3)*SVVLI(3)

CALL SIZEPP (CFSLI(3),VELM,TLI(3),TMAT,FPL,PLI(3),LG(3),MF(3),
            WALL(3),WT(3),WTKINV(3),WTMFI(3),ID(3),MFI)

VISCOS = 1.98227D-2 + 1.36364D-5*TLI(3)
DENSIT = 1.0/SVVLI(3)
CALL HEADLOSS (DENSIT,ID(3),VELM,VISCOS,LG(3),DELPL(3))
CALL QLOSS (TLI(3),LG(3),ID(3),MF(3),MFI,DELHL(3))

PLE(3) = PLI(3) - DELPL(3)
HLE(3) = HLI(3) - DELHL(3)
P = PLE(3)/14.696
CALL TFROMP (P,T)
KSH = 0
CALL KTHRMO (KSH,T,P,VF,VG,HF,HG,HFG,SF,SG,SFG)

IF (HLE(3) .GT. HG) THEN
  HH = HLE(3)
  CALL TFRMHG (HH,P,T,SG,VG,VF)
  TLE(3) = T
  SLE(3) = SG
  SVVLE(3) = VG
  XLE(3) = 1.0
ELSE
  XLE(3) = (HLE(3) - HF)/HFG
  TLE(3) = T
  SLE(3) = SF + SFG*XLE(3)
  SVVLE(3) = VF + XLE(3)*(VG - VF)
ENDIF
CFSLE(3) = MF(3)*SVVLE(3)

CFSLI(4) = MF(4)*SVVLI(4)

CALL SIZEPP (CFSLI(4),VELV,TLI(4),TMAT,FPL,PLI(4),LG(4),MF(4), WALL(4),WT(4),WTINV(4),WTMFI(4),ID(4),MFI)

VISCOS = 1.98227D-2 + 1.36364D-5*TLI(4)
DENSIT = 1.0/SVVLI(4)
CALL HEADLOSS (DENSIT,ID(4),VELV,VISCOS,LG(4),DELPL(4))
CALL QLOSS (TLI(4),LG(4),ID(4),MF(4),MFI,DELHL(4))

PLE(4) = PLI(4) - DELPL(4)
HLE(4) = HLI(4) - DELHL(4)
P = PLE(4)/14.696
CALL TFROMP (P,T)
KSH = 0
CALL KTHRMO (KSH,T,P,VF,VG,HF,HG,HFG,SF,SG,SFG)

IF (HLE(4) .GT. HG) THEN
  HH = HLE(4)
  CALL TFRMHG (HH,P,T,SG,VG,VF)
  TLE(4) = T
  SLE(4) = SG
  SVVLE(4) = VG
  XLE(4) = 1.0
ELSE
  XLE(4) = (HLE(4) - HF)/HFG
  TLE(4) = T
  SLE(4) = SF + SFG*XLE(4)
  SVVLE(4) = VF + XLE(4)*(VG - VF)
ENDIF
CFSLE(4) = MF(4)*SVVLE(4)

CFSLI(5) = MF(5)*SVVLI(5)

TLE(5) = TLE(4)
PLE(5) = PLE(4)

CALL SIZEPP (CFSLI(5),VELM,TLI(5),TMAT,FPL,PLI(5),LG(5),MF(5).
VISCOS = 1.98227D-2 + 1.36364D-5*TLI(5)
DENSIT = 1.0/SVVLI(5)
CALL HEADLOSS (DENSIT,ID(5),VELM,VISCOS,LG(5),DELPL(5))
CALL QLOSS (TLI(5),LG(5),ID(5),MF(5),MFI,DELHL(5))

PLI(5) = PLE(5) + DELPL(5)
HLE(5) = HLI(5) - DELHL(5)
P = PLE(5)/14.696
CALL TFROMP (P,T)
KSH = 0
CALL KTHRMO (KSH,T,P,VF,VG,HF,HG,HFG,SF,SG,SFG)

IF (HLE(5) .GT. HG) THEN
HH = HLE(5)
CALL TFRMHG (HG,P,T,SG,VG,VF)
TLE(5) = T
SLE(5) = SG
SVVLE(5) = VG
XLE(5) = 1.0
ELSE
XLE(5) = (HLE(5) - HF)/HFG
TLE(5) = T
SLE(5) = SF + SFG*XLE(5)
SVVLE(5) = VF + XLE(5)*(VG - VF)
ENDIF
CFSLLE(5) = MF(5)*SVVLE(5)

