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A General Fluid System Simulation Program to Model Secondary Flows in Turbomachinery

Alok K Majumdar
Sverdrup Technology Inc.,
Huntsville, Alabama

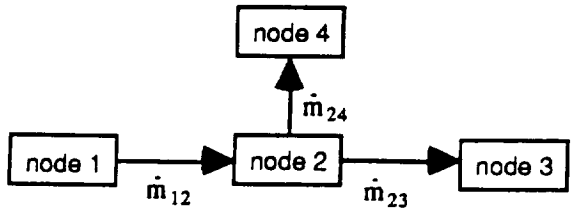
Katherine P Van Hooser
Marshall Space Flight Center
Huntsville, Alabama

INTRODUCTION

Because of the complexity and variety of turbomachinery flow circuits, it is desirable to have a robust, modular, and "user-friendly" computer program to model internal flow rates, pressures, temperatures, and axial thrusts. The objective of this paper is to present a Generalized Fluid System Simulation Program (GFSSP) that has been developed to support Marshall Space Flight Center's turbomachinery internal flow analysis efforts. The paper describes (1) the computational procedure for predicting flow and thermal environment in complex flow circuit involving compressible flow of gas mixtures, (2) the structure and use of the program, (3) the application of the program to model a portion of the internal or secondary flow circuit (Figure 3) of the Alternate High Pressure Oxidizer Turbopump (HPOTP-AT) of the Space Shuttle Main Engine (SSME), and (4) validation of computer predictions by comparison with SSME test data.

METHODOLOGY

Compressible flow analysis of gas mixture involving a change of phase in a complex network requires the simultaneous solution of mass, energy, and species conservation equations in each internal node as well as flowrate equation in each branch of the circuit. A sample circuit and the equations that describe it are listed below.



CONSERVATION EQUATIONS FOR NODE 2

Mass Conservation Equation: $\dot{m}_{12} = \dot{m}_{23} + \dot{m}_{24}$ (1)

Energy Conservation Equation: $\dot{m}_{12}h_1 = \dot{m}_{23}h_2 + \dot{m}_{24}h_2$ (2)

Species "A" Concentration Equation: $\dot{m}_{12}x_1^A = \dot{m}_{23}x_2^A + \dot{m}_{24}x_2^A$ (3)

Flowrate Equation for branch 1-2:

Unchoked Flow

If $\frac{p_2}{p_1} > p_{cr}$, the flowrate in the branch is calculated from

$$p_1 - p_2 = k_{12} \cdot 2\dot{m}_{12}|\dot{m}_{12}| \quad \text{where} \quad k_{12} = \frac{1}{2\rho_1 C_{L_{12}}^2 A_{12}^2} \tag{4}$$

Choked Flow

If $\frac{p_2}{p_1} < p_{cr}$, the flowrate in the branch is calculated from

$$\dot{m}_{12} = C_{L_{12}} A_{12} \sqrt{p_1 \rho_1 \frac{2\gamma}{\gamma - 1} (p_{cr})^{\frac{2}{\gamma}} \left[1 - (p_{cr})^{\frac{\gamma-1}{\gamma}}\right]} \tag{5}$$

where $p_{cr} = \left(\frac{2}{\gamma + 1}\right)^{\frac{1}{\gamma - 1}}$.

$\dot{m}$, p, h, x, ρ, A, and C_L are flowrate, pressure, enthalpy, concentration, density, area, and flow coefficient respectively. The flowrate equations (4 & 5) require density of the fluid at the upstream node. Density is a function of pressure, temperature, and species concentration. The density of the mixture is computed from the law of partial pressure. Mixture density is expressed in terms of density of the individual species, molar concentrations, and gas constant. Real gas properties are computed from a thermodynamic property code GASP** which calculates thermodynamic and transport properties for 10 pure fluids.

The system of equations (1 through 5) are solved by the Newton-Raphson method. In this method, the solution of a set of non-linear equations is achieved through an iterative guess and correction procedure. Instead of solving for the variables directly, correction equations are constructed for all variables. The intent of the correction equations is to eliminate error. The correction equations are constructed in two steps. Residual errors in all equations are estimated. The partial derivatives of all equations with respect to each variable are calculated. The correction equations are then solved by the Gaussian elimination method. Corrections are then applied to each variable and this completes one iteration. The same cycle of calculations is repeated until the residual error in all equations are reduced to an acceptable limit.

COMPUTER PROGRAM

A modular program structure has been adopted. The flow chart of the program appears in Figure 4. It can be seen from the flowchart that MAIN controls all activities, while individual activities are performed in major subroutines shown in the flow chart. Several utility subroutines feed the major subroutines; they are not shown in the flow chart for clarity. The user generates the network interactively (PREPROP) and the data can be stored (WRITEIN) in a file. This stored file can then be used (READIN) for running parametric studies.

