SOLA-STAR:
A One-Dimensional
ICED-ALE Hydrodynamics Program for
Spherically Symmetric Flows

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L. D. Cloutman
SOLA-STAR: A ONE-DIMENSIONAL ICED-ALE HYDRODYNAMICS
PROGRAM FOR SPHERICALLY SYMMETRIC FLOWS

by

L. D. Cloutman

ABSTRACT

This report describes a simple, general-purpose, and efficient algorithm for solving one-dimensional spherically symmetric, transient fluid-dynamics problems using a variation of the ICED-ALE technique. Included are the finite difference equations, three test problems that illustrate various capabilities of the program, and a complete code description, including a listing, sample data decks and output, a summary of important variable names, and hints for conversion to other operating systems.

I. INTRODUCTION

Several years ago we reported a technique for implementing the ICED-ALE methodology in a form suitable for numerically simulating a wide variety of spherically symmetric fluid flows. An experimental computer program, VEGA, was written to test this methodology and was applied to the star formation problem. Although that technique was designed for astrophysical applications, it is by no means limited to them. In the interim, Group T-3 has developed the SOLA series of simplified numerical fluid dynamics programs specifically for public distribution. In response to requests for copies of the VEGA program, we are presenting a simplified version, SOLA-STAR, in this report. This code follows the philosophy of the SOLA series inasmuch as the code is easy to understand and use, it can be used by persons with little numerical fluid dynamics experience, it is easily modified to include more complicated physics, and it is useful both as a teaching device and a serious research tool.
The numerical algorithm used in the present program is basically the same as reported in Ref. 1, so no derivation of the difference equations will be presented in this report. The derivation is based on a volume integration of the governing equations, and the interested reader can find the details in Refs. 1 and 4-6. The algorithm consists of two phases. Phase I is a partially implicit Lagrangian time step. In Phase II, the solution is rezoned (if desired) in a physically motivated manner that conserves mass, momentum, and internal energy. The only stability requirement is that

\[
\frac{|u| \delta t}{\delta r} < 1
\]  

(1)
everywhere on the mesh, where \( u \) is the velocity, \( \delta t \) is the time step, and \( \delta r \) is the width of a computational mesh cell. This limit requires that the fluid moves less than one cell width each computational cycle. Observance of this limit, proper choice of the donor cell parameter \( \alpha \) (to be described later), and choosing the time step such that no variable changes its value by more than some small amount, say 20\%, has been sufficient to achieve numerical stability for all of the problems that we have run. A more detailed discussion of stability of the method (and of many other aspects of the method) can be found in Ref. 1.

II. EQUATIONS FOR SPHERICALLY SYMMETRIC FLOWS

To simplify the program and minimize both computing time and core requirements, SOLA-STAR assumes a single-component ideal gas. The differential equations that we model are

\[
\frac{\partial p}{\partial t} + \frac{1}{r^2} \frac{\partial}{\partial r} (r^2 \rho u) = 0 ,
\]  

(2)

\[
\frac{\partial \rho u}{\partial t} + \frac{1}{r^2} \frac{\partial}{\partial r} (r^2 \rho u^2) = -\rho g - \frac{\partial p}{\partial r} + \frac{1}{r^2} \frac{\partial}{\partial r} \left( r^2 (2\mu + \lambda) \frac{\partial u}{\partial r} \right) - \frac{2u(2\mu + \lambda)}{r^2} + \frac{2u}{r} \frac{\partial \lambda}{\partial r} ,
\]  

(3)
and

\[
\frac{\partial \rho I}{\partial t} + \frac{1}{r} \frac{\partial}{\partial r} \left( r^2 \rho u I \right) = -p \frac{1}{r^2} \frac{\partial}{\partial r} \left( r^2 u \right) + \frac{1}{r^2} \frac{\partial}{\partial r} \left( r^2 K \frac{\partial T}{\partial r} \right) + 2\mu \left( \frac{\partial u}{\partial r} \right)^2 + \frac{2u^2}{r^2} + \lambda \left[ \frac{1}{r^2} \frac{\partial}{\partial r} \left( r^2 u \right) \right]^2,
\]

(4)

where \( t \) is time, \( r \) is radius, \( \rho \) is the density, \( u \) is the radial velocity, \( p \) is the pressure, \( \mu \) is the coefficient of viscosity, \( \lambda \) is the second coefficient of viscosity, \( g \) is the gravitational acceleration, \( I \) is the specific internal energy, \( K \) is the conductivity, and \( T \) is the temperature. Normally we use

\[
\lambda = -\frac{2}{3} \mu,
\]

(5)

which is accurate for an ideal monatomic gas. If experimental values of \( \lambda \) are available for polyatomic gases, they can be used. However, the program will need modification. The gravitational acceleration is computed from a difference approximation to

\[
g = \frac{4\pi G}{r^2} \int_0^r \rho x^2 \, dx,
\]

(6)

where \( G \) is the gravitational constant. This procedure is more accurate than solution of the Poisson equation for the gravitational potential. The set of equations is closed by the equation of state, which we assume to be

\[
p = (\gamma-1) \rho I,
\]

(7)

where \( \gamma \) is the ratio of specific heats.
III. DIFFERENCE EQUATIONS

The SOLA-STAR difference equations are written in terms of the primitive variables $p$, $\rho$, $I$, $r$, and $u$. Furthermore, simple averages are used to find values of variables at points other than those where they are defined. Transformations of variables are frequently advocated as a means of achieving better accuracy on a given computational mesh. However, as discussed in the SOLA-ICE report, this approach has a number of disadvantages and pitfalls for general-purpose programs. First, it is much easier to create conservative difference schemes in the primitive variables. Second, transformations commonly introduce transcendental functions such as square roots and exponentials into the equations, and these functions are expensive to compute. Third, the transformed equations are usually more complicated, resulting in more debugging effort and increased execution time. Fourth, the transformation that gives the best accuracy is problem dependent and, in general, unknown. Heuristic arguments that lead to particular transformations are at best unreliable. Finally, if good resolution is used, all well-behaved transformations will give the same results as the primitive variables.

Advancement of the variables in time is accomplished in two phases. Phase I consists of a partially implicit Lagrangian time step, and Phase II consists of the rezoning procedure. The velocity is defined at cell edges, (or vertices) as shown in Fig. 1, and all other quantities are defined at cell centers.

![Fig. 1.](image)

The SOLA-STAR computing mesh. Cell centers have integer subscripts, and cell edges have half-integer subscripts. We specify the cell edge positions and define the cell center positions by $r_i = 0.5 \times (r_{i+\frac{1}{2}} + r_{i-\frac{1}{2}})$. Cells 1 and $N+1$ are fictitious cells.
The spatial difference approximations for Phase I are derived by integrating the dynamical equations over a control volume taken to be a spherical shell coincident with the computational mesh. This procedure has been adequately described elsewhere, so it will not be repeated here. The equations are written as fully implicit, and then they are made linear in the advanced time quantities. The linearization is illustrated by the equation of state:

\[ \frac{p_{j}^{n+1}}{\rho_{j}^{n+1}} = (\gamma - 1)^{j} \left( \rho_{j}^{n+1} I_{j}^{n+1} + \rho_{j}^{n} I_{j}^{n} - \rho_{j}^{n} I_{j}^{n} \right) \]

where the superscript denotes the time level, and the subscript denotes the spatial computational cell. We have computed protostellar models through central hydrogen dissociation and ionization (where the \( \gamma \) of the gas changes radically) with no sign of instability from the use of the explicit value of \( \gamma \). In such a case we define \( \gamma \) not as the ratio of specific heats, but as \( \gamma - 1 \equiv \frac{P}{\rho I} \). The function \( \gamma - 1 \) is constant over much of the \((\rho, T)\) plane, so a bilinear interpolation is accurate. In the regions of the \((\rho, T)\) plane where \((\gamma - 1)\) is not constant, this interpolation scheme may be preferred over many of the higher order schemes advocated in the literature, including both second and third order polynomials and splines. Indiscriminant use of some of these schemes can introduce spurious oscillations into \( \gamma - 1 \), leading to inaccurate numerical solutions.

Let us write the continuity equation as

\[ \frac{d\rho}{dt} + \rho D = 0 \]

where

\[ D = \frac{1}{r^2} \frac{\partial}{\partial r} \left( r^2 u \right) \]
Define the quantity

\[ \dot{d}_j^n = - \frac{\delta t}{1 + \delta t} d_j^n \]  

(11)

where

\[ d_j^n = \frac{u_{j+\frac{1}{2}}^n - u_{j-\frac{1}{2}}^n}{r_{j+\frac{1}{2}} - r_{j-\frac{1}{2}}} + 2 \frac{u_{j+\frac{1}{2}}^n + u_{j-\frac{1}{2}}^n}{r_{j+\frac{1}{2}} + r_{j-\frac{1}{2}}} \]  

(12)

Then Eq. (9) is approximated by

\[ \rho_j^{n+1} - d_j^n \rho_j^n d_j^{n+1} = \rho_j^n \]  

(13)

which may be expanded to

\[ \rho_j^{n+1} - u_{j+\frac{1}{2}}^{n+1} \rho_j^n d_j^n \left( \frac{2}{r_{j+\frac{1}{2}} + r_{j-\frac{1}{2}}} + \frac{1}{r_{j+\frac{1}{2}} - r_{j-\frac{1}{2}}} \right) - u_{j-\frac{1}{2}}^{n+1} \rho_j^n d_j^n \left( \frac{2}{r_{j+\frac{1}{2}} + r_{j-\frac{1}{2}}} \right) \]

\[ = \rho_j^n \]  

(14)