PLI(6) = PLE(4)
HLE(6) = (MF(4)*HLE(4) + MF(5)*HLE(5))/(MF(4) + MF(5))
P = PLI(6)/14.696
CALL TFROMP (P,T)
KSH = 0
CALL KTHRMO (KSH,T,P,VF,VG,HF,HG,HFG,SF,SG,SFG)

IF (HLI(6) .GT. HG) THEN
HH = HLI(6)
CALL TFRMHG (HH,P,T,SG,VG,VF)
TLI(6) = T
SLI(6) = SG
SVVLI(6) = VG
XLI(6) = 1.0
ELSE
XLI(6) = (HLI(6) - HF)/HFG
TLI(6) = T
SLI(6) = SF + SFG*XLI(6)
SVVLI(6) = VF + XLI(6)*(VG - VF)
ENDIF
CFSLI(6) = MF(6)*SVVLI(6)

CALL SIZEPP (CFSLI(6),VELV,TLI(6),TMAT,FPL,PLI(6),LG(6),MF(6),
& WALL(6),WT(6),WTKINV(6),WTMFI(6),ID(6),MFI)
VISCOS = 1.98227D-2 + 1.36364D-5*TLI(6)
DENSIT = 1.0/SVVLI(6)
CALL HEADLOSS (DENSIT,ID(6),VELV,VISCOS, LG(6),DELPL(6))
CALL QLOSS (TLI(6),LG(6),ID(6),MF(6),MFI,DELHL(6))

PLE(6) = PLI(6) - DELPL(6)
HLE(6) = HLI(6) - DELHL(6)
P = PLE(6)/14.696
CALL TFROMP (P,T)
KSH = 0
CALL KTHRMO (KSH,T,P,VF,VG,HF,HG,HFG,SF,SG,SFG)

IF (HLE(6) .GT. HG) THEN
  HH = HLE(6)
  CALL TFRMHG (HH,P,T,SG,VG,VF)
  TLE(6) = T
  SLE(6) = SG
  SVVLE(6) = VG
  XLE(6) = 1.0
ELSE
  XLE(6) = (HLE(6) - HF)/HFG
  TLE(6) = T
  SLE(6) = SF + SFG*XLE(6)
  SVVLE(6) = VF + XLE(6)*(VG - VF)
ENDIF
CFSLE(6) = MF(6)*SVVLE(6)
PLI(7) = PLE(6) - DPTOTR
TLE(7) = TTRH
T = TLE(7)
P = PLE(7)/14.696
KSH = 1
CALL KTHRMO (KSH,T,P,VF,VG,HF,HG,HFG,SF,SG,SFG)
HLE(7) = HG
SLE(7) = SG
XLE(7) = 1.0
SVVLE(7) = VG
CFSLE(7) = MF(7)*SVVLE(7)

CALL SIZEPP (CFSLE(7),VELV,TLE(7),TMAT,FPL,PLE(7),LG(7),MF(7), &
  WALL(7),WT(7),WTINV(7),WTMFI(7),ID(7),MFI)

VISCOS = 1.98227D-2 + 1.36364D-5*TLI(7)
DENSIT = 1.0/SVVLE(7)
CALL HEADLOSS (DENSIT,ID(7),VELV,VISCOS, LG(7),DELPL(7))
CALL QLOSS (TLI(7),LG(7),ID(7),MF(7),MFI,DELHL(7))

PLE(7) = PLI(7) - DELPL(7)
HLI(7) = HLE(7) + DELHL(7)
P = PLI(7)/14.696
CALL TFROMP (P,T)
KSH = 0
CALL KTHRMO (KSH,T,P,VF,VG,HF,HG,HFG,SF,SG,SFG)
IF (HLI(7) .GT. HG) THEN
HH = HLI(7)
CALL TFRMHG (HH,P,T,SG,VG,VF)
TLI(7) = T
SLI(7) = SG
SVVLI(7) = VG
XLI(7) = 1.0
ELSE
XLI(7) = (HLI(7) - HF)/HFG
TLI(7) = T
SLI(7) = SF + SFG*XLI(7)
SVVLI(7) = VF + XLI(7)*(VG - VF)
ENDIF
CFSLI(7) = MF(7)*SVVLI(7)

