ETFOD, A Point Model Physics Code with Arbitrary Input

K. E. Rothe    S. E. Attenberger
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ACKNOWLEDGMENTS

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ETFOD, A POINT MODEL PHYSICS CODE WITH ARBITRARY INPUT

K. E. Rothe
S. E. Attenberger

ABSTRACT

ETFOD is a zero-dimensional code which solves a set of physics equations by minimization. The technique used is different than normally used, in that the input is arbitrary. The user is supplied with a set of variables from which he specifies which variables are input (unchanging). The remaining variables become the output. Presently the code is being used for ETF reactor design studies. The code was written in a manner to allow easy modification of equations, variables, and physics calculations. The solution technique is presented along with hints for using the code.
1. INTRODUCTION

For many years the fusion physics community has used point model codes to do Tokamak reactor designs. One or more physical equations are written either in terms of variables defined at a point in the center of the plasma, or else in terms of variables averaged over the plasma volume. Depending on the needs of the users, certain of the variables are selected as input and the rest are output variables which define a self-consistent solution.

Now that reactor design studies are beginning in earnest, the point model codes are being pushed to the limit of their accuracy. The most sophisticated techniques and the most advanced physics models available are being incorporated, whenever fast methods are available. As a result, it becomes a nontrivial task to use a program to solve any problem other than the one for which it was originally written. When the input variables are changed, either the code must be extensively rewritten, or else the code must be used to generate reams of graphic output from which the desired data points may be read by hand.

ETFOD has overcome these problems to a very great extent. The user is furnished with a generous list of variables, any subset of which may be identified as input variables. The physics equations may be changed at the whim of the user without fear of destroying the program logic. The secret is to treat the problem as a minimization problem, so that a self-consistent solution is found iteratively. The solution technique will be described in detail in this report.
2. PROGRAM OVERVIEW

Given a set of equations of the form \( y_1 = F_1 (y_1, y_2, \ldots, y_n) \) where the \( y_i \) are arbitrary variables and the \( F_i \) are arbitrary functions, one can always write \( R_i = \frac{y_i - F_i}{y_{0i}} \) where the \( y_{0i} \) are the initial values of the variables and the \( R_i \) are residuals. The set of equations is then solved by minimizing the residuals. In this fashion ETFOD is designed to solve a set of \( 0-D \) equations written in residual form. The minimization package used is E04FAF from the NAG\(^1\) library. E04FAF minimizes the sum of the squares of the residuals.

The residual equations need initial guesses which are supplied by the user. From the list of eligible variables (see section 3.8) some of the variables may be designated "fixed" while others are free or "active". In general there will be more active variables than there are functions \( F_i \). In order to fully determine the solution, an additional set of equations is constructed, also cast in residual form, i.e. \( R_i = \frac{y_{0i} - y_i}{y_{0i}} \) where \( y_{0i} \) is the initial guess for the variable and \( y_i \) is the current value. Thus the solution obtained will be that solution of the original equations which is closest to the initial guess.

Since the solution of the physics equations is of primary importance, weights are assigned to the residuals with a relatively large weight given to the physics equations and small weights given to the other equations.

In order to increase the speed and flexibility of the code, the variables are normalized. This allows uniform restrictions on the variables regardless of their magnitudes. Each variable is normalized
by its initial guess. Thus the initial guess given to E04FAF is a vector of 1's. When the residuals are to be calculated using the new solution generated by E04FAF, each element of the solution vector is multiplied by its respective normalization factor, since the physics equations use the actual value of a variable instead of its normalized value.

A flowchart of the program is listed in Appendix A. The names of the subroutines wherein the calculations occur are listed to the right of the description. A program listing can be found in Appendix D. Two sample cases are included (Appendix E) to show the effect of changing the weight of an initial guess.

ETFOD runs on the FED PDP-10 and contains calls to machine-dependent I/O buffering routines.
3. DESCRIPTION

3.1 MAIN

The main program initializes the I/O units, opens the data input files and output files, and reads all the input data. The input files are ETFOD.DAT and INPUT.DAT. These files are described in detail in sections 3.8 and 3.9. The output files are ETFOD.OUT and SPECS.ETF. The number of input variables from ETFOD.DAT is counted to facilitate changing the variable list. If there are fewer active variables from ETFOD.DAT than physics equations, the problem is overconstrained. A warning is written to unit 5 and ETFOD.OUT. Each active variable in ETFOD.DAT has an associated index number (referring to its relative position in the variable list), weight factor (see section 3.8), and initial value stored in arrays which are passed in common INDEXP to subroutines FIZICS, RESID, and SEARCH. All the information from file ETFOD.DAT is written to file ETFOD.OUT. The normalized solution vector is initialized to 1.0. At the end of the run certain plasma parameters are written to ETFOD.OUT. This routine calls SEARCH.

The following variables are used in MAIN:

EIQNWT weight given to physics residuals.

IND array containing the indices of the variables read from ETFOD.DAT.

INDP array containing the indices of the active variables.

IOUT causes the calculation and output of design specifications when set to 1. (Initially 0.)

IX array containing the weighting flag letters 'F' (fixed), 'P' (preferred), and 'U' (unknown); used in assigning numerical weights to initial guesses.

MEQ number of physics equations, read from ETFOD.DAT.
number of active variables, counted as they are read from ETFOD.DAT. If MEQ > N, the problem is overconstrained.

NAMVAR array holding five-letter names of variables, read from ETFOD.DAT.

NIN unit used when reading ETFOD.DAT, defined 6.

NIN2 unit used when reading INPUT.DAT, defined 28.

NOUT unit used when outputting messages to user, defined 5 (defaults to terminal).

NOUT2 unit used when outputting to ETFOD.OUT, defined 20.

NOUT3 unit used when outputting to SPECS.ETF, defined 27.

NVAR total number of variables from ETFOD.DAT.

UNITS array holding 20 letter unit descriptions of variables in ETFOD.DAT.

WW array holding the weight factors for the active variables.

WWX array holding the weight factors corresponding to 'F' (fixed), 'P' (preferred), 'U' (unknown); read from INPUT.DAT.
3.2 SEARCH

Subroutine SEARCH defines the parameters and limits used in E04FAF. All array sizes which are calculated are tested to ensure sufficient space has been allocated. If not, warnings are printed on unit 5 (terminal by default). The initial guess of the solution is checked, and warnings are written to unit 5 if the residuals are greater than 0.5. The final solution is also tested for accuracy. A warning is written to unit 5 and also to ETFOD.OUT and SPECS.ETF if the physics equations are not accurate within a specified limit. This subroutine is called by the main program and calls RESID, E04FAF, and PRTOUT.

The following variables are used in SEARCH:

APER percent accuracy desired of physics equations. APER = 100 * FRAACC.

F the sum of the squares of the residuals; returned by E04FAF.

FRAACC the fractional accuracy desired for the physics equations.

FTOL the tolerance criterion used by E04FAF on F. Currently FTOL is initialized to 1.0E-6. On return FTOL = 0.0 if the value of F < FTOL. FTOL = 1.0 if a relative test on the range of F is satisfied. FTOL = -1.0 if the XTOL tolerance test is satisfied (see XTOL, below). FTOL and XTOL were chosen such that FTOL = -1.0 would usually be the tolerance criterion satisfied. This insures that the solution is near a minimum.

IFAIL on return from E04FAF designates the reason for exit from E04FAF. IFAIL = 1 signals incorrect input parameters. IFAIL = 2 indicates that the maximum number of iterations has been reached but no tolerance conditions are satisfied.

IPRINT specifies the frequency of calls to MONIT, a printout routine. IPRINT = 1 causes MONIT to be called every iteration. IPRINT = 2 causes MONIT to be called only when F is reduced. If IPRINT < 0 MONIT is not called.

IRC, IW, IX, IST dimensions of RC, W, X, STEPMX, respectively (see below).

LTEST minimum allowable size of array W required by E04FAF. LTEST = 2*M+4*N+M*N+N*(N+1)/2+(N+34N/3)*(M+2+2*N).

M total number of residuals. M = MEQ + N.
MAXCAL | maximum number of iterations attempted before E04FAF is forced to exit.
RC | array containing the residuals.
STEPMX | array containing restraint values. In a given iteration no active variable can change an amount greater than its associated restraint value in STEPMX. This prevents sudden, large fluctuations of variables which could lead to solutions far from the initial estimates. Every element initialized to 0.5.
W | workspace needed by E04FAF.
X | array containing the current normalized solution. Every element is initialized to 1.0.
XTOL | relative accuracy to which the position of the minimum is required. For two successive iterations whose solution vectors are \( \text{Y} \) and \( \text{Z} \), the XTOL criterion is satisfied when \( |\text{Y}_i - \text{Z}_i| < \text{XTOL} \times \text{STEPMX}_i \), \( i = 1, 2, \ldots, N \) (see FTOL above).
3.3 RESID

Subroutine RESID takes the normalized solution generated by E04FAF and multiplies by the normalizing factors (the initial guesses). This yields the actual values of the eligible variables which are needed when calculating the physics residuals. The variables must appear in the data file ETFOD.DAT in the same order as they appear in commons VARBLS (containing the current values of the variables), INITL (containing the normalizing factors), and INDEX (containing the index numbers which locate values in the other commons). RESID is called by SEARCH and the E04FAF package, and calls FIZICS.

The following variables are used in RESID:

M the total number of residuals.
N the number of active variables.
XC array containing E04FAF's current solution (normalized).
XX array containing current solution of all eligible variables, both active and fixed (normalized; hence those not changing are 1.0).
3.4 FIZICS

SUBROUTINE FIZICS contains the physics equations of the 0-D model. The input is primarily from common block VARBLS, which contains the natural values (not normalized) of the eligible variables. All values are in MKS units unless otherwise noted. FIZICS is called by RESID, and calls the physics packages ALFETA, COULM, INJETA, OHMIC, RADIAT, RATE, RFETA, and TAUS.

FIZICS computes all the residuals, both for the physics equations and the initial value equations. (See the description in section 2.) The physics equations are subject to constant revision and improvement, but the following set of equations is representative. (Refer to the table of variables for identification of symbols.)

\[ R_1 = \frac{1}{N_{10}} \left[ N_1 - N_e (1 - Z\xi) \right] \]  
\[ R_2 = \frac{1}{N_{10}} \left[ N_1 - N_e (Z_{eff} - Z^2\xi) \right] \]

where \( \xi = N_Z / N_e \)

\[ R_3 = \frac{1}{\rho_o} \left[ \beta - \frac{(N_1T_i + N_eT_e + N_ZT_i) \times 1.602 \times 10^{-16}}{2\nu_0B_E^2} \right] \]

\[ R_4 = \frac{1}{P_{ao}} \left[ \frac{3}{2} \frac{(N_1T_i + N_eT_e + N_ZT_i)}{\tau_E} \times 1.602 \times 10^{-16} \right] \]
where \( Q_\alpha = 5.607 \times 10^{-13} \) joule (3.52 MeV)

\[
R_5 = \frac{1}{p_{\alpha o}} \left[ p_\alpha - \frac{n_1^2 \langle \sigma v \rangle Q_\alpha}{4} \right] \tag{5}
\]

\[
R_6 = \frac{1}{p_{\alpha o}} \left[ p_\alpha n_\alpha + p_{\text{inj}} n_{\text{inj}} + p_{\text{rf}} n_{\text{rf}} + p_{\text{coul}} \right]
\]

\[
- \frac{3}{2} \frac{T_1 (1.602 \times 10^{-16})}{C_1} \left( \frac{1}{C_{\text{TP}\text{TP}}} + \frac{1}{C_{\text{NC}\text{NC}}} + \frac{1}{C_{\text{RT}\text{RT}}} \right) \tag{6}
\]

\[
R_7 = \frac{1}{p_{\alpha o}} \left[ p_\alpha (1 - n_\alpha) + p_{\text{inj}} (1 - n_{\text{inj}}) + p (1 - n_{\text{rf}}) - p_{\text{coul}} \right]
\]

\[
- \frac{3}{2} \frac{T_e (1.602 \times 10^{-16})}{C_e} \frac{1}{C_{\text{EMP}\text{EMP}}} \tag{7}
\]

\[
R_8 = \frac{1}{p_{f o}} \left[ p_f - 5 p_{\alpha} V \right] \tag{8}
\]

\[
R_9 = \frac{1}{v_{\alpha o}} \left[ v_\alpha - \frac{4}{5} \frac{P_f}{5} \right] \tag{9}
\]

\[
R_{10} = \frac{1}{I_{po}} \left[ I_p - \frac{5.6 \times 10^6 \times B_e (1 + \sigma^2) 1.11}{28 A (1 - \frac{1}{A^2})} \right] \tag{10}
\]
The following variables are used in FIZICS:

A  (Symbol a) Minor radius of the plasma (m).
ALEXT External inductance (H).
ALPI Internal inductance (H).
AR  (Symbol A) Aspect ratio.
AREA  (Symbol S) Surface area of first wall (m²).
BP Poloidal magnetic field (T).
BT Toroidal magnetic field (T).
CC  (Symbol R) The array of residual values. The first MEQ values are the physics residuals. The last N-MEQ values are the initial value residuals.
CE  (Symbol C_e) Multiplier for electron conduction and convection confinement time.
CEMP  (Symbol C_{EMP}) Multiplier for empirical confinement time.
CI  (Symbol C_i) Multiplier for ion conduction and convection confinement time.
CNC  (Symbol C_{NC}) Multiplier for neoclassical confinement time.
CRT  (Symbol C_{RT}) Multiplier for Ripple Trapping confinement time.
CTP  (Symbol C_{TP}) Multiplier for Trapped Particle confinement time.
EB Neutral beam energy (primary component, in keV).
EQNWT A weighting factor used to give the physics residuals more weight than the initial value residuals.
ETAALF  (Symbol \eta_a) The fraction of alpha power absorbed by the ions.
ETAINJ  (Symbol \eta_{inj}) The fraction of injected power absorbed by the ions.
ETARF  (Symbol \eta_{rf}) The fraction of rf power absorbed by the ions.
IP  (Symbol I_p) Plasma current (A).
NE  (Symbol N_e) Electron density (m⁻³).
NI  (Symbol N_i) Ion density (m⁻³).
NZ  (Symbol N_z) Impurity density (m⁻³).
PALFV  \((\text{Symbol } p_\alpha)\) Alpha power per unit volume \((W/m^3)\).