As with all our difference equations, the geometric quantities (that is, \( r, A, \) and \( V \)) are the old-time values. The left-hand side of Eq. (9) is differenced directly because the control volume integration procedure would provide no immediate information on new densities. It would merely give us the trivial fact that the mass in a cell does not change. The advanced-time cell volume, necessary to compute the advanced time density from the cell mass, is not directly available.
The equation for the specific internal energy may be written as

\[ \frac{\partial \rho I}{\partial t} + \frac{1}{r^2} \frac{\partial}{\partial r} \left( r^2 \rho u I \right) = -p D + \frac{1}{r^2} \frac{\partial}{\partial r} \left( r^2 K \frac{\partial T}{\partial r} \right) + \Phi \]  \quad (15)

For numerical reasons we have found it expedient to define the flux

\[ F = K \frac{\partial T}{\partial r} = K \frac{\partial}{\partial r} \left( \frac{I}{c_v} \right) , \quad (16) \]

and carry along this extra equation. For normal gases, \( K = \frac{\mu c_p}{\text{Pr}} \), where \( \text{Pr} \) is the Prandtl number and \( c_p \) is the specific heat at constant pressure. For stellar problems where we are modeling radiation diffusion, \( K \) is the radiative conductivity. The quantity \( c_v \) is defined as \( I/T \), so it is not always the usual specific heat. It is tabulated and treated numerically the same as \( \gamma-1 \) for the general case. Incidentally, the turbulent conductivity defined by Eq. (28) of Ref. 1 did not work well and was replaced by an estimate based on the mixing length theory. The diffusion term in Eq. (15) is replaced by

\[ \frac{1}{r^2} \frac{\partial}{\partial r} \left( r^2 F \right) . \]

Carrying the additional flux equation is necessary wherever \( \chi \equiv \log_{10}(K \delta t/\rho c_v \delta r^2) \) approaches or exceeds the number of digits carried in the calculation, because the coefficient matrix has a term like \( 1 + 2 \times 10^\chi \). The one gets lost in round off if \( \chi \) is too large, and the matrix package cannot successfully recover the one in the course of solving the linear system.

The expression for the viscous dissipation term in Eq. (15) is
The difference approximation to Eq. (15) is derived by integrating over the
spherical shell between \( r = r_{j-\frac{1}{2}} \) and \( r = r_{j+\frac{1}{2}} \), using the procedure described in
Ref. 1. Define normalized cells volumes

\[
V_{c,j} = r_{j+\frac{1}{2}}^3 - r_{j-\frac{1}{2}}^3 ,
\]

and normalized vertex areas

\[
A_{j-\frac{1}{2}} = 3r_{j-\frac{1}{2}}^2 .
\]

Then

\[
\mathbf{I}_{j}^{n+1} = \mathbf{I}_{j}^{n} + \delta t \left\{ \frac{V_{c,j}}{M_{c,j}} \phi_j + \frac{1}{M_{c,j}} \left[ A_{j+\frac{1}{2}} F_{j+\frac{1}{2}}^{n+1} - A_{j-\frac{1}{2}} F_{j-\frac{1}{2}}^{n+1} \right] \right. \\
- \frac{1}{2M_{c,j}} \left[ p_{j}^{n+1} \left( A_{j+\frac{1}{2}} u_{j+\frac{1}{2}}^{n+1} - A_{j-\frac{1}{2}} u_{j-\frac{1}{2}}^{n+1} \right) + p_{j}^{n} \left( A_{j+\frac{1}{2}} u_{j+\frac{1}{2}}^{n} - A_{j-\frac{1}{2}} u_{j-\frac{1}{2}}^{n} \right) \right] \right\} ,
\]

where
\[ M_{c,j}^n = \rho_{j}^n v_{c,j} \]  \hspace{1cm} (21)

and

\[
\phi_j^n = \mu_j \left\{ 2 \left[ \left( u_{j+\frac{1}{2}}^{n+1} - u_{j-\frac{1}{2}}^{n+1} \right) \left( u_{j+\frac{1}{2}}^{n} - u_{j-\frac{1}{2}}^{n} \right) - \left( u_{j+\frac{1}{2}}^{n} - u_{j-\frac{1}{2}}^{n} \right)^2 \right] \frac{r_{j+\frac{1}{2}} - r_{j-\frac{1}{2}}}{r_{j+\frac{1}{2}} + r_{j-\frac{1}{2}}} \right. 
\]
\[ + \left. 2 \left( u_{j+\frac{1}{2}}^{n+1} + u_{j-\frac{1}{2}}^{n+1} \right) \left( u_{j+\frac{1}{2}}^{n} + u_{j-\frac{1}{2}}^{n} \right) - 2 \left( u_{j+\frac{1}{2}}^{n} + u_{j-\frac{1}{2}}^{n} \right)^2 \right] \frac{r_{j+\frac{1}{2}} - r_{j-\frac{1}{2}}}{r_{j+\frac{1}{2}} + r_{j-\frac{1}{2}}} \] 
\[ - \frac{2}{3(v_{c,j})^2} \left[ 2 \left( A_{j+\frac{1}{2}}^{n+1} u_{j+\frac{1}{2}}^{n+1} - A_{j-\frac{1}{2}}^{n+1} u_{j-\frac{1}{2}}^{n+1} \right) \left( A_{j+\frac{1}{2}}^{n} u_{j+\frac{1}{2}}^{n} - A_{j-\frac{1}{2}}^{n} u_{j-\frac{1}{2}}^{n} \right) \right] 
\[ - \left( A_{j+\frac{1}{2}}^{n+1} u_{j+\frac{1}{2}}^{n+1} - A_{j-\frac{1}{2}}^{n+1} u_{j-\frac{1}{2}}^{n+1} \right)^2 \right\} . \hspace{1cm} (22)

The viscous dissipation term is positive-definite if all velocities are at the same time level, but we lose this physical characteristic by using velocities from a mixture of time levels. This is probably not serious, but it should be noted.

The flux equation is

\[ F_{j+\frac{1}{2}}^{n+1} = \frac{2K_{j+\frac{1}{2}}^{n}}{r_{j+2/3}^2 - r_{j-\frac{1}{2}}^2} \left( \frac{r_{j+1}^{n+1}}{c_{v,j+1}^{n}} - \frac{r_{j}^{n+1}}{c_{v,j}^{n}} \right) . \hspace{1cm} (23)\]

The momentum equation is given by

\[
\frac{\partial \rho u}{\partial t} + \frac{1}{r} \frac{\partial}{\partial r} \left( r^2 \rho u^2 \right) = - \rho g - \frac{\partial p}{\partial r} + \frac{1}{r^2} \frac{\partial}{\partial r} \left[ r^2 (2\mu + \lambda) \frac{\partial u}{\partial r} \right] 
\]
\[ - \frac{2u(2\mu + \lambda)}{r^2} + \frac{2u}{r} \frac{\partial \lambda}{\partial r} \hspace{1cm} . \hspace{1cm} (24)\]
The Lagrangian form of Eq. (24) is differenced by integrating over a spherical shell (momentum control volume) between \( r_{j-1} = 0.5(r_{j-3/2} + r_{j-3}) \) and \( r_j = 0.5(r_{j+1/2} + r_{j-1/2}) \).

\[
\frac{M^n_{v,j-1/2}}{\delta t} (u^n_{j-1/2} - u^n_{j+1/2}) = -M^n_{v,j-1/2} g^n_{j-1/2} - 2V^n_{v,j-1/2} \left( \frac{p^n_{j+1} - p^n_{j-1}}{r^n_{j+1/2} - r^n_{j-3/2}} \right) \\
+ \frac{4}{3} A^n_{j} u^n_{j+1/2} \left( \frac{1}{r^n_{j+1/2} - r^n_{j-3/2}} \right) \\
- A^n_{j-1} \mu^n_{j-1} \left( \frac{1}{r^n_{j-3/2} - r^n_{j-1/2}} \right) \\
- \frac{4}{3} V^n_{v,j-1/2} \left[ \frac{u^n_{j-1/2} - u^n_{j-3/2}}{r^n_{j-3/2}} \right] 2 \left( \frac{\mu^n_{j} - \mu^n_{j-1}}{r^n_{j+1/2} - r^n_{j-3/2}} \right) \\
+ \frac{\mu^n_{j} + \mu^n_{j-1}}{r^n_{j-1/2}} \right), \quad (25)
\]

where the vertex masses and vertex volumes are given by

\[
M^n_{v,j-1/2} = (M^n_{c,j} + M^n_{c,j-1})/2 \quad , \quad (26)
\]

\[
V^n_{v,j-1/2} = \frac{r^n_{j}^3 - r^n_{j-1}^3}{3} \quad . \quad (27)
\]

The shell areas, \( A^n_{j} \), are defined at cell centers, as indicated by the integral subscripts. To obtain the gravitational acceleration, we perform the sum

\[
\epsilon_{j-1/2} = \frac{4\pi G}{3} \sum_{i=2}^{j-1} \left( \frac{M^n_{c,i}}{r^n_{j-3/2}} \right) \quad . \quad (28)
\]
The equations form a banded linear system in the advanced time quantities, so they may be solved by a banded matrix package, such as the one by Hindmarsh. The left element of each row of the band is stored in the computer with an index of 1. A simple mnemonic display of the subscripting scheme is given in the program listing in Appendix A.

In Phase II we are modeling the convection term

$$\int \rho Q \left( u_0 - \bar{u} \right) \cdot \hat{n} \, ds$$ \hspace{1cm} \text{(29)}$$

where $u_0$ is the grid velocity and $\bar{u}$ is the fluid velocity at the end of Phase I. We define the difference velocity for our one-dimensional problems, $w_{j-\frac{1}{2}} = u_{g,j-\frac{1}{2}} - \bar{u}_{j-\frac{1}{2}}$, which is the velocity of the mesh relative to the fluid. Then $w_{j-\frac{1}{2}} A_{j-\frac{1}{2}} \partial_t$ is the volume relative to the fluid that is swept out by the moving grid point. One might be tempted to take for, say the density, simply an average of the densities on either side of the moving mesh point. This is called centered differencing, and it is unstable. For this reason we use a mixture of centered differencing and donor cell differencing. The donor cell component adds a strong stabilizing 'diffusional truncation error that compensates for the destabilizing diffusional error of centered differencing.

