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NASA Contractor Report CR-191134

**Potassium-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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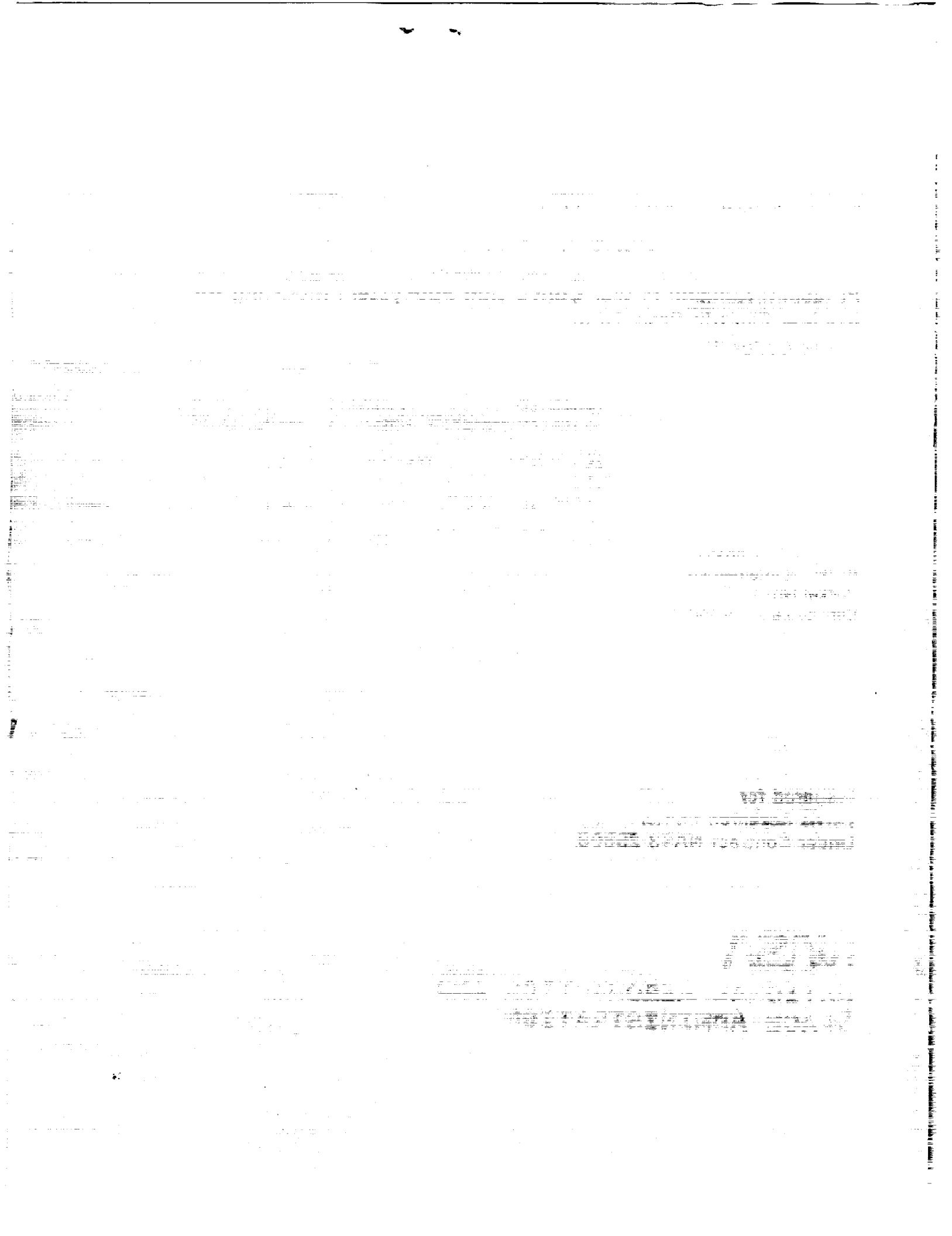
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**NASA**  
**NATIONAL AERONAUTICS AND  
SPACE ADMINISTRATION**



## FOREWORD

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

The following subsystem models have been developed:

