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

(NASA-CR-191134) POTASSIUM-RANKINE POWER CONVERSION SUBSYSTEM MODELING FOR NUCLEAR ELECTRIC PROPULSION (Rockwell International Corp.) 128 p

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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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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.

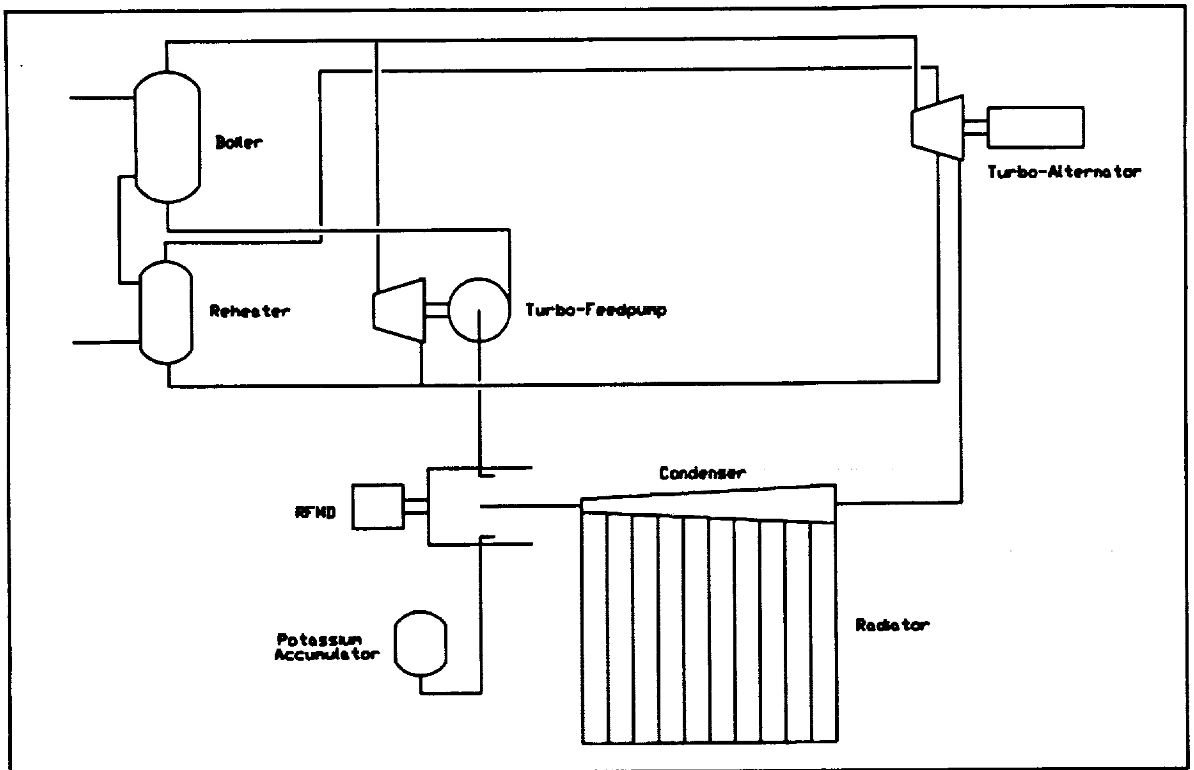

Figure 1. Potassium-Rankine Flow Schematic

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

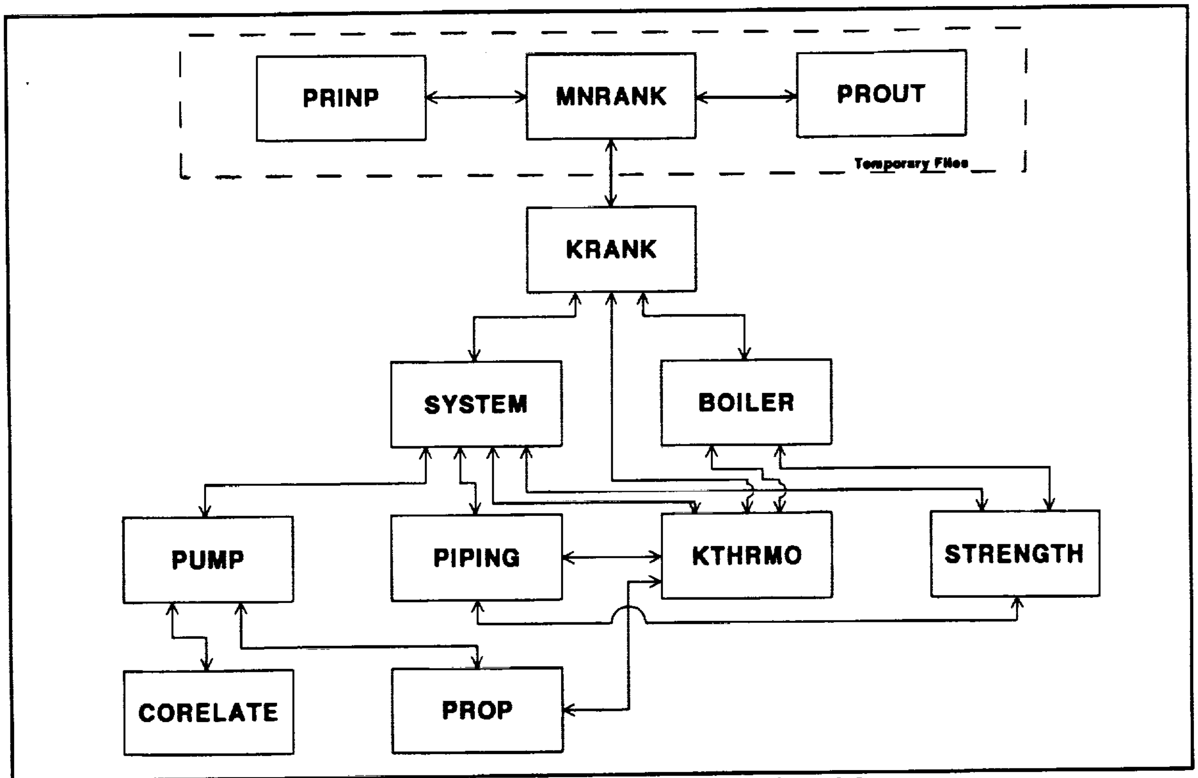

Figure 2. Program Interrelationships

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
BOILER.FOR
KRANK.FOR
KTAGEN.FOR
KTHRMO.FOR
MNRANK.FOR
PIPING.FOR
PRINP.FOR
PROP.FOR
PROUT.FOR
PUMP.FOR
STRNGTH.FOR
SYSTEM.FOR
CORELATE.OBJ
KRANK.IN
KRANK.EXE

In the potassium-Rankine power conversion subsystem, shown in Figure 1, the

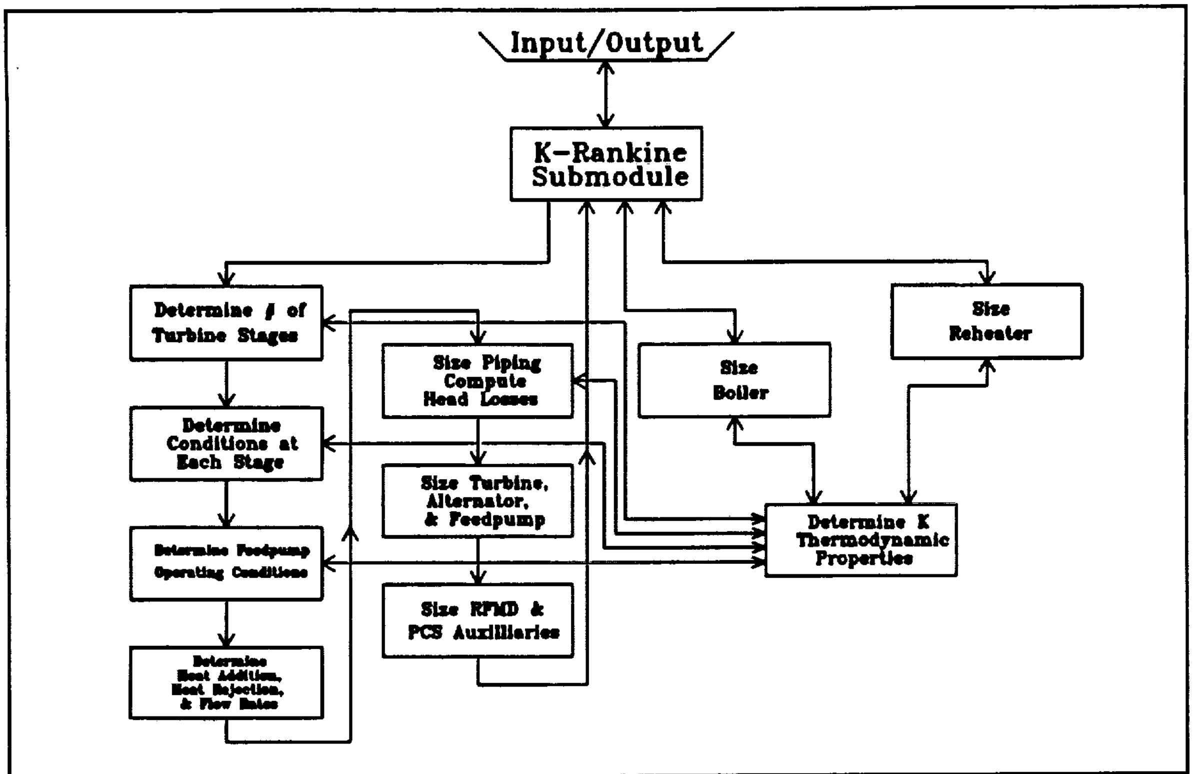

Figure 3. Program Flow Diagram

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-feedpump. The turbo- feedpump 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 performance 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 2. Generator Design Requirements

Generator Power Output (kVA)	56	111	222	555	1,111	2,222	5,555
Generator Type	<---------- TPTL PM ---------->						
Maximum Speed (krpm)	160	120	85	57	41	30	20
Voltage (RMSv l-l)	1,400	1,400	1,400	8,000	8,000	8,000	8,000
Power Factor	<---------- 0.9 lagging ---------->						
Gap Conditions:							
Viscosity (lb/ft-hr)	<---------- 0.030 ---------->						
Temp. (°F)	<---------- 440 ---------->						
Press. (psia)	<---------- 4.88×10^{-4} ---------->						
Density (lb_m/ft^3)	<---------- 1.97×10^{-6} ---------->						
Voltage Regulation	<---------- ± 10% ---------->						
Insulation Class	<---------- 220 °C ---------->						
Rotor Magnet L/D	<---------- ≤ 2.5 ---------->						

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 l-l, 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 Conventionally Wound TPTL Generators Operating at 700 ft/sec Surface Speed

Power (kW_e)	50	100	200	500	1,000	2,000	5,000
kVA (kVA)	56	111	222	556	1,111	2,222	5,556
Alt Type (TPTL)	Conv.	Conv.	Conv.	Conv.	Conv.	Conv.	Conv.
N (rpm)	54,500	48,200	34,200	25,000	18,400	13,700	10,240
V_{base} (l-n RMS)	808	808	808	808	4,620	4,620	4,620
Rotor Dia. (in)	2.94	3.55	4.69	6.42	8.72	11.71	15.67
Stator OD (in)	5.75	6.52	8.53	11.05	13.51	17.7	22.7
Length (in)	12.37	14.20	18.60	24.30	33.60	44.30	59.50
Magnet L/D	2.57	2.51	2.5	2.45	2.53	2.5	2.58
X_{com} (P.U.)	0.121	0.119	0.129	0.114	0.131	0.130	0.137
EM Mass (lb_m)	38.48	65.03	146.3	358.2	724	1682	4101
Rotor Mass (lb_m)	15.58	26.52	61	152	395	940	2314
Efficiency (%)	95.08	95.88	96.14	96.65	95.4	95.8	96.35
Losses (kW_e)	2.56	4.3	8.03	17.3	48.3	88.2	189.3
Tip Speed (ft/s)	700	700	700	700	700	700	700
B_{core} (kL/in^2)	80	80	80	80	140	140	140

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

Power (kW_e)	50	100	200	500	1,000	2,000	5,000
kVA (kVA)	56	111	222	556	1,111	2,222	5,556
Alt Type (TPTL)	R. W.	R. W.	R. W.	R. W.	R. W.	R. W.	R. W.
N (rpm)	80,000	62,000	47,500	32,500	23,000	16,500	11,400
V_{base} (l-n RMS)	808	808	808	808	4,620	4,620	4,620
Rotor Dia. (in)	2.01	2.59	3.38	4.92	6.98	9.72	14.07
Stator OD (in)	3.82	4.80	6.10	8.60	10.80	14.50	20.00
Length (in)	6.20	7.40	9.80	14.30	19.00	27.20	38.00
Magnet L/D	2.49	2.49	2.5	2.5	2.49	2.5	2.51
X_{com} (P.U.)	0.120	0.120	0.130	0.130	0.130	0.120	0.130
EM Mass (lb_m)	14.08	29.40	62.00	182.7	375.0	993.0	3105.0
Rotor Mass (lb_m)	4.82	10.32	23.00	71.0	198.0	536.0	1630.0
Efficiency (%)	96.39	96.68	96.80	96.97	96.44	96.3	96.97
Losses (kW_e)	1.86	3.44	6.60	15.6	36.9	77.0	156.0
Tip Speed (ft/s)	700	700	700	700	700	700	700
B_{core} (kL/in^2)	80	80	80	80	140	140	140

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_e)	50	100	200	500	1,000	2,000	5,000
kVA (kVA)	56	111	222	556	1,111	2,222	5,556
Alt Type (TPTL)	R. W.	R. W.	R. W.	R. W.	R. W.	R. W.	R. W.
N (rpm)	61,200	47,300	36,800	25,700	18,000	14,050	9,700
V_{base} (1-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_m)	14.56	29.63	60.12	168.0	348.9	729.7	2131.0
Rotor Mass (lb_m)	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_e)	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_{core} (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 6. Generator Materials and Technology Assumptions			
Component	Material	Salient Info.	Technology Status
Rotor Magnet	Samarium-Cobalt	30 MGO	Comm. Avail., Select Mat'l
Rotor Hoop	Inconel	180 ksi	Comm. Avail., Special Order
Outer condctrs	Copper		Comm. Available
Inner Condctrs	Litz Wire		Comm. Available
Stator Insultn	Pyre-ML	Organic	Comm. Available
Flux Ret. Path 50-750 kWe	Si-steel [3.5%]	80 kL/in^2	Comm. Available
Flux Ret. Path 750-5000 kWe	Hyperco	140 kL/in^2	Comm. Available
Support Struct	Polyamide		Comm. Available