PCOULV  \((\text{Symbol } p_{\text{coul}})\) Power per unit volume transferred from electrons to ions \((W/m^3)\).

PFUS  \((\text{Symbol } P_f)\) Total alpha + neutron power at 17.6 Mev per reaction.

PINJ  \((\text{Symbol } P_{\text{inj}} = P_{\text{inj}}V)\) Total injected power \((W)\).

POHMV  \((\text{Symbol } P_R)\) Ohmic heating power per unit volume \((W)\).

PRADV  \((\text{Symbol } P_{\text{rad}})\) Power per unit volume lost due to radiation \((W/m^3)\).

PRF  \((\text{Symbol } P_{\text{rf}} = P_{\text{rf}}V)\) Total rf power \((W)\).

Q  \((\text{Symbol } q)\) Safety factor.

REFL Reflection coefficient for synchrotron radiation. (If REFL = 1, no power is lost to the wall.)

RIPPLE Prak-to-average magnetic ripple depth (dimensionless).

RP Plasma resistance (Ohms).

SIGMA  \((\text{Symbol } \sigma)\) Plasma elongation.

SIGMAV  \((\text{Symbol } <v>)\) D-T reaction rate \((m^3/s)\).

TAUE  \((\text{Symbol } \tau_E)\) Global energy confinement time \((s)\).

TAUEMP  \((\text{Symbol } \tau_{\text{emp}})\) Empirical electron conduction time \((s)\).

TAUNC  \((\text{Symbol } \tau_{\text{nc}})\) Neoclassical ion conduction time \((s)\).

TAURT  \((\text{Symbol } \tau_{\text{rt}})\) Ripple trapping ion conduction time \((s)\).

TAUTP  \((\text{Symbol } \tau_{\text{tp}})\) Trapped particle ion conduction and convection time \((s)\).

TE  \((\text{Symbol } T_e)\) Electron temperature, in keV.

TI  \((\text{Symbol } T_i)\) Ion temperature, in keV.

VOL  \((\text{Symbol } V)\) Plasma volume.

WPA  \((\text{Symbol } W_\alpha)\) Neutron wall loading \((W/m^2)\).

ZEFF  \((\text{Symbol } Z_{\text{eff}})\) Effective charge on plasma.

ZETA  \((\text{Symbol } \xi)\) Impurity fraction.

ZMUO  \((\text{Symbol } \mu_0)\) Permeability constant \((H/m)\).
3.5 Physics Packages

The physics portion of the ETFOD code is highly modularized to permit upgrading of the physics models as new models become available. Where possible, the physics packages are borrowed from or benchmarked against those of the WHIST 1-D transport code.²

The following subroutines are among the current physics packages:

**ALFETA** Computes the fraction of the alpha power which is absorbed by the ions.

**COULMN** Computes the electron-ion power transfer due to Coulomb collision.

**INJETA** Computes the fraction of neutral beam energy absorbed by the ions.

**OHMIC** Computes the Ohmic heating rate.

**RADIAT** Computes the power loss due to radiation.

**RATE** Computes the D-T fusion reaction rate.

**RFETA** Computes the fraction of rf power absorbed by the ions.

**TAUS** Computes confinement times predicted by theoretical and empirical models.

The above routines are very primitive at the present time. They will be described in detail in a later memo, after the code has been upgraded to include shape factors and more sophisticated physics models.
3.6 MONIT

Subroutine MONIT allows the user to follow the iterative process of E04FAF and prints warnings in file ETFD.OUT when certain kinds of problems occur during an iteration. It is called from E04FAF and calls PRTOUT.

The following variables are used in MONIT:

- **F** : sum of the squares of the residuals.
- **LIM** : if true, the value of a normalized variable was constrained by STEPMX for this iteration. (See SEARCH for definition of STEPMX.)
- **M** : the total number of residuals.
- **N** : the number of active variables.
- **SING** : if true, the solution has become degenerate. A random number has been generated and incorporated in the solution.
- **X** : current normalized solution array.
3.7 PRTOUT

Subroutine PRTOUT writes out the variable names and their current values. The values of the fixed variables are followed by an 'F'. PRTOUT is called from SEARCH and MONIT.
3.8 ETFOD.DAT

ETFOD.DAT contains the number of physics equations coded in FIZICS and the eligible variables from which one can choose input (fixed) variables and output (active) variables. As seen in the listing in Appendix B, each variable has a five-letter name under the heading VARIABLE, the units of the variable under the heading UNITS, an initial value under the heading VALUE, and either an F, P, or U under the heading WEIGHT. These weights indicate whether the variable is fixed (F) or active (P, U), and for active variables the weights indicate how sure one is of the value. Thus, the value of a variable marked preferred (P) will remain fairly close to the initial value, while a variable marked unknown (U) can more easily be changed significantly. However, even preferred values can change significantly if necessary to find a solution to the physics equations.

At present the following variables are in ETFOD.DAT:

- **TI** ion temperature (keV)
- **TE** electron temperature (keV)
- **ZEFF** effective charge of plasma
- **NI** density of ions ($m^{-3}$)
- **NE** density of electrons ($m^{-3}$)
- **NZ** density of impurities ($m^{-3}$)
- **Q** safety factor
- **BETA** plasma pressure relative to the magnetic pressure
- **BT** toroidal magnetic field (T)
- **TAUE** total energy confinement time (s)
- **PALFV** alpha power per unit volume ($W/m^3$)
- **PFUS** total alpha + neutron power (W)
- **WPA** wall loading due to neutrons ($W/m^2$)
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>minor radius of the plasma (m)</td>
</tr>
<tr>
<td>AR</td>
<td>aspect ratio</td>
</tr>
<tr>
<td>SIGMA</td>
<td>plasma elongation</td>
</tr>
<tr>
<td>PINJ</td>
<td>injected power (W)</td>
</tr>
<tr>
<td>PRF</td>
<td>rf power (W)</td>
</tr>
<tr>
<td>CI</td>
<td>multiplier for ion conduction and convection time</td>
</tr>
<tr>
<td>CE</td>
<td>multiplier for electron conduction and convection time</td>
</tr>
<tr>
<td>IP</td>
<td>plasma current (A)</td>
</tr>
</tbody>
</table>
3.9 INPUT.DAT

The data in INPUT.DAT is read in from MAIN and stored in common
INP. See Appendix C for a listing of the file. The values remain
unchanged.

The following variables are in INPUT.DAT:

\begin{itemize}
  \item \texttt{WWX(1)} the weight given to fixed variables in ETFOD.DAT
  \item \texttt{WWX(2)} the weight given to preferred variables in ETFOD.DAT
  \item \texttt{WWX(3)} the weight given to unknown variables in ETFOD.DAT
  \item \texttt{EQNWT} the weight given to the physics residuals in FIZICS
  \item \texttt{Z} charge of impurity ion
  \item \texttt{CTP} multiplier for trapped particle confinement time
  \item \texttt{CNC} multiplier for neoclassical confinement time
  \item \texttt{CRT} multiplier for ripple trapping confinement time
  \item \texttt{CEMP} multiplier for empirical confinement time
  \item \texttt{AMU} mass of plasma ions (AMU)
  \item \texttt{AMZ} mass of impurity ions (AMU)
  \item \texttt{EB} neutral beam energy (primary component, in keV)
  \item \texttt{LI} internal inductance parameter (dimensionless)
  \item \texttt{REFL} reflection coefficient for synchrotron radiation
  \item \texttt{RIPPLE} peak-to-average magnetic ripple depth (dimensionless)
  \item \texttt{FACTOR} low beta multiplier for plasma current
  \item \texttt{GAMMA} resistive loss factor
  \item \texttt{SCAPL} scrape off layer width (m)
  \item \texttt{PBURN} burn pressure (TORR)
  \item \texttt{PQNC} quench pressure (TORR)
\end{itemize}
4. ADDITIONAL HINTS FOR USING ETFOD

Occasionally the code will find a solution to the least squares problem which is not a solution to the physics equations. (If so, there is an error message in the output file.) When this occurs, we have found it to be due to one of two things: either the equations are overconstrained or else they are badly underconstrained.

4.1 Overconstrained Equations

If there are fewer free variables than physics equations, the program prints an error message but solves the problem anyway. If the initial guess is very good, the solution to the physics equations may still be found. It is also possible that a certain subset of the physics equations is overconstrained. The program cannot tell you whether this has happened, but you should suspect that it has if all the output values seem very reasonable, but nevertheless the physics equations do not quite balance. The remedy is to float another variable or two. If this fails to work, then one or more of your initial guesses is much too low.

4.2 Badly Underconstrained Equations

This problem tends to occur when developing a brand new data set. The initial guesses are frequently poor, and there are usually a large number of free variables (free + "preferred" or "unknown"). The solution will contain values that are way out of line with the values expected. Also the execution time may be very long, especially if the initial guesses are too low (it is better to guess large values if unsure). The remedy is to tighten constraints on wayward variables.
REFERENCES


Appendix A Flowchart
Appendix B ETF0D.DAT

TEST INPUT DATA. TNS REF. DESIGN ORNL/TM-6721

10 = NUMBER OF CONSTRAINT EQUATIONS

F=FIXED

P=PREFERRED VALUE

U=UNKNOWN

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<td>P</td>
<td>NI</td>
<td>(M**3)</td>
</tr>
<tr>
<td>5</td>
<td>1.70E20</td>
<td>P</td>
<td>NE</td>
<td>(M**3)</td>
</tr>
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<td>P</td>
<td>NZ</td>
<td>(M**3)</td>
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<td>7</td>
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<td>F</td>
<td>Q</td>
<td>(SAFETY FACTOR)</td>
</tr>
<tr>
<td>8</td>
<td>7.0E-2</td>
<td>F</td>
<td>BETA</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>5.01E0</td>
<td>F</td>
<td>BT</td>
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<tr>
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<td>U</td>
<td>TAUE</td>
<td>(SEC)</td>
</tr>
<tr>
<td>11</td>
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<td>U</td>
<td>PALFV</td>
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</tr>
<tr>
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<td>U</td>
<td>PFUS</td>
<td>(W)</td>
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<tr>
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<td>P</td>
<td>WPA</td>
<td>(W/M**2)</td>
</tr>
<tr>
<td>14</td>
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<td>F</td>
<td>A</td>
<td>(M)</td>
</tr>
<tr>
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<td>F</td>
<td>AR</td>
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<tr>
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<td>F</td>
<td>SIGMA</td>
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</tr>
<tr>
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<td>F</td>
<td>PINJ</td>
<td>(W)</td>
</tr>
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<td>P</td>
<td>PRF</td>
<td>(W)</td>
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<td>P</td>
<td>CI</td>
<td></td>
</tr>
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<td>1.00</td>
<td>P</td>
<td>CE</td>
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</tr>
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<td>U</td>
<td>IP</td>
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END
Appendix C  INPUT.DAT