Define the donor cell parameter, $\alpha_{j+\frac{1}{2}}$, by

$$\alpha_{j+\frac{1}{2}} = - \bar{\alpha} \, \text{sgn} \left( w_{j+\frac{1}{2}} \right)$$ \hspace{1cm} \text{(30)}$$

where the function sgn is the sign of the argument, and $\bar{\alpha}$ is a constant, $0 \leq \bar{\alpha} \leq 1$. As an example of the difference form of the convection term for a cell centered quantity,

$$m_{c,j}^{n+1} = m_{c,j}^n - \frac{\delta t}{2} \left\{ w_{j-\frac{1}{2}} A_{j-\frac{1}{2}} \left[ (1 + \alpha_{j-\frac{1}{2}}) \bar{\rho}_{j-1} + (1 - \alpha_{j-\frac{1}{2}}) \bar{\rho}_{j} \right] \right. \\
- \left. w_{j+\frac{1}{2}} A_{j+\frac{1}{2}} \left[ (1 + \alpha_{j+\frac{1}{2}}) \bar{\rho}_{j} + (1 - \alpha_{j+\frac{1}{2}}) \bar{\rho}_{j+1} \right] \right\}$$ \hspace{1cm} \text{(31)}$$

11
The tildes denote results from Phase I. This is a straightforward approximation to Eq. (29) for $Q = 1$. The density is obtained by calculating volumes from the new mesh position

$$r_{j-\frac{1}{2}}^{n+1} = r_{j-\frac{1}{2}}^n + u_{g,j-\frac{1}{2}} \delta t .$$

(32)

Then

$$\rho_{j}^{n+1} = \frac{M_{n+1}^{c,j}}{V_{n+1}^{c,j}} ,$$

(33)

which ensures mass conservation. The convection of internal energy is handled in exactly the same manner.

For momentum the control volume runs from cell center to cell center, and a slight modification is necessary. The difference velocity must be obtained by averaging the difference velocities of the neighboring vertices. This leads to

$$u_{j-\frac{1}{2}}^{n+1} = \frac{1}{M_{n+1}^{v,j-\frac{1}{2}}} \left[ \frac{M_{n+1}^{v,j-\frac{1}{2}}}{v_{n+1}^{c,j}} u_{j-\frac{1}{2}}^n - \frac{\delta t}{4} \left[ \beta_{j-1}^{w_{j-\frac{1}{2}}+w_{j-3/2}} A_{j-1}^{(1+\alpha_{j-1})u_{j-3/2}} 

+ (1-\alpha_{j-1})u_{j-\frac{1}{2}}^{j-1} \right] - \beta_j^{w_{j-\frac{1}{2}}+w_{j-3/2}} A_j^{(1-\alpha_j)u_{j-3/2}} 

+ (1-\alpha_j)u_{j+\frac{1}{2}}^{j+1} \right] \right] ,$$

(34)

where

$$\alpha_j = -\bar{\alpha} \text{ sgn} \ (w_{j-\frac{1}{2}} + w_{j+\frac{1}{2}}) .$$

(35)

It is not necessary to use the same $\bar{\alpha}$ in the momentum equation as in the equation for the mass or energy. We have found empirically that we need more donor cell in the mass and energy equations to keep cells from emptying out in the neighborhood of steep gradients.
For problems with strong shocks, an explicit artificial viscous pressure is helpful in attaining numerical stability and accurate jump conditions. The form we have chosen is

\[ q^n_j = - \Lambda \rho^n_j (x_{j+1/2}^n - x_{j-1/2}^n)^2 D^n_j \min(0, D^n_j) \]

where \( \Lambda \) is a constant of order unity. To the right side of Eq. (20), we add \( \delta t q^n_j D^n_j \). To the right side of Eq. (25), we add \( 2V_{v,j-3/2} (q^n_{j-1} - q^n_j)/(r_{j+1/2} - r_{j-3/2}) \). In regions of expansion, \( q \) vanishes. In regions of compression, the \( q \) terms provide velocity diffusion in the momentum equation and "viscous" conversion of kinetic energy to thermal energy in the \( H \) equation. These terms have an effective kinematic viscosity that is roughly the fluid velocity times a mesh cell size in the neighborhood of a shock. The artificial viscous effects are concentrated in the regions of strongest compression, precisely where they are needed the most. For problems with no shocks, \( \Lambda = 0 \) is recommended.

IV. NUMERICAL EXAMPLES

This section contains three numerical examples that illustrate the kinds of problems that may be solved with SOLA-STAR. The first example provides a test problem to be used to check out new copies of the code. These examples are crude simulations of physical problems, and are not intended to be compared to observations without some refinement. The first problem is the early collapse phase of a protostellar cloud. This is basically the same problem solved by Larson. The second test problem is a simple blast wave for which there is an analytical solution. The third problem is the solar wind solution by Hundhausen and Gentry. They considered the effects of transients imposed on a steady state solar wind.

A. Collapse Of a Protostellar Cloud

The first numerical fluid dynamics calculation of the collapse of a dense interstellar cloud to form a protostar was published by Larson. His initial condition was an isothermal cloud of uniform density that was just unstable toward gravitational collapse according to the Jeans criterion. The outer boundary condition was \( u=0 \) at just under the Jeans' radius. Larson's solution for a one solar mass cloud was confirmed by Ruppel and Cloutman, and the results
presented in this subsection and the code listing and output in Appendix A are for a similar one solar mass cloud.

Since some results of VEGA calculations were described fully and compared to Larson's results in reference 1, we will limit the present discussion to the use of this problem as a test case for new copies of the program. Appendix A provides the actual computer output at 0, 1, 500, and 3000 cycles. The following physical events can be seen in the solution as it develops. First, a rarefaction is created at the outer boundary at \( t = 0 \) by the collapse of the cloud. It travels inward at the speed of sound. The density is spatially constant but temporally increasing inside the rarefaction, and it falls off as \( 1/r^2 \) outside. This behavior is illustrated in figure 2 with the curve from cycle 300 (\( t = 2.981 \times 10^{12} \) s). The velocity profile consists of two linear segments with the minimum at the rarefaction, as illustrated in figure 3. The material is isothermal at 10 K. When the rarefaction reaches the center, the embryonic star is formed. The density becomes peaked at the center, forming a body nearly in hydrostatic equilibrium, surrounded by an accretion shock. The central body contains roughly \( 10^{-3} \) solar masses and has a radius of about \( 10^{14} \) cm. Upon its creation, the protostar may oscillate briefly. Cloud material falls supersonically to the accretion shock, is decelerated, and added to the protostar. The central density continues to rise. When it reaches about \( 10^{-13} \) g/cm\(^3\), the central temperature also begins to rise. This phase is illustrated in figures 2 and 3 with the curves from cycle 900 (\( t = 8.578 \times 10^{12} \) s). When the central temperature reaches 2000 K, the calculation is terminated. Figure 4 shows the structure at 3500 cycles (\( t = 8.653 \times 10^{12} \) s), shortly before termination. Real gas physics is needed to go farther because of the importance of \( \text{H}_2 \) dissociation. This has been done in VEGA by making tables of \( (\gamma-1) \equiv \rho/\rho T \) and \( c_\gamma \equiv T/\rho \) using the equation of state in Paczynski's stellar envelope program. This pseudo-\( \gamma \) and pseudo-specific heat are easy to insert into the code, and they need to be evaluated only at time level \( n \) for use in the coefficient matrix. In addition, they are constant over large parts of the \( \rho-T \) plane, so bilinear interpolation is sufficiently accurate.

B. Spherical Blast Wave

The spherical blast wave is a classical test problem for numerical fluid dynamics codes, and it is a much more severe test than piston-driven shocks or shock tubes. In these latter cases, the solutions are piece-wise constant except for the expansion wave in a shock tube, which generally has only modest
Runs of density at cycles 300 and 900 in the protostar calculation.

Runs of velocity at 300 and 900 cycles in the protostar calculation.

The protostar solution at 3500 cycles. The vertical axis runs from $-3 \times 10^5$ to $0 \text{ cm-s}^{-1}$ for the radial velocity ($u$), $0$ to $1.5 \times 10^{-8} \text{ g-cm}^{-3}$ for the density ($\rho$), and $0$ to $10^{11}$ for the specific internal energy ($I$).
curvature. On the other hand, the blast wave solution is sharply peaked, presenting a real challenge for finite difference methods.

The sample problem discussed in this section is based on a $10^{51}$ erg point explosion in a 10,000 K and $\rho = 2.4 \times 10^{-9} \text{ g/cm}^3$ ambient medium with $\gamma = 5/3$. Appendix B gives UPDATE modifications and the data deck.

Figure 5 shows the numerical solution for the density at two different times. The solid curves are for $\alpha = 1.0$ (pure donor cell transport) and the dashed curve is for $\alpha = 0.6$. Note that decreasing $\alpha$ reduces the numerical diffusion, thereby sharpening the peaks. Note also the improvement in the density jump condition as the wave progresses. This is due to two phenomena. First, the initial condition is not the Taylor-Sedov solution, toward which the solution evolves. Second, and more importantly, the resolution of the sharp self-similar peak improves as the radius of the shock grows to include more cells.

C. Solar Wind

A simple solar wind model is presented to illustrate use of the code with inflow and outflow boundaries. It also has the left-most vertex away from the...
origin. This feature is also useful for running a Cartesian problem merely by making \( X(2) \) much larger than the total width of the mesh.

The sample solutions presented here are repetitions of solutions by Hundhausen and Gentry (HG).\(^9\) The first step in this problem is to find a steady state solar wind solution. This could be accomplished by letting the program go through a transient phase. However, the computational effort was minimized by using an inviscid analytical solution as the initial condition. Then transient disturbances were introduced into the solution to represent perturbations by solar flares, and their propagation was followed.