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 ND^2L [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:

$$D_{rotor} = [(U_{tip}/700)^{0.468} * (40.65 + 6.6E\text{-}4 * V * (U_{tip}/700)^{2.5}) * kVA^{-.075}] * [kVA/(N * \{L/D\}_{rotor})]^{1/3} \quad [1]$$

$$M_{em} = 1.938 * (U_{tip}/700)^{-0.591} * (1.0467 - 3.3E\text{-}5 * V) * D_{rotor}^{2.85} * (\{L/D\}_{rotor} + 0.48)/2.98 \quad [2]$$

$$D_{stator} = (U_{tip}/700)^{-0.4} * (2.14 - 0.12 * kVA^{0.175} - 2.25E\text{-}5 * V) * D_{rotor} \quad [3]$$

$$L_{o/a} = (2.98 - 0.02 * D_{rotor}) * D_{rotor} * (\{L/D\}_{rotor} + 0.48)/2.98 \quad [4]$$

Where;

D_{rotor} = Rotor Outside Diameter [including sleeve], inches

$\{L/D\}_{rotor}$ = Rotor L/D; Magnet Length/Sleeve OD

M_{em} = Generator Electro-magnetic Weight, lb_m
* Copper and insulation
* Magnet and Sleeve
* Polyamide Structure
* Complete Flux Return Path Laminant

D_{stator} = Generator Stator Outside Diameter, inches

$L_{o/a}$ = 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_{tip} = 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 to 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 D^2L 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 fabracability 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/condensor temperature ratios, 100 kW_e to 10 MW_e 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

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APPENDIX A
RECOMMENDED VALUES/RANGES FOR INPUT PARAMETERS

Input Parameter	Recommended Value/Range
General Parameters	
System full power life (years)	1 - 10
Flow velocity in vapor lines (m/sec)	140.0
Flow velocity in wet vapor lines (m/sec)	50.0
Flow velocity in liquid lines (m/sec)	3.5
Temperature for material switch (K)	1350.0
High Temperature material	1.0
Low Temperature material	3.0
1 - ASTAR 811C 2 - Nb-1%Zr	
3 - TZM 4 - 316SS	
Thermal cond., high temp. alloy (W/m-K)	53.6
Thermal cond., low temp. alloy (W/m-K)	53.6
# operating units	3.0
# total units	4.0
Reactor Parameters	
Reactor outlet temperature (K)	1550.0
Reactor inlet temperature (K)	1450.0
Electrical Parameters	
System net power output (kWe)	10 - 10,000
Alternator efficiency	0.97
Fraction of alternator gross output used for -	
Lithium pumps	NA
Potassium feed pumps	NA
Other loads	NA
Alternator Parameters	
Power factor	0.7 - 0.9
Voltage (volts)	1000 - 10,000
Aspect ratio (L/D)	2 - 3
Coolant inlet temperature (K)	511.1
Coolant outlet temperature (K)	522.2
Coolant heat capacity (kJ/kg-K)	2.1

Turbine Parameters

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

Feed Pump Parameters

Pump turbine efficiency	0.45

RFMD Parameters

Pressure rise through RFMD (kPa)	3.5 - 140
RFMD pump efficiency	.32
RFMD motor efficiency	.45

Boiler Parameters

Maximun K side pressure drop (kPa)	3.5 - 140
Boiler tube diameter (cm)	1.27
Number of boiler tubes	100.0

Reheat Parameters

Maximum reheater pressure loss (kPa)	3.5 - 140
Superheat after reheat K	25 - 100
Reheater tube diameter (cm)	1.27
# tubes in reheater	100.0

Line Parameters

Line Label	Length (m)
Boiler Outlet	1.0
Turbine Inlet	1.0
Pump Turbine Inlet	1.0
HP Turbine Outlet	1.0
Pump Turbine Outlet	1.0
Reheater Inlet	1.0
Reheater Outlet	1.0
Condenser Inlet	1.0
Condenser Outlet	1.0
Feed Pump Inlet	1.0
Feed Pump Outlet	1.0

APPENDIX B
INPUT PARAMETER DEFINITIONS

ALPHAT	Turbine inlet stator angle
BFP	Power for potassium pumps (kWe)
BPL	Other loads (kWe)
BPP	Power for lithium pumps (kWe)
CPCLNT	Generator coolant specific heat (kJ/kg-K)
DEFF	Turbine dry stage efficiency
DIARH	Reheater tube diameter (cm)
DIATB	Boiler tube diameter (cm)
DPCON	Condenser pressure losses (kPa)
DPMAXB	Max. K side pressure losses (kPa)
DPMAXR	Max. K side pressure losses (kPa)
DPRFMD	RFMD pressure rise (kPa)
DTRH	Superheat added during reheat (K)
DUM1	Undefined, not used
DUM2	Undefined, not used
DUM3	Undefined, not used
DUM4	Undefined, not used
EFRFMD	RFMD pump efficiency
EMRFMD	RFMD motor efficiency
EXLOSS	Turbine exhaust losses (kJ/kg)
FPL	System full power life (years)
GEFF	Alternator efficiency
GENASP	Generator Length/Diameter aspect ratio
KA	Thermal conductivity of high temp. material (W/m-K)
KB	Thermal conductivity of low temp. material (W/m-K)
KWNET	PCS net power (kWe)
LG(i)	Length of line number i (m)
NOTUBB	Initial guess of number of boiler tubes required
NOTUBR	Initial guess of number of boiler tubes required
NUMOP	Number of operating PCS units
NUMTOT	Total number of PCS units
PTEFF	Pump turbine efficiency
PWRFCTR	Generator power factor - lagging
RSTT	Spouting velocity (m/sec)
SCCON	Condensate subcooling (K)
TBOIL	Turbine inlet saturation temp. (K)
TCON	Condensing temp. (K)
TINCLNT	Generator coolant inlet temperature (K)
TMAT	Temperature for material switch (K)
TOUTCLNT	Generator coolant outlet temperature (K)
TRIN	Reactor inlet temp. (K)
TROUT	Reactor outlet temp. (K)
VELL	Liquid lines flow velocity (m/sec)
VELM	Wet vapor lines flow velocity (m/sec)
VELV	Vapor lines flow velocity (m/sec)
VOLTAGE	Generator voltage, l-l rms (volts)
VTIP	Last stage tip velocity (m/sec)
XBOIL	Turbine inlet quality/superheat (K)
XMATC	Code for low temperature material selection
XMATH	Code for high temperature material selection
XMFI	Layers of multifoil insulation

APPENDIX C
INPUT PARAMETER ARRAY CROSS REFERENCE

FPL	PRIN(1)
VELV	PRIN(2)
VELM	PRIN(3)
VELL	PRIN(4)
TMAT	PRIN(5)
XMATH	PRIN(6)
XMATC	PRIN(7)
DUM1	PRIN(8)
DUM2	PRIN(9)
KA	PRIN(10)
KB	PRIN(11)
NUMOP	PRIN(12)
NUMTOT	PRIN(13)
TROUT	PRIN(14)
TRIN	PRIN(15)
KWNET	PRIN(16)
GEFF	PRIN(17)
DUM3	PRIN(18)
BPP	PRIN(19)
BFP	PRIN(20)
BPL	PRIN(21)
PWRFCTR	PRIN(22)
VOLTAGE	PRIN(23)
GENASP	PRIN(24)
TINCLNT	PRIN(25)
TOUTCLNT	PRIN(26)
CPCLNT	PRIN(27)
TBOIL	PRIN(28)
XBOIL	PRIN(29)
DUM4	PRIN(30)
TCON	PRIN(31)
DEFF	PRIN(32)
EXLOSS	PRIN(33)
VTIPO	PRIN(34)
SCCON	PRIN(35)
ALPHAT	PRIN(36)
RSTT	PRIN(37)
XMFI	PRIN(38)
DPCON	PRIN(39)
PTEFF	PRIN(40)
DPRFMD	PRIN(41)
EFRFMD	PRIN(42)
EMRFMD	PRIN(43)
DPMAXB	PRIN(44)
DIATB	PRIN(45)
NOTUBB	PRIN(46)
DPMAXR	PRIN(47)
DTRH	PRIN(48)
DIARH	PRIN(49)
NOTUBR	PRIN(50)
LG(i)	PRIN(51 - 61)

APPENDIX D
INPUT PARAMETER ALPHABETIC CROSS REFERENCE

ALPHAT	PRIN(36)
BFP	PRIN(20)
BPL	PRIN(21)
BPP	PRIN(19)
CPCLNT	PRIN(27)
DEFF	PRIN(32)
DIARH	PRIN(49)
DIATB	PRIN(45)
DPCON	PRIN(39)
DPMAXB	PRIN(44)
DPMAXR	PRIN(47)
DPRFMD	PRIN(41)
DTRH	PRIN(48)
DUM1	PRIN(8)
DUM2	PRIN(9)
DUM3	PRIN(18)
DUM4	PRIN(30)
EFRFMD	PRIN(42)
EMRFMD	PRIN(43)
EXLOSS	PRIN(33)
FPL	PRIN(1)
GEFF	PRIN(17)
GENASP	PRIN(24)
KA	PRIN(10)
KB	PRIN(11)
KWNET	PRIN(16)
LG(i)	PRIN(51 - 61)
NOTUBB	PRIN(46)
NOTUBR	PRIN(50)
NUMOP	PRIN(12)
NUMTOT	PRIN(13)
PTEFF	PRIN(40)
PWRFCTR	PRIN(22)
RSTT	PRIN(37)
SCCON	PRIN(35)
TBOIL	PRIN(28)
TCON	PRIN(31)
TINCLNT	PRIN(25)
TMAT	PRIN(5)
TOUTCLNT	PRIN(26)
TRIN	PRIN(15)
TROUT	PRIN(14)
VELL	PRIN(4)
VELM	PRIN(3)
VELV	PRIN(2)
VOLTAGE	PRIN(23)
VTIPO	PRIN(34)
XBOIL	PRIN(29)
XMATC	PRIN(7)
XMATH	PRIN(6)
XMFI	PRIN(38)

APPENDIX E
OUTPUT PARAMETER DEFINITIONS

ALTWT	Alternator mass (kg)
COE	Alternator sizing coefficient
COOLING	Alternator cooling load (kWt)
CYCEFF	Cycle efficiency
DGENRTR	Diameter of alternator rotor (cm)
DGENSTR	Diameter of alternator stator (cm)
DLPBB	Boiler lithium side pressure loss (kPa)
DLPBR	Reheater lithium side pressure loss (kPa)
DOUTEB	Boiler outside diameter (cm)
DOUTER	Reheater outer diameter (cm)
DPTOTB	Pressure drop across boiler (kPa)
DPTOTR	Pressure drop across reheater (kPa)
DTSB	Boiler tube sheet diameter (cm)
DTSR	Reheater tube sheet diameter (cm)
DT(NSTG)	Turbo-pump stage tip diameter (cm)
EFFGRS	PCS gross efficiency
EFFNET	PCS net efficiency
EFF(0:15)	Turbine stage efficiency
FMDEL	Turbo-pump flow rate (kg/sec)
GNLOSS	Alternator losses (kWe)
HKBOIB	Boiler boiling heat transfer coefficient (kW/m^2-K)
HKBOIR	Reheater boiling heat transfer coefficient (kW/m^2-K)
HKPHB	Boiler preheat heat transfer coefficient (kW/m^2-K)
HKPHR	Reheater preheat heat transfer coefficient (kW/m^2-K)
HKSHB	Boiler superheat heat transfer coefficient (kW/m^2-K)
HKSHR	Reheater superheat heat transfer coefficient (kW/m^2-K)
HLE(11)	Line exit enthalpy (kJ/kg)
HLILIB	Boiler lithium side heat transfer coefficient (kW/m^2-K)
HLILIR	Reheater lithium side heat transfer coefficient (kW/m^2-K)
HLI(11)	Line inlet enthalpy (kJ/kg)
HRH	Reheat enthalpy (kJ/kg)
HTBB	Boiler height (cm)
HTBR	Reheater height (cm)
H(0:15)	Turbine stage exhaust enthalpy (kJ/kg)
ID(11)	Line inside diameter (cm)
KVA	Alternator apparent power; (kVA)
KWOUT	Gross electric power out (kWe)
LBOILB	Boiler boiling length (cm)
LBOILR	Reheater boiling length (cm)
LGENTOT	Total alternator length (cm)
LPHB	Boiler preheat length (cm)
LPHR	Reheater preheat length (cm)
LSHB	Boiler superheat lenght (cm)
LSHR	Reheater superheat length (cm)
LTOTB	Boiler total tube lenght (cm)
LTOTR	Reheater total tube lenght (cm)
MASSGEN	Alternator mass (kg)
MFITOT	Total line multifoil insulation mass (kg)
MFIWTB	Boiler multifoil insulation weight (kg)

MFIWTR	Reheater multifoil insulation weight (kg)
MF(11)	Line flow rate (kg/sec)
MMAIN	Main potassium flow rate (kg/sec)
MQADD	Heat addition to PCS (kWt)
MQREJ	Heat rejected by PCS (kWt)
NS	Number of turbine stages
NSTAGE	Number of turbo-pump stages
PAB	Boiler tube pitch (cm)
PAR	Reheater tube pitch (cm)
PCSACM	PCS volume accumulator mass (kg)
PDIS	Turbo-pump discharge pressure (kPa)
PENG	Turbo-pump inlet pressure (kPa)
PHI(NSTG)	Turbo-pump stage flow coefficient
PLE(11)	Line exit pressure (kPa)
PLI(11)	Line inlet pressure (kPa)
PLNTEF	Plant efficiency
PP(0:15)	Turbine stage exhaust pressure (kPa)
PRSTAG	Turbine stage number for reheat
PSI(NSTG)	Turbo-pump head coefficient
PUMPEFF	Turbo-pump efficiency
RPM	Turbine speed (rpm)
SLE(11)	Line exit entropy (kJ/kg-K)
SLI(11)	Line inlet entropy (kJ/kg-K)
SPMASS	PCS specific mass (kg/kWe)
SRH	Reheat entropy (kJ/kg-K)
SSMARG	Turbo-pump NPSH margin
SVRH	Reheat specific volume (m^3/kg)
SVVLE(11)	Line exit specific volume (m^3/kg)
SVVLI(11)	Line inlet specific volume (m^3/kg)
SVV(0:15)	Turbine stage exhaust specific volume (m^3/kg)
S(0:15)	Turbine stage exhaust entropy (kJ/kg-K)
TENG	Turbo-pump inlet temp. (K)
THSB	Boiler shell hickness (cm)
THSR	Reheater shell thickness (cm)
TIPSPDG	Alternator rotor tip speed (m/sec)
TITCON	Turbine inlet temp. / condensing temp. ratio
TKTUBB	Boiler tube thickness (cm)
TKTUBR	Reheater tube thickness (cm)
TLE(11)	Line exit temp. (K)
TLI(11)	Line inlet temp. (K)
TORQ	Turbo-pump torque (Nt-m)
TORQUE	Turbine torque (Nt-m)
TOTHP	Turbo-pump power (kW)
TOTWT	Total line mass (kg)
TRBPWR	Turbine power (kW)
TSATRH	Reheat saturation temp. (K)
TSAT(0:15)	Turbine stage saturation temp. (K)
TTP(NSTG)	Turbo-pump stage temp. (k)
TTRH	Degress superheat added to reheated vapor (k)
TT(0:15)	Turbine stage exhaust temp. (K)
TURBWT	Turbine weight (kg)
UTLIM	Turbo-pump inducer tip speed limit (m/sec)
UT(NSTG)	Turbo-pump stage tip speed (m/sec)