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<th>WWX(1)</th>
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<th>EQNWT</th>
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SUBROUTINE FIZICS(CC,M)
DIMENSION CC(M),AK(100),BK(100)
COMMON/XS,XX(100)
COMMON/INDEXP,EQNWT,WW(100),INDP(100),MEQ,MAXDIM
COMMON/INITL,TIO,TEO,ZEFFO,NIO,NEO,NO,QQ,BETA0,
# BTO,TAUE0,PAVF0,PFUS0,WPA0,QO,AR0,SIGMA0,P,NJO,PRF0,CIO,
# CE0,IP0,
# DUMINI79)
COMMON/INP/Z,CTP,CNC,CRT,CEMP,AM1;AMZ,EB,REFL,RIPPLE,
1 FACTOR,GAMMA,SCRA.1,F,FBURN,POUNG,LI
COMMON/SPECS/ETAALF,PCOULV,ETAINJ,POHMV,PRADV,SIGMAV,ETARF,
1 TAOF,TAUEM,TAUR,TAUNC
COMMON/VARBLS/TI,TE,ZEFF,NI,NE,NO,C,BETA,BT,TAUE
# ,PALFV,PFUS,WPA,AR,SIGMA,PINJ,PRF,CI,CE,IP
# ,DUMVAR79)
COMMON/OU1FL/I0UT
COMMON/IO/NIN,NIN2,NOUT,NOUT2,NOUT3
REAL NIC,NEO,NO,IP0,LI,NI,NE,NO,IP,IBTA,LP,LW,MTAU,LP
EQUIVALENCE(AK(1),TI),(BK(1),TI0)
DATA ZMUO/1.2566E-G/
DATA QALPHA/5.607E-13/
C****DEFINE INTERNAL VARIABLES*******************************
EI=1.5*(1.602E-16)*TI
EE=1.5*(1.602E-16)*TE
ZETA=NO/NE
VOL=2.*3.1t159**2*A**3*AR*SIGMA
AREA=U.*3.11H59**2*A**2*AR*SQRT((1.+SIGMA**2)*.5)
C****PHYSICS PACKAGES**************************************
CALL ALFETA(TE,ETAALF)
CALL COULM(NE,NI,AMU,TE,TI,PCOULV)
CALL INJETA(NI,NO,Z,AMU,AMZ,TE,EB,ETAINJ)
CALL OHMIC(NE,TE,ZEFF,A,IP,POHMV)
CALL RADIAT(NE,ZEFF,TE,REFL,BT,BETA,A,NO,PRADV)
CALL RATE(I',SIGMAV)
CALL RFETA(ETARF)
CALL TAPUS(NE,A,BT,BETA,ZEFF,AR,TE,SIGMA,
# AMU,RIPPLE,Q,TE,NI,TAUTP,TAUEMP,TAUR,TAUNC)
TAUTP=CIF*TAUTP
TAUC=CINF*TAUNC
TAUR=CRT*TAUR
C****CONSTRAINT EQUATIONS***********************************
CC(1)=(NI-NE*(1.-Z*ZETA))/NIO
CC(2)=(NI-NE*(Z-2*ZETA))/NIO
CC(3)=(BETA-(NI*TI+NE*TE+NO*TI)+1.602E-16
# /(BT**2/(2.*ZMUO)))/BETA0
CC(1)=(NI*EI+NE*EE+NO*EI)/TAUE)/PAVF0
CC(5)=(PAVF-NI*SIGMAV*ZGALPHA/4.0)/PAVF0
CC(6)=(PAVF*ETAALF+ETAINJ*PINJ/VOL+ETARF*PRF/VOL+POULV
# +NI*EI)/CI * (1./TAUTP+1./TAUNC
# +1./TAUTC))/PAVF0
CC(7)=(PAVF*(1.-ETAALF)+(1.-ETAINJ)*PINJ/VOL+(1.-ETARF)*PRF/VOL
# -POULV+POHMV+PRADV-(NE*EE)/CE * (1./(CEMP*TAUEMP)))
# 

/PAHFVO

CC(8)=(PFUS-5.0286*PALFV*VOL)/PFUSO
CC(9)=(WPA-(PFUS*0.79213/AREA))/WPAO
CC(10) = (I2-5-6E6*AR*BT*(1.0+SICMA^2)*1.11/

1 (2.0*Q*AR*(1.0-1.0/AR^2)*AR))/IP0

DO 143 I=1,MEQ
143 CC(I)=CC(I)*EQNWT

C SINCE WE DON'T CALCULATE F OURSELVES, THE WEIGHTED VARIABLES
C MUST BE TREATED AS CONSTRAINTS
C

NN=M-MEQ
DO 100 II=1,NN
I=INDP(II)
100 CC(II+MEQ)=WW(JT)*(AK(I)-BK(I))/BK(I)

C********COMPUTE OUTPUT VARIABLES***************

IF(IOUT.NE.1) RETURN
PALF=PALFV*VOL*1.0E-6
RO=A*AR
LPI=ZMUO*RO^LI/2.0
ALEXT=ZMUO*RO^((ALOG(8.0*RO/(A*SQRT(SIGMA))))-2.0)
LP=ALEXT+LPI
RP=2.0*RO^1.638E-9*2.0*ZEFF*(24.0-ALOG(SQRT(NI/1.0E6))/

1 (TE*1000.0))/(TE*1.5*A^2*SIGMA)

V=RP^IP
DRATEB=PALFV*VOL/QALPHA
TAUP=TAUE
DRATEL=NI*VOL/(2.0*TAL^2)
FB=DRATEB/(DRATEL+DRATEB)
B=SIGMA*A
NTAU=NE*TAUE
PB=PWX*1.0E-6
LPI=LA*IP
POWFUS=PFUS*1.0E-6
ALPPOW=PALFV*VOL*1.0E-6
RADPOW=PRADV*VOL*1.0E-6
POWEQV=PFUS*0.35*1.0E-6
IP=IP*1.0E-6
ILBTA=FACTOR*IP
VSIND=LP*ILBTA

C WRITE OUT SPECIFICATIONS
C

WRITE(NOUT2,140)PALF,RO,LPI,ALEXT,VSIND,RP,V,DRATEB,DRATEL,FB

140 FORMAT(/' TOTAL ALPHA POWER',13X,E14.6,5X,'MAJOR RADIUS',18X,

1 E14.6,'INTERNAL INDUCTANCE',11X,E14.6,5X,'EXTERNAL ',

2 'INDUCTANCE',11X,E14.6,'INDUCTIVE VOLT-SECONDS',8X,E14.6,5X,

3 'PLASMA RESISTANCE',13X,E14.6,'PLASMA VOLTAGE',16X,E14.6,5X,

4 'DEUTERIUM BURN-UP RATE',8X,E14.6,'DEUTERIUM DIFFUSION '

5 'LOSS RATE',1X,E14.6,5X,'FRACTION OF FUEL BURNED',7X,E14.6)

RIIPPLE=RIPPLE*100.0

WRITE(NOUT3,180)A,Q,AR,Z,SIGMA,ZEFF,BETA,GAMMA,BT,

1 LI,TE,SCRP,FACT,RIIPPLE,PBURN,PQCH

180 FORMAT(2X,'PLASMA RADIUS (M) =',F10.3,7X,'Q',21X,'=',F10.3/

1 2X,'ASPECT RATIO =',F10.3,7X,'IMPURITY Z =',)
2 F10.3/2X,'ELONGATION' = ',F10.3,7X,'ZEFF',18X,',' = ',
3 F10.3/2X,'BETA',15X,',' = ',F10.3,7X,'GAMMA (RES LOSS) ' = ',
4 F10.3/2X,'FIELD ON AXIS(T) ' = ',F10.3,7X,'PLASMA INT IND ' ,
5 ' (LI) ' = ',F10.3/2X,'ION TEMP (KEV) ' = ',F10.3,7X,
6 'SCRAPE OFF LAYER (M) ' = ',F10.3/2X,'ELE TEMP (KEV) ' = ',
7 F10.3,7X,'IP FACTOR',13X,',' = ',F10.3/2X,'RIPPLE (%)',9X,',' = ',
8 F10.3,7X,9X,'BURN PRESS (TORR) ' = ',E10.4/39X,'QUENCH PRESS (TORR) ' = ',
9 E10.4)

WRITE(NOUT3,200)R0,IP,B,ILBTA,VLAT,VP,LP,MI,NE
200 FORMAT(//72X/MAJOR RADIUS (M) = ',F10.3,
1 7X,'PLASMA-CRNT-HB (MA) = ',F10.3/
2 2X,'PLASMA HEIGHT (M) = ',F10.3,
B 7X,'PLASMA-CRNT-LE (MA) = ',F10.3/
C 2X,'PLASMA VOLUM (M**3) = ',F10.3,7X,
3 'PLASMA VOL-BURN (V) = ',F10.3/
D 2X,'PLASMA IND (H) = ',E10.4,
4 7X,'PLASMA RES-BURN (OHM) = ',E10.4/2X,'ION DENSITY (/M**3) = ',
5 E10.4/2X,'ELE DENSITY (/M**3) = ',E10.4)

WRITE(NOUT3,220)ZETA,Z,ZEFF
220 FORMAT(//2X,'IMPURITY CONCENT. = ',F10.3/2X,'IMPURITY Z' 9X,'= ',
1 F10.3/2X,'ZEFF',15X,',' = ',F10.3,7X)

WRITE(NOUT3,240)NTAU,TAUE,TAUEMP,TAUP
240 FORMAT(//2X,'NTAU (SEC/H) ' = ',E10.4/2X,'TAUE (SEC)' 9X,'= ',
1 F10.3/2X,'TAUE-TP (SEC)' 6X,
2 ' = ',F10.3/2X,'TAUE-SEC (SEC)' 9X,',' = ',F10.3)

WRITE(NOUT3,260)PB,EB,LW,POWUS,ALPPW,RADWP,POWERP
260 FORMAT(//2X,'BEAM POWER (MW) = ',F10.3/2X,'BEAM ENERGY (KEV) ' 9X,'= ',
1 'F10.3/2X,'PLASMA EDGE NEU. LOAD (MW/H**3) = ',F12.2/2X,
2 'FUSION POWER (MW)' 15X,',' = ',F12.2/2X,'ALPHA (MW)' 22X,',' = ',
3 F12.2/2X,'RADIATION (MW)' 18X,',' = ',F12.2/2X,'ELEC. POWER',
4 '(MW)' 16X,',' = ',F12.2)

RETURN
END

C
C--THE CC ELEMENTS ARE RESIDUALS OF THE CONSTRAINT EQUATIONS.
C--CONSTRAINTS HAVE THE FORM CC=0 FOR ALLOWED
C--VALUES OF X.

COMMON/INDEXP/EQWMT,WW(100),INDP(100),MEQ,MADIM
COMMON/VARLSS/TT,TE,TEF,NE,NEF,Q,FET,BT,TAUE
# ,PALFV,PFUS,WA,AR,SIK,PIJ,IPF,CI,CE,IP
# ,DUMVAR(79)
COMMON/INDEX/I11,ITE,IZEFF,INJ,INE,
# INZ,IQ,IBET,IBU,ITAUE,IPALFV,IPFUS,IPWA,IA,AR,SIM,IP
# IPJ,IPF,CI,CE,IP
# ,DUMIND(79)
COMMON/INITL/TO,TE,TEF,NE,NEF,QQ,FET,CTE
# ,BTO,TAUE,PA,PFUS,MPAO,AR,AR,SGM,IPJ,IPF,CTE
# ,EO,IP0
# ,DUMINI(79)
COMMON/XS/XS(1C0)
DIMENSION X(N),RC(M)
REAL NIO, NEO, NZO, IPO, LI, NI, NE, NZ, IP, ILBTA, LP, LW, NTAU, LPI
C--VARIABLES MUST APPEAR IN THE DATA FILE IN THE SAME ORDER
C--AS THEY APPEAR IN COMMON.
C
DO 100 I=1, MAXDIM
100 XX(I)=1.0
DO 105 II=1, N
I=INDP(II)
105 XX(I)=XC(II)
C--ALL OTHER XX(I)=1.
TI =XX(ITI )*TIO
TE =XX(ITE )*TEO
ZEFF =XX(IZEFF )*ZEFFO
NI =XX(INI )*NIO
NE =XX(INE )*NEO
NZ =XX(INZ )*NZO
Q =XX(IQ )*Q0
BETA =XX(IBETA )*BETAO
BT =XX(IBT )*BTO
TAUE =XX(ITAUE )*TAUEO
PALFV =XX(IPALFV)*PALFVO
PFUS =XX(IPFUS )*PFUSO
WPA =XX(IWPA )*WPAO
A =XX(IA )*A0
AR =XX(IAR )*ARO
SIGMA =XX(ISIGMA)*SIGMAO
PINJ =XX(IPINJ )*PINJO
PRF =XX(IPRF )*PRFO
CI =XX(ICI )*CIO
CE =XX(ICE )*CEO
IP =XX(IIP )*IPO
C
CALL FIZICS(RC,M)
RETURN
END
C

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9104-2 BOX Y, OAK RIDGE, TN 37830
4-0613 4-0637
C

MAIN ROUTINE
COMMON/INDEX/IND(100)
COMMON/INDEXP/EQWN'T, WW(100), INDP(100), MEQ, MAXDIM
COMMON/SPECS/ETAALF, FCOULV, ETAINJ, POHMV, PARAV, SIGMAV, ETAEF, 1
TAUP, TAUEMP, TAURT, TAUNC
COMMON/INITL/VAR(100)
COMMON/INP/Z, CTP, CNE, CRT, CEMP, AMU, AMZ, EB, REFL, RIPPLE,
1
FACTOR, GAMMA, SCRPL, PPURN, PQNCH, LI
COMMON/IO/NIN, NIN2, NOUT, NOUT2, NOUT3
COMMON/NAMES/NAMVAR(100), IFPU(100)
COMMON/PRT/NVAR
COMMON/XS/ XX(100)
REAL NIO,NEO,NZO,IFO,LI,NI,NE,NZ,IF,ILBTA,LP,LW,NTAU,LPI
DIMENSION UNITS('),IX(3),WWX(3)

C THE WEIGHTS ARE READ IN FROM INPUT.DAT AND ARE DETERMINED FROM
C TEST RUNS TO BE GENERALLY WORKABLE
C F=FIXED  P=PREFERRED  U=UNKNOWN
C
DATA IEND/4H END/,'F','P','U'/,IOUT/O/,MAXDIM/100/
DATA IFPU/100*'F'/,IBLNK*/'/