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

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

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

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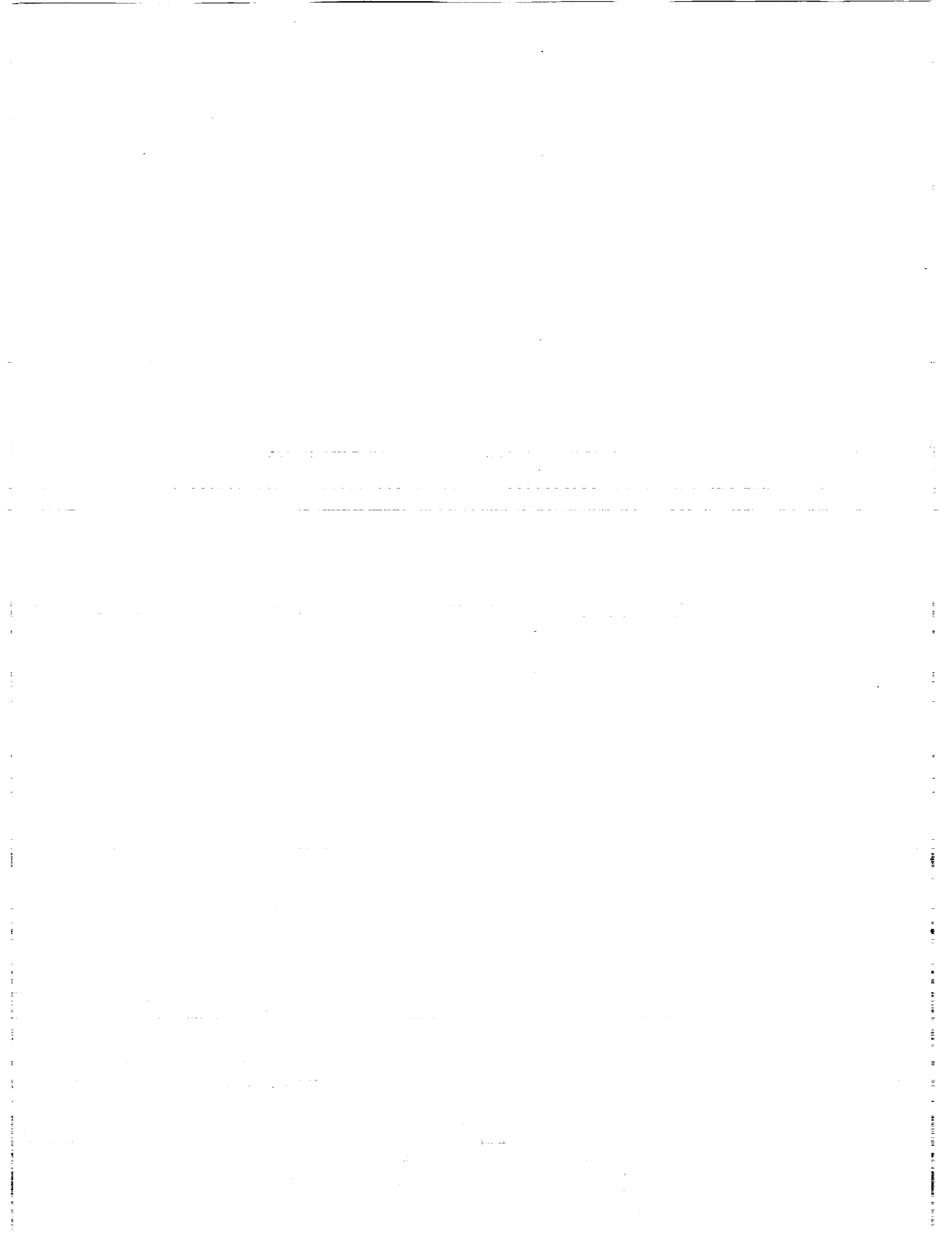
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## 1.0 SUMMARY

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.