The initial condition is an inviscid adiabatic radial expansion of an ideal gas:

\[
p = (\gamma - 1) \rho I = C_1 \rho^\gamma ,
\]

\[
r^2 \rho u = C_2 ,
\]

and

\[
 u \frac{du}{dr} + \frac{1}{\rho} \frac{dp}{dr} + \frac{GM}{r} = 0 ,
\]

which is the Bernoulli equation for this problem. The constants \( C_1, C_2, \) and \( C_3 \) are evaluated by specifying the values of all variables at \( r = 1.25 \times 10^{12} \) cm, which is outside the critical point of the inviscid solar wind. Elimination of all dependent variables except \( \rho \) leads to a transcendental equation for \( \rho \):

\[
\rho^2 \left( C_3 + \frac{GM}{r} - \frac{\gamma C_1}{\gamma - 1} \rho^{\gamma - 1} \right) = \frac{C_2^2}{2r^4}
\]
This form is solved iteratively by the program, and then the other variables are found trivially by using equations (37) and (38).

The inflow boundary at the left is straightforward, as can be seen from the UPDATE modifications given in the appendix C. However, outflow boundaries are always more troublesome. One simple form that is frequently useful is the continuative boundary, where all gradients are set to zero on the boundary. This procedure is often adequate for supersonic flows, but can reflect unwanted signals into the mesh for subsonic flows. We use an alternate approach, the radiation condition

$$\frac{\partial c}{\partial t} + u \frac{\partial c}{\partial r} = 0,$$

(42)

where c is one of the flow variables, in place of the continuative boundary. A small bump in the velocity at the right end of the mesh is strictly a numerical artifact of the outflow boundary. It is slightly smaller using equation (42) than the continuative boundary, and the supersonic outflow prevents it from propagating into the mesh. The user may have to develop a better outflow boundary condition for some problems.

The first numerical solution we ran was the generation of a steady state solution. The analytic solution from equations (37), (38), and (41) was used as the initial condition. The parameters of HG were used. The problem was run beyond the time it takes an element of fluid to cross the mesh, and the numerical and analytic steady states were compared. During the transient, the interface between the fluid originally in the mesh and the fluid that subsequently flowed into the mesh propagated to the right, showing a small disturbance of increasing amplitude that exited the mesh without reflection. Comparison of the computer-generated plots shows the analytic and computational solutions are almost indistinguishable. Examination of the numerical output shows that the worst errors are near the left boundary where gradients of the variables are the largest. The mesh has been compressed in this region to reduce the error, which has a maximum of 4% in the pressure. The other variables are computed more accurately, and the accuracy of all variables improves at larger r.

The second numerical solution was the same as the transient shock problem solved by HG. A disturbance lasting 2.1 hours was introduced into the mesh at
$t_0 = 2 \times 10^5$ s. This initial period was introduced to allow the inner boundary perturbation to propagate well into the mesh where it could be ignored. This procedure is probably not necessary. Figure (6) corresponds to figures (1)-(3) of HG, and the interested reader is invited to compare the results. The top row of figure 6 shows the solution at 2.0 hrs. after $t_0$. The analytical solution has a velocity of 1570 km/s just behind the shock, in good agreement with our calculation. The velocity jump in HG's figure 1 is a bit too high. Our velocity profile has a spike behind the shock. As we are running with $\alpha = 0.5$, this feature is probably a dispersive truncation error. HG show no spike, suggesting that perhaps their solution was obtained using full donor cell transport ($\alpha = 1$). However, Gentry (private communication) has pointed out that at least part of the HG work was done with a scheme that was more closely related to the truncation error cancellation technique of Rivard and collaborators, which is similar in principle to locally computing and applying the minimum $\alpha$ needed in each cell to get numerical stability. This procedure often allows significant dispersive errors to occur, especially near a strong shock, so it is not clear what differencing scheme HG used to obtain their published results.

An unexpected feature of the numerical solutions is the density jump across the shock. The analytic value is a factor of four. Our solution gives a factor of seven, and HG's jump is about the same in spite of the label on their graph showing good agreement with a factor of four jump. The explanation may be that the density gradient is quite large in this region, so shocked material compressed by the correct amount is more than four times as dense as the material ahead of the shock, several cells away.

The second row of figure 6 is taken at $t_0 + 4.3$ hr. The agreement with HG is better than at $t_0 + 2.1$ hr, especially in the velocity field. The density jump in the SOLA-STAR solution is still apparently a bit higher than expected.

The bottom row of figure 6 was taken at $t_0 + 20.1$ hr, as was HG's figure 3. HG's velocity curve is slightly broader and smoother. Their density jump and ours now are close to the desired factor of four, but the velocity and density profiles differ somewhat in detail. Although our solution is in qualitative agreement with that of HG, it is clear that some unanswered questions about these solar wind solutions remain.
Fig. 6 (con't)
The solar wind solution at 2.0 hr., 4.3 hr., and 20.1 hr. after beginning the shock wave inflow for the top, middle, and bottom rows of figures respectively. Dashed lines indicate the steady state solar wind.
REFERENCES


APPENDIX A
SAMPLE PROBLEM

This appendix provides a listing of SOLA-STAR, a list of main variables, and some information to help the new user convert the code to a non-LASL operating system. We begin by noting that, for the most part, the code is written in ANSI-standard FORTRAN. The CDC computers carry approximately 13 digits, which has proved adequate. However for machines with a short word length, such as IBM, it will be necessary to use double precision throughout the code. This is good practice for any hydrodynamics program, but especially so for SOLA-STAR with its large linear system solver.

SOLA-STAR can be used on quite modest computers. This version of SOLA-STAR requires 77 K₈ words of memory. However, this number can be reduced if necessary by adjusting the size of dimensioned arrays or by sacrificing the plotting capability. The arrays B and AA are dimensioned for a maximum of JBAR = 150 real cells. The grind time, that is the time required to complete one time step for one cell, is 5.3 ms on a CDC 6400. This is approximately a factor of 10 longer than for a CDC 7600 and a factor of 2 larger than for a CDC 6600.

The main system-dependent feature is the graphics package. Logical unit 7 is the film file, and it can be eliminated if graphics output is not desired. The following is a list of graphical output routines used by SOLA-STAR. These routines will have to be replaced by the non-LASL user’s local equivalent or deleted from the program.

1. CALL ADV(NF): If 1 ≤ NF ≤ 21, the film is advanced NF frames. Otherwise, the call is ignored.
2. CALL EMPTY: Empty the FILM file buffer onto disk. Unless the run is unexpectedly aborted, this routine is superfluous.
3. CALL LINCNT(N): N is modulo 64. The next line of output directed to the film file is directed to the Nth line.
4. CALL SPLØT(IØP,N,X,Y,ICHAR,ICØN): Standardized plot routine. Four types of grid: IØP = 1, 2, 3, or 4 gives linear-linear, linear-log, log-linear, or log-log plots respectively. N successive points are plotted from the tables X and Y (abscissas and ordinates respectively). ICHAR is a code number for a character to be plotted at each point.
(ICHAR = 42 is a dot). If ICON ≠ 0, the points are connected by straight lines.

5. CALL WLCH(IX, IY, CN, NCH, NS): Writes large horizontal characters beginning with SC 4020 coordinates (IX, IY). SC 4020 coordinates define a location on the film frame, with (0, 0) at the upper left hand corner and (1023, 1023) at the lower right hand corner. NC is the number of characters to be written beginning with the variable NCH. NS is an integer character size parameter, 1 ≤ NS ≤ 5.

The sample problems in the Appendixes require minor changes to the basic code, and it is convenient to specify the changes in CDC UPDATE format, even though many users will not have this software. A statement of the form *INSERT SV.n means insert the FORTRAN statements between the *INSERT card and the next statement beginning with an * behind statement number SV.n. The card *DELETE SV.m,SV.n means delete statements SV.m through SV.n and replace them with any statements between the *DELETE and the next * card. The *IDENT statement merely specifies a name to be associated with the set of modifications and may be ignored by users not using the UPDATE utility.

Table I lists the major program variables and their definitions. The remainder of this appendix is a program listing and sample output suitable for testing new SOLA-STAR decks. It is recommended that the new user try these problems to become thoroughly familiar with this code before embarking on his or her own research program.
TABLE I