NIN=6
NIN2=28
NOUT=5
NOUT2=20
NOUT3=27
OPEN(UNIT=NIN,DEVICE='DSK',ACCESS='SEQIN',FILE='ETFOD.DAT')
OPEN(UNIT=NIN2,DEVICE='DSK',ACCESS='SEQIN',FILE='INPUT.DAT')
OPEN(UNIT=NOUT2,DEVICE='DSK',ACCESS='SEQOUT',FILE='ETFOD.OUT')
OPEN(UNIT=NOUT3,DEVICE='DSK',ACCESS='SEQOUT',FILE='SPECS.ETF')
DUM=0.
1 FORMAT(SOAI)
2 FORMAT(S10)
3 FORMAT(A4,E12.4,9X,A1,5X,A5,4A5)
READ(NIN2,10)WWX,EQNWT
READ(NIN2,10)Z,CTP,CNC,CRT,CEMP,AMU,AMZ,EB,LI,REFL,RIPPLE,
1 FACTOR,GAMMA,SCRAPL,PBURN,PQNCN
10 FORMAT(/SE12.4)
C
READ(NIN,1)DUM
READ(NIN,2)MEQ
READ(NIN,1)DUM
C
N=0
NVAR=0
DO 100 I=1,MAXDIM
READ(NIN,3)IVAR,VARO(I),LX,NAMVAR(I),UNITS
IF(IVAR.EQ.IEND) GO TO 150
WRITE(NOUT2,3)IVAR,VARO(I),LX,NAMVAR(I),UNITS
NVAR=NVAR+1
IND(I)=NVAR
DO 80 J=1,3
IF(LX.EQ.IX(J))WX=WWX(J)
80 CONTINUE
IF(WX.EQ.1.0) GO TO 100
N=N+1
INDP(N)=I
IFPU(I)=IBLNK
WW(N)=WX
100 CONTINUE
C
150 WRITE(NOUT2,160)
160 FORMAT(/' WHERE:  F=FIXED VALUE'/7X,' P=PREFERRED VALUE'/
1 7X,' U=UNKNOWN VALUE')
IF(MEQ.GT.N) WRITE(NOUT,4)
IF(MEQ.GT.N) WRITE(NOUT2,4)

4 FORMAT(47H WARNING NUMBER OF CONSTRAINTS EXCEEDS NUMBER,
# 19H OF FREE VARIABLES )

C TYPE 10,(WW(I),I=1,N)
C CALL SEARCH(N,MEQ)
WRITE(NOUT2,240) ETAALF,PCOULV,ETAINJ,POHMV,PRADV,SIGMAV,ETARF,
1 TAUFP,TAUEMP,TAURT,TAUNC
240 FORMAT(' ETAALF ',20X,E13.6//' PCOULV ',20X,E13.6//' ETAINJ ',20X,
1 E13.6//' POHMV ',20X,E13.6//' PRADV ',20X,E13.6//' SIGMAV ',
2 20X,E13.6//' ETARF ',20X,E13.6//' TAUFP ',20X,E:3.6//' TAUEMP ',
3 20X,E13.6//' TAURT ',20X,E13.6//' TAUNC ',20X,E13.6)
C STOP
END
C
C ***************
C SUBROUTINE SEARCH(N,MEQ)
C
C DIMENSIONS
C
C X(N) GUESS AT SOLUTION
C R(M) RESIDUALS
C W(IW) WORK SPACE
C STEPMX(N) RANGE LIMITS ON X
C
C DIMENSION X(100),W(1500),RC(100),STEPMX(100)
COMMON/INDEXP/EQNWT, WW(100),INDP(100),MDUM,MAXDIM
COMMON/PARAMS/COND1,ACCURC,CNORM
COMMON/IO/NIN,NIN2,NOUT,NOUT2,NOUT3
COMMON/OUTFL/I0UT
REAL NIO,NEO,NZO,IP0,LI,NI,NE,NZ,IP,ILBTA,LP,LW,NTAU,LPI
EXTERNAL RESID,M0NIT
DATA FRAACC/0.01/
DATA X,W,RC/100*1.0,1500*0.0/
DATA IX,IW,IRC,ISTP/100,1500,100,100/
C ALL VARIABLES ARE NORMALIZED TO 1 AT THE INITIAL VALUE.
M=MEQ+N
C IPRINT MUST BE .GE.0,CAUSING MONIT TO BE CALLED AND VALUES
C IN COMMON PARAMS TO BE DEFINED
IPRINT=1
MAXCAL=1500
C MAXCAL=100*(N+5)*NX
C XTOL=8.631675E-03
XTOL=0.1
FTOL=1.0E-6
WRITE(NOUT2,40)XTOL,FTOL
40 FORMAT(' XTOL =',1PE13.6,6X,'FTCL =',1PE13.6)
DO 50 I=1,N
50 STEPMX(I)=0.5
WRITE(NOUT2,52)STEPMX(1)
52 FORMAT(' STEPMX = ',1PE13.6)
III=N+3+N/3
LTEST$=2^M+4^N+M^N+N^M+(N+1)/2+III^*(M+2+2^M)
IF(IW.LT.LTEST) WRITE(NOUT,2) LTEST
IF(IW.LT.LTEST) WRITE(NOUT2,2) LTEST

2 FORMAT(36H INCREASE DIMENSION OF W TO AT LEAST,110)
C
IF(N.LE.IX)GO TO 120
WRITE(NOUT,115)N
WRITE(NOUT2,115)N
115 FORMAT(// ' INCREASE X DIMENSION TO AT LEAST',I5)
120 IF(M.LE.IRO)GO TO 130
WRITE(NOUT,125)M
WRITE(NOUT2,125)M
125 FORMAT(// ' INCREASE RC DIMENSION TO AT LEAST',I5)
130 IFAIL=0
C--TEST OF INITIAL VALUES
CALL RESID(M,N,X,RC)
DO 150 I=1,M
150 IF(ABS(RC(I)).GT.0.5) WRITE(NOUT,155)I
155 FORMAT(13H BAD GUESS AT SOLUTION FOR EQUATION',I3)
F=0.0
WRITE(NOUT2,23)F,(RC(I),I=1,M)
23 FORMAT(1H SUM OF SQUARES =',F10.4,' RESIDUALS: '/(1P10E10.3))
DO 160 I=1,IRC
160 RC(I)=0.0
C
CALL EO4FAF(M,N,X,RC,F,FTOL,XTOL,STEPX,W,IW,RESID,MONIT,1
1 IPRINT,MAXCAL,IFAIL)
C
IF(IFAIL.EQ.0) WRITE(NOUT,20)
IF(IFAIL.EQ.0) WRITE(NOUT2,20)
20 FORMAT(27H A SOLUTION HAS BEEN FOUND.)
C--CALL RESID TO UPDATE VALUES OF VARS.
IOUT=1
CALL RESID(M,N,X,RC)
WRITE(NOUT2,170)F,FTCL,IFAIL,(RC(I),I=1,M)
170 FORMAT(1H SUM OF SQUARES =',E10.4,4X,'FTOL '='F4.1,4X,
1 'IFAIL '='I2//' RESIDUALS: '/(1P10E11.4))
PERCENT=FRAACC X 100.0
DO 200 I=1,MEQ
RC(I)=RC(I)/EQNWT
IF(ABS(RC(I)).GT.FRAACC)GO TO 220
200 CONTINUE
GO TO 250
220 WRITE(NOUT2,240)PERCENT
WRITE(NOUT,240)PERCENT
WRITE(NOUT3,240)PERCENT
240 FORMAT(1H THIS SOLUTION DOES NOT SATISFY PHYSICS EQUATIONS',
1 ' WITHIN ','F3.1,''))
GO TO 270
250 WRITE(NOUT2,260)PERCENT
WRITE(NOUT,260)PERCENT
260 FORMAT(1H THIS SOLUTION DOES SATISFY PHYSICS EQUATIONS',
1 ' WITHIN ','F3.1,'))
270 WRITE(NOUT2,271)
271 FORMAT(1X)
DO 272 I=1,MEQ
   RC(I)=RC(I)*100.0
272 WRITE(NOUT2,274)I,RC(I)
274 FORMAT(' EQUATION ',I2,' IS BALANCED WITHIN ',F5.2,'$')
   WRITE(NOUT2,280)(X(I),I=1,N)
280 FORMAT(/' NORMALIZED X:'/(1P10E11.4))
   WRITE(NOUT2,290)F(N)
290 FORMAT(' FTOL = ',F4.1)
   CALL PRTOUT
END
C
C SUBROUTINE MONIT(M, N, X, F, NITER, SING, LIM)
LOGICAL SING, LIM
DIMENSION X(N)
COMMON/IO/NIN, NIN2, NOUT, NOUT2, NOUT3
C—IF IPRINT .GT. 0, THIS ROUTINE IS CALLED TO MONITOR THE
C—PROGRESS OF THE CONVERGENCE.
C
10 FORMAT(//' SUM OF SQUARES =',E10.4,' AFTER ',I10,
1 ' ITERATIONS'/ ' SING =',L10,' (IF TRUE, RANDOM POINT HAS',
2 ' BEEN USED)'/ ' CURRENT SOLUTION: '/(1P10E10.3))
15 FORMAT(//' THE VALUE OF AN X WAS CONSTRAINED BY STEPMX')
   CALL PRTOUT
END
C
C SUBROUTINE PRTOUT
COMMON/IO/NIN, NIN2, NOUT, NOUT2, NOUT3
COMMON/NAMES/NAMVAR(100), IFPU(100)
COMMON/OUTFL/IOUT
COMMON/PRT/NVAR
COMMON/VARBLS/VALUE(100)
C
WRITE(NOUT2,90)
90 FORMAT(1X)
   DO 100 I=1,NVAR
100 WRITE(NOUT2,1) NAMVAR(I), VALUE(I), IFPU(I)
1 FORMAT(2X,A5,3H = ,E15.3,2X,A1)
   IF(IOUT.NE.1) RETURN
END
SUBROUTINE ALFETA(TEKEV, ETAALF)
C—REF ORNL/TM-5509
C—(NOT ACCURATE FOR TE ABOVE 20 KEV)
ETAALF=TEKEV/50.
IF(ETAALF.GT.1.) ETAALF=1.
RETURN
END

SUBROUTINE COULM(DENE, DENI, AMU, TEKEV, TKEV, PCOULV)
C—REF ORNL/TM-5509
C—(PCOULV IS POSITIVE WHEN POWER IS TRANSFERRED TO IONS)
ALOGLM=24.6-ALOG((1.E-6)*SQRT(DENE)/TEKEV)
PCOULV=(1.5E-19*DENE)/TEKEV**1.5
# *DENI/AMU *ALOGLM *(TEKEV-TKEV)**1.6E-16
RETURN
END

SUBROUTINE INJETA(DENI, DENZ, Z, AMU, AMZ, TEKEV, EBEAM, ETAINJ)
C—REF ORNL/TM-5509
C—EBEAM IS IN KEV
ZBR=(DENI+DENZ*Z**2*(AMU/AMZ))/(DENI+Z*DENZ)
C ASSUME BEAM SPECIES MIX = PLASMA SPECIES MIX
AMB=AMU
ECRIT=14.8*TEKEV*(AMB*(ZBR*AMB/AMU)**2)**(1./3.)
GI=0.5*EXP(-0.0916*EBEAM/ECRIT)+0.5*EXP(-0.635*EBEAM/ECRIT)
C—GE=1.-GI
ETAINJ=GI
RETURN
END

SUBROUTINE OHMIC(DENE, TEKEV, ZEFF, AMINOR, CURRT, POHMV)
C—REF ORNL/TM-5509
ALOGLM=24.6-ALOG((1.E-6)*SQRT(DENE)/TEKEV)
RSPITZ=ALOGLM*1.65E-9*ZEFF/(TEKEV**1.5)
C—APPROPRIATE FOR HYDROGEN
CURDEN=CURRT/(3.14159*AMINOR**2)
POHMV=RSPITZ*CURDEN**2
RETURN
END

SUBROUTINE RADIA(DENE, ZEFF, TKEV, REFL, BT, BETA, AMINOR, DENZ, PRA DV)
C—REF ORNL/TM-5509
PBREMV=(0.3E-20*DENE)*DENE*ZEFF*SQRT(TKEV)*1.6E-16
PSYNCV=1.5E5*TKEV**3*(1.-REFL)*(1.+TKEV/204.)*1.6E-16
# *SQRT(DENE)*(BT*SQRT(1.-BETA))**5/(AMINOR*TKEV))
PLINEV=(.32E-32*DENE)*DENZ
C—THIS LINE RADIATION IS APPROPRIATE FOR IRON ABOVE 2 KEV.
PLINEV=0.
PRA DV=PBREMV+PSYNCV+PLINEV
RETURN
END

SUBROUTINE RATE(TKEV, SIGMAV)
C SIGMAVs(3.14*TKEV-20.6)*1.E-23
C IF(SIGMAV.LT.1.E-35) SIGMAV=0.0
TIEV=TKEV*1.E3
SIGMAV=1.E-6*SVFUSE(TIEV,3)
RETURN
END