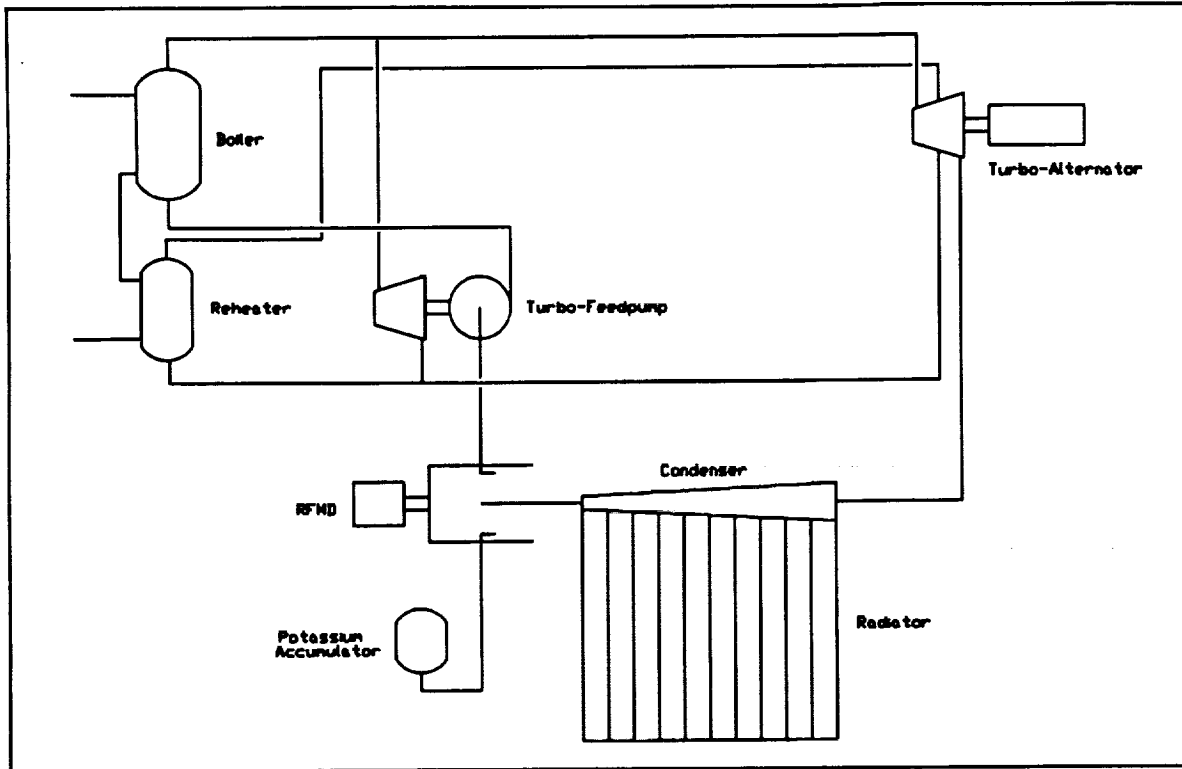


Figure 1. Potassium-Rankine Flow Schematic

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

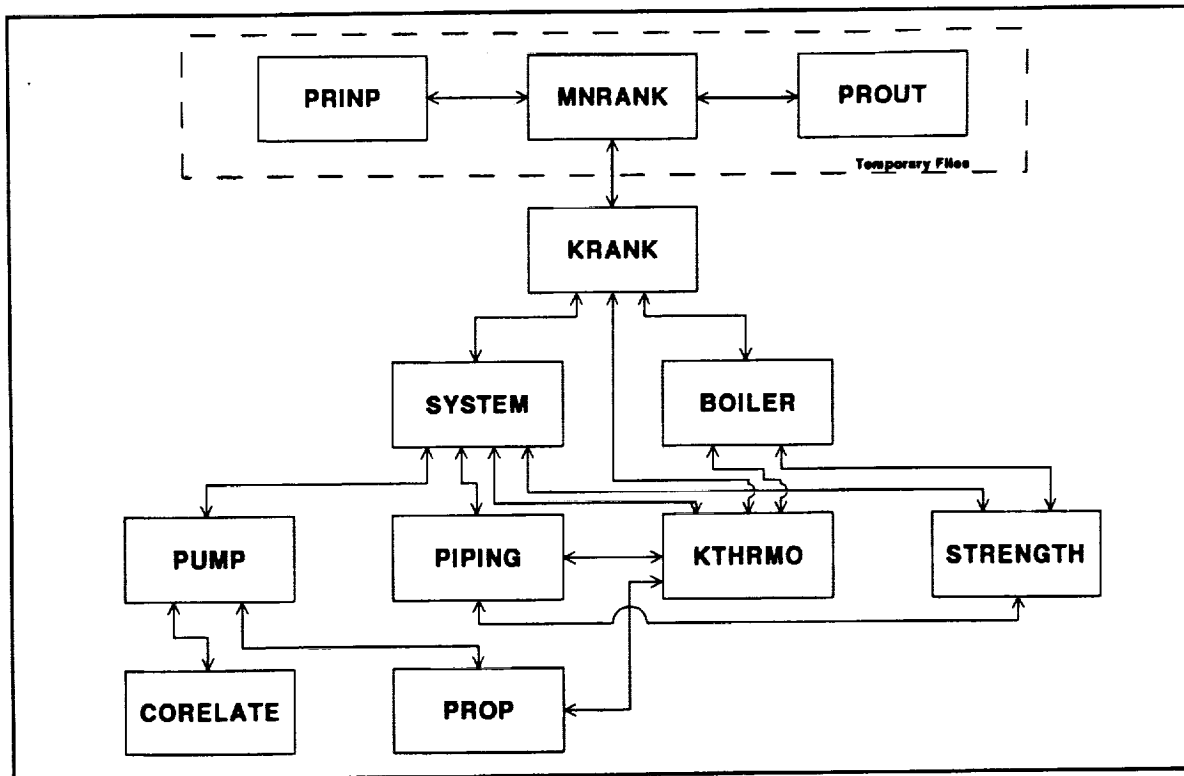


Figure 2. Program Interrelationships

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

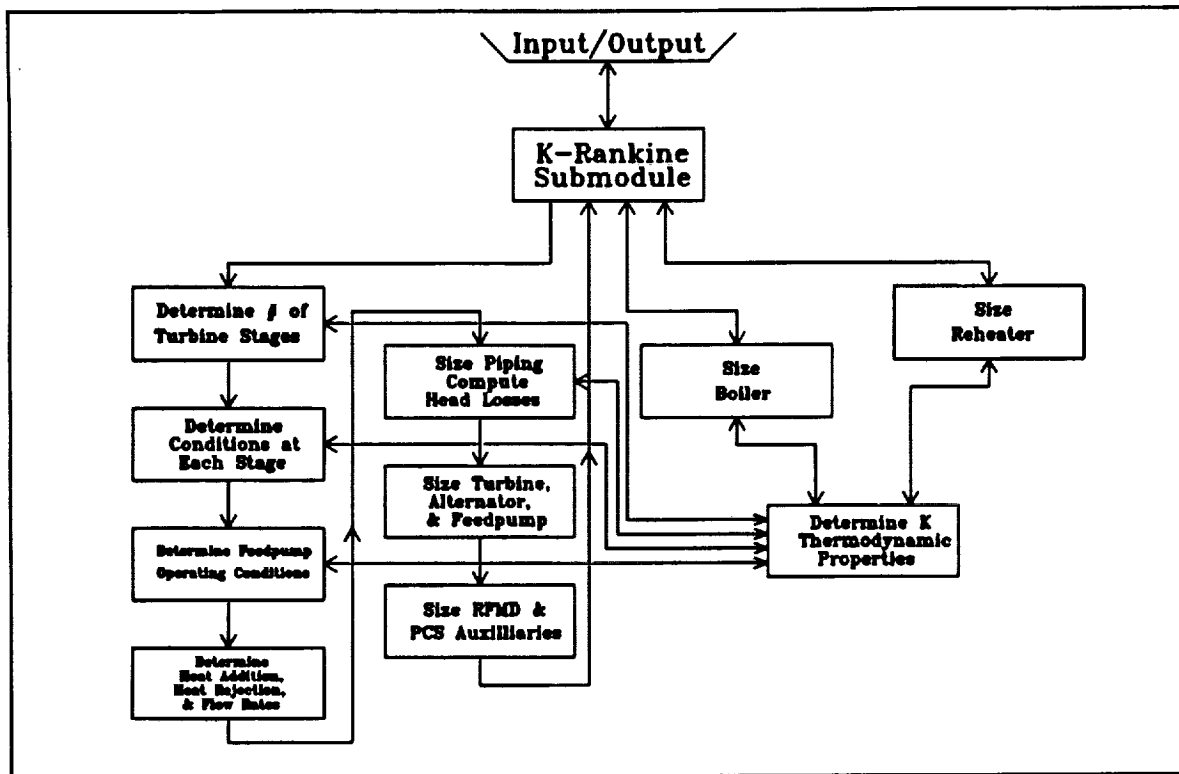


Figure 3. Program Flow Diagram

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 per-

formance and thermodynamic and transport properties for the working fluid. These properties are calculated in subroutines developed from data presented in Reference 2. The energy and mass balances are first calculated on a per mass basis of prime vapor and are subsequently adjusted to the full size system.

### 3.1 BOILER AND REHEATER

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

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

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

Shell side heat transfer is based on Dwyer's equation for liquid metals flowing parallel through equilateral triangular tube bundles (Ref. 3). Preheater heat transfer is based on Dwyer's equation for liquid metals in circular pipes (Ref. 3). Boiling heat transfer is based on single tube boiler, boiling potassium experiments (Ref. 4). While superheater heat transfer is based on Petukhov's equation for circular pipes (Ref. 5).

Pressure losses for the shell side and the tube side of the preheater and the superheater are based on Darcy's friction equation (Ref. 6). Pressure losses in the boiling section of the tubes is based on procedures outlined in Reference 7.

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

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

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

### 3.2 TURBINES :

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

The input values affecting the turbine model along with their recommended values are given in the appendices. From these parameters, number of stages,

efficiency and thermodynamic conditions at each stage, and turbine mass are developed.

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

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

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

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

### 3.3 ALTERNATOR

This section discusses the development of the generator design algorithms, KTAGEN.FOR, in support of the power conversion systems code development. Specifically, numerous point design studies have been completed and algorithms



developed to support generator sizing in the full-up system evaluation code.

### 3.3.1 Study Guidelines

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

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

Table 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)	<----- $4.88 \times 10^4$ ----->						
Density (lb <sub>m</sub> /ft <sup>3</sup> )	<----- $1.97 \times 10^{-6}$ ----->						
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 1-1, 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 <sub>e</sub> )	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 <sub>base</sub> (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 <sub>com</sub> (P.U.)	0.121	0.119	0.129	0.114	0.131	0.130	0.137