DEFINITION OF SOLA-STAR VARIABLES

<table>
<thead>
<tr>
<th>Definition</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AA</td>
<td>Coefficient matrix (band only) of the linear system.</td>
</tr>
<tr>
<td>AJ</td>
<td>Areas of cell faces.</td>
</tr>
<tr>
<td>B</td>
<td>Right hand side of the linear system.</td>
</tr>
<tr>
<td>CND</td>
<td>Thermal conductivity.</td>
</tr>
<tr>
<td>DØNM</td>
<td>Donor cell parameter $\alpha$ for the $\rho$ and $I$ equations.</td>
</tr>
<tr>
<td>DØNMØM</td>
<td>Donor cell parameter for the $u$ equation.</td>
</tr>
<tr>
<td>DT</td>
<td>Time step.</td>
</tr>
<tr>
<td>DTK</td>
<td>Maximum allowed value of $</td>
</tr>
<tr>
<td>DTMAX</td>
<td>Maximum value of DT allowed in the run.</td>
</tr>
<tr>
<td>DX</td>
<td>Width of the innermost two real cells and left hand fictitious cell.</td>
</tr>
<tr>
<td>EI</td>
<td>Specific internal energy $I$.</td>
</tr>
<tr>
<td>EM</td>
<td>Vertex masses.</td>
</tr>
<tr>
<td>EMc</td>
<td>Cell masses.</td>
</tr>
<tr>
<td>FMASS</td>
<td>Total mass of the system.</td>
</tr>
<tr>
<td>FMØM</td>
<td>Total momentum of the system.</td>
</tr>
<tr>
<td>FOURPI</td>
<td>Four times $\pi$.</td>
</tr>
<tr>
<td>G</td>
<td>Gravitational constant.</td>
</tr>
<tr>
<td>GAMMA</td>
<td>$\gamma$, the ratio of specific heats.</td>
</tr>
<tr>
<td>GRDVL</td>
<td>Velocity of grid points as fraction of fluid velocity; zero for Eulerian run, unity for Lagrangian calculation. Can also be fractional or SUBROUTINE GRID can be rewritten to provide an arbitrary, user-chosen grid motion.</td>
</tr>
<tr>
<td>JBAR</td>
<td>Number of real cells.</td>
</tr>
<tr>
<td>JP1</td>
<td>JBAR + 1.</td>
</tr>
<tr>
<td>JP2</td>
<td>JBAR + 2.</td>
</tr>
<tr>
<td>JP3</td>
<td>JBAR + 3.</td>
</tr>
<tr>
<td>KPR</td>
<td>Get one line summary print every KPR cycles.</td>
</tr>
<tr>
<td>LFILM</td>
<td>Get film output every LFILM cycles.</td>
</tr>
<tr>
<td>MUVISC</td>
<td>Coefficient of viscosity $\mu$.</td>
</tr>
</tbody>
</table>
NDIM  Dimension of B and first dimension of AA. Must be at least NEQ * JP2.
NDIM2 Second dimension of AA.
NDT  Number of time steps.
NEQ  Number of dependent variables in the linear system.
NM  Get full printout every NM cycles.
P  Pressure p.
PDVCEN Time centering parameter for p\(\nabla\cdot u\) in the I equation.
RCV  Reciprocal of the specific heat, T/I.
RH\(\bar{\phi}\) Density \(\rho\).
RHOL  Density at the end of Phase I.
RMAX  Coordinate r of the right hand boundary.
RMIN  Coordinate r of the left hand boundary.
RSAV Central density (RH\(\bar{O}(2)\)) as a function of t. Saved for plotting purposes only.
T  Time t.
TIM  Array containing t for use in plotting RSAV.
U  Fluid velocity \(u_{j-\frac{1}{2}}\).
UD  Difference velocity \(w_{j-\frac{1}{2}}\).
UG  Grid velocity.
ULT  Fluid velocity at the left boundary.
UTMAX  Fluid velocity at the right boundary.
VJC  Cell volumes.
VJV  Vertex volumes.
VLAM  \(\alpha\), the artificial viscosity parameter.
UT  Velocity after Phase I.
X  Vertex positions \(r_{j-\frac{1}{2}}\).
PROGRAM VEGA (OUTPUT=100, TAPE5=100, TTY, TAPE59=TTY), SV 2
$ TAPE5=100), SV 3
REAL MUVISC, SV 4
COMMON /AI/ JBAR, JPL, JP2, JP3, DO, T, N, NOT, FMASS, FMOM, ET, EINT, NM, LFILMS, SV 5
COMMON /A2/ EM(200), X(200), U(200), MUVISC(200), SV 6
COMMON /A3/ EI(200), E(200), DMAX, VLAM, DT, SV 7
COMMON /A4/ RHJ(200), EHC(200), P(200), RHJL(200), SV 8
COMMON /A5/ UT(200), JD(200), SV 9
COMMON /A6/ GAMMA, UT1, UMAX, DONM, DONMM, GROVEL, SV 10
COMMON /A14/ EMCT(200), UG(200), DPHI(200), SV 11
COMMON /A15/ RCV(200), CND(200), R2DR(200), TNOT4, SV 12
COMMON /A40/ FJURPI, AJ(200), XM(160), SV 13
COMMON LA, LB, AA(777, 16), JBVEQ, NDIM, IP(777), SV 15
DIMENSION ZNU(200), THE(200), ALF(200), BET(200), ZKAP(200), TAU(200), SV 16
DIMENSION B(777), R4(200), RDX(200), AJC(200), SV 17
DIMENSION RJC(200), VJC(200), RJC(200), PHI(200), ZZ(200), SV 18
1 ZN(200), RA(200), RB(200), RC(200), RD(200), VJ(200), SV 19
DATA T, N/O, 0/, SV 20
DATA FJURPI, G/12, 56537362, 5.63E-8/, SV 21
DATA DVCEN/1, 0/, SV 22
DATA LFILM, KPR, NM/25, 1, 50/, SV 23
C *** SET UP
C ***
CALL INPUT,
GM1= GAMMA-1,
TNOT4=(EI(JP1)*RCV(JP1))**4
WRITE (5, 230) TNOT4
WRITE (7, 230) TNOT4
C *** LA IS NUMBER OF ELEMENTS TO LEFT OF DIAGONAL, LB TO RIGHT
LA=5
LB=5
NEQ=5
NDIM=777
NDIM2=15
JBVEQ=JP1*NEQ
DO 10 J=2, JPZ
RDX(J)=1.0/(X(J)+1-X(J))
RJC(J)=.5*(X(J)+X(J+1))
END
AJC(J)=3.*RJC(J)*RJC(J) 
RRC(J)=0.5/RJC(J) 
RA(J)=RD(J)+2.*RRJ(J) 
RB(J)=RD(J)-2.*RRJC(J) 
RC(J)=(RD(J)+RRJC(J))*RRJC(J) 
RD(J)=(RD(J)-RRJC(J))*RRJC(J) 
VJC(J)=X(J+1)**3-X(J)**3 
EMC(J)=2.20(J)*VJC(J) 
10 CONTINUE 
RJC(J)=0.5*(X(1)+X(2)) 
C *** R2DR(2)=0 TO MAKE DI/DR=0 AT ORIGIN 
R2DR(2)=0. 
DO 20 J=3,JP2 
R2DR(J)=1./(X(J+1)-X(J-1)) 
AJ(J)=3.*X(J)*X(J) 
VJ(J)=RJC(J)**3-RJC(J-1)**3 
20 EM(J)=0.5*(EMC(J-1)+EMC(J)) 
AJ(JP3)=3.*X(JP3)*X(JP3) 
VJ(JP3)=RJC(JP3)**3-X(JP3)**3 
EM(JP3)=0.5*EMC(JP3) 
CALL CONDUCT 
CALL OUTPUT 
DT=DT 
ITIME=0 
C *** 
C *** :RDRDYNAMICS LOOP 
C *** 
DO 200 N=1,NDT 
ITIME=ITIME+1 
IF (ITIME.GT.500) ITIME=1 
DT=DMIN(DT,1.1*DT) 
T=T+DT 
TME=EI(1)*RCV(1) 
IF(MD(1,PR).EQ.0) WRITE (6,220) DT,T,N,RHO(2),U(15),TEMPE 
IF (MD(N,PR).EQ.0) WRITE (7,220) DT,T,N,RHO(2),U(15),TEMPE 
IF (TEMPE .GT. 3000.) CALL EXIT 
JBM=JBA+1 
SET(2)=0. 
BET(JP2)=X(JP2)**2*RD(JP1)
DPHI(2) = 0.
SUM = 0.
DUG = FJURPI*G/3.
DD = 30 J = 3, JP1
SET(J) = X(J) + X(J)/(RJC(J) - RJC(J - 1))
SUM = SUM + E4C(J - 1) * DUG
DPHI(J) = SUM / (X(J) * X(J))
30 CONTINUE

DPHI(JP2) = (SUM + EMC(JP1) * DUG) / (X(JP2) * X(JP2))
GMAX = ABS(DPHI(JP2))
CALL CJNDUCT
R2DR(JP3) = 0.
DD = 80 J = 2, JP2
T1 = U(J + 1) - U(J)
T2 = U(J + 1) + U(J)
T3 = 0.
IF (J .NE. JP2) T3 = DT / EMC(J)
ZD = T1 * RDX(J) + 2. * T2 * RRJC(J)
T4 = -DT / (1. + DT * ZD)
T5 = 2. * T1 * RDX(J) ** 2
T6 = 4. * T2 * RRJC(J) ** 2
SET(J) = (T1 * RDX(J)) ** 2 + 2. * (T2 * RRJC(J)) ** 2
ZNU(J) = 0.5 * T3
ALF(J) = 2. * T3 * MUJCVS(J) * VJC(J)
THE(J) = U(J + 1) - AJ(J + 1) - U(J) * AJ(J)
ZKAP(J) = T5 + T6
TAU(J) = T5 - T6
RM(J) = DT / EM(J)
PHI(J) = T4 * R4J(J)
30 CONTINUE
C *** MATRIX STRUCTURE
C ***
C *** FORMAT 3BLOCK
C ***/
C RHD U P I F
C
C
C
C