SUBROUTINE RFETA(ETARF)
C—FOR NOW, ASSUME ALL RF POWER GOES TO IONS
ETARF=1.0
RETURN
END

SUBROUTINE TAUS(DENE,AMINOR,BT,BETA,ZEFF,ASP,TIKEV,ELONG,
# AMU,DELTA,QS,TEKEV,DENI,TAUTP,TAUEMP,TAURT,TAUNC)
C—TRAPPED PARTICLE MODE FROM MARTIN PENG
TAUTP=(2.4E20/DENE)
# *(AMINOR/1.2)**4.
# *(BT/5.3)**6
# *(BETA/0.07)**2
# *(ZEFF/1.1)
# *(ASP/4.17)**2.5
# *(12./TIKEV)**5.5
# *(1.+ELONG**2)/(2.*1.78)
C—EMPIRICAL SCALING FROM MARTIN PENG
TAUEMP=(5.E-21•DENE)•AMINOR*2
C—RIPPLE TRAPPING DERIVED FROM STRINGER'S DIFF. COEFF.
RO=ASP*AMINOR
ZNUE=1.6E4*ZEFF*(DENE/1.E19)*(TIKEV)**-1.5
SQRAM=SQRT(AMU*185.5.)
BTG=BT*10.
VD=1.E6*TIKEV/(BTG*RO)
XRT=6.5*DELTA**1.5*SQRAM*VD**2/(ZNUE*ELONG**2)
TAUR=AMINOR**2/(4.*XRT**1.4)
C—NEOCLASSICAL DIFFUSION DERIVED FROM DIAGONAL TERMS OF
C—HINTON-MOORE MODEL FOR ION THERMAL CONDUCTIVITY.
BP=BT*((1.+ELONG**2)/2.)/(QS*ASP)
EPS=1./ASP
ZL=24.-ALO(G((1.E-6)*SQR(DENE)/TEKE)
ZNUI=6.71E-14*DENI*ZL/(TIKEV*1.E3)**1.5
OMEGBI=9.78E3*BP/(BTG*RO)*SQR(1.E3*TEKE)/(EPS*AMU))
SNI=2*PN*(EPS•OMEGBI)
RHOIT=1.25E-04*SQR(AMU*1.E3*TIKEV)/BP
XK2=.66 Linear(1.)/(1.+1.03*SQR(SNI)+31*SNI)
# +EPS**3*1.77*SNI/(1.+74*SNI*EPS**1.5)
XINC=SQR(EP)•ZNUI*RHOIT**2*XX2
TAUNC=AMINOR**2/(4.*XINC**1.4)
RETURN
END

FUNCTION SVFUSE(TI,IRATE)
C-------------------------------
C**W.A.HOULBERG ORNL 2/79. •
C**TABULATED DATA PROVIDED BY J.R.MCNALLY, Jr.
C-------------------------------
C**SVFUSE IS <SIGMA*VEL> AVERAGED OVER TWO MAXWELLIAN DISTRIBUTIONS •
C**WITH TEMPERATURE TI. UNITS ARE IN CM**3/SEC FOR SVFUSE.
C**IRATE=INDEX DENOTING REACTION
C***** = 1  D+D = 3HE( 817KEV) +N( 2450KEV)  REF 1  *
C***** = 2  D+D = T( 1008KEV) +P( 3024KEV)  REF 1  *
C***** = 3  D+T = A( 3517KEV) +N(14069KEV)  REF 1  *
C***** = 4  T+T = A( 1259KEV) +N( 3517KEV) +P( 3024KEV)  REF 2  *
C***** = 5  3HE+T = D( 9594KEV) +A( 4773KEV)  41% REF 2  *
C***** = 6  3HE+D = P(14681KEV) +A( 1344KEV)  4% REF 2  *

C***THE ENERGIES FOR THE PRODUCTS ARE INVERSELY PROPORTIONAL TO THE
C***MASS OF EACH PRODUCT.
C***THE BRANCHING RATIO FOR REACTION 5 IS ENERGY SENSITIVE.
C*****REF 1: UCRL-70552 (1967)
C*****REF 2: BNWL-1685 (1975) P. 75
C*****SOV PHYS JETP 12 (1961) P. 163
C*****TI=MAXWELLIAN TEMPERATURE IN EV.
C***CROSS-SECTIONS TABULATED IN STEPS OF .2 KEV FOR 1.<T< 10. KEV
C*****2. KEV FOR 10.<T<100. KEV
C*****20. KEV FOR 100.<T<200. KEV

DIMENSION SV(96,6),SV1(96),SV2(96),SV3(96),SV4(96),SV5(96),SV6(96)
EQUIVALENCE (SV(1,1),SV1(1)),(SV(1,2),SV2(1)),(SV(1,3),SV3(1))
EQUIVALENCE (SV(1,4),SV1(1)),(SV(1,5),SV5(1)),(SV(1,6),SV6(1))
DATA SV1/9.65E-23,2.61E-22,5.75E-22,1.10E-21,1.90E-21,
# 3.04E-21,4.58E-21,6.57E-21,9.06E-21,1.21E-20,
# 1.57E-20,2.00E-20,2.49E-20,3.04E-20,3.67E-20,
# 4.37E-20,5.14E-20,5.98E-20,6.90E-20,7.90E-20,
# 8.97E-20,1.01E-19,1.13E-19,1.26E-19,1.40E-19,
# 1.55E-19,1.70E-19,1.86E-19,2.03E-19,2.21E-19,
# 2.39E-19,2.58E-19,2.78E-19,2.99E-19,3.20E-19,
# 3.42E-19,3.64E-19,3.88E-19,4.12E-19,4.37E-19,
# 4.62E-19,4.88E-19,5.15E-19,5.42E-19,5.70E-19,
# 5.99E-19,9.18E-19,1.29E-18,1.71E-18,2.16E-18,
# 2.65E-18,3.17E-18,3.71E-18,4.27E-18,4.85E-18,
# 5.44E-18,6.04E-18,6.66E-17,7.28E-17,7.90E-17,
# 8.54E-18,9.18E-18,9.82E-18,1.05E-17,1.11E-17,
# 1.18E-17,1.24E-17,1.30E-17,1.37E-17,1.43E-17,
# 1.50E-17,1.56E-17,1.63E-17,1.69E-17,1.76E-17,
# 1.82E-17,1.88E-17,1.95E-17,2.01E-17,2.07E-17,
# 2.13E-17,2.20E-17,2.26E-17,2.32E-17,2.38E-17,
# 2.44E-17,2.50E-17,2.56E-17,2.62E-17,2.68E-17,
# 2.74E-17,3.32E-17,3.86E-17,4.37E-17,4.86E-17,
# 5.32E-17/
DATA SV2/9.66E-23,2.61E-22,5.76E-22,1.10E-21,1.91E-21,
# 3.05E-21,4.59E-21,6.58E-21,9.07E-21,1.21E-20,
# 1.57E-20,1.99E-20,2.48E-20,3.04E-20,3.66E-20,
# 4.35E-20,5.11E-20,5.95E-20,6.86E-20,7.84E-20,
# 8.90E-20,1.00E-19,1.26E-19,1.52E-19,1.83E-19,
# 1.53E-19,1.68E-19,1.83E-19,2.00E-19,2.17E-19,
# 2.35E-19,2.53E-19,2.72E-19,2.92E-19,3.12E-19,
# 3.33E-19,3.55E-19,3.77E-19,4.00E-19,4.23E-19,
# 4.48E-19,4.72E-19,4.97E-19,5.23E-19,5.49E-19,
# 5.76E-19,8.72E-19,1.21E-18,1.58E-18,1.99E-18,
# 2.41E-18,2.85E-18,3.31E-18,3.79E-18,4.27E-18,
# 4.76E-18,5.25E-18,5.75E-18,6.26E-18,6.77E-18,
# 7.28E-18,7.79E-18,8.30E-18,8.81E-18,9.32E-18,
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<tr>
<td>4.29E-17</td>
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**DATA SV3/6.27E-21, 1.86E-20, 4.44E-20, 9.11E-20, 1.67E-19, 2.83E-19, 4.47E-19, 6.72E-19, 9.67E-19, 1.34E-18, 1.81E-18, 2.38E-18, 3.06E-18, 3.86E-18, 4.79E-18, 5.86E-18, 7.07E-18, 8.43E-18, 9.95E-18, 1.16E-17, 1.35E-17, 1.55E-17, 1.77E-17, 2.00E-17, 2.26E-17, 2.53E-17, 2.81E-17, 3.12E-17, 3.44E-17, 3.78E-17, 4.14E-17, 4.52E-17, 4.91E-17, 5.31E-17, 5.74E-17, 6.17E-17, 6.63E-17, 7.09E-17, 7.57E-17, 8.07E-17, 8.57E-17, 9.09E-17, 9.62E-17, 1.02E-16, 1.07E-16, 1.13E-16, 1.47E-16, 1.62E-16, 1.74E-16, 1.93E-16, 2.14E-16, 2.32E-16, 2.51E-16, 2.71E-16, 3.12E-16, 3.34E-16, 3.56E-16, 3.79E-16, 4.03E-16, 4.27E-19, 4.52E-19, 4.77E-19, 5.03E-19, 5.30E-19, 5.57E-19, 6.19E-19, 1.19E-18, 1.56E-18, 1.96E-18, 2.37E-18, 2.80E-18, 3.24E-18, 3.68E-18, 4.13E-18, 4.59E-18, 5.04E-18, 5.50E-18, 5.96E-18, 6.41E-18, 6.87E-18, 7.33E-18, 7.78E-18, 8.23E-18, 8.68E-18, 9.12E-18, 9.57E-18, 1.00E-17, 1.04E-17, 1.09E-17, 1.13E-17, 1.17E-17, 1.22E-17, 1.26E-17, 1.30E-17, 1.34E-17, 1.39E-17, 1.43E-17, 1.47E-17, 1.51E-17, 1.55E-17, 1.59E-17, 1.63E-17, 1.67E-17, 1.71E-17, 1.75E-17, 1.79E-17, 1.83E-17, 1.87E-17, 1.91E-17, 1.95E-17, 2.32E-17, 2.66E-17, 2.97E-17, 3.25E-17, 3.48E-17 |

**DATA SV4/3.28E-23, 1.02E-22, 2.52E-22, 5.29E-22, 9.84E-22, 1.68E-21, 2.66E-21, 4.00E-21, 5.75E-21, 7.96E-21, 1.07E-20, 1.40E-20, 1.79E-20, 2.24E-20, 2.76E-20, 3.35E-20, 4.01E-20, 4.75E-20, 5.56E-20, 6.45E-20, 7.42E-20, 8.47E-20, 9.60E-20, 1.08E-19, 1.21E-19, 1.35E-19, 1.49E-19, 1.64E-19, 1.80E-19, 1.97E-19, 2.14E-19, 2.32E-19, 2.51E-19, 2.71E-19, 2.91E-19, 3.12E-19, 3.34E-19, 3.56E-19, 3.79E-19, 4.03E-19, 4.27E-19, 4.52E-19, 4.77E-19, 5.03E-19, 5.30E-19, 5.57E-19, 6.19E-19, 1.19E-18, 1.56E-18, 1.96E-18, 2.37E-18, 2.80E-18, 3.24E-18, 3.68E-18, 4.13E-18, 4.59E-18, 5.04E-18, 5.50E-18, 5.96E-18, 6.41E-18, 6.87E-18, 7.33E-18, 7.78E-18, 8.23E-18, 8.68E-18, 9.12E-18, 9.57E-18, 1.00E-17, 1.04E-17, 1.09E-17, 1.13E-17, 1.17E-17, 1.22E-17, 1.26E-17, 1.30E-17, 1.34E-17, 1.39E-17, 1.43E-17, 1.47E-17, 1.51E-17, 1.55E-17, 1.59E-17, 1.63E-17, 1.67E-17, 1.71E-17, 1.75E-17, 1.79E-17, 1.83E-17, 1.87E-17, 1.91E-17, 1.95E-17, 2.32E-17, 2.66E-17, 2.97E-17, 3.25E-17, 3.48E-17 |
\[
\begin{array}{cccccccc}
& 0.00E-00 & 0.00E-00 & 0.00E-00 & 0.00E-00 & 0.00E-00 & 0.00E-00 & 0.00E-00 & 0.00E-00 \\
& 2.62E-18 & 3.30E-18 & 3.80E-18 & 4.29E-18 & 4.79E-18 & 5.29E-18 & 5.93E-18 & 7.22E-18 \\
& 8.52E-18 & 9.29E-18 & 1.01E-17 & 1.09E-17 & 1.16E-17 & 1.24E-17 & 1.33E-17 & 1.42E-17 \\
& 1.69E-17 & 1.78E-17 & 1.88E-17 & 1.98E-17 & 2.08E-17 & 2.18E-17 & 2.29E-17 & 2.39E-17 \\
& 2.71E-17 & 2.80E-17 & 5.30E-17 & 6.59E-17 & 7.88E-17 & 9.18E-17 & 1.30E-16 & 1.31E-16 \\
& 1.67E-16 & 1.79E-16 & 2.19E-16 & 2.45E-16 & 2.52E-16 & & & \\
\end{array}
\]