TLI(8) = TT(NS)
PLI(8) = PP(NS)
HLI(8) = H(NS)
SLI(8) = S(NS)
XLI(8) = X(NS)
SVVLI(8) = SVV(NS)
CFSLI(8) = MF(8)*SVVLI(8)

CALL SIZEPP (CFSLI(8),VELV,TLI(8),TMAT,FPL,PLI(8),LG(8),MF(8),
& WALL(8),WT(8),WTINV(8),WTMFI(8),ID(8),MFI)

VISCOS = 1.98227D-2 + 1.36364D-5*TLI(8)
DENSIT = 1.0/SVVLI(8)
CALL HEADLOSS (DENSIT,ID(8),VELV,VISCOS,LG(8),DELPL(8))
CALL QLOSS (TLI(8),LG(8),ID(8),MF(8),MFI,DELHL(8))

PLE(8) = PLI(8) - DELPL(8)
HLE(8) = HLI(8) - DELHL(8)
P = PLE(8)/14.696
CALL TFROMP (P,T)
KSH = 0
CALL KTHRMO (KSH,T,P,VF,VG,HF,HG,HFG,SF,SG,SFG)

IF (HLE(8) .GT. HG) THEN
HH = HLE(8)
CALL TFRMHG (HH,P,T,SG,VG,VF)
TLE(8) = T
SLE(8) = SG
SVVLE(8) = VG
XLE(8) = 1.0
ELSE
XLE(8) = (HLE(8) - HF)/HFG
TLE(8) = T
SLE(8) = SF + SFG*XLE(8)
SVVLE(8) = VF + XLE(8)*(VG - VF)
ENDIF
CFSLE(8) = MF(8)*SVVLE(8)

PLI(9) = PLE(8) - DPCON
P = PLI(9)/14.696
CALL TFRMP(P,T)
KSH = 0
CALL KTHRMO(KSH,T,P,VF,VG,HF,HG,HFG,SG,SFG)
TLI(9) = T - SCON
T = TLI(9)
CALL KTHRML(T,P,VF,HF,SF)
HLI(9) = HF
SLI(9) = SF
XLI(9) = 0.0
SVVLI(9) = VF
CFSLI(9) = MF(9)*SVVLI(9)

CALL SIZEPP(CFSLI(9),VELL,TLI(9),TMAT,FPL,PLI(9),LG(9),MF(9),
            WALL(9),WT(9),WTKINV(9),WTMFI(9),ID(9),MFI)

CALL KXPORT(TLI(9),VISCOS,KK,CP,RHOFL)
DENSIT = RHOFL
CALL HEADLOSS(DENSIT,ID(9),VELL,VISCOS,LG(9),DELPL(9))
CALL QLOSS(TLI(9),LG(9),ID(9),MF(9),MFI,DELHL(9))

PLE(9) = PLI(9) - DELPL(9)
HLE(9) = HLI(9) - DELHL(9)
HH = HLE(9)
P = PLE(9)/14.696
CALL TFRMHF(HH,T,P,VF,SF)
TLE(9) = T
SLE(9) = SF
XLE(9) = 0.0
SVVLE(9) = VF
CFSLE(9) = MF(9)*SVVLE(9)

PLI(10) = PLE(9) + DPRFMD
WKRFMD = DPRFMD*144.0*SVVLE(9)/778.0
HLI(10) = HLE(9) + WKRFMD/EFRFMD
HH = HLI(10)
P = PLI(10)/14.696
CALL TFRMHF(HH,T,P,VF,SF)
TLI(10) = T
SLI(10) = SF
XLI(10) = 0.0
SVVLI(10) = VF
CFSLI(10) = MF(10)*SVVLI(10)

CALL SIZEPP(CFSLI(10),VELL,TLI(10),TMAT,FPL,PLI(10),LG(10),MF(10),
            WALL(10),WT(10),WTKINV(10),WTMFI(10),ID(10),MFI)