RESULTS

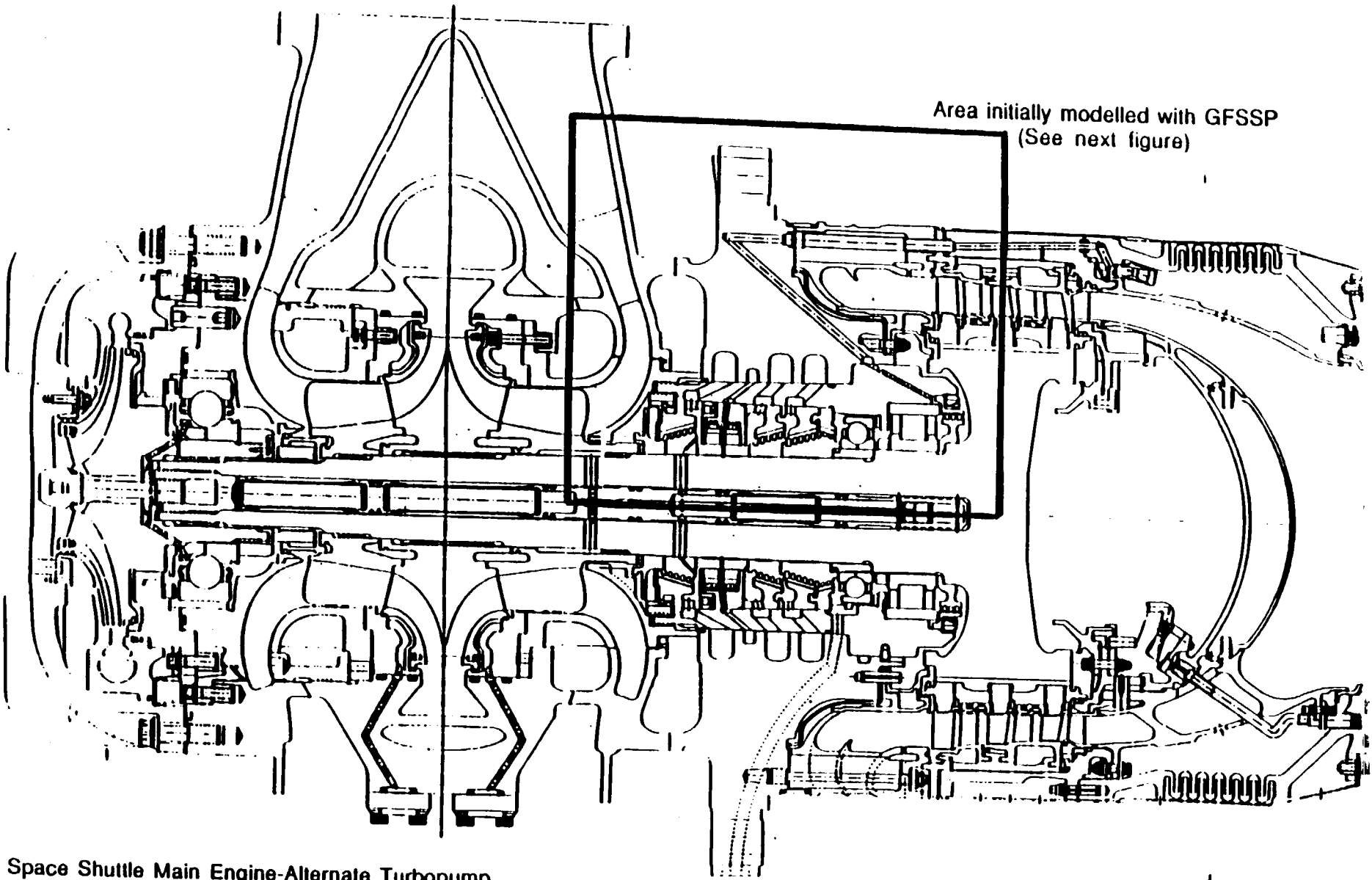
GFSSP has been used to model internal flows of the SSME HPOTP-AT (Figure 1). Results will be used for design review and test data anomaly resolution. The portion of the flow circuit modeled with GFSSP is shown in Figures 2 & 3. Pressures and temperatures are specified by the user at the boundary nodes. The computed results are also shown in the figure. The pressures and flowrates compare well with SSME test data. The code also computes the temperatures and concentrations of each constituent at all nodes. The full paper will contain a detailed comparison of predictions with test data.