DATA SV6/3.10E-26, 1.80E-25, 7.28E-25, 2.31E-24, 6.11E-24,
\[
& 1.41E-23, 2.94E-23, 5.65E-23, 1.01E-22, 1.70E-22, \\
& 2.73E-22, 4.22E-22, 6.29E-22, 9.09E-22, 1.28E-21, \\
& 1.75E-21, 2.36E-21, 3.11E-21, 4.03E-21, 5.14E-21, \\
& 6.46E-21, 8.03E-21, 9.87E-21, 1.20E-20, 1.45E-20, \\
& 1.73E-20, 2.05E-20, 2.41E-20, 2.81E-20, 3.26E-20, \\
& 3.76E-20, 4.32E-20, 4.93E-20, 5.61E-20, 6.35E-20, \\
& 7.15E-20, 8.03E-20, 8.98E-20, 1.00E-19, 1.19E-19, \\
& 1.23E-19, 1.36E-19, 1.50E-19, 1.65E-19, 1.81E-19, \\
& 1.97E-19, 4.33E-19, 8.17E-19, 9.39E-18, 2.19E-18, \\
& 3.26E-18, 4.61E-18, 6.26E-16, 8.27E-18, 1.06E-17, \\
& 1.32E-17, 1.62E-17, 1.95E-17, 2.30E-17, 2.68E-17, \\
& 3.09E-17, 3.52E-17, 3.96E-17, 4.42E-17, 4.89E-17, \\
& 5.37E-17, 5.87E-17, 6.36E-17, 6.87E-17, 7.37E-17, \\
& 7.88E-17, 8.38E-17, 8.88E-17, 9.38E-17, 9.87E-17, \\
& 1.04E-16, 1.08E-16, 1.13E-16, 1.18E-16, 1.22E-16, \\
& 1.27E-16, 1.31E-16, 1.36E-16, 1.40E-16, 1.44E-16, \\
& 1.48E-16, 1.52E-16, 1.56E-16, 1.60E-16, 1.63E-16, \\
& 1.67E-16, 1.79E-16, 2.19E-16, 2.34E-16, 2.45E-16, \\
& 2.52E-16/
\]

SVFUSE=0.
T=TI/1000.
IF(T.LT.1. AND. IRATE.EQ.3) GO TO 20
IF(T.LT.1. OR. T.GT. 200.) RETURN
DTX=.2
IPT=4
IF(T.LT.10.) GOTO 10
DTX=2.
IPT=41
IF(T.LT.100.) GOTO 10
DTX=20.
IPT=86
10 IX=IFIX(T/DTX)+IPT
TX=DTX*(IX-IPT)
SVFUSE=SV(IX,IRATE)+(SV(IX+1,IRATE)-SV(IX,IRATE))*T-TX)/DTX
RETURN
20 TL=ALOG10(TI)
SVL=((-1.110333*TL+12.26350)*TL-49.01817)*TL+86.86500
IF(SVL.LT.37.) SVFUSE=10.*(-SVL)
C THIS FIT IS GOOD TO SVL=50. BUT DEC MACHINES CAN'T HANDLE 1.E-50
RETURN
END
Appendix E  Sample Cases

Following are two test runs. The first example is obtained with the impurity density, NZ, flagged as unknown. In the second example NZ is flagged as a preferred value. A comparison of the two shows that NZ stayed closer to its initial value when marked preferred.

The file ETFOD.OUT contains the input data from ETFOD.DAT followed by three parameters fixed in the code. The initial residuals of the physics equations are listed next. Following those is the trace of the iterative process in E04FAF as output by MONIT. Upon exit from E04FAF, a statement is written in this file indicating whether a solution has or has not been found. Following this are some plasma parameters, the final residuals of all the equations, the accuracy of the physics equations, the normalized solution vector, and the final values of the input variables.

In these examples some of the intermediate printout from MONIT has been left out due to the length of the listing.

The file SPECS.ETF contains the final design specifications.
File ETFOD.OUT (Example 1)

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<td>TI</td>
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<td>F</td>
<td>TE</td>
<td>(KEV)</td>
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<tr>
<td>4</td>
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<td>P</td>
<td>W</td>
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<td>P</td>
<td>HE</td>
<td>(H(^{#-3}))</td>
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<tr>
<td>6</td>
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<td>U</td>
<td>NZ</td>
<td>(H(^{#-3}))</td>
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<td>7</td>
<td>0.3000E+01</td>
<td>F</td>
<td>Q</td>
<td>(SAFETY FACTOR)</td>
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<td>8</td>
<td>0.7000E+01</td>
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<td>BETA</td>
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<td>9</td>
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<td>ST</td>
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<td>10</td>
<td>0.1500E+01</td>
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<td>TAU</td>
<td>(SEC)</td>
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<tr>
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<td>A</td>
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<td>17</td>
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<td>18</td>
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<td>P</td>
<td>PRF</td>
<td>(W)</td>
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<td>CI</td>
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<td>CE</td>
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<td>21</td>
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<td>IP</td>
<td>(AMPs)</td>
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</table>

WHERE:  
F = FIXED VALUE  
P = PREFERRED VALUE  
U = UNKNOWN VALUE

EITOL = 1.000000E-01  
FTOL = 1.000000E-06  
STIMX = 5.000000E-01

SUM OF SQUARES = 0.0000

RESIDUALS:
2.541E-02  1.253E+00  6.023E-01  9.298E+00  9.239E+00  2.213E-00  7.173E+00  9.095E+00  3.672E+00  5.250E-01  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00

SUM OF SQUARES = .5003E+03 AFTER 0 ITERATIONS

SING = F (IF TRUE, RANDOM POINT HAS BEEN USED)

CURRENT SOLUTION:
1.000E+00  1.000E+00  1.000E+00  1.000E+00  1.000E+00  1.000E+00  1.000E+00  1.000E+00  1.000E+00  1.000E+00  1.000E+00  1.000E+00  1.000E+00  1.000E+00  1.000E+00  1.000E+00  1.000E+00  1.000E+00  1.000E+00  1.000E+00  1.000E+00
TI = 0.120E+02 F
TE = 0.120E+02 F
ZEFF = 0.150E+01
NI = 0.170E+21
ME = 0.170E+21
N2 = 0.540E+19
Q = 0.380E+01 F
BATA = 0.700E+01 F
BT = 0.501E+01 F
TAUE = 0.150E+01
FALF = 0.920E+07
FURS = 0.100E+11
WPA = 0.310E+08
A = 0.134E+01 F
AR = 0.918E+01 F
SIGMA = 0.160E+01 F
PINJ = 0.000E+00 F
PFB = 0.100E-23
CI = 0.100E+01
CE = 0.100E+01
IF = 0.500E+07

SUM OF SQUARES = .24465E+03 AFTER 0 ITERATIONS
SING = F (IF TRUE, RANDOM POINT HAS BEEN USED)

CURRENT SOLUTION:
1.500E+00 1.000E+00 1.500E+00 1.000E+00 1.000E+00 1.500E+00 1.000E+00 1.000E+00 1.000E+00 1.000E+00 1.000E+00 1.000E+00
1.000E+00 1.000E+00

TI = 0.120E+02 F
TE = 0.120E+02 F
ZEFF = 0.225E+01
NI = 0.170E+21
ME = 0.255E+21
N2 = 0.540E+19
Q = 0.380E+01 F
BETA = 0.700E-01 F
HT = 0.501E+01 F
TAUE = 0.150E+01
FALF = 0.920E+07
PFUS  =  0.156E+11
WPA  =  0.330E+08
A    =  0.134E+01 F
AR   =  0.419E+01 F
SIGMA =  0.160E+01 F
PINJ =  0.000E+00 F
PRF  =  0.100E-23
CI   =  0.100E+01
CE   =  0.100E+01
IP   =  0.750E+07

SUM OF SQUARES = 1.003E+03 AFTER 1 ITERATIONS
SING = F (IF TRUE, RANDOM POINT HAS BEEN USED)
CURRENT SOLUTION:
1.461E+00 9.681E-01 1.375E+00 8.982E-01 1.036E+00 6.682E-01 1.000E+00 6.655E-01 9.996E-01 7.171E-01
9.556E-01 1.019E+00
THE VALUE OF AN X WAS CONSTRAINED BY STEPMX

TI   =  0.120E+02 F
TE   =  0.120E+02 F
ZDEP =  0.219E+01
HX   =  0.168E+21
HE   =  0.238E+21
NZ   =  0.485E+19
Q    =  0.390E+01 F
BETA =  0.700E-01 F
BT   =  0.501E+01 F
TAU2K =  0.135E+01
PALFV =  0.615E+07
PFUS =  0.104E+11
WPA  =  0.229E+08
A    =  0.134E+01 F
AR   =  0.419E+01 F
SIGMA =  0.160E+01 F
PINJ =  0.000E+00 F
PRF  =  0.100E-23
CI   =  0.717E+00
CE   =  0.956E+00
IP   =  0.509E+07
SUM OF SQUARES = .1950E+02 AFTER 2 ITERATIONS
SING = F (IP TRUE, RANDOM POINT HAS BEEN USED)
CURRENT SOLUTION:
1.396E+00 9.823E-01 1.245E+00 7.564E-01 1.027E+00 3.364E-01 5.000E-01 3.309E-01 9.833E-01 6.733E-01
8.291E-01 1.038E+00

THE VALUE OF AN X HAS CONSTRAINED BY STEPMX

TI = 0.120E+02 F
TE = 0.120E+02 F
ZEFF = 0.209E+01
NI = 0.167E+21
ME = 0.212E+21
WZ = 0.508E+19
Q = 0.380E+01 F
BETA = 0.700E-01 F
BT = 0.501E+01 F
TAUE = 0.154E+01
PALFY = 0.310E+07
PFUS = 0.521E+10
NPA = 0.108E+08
A = 0.134E+01 F
AR = 0.418E+01 F
SIGMA = 0.160E+01 F
PINJ = 0.000E+00 F
PRF = 0.983E-24
CI = 0.673E+00
CE = 0.829E+00
IP = 0.519E+07

SUM OF SQUARES = .7881E-02 AFTER 3 ITERATIONS
SING = F (IP TRUE, RANDOM POINT HAS BEEN USED)
CURRENT SOLUTION:
1.268E+00 9.880E-01 1.133E+00 7.095E-01 1.056E+00 7.501E-02 1.058E-01 6.695E-02 9.302E-01 5.103E-01
7.823E-01 1.053E+00

TI = 0.120E+02 F
TE = 0.120E+02 F
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<th>Value</th>
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</thead>
<tbody>
<tr>
<td>ZEFF</td>
<td>0.190E+01</td>
</tr>
<tr>
<td>WI</td>
<td>0.168E+21</td>
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<tr>
<td>WS</td>
<td>0.193E+21</td>
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<tr>
<td>NZ</td>
<td>0.308E+19</td>
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<tr>
<td>Q</td>
<td>0.380E+01</td>
</tr>
<tr>
<td>BETA</td>
<td>0.700E-01</td>
</tr>
<tr>
<td>BT</td>
<td>0.501E+01</td>
</tr>
<tr>
<td>TAU</td>
<td>0.151E-01</td>
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<tr>
<td>PALFV</td>
<td>0.690E+06</td>
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<tr>
<td>PFUS</td>
<td>0.110E+10</td>
</tr>
<tr>
<td>WPA</td>
<td>0.221E+07</td>
</tr>
<tr>
<td>A</td>
<td>0.134E+01</td>
</tr>
<tr>
<td>AR</td>
<td>0.818E-01</td>
</tr>
<tr>
<td>SIGMA</td>
<td>0.160E-01</td>
</tr>
<tr>
<td>PINJ</td>
<td>0.000E+00</td>
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<td>PFP</td>
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<td>0.510E+06</td>
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<tr>
<td>CE</td>
<td>0.782E+00</td>
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<tr>
<td>IP</td>
<td>0.526E+07</td>
</tr>
</tbody>
</table>

SUM OF SQUARES = .6987E-01 AFTER 4 ITERATIONS
SING = F (IF TRUE, RANDOM POINT HAS BEEN USED)
CURRENT SOLUTION:
1.170E+00  9.994E-01  1.124E+00  4.907E-01  1.007E+00  7.636E-02  1.070E-01  6.815E-02  1.028E+00  9.683E-01
7.012E-01  1.053E+00

<table>
<thead>
<tr>
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<th>Value</th>
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<tr>
<td>TE</td>
<td>0.120E+02</td>
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<tr>
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<tr>
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<tr>
<td>TAU</td>
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<td>A</td>
<td>0.134E+01</td>
</tr>
<tr>
<td>Variable</td>
<td>Value</td>
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<tr>
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</tr>
<tr>
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</tr>
<tr>
<td>SIGMA</td>
<td>0.160E+01</td>
</tr>
<tr>
<td>PINJ</td>
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<td>PRF</td>
<td>0.103E-23</td>
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<td>CI</td>
<td>0.968E+00</td>
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<td>CE</td>
<td>0.781E+00</td>
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<tr>
<td>IP</td>
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</tr>
</tbody>
</table>

**SUM OF SQUARES = 0.1224E-01 AFTER 5 ITERATIONS**

**CURRENT SOLUTION:**

- **Ti** = 0.120E+02 F
- **Tc** = 0.120E+02 F
- **Zeff** = 0.177E+01 F
- **NI** = 0.170E+21
- **ME** = 0.191E+21
- **NE** = 0.265E+19
- **Q** = 0.380E+01 F
- **BETA** = 0.700E-01 F
- **BT** = 0.501E+01 F
- **TAUE** = 0.148E+01 F
- **PALFV** = 0.705E+06
- **PFUS** = 0.113E+10
- **WPA** = 0.225E+07
- **A** = 0.133E+01 F
- **AR** = 0.418E+01 F
- **SIGMA** = 0.160E+01 F
- **PINJ** = 0.000E+00 F
- **PRF** = 0.886E-24
- **CI** = 0.641E+00
- **CE** = 0.715E+00
- **IP** = 0.526E+07