CALL KXPORT(TLI(10),VISCOS,KK,CP,RHOFL)
DENSIT = RHOFL
CALL HEADLOSS(DENSIT,ID(10),VELL,VISCOS,LG(10),DELPL(10))
CALL QLOSS(TLI(10),LG(10),ID(10),MF(10),MFI,DELHL(10))

PLE(10) = PLI(10) - DELPL(10)
HLE(10) = HLI(10) - DELHL(10)
HH = HLE(IO)
P = PLE(IO)/14.696
CALL TFRMFH(HH,T,P,VF,SF)
TLE(IO) = T
SLE(IO) = SF
XLE(IO) = 0.0
SVVLE(IO) = VF
CFSLE(IO) = MF(IO)*SVVLE(IO)

TLI(11) = TPUMP
HLI(11) = HPUMP
SLI(11) = SFPUMP
XLI(11) = 0.0
SVVL(11) = VFPUMP
CFSLI(11) = MF(11)*SVVL(11)

CALL SIZEPP (CFSLI(11),VELL,TLI(11),TMAT,FPL,PLI(11),LG(11),
& MF(11),WALL(11),WT(11),WTKINV(11),WTMFI(11),ID(11),MFI)

CALL KXPORT (TLI(11),VISCOS,KK,CP,RHOFL)
DENSIT = RHOFL
CALL HEADLOSS (DENSIT,ID(11),VELL,VISCOS,LG(11),DELPL(11))
CALL QLOSS (TLI(11),LG(11),ID(11),MF(11),MFI,DELHL(11))

PLE(11) = PLI(11) + DPTOTB
PLI(11) = PLE(11) + DELPL(11)
HLE(11) = HLI(11) - DELHL(11)
HH = HLE(11)
P = PLE(11)/14.696
CALL TFRMFH(HH,T,P,VF,SF)
TLE(11) = T
SLE(11) = SF
XLE(11) = 0.0
SVVLE(11) = VF
CFSLE(11) = MF(11)*SVVLE(11)

TOTWT = 0.DO
WTKTOT = 0.DO
MFITOT = 0.DO

DO 1705 I = 1,11
WTKTOT = WTKTOT + WTKINV(I)
TOTWT = TOTWT + WT(I)
MFITOT = MFITOT + WTMFI(I)
1705 CONTINUE

RETURN
END
SUBROUTINE SIZEPP (CFS, VELO, TR, TMAT, FPL, PL, LG, MF, &
     WALL, WT, WTKINV, WTMFI, ID, MFI)

IMPLICIT DOUBLE PRECISION (A-H,O-Z)
DOUBLE PRECISION ID, LG, MF

DATA PI /3.141592654/
DATA SEP, THK, RHOMFI /5.D-3, 3.D-4, 0.1626D0/

ID = 12.0*DSQRT(4.0*CFS/(PI*VELO))
CALL STRNTH (TR, TMAT, MATH, MATC, FPL, SIGPV, RHO)
SIGMAL = SIGPV
IF (SIGMAL .EQ. 0) GO TO 10
WALL = PL*ID/(2.0*SIGMAL)
IF (WALL .LT. 0.02) WALL = 0.02
WT = 37.7*LG*RHO*WALL*(ID + WALL)
WTKINV = MF*LG/VELO
WTMFI = PI*LG*((ID + 2.DO*MFI*(SEP + THK))**2.DO - ID**2.DO)/4.DO
WTMFI = WTMFI*RHOMFI/(SEP/THK + 1.DO)
IF (ID .EQ. 0.0) THEN
WT = 0.DO
WTKINV = 0.DO
WTMFI = 0.DO
ENDIF

10 RETURN
END
SUBROUTINE HEADLOSS (DENSIT,ID,VELO,VISCOS,LG,DELP)
IMPLICIT DOUBLE PRECISION (A-H,O-Z)
DOUBLE PRECISION ID,LG

REYNLD = 3.D2*ID*VELO*DENSIT/VISCOS

IF (REYNLD.EQ.0.DO) THEN
FRIC = 0.DO
ELSE
FRIC = (1.82*DLOG10(REYNLD) - 1.64)**(-2.0)
ENDIF

IF (FRIC.EQ.0.DO) THEN
DELP = 0.DO
ELSE
DELP = FRIC*(LG*12.0/ID)*(VELO**2.0/64.348)*
       (DENSIT/1.44D2)
ENDIF

RETURN
END
SUBROUTINE QLOSS (TR,LG,ID,MF,MFI,QLOST)