CONCLUSIONS

A computational procedure to solve coupled mass, momentum, energy, and species conservation equations has been developed. The procedure uses real gas properties to compute mixture density and temperatures. The numerical procedure and the gas property code have been incorporated in a user-friendly computer code. No knowledge of programming language or numerical method techniques is necessary to operate the code and interpret the calculated results. The code has been validated by comparing the predictions with test data.

** GASP -- A Computer Code for Calculating the Thermodynamic and Transport Properties for Ten Fluids: Parahydrogen, Helium, Neon, Methane, Nitrogen, Carbon Monoxide, Oxygen, Fluorine, Argon, and Carbon Dioxide. Robert C. Hendricks, Anne K. Baron, and Ildiko C. Peller; Lewis Research Center, Report No. NASA TN D-7808, February 1975.

Figure 1



Space Shuttle Main Engine-Alternate Turbopump
High Pressure Oxidizer Turbopump
(SSME-AT HPOTP)

Figure 2

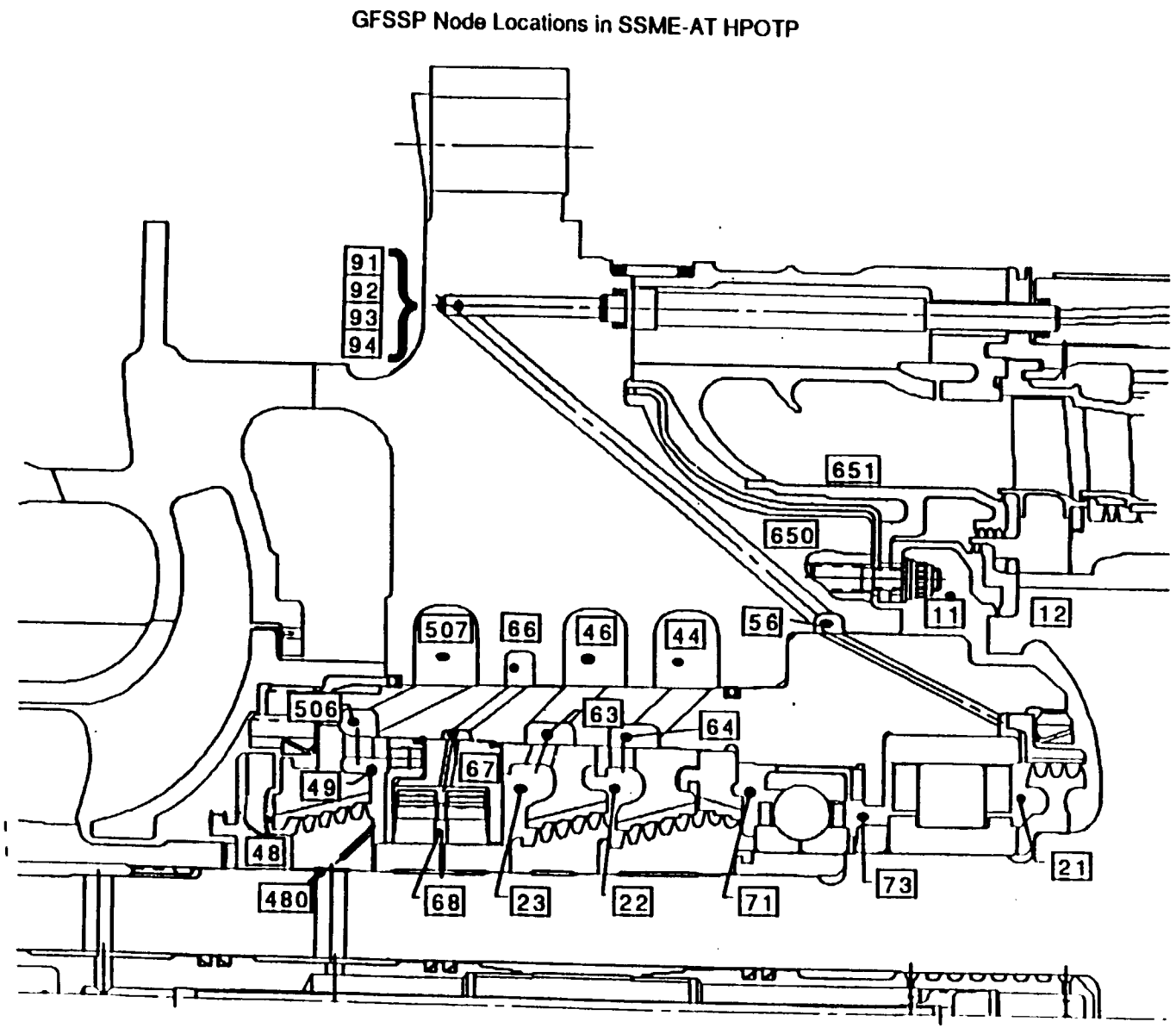

GFSSP Node Locations in SSME-AT HPOTP
91
92
93
94
651
650
56
11
12
507
66
46
44
506
63
64
67
49
48
480
68
23
22
71
73
21