**SUM OF SQUARES = 0.1076E+02 AFTER 6 ITERATIONS**

**CURRENT SOLUTION:**
SUM OF SQUARES = .2514E-02 AFTER 19 ITERATIONS
SING = F (IF TRUE, RANDOM POINT HAS BEEN USED)
CURRENT SOLUTION:
1.120E+00 1.008E+00 1.117E+00 4.285E-01 9.771E-01 7.784E-02 1.097E-01 6.958E-02 9.093E-01 5.753E-01
7.286E-01 1.052E+00

| TI    | 0.120E+02 | F |
| TE    | 0.120E+02 | F |
| ZEFF  | 0.168E+01 | F |
| N1    | 0.111E+01 | F |
| N2    | 0.168E+01 | F |
| Q     | 0.390E+01 | F |
| BETA  | 0.700E-01 | F |
| BT    | 0.501E+01 | F |
| TAUu  | 0.175E+01 | F |
| PALEV | 0.823E+00 | F |
| PFIN  | 0.268E+00 | F |
| WPA   | 0.712E+07 | F |
| A     | 0.131E+01 | F |
| AR    | 0.181E+01 | F |
| SIGMA | 0.160E+01 | F |
| PINJ  | 0.140E+00 | F |
| PRF   | 0.944E-24 | F |
| CI    | 0.609E+00 | F |
| CE    | 0.627E+00 | F |
| IP    | 0.291E+07 | F |
SUM OF SQUARES = .2134E-02 AFTER 20 ITERATIONS
SING = F (IF TRUE, RANDOM POINT HAS BEEN USED)
CURRENT SOLUTION:
1.177E+00 1.009E+00 1.177E+00 4.239E-01 9.755E-01 7.792E-02 1.098E-01 6.973E-02 9.071E-01 5.960E-01
7.237E-01 1.052E+00

T1 = 0.120E+02 F
T2 = 0.120E+02 F
ZEFF = 0.168E+01
W1 = 0.172E+21
W2 = 0.190E+21
NW = 0.229E+19
Q = 0.380E+01 F
BETA = 0.700E-01 F
BT = 0.501E+01 F
TAUE = 0.146E+01
PALFY = 0.717E+06
PFUS = 0.114E+10
WPA = 0.230E+07
A = 0.139E+01 F
AR = 0.418E+01 F
SIGMA = 0.160E+01 F
**SUM OF SQUARES = 0.2105E-02 AFTER 21 ITERATIONS**

**CURRENT SOLUTION:**

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<td>PRF</td>
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</tr>
<tr>
<td>CI</td>
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<td></td>
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<tr>
<td>CE</td>
<td>0.724E+00</td>
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</tr>
<tr>
<td>IP</td>
<td>0.526E+07</td>
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<tr>
<td>TI</td>
<td>0.120E+02</td>
<td>$F$</td>
</tr>
<tr>
<td>TE</td>
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<td>$F$</td>
</tr>
<tr>
<td>ZEFF</td>
<td>0.169E+01</td>
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</tr>
<tr>
<td>NI</td>
<td>0.171E+21</td>
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</tr>
<tr>
<td>NE</td>
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<td></td>
</tr>
<tr>
<td>NZ</td>
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<tr>
<td>Q</td>
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<td>$F$</td>
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<tr>
<td>BETA</td>
<td>0.700E+01</td>
<td>$F$</td>
</tr>
<tr>
<td>BT</td>
<td>0.501E+01</td>
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<td>TAUE</td>
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</tr>
<tr>
<td>A</td>
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</tr>
<tr>
<td>AR</td>
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<td>$F$</td>
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<tr>
<td>SIGMA</td>
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<tr>
<td>PINJ</td>
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<tr>
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</tr>
</tbody>
</table>

A solution has been found.

**TOTAL ALPHA POWER** 0.22728E+03  **MAJOR RADIUS** 0.550886E+01
**INTERNAL INDUCTANCE** 0.577759E-05  **EXTERNAL INDUCTANCE** 0.906846E-05
**INDUCTIVE VOLT-SECONDS** 0.599751E-04  **PLASMA RESISTANCE** 0.880346E-08
**PLASMA VOLTAGE** 0.463276E-01  **DEUTERIUM BURN-UP RATE** 0.405351E+21
**DEUTERIUM DIFFUSION LOSS RATE** 0.185700E+23  **FRACTION OF FUEL BURNED** 0.213620E-01
SUM OF SQUARES * 2105E-02  FTOL = 1.0  IFAIL = 0

RESIDUALS:
4.9335E-03  3.2210E-04  4.6944E-03  5.6937E-03  2.3134E-03  9.2221E-04  8.9035E-03  3.7221E-02  3.5760E-03  1.7076E-02
-1.0921E-02  5.2487E-04

THIS SOLUTION DOES SATISFY PHYSICS EQUATIONS WITHIN 1.0%

EQUATION 1 IS BALANCED WITHIN 0.01%
EQUATION 2 IS BALANCED WITHIN 0.07%
EQUATION 3 IS BALANCED WITHIN 0.01%
EQUATION 4 IS BALANCED WITHIN 0.00%
EQUATION 5 IS BALANCED WITHIN 0.01%
EQUATION 6 IS BALANCED WITHIN 0.01%
EQUATION 7 IS BALANCED WITHIN 0.00%
EQUATION 8 IS BALANCED WITHIN 0.01%
EQUATION 9 IS BALANCED WITHIN 0.01%
EQUATION 10 IS BALANCED WITHIN 0.01%

NORMALIZED X:
1.1234E+00  1.0081E+00  1.1174E+00  9.3063E-01  9.7687E-01  7.7793E-02  1.0965E-01  6.9167E-02  9.1060E-01  5.7310E-01
7.2698E-01  1.0525E+00

TI = 0.1206E+02 F
TE = 0.1206E+02 F
ZEFF = 0.1369E+01
MI = 0.1716E+21
ME = 0.1900E+21
NJ = 0.2336E+19
G = 0.3800E+01 F
BETA = 0.7000E+01 F
BT = 0.5010E+01 F
TAUE = 0.1478E+01
PALFV = 0.7160E+06
FFUS = 0.1160E+10
WPA = 0.2292E+07
A = 0.1348E+01 F
AR = 0.4480E+01 F
SIGMA = 0.1600E+01 F
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Plasma radius (M)</td>
<td>1.340</td>
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<tr>
<td>Aspect ratio</td>
<td>4.179</td>
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<td>1.600</td>
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<td>Beta</td>
<td>0.070</td>
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<tr>
<td>Field on axis (T)</td>
<td>5.010</td>
</tr>
<tr>
<td>Ion temp (kev)</td>
<td>12.000</td>
</tr>
<tr>
<td>Ele temp (kev)</td>
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<tr>
<td>Ripple (%)</td>
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<td>Plasma ind (h)</td>
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<td>Ion density (/m**3)</td>
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<tr>
<td>Ele density (/m**3)</td>
<td>.1900E+21</td>
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<tr>
<td>Impurity conc.</td>
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<tr>
<td>Impurity z</td>
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<tr>
<td>Zeff</td>
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<tr>
<td>Ntau (sec/m**3)</td>
<td>.2783E+21</td>
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<td>Tau (sec)</td>
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<tr>
<td>Tau-emp (sec)</td>
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<tr>
<td>Tau-tp (sec)</td>
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<tr>
<td>Beam power (MW)</td>
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<tr>
<td>Beam energy (kev)</td>
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<tr>
<td>Plasma edge neu. load (MW/m**2)</td>
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<tr>
<td>Fusion power (MW)</td>
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<tr>
<td>Alpha (MW)</td>
<td>227.28</td>
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<tr>
<td>Radiation (MW)</td>
<td>32.35</td>
</tr>
<tr>
<td>Elec. power (MW)</td>
<td>399.90</td>
</tr>
</tbody>
</table>
File ETFOD.OUT (Example 2)

1 0.1200E+02 F TI (KEV)
2 0.1200E+02 F TE 'KEV)
3 0.1500E+01 P ZEFF
4 0.1700E+21 P N (M^4-3)
5 0.1700E+21 P WE (M^4-3)
6 0.1700E+19 P N (M^4-3)
7 0.3000E+01 F Q (SAFETY FACTOR)
8 0.7000E-01 F BETA
9 0.5010E+01 F BT (TESLA)
10 0.1500E+01 U TAUE (SEC)
11 0.9200E+07 U PALFV (M^4#3)
12 0.1042E+11 U PFUS (W)
13 0.3300E+08 F MPA (M^4#2)
14 0.1300E+01 F A (M)
15 0.1789E+01 F AR
16 0.1600E+01 F SIGMA
17 0.0000E+00 F PINJ (W)
18 0.1000E-23 P PPF (W)
19 0.1000E+01 P CI
20 0.1000E+01 P CE
21 0.5000E+07 U IP (AMPS)

WHERE:
F=FIXED VALUE
P=PREFERRED VALUE
U=UNKNOWN VALUE

ITOL = 1.000000E-01 FTOL = 1.000000E-06
STEPX = 1.000000E-01

SUM OF SQUARES = 0.0000

RESIDUALS:
2.541E-07 1.533E+01 5.023E-01 9.278E+00 9.234E+00 2.293E+00 7.173E+00 1.099E+00 3.672E+00 5.260E+01
0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00 0.0000E+00
0.0000E+00 0.0000E+00 0.0000E+00

SUM OF SQUARES = 5003E+03 AFTER 0 ITERATIONS
SING = F (IF TRUE, RANDOM POINT HAS BEEN USED)
CURRENT SOLUTION:
1.0000E+00 1.0000E+00 1.0000E+00 1.0000E+00 1.0000E+00 1.0000E+00 1.0000E+00 1.0000E+00 1.0000E+00
1.0000E+00 1.0000E+00

XTOL = 1.000000E-01 FTOL = 1.000000E-06
SUM OF SQUARES = 0.0000

OITERATIONS
SING = F (IF TRUE, RANDOM POINT HAS BEEN USED)
CURRENT SOLUTION:
PFUS = 0.156E+11
WPA = 0.330E+08
A = 0.134E+01 F
AR = 0.418E+01 F
SIGMA = 0.160E+01 F
PINJ = 0.600E+00 F
PRF = 0.100E-23
CI = 0.100E+01
CE = 0.100E+01
IP = 0.750E+07

SUM OF squares = 1.011E+03 AFTER 8 ITERATIONS
SING = F (IF TRUE, RANDOM POINT HAS BEEN USED)
CURRENT SOLUTION:
1.486E-00 9.851E-01 9.376E-01 1.046E+00 6.61E-01 1.000E+00 6.555E-01 1.000E+00 7.237E-01
9.862E-01 1.019E+00
THE VALUE OF AN X WAS CONSTRAINED BY STEPMX

TI = 0.120E+02 F
TE = 0.120E+02 F
ZEPF = 0.223E-01
NZ = 0.167E+21
WE = 0.234E+21
N = 0.497E+19
Q = 0.380E+01 F
MET = 0.700E-01
BT = 0.501E+01 F
TAUE = 0.157E+01
PALFV = 0.615E+07
PFUS = 0.324E+11
WPA = 0.220E+08
A = 0.134E+01 F
AR = 0.418E+01 F
SIGMA = 0.160E+01 F
PINJ = 0.600E+00 F
PRF = 0.100E-23
CI = 0.724E+00
CE = 0.386E+00
IP = 0.109E+07
SUM OF SQUARES = .1994E+02 AFTER 2 ITERATIONS
SING = F (IF TRUE, RANDOM POINT HAS BEEN USED)
CURRENT SOLUTION:
1.957E-01 9.729E-01 1.253E+00 8.231E-01 1.005E+00 3.353E-01 5.000E-01 3.310E-01 9.835E-01 6.731E-01
8.975E-01 1.038E+00

THE VALUE OF AN X WAS CONSTRAINED BY STEPMX

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
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<tbody>
<tr>
<td>TI</td>
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</tr>
<tr>
<td>TE</td>
<td>0.120E+02 F</td>
</tr>
<tr>
<td>IEFF</td>
<td>0.219E+01</td>
</tr>
<tr>
<td>NI</td>
<td>0.165E+21</td>
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<tr>
<td>NE</td>
<td>0.213E+21</td>
</tr>
<tr>
<td>NZ</td>
<td>0.444E+19</td>
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<tr>
<td>Q</td>
<td>0.380E+01 F</td>
</tr>
<tr>
<td>BETA</td>
<td>0.700E-01 F</td>
</tr>
<tr>
<td>BT</td>
<td>0.501E+01 F</td>
</tr>
<tr>
<td>TAU</td>
<td>0.158E+01</td>
</tr>
<tr>
<td>PALFY</td>
<td>0.309E+07</td>
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<tr>
<td>PFUS</td>
<td>0.521E+10</td>
</tr>
<tr>
<td>WPA</td>
<td>0.109E+08</td>
</tr>
<tr>
<td>A</td>
<td>0.134E+01 F</td>
</tr>
<tr>
<td>AR</td>
<td>0.418E+01 F</td>
</tr>
<tr>
<td>SIGMA</td>
<td>0.160E+01 F</td>
</tr>
<tr>
<td>PINJ</td>
<td>0.000E+00 F</td>
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<tr>
<td>PFP</td>
<td>0.944E-27</td>
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<tr>
<td>CI</td>
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<td>CE</td>
<td>0.698E+00</td>
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<tr>
<td>IF</td>
<td>0.519E+07</td>
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</tbody>
</table>