VTIP	Main power turbine maximum tip speed (m/sec)
WALL(11)	Line thickness (cm)
WBOILB	Dry weight of boiler (kg)
WCLNT	Alternator coolant flow rate (kg/sec)
WFPUMP	Turbo-pump mass (kg)
WRHT	Dry weight of reheater (kg)
WSHELB	Boiler shell weight (kg)
WSHELR	Reheater shell weight (kg)
WTAPEB	Boiler twisted tape weight (kg)
WTAPER	Reheater twisted tape weight (kg)
WTCLOB	Boiler closure head weight (kg)
WTCLOR	Reheater closure head weight (kg)
WTKINV(11)	Line potassium inventory (kg)
WTKTOT	Total potassium inventory in lines (kg)
WTLIB	Boiler lithium inventory (kg)
WTLIR	Reheater lithium inventory (kg)
WTMFI(11)	Line multifoil insulation mass (kg)
WTPCS	Power Conversion Subsystem weight (kg)
WTPOTB	Boiler potassium inventory (kg)
WTPOTR	Reheater potassium inventory (kg)
WTPUMP	Feed pump mass (kg)
WTRFMD	RFMD mass (kg)
WTTSB	Boiler tube sheet weight (kg)
WTTSR	Reheater tube sheet weight (kg)
WTUBEB	Boiler tube weight (kg)
WTUBER	Reheater tube weight (kg)
WTURBN	Turbine mass (kg)
WTWETB	Wet weight of boiler (kg)
WTWETR	Wet weight of reheater (kg)
WT(11)	Line mass (kg)
XLE(11)	Line exit quality
XLI(11)	Line inlet quality
XN	Turbo-pump speed (rpm)
XNPSHA	Turbo-pump NPSH
XNSSTG(NSTG)	Turbo-pump stage specific speed
XRH	Reheat quality
XTHKB	Boiler tube sheet thickness (cm)
XTHKR	Reheater tube sheet thickness (cm)
XX1	Constant for turbine speed algorithm
X(0:15)	Turbine stage exhaust quality

APPENDIX F
OUTPUT PARAMETER ARRAY CROSS REFERENCE

MMAIN	PROUT(1)
TT(0:15)	PROUT(2 - 17)
PP(0:15)	PROUT(18 - 33)
H(0:15)	PROUT(34 - 49)
S(0:15)	PROUT(50 - 65)
X(0:15)	PROUT(66 - 81)
SVV(0:15)	PROUT(82 - 97)
TLI(11)	PROUT(98 - 108)
TLE(11)	PROUT(109 - 119)
PLI(11)	PROUT(120 - 130)
PLE(11)	PROUT(131 - 141)
HLI(11)	PROUT(142 - 152)
HLE(11)	PROUT(153 - 163)
SLI(11)	PROUT(164 - 174)
SLE(11)	PROUT(175 - 185)
XLI(11)	PROUT(186 - 196)
XLE(11)	PROUT(197 - 207)
SVVLI(11)	PROUT(208 - 218)
SVVLE(11)	PROUT(219 - 229)
MF(11)	PROUT(230 - 240)
WALL(11)	PROUT(241 - 251)
WT(11)	PROUT(252 - 262)
WTKINV(11)	PROUT(263 - 273)
ID(11)	PROUT(274 - 284)
DPTOTB	PROUT(285)
WTKTOT	PROUT(286)
TOTWT	PROUT(287)
TTRH	PROUT(288)
DPTOTR	PROUT(289)
NS	PROUT(290)
WTMFI(11)	PROUT(291 - 301)
MFITOT	PROUT(302)
PENG	PROUT(303)
TENG	PROUT(304)
FMDEL	PROUT(305)
PDIS	PROUT(306)
UTLIM	PROUT(307)
TTP(NSTG)	PROUT(308 - 322)
XNPSHA	PROUT(323)
DT(NSTG)	PROUT(324 - 338)
UT(NSTG)	PROUT(339 - 353)
PHI(NSTG)	PROUT(354 - 368)
NSTAGE	PROUT(369)
PSI(NSTG)	PROUT(370 - 384)
XN	PROUT(385)
TOTHP	PROUT(386)
PUMPEFF	PROUT(387)
SSMARG	PROUT(388)
XNSSTG(NSTG)	PROUT(389 - 403)
WFPUMP	PROUT(404)

TORQ	PROUT(405)
KWOUT	PROUT(406)
ALTWT	PROUT(407)
CYCEFF	PROUT(408)
PCSACM	PROUT(409)
MQADD	PROUT(410)
MQREJ	PROUT(411)
PRSTAG	PROUT(412)
WTRFMD	PROUT(413)
WTURBN	PROUT(414)
XRH	PROUT(415)
EFF(0:15)	PROUT(416 - 431)
DLPBB	PROUT(432)
WBOILB	PROUT(433)
WTWETB	PROUT(434)
DLPBR	PROUT(435)
WRHT	PROUT(436)
WTWETR	PROUT(437)
HTBB	PROUT(438)
DOUTEB	PROUT(439)
DTSB	PROUT(440)
THSB	PROUT(441)
XTHKB	PROUT(442)
LPHB	PROUT(443)
LBOILR	PROUT(444)
LSHB	PROUT(445)
LTOTB	PROUT(446)
TKTUBB	PROUT(447)
PAB	PROUT(448)
HLILIB	PROUT(449)
HKPHB	PROUT(450)
HKBOIB	PROUT(451)
HKSHB	PROUT(452)
WSHELB	PROUT(453)
WTUBEB	PROUT(454)
WTAPEB	PROUT(455)
WTTSB	PROUT(456)
WTCLOB	PROUT(457)
MFIWTB	PROUT(458)
WTPOTB	PROUT(459)
WTLIB	PROUT(460)
HTBR	PROUT(461)
DOUTER	PROUT(462)
DTSR	PROUT(463)
THSR	PROUT(464)
XTHKR	PROUT(465)
LPHR	PROUT(466)
LBOILR	PROUT(467)
LSHR	PROUT(468)
LTOTR	PROUT(469)
TKTUBR	PROUT(470)
PAR	PROUT(471)
HLILIR	PROUT(472)
HKPHR	PROUT(473)

HKBOIL	PROUT(474)
HKSHR	PROUT(475)
WSHELR	PROUT(476)
WTUBER	PROUT(477)
WTAPER	PROUT(478)
WTTSR	PROUT(479)
WTCLOR	PROUT(480)
MFIWTR	PROUT(481)
WTPOTR	PROUT(482)
WTLIR	PROUT(483)
WTPCS	PROUT(484)
SPMASS	PROUT(485)
EFFNET	PROUT(486)
EFFGRS	PROUT(487)
WTPUMP	PROUT(488)
TITCON	PROUT(489)
PLNTEF	PROUT(490)
GNLOSS	PROUT(491)
TORQUE	PROUT(492)
TRBPWR	PROUT(493)
XX1	PROUT(494)
TURBWT	PROUT(495)
RPM	PROUT(496)
SVRH	PROUT(497)
TSATRH	PROUT(498)
HRH	PROUT(499)
SRH	PROUT(500)
TSAT(0:15)	PROUT(501 - 516)
VTIP	PROUT(517)
DGENRTR	PROUT(518)
KVA	PROUT(519)
DGENSTR	PROUT(520)
LGENTOT	PROUT(521)
MASSGEN	PROUT(522)
TIPSPDG	PROUT(523)
COE	PROUT(524)
COOLING	PROUT(525)
WCLNT	PROUT(526)

APPENDIX G
OUTPUT PARAMETER ARRAY CROSS REFERENCE

ALTWT	PROUT(407)
COE	PROUT(524)
COOLING	PROUT(525)
CYCEFF	PROUT(408)
DGENRTR	PROUT(518)
DGENSTR	PROUT(520)
DLPBB	PROUT(432)
DLPBR	PROUT(435)
DOUTEB	PROUT(439)
DOUTER	PROUT(462)
DPTOTB	PROUT(285)
DPTOTR	PROUT(289)
DTSB	PROUT(440)
DTSR	PROUT(463)
DT(NSTG)	PROUT(324 - 338)
EFFGRS	PROUT(487)
EFFNET	PROUT(486)
EFF(0:15)	PROUT(416 - 431)
FMDEL	PROUT(305)
GNLOSS	PROUT(491)
HKBOIB	PROUT(451)
HKBOIL	PROUT(474)
HKPHB	PROUT(450)
HKPHR	PROUT(473)
HKSHB	PROUT(452)
HKSHR	PROUT(475)
HLE(11)	PROUT(153 - 163)
HLILIB	PROUT(449)
HLILIR	PROUT(472)
HLI(11)	PROUT(142 - 152)
HRH	PROUT(499)
HTBB	PROUT(438)
HTBR	PROUT(461)
H(0:15)	PROUT(34 - 49)
ID(11)	PROUT(274 - 284)
KVA	PROUT(519)
KWOUT	PROUT(406)
LBOILR	PROUT(444)
LBOILR	PROUT(467)
LGENTOT	PROUT(521)
LPHB	PROUT(443)
LPHR	PROUT(466)
LSHB	PROUT(445)
LSHR	PROUT(468)
LTOTB	PROUT(446)
LTOTR	PROUT(469)
MASSGEN	PROUT(522)
MFITOT	PROUT(302)
MFIWTB	PROUT(458)
MFIWTR	PROUT(481)

MF(11)	PROUT(230 - 240)
MMAIN	PROUT(1)
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)
SVVLI(11)	PROUT(208 - 218)
SVV(0:15)	PROUT(82 - 97)
S(0:15)	PROUT(50 - 65)
TENG	PROUT(304)
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)
TOTHP	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)

WBOILB	PROUT(433)
WCLNT	PROUT(526)
WFPUMP	PROUT(404)
WRHT	PROUT(436)
WSHELB	PROUT(453)
WSHELR	PROUT(476)
WTAPEB	PROUT(455)
WTAPER	PROUT(478)
WTCLOB	PROUT(457)
WTCLOR	PROUT(480)
WTKINV(11)	PROUT(263 - 273)
WTKTOT	PROUT(286)
WTLIB	PROUT(460)
WTLIR	PROUT(483)
WTMFI(11)	PROUT(291 - 301)
WTPCS	PROUT(484)
WTPOTB	PROUT(459)
WTPOTR	PROUT(482)
WTPUMP	PROUT(488)
WTRFMD	PROUT(413)
WTTSB	PROUT(456)
WTTSR	PROUT(479)
WTUBEB	PROUT(454)
WTUBER	PROUT(477)
WTURBN	PROUT(414)
WTWETB	PROUT(434)
WTWETR	PROUT(437)
WT(11)	PROUT(252 - 262)
XLE(11)	PROUT(197 - 207)
XLI(11)	PROUT(186 - 196)
XN	PROUT(385)
XNPSHA	PROUT(323)
XNSSTG(NSTG)	PROUT(389 - 403)
XRH	PROUT(415)
XTHKB	PROUT(442)
XTHKR	PROUT(465)
XX1	PROUT(494)
X(0:15)	PROUT(66 - 81)

APPENDIX H
KRANK SAMPLE CASE

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

General Parameters

System full power life (years)	7.0
Flow velocity in vapor lines (m/sec)	140.0
Flow velocity in wet vapor lines (m/sec)	50.0
Flow velocity in liquid lines (m/sec)	3.5
Temperature for material switch (K)	1350.0
High Temperature material	1.0
Low Temperature material	2.0
1 - ASTAR 811C 2 - Nb-1%Zr	
3 - TZM 4 - 316SS	
Thermal cond., high temp. alloy (W/m-K)	53.6
Thermal cond., low temp. alloy (W/m-K)	53.6
# operating units	3.0
# total units	4.0

Reactor Parameters

Reactor outlet temperature (K)	1550.0
Reactor inlet temperature (K)	1450.0

Electrical Parameters

System net power output (kWe)	5000.0
Alternator efficiency	0.97
Fraction of alternator gross output used for -	
Lithium pumps	9.0
Potassium feed pumps	0.0
Other loads	3.7

Alternator Parameters

Power factor	0.9
Voltage (Volts)	1000.0
Aspect ratio (L/D)	2.5
Coolant inlet temperature (K)	511.1
Coolant outlet temperature (K)	522.2
Coolant heat capacity (kJ/kg-K)	2.1

Turbine Parameters

Turbine inlet saturation temp. (K)	1450.0
Turbine inlet - quality if <= 1	50.0
- superheat, K, if > 1	

Condensing temperature (K)	1050.0
Turbine dry stage efficiency	0.85
Turbine exhaust losses (kJ/kg)	11.6
Turbine last stage tip velocity (m/sec)	366.0
Condenser subcooling (K)	2.0
Turbine inlet stator angle	13.6
Spouting velocity (m/sec)	389.0
Layers of Multifoil Insulation	20.0
Condenser pressure drop (kPa)	14.0

Feed Pump Parameters

Pump turbine efficiency	0.45

RFMD Parameters

Pressure rise through RFMD (kPa)	105.0
RFMD pump efficiency	0.32
RFMD motor efficiency	0.45

Boiler Parameters

Maximun K side pressure drop (kPa)	70.0
Boiler tube diameter (cm)	1.27
Number of boiler tubes	849.0

Reheat Parameters

Maximum reheater pressure loss (kPa)	35.0
Superheat after reheat K	50.0
Reheater tube diameter (cm)	1.27
# tubes in reheater	531.0

Line Parameters

Line Label	Length (m)
Boiler Outlet	1.0
Turbine Inlet	1.0
Pump Turbine Inlet	1.0
HP Turbine Outlet	1.0
Pump Turbine Outlet	1.0
Reheater Inlet	1.0
Reheater Outlet	1.0
Condenser Inlet	1.0
Condenser Outlet	1.0
Feed Pump Inlet	1.0
Feed Pump Outlet	1.0