C
C RHO K+2, L-2
C FLUX K+3, L+1
C EI K+4, L-1
DO 90 I=1, NDIM
DO 90 J=1, NDIY2
90 AA(I,J)=0.
AA(2,6)=1.
AA(4,7)=1.
K=1-NEQ
L=L+1
DIVR=0.
ARTTP=0.
DO 120 J=2, JP2
K=K+NEQ
AA(2,L)=-GM1*EI(J)
AA(K,L+1)=1.
AA(K,L+3)=-GM1*RH(J)
DIVL=DIVR
DIVR=0.
IF (J .LT. JP2) DIVR=(AJ(J+1)*U(J+1)-AJ(J)*U(J))/VJC(J)
IF (DIVR .GT. 0.) DIVR=0.
ARTPM=ARTPP
ARTPP=VLAM*RH(J)*DIVR*DIVR/(RDX(J)*RDX(J))
IF (J .EQ. 2) GO TO 100
AA(K+1,L-5)=-4.*VJV(J)*RM(J)*MUVIS(J-1)*(R2DR(J)*RDX(J-1)-RC(J-1))
1)
AA(K+1,L-4)=-RM(J)*AJ(J)
AA(K+1,L)+4.+4.*VJV(J)*RM(J)*MUVIS(J)*R2DR(J)*RDX(J)+RC(J)
+MUVIS(J-1)*(R2DR(J)*RDX(J-1)-RD(J-1))
AA(+1,L+1)=RM(J)*AJ(J)
AA(K+1,L+5)=-4.*VJV(J)*RM(J)*MUVIS(J)*R2DR(J)*RDX(J)+RD(J)
AA(+3,L-5)=2.*CNO(J)*RCV(J)*R2DR(J)
AA(K+3,L+1)=1.
AA(K+3,L)-2.*CND(J)*RCV(J+1)+R2DR(J)
100 AA(+4,L-3)=ALF(J)*TAN(J)-PDVCEN*ZNU(J)*P(J)*AJ(J)+2.
AA(K+4,L-2)=Z*ZNU(J)*THE(J)
$ *PDVCEN
AA(K+4, L-1) = 1.
IF (J.EQ.JP2) GO TO 110
AA(K+4, L) = 2.*ZNU(J)*AJ(J)
AA(K+4, L+5) = -2.*ZNU(J)*AJ(J+1)
110 CONTINUE
AA(K+4, L+2) = 2.*PDVCEN*ZNJ(J)*P(J)*AJ(J+1) - ALF(J)*ZKAP(J)
AA(K+2, L-2) = 1.
AA(K+2, L-1) = PHI(J)*RB(J)
AA(K+2, L+4) = -PHI(J)*RA(J)
B(K) = -3.*RHO(J)*EI(J)
B(K+1) = U(J)
IF (J.GT. 2) B(K+1) = B(K+1) + R(M(J))*AJ(J)*(ARTPM-ARTPP)
B(K+1) = B(K+1) - DT*PHI(J)
B(K+2) = RHO(J)
B(K+3) = 0.
3(K+4) = EI(J) - ALF(J) - BET(J) - DT*ARTPP*DIVR/RHO(J)
$ + 2.*(2.*PDVCEN-1.*)*ZNU(J)*THE(J)*P(J)
120 CONTINUE
AA(K+1, L-5) = 0.
AA(K+1, L-4) = 0.
AA(K+1, L-1) = 0.
AA(K+1, L+5) = 0.
AA(K+1, L) = 0.
B(K+1) = 0.
AA(K, L) = 0.
AA(K, L+3) = 0.
AA(K, L-3) = 0.
B(K) = 0.
AA(K+2, L-1) = 0.
AA(K+2, L+4) = 0.
CALL DEC8 (IER)
CALL SOLB (B)
K = 1 - NEQ
DO 130 J = 2, JP2
K = K + NEQ
RHO(J) = B(K)
UT(J) = B(K+1)
P(J) = 3(K+2)
EI(J) = B(K+3)
PHI(J) = B(K+4)
130 CONTINUE
   JT(2)=UT1
   RHOL(1)=RHOL(2)
   RHOL(JP2)=RHOL(JP1)
C ***
C *** RZONE SECTION
C ***
   CALL GRID
   DO 150 J=2,JP1
   DUB1=-ABS(DONM)*SIGN(1.,UD(J))
   DUB2=-ABS(DONM)*SIGN(1.,UD(J+1))
   EMCT(J)=EMC(J)-0.5*DT*(UD(J)-AJ(J)+((1.+DUB1)*RHOL(J-1)+(1.-DUB1))
   1RHOJ(J))=JD(J+1)*AJ(J+1)*(1.+DUB2)*RHOL(J)+(1.-DUB2)*RHOL(J+1))
   E(J)=(E(J)*EMC(J)-5*DT*(UD(J)+AJ(J))*((1.+DUB1)*RHOL(J-1)*EI(J))
   1+(1.-DUB1)*RHOL(J)*EI(J)-UD(J+1)*AJ(J+1)*(1.+DUB2)*RHOL(J-1)*EI(J)
   2*(1.-DUB2)*RHOL(J+1)*EI(J+1))/EMCT(J)
C CONTINUE
150 CONTINUE
   EMCT(JP2)=EMC(JP2)
   E(JP2)=EI(JP2)
   DO 160 J=3,JP2
   DUB1=-ABS(DONM(1))**SIGN(1.,UD(J)+UD(J-1))
   DUB2=-ABS(DONM(2))**SIGN(1.,UD(J)+UD(J+1))
   U(J)=UM(J)+UT(J)-2*DT*(RHOL(J-1)*(UD(J)+UD(J-1)))*AJC(J-1)*(1.+DUB1)
   1DUB1)*UT(J-1)+(1.-DUB1)*UT(J)-RHOL(J))*(UD(J)+UD(J+1)))*AJC(J)*
   2*(1.+DUB2)*UT(J)+(1.-DUB2)*UT(J+1))
160 CONTINUE
   U(JP2)=0.
   DPHI(J)=0.
   DO 170 J=2,JP2
   RX(J)=1./(X(J+1)-X(J))
   RJC(J)=.5*(X(J)+X(J+1))
   AJC(J)=3.*RJC(J)*RJC(J)
   RRJC(J)=.5/RJC(J)
   RA(J)=RX(J)+2.*RRJC(J)
   RB(J)=RX(J)-2.*RRJC(J)
   RC(J)=(RX(J)+RRJC(J))*RRJC(J)
   RD(J)=(RX(J)-RRJC(J))*RRJC(J)
   VJC(J)=X(J+1)**3-X(J)**3
   EMCT(J)=EMC(J)/VJC(J)
   RHOL(J)=EMC(J)/VJC(J)
C CONTINUE
EI(J) = E(J)

170 CONTINUE
RJC(1) = 0.5*(X(1)+X(2))
DTT = DTMAX
DO 180 J = 3, JP2
R2DR(J) = 1./(X(J+1)-X(J-1))
AJ(J) = 3.*X(J)*X(J)
JJV(J) = RJC(J)*3.-RJC(J-1)**3
EM(J) = 0.5*(EM(J-1)+EM(J))
U(J) = U(J)/E1(J)
IF (U(J) .NE. 0.) DTT = AMIN1(DTT, DTK*(X(J+1)-X(J))/ABS(U(J)))
180 CONTINUE
VJV(2) = RJC(2)*3.-X(2)**3
AJ(2) = 3.*X(2)*X(2)
AJ(JP3) = 3.*X(JP3)*X(JP3)
EM(2) = 0.5*EMCT(2)
U(2) = UT1
RHO(1) = RHO(2)
RHO(JP2) = RHO(JP1)
EI(1) = EI(2)

C ***
C *** TIME ACCOUNTING
C ***
IF (MOD(NM, NM).NE. 0 .AND. MOD(NMFILM, NM).NE. 0 .AND. N.GT.1)
$ GO TO 192
ET = 0.
EINT = 0.
FMMASS = 0.
FMOM = 0.
DO 190 J = 2, JP2
FMOM = FMOM + EM(J)*UT(J)
ET = ET + 0.5*EM(J)*UT(J)*UT(J)
IF (J .EQ. JP2) GO TO 190
ET = ET + EMCT(J)*EI(J)
EINT = EINT + EMC(J)*EI(J)
FMMASS = FMMASS + EMCT(J)
FMOM = FMOM + EM(J)*UT(J)
190 CONTINUE
ET = ET + FOURPI/3.
EINT = EINT + FOURPI/3.
FMASS=FMASS*FOURIPI/3.
FMOU=FMOU*FOURIPI/3.

192 CONTINUE
RSAV(NTIME)=ALOG10(RHO(2))
TIM(NTIME)=T
IF (N.EQ.1) CALL OUTPUT
IF (M3D(N,NM)*EQ.0.JR-M3D(N,NFILM)*EQ.0) CALL OUTPUT

200 CONTINUE
CALL EXIT

C *** FORMAT BLOCK
C ***

220 FORMAT (2X,4HDT,=,1PE17.8,2X,3HT,=,E17.8,I5,3E13.5)
230 FORMAT (1X,1PE20.8)
END

SUBROUTINE INPUT
COMMON /A2/ EM(200),X(200),U(200),MUVEC(200)
COMMON /A3/ EI(200),E(200),DTMAX,VLAM,OTK
COMMON /A4/ RHO(200),EMC(200),P(200),RHDL(200)
COMMON /A5/ UT(200),UD(200)
COMMON /A6/ ITITLE(8)
COMMON /A7/ GAMMA,UT,UTMAX,DOM,DOMOM,GRDVEL
COMMON /A8/ EMCT(200),UG(200),DPI(200)
COMMON /A9/ RCV(200),CND(200),R2DR(200),TNDT4
REAL MUVEC
DATA (EM(J),J=1,200)/200*0.1/
DATA (MUVEC(J),J=1,200)/200*0.1/
DATA (UT(J),J=1,200)/200*0.1/
DATA (UG(J),J=1,200)/200*0.1/
DATA (RCV(J),J=1,200)/200*1.911108562E-08/