IMPLICIT DOUBLE PRECISION (A-H,O-Z)
DOUBLE PRECISION ID,LG,MF

DATA SIGMA,EPS,PI /4.7547D-13,0.2,3.141592654/

XMFI = DFLOAT(MFI)
IF (MFI .EQ. 0.0) XMFI = 1.0
AREA = PI*ID*LG/12
QLOST = AREA*EPS*SIGMA*TR**4.0/MF
QLOST = QLOST/XMFI

RETURN
END
SUBROUTINE KTHRMO (KSH,T,P,VF,VG,HF,HG,HFG,SF,SG,SFG)
IMPLICIT DOUBLE PRECISION (A-H,O-Z)

IF (KSH .EQ. 0) THEN
  P = 10.0**((6.12758 - 8128.77/T - 0.53299*DLOG10(T))
ENDIF

RHOFL = 52.768 - 7.4975D-3*(T-459.67) - 0.5255D-6*(T-459.67)**2.0
& + 0.0498D-9*(T-459.67)**3.0
VF = 1.0/RHOFL
B = -T*10.0**(-3.8787 + 4890.7/T)
DBDT = B/T*(1.0 - 4890.7*DLOG1.01)/T)
C = 10.0**((0.5873 + 6385.7/T)
DCDT = -6385.7*DLOG1.01)*C/T**2.0
D = -1.0*10**((1.4595 + 7863.8/T)
DDDT = -7863.8*DLOG1.01)*D/T**2.0

VI = 0.7302*T/P
DO 10 I=1,100
  FUNC = P*VI/(0.7302*T) - (1.0 + B/VI + C/VI**2 + D/VI**3)
  SLOPE = P/(0.7302*T) + (B/VI**2 + 2.0*C/VI**3 + 3.0*D/VI**4)
  V2 = VI - FUNC/SLOPE
  IF (DABS(FUNC) .LT. 1.D-6) GO TO 20
  V1 = V2
10 CONTINUE
20 VG = V2

HFG = (1.9872/0.7302)*P*(8128.77*DLOG1.01)/T - 0.53299)*
& (VG/39.0983 - VF)
HGO = 998.95 + 0.127*T + 24836.0*DEXP(-39375.0/T)
DELHRT = T/VG*((DBDT - B/T) + 1.0/VG*(DCDT/2.0 - C/T) +
& 1.0/VG**2.0*(DDDT/3.0 - D/T))
HG = HGO - (1.9872*T/39.0983)*DELHRT
HF = HG - HFG
SFG = HFG/T
SGO = 0.18075 + 0.127*DLOG(T) + 0.7617*DEXP(-31126.0/T)
DELSR = T/VG*((DBDT + B/T) + 1.0/(2.0*VG)*(DCDT + C/T) +
& 1.0/(3.0*VG**2.0)*(DDDT + D/T)) - DLOG(P*VG/(0.7302*T))
SG = SGO - (1.987/39.0983)*(DLOG(P) + DELSR)
SF = SG - SFG
VG = VG/39.0983

RETURN
END
SUBROUTINE KTHRML (T,P2,VF,HF,SF)

IMPLICIT DOUBLE PRECISION (A-H,O-Z)

KSH = 0
CALL KTHRMO (KSH,T,P1,VF,VG,HF1,HG,HFG,SF1,SG,SFG)
RHOFL = 1.0/VF
DRHODT = - 7.4975D-3 - 2.0*0.5255D-6*(T-459.67) & + 3.0*0.0498D-9*(T-459.67)**2.0
HF = HF1 + (1.0 + T*DRHODT/RHOFL)*(P2 - P1)/RHOFL*(1.9872/0.7302)
SF = SF1 + DRHODT*(P2 - P1)/RHOFL**2.0*(1.9872/0.7302)

RETURN
END
SUBROUTINE VFROMT(T,VF)

IMPLICIT DOUBLE PRECISION (A-H,O-Z)

RHOFL = 52.768 - 7.4975D-3*(T-459.67) - 0.5255D-6*(T-459.67)**2.0 
& + 0.0498D-9*(T-459.67)**3.0
VF = 1.0/RHOFL

RETURN
END
SUBROUTINE TFROMP(P, TEMP)