POWER CONVERSION CYCLE PARAMETERS

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

TURBINE CONDITIONS AT EACH STAGE

ns	Temp (K)	Tsat (K)	Pres (kPa)	Quality	Enthalpy (kJ/kg)	Entropy (kJ/kg-K)	Sp Vol (m3/kg)	Eff
0	1500.0	1450.0	1577.27	1.0000	2905.0	4.2650	0.17	
1	1414.0	1400.0	1243.93	1.0000	2852.7	4.2715	0.20	0.8500
2	1350.0	1350.0	963.26	0.9860	2800.1	4.2788	0.25	0.8430
3	1300.0	1300.0	730.84	0.9624	2747.3	4.2874	0.31	0.8242
4	1250.0	1250.0	541.93	0.9457	2706.0	4.3073	0.40	0.8008
RH	1287.6	1237.6	501.21	1.0000	2859.2	4.4438	0.49	
5	1195.5	1190.7	367.48	1.0000	2797.8	4.4529	0.61	0.8500
6	1143.8	1143.8	262.44	0.9748	2736.7	4.4633	0.81	0.8374
7	1096.9	1096.9	181.94	0.9473	2675.8	4.4762	1.10	0.8110
8	1050.0	1050.0	121.94	0.9269	2626.9	4.5032	1.55	0.7840

POWER CONVERSION CYCLE CHARACTERISTICS

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

SCHEDULE OF PIPING RUNS
Thermodynamic Properties

No.	Description	Temp (K)	Press (kPa)	Enthalpy (kJ/kg)	Entropy (kJ/kg-K)	Quality	Sp Vol (m3/kg)
1	Boiler Outlet	1501.9	1591.50	2905.4	4.2636	1.0000	0.169
		1500.9	1584.43	2905.2	4.2643	1.0000	0.170
2	Turbine Inlet	1500.9	1584.43	2905.2	4.2643	1.0000	0.170
		1500.0	1577.27	2905.0	4.2650	1.0000	0.170
3	Pump Turbine Inlet	1500.9	1584.43	2905.2	4.2643	1.0000	0.170
		1499.0	1580.00	2903.6	4.2637	1.0000	0.170
4	HP Turbine Outlet	1250.0	541.93	2706.0	4.3073	0.9457	0.402
		1249.4	539.85	2705.9	4.3078	0.9457	0.403
5	Pump Turbine Outlet	1249.7	541.06	2790.0	4.3748	0.9927	0.422
		1249.4	539.85	2788.7	4.3742	0.9921	0.423
6	Reheater Inlet	1249.4	539.85	2708.5	4.3100	0.9472	0.404
		1248.8	537.83	2708.4	4.3105	0.9472	0.405

7	Reheater Outlet	1288.1	502.76	2859.4	4.4434	1.0000	0.486
		1287.6	501.21	2859.2	4.4438	1.0000	0.487
8	Condenser Inlet	1050.0	121.94	2626.9	4.5032	0.9269	1.554
		1049.7	121.65	2626.8	4.5035	0.9268	1.558
9	Condenser Outlet	1034.2	107.65	838.7	2.8000	0.0000	0.002
		1034.2	106.64	838.7	2.8000	0.0000	0.002
10	Feed Pump Inlet	1034.7	211.64	839.2	2.8003	0.0000	0.002
		1034.6	210.63	839.1	2.8003	0.0000	0.002
11	Feed Pump Outlet	1037.4	1662.56	842.8	2.8017	0.0000	0.002
		1037.4	1661.55	842.7	2.8017	0.0000	0.002

Flows & Dimensions

No.	Description	Flow (kg/sec)	Length (m)	ID (cm)	Wall (cm)
1	Boiler Outlet	4.15	1.00	8.00	0.114
2	Turbine Inlet	4.02	1.00	7.89	0.111
3	Pump Turbine Inlet	0.13	1.00	2.39	0.051
4	HP Turbine Outlet	4.02	1.00	12.12	0.051
5	Pump Turbine Outlet	0.13	1.00	3.78	0.051
6	Reheater Inlet	4.15	1.00	12.35	0.051
7	Reheater Outlet	4.15	1.00	13.56	0.051
8	Condenser Inlet	4.15	1.00	24.23	0.051
9	Condenser Outlet	4.15	1.00	4.77	0.051
10	Feed Pump Inlet	4.15	1.00	4.77	0.051
11	Feed Pump Outlet	4.15	1.00	4.78	0.051

Weights

No.	Description	Pipe Wt (kg)	K Wt (kg)	MFI Wt (kg)
1	Boiler Outlet	4.84	0.030	0.015
2	Turbine Inlet	4.65	0.029	0.015
3	Pump Turbine Inlet	0.65	0.003	0.005
4	HP Turbine Outlet	3.25	0.029	0.022
5	Pump Turbine Outlet	1.02	0.003	0.007
6	Reheater Inlet	3.31	0.030	0.023
7	Reheater Outlet	3.63	0.030	0.025
8	Condenser Inlet	6.47	0.030	0.044
9	Condenser Outlet	1.29	1.185	0.009
10	Feed Pump Inlet	1.29	1.185	0.009
11	Feed Pump Outlet	1.29	1.185	0.009
Totals		126.73	14.947	0.730

CHARACTERISTICS OF ALTERNATOR

RING WOUND TPTL PMG		TRANSFORMER			DOWTHERM
Voltage	=	1000.0 Volts	Volt-Amperes	=	1794.0 kVA
Power	=	1704.3 kWe	Speed	=	20054.4 rpm
Rotor Diameter	=	19.1 cm	Tip Speed	=	200.9 m/s
Weight	=	349.4 kg	Stator Diameter	=	32.8 cm
Total Length	=	54.1 cm	Aspect Ratio	=	2.5
Sizing Coef.	=	22.9	Efficiency	=	96.6 %
Cooling Load	=	59.6 kWt	Coolant Flow	=	2.6 kg/s
Clnt inlet Temp.	=	511.1 K	Clnt outlet Temp.	=	522.2 K
Design Life	=	7.0 yrs			

CHARACTERISTICS OF TURBINE

Constant xxl	=	176.89	Tip velocity	=	363.4 m/sec
Power	=	1762.3 kW	Torque	=	840.1 Nt-m
Speed	=	20054.4 rpm	Spouting velocity	=	389.0 m/sec
Stator angle	=	13.6 deg	Turbine weight	=	382.6 kg

TURBO-FEEDPUMP CHARACTERISTICS

Mass flow rate	=	4.15 kg/sec	Inlet pressure	=	210.6 kPa
Discharge pressure	=	1662.6 kPa	Inlet temp	=	1034.6 K
Discharge temp	=	1037.4 K	Tip speed limit	=	51.8 m/sec
Horsepower	=	15.1 kW	Torque	=	4.3 Nt-m
Efficiency	=	60.3 %	Speed	=	33801.5 rpm
Specific speed	=	2635.4	Weight	=	79.5 kg
Stage number	=	2	NPSH margin	=	220.0 %
NPSH	=	16.1 m	Inducer flow coef	=	0.1990
Inducer head coef	=	0.1000	Inducer tip diameter	=	2.92 cm
Inducer tip speed	=	51.7 m/sec	Impeller tip diameter	=	4.39 cm
Impeller flow coef	=	0.1000	Impeller head coef	=	0.3500
Impeller tip speed	=	77.8 m/sec			

BOILER CHARACTERISTICS
General Dimensions

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

Tube dimensions

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

Summary of Heat Transfer Coefficients

Li side	= 4.6 kW/m2-K	K preheat	= 14.2 kW/m2-K
K boiling	= 39.7 kW/m2-K	K superheat	= 0.3 kW/m2-K

Summary of Pressures

Li side pressure drop	= 1.55 kPa	Boiler inlet pressure	= 1661.6 kPa
Boiler outlet pressure	= 1591.5 kPa	Boiler pressure drop	= 70.05 kPa

Summary of boiler weights

Shell	= 3416.3 kg	Boiler tubes	= 2408.6 kg
Twisted tapes	= 722.6 kg	Tube sheets	= 699.0 kg
Heads	= 206.2 kg	Multifoil insulation	= 8.6 kg
Total dry weight	= 7461.3 kg	Weight of Potassium	= 172.5 kg
Weight of lithium	= 401.8 kg	Wet weight of boiler	= 8035.6 kg

REHEATER CHARACTERISTICS
General Dimensions

Height	= 111.8 cm	Diameter	= 53.1 cm
Tube sheet diameter	= 52.7 cm	Shell thickness	= 0.2 cm
Tube sheet thickness	= 3.4 cm		

Tube dimensions

Number of reheater tubes	= 531.0	Preheat length	= 0.0 cm
Boiling length	= 5.1 cm	Superheat length	= 50.8 cm
Total tube length	= 55.9 cm	Tube inside diameter	= 1.27 cm
Tube wall thickness	= 0.051 cm	Tube pitch	= 1.886 cm

Summary of Heat Transfer Coefficients

Li side	= 5.9 kW/m2-K	K preheat	= 14.8 kW/m2-K
K boiling	= 39.7 kW/m2-K	K superheat	= 0.4 kW/m2-K

Summary of Pressures

Li side pressure drop	= 0.96 kPa	Reheater inlet pressure	= 537.8 kPa
Reheater outlet pressure	= 502.8 kPa	Reheater pressure drop	= 35.06 kPa

Summary of reheater weights

Shell	= 57.4 kg	Reheater tubes	= 156.6 kg
Twisted tapes	= 47.0 kg	Tube sheets	= 130.9 kg
Heads	= 13.7 kg	Multifoil insulation	= 0.9 kg
Total dry weight	= 406.5 kg	Weight of Potassium	= 1.0 kg
Weight of lithium	= 27.2 kg	Wet weight of reheater	= 434.7 kg

MASS OF POWER CONVERSION SUBSYSTEM

Component	Mass (KG)
Boiler (wet)	8035.6
Reheater (wet)	434.7
Turbines	1530.4
Alternator	1397.6
Feed Turbo-pumps	317.9
RFMDs	766.0
K piping	126.7
K inventory	14.9
Accumulators	217.9
Total	12842.5

SYSTEM PERFORMANCE CHARACTERISTICS

Specific Mass (kg/kWe)	2.568
Net Efficiency (%)	17.998
Gross Efficiency (%)	18.405
TIT/TCON	1.381

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

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

      COMMON /INPUT/   PRIN(61)
      COMMON /OUTPUT/ PROUT(526)
      COMMON/CONFIG/   GENTYPE,INTTYPE,CLNTTYPE
      COMMON/DIAGNOS/ ERRORG,WARNINGG

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

      OPEN (1,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(11)*25,FNAME(50)*50
      COMMON /INPUT/ PRIN(61)

      READ (1,5) TITLE(1),TITLE(2)
    5 FORMAT(/,A80,///A80,/)
      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)
      DO 50 I = 19,21
   50 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)
      DO 80 I = 31,39
   80 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,
     &                 KWNET,NOTUBB,NOTUBR,LG,MMAIN,MF,ID,MFITOT,
     &                 MQADD,MQREJ,LPHB,LBOILB,LSHB,LTOTB,MFIWTB,LPHR,
     &                 LBOILR,LSHR,LTOTR,MFIWTR,MFLOPT

      CHARACTER TITLE(13)*80,LLBL(11)*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,VELM,VELL,TMAT,XMATH,XMATC,DUM1,DUM2,KA,
     &               KB,NUMOP,NUMTOT,TROUT,TRIN,KWNET,GEFF,DUM3,BPP,BFP,
     &               BPL,PWRFCTR,VOLTAGE,GENASP,TINCLNT,TOUTCLNT,
     &               CPCLNT,TBOIL,XBOIL,DUM4,TCON,DEFF,EXLOSS,VTIPO,
     &               SCCON,ALPHAT,RSTT,XMFI,DPCON,PTEFF,DPRFMD,EFRFMD,
     &               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),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,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,
     &               WTRFMD,WTURBN,XRH,EFF(0:15),DLPBB,WBOILB,WTWETB,
     &               DLPBR,WRHT,WTWETR,HTBB,DOUTEB,DTSB,THSB,XTHKB,LPHB,
     &               LBOILB,LSHB,LTOTB,TKTUBB,PAB,HLILIB,HKPHB,HKBOIB,
     &               HKSHB,WSHELB,WTUBEB,WTAPEB,WTTSB,WTCLOB,MFIWTB,
     &               WTPOTB,WTLIB,HTBR,DOUTER,DTSR,THSR,XTHKR,LPHR,
     &               LBOILR,LSHR,LTOTR,TKTUBR,PAR,HLILIR,HKPHR,HKBOIR,
     &               HKSHR,WSHELR,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,SFPUMP,VFPUMP,WKRFMD,PI,G,TOL,XLAMIN,
     &               XLAMOUT,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,XNPHSA,XNPSHOP,HD(NSTG),
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     &                 EFFP(0:NSTG),HP(NSTG),XIMPNSS,XNSSIMP,QBOILL,
     &                 QRHLSS,PEFF,RPMT,VPOTSB,VPOTSR,XRHEAT,PTI,FRACRH,
     &                 RSTAGE,TTI,TFW,FLOC,TBLOUT,TBLIN,TRHOUT,TRHIN,
     &                 REHEAT,MATH,MATC,RPMA

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


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

      EQUIVALENCE (FPL,PRIN(1)),(MMAIN,PROUT(1))

      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,///,A80,//,7(T6,A50,T60,F10.1,/),2(T6,A50,/),
     &                        4(T6,A50,T60,F10.1,/))

C  WRITE REACTOR INPUT PARAMETERS

      WRITE (6,20) TITLE(3),(FNAME(I),PRIN(I),I=14,15)
   20 FORMAT(/,A80,//,2(T6,A50,T60,F10.1,/))

C  WRITE ELECTRICAL PARAMETERS

      WRITE (6,30) TITLE(4),(FNAME(I),PRIN(I),I=16,17),FNAME(18),
     &             (FNAME(J),PRIN(J),J=19,21)
   30 FORMAT(/,A80,//,T6,A50,T60,F10.1,/,T6,A50,T60,F10.2,/,T6,A50,/,
     &                3(T6,A50,T60,F10.1,/))

C  WRITE ALTERNATOR PARAMETERS

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

C  WRITE TURBINE PARAMETERS

      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,/))

C  WRITE FEED PUMP PARAMETERS

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

C  WRITE RFMD PARAMETERS

      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,/))

C  WRITE BOILER PARAMETERS
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```
      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,F10.1,/),T6,A50,T60,F10.2,/,
     &                  T6,A50,T60,F10.1,/)

C  WRITE LINE PARAMETERS

      WRITE (6,90) TITLE(11),TITLE(12),TITLE(13),
     &              (LLBL(I),PRIN(I+50),I=1,11)
   90 FORMAT(/,A80,//,A80,/A80,//,11(T6,A25,T66,F10.1,/))