EM Mass (lb <sub>m</sub> )	38.48	65.03	146.3	358.2	724	1682	4101
Rotor Mass (lb <sub>m</sub> )	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 <sub>e</sub> )	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 <sub>core</sub> (kL/in <sup>2</sup> )	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 <sub>e</sub> )	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 <sub>base</sub> (1-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 <sub>com</sub> (P.U.)	0.120	0.120	0.130	0.130	0.130	0.120	0.130
EM Mass (lb <sub>m</sub> )	14.08	29.40	62.00	182.7	375.0	993.0	3105.0
Rotor Mass (lb <sub>m</sub> )	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 <sub>e</sub> )	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 <sub>core</sub> (kL/in <sup>2</sup> )	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.

	50	100	200	500	1,000	2,000	5,000
Power (kW <sub>e</sub> )	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 <sub>base</sub> (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 <sub>com</sub> (P.U.)	0.130	0.130	0.130	0.130	0.120	0.130	0.130
EM Mass (lb <sub>m</sub> )	14.56	29.63	60.12	168.0	348.9	729.7	2131.0
Rotor Mass (lb <sub>m</sub> )	3.89	8.40	17.70	51.9	152.0	316.0	960.0
Efficiency (%)	96.55	96.71	96.76	96.88	96.29	96.49	96.69
Losses (kW <sub>e</sub> )	1.77	3.40	6.69	16.1	38.6	72.7	171.4
Tip Speed (ft/s)	500	500	500	500	500	500	500
B <sub>core</sub> (kL/in <sup>2</sup> )	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 <sup>2</sup>	Comm. Available
Flux Ret. Path 750-5000 kWe	Hyperco	140 kL/in <sup>2</sup>	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:

$$D_{rotor} = \left[ \frac{(U_{tip}/700)^{0.466} * (40.65 + 6.6E-4 * V * (U_{tip}/700)^{2.5}) * kVA^{0.075}}{[kVA / (N * \{L/D\}_{rotor})]} \right]^{1/3} \quad [1]$$

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

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

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

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<sub>m</sub>  
\* Copper and insulation  
\* Magnet and Sleeve  
\* Polyamide Structure  
\* Complete Flux Return Path Laminant

$D_{stator}$  = Generator Stator Outside Diameter, inches

$L_{oia}$  = 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 too prohibitive for the intended purposes of the program. Therefore, based on Rocketdyne's experience with turbopumps, it was assumed that the turbine would have 10% partial admission and would be 45% efficient.

Pump modeling begins by calculating the pump speed. The pump speed is determined through iteration between the NPSH margin and inducer flow coefficient. Iteration is continued until a design is found which has a tip speed equal to or less than the maximum set by life or material tip speed considerations. The multi-megawatt design had an inducer tip speed limit of 170 ft/sec and this is currently implemented in this program. Within the inducer tip



speed limit loop, the NPSH margin and flow coefficient are varied to meet the tip speed constraint. An inducer tip diameter limit of 0.5 inches is set as an absolute minimum based on the minimum inlet pipe diameter which would be used in the system.