C ***
C *** READ DATA DECK
C ***

READ (5,50) (ITITLE(J),J=1,8)
WRITE (5,50) (ITITLE(J),J=1,8)
WRITE (7,50) (ITITLE(J),J=1,8)
READ (5,60) JBAR,NDT
WRITE (6,60) JBAR,NDT
WRITE (7,60) JBAR, NOT
JP1=JBAR+1
JP2=JP1+1
JP3=JP2+1
READ (5,70) DT, DX, GROVEL
WRITE (6,70) DT, DX, GROVEL
WRITE (7,70) DT, DX, GROVEL
READ (5,70) RMIN, RMAX
WRITE (6,70) RMIN, RMAX
WRITE (7,70) RMIN, RMAX
READ (5,70) DMNP, DONMOM
WRITE (6,70) DMNP, DONMOM
WRITE (7,70) DMNP, DONMOM
READ (5,70) GAMMA, UT1, UMAX
WRITE (6,70) GAMMA, UT1, UMAX
WRITE (7,70) GAMMA, UT1, UMAX
READ (5,70) VLM, DTMAX, DTK
WRITE (6,70) VLM, DTMAX, DTK
WRITE (7,70) VLM, DTMAX, DTK
U(2)=UT1
U(JP2)=UTMAX
C *** SET U*, MESH
C ***
X(2)=RMIN
RMLD=0.5
RMLH=2.0
RATIO=1.0
DRB=DX
10 CONTINUE
DX=DRB
DO 20 J=3, JP3
IF (J.GT.4.AND.J.LT.JBAR) DX=DX*RATIO
X(J)=X(J-1)+DX
20 CONTINUE
WRITE (6,80) RATIO, X(JP2), DX
IF (RATIO.GT.2.95.AND.X(JP2).LT.RMAX) CALL EXIT
IF (ABS((X(JP2)-RMAX)/RMAX).LT.1.E-4) GO TO 30
IF (X(JP2).GT.RMAX) RMHI=RATIO
IF (X(JP2).LE.RMAX) RMLD=RATIO
RATIO = 0.5 * (RMLO + RMHI)
GO TO 10
30 CONTINUE
X(1) = 2 * X(2) - X(3)
C *** INITIALIZE DEPENDENT VARIABLES
C ***
DO 40 J = 1, JP2
RHOD(J) = 1.10E-19
RHOD(J) = 1.26E-19
P(J) = 3.696E-11
P(J) = 4.39758E-11
UT(J) = 0.
EI(J) = P(J) / ((GAMMA - 1) * RHOD(J))
40 CONTINUE
U(2) = UT1
U(JP3) = U(JP2)
UD(JP3) = 0.
UT(JP3) = 0.
CALL SETKAP
RETURN
C 50 FORMAT (BA10)
60 FORMAT (10H , Il, 10H , Il0)
70 FORMAT (10H , E10.3, 10H , E10.3, 10H ,)
1 1 E10.3)
80 FORMAT (1X,*RATIO, RMAX FROM MESH GEN*, 1P3E16.8)
END
SUBROUTINE SETKAP
COMMON/KAPA/KAP(51, 31), XMFXMF, YMF, ZMF
REAL <AP
C ***
C *** READS GDB OPACITY DECK
C ***
READ (5, 100) XMFXMF
100 FORMAT (10F8.5)
ZMF = 1. - XMFXMF
I = 0
K2 = 0
300 CONTINUE
I=I+1  
IF (I .GT. 51) G0 TO 304  
301 FORMAT (1X, I5, 14F5.2)  
K2=K2+1  
READ (5, 301) K1, (KAP(I,J)), J=1,14  
IF (K1 .NE. K2) G0 TO 302  
K2=K2+1  
READ (5, 301) K1, (KAP(I,J)), J=15,29  
IF (K1 .NE. K2) G0 TO 302  
K2=K2+1  
READ (5, 301) K1, (KAP(I,J)), J=29,31  
IF (K1 .NE. K2) G0 TO 302  
G0 TO 300  
302 CONTINUE  
303 FORMAT (1X, 21HWRONG JAPACITY CARD, K=I3)  
WRITE (6, 303) K2  
CALL EXIT  
304 CONTINUE  
RETURN  
END  
SUBROUTINE OUTPJ  
REAL MUVISC  
COMMON /A2/ EM(200), X(200), U(200), MUVISC(200)  
COMMON /3/ EI(200), E(200), DTMAX, VLAM, DT  
COMMON /4/ RHO(200), EMC(200), P(200), RHO(200)  
COMMON /A5/ UT(200), JD(200)  
COMMON /10/ ITITLE(9)  
COMMON /12/ GAMMA, JTI, UTMAX, DONM, DONMOM, GROVEL  
COMMON /A14/ EMCT(200), JG(200), DP4H(200)  
COMMON /A15/ RCV(200), CND(200), R2DR(200), TNDT  
COMMON /A40/ F4URPI, AJ(200), XMR(160)  
COMMON /TIMEV/ RSAV(200), TIM(2000), ITIME  
DIMENSION AL(200), BL(200), CL(200)  
DIMENSION XC(200), TEM(200)  
DATA UTITLE/10HX-VELLCITY/  
DATA (DPH(J), J=1,200)/200+0./  
DATA PTITLE/8HPRESSURE/  
DATA (XMR(J), J=1,160)/160+0./  
DATA RHOITIL/7HDENSITY/  
DATA XITLE/3HSIE/  
SV  402  
SV  403  
SV  404  
SV  405  
SV  406  
SV  407  
SV  408  
SV  409  
SV  410  
SV  411  
SV  412  
SV  413  
SV  414  
SV  415  
SV  416  
SV  417  
SV  418  
SV  419  
SV  420  
SV  421  
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SV  423  
SV  424  
SV  425  
SV  426  
SV  427  
SV  428  
SV  429  
SV  430  
SV  431  
SV  432  
SV  433  
SV  434  
SV  435  
SV  436  
SV  437  
SV  438  
SV  439  
SV  440  
SV  441  
SV  442
C *** BCD OUTPUT.
C ***
DO 25 J=2,JP2
  IF (J .GT. 2) XM(R(J))=XM(R(J-1)+FOURPI*EMC(J-1)/3.
  DPHI(J)*=-FOURPI*A(J)*DPHI(J)/3.
  TEM(J)*=EI(J)*R(J)
25 CONTINUE
IUMIN=6
IUMAX=7
IF (N.LE.1) GO TO 10
IF ((N,LE.NM).NE.0) IUMIN=7
IF ((M0D(N,NFLM)).NE.0) IUMAX=6
IF (IUMIN.GT.IUMAX) IUMAX=7
10 DO 20 IU=IUMIN,IUMAX
  WRITE (IU,40) EINT,ET,FMAS,FMOD,N
  IF (IU.EQ.7) CALL ADV (1)
  WRITE (IU,50)
  WRITE (IU,60)(I,X(I),U(I),RHO(I),EI(I),P(I),CND(I),DPHI(I),
  1  XM(R(I)),TEM(I),I=2,JP2)
20 CONTINUE
C *** GRAPHICAL OUTPUT
C ***
IF (IUMAX .EQ. 6) RETURN
CALL SPLOT (1,JP1,X(2),U(2),42,1)
CALL WCH (0,0,56,ITITLE,1)
CALL WLCH (0,25,10,UTITLE,1)
CALL LINCNT (60)
WRITE (7,70) T,N
DO 30 J=2,JP1
  XC(J)=5*(X(J)+X(J+1))
  AL(J)=ALG10(RHO(J))
  BL(J)=ALG10(EI(J))
  CL(J)=ALG10(P(J))
30 CONTINUE
CALL SPLOT (1,JP1-1,XC(2),P(2),42,1)
CALL WCH (0,0,56,ITITLE,2)
CALL WLCH (0,25,8,PTITLE,1)
CALL LINCNT (60)
WRITE (7,70) TN
CALL SPLOTT (1,JP1-1,XC(2),EI(2),42,1)
CALL WLCH (0,0,55,ITITLE,2)
CALL WLCH (0,25,3,XITLE,1)
CALL LINCNT (60)
WRITE (7,70) TN
CALL SPLOTT (1,JP1-1,XC(2),RH0(2),42,1)
CALL WLCH (0,0,55,ITITLE,2)
CALL WLCH (0,25,7,HR0,TITLE,1)
CALL LINCNT (60)
WRITE (7,70) TN
CALL SPLOTT (1,JP1-1,XC(2),CND(2),42,1)
CALL WLCH (0,0,55,ITITLE,2)
CALL WLCH (0,25,3,HCND,1)
CALL LINCNT (60)
WRITE (7,70) TN
IF (N.GT.10) CALL SPLOTT (2,ITIME,TIME,SAV,42,1)
IF (N.GT.10) CALL WLCH (0,25,8,HRHO VS T,1)
CALL LINCNT (60)
WRITE (7,70) TN
JBAR=JP1-1
CALL SPLOTT (2,JBAR,XC(2),AL(2),42,1)
CALL WLCH (0,25,7,HRHOTITLE,1)
CALL SPLOTT (2,JBAR,XC(2),BL(2),42,1)
CALL WLCH (0,25,3,XITLE,1)
CALL SPLOTT (2,JBAR,XC(2),CL(2),42,1)
CALL WLCH (0,25,8,PTITLE,1)
XJCL=JL.E-3*X(JP2)
DO 7000 J=2,JP1
JCL=J
IF (X(J) .GT. XJCL) GO TO 7001
7000 CONTINUE
7001 CONTINUE
IF (JCL .EQ. JP1 .OR. JCL .LT. 3) GO TO 7002
CALL SPLOTT (1,JCL,XC(2),U(2),42,1)
CALL WLCH (0,25,10,UTITLE,1)
CALL SPLOTT (1,JCL-1,XC(2),P(2),42,1)
CALL WLCH (0,25,8,PTITLE,1)
CALL SPLOTT (1,JCL-1,XC(2),EI(2),42,1)
CALL WLCH (0,25,3,XITLE,1)
CALL SPLT(1,JCL-1,XC(2),RHO(2),42,1)
CALL DLCH(0,257,RHOTITL,1)

7002 CONTINUE
WRITE (59,70) T,N
IF (TEM(2) .GT. 2000.) CALL EXIT
RETURN

C *** FORMAT BLOCK

C *** FORMAT (IX,17HINTERNAL ENERGY =,1PE13.6,
1 15H TOTAL ENERGY =,E13.6,7H MASS =,E13.6,11H MOMENTUM =,E13.6,
1 8H CYCLE =I7)
50 FORMAT (4X,1HJ,7X,1HX,12X,1HU,11X,3HR40,10X,2HEI,11X,1HP,
$ 10X,3HCND,11X,1HL,10X,24MR,11X,1HT)
60 FORMAT (1X,I3,I9PE13.5)
70 FORMAT (54 TIME=,1PE10.3,7H CYCLE=,I5)