IMPLICIT DOUBLE PRECISION (A-H,O-Z)

C CALCULATES SATURATION TEMPERATURE (R) FROM GIVEN PRESSURE (ATM)
T1 = 1000.
DO 6315 I = 1, 100
FUNC = DLOG10(P) - 6.12758 + 8128.77/T1 + 0.53299*DLOG10(T1)
SLOPE = -8128.77/T1**2.0 + 0.53299*DLOG10(DEXP(1.0D0))/T1
T2 = T1 - FUNC/SLOPE
IF (DABS(FUNC) .LT. 1.D-6) GO TO 6345
T1 = T2
6315 CONTINUE
6345 TEMP = T2
RETURN
END
SUBROUTINE TFRMHG (HG,P,T,SG,VG,VF)

C Calculates superheated vapor temperature from enthalpy and temperature

IMPLICIT DOUBLE PRECISION (A-H,O-Z)

C Get initial temperature guess

CALL TFROMP(P,TI)
KSH = 1
T2 = 1.05*TI
CALL KTHRMO (KSH,T1,P,VF,VG,HF,HG1,HFG,SG,SFG)
FUNC1 = HG - HG1

DO 10 J = 1,100
CALL KTHRMO (KSH,T2,P,VF,VG,HF,HG2,HFG,SG,SFG)
FUNC2 = HG - HG2
DELTA = (T2 - T1)*FUNC2/(FUNC2 - FUNC1)
T1 = T2
T2 = T2 - DELTA
FUNC1 = FUNC2
IF (DABS(FUNC2) .LT. 1.D-6) GOTO 20
10 CONTINUE
20 T = T2
RETURN
END
SUBROUTINE TFRMSG (SG,P,T,HG,VG,VF)
IMPLICIT DOUBLE PRECISION (A-H,O-Z)
CALL TFROMP(P,T1)
KSH = 1
T2 = 1.05*T1
CALL KTHRMO (KSH,T1,P,VF,VG,HF,HG,HFG,SF,SG1,SFG)
FUNC1 = SG - SG1
DO 10 J = 1,100
CALL KTHRMO (KSH,T2,P,VF,VG,HF,HG,HFG,SF,SG2,SFG)
FUNC2 = SG - SG2
DELTA = (T2 - T1)*FUNC2/(FUNC2 - FUNC1)
T1 = T2
T2 = T2 - DELTA
FUNC1 = FUNC2
IF (DABS(FUNC2) .LT. 1.D-6) GOTO 20
10 CONTINUE
20 T = T2
RETURN
END
SUBROUTINE TFRMHF(H,T,P,VF,SF)

IMPLICIT DOUBLE PRECISION (A-H,O-Z)

C CALCULATES TEMP (R) FROM HF & P

CALL TFROMP(P,T)
T1 = T
T2 = 1.05*T
CALL KTHRML (T1,P,VF,HF,SF)
FUNC1 = H - HF
DO 10 J = 1,100
CALL KTHRML (T2,P,VF,HF,SF)
FUNC2 = H - HF
DELTA = (T2 - T1)*FUNC2/(FUNC2 - FUNC1)
T1 = T2
T2 = T2 - DELTA
FUNC1 = FUNC2
IF (DABS(FUNC2) .LT. 1.D-6) GOTO 20
10 CONTINUE
20 CONTINUE
T = T2

RETURN
END
SUBROUTINE KXPORT(TR,MU,K,CP,RHOFL)
IMPLICIT DOUBLE PRECISION (A-H,O-Z)
DOUBLE PRECISION MU,K

****** LIQUID POTASSIUM TRANSPORT PROPERTIES SUBROUTINE *****

TF = TR - 459.67
TC = TR/1.8 - 273.15
MU = DEXP(1353.9D0/TR - 1.9206D0)
K = 32.2036D0 - 7.6789D-3*TR
CP = 0.22713 - 64.848D-6*TR + 23.178D-9*TR**2.0
RHOFL = 52.768 - 7.4975D-3*TF - 5.255D-7*TF**2.0 + 4.98E-11*TF**3.0