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

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

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

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

### **3.5 RFMD AND VOLUME ACCUMULATOR**

The RFMD and volume accumulator are located at the condenser outlet. These two components provide two-phase fluid inventory management for the potassium Rankine cycle in a microgravity environment. The RFMD also provides NPSH to the boiler feedpump.

Both the RFMD and volume accumulator performance and mass characteristics models are tied to the Multimegawatt design (Ref. 11). Weights for cases where different materials are used are adjusted with a creep strength to density ratio scaling factor obtained from the materials properties routine. The RFMD model uses the same head and flow coefficients and efficiency as the multimegawatt RFMD design. RFMD mass is estimated by using a simple  $D^2L$  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 fabricability and compatibility with alkali metals may make it the material of choice in situations where creep concerns are not too great. 316SS is included for low temperature operating regimes where a familiar material with vast amounts of experience is desired. In general, for the potassium-Rankine operating temperature ranges, 316SS has poor creep strength characteristics.

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

### 4.0 CONCLUSIONS AND RECOMMENDATIONS

The potassium-Rankine power conversion subsystem model presented in this report will give reasonable predictions of subsystem performance when the input parameters are kept within their recommended ranges. These ranges are 1200 K to 1600 K for turbine inlet temperature, 1.25 to 1.6 for turbine inlet/condensor temperature ratios, 100 kW<sub>e</sub> to 10 MW<sub>e</sub> 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
<b>General Parameters</b>	
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
 <b>Reactor Parameters</b>	
Reactor outlet temperature (K)	1550.0
Reactor inlet temperature (K)	1450.0
 <b>Electrical Parameters</b>	
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
 <b>Alternator Parameters</b>	
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 $\leq 1$	1 - 100
- superheat, K, if $> 1$	
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
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### RFMD Parameters

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

### Boiler Parameters

Maximum 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, 1-1 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)
DOUSER	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 <sup>2</sup> -K)
HKBOIR	Reheater boiling heat transfer coefficient (kW/m <sup>2</sup> -K)
HKPHB	Boiler preheat heat transfer coefficient (kW/m <sup>2</sup> -K)
HKPHR	Reheater preheat heat transfer coefficient (kW/m <sup>2</sup> -K)
HKSHB	Boiler superheat heat transfer coefficient (kW/m <sup>2</sup> -K)
HKSHR	Reheater superheat heat transfer coefficient (kW/m <sup>2</sup> -K)
HLE(11)	Line exit enthalpy (kJ/kg)
HLILIB	Boiler lithium side heat transfer coefficient (kW/m <sup>2</sup> -K)
HLILIR	Reheater lithium side heat transfer coefficient (kW/m <sup>2</sup> -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 length (cm)
LSHR	Reheater superheat length (cm)
LTOTB	Boiler total tube length (cm)
LTOTR	Reheater total tube length (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 <sup>3</sup> /kg)
SVVLE(11)	Line exit specific volume (m <sup>3</sup> /kg)
SVVLI(11)	Line inlet specific volume (m <sup>3</sup> /kg)
SVV(0:15)	Turbine stage exhaust specific volume (m <sup>3</sup> /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)
WSHELRL	Reheater shell weight (kg)
WTAPEB	Boiler twisted tape weight (kg)
WTAPER	Reheater twisted tape weight (kg)
WTCLOB	Boiler closure head weight (kg)
WTCLOL	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)
WTTSL	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)
MF IWTB	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)
WSHEL	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)
WSHELRL	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 $\leq 1$	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
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#### RFMD Parameters

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

#### Boiler Parameters

Maximum 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

##### Length

Line Label	(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 $\alpha$ 1 =	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/m <sup>2</sup> -K	K preheat	=	14.2 kW/m <sup>2</sup> -K
K boiling	=	39.7 kW/m <sup>2</sup> -K	K superheat	=	0.3 kW/m <sup>2</sup> -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/m <sup>2</sup> -K	K preheat	=	14.8 kW/m <sup>2</sup> -K
K boiling	=	39.7 kW/m <sup>2</sup> -K	K superheat	=	0.4 kW/m <sup>2</sup> -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
<hr/>	
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,  
& KUNET,NOTUBB,NOTUBR,LG,MMAIN,MF,ID,MFITOT,  
& MQADD,MQREJ,LPHB,LBOILB,LSHB,LTOTB,MFIWTR,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,KUNET,GEFF,DUM3,BPP,BFP,  
& BPL,PWRFCR,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,WKTOT,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,DOUTE,DTSE,THSB,XTHKB,LPHB,  
& LBOILB,LSHB,LTOTB,TKTUBB,PAB,HLILIB,HKPHB,HKBOIB,  
& HKSHB,WSHELB,WTUBEB,WTAPEB,WTTSE,WTCLOB,MFIWTR,  
& WTPOTB,WTLIB,HTBR,DOUTER,DTSR,THSR,XTHKR,LPHR,  
& LBOILR,LSHR,LTOTR,TKTUBR,PAR,HLILIR,HKPHR,HKBOIR,  
& HKSHR,WSHELIR,WTUBER,WTAPER,WTTSR,WTCLOB,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 /SYSTEM/ 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,XNPSHA,XNPESHOP,HD(NSTG),

```

&          EFP(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



```

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)

```

160 CONTINUE

WRITE(6,170)

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

WRITE(6,180) KWOUT,CYCEFF\*100.,MQADD,PLNTEF\*100.,MQREJ,  
& MMMAIN,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, 'Condenser 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,

& 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 x1' = ',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,torg,  
& 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,' %',/,