C  WRITE OUTPUT FILE

      WRITE(6,100) TT(0),TBOIL,XBOIL,TCON,VTIPO,DEFF*100.,NS,
     &             PTEFF*100.,GEFF*100.,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(0),TBOIL,PP(0),X(0),H(0),S(0),SVV(0)

  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,' 0',2F10.1,1F10.2,1F10.4,
     &  1F10.1,1F10.4,1F10.2,1F10.4)


      DO 130 N = 1,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)
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160 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(T10, 'Generator output  = ',F10.2,' kWe',T55,
   &        'Cycle efficiency = ',F7.2,' %' /
   &        T10, 'Thermal input     = ',F10.2,' kWt',T55,
   &        'Plant efficiency = ',F7.2,' %' /
   &        T10, 'Condensor reject  = ',F10.2,' kWt',T55,
   &        'Main vapor flow  = ',F7.2,' kg/sec' /
   &        T10, 'Generator losses  = ',F10.2,' kWe',//)

    WRITE(6,190)
190 FORMAT(/,T39,'SCHEDULE OF PIPING RUNS',/,T39,
   &        'Thermodynamic Properties',//,
   &        T33,'Temp',T42,'Press',T51,'Enthalpy',
   &        T62,'Entropy',T72,'Quality',T83,'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(I3,T8,A19,T28,1F10.1,1F10.2,1F10.1,2F10.4,1F10.3)
    WRITE(6,210) TLE(I),PLE(I),HLE(I),SLE(I),XLE(I),SVVLE(I)
210 FORMAT(T4,T28,1F10.1,1F10.2,1F10.1,2F10.4,1F10.3)
220 CONTINUE

    WRITE(6,230)
230 FORMAT(///,T37,'Flows & Dimensions',//,
   &        T44,'Flow',T53,'Length',T65,'ID',T74,'Wall',/,
   &        T10,' No.',T19,'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=1,11)
240 FORMAT(11(T10,I3,T18,A19,T38,3F10.2,1F10.3,/))

    WRITE(6,250)
250 FORMAT(//,T47,'Weights',//,
   &        T52,'Pipe Wt',T64,'K Wt',T73,'MFI Wt',/
   &        T10,' No.',T19,'Description',T53,'(kg)',T64,'(kg)',
   &        T74,'(kg)', /)

    WRITE(6,260) (I,LLBL(I),WT(I),WTKINV(I),WTMFI(I),I=1,11)
260 FORMAT(11(T10,I3,T18,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,
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  & GENASP,COE,100.0*GEFF,COOLING,WCLNT,TINCLNT,TOUTCLNT,FPL

275 FORMAT (/,T37,'CHARACTERISTICS OF ALTERNATOR',//
   &       2(T10,A64,/),T10,A20,11X,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,
   &             TURBWT
280 FORMAT(//,T38,'CHARACTERISTICS OF TURBINE' //
   &       T10,'Constant xx1       = ',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),wfpump,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,' %',/,
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     &        T10,'NPSH                      = ',F8.1,' m',T55,
     &            'Inducer flow coef     = ',F8.4,/,
     &        T10,'Inducer head coef     = ',F8.4,T55,
     &            'Inducer tip diameter  = ',F8.2,' cm',/,
     &        T10,'Inducer tip speed     = ',F8.1,' m/sec',T55,
     &            'Impeller tip diameter = ',F8.2,' cm',/,
     &        T10,'Impeller flow coef    = ',F8.4,T55,
     &            'Impeller head coef    = ',F8.4,/,
     &        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',/,
     &    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',/,
     &    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',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(11),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,WTUBEB,WTAPEB,WTTSB,
     &             WTCLOB,MFIWTB,WBOILB,WTPOTB,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',/,
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     &    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',T55,
     &        '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,
     &             WTCLOR,MFIWTR,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,KB,NUMOP,NUMTOT,
     &                 KWNET,NOTUBB,NOTUBR,LG,MMAIN,MF,ID,MFITOT,
     &                 MQADD,MQREJ,LPHB,LBOILB,LSHB,LTOTB,MFIWTB,LPHR,
     &                 LBOILR,LSHR,LTOTR,MFIWTR,MFLOPT