Figure 3

Inter Propellant Seal Flow Circuit of Alternate High Pressure Oxidizer Turbopump

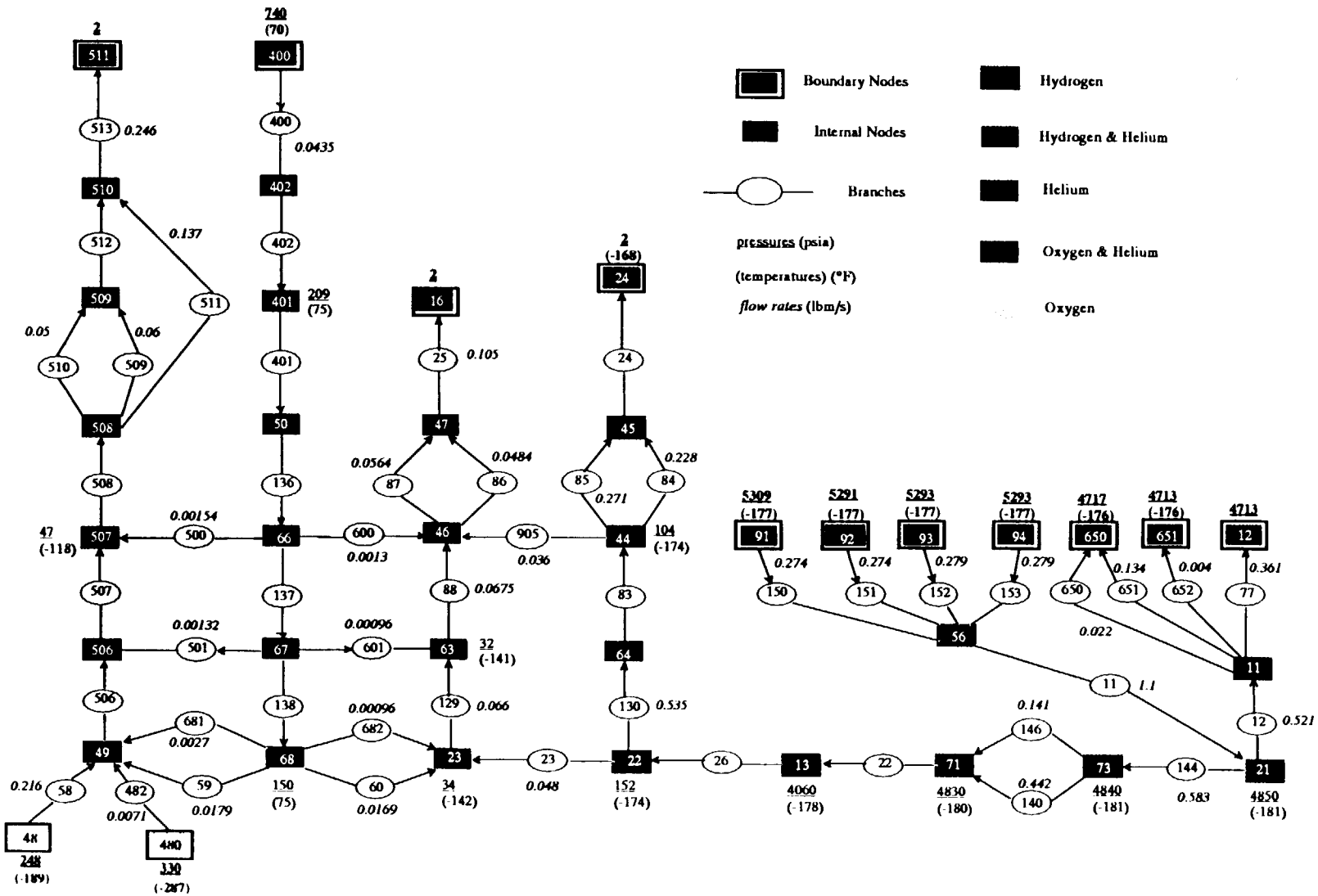
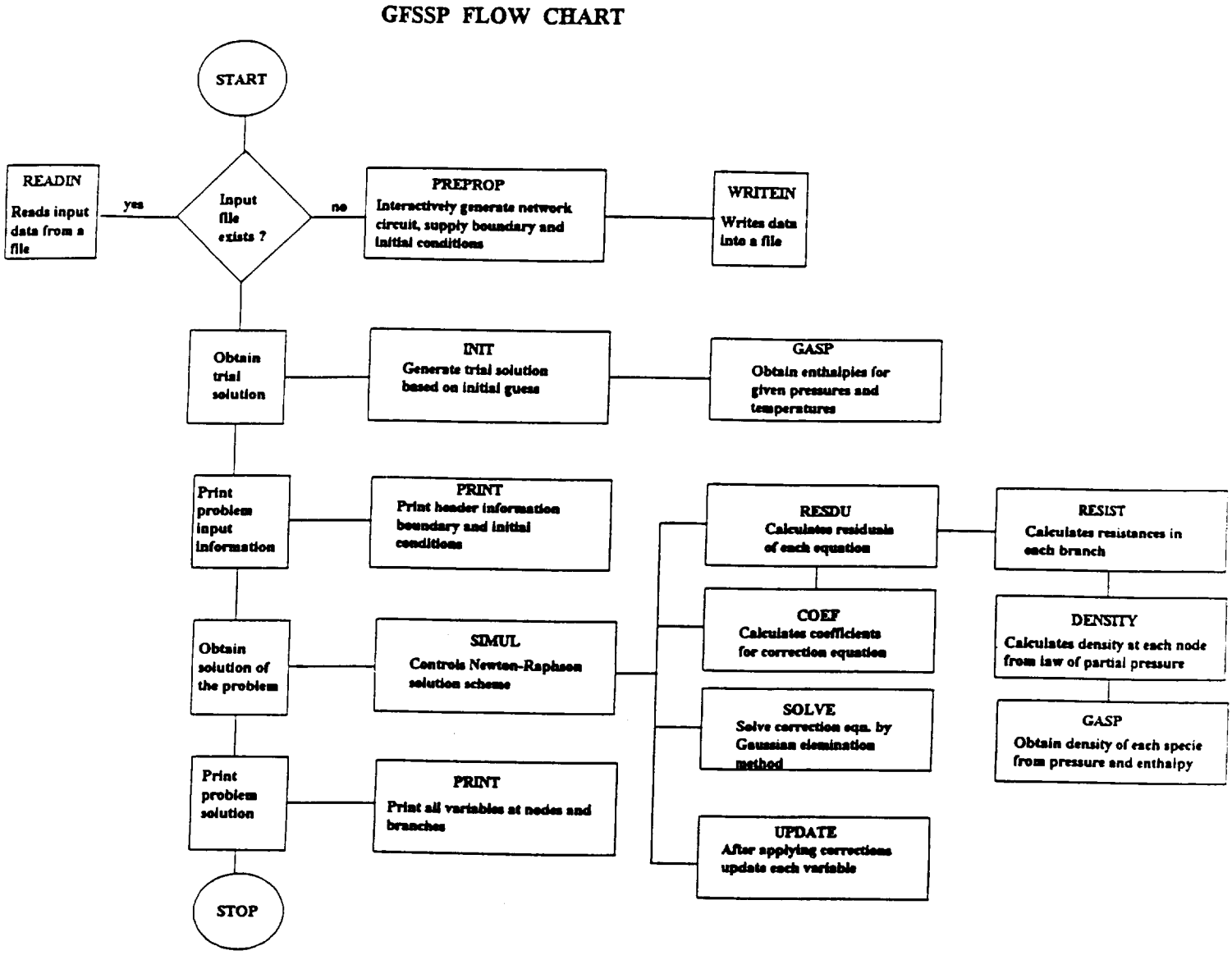


Figure 4


GFSSP FLOW CHART
START
READIN
Reads input data from a file
yes
Input file exists ?
no
PREPROP
Interactively generate network circuit, supply boundary and initial conditions
WRITEIN
Writes data into a file
Obtain trial solution
INIT
Generate trial solution based on initial guess
GASP
Obtain enthalpies for given pressures and temperatures
Print problem input information
PRINT
Print header information boundary and initial conditions
Obtain solution of the problem
SIMUL
Controls Newton-Raphson solution scheme
Print problem solution
PRINT
Print all variables at nodes and branches
STOP
RESDU
Calculates residuals of each equation
COEF
Calculates coefficients for correction equation
SOLVE
Solve correction eqn. by Gaussian elemination method
UPDATE
After applying corrections update each variable
RESIST
Calculates resistances in each branch
DENSITY
Calculates density at each node from law of partial pressure
GASP
Obtain density of each specie from pressure and enthalpy