```

```

&      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(i1),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',/,

```

```

& 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) WSHELIR,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,  
& KUNET, 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, KUNET, GEFF, DUM3, BPP, BFP,  
& BPL, PWRFCNT, 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, FMDL, 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, WSHEL, WTUBEB, WTAPEB, WTTSB, WTCLOB, MFIWTB,  
& WTPOTB, WTLIB, HTBR, DOUTER, DTSR, THSR, XTHKR, LPHR,  
& LBOILR, LSHR, LTOTR, TKTUBR, PAR, HLILIR, HKPHR, HKBOIR,  
& HKSHR, WSHEL, WTUBER, WTAPER, WTTSR, WTCLO, 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 /SYSTEM/ 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, XNPSA, XNPSHOP, HD(NSTG),  
& EFFP(0:NSTG), HP(NSTG), XIMPNS, 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 PARAMETERS

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 PARAMETERS

DPRFMD = 0.145\*DPRFMD

C CONVERT UNITS

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

C CONVERT UNITS

DPMAXR = 0.145\*DPMAXR



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

```
C convert units
```

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

```
*****
```

```
C CALL PROCESS SUBROUTINES
```

```
DO 20 J = 1,10
```

```
CALL SYSTEM
CALL GENRTR
```

```
TAVLI = (TRIN + TROUT)/2.DO
CALL LIORT (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.DO - 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
ALWT = ALWT/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 PARAMETERES

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  
WSHEL R = WSHEL R/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, KUNET, GEFF, DUM3, BPP, BFP,  
& BPL, PWRFCR, VOLTAGE, GENASP, TINCLNT, TOUTCLNT,  
& CPCLNT, TBOIL, XBOIL, DUM4, TCON, DEFF, EXLOSS, VTIP0,  
& 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, ALWT, 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, WTTSEB, WTCLOB, MFIWTB,  
& WTPOTB, WTLIB, HTBR, DOUTER, DTSR, THSR, XTHKR, LPHR,  
& LBOILR, LSHR, LTOTR, TKTUBR, PAR, HLILIR, HKPHR, HKBOIR,  
& HKSHR, WSHELIR, WTUBER, WTAPER, WTTSR, WTCLOIR, 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 /SYSTEM/ 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, XNPSHA, XNPSHOP, HD(NSTG),

```

&          EFP(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
DRISDI = HHQUAL - HH
IF (PLE(7) .EQ. 0.0) PLE(7) = PP(N)
PRSTAG = PP(N) - DELPL(4) - DELPL(6) - DELPL(7) - DPTOTR
P = PRSTAG/14.696
CALL TFROMP(P,T)
TSATRH = T
TTRH = T + DTRH
KSH = 1
CALL KTHRMO(KSH,TTRH,P,VF,VG,HF,HG,HFG,SF,SG,SFG)
IF (HLI(7) .EQ. 0.0) HLI(7) = HG
IF (HLE(6) .EQ. 0.0) HLE(6) = H(N)
DELRH = HLI(7) - HLE(6)
HRH = HG
SRH = SG
XRH = 1.0
SVRH = VG
GOTO 300
ENDIF

```

```

295 CONTINUE

```

```

300 CONTINUE

```

```

XX = (SRH - SFCON)/SFGCON
HH = HFCON + XX*HFGCON
D = HRH - HH

```

```

DRISD2 = D
L = RSTT**2.DO/(64.348*778.16) - 1.25
XNSRH = 1.1*D/L
NSRH = NINT(XNSRH)
NS = RSTAGE + NSRH

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

DO 320 N = RSTAGE+1,NS
TEMP = TEMP - DELTS
T = TEMP
KSH = 0
CALL KTHRMO(KSH,T,P,VF,VG,HF,HG,HFG,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. 0.0) FMDEL = 5.00
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*550.00/(778.00*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 = VTIP0
      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
MFIOT  = NUMTOT*MFIOT
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,  
& KUNET, NOTUBB, NOTUBR, LG, MMAIN, MF, ID, MFIOT,  
& 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, KUNET, GEFF, DUM3, BPP, BFP,  
& BPL, PWRFCR, VOLTAGE, GENASP, TINCLNT, TOUTCLNT,  
& CPCLNT, TBOIL, XBOIL, DUM4, TCON, DEFF, EXLOSS, VTIP0,  
& 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),  
& MFIOT, PENG, TENG, FMDEL, PDIS, UTLIM, TTP(NSTG), XNPSHA,  
& DT(NSTG), UT(NSTG), PHI(NSTG), NSTAGE, PSI(NSTG), XN,  
& TOTHP, PUMPEFF, SSMARG, XNSSTG(NSTG), WFPUMP, TORQ,  
& KWOUT, ALWT, 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, WTTSEB, WTCLOB, MFIWTB,  
& WTPOTB, WTLIB, HTBR, DOUTER, DTSR, THSR, XTHKR, LPHR,  
& LBOILR, LSHR, LTOTR, TKTUBR, PAR, HLILIR, HKPHR, HKBOIR,  
& HKSHR, WSHEL, WTUBER, WTAPER, WTTSR, WTCLOB, 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 /SYSTEM/ 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