      CHARACTER CLNTYPE*10,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,KWNET,GEFF,DUM3,BPP,BFP,
     &               BPL,PWRFCTR,VOLTAGE,GENASP,TINCLNT,TOUTCLNT,
     &               CPCLNT,TBOIL,XBOIL,DUM4,TCON,DEFF,EXLOSS,VTIPO,
     &               SCCON,ALPHAT,RSTT,XMFI,DPCON,PTEFF,DPRFMD,EFRFMD,
     &               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),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,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,
     &               WTRFMD,WTURBN,XRH,EFF(0:15),DLPBB,WBOILB,WTWETB,
     &               DLPBR,WRHT,WTWETR,HTBB,DOUTEB,DTSB,THSB,XTHKB,LPHB,
     &               LBOILB,LSHB,LTOTB,TKTUBB,PAB,HLILIB,HKPHB,HKBOIB,
     &               HKSHB,WSHELB,WTUBEB,WTAPEB,WTTSB,WTCLOB,MFIWTB,
     &               WTPOTB,WTLIB,HTBR,DOUTER,DTSR,THSR,XTHKR,LPHR,
     &               LBOILR,LSHR,LTOTR,TKTUBR,PAR,HLILIR,HKPHR,HKBOIR,
     &               HKSHR,WSHELR,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,SFPUMP,VFPUMP,WKRFMD,PI,G,TOL,XLAMIN,
     &               XLAMOUT,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,XNPHSA,XNPSHOP,HD(NSTG),
     &               EFFP(0:NSTG),HP(NSTG),XIMPNSS,XNSSIMP,QBOILL,
     &               QRHLSS,PEFF,RPMT,VPOTSB,VPOTSR,XRHEAT,PTI,FRACRH,
     &               RSTAGE,TTI,TFW,FLOC,TBLOUT,TBLIN,TRHOUT,TRHIN,
     &               REHEAT,MATH,MATC,RPMA
```

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

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

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
      MATH = IDINT(XMATH)
      MATC = IDINT(XMATC)

C  CONVERT UNITS OF REACTOR INPUT PARAMETERS

      TROUT = 1.8D0*TROUT
      TRIN  = 1.8D0*TRIN
      KWOUT = (KWNET + BPP + BFP + BPL)*1.02D0

C  CONVERT UNITS OF ALTERNATOR INPUT PARAMETERS

      TINCLNT = 1.8D0*TINCLNT
      TOUTCLNT = 1.8D0*TOUTCLNT
      CPCLNT = CPCLNT/4.185D0

C  CONVERT UNITS OF TURBINE INPUT PARAMTERES

      TBOIL = TBOIL*1.8D0
      IF (XBOIL .GT. 1) XBOIL = XBOIL*1.8D0
      TCON = TCON*1.8D0
      SCCON = SCCON*1.8D0
      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 PRAMETERS

      DPRFMD = 0.145*DPRFMD

C  CONVERT UNITS

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

C  CONVERT UNITS

      DPMAXR = 0.145*DPMAXR
```

```
      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.D0
      CALL LIPORT (TAVLI,MULI,KLI,CPLI,RHOLI,P)
      PMIN = P*14.696D0
      FLOC = (MQADD + QBOILL + QRHLSS)/(CPLI*(TROUT - TRIN))
      KWOUT = (KWNET + BPP + BFP + BPL)*1.02D0

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

      TBLIN = TROUT
      TBLOUT = TROUT*FRACRH + (1.D0 - FRACRH)*TRIN

      REHEAT = 0
      CALL BOILER

      TRHOUT = TRIN
      TRHIN  = TBLOUT
      REHEAT = 1

      CALL  BOILER

   20 CONTINUE

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

C  CONVERT MASS UNITS

      WTWETB  = WTWETB/2.205D0
      WTURBN  = WTURBN/2.205D0
      WTPUMP  = WTPUMP/2.205D0
      TOTWT   = TOTWT/2.205D0
      WTKTOT  = WTKTOT/2.205D0
      MFITOT  = MFITOT/2.205D0
      ALTWT   = ALTWT/2.205D0
      WTWETR  = WTWETR/2.205D0
      WTRFMD  = WTRFMD/2.205D0
      PCSACM  = PCSACM/2.205D0
```

```
C  TOTAL MASS

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

C   Compute system performance characteristics

      PWRT   = (MQADD + QBOILL + QRHLSS)*3.6D0/3.413D0
      SPMASS = WTPCS/KWNET
      EFFNET = KWNET/PWRT*1.D2
      EFFGRS = KWOUT/PWRT*1.D2
      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 PARAMTERES

      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 PRAMETERS

      DPRFMD = DPRFMD/0.145

C  CONVERT UNITS

      DPMAXB = DPMAXB/0.145
```

```
      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
      WTKINV(I)  = WTKINV(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
WTUBEB  = WTUBEB/2.205
WTAPEB  = WTAPEB/2.205
WTTSB   = WTTSB/2.205
WTCLOB  = WTCLOB/2.205
MFIWTB  = MFIWTB/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
WSHELR  = 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
DGENRTR = DGENRTR*2.54
TIPSPDG = TIPSPDG*0.3048
DGENSTR = DGENSTR*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(11),DELHT(0:15),FLOW(0:15),MFLO(0:15),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,TINCLNT,TOUTCLNT,
     &               CPCLNT,TBOIL,XBOIL,DUM4,TCON,DEFF,EXLOSS,VTIPO,
     &               SCCON,ALPHAT,RSTT,XMFI,DPCON,PTEFF,DPRFMD,EFRFMD,
     &               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),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,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,
     &               WTRFMD,WTURBN,XRH,EFF(0:15),DLPBB,WBOILB,WTWETB,
     &               DLPBR,WRHT,WTWETR,HTBB,DOUTEB,DTSB,THSB,XTHKB,LPHB,
     &               LBOILB,LSHB,LTOTB,TKTUBB,PAB,HLILIB,HKPHB,HKBOIB,
     &               HKSHB,WSHELB,WTUBEB,WTAPEB,WTTSB,WTCLOB,MFIWTB,
     &               WTPOTB,WTLIB,HTBR,DOUTER,DTSR,THSR,XTHKR,LPHR,
     &               LBOILR,LSHR,LTOTR,TKTUBR,PAR,HLILIR,HKPHR,HKBOIR,
     &               HKSHR,WSHELR,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,SFPUMP,VFPUMP,WKRFMD,PI,G,TOL,XLAMIN,
     &               XLAMOUT,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,XNPHSA,XNPSHOP,HD(NSTG),
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```
     &                  EFFP(0:NSTG),HP(NSTG),XIMPNSS,XNSSIMP,QBOILL,
     &                  QRHLSS,PEFF,RPMT,VPOTSB,VPOTSR,XRHEAT,PTI,FRACRH,
     &                  RSTAGE,TTI,TFW,FLOC,TBLOUT,TBLIN,TRHOUT,TRHIN,
     &                  REHEAT,MATH,MATC,RPMA

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

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

      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.D0/(64.348*778.16) - 1.25
```

```
      XNS = 1.1D0*D/L
      NS = NINT(XNS)
      XRHEAT = DFLOAT(NS)/2.D0

  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,HF,HG,HFG,SF,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,HF,HG,HFG,SF,SG,SFG)

C TEST FOR SUPERHEAT

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

  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-1)/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 + (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) = (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(0) - SF)/SFG
      HHQUAL = HF + XQUAL*HFG
      DRISD1 = 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.D0/(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,SF,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,SF,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

  350 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(10) .EQ. 0.0) TLE(10) = TCON - SCCON
      T = TLE(10)
      THW = T
      IF (PLE(10) .EQ. 0.0) PLE(10) = PP(NS) + DPRFMD
```

```
      PHW = PLE(10)
      P = PHW/14.696
      CALL KTHRML (T,P,VF,HF,SF)
      VFHW = VF
      HHW = HF
      SHW = SF

      IF (PLI(11) .EQ. 0.0) PLI(11) = PP(0)
      FMDEL = MF(10)
      IF (FMDEL .EQ. 0.D0) FMDEL = 5.D0
      PENG = PLE(10)
      TENG = TLE(10)
      PDIS = PLI(11)
      CALL PSIZE
      TREF = 2.7D3
      NMATH = 1
      NMATC = 2
      CALL STRNTH (TREF, TMAT, NMATH, NMATC, FPL, SIGPV, RHOAST)
      STRHO = SIGPV/RHOAST
      CALL STRNTH (TT(0), TMAT, MATH, MATC, FPL, SIGPV, RHOAST)
      WFPUMP = WFPUMP*SIGPV/(RHOAST*STRHO)

  455 WORKP = TOTHP*550.D0/(778.D0*FMDEL)
      WRKSHT = WORKP
      HPUMP = HHW + WRKSHT
      HH = HPUMP
      T = THW
      P = PLI(11)/14.696
      CALL TFRMHF(HH,T,P,VF,SF)
      TPUMP = T
      TFW = TPUMP
      VFPUMP = VF
      SFPUMP = SF
      FLOWPT = WRKSHT/(HIN - HLI(5))
      FLOW(0) = 1.0 - FLOWPT
      WORK = 0.0

      DO 545 I = 1,NS
      FLOW(I) = FLOW(I-1)
      IF (I .EQ. (RSTAGE + 1)) FLOW(I) = FLOW(I-1) + FLOWPT
      WORKS(I) = FLOW(I)*DELHT(I)
      WORK = WORK + WORKS(I)
  545 CONTINUE

      IF (HLI(1) .EQ. 0.0) HLI(1) = H(0)
      IF (HLE(11) .EQ. 0.0) HLE(11) = HPUMP
  555 QADD = HLI(1) - HLE(11) + DELRH
      IF (HLE(8) .EQ. 0.0) HLE(8) = H(NS)
      IF (HLI(9) .EQ. 0.0) HLI(9) = HHW
      QREJ = FLOW(NS)*(HLE(8) - HLI(9))
      CYCEFF = WORK/QADD

C     '
C     'SIZE TURBINE CYCLE FOR DESIRED OUTPUT
```

```
C      '
C      FACTOR              LB/SEC

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

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

      MQADD = QADD*MMAIN
      MQREJ = QREJ*MMAIN

C     '**** PIPING DESIGN ****

      CALL PIPER

 1450 CONTINUE

      PCSACM = (WTKTOT*SVVLE(9) + VPOTSB + VPOTSR)*2.5D0*13.5D0

      CFSRFM = (CFSLE(9) + CFSLI(10))/2.D0
      HEAD   = 32.174D0*1.44D2*DPRFMD*(SVVLE(9) + SVVLI(10))/2.D0
      PWRFMD = HEAD*MF(10)*3.6D3/(32.174D0*778.D0*3.414D3*EFRFMD*EMRFMD)
      RPMRFM = 4.5D0*HEAD**0.75D0/DSQRT(PI*CFSRFM)
      WTRFMD = 6.01D4*2.205D0*PWRFMD/RPMRFM
      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)

C     '
C     'SIZE TURBINE
C     '

      VTIP = VTIPO
      DO 2050 DJINT = 1,100
      ALPHAR = PI*ALPHAT/1.8D2
      XX1    = RSTT*(DSIN(ALPHAR))*(PI/4.D0)*0.75D0
      DTIP   = 1.2D1*DSQRT(CFSLI(8)/XX1)
      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.D0) GOTO 2070
      IF (RPMT .GT. RPM) THEN
      ALPHAT = 77.6234/RPM**0.175736
```

```
      ALPHAR = PI*ALPHAT/1.8D2
      VTIP   = RPM/15.D0*DSQRT(PI*CFSLI(8)/(3.D0*RSTT*DSIN(ALPHAR)))
      XX1    = RSTT*(DSIN(ALPHAR))*(PI/4.D0)*0.75D0
      DTIP   = 1.2D1*DSQRT(CFSLI(8)/XX1)
      RPMT   = RPM
      ENDIF

 2070 TORQUE = WORK*MMAIN*778.D0*30.D0/(RPMT*PI)
      TRBPWR = TORQUE*(RPMT*PI)/(3.D1*5.5D2)
      TURBWT = 17.82D0*TORQUE**0.6D0
      TREF = 2.7D3
      NMATH = 1
      NMATC = 2
      CALL STRNTH (TREF, TMAT, NMATH, NMATC, FPL, SIGPV, RHOAST)
      STRHO = SIGPV/RHOAST
      CALL STRNTH (TT(0), TMAT, MATH, MATC, FPL, SIGPV, RHOAST)
      TURBWT = TURBWT*SIGPV/(RHOAST*STRHO)

C     '
C     'FRACTION OF HEAT FROM REHEATER AND POTASSIUM FLOW TO REHEATER
C     '

      FRACRH = (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
      PCSACM = NUMTOT*PCSACM
      WTRFMD = NUMTOT*WTRFMD
      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,
     &                 KWNET,NOTUBB,NOTUBR,LG,MMAIN,MF,ID,MFITOT,
     &                 MQADD,MQREJ,LPHB,LBOILB,LSHB,LTOTB,MFIWTB,LPHR,
     &                 LBOILR,LSHR,LTOTR,MFIWTR,MFLOPT,MULI,MUF1,MUF2,
     &                 MUG1,MUG2,MUPH,MUSH,KKPH,KKSH,IDTUBE,KLI,KTUBE,
     &                 NULI,KK,NUPH,NUSH,NOTUB1,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,KWNET,GEFF,DUM3,BPP,BFP,
     &               BPL,PWRFCTR,VOLTAGE,GENASP,TINCLNT,TOUTCLNT,
     &               CPCLNT,TBOIL,XBOIL,DUM4,TCON,DEFF,EXLOSS,VTIPO,
     &               SCCON,ALPHAT,RSTT,XMFI,DPCON,PTEFF,DPRFMD,EFRFMD,
     &               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),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,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,
     &               WTRFMD,WTURBN,XRH,EFF(0:15),DLPBB,WBOILB,WTWETB,
     &               DLPBR,WRHT,WTWETR,HTBB,DOUTEB,DTSB,THSB,XTHKB,LPHB,
     &               LBOILB,LSHB,LTOTB,TKTUBB,PAB,HLILIB,HKPHB,HKBOIB,
     &               HKSHB,WSHELB,WTUBEB,WTAPEB,WTTSB,WTCLOB,MFIWTB,
     &               WTPOTB,WTLIB,HTBR,DOUTER,DTSR,THSR,XTHKR,LPHR,
     &               LBOILR,LSHR,LTOTR,TKTUBR,PAR,HLILIR,HKPHR,HKBOIR,
     &               HKSHR,WSHELR,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,SFPUMP,VFPUMP,WKRFMD,PI,G,TOL,XLAMIN,
     &               XLAMOUT,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),
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     &              F3S(NSTG),XMARG,XNPHSA,XNPSHOP,HD(NSTG),
     &              EFFP(0:NSTG),HP(NSTG),XIMPNSS,XNSSIMP,QBOILL,
     &              QRHLSS,PEFF,RPMT,VPOTSB,VPOTSR,XRHEAT,PTI,FRACRH,
     &              RSTAGE,TTI,TFW,FLOC,TBLOUT,TBLIN,TRHOUT,TRHIN,
     &              REHEAT,MATH,MATC,RPMA

      COMMON/CONFIG/GENTYPE,INTTYPE,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.D0
      WXOT = MMAIN*NUMOP
      WXOC = FLOC
      CALL STRNTH (TLIIN, TMAT, MATH, MATC, FPL, SIGPV, RHOAST)
```

```
C  INITIAL GUESS OF TUBE LENGTH (IN)

      TKTUB = POUT*IDTUBE/SIGPV
      IF (TKTUB .LT. 2.D-2) TKTUB = 2.D-2
      NOTUB  = NOTUB1*NUMTOT/NUMOP
      ODTUBE = (IDTUBE + 2.D0*TKTUB)

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

      PA = 1.375D0*ODTUBE

C    LITHIUM SIDE

      TAVLI = (TLIOUT + TLIIN)/2.D0
      CALL LIPORT(TAVLI,MULI,KLI,CPLI,RHOLI,P)

      IF (TLIIN .GT. TMAT) KTUBE = KA/(1.2D1*3.6D3)
      IF (TLIIN .LE. TMAT) KTUBE = KB/(1.2D1*3.6D3)

      DO 90 I = 1,100

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

      VLI = WXOC*1.44D2/(RHOLI*NOTUB*ODTUBE**2.D0*8.51931D-1)
      RELI = 1.0847D0*3.D2*ODTUBE*VLI*RHOLI/MULI
      FELI = (1.82D0*DLOG10(RELI) - 1.64D0)**(-2.D0)
      IF (RELI .LT. 2.D3) FELI = 6.4D1/RELI
      PRLI = CPLI*MULI/KLI
      EDDY = - 7.2767D-1 + 1.5054D-1*DLOG10(RELI) +
     &         7.2749D-2*(DLOG10(RELI))**2.D0
      EDDY = 10.D0**EDDY
      PSIBAR = 1.D0 - 1.82D0/(PRLI*EDDY**1.4D0)
      IF (PSIBAR .LT. 0.D0) PSIBAR = 0.D0
      NULI = 1.19936D1 + 2.74889D-2*(PSIBAR*RELI*PRLI)**0.8D0
      IF (NULI .LT. 12.266D0) NULI = 12.266D0
      IF (RELI .LT. 2.D3) NULI = 4.8D1/1.1D1
      HLILI = 0.15*NULI*KLI/(ODTUBE*1.2D1*3.6D3)
      DLPB = (FELI*LTOT/(1.0847D0*ODTUBE) + 1.5D0)*
     &       (VLI**2.D0*RHOLI/6.4348D1)
      DLPB = DLPB/1.44D2

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

      PBOIL1 = PIN - DPPH
      P = PBOIL1/14.696D0
      CALL TFROMP (P,TBOIL1)
      KSH = 0
      CALL KTHRMO(KSH,TBOIL1,P,VF,VG,HF,HG,HFG,SF,SG,SFG)
      PBOIL1 = 14.696D0*P
      HBOIL1 = HF + XIN*HFG
      RHOBF1 = 1.D0/VF
```

```
      RHOBG1 = 1.D0/VG
      CALL KXPORT (TBOIL1,MUF1,KK,CP,RHOFL)
      CALL KVPORT (KSH,TBOIL1,P,MUG1,KK,CP,RHOFL)
      VF1  = WXOT*1.44D2/(PI*IDTUBE**2.D0*NOTUB1*RHOBF1/4.D0)
      REL1 = IDTUBE*VF1*RHOBF1*3.D2/MUF1
      VG1  = WXOT*1.44D2/(PI*IDTUBE**2.D0*NOTUB1*RHOBG1/4.D0)
      REG1 = IDTUBE*VG1*RHOBG1*3.D2/MUG1

      PBOIL2 = PBOIL1 - DPBOIL
      P = PBOIL2/14.696D0
      CALL TFROMP (P,TBOIL2)
      KSH = 0
      CALL KTHRMO(KSH,TBOIL2,P,VF,VG,HF,HG,HFG,SF,SG,SFG)
      PBOIL2 = P*14.696D0
      HBOIL2 = HF + XOUT*HFG
      RHOBF2 = 1.D0/VF
      RHOBG2 = 1.D0/VG
      CALL KXPORT (TBOIL2,MUF2,KK,CP,RHOFL)
      CALL KVPORT (KSH,TBOIL2,P,MUG2,KK,CP,RHOFL)
      VF2  = WXOT*1.44D2/(PI*IDTUBE**2.D0*NOTUB1*RHOBF2/4.D0)
      REL2 = IDTUBE*VF2*RHOBF2*3.D2/MUF2