RETURN
END
**POTASSIUM VAPOR TRANSPORT PROPERTIES SUBROUTINE**

\[\begin{align*}
\text{MU} &= 1.0282D-2 + 2.5649D-5\times TR - 3.125D-9\times TR^2 \times 2.0 \\
\text{K} &= 1.8786D-3 + 4.3527D-6\times TR - 5.2198D-10\times TR^2 \times 2.0 \\
\text{CP} &= 0.22713 - 64.848D-6\times TR + 23.178D-9\times TR^2 \times 0.0 \\
\text{CALL KTHRMO} (\text{KSH}, TR, P, VF, VG, HF, HG, HFG, SF, SG, SFG) \\
\text{RHOFL} &= 1.00/\text{VG} \\
\text{KSH1} &= \text{KSH} \\
\text{KSH} &= 1 \\
\text{TR2} &= TR + 1.0D-2 \\
\text{CALL KTHRMO} (\text{KSH}, TR2, P, VF, VG, HF, HG2, HFG, SF, SG, SFG) \\
\text{TR1} &= TR - 1.0D-2 \\
\text{CALL KTHRMO} (\text{KSH}, TR1, P, VF, VG, HF, HG1, HFG, SF, SG, SFG) \\
\text{CP} &= (HG2 - HG1)/2.0D-2 \\
\text{KSH} &= \text{KSH1} \\
\end{align*}\]

RETURN
END
SUBROUTINE LIPORT(TR,MU,K,CP,RHOFL,PSAT)
IMPLICIT DOUBLE PRECISION (A-H,O-Z)
DOUBLE PRECISION MU,K

C '***** LIQUID LITHIUM TRANSPORT PROPERTIES SUBROUTINE *****

        MU = DEXP(1183.D0/TR - 1.05415)
        K = 30.319D0 - 4.2284D-3*TR
        IF (TR .LE. 1500.D0) THEN
          CP = 1.2024D0 - 2.5008D-4*TR + 7.4405D-8*TR**2.D0
        ELSE
          CP = 1.0058D0 - 7.0749D-6*TR - 2.9533D-10*TR**2.D0
        ENDIF
        RHOFL = 34.388D0 - 3.4473D-3*TR + 2.0664D-7*TR**2.D0
        PSAT = DEXP(11.095D0 - 31976.D0/TR)

RETURN
END
SUBROUTINE STRNTH (TT, TMAT, MATH, MATC, FPL, SIGPV, RHO)

IMPLICIT DOUBLE PRECISION (A-H,O-Z)

***** DESIGN STRENGTH SUBROUTINE *****

TT = TT/1.8D0
TMAT = TMAT/1.8D0
IF ( TT .EQ. 0.0D0) RETURN
IF (TT .GT. TMAT) THEN
    IF (MATH .EQ. 1) GOTO 10
    IF (MATH .EQ. 2) GOTO 20
    IF (MATH .EQ. 3) GOTO 30
    IF (MATH .EQ. 4) GOTO 100
ELSE
    IF (MATC .EQ. 1) GOTO 10
    IF (MATC .EQ. 2) GOTO 20
    IF (MATC .EQ. 3) GOTO 30
    IF (MATC .EQ. 4) GOTO 100
ENDIF

C ASTAR 811C

10 RHO = 0.604D0
    CH = -13.834D0
    A = -3.112D4
    B = 1.918D4
    C = -4.498D3
    D = 4.776D4
    GOTO 40

C Nb-1%Zr

20 RHO = 0.31D0
    CH = -7.392D0
    A = -2.879D0*TT
    B = 0.0D0
    C = 0.0D0
    D = 1.8276D4
    GOTO 40

C TZM

30 RHO = 0.37D0
    CH = -22.0356D0
    A = -77.43D0
    B = -2530.33D0
    D = 39963.9D0
    GOTO 70

40 THET = DLOG10(FPL*8.76D3)
    SIGMA = 4.0D0
    DO 50 I=1,100

50   CONTINUE
\[ \theta = \text{CH} + \left( A\sigma + B\sigma^2 + C\sigma^3 + D \right) / \text{TT} \]

\[ \text{FUNC} = \theta - \theta \]

\[ \text{FPRIME} = -(A + 2B\sigma + 3C\sigma^2) / \text{TT} \]