SUM OF SQUARES = .3025E-02 AFTER 3 ITERATIONS
SING = F (IF TRUE, RANDOM POINT HAS BEEN USED)
CURRENT SOLUTION:
1.909E-00 9.669E-01 1.149E+00 7.718E-01 1.057E+00 7.155E-02 1.154E-01 6.786E-02 9.554E-01 5.282E-01
8.740E-01 1.053E+00

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
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<tbody>
<tr>
<td>TI</td>
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</tr>
<tr>
<td>TE</td>
<td>0.120E+02 F</td>
</tr>
<tr>
<td>Variable</td>
<td>Value</td>
</tr>
<tr>
<td>----------</td>
<td>-----------</td>
</tr>
<tr>
<td>ZEFF</td>
<td>0.211E+01</td>
</tr>
<tr>
<td>MI</td>
<td>0.164E+21</td>
</tr>
<tr>
<td>ME</td>
<td>0.195E+21</td>
</tr>
<tr>
<td>NZ</td>
<td>0.385E+19</td>
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<tr>
<td>Q</td>
<td>0.380E+01</td>
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<tr>
<td>BETA</td>
<td>0.700E-01</td>
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<td>BT</td>
<td>0.501E+01</td>
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<tr>
<td>TAU</td>
<td>0.159E+01</td>
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<tr>
<td>PALFY</td>
<td>0.658E+06</td>
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<tr>
<td>PFUS</td>
<td>0.105E+10</td>
</tr>
<tr>
<td>WPA</td>
<td>0.211E+07</td>
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<tr>
<td>A</td>
<td>0.134E+01</td>
</tr>
<tr>
<td>AR</td>
<td>0.118E+01</td>
</tr>
<tr>
<td>SIGMA</td>
<td>0.160E+01</td>
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<tr>
<td>PINJ</td>
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<td>CE</td>
<td>0.874E+00</td>
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<td>IP</td>
<td>0.526E+07</td>
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</tbody>
</table>

SUM OF SQUARES = 1.110E-01 AFTER % ITERATIONS
STNG = F (IF TRUE, RANDOM POINT HAS BEEN USED)

CONVERGENCE SOLUTION:
1.124E+00 9.699E-01 1.147E+00 6.976E-01 1.069E+00 7.183E-02 1.013E-01 6.412E-02 1.062E+00 6.517E-01 8.928E-01 1.053E+00

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
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<tbody>
<tr>
<td>TI</td>
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<tr>
<td>TE</td>
<td>0.120E+02</td>
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<tr>
<td>ZEFF</td>
<td>0.208E+01</td>
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<tr>
<td>MI</td>
<td>0.165E+21</td>
</tr>
<tr>
<td>ME</td>
<td>0.195E+21</td>
</tr>
<tr>
<td>NZ</td>
<td>0.377E+19</td>
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<tr>
<td>Q</td>
<td>0.380E+01</td>
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<tr>
<td>BETA</td>
<td>0.700E-01</td>
</tr>
<tr>
<td>BT</td>
<td>0.501E+01</td>
</tr>
<tr>
<td>TAU</td>
<td>0.160E+01</td>
</tr>
<tr>
<td>PALFY</td>
<td>0.661E+06</td>
</tr>
<tr>
<td>PFUS</td>
<td>0.106E+10</td>
</tr>
<tr>
<td>WPA</td>
<td>0.212E+07</td>
</tr>
<tr>
<td>A</td>
<td>0.134E+01</td>
</tr>
</tbody>
</table>
AR = 0.418E+01  F
SIGMA = 0.160E+01  F
PINJ = 0.000E+00  F
PRF = 0.106E-23
CI = 0.852E+00
CE = 0.893E+00
IP = 0.526E+07

SUM OF SQUARES = .11676-01 AFTER 5 ITERATIONS
SING = F (IF TRUE, RANDOM POINT HAS BEEN USED)
CURRENT SOLUTION:
1.3586*00 9.73*16-01 1.144B*00 6.726E-01 1.041B*00 7.278E-02
1.026S-01 6.4966-02 8.6626-01 6.488E-01
8.170E-01 1.053E+00

TI = 0.120E+02  F
TE = 0.120E+02  F
IEFF = 0.204E+01
NI = 0.165E+21
NE = 0.195E+21
NZ = 0.363E+19
Q = 0.380E+01  F
BETA = 0.700E-01  F
BT = 0.501E+01  F
TAUE = 0.156E+01
PALFY = 0.670E+06
PFUS = 0.107E+10
WPA = 0.214E+07
A = 0.134E+01  F
AR = 0.418E+01  F
SIGMA = 0.160E+01  F
PINJ = 0.000E+00  F
PRF = 0.866E+24
CI = 0.649E+00
CE = 0.380E+01
IP = 0.526E+07

SUM OF SQUARES = .23786*02 AFTER 6 ITERATIONS
SING = T (IF TRUE, RANDOM POINT HAS BEEN USED)
CURRENT SOLUTION:
SUM OF SQUARES = .5602E-02 AFTER 25 ITERATIONS
SING = F (IF TRUE, RANDOM POINT HAS BEEN USED)
CURRENT SOLUTION:
1.306E+00 1.19S5E+00 1.093E+00 6.102E-01 1.285E+00 9.250E-02 3.212E-01 2.800E-01 9.750E-01 6.714E-01
1.084E+00 1.240E+00
 TI = 0.120E+02 F
 TE = 0.120E+02 F
 ZEFF = 0.196E+01
 WI = 0.203E+21
 WE = 0.186E+21
 WZ = 0.329E+19
 Q = 0.380E+01 F
 BETA = 0.700E-01 F
 BT = 0.501E+01 F
 TAUR = 0.193E+01
 PALFV = 0.851E+06
 PFW3 = 0.335E+10
 WPA = 0.924E+07
 A = 0.134E+01 F
 AR = 0.418E+01 F
 SIGMA = 0.160E+01 F
 PINJ = 0.000E+00 F
 PRF = 0.976E-24
 CI = 0.671E+00
 CE = 0.108E+01
 IF = 0.620E+07

.
ME = 0.195E+21
MZ = 0.376E+19
Q = 0.380E+01 F
BETA = 0.700E-01 F
BT = 0.501E+01 F
TAUE = 0.159E+01
PAlFY = 0.657E+06
PFUS = 0.105E+10
WPA = 0.210E+07
A = 0.138E+01 F
AR = 0.418E+01 F
SIGMA = 0.160E+01 F
PINJ = 0.000E+00 F
EF = 0.100E-23
CI = 0.850E+00
CE = 0.863E+00
IP = 0.526E+07

SUM OF SQUARES = 0.4619E-02 AFTER 26 ITERATIONS
SING  =  F (IF TRUE, RANDOM POINT HAS BEEN USED)
CURRENT SOLUTION:
1.379E+00 9.711E-01 1.146E+00 6.888E-01 1.052E+00 7.217E-02 1.019E-01 6.453E-02 9.740E-01 7.868E-01 8.596E-01 1.053E+00

TI = 0.120E+02 F
TE = 0.120E+02 F
ZEFF = 0.207E+01
MI = 0.165E+21
ME = 0.195E+21
MZ = 0.372E+19
Q = 0.380E+01 F
BETA = 0.700E+01 F
BT = 0.501E+01 F
TAUE = 0.158E+01
PAlFY = 0.664E+06
PFUS = 0.106E+10
WPA = 0.213E+07
A = 0.138E+01 F
AR = 0.418E+01 F
SIGMA = 0.160E+01 F
FINJ = 0.0000E+00 F
PRF = 0.971E-24
CI = 0.787E+00
CE = 0.860E+00
IP = 0.527E+07

SUM OF SQUARES = 0.2525E-02 AFTER 27 ITERATIONS
SING = F (IF TRUE, RANDOM POINT HAS BEEN USED)
CURRENT SOLUTION:
1.389E+00 9.699E-01 1.148E+00 6.993E-01 1.056E+00 7.198E-02 1.014E-01 6.162E-01 8.667E-01 1.052E+00
0.1206E+02 F
0.1206E+02 F
0.208E+01
0.165E+21
0.195E+21
0.378E+19
0.306E+01 F
0.700E-01 F
0.501E+01 F
0.158E+01
0.662E+06
0.106E+10
0.712E+07
0.139E+01 F
0.418E+01 F
0.160E-01 F
0.000E+00 F
0.953E-28
0.616E+00
0.867E+00
0.526E+07

A SOLUTION HAS BEEN FOUND.

TOTAL ALPHA POWER 0.209814E+03 MAJOR RADIUS 0.559968E+01
INTERNAL INDUCTION 0.527759E-05 EXTERNAL INDUCTION 0.89684E+05
INDUCTIVE VOLT-SECONDS 0.599928E-04 PLASMA RESISTANCE 0.109192E-07
PLASMA VOLTAGE 0.57462E+01 DEUTERIUM BURN-UP RATE 0.37420E+21
DEUTERIUM DIFFUSION LOSS RATE 0.165004E+23 FRACTION OF FUEL BURNED 0.221753E+01
SUM OF SQUARES = .233E-02  FTOL =-1.0  IFAIL = 0

RESIDUALS:
-1.0218E-03 1.0623E-03-2.594E-04-7.4855E-04-1.6471E-03 1.9612E-03 1.3849E-03 1.2088E-03 .52465E-04 5.5625E-05
1.5671E-02-1.2298E-03 5.9087E-03-1.1925E-02 5.7077E-04-9.2819E-03-8.9862E-03-3.7431E-02-2.2454E-03-1.7202E-02
5.2006E-03 5.2607E-04

THIS SOLUTION DOES SATISFY PHYSICS EQUATIONS WITHIN 1.0%

EQUATION 1 IS BALANCED WITHIN -0.01%
EQUATION 2 IS BALANCED WITHIN 0.01%
EQUATION 3 IS BALANCED WITHIN -0.00%
EQUATION 4 IS BALANCED WITHIN -0.01%
EQUATION 5 IS BALANCED WITHIN -0.02%
EQUATION 6 IS BALANCED WITHIN 0.02%
EQUATION 7 IS BALANCED WITHIN 0.01%
EQUATION 8 IS BALANCED WITHIN 0.01%
EQUATION 9 IS BALANCED WITHIN 0.01%
EQUATION 10 IS BALANCED WITHIN 0.00%

NORMALIZED X:
1.3918E+00 9.6925E-01 1.1477E+00 7.0188E-01 1.0571E+00 7.1865E-02 1.0138E-01 6.4218E-02 9.4386E-01 5.6995E-01
8.6999E-01 1.0526E+00

TI  = 0.120E+02 F
TE  = 0.120E+02 F
ZEFF = 0.209E+01
NI  = 0.165E+21
NE  = 0.195E+21
WZ  = 0.379E+19
Q   = 0.380E+01 F
BETA = 0.790E-01 F
ST  = 0.501E+01 F
TAUE = 0.159E+01
PALFY = 0.661E+06
PFUS = 0.106E+10
WPA = 0.212E+07
A   = 0.134E+01 F
AR  = 0.418E+01 F
SIGMA = 0.160E+01 F
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<tr>
<th>Parameter</th>
<th>Value</th>
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<tr>
<td>Plasma Radius (M)</td>
<td>1.340</td>
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<tr>
<td>Aspect Ratio</td>
<td>4.179</td>
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<tr>
<td>Elongation</td>
<td>1.600</td>
</tr>
<tr>
<td>Beta</td>
<td>0.070</td>
</tr>
<tr>
<td>Field on Axis (T)</td>
<td>5.010</td>
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<tr>
<td>Ion Temp (KEV)</td>
<td>12.000</td>
</tr>
<tr>
<td>Ele Temp (KEV)</td>
<td>12.000</td>
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<tr>
<td>Ripple (%)</td>
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<tr>
<td>Major Radius (M)</td>
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<tr>
<td>Plasma Height (M)</td>
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<tr>
<td>Plasma Volum (M³)</td>
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<tr>
<td>Plasma Ind (H)</td>
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<tr>
<td>Ion Density (/M³)</td>
<td>1.648E+21</td>
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<tr>
<td>Ele Density (/M³)</td>
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<tr>
<td>Impurity Concent.</td>
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<td>Impurity Z</td>
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<td>Zeff</td>
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<td>Ntau (SEC/M³)</td>
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<td>Taue-emp (SEC)</td>
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<td>Taue-tp (SEC)</td>
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<td>Beam Power (MW)</td>
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<td>Beam Energy (KEV)</td>
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<td>Plasma Edge Neu. Load (MW/M²)</td>
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<td>Fusion Power (MW)</td>
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<td>Alpha (MW)</td>
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<td>Radiation (MW)</td>
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<td>Elec. Power (MW)</td>
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