      VG2  = WXOT*1.44D2/(PI*IDTUBE**2.D0*NOTUB1*RHOBG2/4.D0)
      REG2 = IDTUBE*VG2*RHOBG2*3.D2/MUG2

      RHOBFA = (RHOBF1 + RHOBF2)/2.D0
      RHOBGA = (RHOBG1 + RHOBG2)/2.D0
      REL = (REL1 + REL2)/2.D0*(1.D0 - XOUT/2.D0 - XIN/2.D0)
      REG = (REG1 + REG2)/2.D0*(XOUT/2.D0 + XIN/2.D0)

C    PREHEAT

      TAVEPR = (TIN + TBOIL1)/2.D0
      CALL KXPORT(TAVEPR,MUPH,KKPH,CPPH,RHOPH)
      VPH  = WXOT*1.44D2/(PI*IDTUBE**2.D0*NOTUB1*RHOPH/4.D0)
      REPH = IDTUBE*VPH*RHOPH*3.D2/MUPH
      FEPH = (1.82D0*DLOG10(REPH) - 1.64D0)**(-2.D0)
      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.D0
      EDDY = 10.D0**EDDY
      PSIBAR = 1.D0 - 1.82D0/(PRPH*EDDY**1.4D0)

      IF (PSIBAR.LT.0.D0) PSIBAR = 0.D0

      NUPH = 7.D0 + 2.5D-2*(PSIBAR*REPH*PRPH)**0.8D0
      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.D0
      PAVESH = POUT + DPSH/2.D0
      P = PAVESH/14.696D0
      KSH = 1
      CALL KVPORT (KSH,TAVESH,P,MUSH,KKSH,CPSH,RHOSH)
      VSH = WXOT*1.44D2/(PI*IDTUBE**2.D0*NOTUB1*RHOSH/4.D0)
      RESH = IDTUBE*VSH*RHOSH*3.D2/MUSH
      FESH = (1.82D0*DLOG10(RESH) - 1.64D0)**(-2.D0)
      IF (RESH .LT. 2.D3) FESH = 6.4D1/RESH
      PRSH = CPSH*MUSH/KKSH
      NUSH = ((FESH/8.D0)*RESH*PRSH)/
     +(1.07D0 + 1.27D1*DSQRT(FESH/8.D0)*(PRSH**(2.D0/3.D0) - 1.D0))
      IF (RESH .LT. 2.D3) NUSH = 1.1D1/3.D0
      HKSH = NUSH*KKSH/(IDTUBE*1.2D1*3.6D3)

C    Compute overall heat transfer coefficients

      UIPH = 1.D0/(1.D0/HKPH + IDTUBE*DLOG(ODTUBE/IDTUBE)/(2.D0*KTUBE)
     +          + IDTUBE/(HLILI*ODTUBE))

      UIBOIL = 1.D0/(1.D0/HKBOIL + IDTUBE*DLOG(ODTUBE/IDTUBE)
     +            /(2.D0*KTUBE) + IDTUBE/(HLILI*ODTUBE))

      UISH = 1.D0/(1.D0/HKSH + IDTUBE*DLOG(ODTUBE/IDTUBE)/(2.D0*KTUBE)
     +          + IDTUBE/(HLILI*ODTUBE))

      QPH = WXOT*(HBOIL1 - HIN)
      QBOIL = WXOT*(HBOIL2 - HBOIL1)
      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.D0
      ENDIF

c    Compute tube lengths & number of reheater tubes required

      LPH    = QPH/(UIPH*DTLMPH*PI*IDTUBE*NOTUB1)
      LBOIL  = QBOIL/(UIBOIL*DTLMBL*PI*IDTUBE*NOTUB1)

      IF (TOUT .GT. TBOIL2) THEN
      LSH    = QSH/(UISH*DTLMSH*PI*IDTUBE*NOTUB1)
      ELSE
      LSH = 0.D0
      ENDIF
```

```
      LTOT   = LPH + LBOIL + LSH

c   compute pressure drops in boiler tubes
c   first the superheater

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

      DPSH = (FESH*(LSH/IDTUBE) + 1.D0)*(VSH**2.D0*RHOSH/6.4348D1)
      DPSH = DPSH/1.44D2

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

c   next the boiling section

      PARAM = DSQRT(RHOBFA/RHOBGA)

      R1 = (1.D0 + PARAM*XOUT)**2.D0 - 1.D0
      DPINRT = R1*VPH**2.D0*RHOPH/3.2174D1
      DPINRT = DPINRT/1.44D2

C     R2 = (1.D0/PARAM - 1.D0)/(PARAM - 1.D0) +
C    &      (PARAM - 1.D0/PARAM)/(XOUT*(PARAM - 1.D0)**2.D0) +
C    &      DLOG(1.D0 + XOUT*(PARAM - 1.D0))

C     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.D0*RHOPH/3.2174D1)*
     &         (R1 + 2.D0)
      DPDRAG = DPDRAG/1.44D2

      DPBOIL = DPINRT + DPDRAG

c   Now compute pressure drop in the preheater

      DPPH = (FEPH*(LPH/IDTUBE) + 0.5D0)*(VPH**2.D0*RHOPH/6.4348D1)
      DPPH = DPPH/1.44D2

      DPTOT = DPBOIL + DPPH + DPSH
      PIN   = POUT + DPTOT

      FUNC2 = DPTOT - DPMAX
      CHECK = -0.7D0*DPMAX

      IF ((FUNC2  .GT. 1.D1) .OR. (FUNC2 .LT. CHECK)) THEN
      NOTUB1 = NOTUB1*DSQRT(DPTOT/DPMAX)
      NOTUB = NOTUB1*NUMTOT/NUMOP
      PIN = POUT
      DPBOIL = 0.D0
      DPPH = 0.D0
      DPSH = 0.D0
      GOTO 90
      ENDIF
```

```
      IF (NOTUBO.EQ.0.DO) THEN
      FUNC1 = FUNC2
      NOTUBO = 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*(NOTUB1 - NOTUBO)/(FUNC2 - FUNC1)
      IF (DELTA .GT. NOTUB1) DELTA = DELTA/2.DO
      NOTUBO = NOTUB1
      NOTUB1 = NOTUB1 - DELTA
      FUNC1  = FUNC2
      NOTUB = NOTUB1*NUMTOT/NUMOP
      GOTO 80
      ENDIF

      IF (JTUBE .EQ. 0) THEN
      J = NINT(NOTUB1/NUMOP)
      NOTUB1 = DFLOAT(J)*NUMOP
      NOTUB = NOTUB1*NUMTOT/NUMOP
      JTUBE = 1
      GOTO 80
      ENDIF

   75 IF (ABS(LTOT - HTTUB).LT.0.5DO) 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 = 1.444DO*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 = DMIN1(A1,A2)
      BSHEET = DTS/2.DO
      KSHEET = BSHEET/ASHEET
      PPRIME = ASHEET*DSQRT(PI/(NOTUB*DSIN(PI/3.DO)))
      ETASHT = (PPRIME - ODTUBE)/PPRIME
      FSTAR  = 0.556DO*KSHEET**(0.39DO*DLOG(ETASHT))
      OMEGA1 = 1.5/ETASHT
      OMEGA2 = 2.0
```

```
      OMEGA   = DMIN1(OMEGA1,OMEGA2)
      H1SHT   = DTS*FSTAR*DSQRT(PIN/(OMEGA*SIGPV*ETASHT))
      H2SHT   = PIN*ASHEET/(1.6D0*SIGPV*(PA - ODTUBE)/PA)
      XTHK    = DMAX1(H1SHT,H2SHT)

      VTS = (DTS**2.D0 - NOTUB*ODTUBE**2.D0)*PI*XTHK/2.D0

c  calculate the length of the boiler, lcl=3" + dia of tube sheet

      LCL = DTS/2.D0 + XTHK
      HTB = LTOT + 2.D0*LCL

C  CALCULATE THE VOLUME OF METAL PARTS - DENSITY = 0.31 lb/in3
c  volume of the shell

      THS = PIN*DTS/(2.D0*SIGPV)
      SIXTENH = 1.D0/16.D0
      IF (THS.LT.SIXTENH) THS = SIXTENH
      DOUTER = DTS + 2.D0*THS

c  assume 18 inches added to accomodate reheat tubes

      VSHELL = (PI/4.D0)*(DOUTER**2.D0 - DTS**2.D0)*HTB

c  volume of the tubes

      VTUBE = NOTUB*(LTOT + 2.D0*XTHK)*(PI/4.D0)*
     &          (ODTUBE**2.D0 - IDTUBE**2.D0)

c volume of closure, assume spherical end caps
c assume a flat end plate closure

      VCLO =  (PI/2.D0)*(DOUTER**2.D0)*THS

      VMFI = PI/4.D0*((DOUTER + 1.06D-2*MFI)**2.D0 - DOUTER**2.D0)*
     &       (LTOT + XTHK)
      VMFI = VMFI + PI/6.D0*((DOUTER + 1.06D-2*MFI)**3.D0 -
     &       DOUTER**3.D0)

      WTSHELL = VSHELL*RHOAST
      WTUBE = VTUBE*RHOAST
      WTAPE = WTUBE*0.3D0
      WTTS = VTS*RHOAST
      WTCLO = VCLO*RHOAST
      MFIWT = VMFI*9.2D-3

      WBOIL = WTSHELL + WTUBE + WTAPE + WTTS + WTCLO + MFIWT
      VTOT = VSHELL + VTUBE + VTS + VCLO

c  calculate the volume of the Lithium

      VCYL = (PI/4.D0)*DTS**2.D0*LTOT

c  take out primary helix tubes and shroud and reheater tubes
```

```
      V2 = NOTUB*LTOT*(PI/4.D0)*ODTUBE**2.D0
      VLI  = VCYL - V2

c     compute weight of potassium in the boiler

      FACTOR = 1.D0 - (XIN + XOUT)/2.D0
      V2 = V2*((LPH + LBOIL*FACTOR)/LTOT)*(IDTUBE/ODTUBE)**2.D0
      VHEAD = PI*DTS**3.D0*FACTOR/6.D0
      VPOTAS = (VHEAD + V2)/(12.D0**3.D0*NUMTOT)
      WTPOTS = VPOTAS*RHOPH*NUMOP

      WTLI = VLI*RHOLI/1.2D1**3.D0
      WTWET = WBOIL + WTLI + WTPOTS

c   compute heat losses

      TRADAV = (TLIIN**5.D0 - TLIOUT**5.D0)/(TLIIN - TLIOUT)
      QLOSS  = PI*DOUTER*HTB*0.2D0*3.305D-15*TRADAV
      QLOSS  = QLOSS/DFLOAT(MFI)
      TRADAV = TRADAV**0.25D0

c   parameter transformation

      IF (REHEAT .EQ. 0) THEN
      NOTUBB = NOTUB1
      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
      LTOTB = LTOT
      TKTUBB = TKTUB
      PAB = PA
      HLILIB = HLILI
      HKPHB = HKPH
      HKBOIB = HKBOIL
      HKSHB = HKSH
      WSHELB = WTSHELL
      WTUBEB = WTUBE
      WTAPEB = WTAPE
      WTTSB = WTTS
      WTCLOB = WTCLO
      MFIWTB = MFIWT
      WTPOTB = WTPOTS
```

```
WTLIB = WTLI

ELSE

NOTUBR = NOTUB1
QRHLSS = QLOSS
PLE(6) = PIN
DLPBR = DLPB
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
WTUBER = WTUBE
WTAPER = WTAPE
WTTSR = WTTS
WTCLOR = WTCLO
MFIWTR = MFIWT
WTPOTR = WTPOTS
WTLIR = WTLI

ENDIF

RETURN
END
```

```
      subroutine psize
c
c     ***************************************************************
c     *                                                             *
c     *   this program is a generalized conceptual design program   *
c     *        for a centrifugal stage + inducer are sized          *
c     *                   ghp 2/92                                  *
c     *                                                             *
c     ***************************************************************
c
      implicit double precision (a-h,o-z)
c
      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,PWRFCTR,VOLTAGE,GENASP,TINCLNT,TOUTCLNT,
     &                CPCLNT,TBOIL,XBOIL,DUM4,TCON,DEFF,EXLOSS,VTIPO,
     &                SCCON,ALPHAT,RSTT,XMFI,DPCON,PTEFF,DPRFMD,EFRFMD,
     &                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),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,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,
     &                WTRFMD,WTURBN,XRH,EFF(0:15),DLPBB,WBOILB,WTWETB,
     &                DLPBR,WRHT,WTWETR,HTBB,DOUTEB,DTSB,THSB,XTHKB,LPHB,
     &                LBOILB,LSHB,LTOTB,TKTUBB,PAB,HLILIB,HKPHB,HKBOIB,
     &                HKSHB,WSHELB,WTUBEB,WTAPEB,WTTSB,WTCLOB,MFIWTB,
     &                WTPOTB,WTLIB,HTBR,DOUTER,DTSR,THSR,XTHKR,LPHR,
     &                LBOILR,LSHR,LTOTR,TKTUBR,PAR,HLILIR,HKPHR,HKBOIR,
     &                HKSHR,WSHELR,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,SFPUMP,VFPUMP,WKRFMD,PI,G,TOL,XLAMIN,
     &                XLAMOUT,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,XNPHSA,XNPSHOP,HD(NSTG),
     &                   EFFP(0:NSTG),HP(NSTG),XIMPNSS,XNSSIMP,QBOILL,
     &                   QRHLSS,PEFF,RPMT,VPOTSB,VPOTSR,XRHEAT,PTI,FRACRH,
     &                   RSTAGE,TTI,TFW,FLOC,TBLOUT,TBLIN,TRHOUT,TRHIN,
     &                   REHEAT,MATH,MATC,RPMA

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

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

c
c     set constants
c
      g = 32.174
      tol = 0.0000001
c
c     set default values
c
      ssmarg = 2.00
      psi(1) = 0.10
      phi(1) = 0.14
      effp(1) = 0.848
      utlim = 170.D0
      do 100 i = 2, nstg
       phi(i) = 0.1
       psi(i) = 0.35
       effp(i) = 0.848
100   continue
      xlamin = 0.3
      xlamout = 0.6
c
c     begin pump sizing
c
      call indsize
c
      torq = 5252.*tothp/xn
      call corelate(5,torq,wfpump)
c
      return
      end
```

```
      subroutine indsize
c
c     *****************************************************************
c     *                                                               *
c     *   This subroutine evaluates the size and state conditions     *
c     *    on and around the inducer.   ghp 2/92                      *
c     *                                                               *
c     *****************************************************************
c
      implicit double precision (a-h,o-z)
c
      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,PWRFCTR,VOLTAGE,GENASP,TINCLNT,TOUTCLNT,
     &               CPCLNT,TBOIL,XBOIL,DUM4,TCON,DEFF,EXLOSS,VTIPO,
     &               SCCON,ALPHAT,RSTT,XMFI,DPCON,PTEFF,DPRFMD,EFRFMD,
     &               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),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,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,
     &               WTRFMD,WTURBN,XRH,EFF(0:15),DLPBB,WBOILB,WTWETB,
     &               DLPBR,WRHT,WTWETR,HTBB,DOUTEB,DTSB,THSB,XTHKB,LPHB,
     &               LBOILB,LSHB,LTOTB,TKTUBB,PAB,HLILIB,HKPHB,HKBOIB,
     &               HKSHB,WSHELB,WTUBEB,WTAPEB,WTTSB,WTCLOB,MFIWTB,
     &               WTPOTB,WTLIB,HTBR,DOUTER,DTSR,THSR,XTHKR,LPHR,
     &               LBOILR,LSHR,LTOTR,TKTUBR,PAR,HLILIR,HKPHR,HKBOIR,
     &               HKSHR,WSHELR,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,SFPUMP,VFPUMP,WKRFMD,PI,G,TOL,XLAMIN,
     &               XLAMOUT,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,XNPHSA,XNPSHOP,HD(NSTG),
     &                 EFFP(0:NSTG),HP(NSTG),XIMPNSS,XNSSIMP,QBOILL,
     &                 QRHLSS,PEFF,RPMT,VPOTSB,VPOTSR,XRHEAT,PTI,FRACRH,
     &                 RSTAGE,TTI,TFW,FLOC,TBLOUT,TBLIN,TRHOUT,TRHIN,
     &                 REHEAT,MATH,MATC,RPMA

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

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

c
c     determine inlet conditions at engine interface
c
      call ept2d(peng,teng,rhoeng,kfluid)
      call ept2h(peng,teng,heng,steng,kfluid)

c
c     flow rate for pump allows for variation through stages later
c
      f3s(1) = (fmdel/rhoeng)
c
c     begin iteration on inducer size
c
      dindg = 0.0
      cm(1) = 0.0
      tshg = 1000.0
      ttp(1) = teng
      rho(1) = rhoeng
      ht(1) = heng
      vduct = 0.0
   30 pt(1) = peng + (0.5*xkloss*rho(1)*vduct**2.0)*(1./g*144.)
      ps(1) = pt(1) - (cm(1)**2.0*rho(1))/(2.*g*144.)
      call ept2h(pt(1),ttp(1),ht(1),steng,kfluid)
      hsp(1) = ht(1) - (cm(1)**2./(2.*g*778.26))
      call eph2s(pt(1),ht(1),st(1),ttp(1))
      call eph2d(ps(1),hsp(1),rho(1),ttp(1))
      call et2vap(ttp(1),dum,pvapor,kfluid)
c
      xnpsha = ((pt(1)-pvapor)/rho(1))*144.
c
c     size inducer given flow coefficient, inlet conditions, and margin
c
   31 call corelate(1,phi(1),xnsstr)
c
    xnssh2o = xnsstr*dsqrt(1.-xlamin**2.)
          tsh1 = 0.5*pvapor/rho(1)*144.
          tsh2 = (1./(2.*g))*cm(1)**2.
          if (tsh2 .eq. 0.00) tsh2 = tsh1
          if (tsh1 .le. tsh2) tsh = tsh1
          if (tsh2 .le. tsh1) tsh = tsh2
          xnpshop = xnpsha/(1.+ssmarg)
          xn = (xnssh2o*((xnpshop+tsh)**(3./4.)))/dsqrt(f3s(1)*448.83)
```

```
        dt(1) = ((4.*60./pi**2.)*(f3s(1)/(xn*(1-xlamin**2.)*
     &           phi(1))))**(1./3.)
c
      if (dt(1) .lt. 0.5/12.) then
        dt(1) = 0.5/12.
      endif
c
        ut(1) = (pi/60.)*(xn*dt(1))
        cm(1) = phi(1)*ut(1)
c
        if (dabs(tshg-tsh) .gt. 0.00001 ) then
          tshg = tsh
          goto 31
        endif
c
        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
c
        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
c
        xnss = xn*dsqrt(f3s(1)*448.83)/xnpsha**0.75
        pengi = pt(1) + (0.5*xkloss*rho(1)*vduct**2.)*(1./(g*144.))
c
c      suction performance correction for small pumps
c
        if (dt(1) .lt. 2.778/12.) xnss = xnss*0.48*dsqrt(dt(1)/.64)
c
       if (dabs(dindg-dt(1)) .gt. .0001) then
         dindg = dt(1)
         go to 30
       endif
c
         n = 1
         call convrg3(n,peng,pengi,pt(1),tol,k,500)
```

```
      if (k) 10,20,30
10    print 11, n
11    format(10x,'error at loop',i3/)
      stop
20    call eph2t(ps(1),hsp(1),ts(1),ttp(1))
c
c     calculate discharge of first inducer
c
      dh(2) = dt(1)*xlamout
c
c
      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))
c
      hp(1) = (xiht(2)-ht(1))*778.26/effp(1)*fmdel/550.0
      tothp = hp(1)
c
c     assume one stage centrifugal with an inducer
c
      if (dabs(pt(2)-pdis) .lt. 1.0) then
        pt(2) = pdis
      endif