\[ \Delta = \text{FUNC} / \text{FPRIME} \]

\[ \sigma = \sigma - \Delta \]

\[ \text{IF} (|\text{FUNC}| < 1.0^{-6}) \text{ GO TO 60} \]

\[ \text{CONTINUE} \]

\[ \text{SIGPV} = (1.0^{\sigma}) \cdot 14.696 / 0.101325 \]

\[ \text{GOTO 130} \]

\[ \text{THET} = \log_{10}(FPL \cdot 8.76) \]

\[ \text{SIGMA} = 4 \]

\[ \text{DO 80 I = 1, 100} \]

\[ \theta = \text{CH} + (A\sigma + \log_{10}(\sigma) + D) / \text{TT} \]

\[ \text{FUNC} = \theta - \theta \]

\[ \text{FPRIME} = -(A + B / (\sigma \log_{10}(\sigma))) / \text{TT} \]

\[ \Delta = \text{FUNC} / \text{FPRIME} \]

\[ \sigma = \sigma - \Delta \]

\[ \text{IF} (|\text{FUNC}| < 1.0^{-6}) \text{ GO TO 90} \]

\[ \text{CONTINUE} \]

\[ \text{SIGPV} = 1.0^{\sigma} \]

\[ \text{GOTO 130} \]

C 316 Stainless Steel

\[ \rho = 0.285 \]

\[ \text{TIME} = FPL \cdot 8.76 \]

\[ \text{DO 110 I = 1, 100} \]

\[ \text{IF} (1 \neq I) \sigma = 5 \]

\[ \text{TIMEI} = 63.502 - 18.889 \sigma \log_{10}(\sigma) + 0.06812 \text{TT} + 0.01963 \sigma \log_{10}(\sigma) \]

C Solve for type I creep

\[ \dot{\epsilon} = -44.39 + 7.867 \log_{10}(\sigma) + 0.0312 \text{TT} - 8.887 \sigma \log_{10}(\sigma) \]

\[ \dot{\epsilon} = 1.0^{\dot{\epsilon}} \]

\[ \pi = 1.0^{\dot{\epsilon}} \]

\[ C = 0.76 D \]

\[ E = C \pi \]

C Solve for type II creep

\[ \dot{\epsilon} = -5.164 - 9.136 \log_{10}(\sigma) + 0.01551 \text{TT} + 0.02052 \sigma \log_{10}(\sigma) \]

\[ \dot{\epsilon} = 1.0^{\dot{\epsilon}} \]

\[ P = 3.45 \]

\[ C = 0.64 \]

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BC = EI*P2 - C2*P2 - EM2DOT
TIMEC = (BC + DSQRT(BC**2.DO + 4.DO*EI*P2*EM2DOT))/
& (2.DO*P2*EM2DOT)

TIME2 = TIME - TIMEI + TIMEC
IF (TIME2 .LT. TIME) TIME2 = TIME
EC = C2*P2*TIME2/(1.DO + P2*TIME2) + EM2DOT*TIME2

FUNC = EC - 1.DO
IF (I .EQ. 1) THEN
SIGMA1 = SIGMA
SIGMA = 2.DO
FUNC1 = FUNC
GOTO 110
ENDIF

DELTA = (SIGMA - SIGMA1)*FUNC/(FUNC - FUNC1)
SIGMA1 = SIGMA
SIGMA = SIGMA - DELTA
FUNC1 = FUNC
IF (DABS(FUNC) .LT. 1.DO-6) GOTO 120
110 CONTINUE
120 SIGPV = SIGMA*14.696DO/0.101325DO
130 TT = TT*1.8DO
TMAT = TMAT*1.8DO
RETURN
END
A potassium-Rankine power conversion system model was developed under Contract No. NAS3-25808 for the NASA-LeRC. This model predicts potassium-Rankine performance for turbine inlet temperatures (TIT) from 1200 - 1600 K, TIT to condenser temperature ratios from 1.25-1.6, power levels from 100 to 10,000 kWe, and lifetimes from 2-10 years. The model is for a Rankine cycle with reheat for turbine stage moisture control. The model assumes heat is supplied from a lithium heat transport loop. The model does not include a heat source or a condenser/heat rejection system model. These must be supplied by the user.