```

\*\*\*\*\*

```

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

```

```

NOTUB0 = 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.DO*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.DO
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.DO*8.51931D-1)
RELI = 1.0847D0*3.D2*ODTUBE*VLI*RHOLI/MULI
FELI = (1.82D0*DLOG10(RELI) - 1.64D0)**(-2.DO)
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.DO
EDDY = 10.DO**EDDY
PSIBAR = 1.DO - 1.82D0/(PRLI*EDDY**1.4D0)
IF (PSIBAR .LT. 0.DO) PSIBAR = 0.DO
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.DO*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
RHOF1 = 1.DO/VF
```

```

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

```

```

PBOIL2 = PBOIL1 - DPBOIL
P = PBOIL2/14.696D0
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.DO/VF
RHOBG2 = 1.DO/VG
CALL KXPORT (TBOIL2,MUF2,KK,CP,RHOFL)
CALL KVPOR (KSH,TBOIL2,P,MUG2,KK,CP,RHOFL)
VF2 = WXOT*1.44D2/(PI*IDTUBE**2.DO*NOTUB1*RHOBF2/4.DO)
REL2 = IDTUBE*VF2*RHOBF2*3.D2/MUF2
VG2 = WXOT*1.44D2/(PI*IDTUBE**2.DO*NOTUB1*RHOBG2/4.DO)
REG2 = IDTUBE*VG2*RHOBG2*3.D2/MUG2

```

```

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

```

### C PREHEAT

```

TAVEPR = (TIN + TBOIL1)/2.DO
CALL KXPORT(TAVEPR,MUPH,KKPH,CPPH,RHOPH)
VPH = WXOT*1.44D2/(PI*IDTUBE**2.DO*NOTUB1*RHOPH/4.DO)
REPH = IDTUBE*VPH*RHOPH*3.D2/MUPH
FEPH = (1.82D0*DLOG10(REPH) - 1.64D0)**(-2.DO)
IF (REPH.LT. 2.D3) FEPH = 6.4D1/REPH
PRPH = CPPH*MUPH/KKPH
EDDY = - 6.115D-1 + 2.7792D-1*DLOG10(RELI) +
&      6.4292D-2*(DLOG10(RELI))**2.DO
EDDY = 10.DO**EDDY
PSIBAR = 1.DO - 1.82D0/(PRPH*EDDY**1.4D0)

```

```

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

```

```

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

```

C Compute overall heat transfer coefficients

```

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

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

UISSH = 1.DO/(1.DO/HKSH + IDTUBE*DLOG(ODTUBE/IDTUBE)/(2.DO*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.DO
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/(UISSH*DTLMSH*PI*IDTUBE*NOTUB1)
ELSE
LSH = 0.DO
ENDIF

```

LTOT = LPH + LBOIL + LSH

c compute pressure drops in boiler tubes  
c first the superheater

\*\*\*\*\*

DPSH = (FESH\*(LSH/IDTUBE) + 1.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 (NOTUB0.EQ.0.DO) THEN
FUNC1 = FUNC2
NOTUB0 = NOTUB1
NOTUB1 = NOTUB1*DSQRT(DPTOT/DPMAX)
NOTUB = NOTUB1*NUMTOT/NUMOP
GOTO 90
ENDIF

```

```

IF (JTUBE .EQ. 1) GOTO 75
IF (DABS(FUNC2).GE.1.D-6) THEN
DELTA = FUNC2*(NOTUB1 - NOTUB0)/(FUNC2 - FUNC1)
IF (DELTA .GT. NOTUB1) DELTA = DELTA/2.DO
NOTUB0 = 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.0.5D0) GO TO 99

```

```

80 HTTUB = LTOT

```

```

90 CONTINUE

```

```

99 JTUBE = 0

```

```

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

```

```

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

```

```

C Routine for determining tube sheet thickness

```

```

A1 = (DTS - ODTUBE)/2.DO
A2 = DSQRT(NOTUB*PA**2.DO*DSIN(PI/3.DO)/PI) +
& (ODTUBE - PA)/2.DO
ASHEET = DMIN1(A1,A2)
BSHEET = DTS/2.DO
KSHEET = BSHEET/ASHEET
PPRIME = ASHEET*DSQRT(PI/(NOTUB*DSIN(PI/3.DO)))
ETASHT = (PPRIME - ODTUBE)/PPRIME
FSTAR = 0.556D0*KSHEET**(0.39D0*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.DO)*ODTUBE**2.DO
VLI = VCYL - V2
```

c compute weight of potassium in the boiler

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

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

c compute heat losses

```
TRADAV = (TLIIN**5.DO - TLIOUT**5.DO)/(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 = WTTB
WTCLOB = WTCLO
MFIWTB = MFIWT
WTPOTB = WTPOTS
```

```
WTLIB = WTLI

ELSE

NOTUBR = NOTUBI
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
WSHELIR = WTSHELL
WTUBER = WTUBE
WTAPER = WTAPE
WTTSR = WTTS
WTCLOR = WTCLO
MFIWTR = MFIWT
WTPOTR = WTPOTS
WTLIR = WTLI

ENDIF

RETURN
END
```



subroutine psize

C  
C  
C  
C  
C  
C  
C  
C  
C  
C

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

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

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

INTEGER REHEAT,RSTAGE

PARAMETER (NSTG=15)