c
      if (pt(2) .lt. pdis) then
c
      numstg = 1
   70 numstg = numstg + 1
      do 60 jstage = 2,numstg
      in = jstage
      i = in + 1
      dtg = 0.0
50    continue
c
        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(in) + 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))
c
c     size centrifugal stage
c
      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))
c
c    re-evaluate efficiency
c
  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))
c
      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
c
      if (dt(in) .lt. 5.0/12.0 .and. dt(1) .ne. dt(in)) then
        xks = (5./12./dt(in))**1.5*(0.004/0.004)*
     &           (dt(1)/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) .ge. 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
c
c    loop around stage to correct efficiency
c
      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
         endif
        goto 50
      endif
c
c    calculate pump power requirment
c
      hp(in) = (xiht(i)-ht(i-1))*778.26/effp(in)*fmdel/550.0
  60  tothp = tothp + hp(in)
c
```

```
c
      nstage = in
c
      else
        nstage = 1
        effp(in) = 0.848
      endif
c
c     setup the analysis of the stages
c
      do 100 in = 1, nstage
        dt(in) = dt(in)*12.
        dh(1) = dt(1)*xlamin
        dh(in) = dt(1)*xlamout
 100  continue
c
c     calculate pump efficiency
c
      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))
c
      return
      end
```

```
      subroutine isen(pres,gh,strue,n,tol,hout,temp)
c
c     *****************************************************************
c     *                                                               *
c     *  Calculates isentropic enthalpy - ghp 2/92                    *
c     *                                                               *
c     *****************************************************************
c
      implicit double precision (a-h,o-z)
c
      tol = 0.0001
c
   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
c
      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
C          CHECK K IN MAIN PROGRAM COMING OUT OF CONVRG
C
C     N IS MAXIMUM NUMBER OF ITERATIONS TO BE ALLOWED
C
      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
```

```
c     program propfunct
c
c     ******************************************************************
c     *                                                                *
c     *     This program is an interface between the pump sizing      *
c     * program and the properties routines.  The correct property    *
c     * routine must be bound along with this program to the main     *
c     * pump sizing program.  This method is similar to that used in  *
c     * the gas path program. ghp 2/92                                 *
c     *                                                                *
c     ******************************************************************
c
c
      subroutine ept2d(p,t,density,kfluid)
c
c     ******************************************************************
c     *                                                                *
c     *     This subroutine determines the density from p and t       *
c     *                                                                *
c     ******************************************************************
c
      implicit double precision (a-h,o-z)
c
c
        call vfromt(t,vf)
        density = 1.0/vf
c
      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
```

```
c
c
      subroutine eph2d(p,h,density,temp)
c
c     *****************************************************************
c     *                                                               *
c     *    This subroutine determines the density from  p and h       *
c     *                                                               *
c     *****************************************************************
c
      implicit double precision (a-h,o-z)
c
         patm = p/14.696
         call tfrmhf(h,temp,patm,vf,sf)
         density = 1.0/vf
c
      return
      end
```

```
c
c
      subroutine ept2h(p,t,enthalpy,st,kfluid)
c
c     ******************************************************************
c     *                                                                *
c     *    This subroutine determines the enthalpy from  p and t       *
c     *                                                                *
c     ******************************************************************
c
      implicit double precision (a-h,o-z)
c
         patm = p/14.696
         call kthrml(t,patm,vf,hf,sf)
         enthalpy = hf
c
      return
      end
```

```
c
c
      subroutine eph2s(p,h,entropy,temp)
c
c     *****************************************************************
c     *                                                               *
c     *    This subroutine determines the entropy from  p and h       *
c     *                                                               *
c     *****************************************************************
c
      implicit double precision (a-h,o-z)
c
      patm = p/14.696
      call tfrmhf(h,temp,patm,vf,entropy)
c
      return
      end
```

```
c
c
      subroutine eph2t(p,h,temp,templ)
c
c     *****************************************************************
c     *                                                               *
c     *  This subroutine determines the temperature from  p and h     *
c     *                                                               *
c     *****************************************************************
c
      implicit double precision (a-h,o-z)
c
        patm = p/14.696
        call tfrmhf(h,templ,patm,dum,duml)
        temp = templ
c
      return
      end
```

```
c
c
      subroutine et2vap(t,dum,pvap,kfluid)
c
c     *****************************************************************
c     *                                                               *
c     *  This subroutine determines the vapor pressure for the given t *
c     *                                                               *
c     *****************************************************************
c
      implicit double precision (a-h,o-z)
c
        ksh = 0
        call kthrmo(ksh,t,pvap,dum1,dum2,dum3,dum4,dum5,dum6,dum7,
     &              dum8)
        pvap = pvap*14.696
c
      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,
     &               CPCLNT,TBOIL,XBOIL,DUM4,TCON,DEFF,EXLOSS,VTIPO,
     &               SCCON,ALPHAT,RSTT,XMFI,DPCON,PTEFF,DPRFMD,EFRFMD,
     &               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),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,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,
     &               WTRFMD,WTURBN,XRH,EFF(0:15),DLPBB,WBOILB,WTWETB,
     &               DLPBR,WRHT,WTWETR,HTBB,DOUTEB,DTSB,THSB,XTHKB,LPHB,
     &               LBOILB,LSHB,LTOTB,TKTUBB,PAB,HLILIB,HKPHB,HKBOIB,
     &               HKSHB,WSHELB,WTUBEB,WTAPEB,WTTSB,WTCLOB,MFIWTB,
     &               WTPOTB,WTLIB,HTBR,DOUTER,DTSR,THSR,XTHKR,LPHR,
     &               LBOILR,LSHR,LTOTR,TKTUBR,PAR,HLILIR,HKPHR,HKBOIR,
     &               HKSHR,WSHELR,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,SFPUMP,VFPUMP,WKRFMD,PI,G,TOL,XLAMIN,
     &               XLAMOUT,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,XNPHSA,XNPSHOP,HD(NSTG),
     &               EFFP(0:NSTG),HP(NSTG),XIMPNSS,XNSSIMP,QBOILL,
     &               QRHLSS,PEFF,RPMT,VPOTSB,VPOTSR,XRHEAT,PTI,FRACRH,
     &               RSTAGE,TTI,TFW,FLOC,TBLOUT,TBLIN,TRHOUT,TRHIN,
     &               REHEAT,MATH,MATC,RPMA

      COMMON/CONFIG/GENTYPE,INTTYPE,CLNTTYPE
      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(0)
      PLE(2)   = PP(0)
      HLE(2)   = H(0)
      SLE(2)   = S(0)
      XLE(2)   = X(0)
      SVVLE(2) = SVV(0)
      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)
```

```
      SVVLE(1) = SVVLI(2)
      CFSLE(1) = MF(1)*SVVLE(1)

      CALL SIZEPP (CFSLE(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,SF,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),WTKINV(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),
```

```
&             WALL(5),WT(5),WTKINV(5),WTMFI(5),ID(5),MFI)

      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
      CFSLE(5) = MF(5)*SVVLE(5)

      PLI(6) = PLE(4)
      HLI(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),WTKINV(7),WTMFI(7),ID(7),MFI)

      VISCOS = 1.98227D-2 + 1.36364D-5*TLE(7)
      DENSIT = 1.0/SVVLE(7)
      CALL HEADLOSS (DENSIT,ID(7),VELV,VISCOS,LG(7),DELPL(7))
      CALL QLOSS (TLE(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),WTKINV(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 TFROMP (P,T)
      KSH = 0
      CALL KTHRMO (KSH,T,P,VF,VG,HF,HG,HFG,SF,SG,SFG)
      TLI(9) = T - SCCON
      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(10)
      P = PLE(10)/14.696
      CALL TFRMHF(HH,T,P,VF,SF)
      TLE(10) = T
      SLE(10) = SF
      XLE(10) = 0.0
      SVVLE(10) = VF
      CFSLE(10) = MF(10)*SVVLE(10)

      TLI(11) = TPUMP
      HLI(11) = HPUMP
      SLI(11) = SFPUMP
      XLI(11) = 0.0
      SVVLI(11) = VFPUMP
      CFSLI(11) = MF(11)*SVVLI(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(1) + DPTOTB
      PLI(11) = PLE(11) + DELPL(11)
      HLE(11) = HLI(11) - DELHL(11)
      HH = HLE(11)
      P = PLE(11)/14.696
      CALL TFRMHF(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.D0
      WTKTOT = 0.D0
      MFITOT = 0.D0

      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.D0*MFI*(SEP + THK))**2.D0 - ID**2.D0)/4.D0
      WTMFI = WTMFI*RHOMFI/(SEP/THK + 1.D0)
      IF (ID .EQ. 0.0) THEN
      WT = 0.D0
      WTKINV = 0.D0
      WTMFI = 0.D0
      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.D0) THEN
      FRIC = 0.D0
      ELSE
      FRIC   = (1.82*DLOG10(REYNLD) - 1.64)**(-2.0)
      ENDIF

      IF (FRIC.EQ.0.D0) THEN
      DELP = 0.D0
      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
```

```
C  REM SUBROUTINE RETURNS THERMODYNAMIC PROPERTIES OF POTASSIUM FROM T

      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*DLOG(1.D1)/T)
      C = 10.0**(0.5873 + 6385.7/T)
      DCDT = -6385.7*DLOG(1.D1)*C/T**2.0
      D = -1.0*10**(1.4595 + 7863.8/T)
      DDDT = -7863.8*DLOG(1.D1)*D/T**2.0

      V1 = 0.7302*T/P
      DO 10 I=1,100
      FUNC = P*V1/(0.7302*T) - (1.0 + B/V1 + C/V1**2 + D/V1**3)
      SLOPE = P/(0.7302*T) + (B/V1**2 + 2.0*C/V1**3 + 3.0*D/V1**4)
      V2 = V1 - 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*DLOG(1.D1)/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.D0))/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,T1)
      KSH = 1
      T2 = 1.05*T1
      CALL KTHRMO (KSH,T1,P,VF,VG,HF,HG1,HFG,SF,SG,SFG)
      FUNC1 = HG - HG1

      DO 10 J = 1,100
      CALL KTHRMO (KSH,T2,P,VF,VG,HF,HG2,HFG,SF,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

C     ****** 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
```

```
      SUBROUTINE KVPORT(KSH,TR,P,MU,K,CP,RHOFL)
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      DOUBLE PRECISION MU,K

C     ****** POTASSIUM VAPOR TRANSPORT PROPERTIES SUBROUTINE *****

      MU = 1.0282D-2 + 2.5649D-5*TR - 3.125D-9*TR**2.D0
      K  = 1.8786D-3 + 4.3527D-6*TR - 5.2198D-10*TR**2.D0
      CP = 0.22713 - 64.848D-6*TR + 23.178D-9*TR**2.0
      CALL KTHRMO (KSH,TR,P,VF,VG,HF,HG,HFG,SF,SG,SFG)
      RHOFL = 1.D0/VG
      KSH1 = KSH
      KSH = 1
      TR2 = TR + 1.D-2
      CALL KTHRMO (KSH,TR2,P,VF,VG,HF,HG2,HFG,SF,SG,SFG)
      TR1 = TR - 1.D-2
      CALL KTHRMO (KSH,TR1,P,VF,VG,HF,HG1,HFG,SF,SG,SFG)
      CP = (HG2 - HG1)/2.D-2
      KSH = KSH1

      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)

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

      TT = TT/1.8D0
      TMAT = TMAT/1.8D0
      IF ( TT .EQ. 0.D0) 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.D0
      C = 0.D0
      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.D0
      DO 50 I=1,100
```

```
      THETA = CH + (A*SIGMA + B*SIGMA**2.D0 + C*SIGMA**3.D0 + D)/TT
      FUNC = THET - THETA
      FPRIME = -(A + 2.D0*B*SIGMA + 3.D0*C*SIGMA**2.D0)/TT
      DELTA = FUNC/FPRIME
      SIGMAO = SIGMA
      SIGMA = SIGMA - DELTA
      IF (DABS(FUNC) .LT. 1.D-6) GO TO 60
   50 CONTINUE

   60 SIGPV = (1.D1**SIGMA)*14.696D0/0.101325D0
      GOTO 130

   70 THET = DLOG10(FPL*8.76D3)
      SIGMA = 4.D0
      DO 80 I = 1,100
      THETA = CH + (A*SIGMA + B*DLOG10(SIGMA) + D)/TT
      FUNC = THET - THETA
      FPRIME = -(A +B/(SIGMA*DLOG(1.D1)))/TT
      DELTA = FUNC/FPRIME
      SIGMAO = SIGMA
      SIGMA = SIGMA - DELTA
      IF (DABS(FUNC) .LT. 1.D-6) GOTO 90
   80 CONTINUE

   90 SIGPV = 1.D3*SIGMA
      GOTO 130

C  316 Stainless Steel

  100 RHO  = 0.285D0
      TIME = FPL*8.76D3

      DO 110 I = 1,100
      IF (I .EQ. 1) SIGMA = 5.D1
      TIMEI = 63.502D0 - 18.889D0*DLOG10(SIGMA) - 0.06812D0*TT +
     &         0.01963D0*TT*DLOG10(SIGMA)

C  Solve for type I creep

      EM1DOT = -44.39D0 + 7.867*DLOG10(SIGMA) + 0.0312D0*TT -
     &      8.887D-7*TT*SIGMA
      EM1DOT = 1.D1**EM1DOT
      P1     = 1.D1*EM1DOT**0.87D0
      C1     = 0.76D0*EM1DOT**0.03D0
      EI     = C1*P1*TIMEI/(1.D0 + P1*TIMEI) + EM1DOT*TIMEI

C  Solve for type II creep

      EM2DOT = -5.164D0 - 9.136D0*DLOG10(SIGMA) - 0.01551D0*TT +
     &      0.02052D0*TT*DLOG10(SIGMA)
      EM2DOT = 1.D1**EM2DOT
      P2     = 3.45D0*EM2DOT**0.87D0
      C2     = 0.64D0*EM2DOT**0.03D0
```

```
      BC      = EI*P2 - C2*P2 - EM2DOT
      TIMEC   = (BC + DSQRT(BC**2.D0 + 4.D0*EI*P2*EM2DOT))/
     &           (2.D0*P2*EM2DOT)

      TIME2 = TIME - TIMEI + TIMEC
      IF (TIME2 .LT. TIME) TIME2 = TIME
      EC    = C2*P2*TIME2/(1.D0 + P2*TIME2) + EM2DOT*TIME2

      FUNC = EC - 1.D0
      IF (I .EQ. 1) THEN
      SIGMA1 = SIGMA
      SIGMA = 2.D1
      FUNC1 = FUNC
      GOTO 110
      ENDIF

      DELTA = (SIGMA - SIGMA1)*FUNC/(FUNC - FUNC1)
      SIGMA1 = SIGMA
      SIGMA = SIGMA - DELTA
      FUNC1 = FUNC
      IF (DABS(FUNC) .LT. 1.D-6) GOTO 120
  110 CONTINUE

  120 SIGPV = SIGMA*14.696D0/0.101325D0

  130 TT = TT*1.8D0
      TMAT = TMAT*1.8D0

      RETURN
      END
```

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15. Supplementary Notes

16. Abstract

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.

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