```
COMMON /INPUT/ FPL,VELV,VELM,VELL,TMAT, XMATH, XMATC, DUM1, DUM2, KA,  
& KB, NUMOP, NUMTOT, TROUT, TRIN, KWNET, GEFF, DUM3, BPP, BFP,  
& BPL, PWRFCR, 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, WTTSEB, WTCLOB, MFIWTB,  
& WTPOTB, WTLIB, HTBR, DOUTER, DTSR, THSR, XTHKR, LPHR,  
& LBOILR, LSHR, LTOTR, TKTUBR, PAR, HLILIR, HKPHR, HKBOIR,  
& HKSHR, WSHELIR, WTUBER, WTAPER, WTTSEIR, WTCLOIR, 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 /SYSTEM/ 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
C   g = 32.174
C   tol = 0.0000001
C
C   set default values
C
C   ssmarg = 2.00
C   psi(1) = 0.10
C   phi(1) = 0.14
C   effp(1) = 0.848
C   utlim = 170.D0
C   do 100 i = 2, nstg
C     phi(i) = 0.1
C     psi(i) = 0.35
C     effp(i) = 0.848
100 continue
C   xlamIn = 0.3
C   xlamout = 0.6
C
C   begin pump sizing
C
C   call indsize
C
C   torq = 5252.*tothp/xn
C   call correlate(5,torq,wfpump)
C
C   return
C   end

```

subroutine indsize

C  
C  
C  
C  
C  
C  
C  
C  
C

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

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

```
DOUBLE PRECISION KA,KB,NUMOP,NUMTOT,KWNET,NOTUBB,  
& NOTUBR, 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, GEF, DUM3, BPP, BFP,  
& BPL, PWRFCR, 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, WSHEL, WTUBEB, WTAPB, WTTSB, WTCLOB, MFIWTB,  
& WTPOTB, WTLIB, HTBR, DOUTER, DTSR, THSR, XTHKR, LPHR,  
& LBOILR, LSHR, LTOTR, TKTUBR, PAR, HLILIR, HKPHR, HKBOIR,  
& HKSHR, WSHEL, WTUBER, WTAPER, WTTSR, WTCLO, 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 /SYSTEM/ 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
C   call ept2d(peng,teng,rhoeng,kfluid)
C   call ept2h(peng,teng,heng,steng,kfluid)
C
C   flow rate for pump allows for variation through stages later
C
C   f3s(1) = (fmdel/rhoeng)
C
C   begin iteration on inducer size
C
C   dindg = 0.0
C   cm(1) = 0.0
C   tshg = 1000.0
C   ttp(1) = teng
C   rho(1) = rhoeng
C   ht(1) = heng
C   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
C   xnpsha = ((pt(1)-pvapor)/rho(1))*144.
C
C   size inducer given flow coefficient, inlet conditions, and margin
C
C   31 call correlate(1,phi(1),xnsstr)
C
C   xnssh2o = xnsstr*dsqrt(1.-xlamina**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 correlate(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 ll, 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)*fmde1/550.0
    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
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 correlate(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 correlate(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 correlate(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
C   implicit double precision (a-h,o-z)
C
C
C   call vfromt(t,vf)
C   density = 1.0/vf
C
C   return
C   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
c      subroutine eph2d(p,h,density,temp)
c
c      *****
c      *
c      *   This subroutine determines the density from p and h
c      *
c      *****
c
c      implicit double precision (a-h,o-z)
c
c      patm = p/14.696
c      call tfrmhf(h,temp,patm,vf,sf)
c      density = 1.0/vf
c
c      return
c      end

```

```

C
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
C      implicit double precision (a-h,o-z)
C
C      patm = p/14.696
C      call kthrm1(t,patm,vf,hf,sf)
C      enthalpy = hf
C
C      return
C      end

```

```

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

```

```

C
C
C      subroutine eph2t(p,h,temp,templ)
C
C      *****
C      *
C      *   This subroutine determines the temperature from p and h   *
C      *
C      *****
C
C      implicit double precision (a-h,o-z)
C
C      patm = p/14.696
C      call tfrmhf(h,templ,patm,dum,dum1)
C      temp = templ
C
C      return
C      end

```



```

C
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
C      implicit double precision (a-h,o-z)
C
C      ksh = 0
C      call kthrho(ksh,t,pvap,dum1,dum2,dum3,dum4,dum5,dum6,dum7,
&      dum8)
C      pvap = pvap*14.696
C
C      return
C      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,WKTOT,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,WTTSEB,WTCLOB,MFIWTB,
& WTPOTB,WTLIB,HTBR,DOUTER,DTSR,THSR,XTHKR,LPHR,
& LBOILR,LSHR,LTOTR,TKTUBR,PAR,HLILIR,HKPHR,HKBOIR,
& HKSHR,WSHELIR,WTUBER,WTAPER,WTTSEB,WTCLOB,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 /SYSTEM/ 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),WTFI(5),ID(5),MFI)

VISCOS = 1.98227D-2 + 1.36364D-5\*TLI(5)  
DENSIT = 1.0/SVLI(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),WTFI(6),ID(6),MFI)

```

VISCOS = 1.98227D-2 + 1.36364D-5*TLI(6)
DENSIT = 1.0/SVCLI(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 = 0.00
WTKTOT = 0.00
MFITOT = 0.00

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 + 2.0D0*MFI*(SEP + THK))**2.0D0 - ID**2.0D0)/4.0D0  
WTMFI = WTMFI*RHOMFI/(SEP/THK + 1.0D0)  
IF (ID .EQ. 0.0) THEN  
WT = 0.0D0  
WTKINV = 0.0D0  
WTMFI = 0.0D0  
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.DO))/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 LIPTORT(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.DO + C*SIGMA**3.DO + D)/TT
    FUNC = THET - THETA
    FPRIME = -(A + 2.DO*B*SIGMA + 3.DO*C*SIGMA**2.DO)/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.DO
    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

```



# Report Documentation Page

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