END

SUBROUTINE GRID
REAL MUVEL
COMMON /A2/E5(200),XM(200),UM(200),MUVEL(200)
COMMON /A5/UT(200),UD(200)
COMMON /A12/GAMMA,UT1,UTMAX,DOM,DONM,GROVEL
COMMON /A14/EMC(200),UG(200),PHI(200)

C ***
C *** DEFINE GRID VELOCITY UG, REZONE (DIFFERENCE) VELOCITY UD,
C *** AND NEW VERTEX POSITIONS X.
C *** GRDVEL = 0., EULERIAN. GRDVEL = 1., LAGRANGIAN.
C ***

DO 10 J=2,JP2
JG(J)=GRDVEL*UT(J)
UD(J)=UG(J)-UT(J)
X(J)=X(J)+DT*UG(J)
10 CONTINUE
X(JP3)=2.*X(JP2)-X(JP1)
X(1)=2.*X(2)-X(3)
RETURN
END

REAL FUNCTION KAPPA(R01,TE)

C *** T LIMITS IF TABLE ARE LOG(T)=3.3 AND 3.2
C *** RHJ TABLE LIMITS ARE 1.E-12 AND 1000.
COMMON/ΚΑΠ,ΚΑΠ(51,31),ΧΜ,ΤΜ,ΖΜ
REAL ΚΑΠ,ΚΑΠ
INTEGER DI,TI
DATA DUSTK/0.15/
C *** DUST OPACITY ONLY
ΚΑΠΑ=DUSTK
IF (ΤΕ*LE. 1500.) RETURN
C *** GAS OPACITY
ΤΟ=ΤΟ
D=2.0*ALOG10(Ο)+25.0
ΩΙ=1
D=D-ΩΙ
Τ=20.0*ALOG10(ΤΕ)-65.
IF (ΤΩ*LE. 35.) Τ=35.0+(Τ-35.0)*0.25
ΩΙ=1
Τ=Τ-ΩΙ
IF (ΩΙ*GE. 10) GOTO 30
ΩΙ=1
C=0.
30 CONTINUE
IF (ΩΙ*LE. 30) GOTO 31
ΩΙ=30
D=1.
31 CONTINUE
IF (ΩΙ*GE. 1) GOTO 32
ΩΙ=1
Τ=0.
32 CONTINUE
IF (ΩΙ*LE. 50) GOTO 33
ΩΙ=50
Τ=1.
33 ΚΑΠΑ=(1.-Τ)*((1.-D)*ΚΑΠ(ΤΙ,ΩΙ)+D*ΚΑΠ(ΤΙ+1,ΩΙ+1))
1 T*(1.-D)*ΚΑΠ(ΤΙ+1,ΩΙ)+D*ΚΑΠ(ΤΙ+1,ΩΙ+1)
ΚΑΠΑ=EXP(2.3026*ΚΑΠΑ)
IF (ΤΕ*GE. 2000.) RETURN
C *** DUST PLUS GAS OPACITIES
Τ=(2000.-ΤΕ)*0.002
ΚΑΠΑ=Τ*DUSTK+(1.-Τ)*ΚΑΠΑ
RETURN
END
SUBROUTINE CONDUCT
REAL KAPPA, MUVISC
COMMON /A2/ _Y(200),X(200),U(200),MUVISC(200)
COMMON /A3/ EI(200),E(200),DTMAX,VLAM,DTK
COMMON /A4/ RHO(200)
COMMON /A5/ RCV(200),CND(200),R2DR(200),TN1
DATA PR/1.0/

C ***
C *** COMPUTE CONDUCTIVITY CND AND VISCOITY MUVISC.
C ***

DO 10 J=2,JP1
TEM=EI(J)*RCV(J)
MUVISC(J)=7.15E-05*SQR(TEM)
TEM=0.5*(TEM+EI(J-1)*RCV(J-1))
ROE=0.5*(RHO(J)+RHO(J-1))
AA=ROE*TEM*KAPPA(ROE*TEM)
TGRAD=2.*(RCV(J)*EI(J)-EI(J-1)*RCV(J-1))*R2DR(J)
CND(J)=3.02383E-04*(TEM**4-TN14)/(1.-4.*TGRAD/(3.*AA)*AA)
C CND(J)=3.02383E-04*TEM*TEM*TEM/(ROE*KAPPA(ROE*TEM))
C CND(J)=0.5*(MUVISC(J)+MUVISC(J-1))/PR

10 CONTINUE
MUVISC(1)=MUVISC(2)
MUVISC(JP2)=MUVISC(JP1)
CND(JP1)=CND(JP1-1)
CND(JP1+1)=CND(JP1)
RETURN
END

SUBROUTINE DECBIER
COMMON ML,MU,3(770,15),N,NDIM,IP(770)

C C
C LU DECOMPOSITION OF BAND MATRIX A. L*U=P*A, WHERE P IS A
C PERMUTATION MATRIX, L IS A UNIT LOWER TRIANGULAR MATRIX,
C AND U IS AN UPPER TRIANGULAR MATRIX.
C N = ORDER OF MATRIX.
C B = N BY (2*ML+MU+1) ARRAY CONTAINING THE MATRIX A ON INPUT
C AND ITS FACTORED FORM ON OUTPUT.
C ON INPUT, B(I,K) (I.LE.I.LE.N) CONTAINS THE K-TH
C DIAGONAL OF A, OR A(I,J) IS STORED IN B(I,J-I+ML+1).
C
ON OUTPUT, B CONTAINS THE L AND U FACTORS, WITH
U IN COLUMNS 1 TO ML+MU+1, AND L IN COLUMNS
ML+MU+2 TO 2*ML+MU+1.
ML+MU= WIDTHS OF THE LOWER AND UPPER PARTS OF THE BAND, NOT
COUNTING THE MAIN DIAGONAL. TOTAL BANDWIDTH IS ML+MU+1.
NOIM = THE FIRST DIMENSION (COLUMN LENGTH) OF THE ARRAY B.
NOIM MUST BE > GE. N.
IP = ARRAY OF LENGTH N CONTAINING PIVOT INFORMATION.
IER = ERROR INDICATOR.
= 0 IF NO ERROR,
= K IF THE K-T+1 PIVOT CHOSEN WAS ZERO (A IS SINGULAR).
CAUTION: IF ML=0, THIS ROUTINE CONTAINS EMPTY DO-LOOPS
WHICH MUST BE COMPILED CORRECTLY (I.E. NO ACTION TAKEN).
The input arguments are NOIM, N, ML, MU, B.
The output arguments are B, IP, IER.

IER=0
LL=ML+MU+1
N1=N-1
DO 3 I=1,ML
II=MU+I
K=ML+1-I
DO 1 J=1,II
1 B(I,J)=B(I,J+K)
  K=II+1
DO 2 J=K,LL
2 B(I,J)=0.
3 CONTINUE
LR=ML
DO 9 NR=1,N1
NP=NR+I
IF( LR<NE*N) LR=LR+1
MX=NR
XM=ABS(B(NR))
DO 4 I=NP*LR
IF(ABS(3(I))*LE.XM) GO TO 4
MX=I
XM=ABS(3(I))
4 CONTINUE
IP(NR)=MX
IF(IX.EQ.NR)GO TO 6
10 I=1,LL
XX=B(NR,I)
B(NR,I)=B(MX,I)
5 B(MX,I)=XX
6 XM=B(NR)
IF(XM.EQ.0.)GO TO 10
B(NR)=1./XM
XM=-B(NR)
KK=MINS(N-NR,LL-1)
DJ 8 I=1,LR
J=LL+I-NR
XX=B(I)*XM
B(NR,J)=XX
DO 7 II=1,KK
7 B(I,II)=B(I,II+1)+XX*B(NR,II+1)
8 B(I,LL)=0.
9 CONTINUE
RETURN
10 IER=NR
RETURN
END
SUBROUTINE SOLB(Y)
COMMON ML,MU,3(770,16),N,NR,DIM,IP(770)
DIMENSION Y(1)

C SOLUTION OF A*X=C GIVEN LU DECOMPOSITION OF A FROM DECB.
C Y = RIGHT-HAND VECTOR C, OF LENGTH N, ON INPUT;
C = SOLUTION VECTOR X ON OUTPUT.
C CAUTION: IF ML=0, THIS ROUTINE CONTAINS EMPTY DO-LOOPS
C WHICH MUST BE COMPILED CORRECTLY (I.E. NO ACTION TAKEN).
C ALL THE ARGUMENTS ARE INPUT ARGUMENTS.
C THE OUTPUT ARGUMENT IS Y.

C N1=N-1
LL=ML+MU+1
DO 3 NR=1,N1
IF(IP(NR).EQ.NR)GO TO 1  
J=IP(NR)  
XX=Y(NR)  
Y(NR)=Y(J)  
Y(J)=XX  
1  
KK=MIND(N-NR,ML)  
DO 2 I=1KK  
2  
Y(NR+I)=Y(NR+I)+Y(NR)*B(NR,LL+I)  
CONTINUE  
LL=LL-1  
Y(N)=Y(N)*B(N)  
KK=0  
DO 5 NB=1,N1  
5  
NR=N-N3  
IF(KK.LT.LELL)KK=KK+1  
DP=0.  
DO 4 I=1,KK  
4  
DP=DP+B(NR,I+I)*Y(NR+I)  
5  
Y(NR)=(Y(NR)-DP)*3(NR)  
RETURN  
END  
SUBROUTINE NDROP  
CALL GRBDO(1HU,4HVEGA,4,3H1C5,5HT3LDC,4HKEEP)  
CALL GRPHLUN(7)  
CALL LIB4020  
CALL GRPHFTN  
CALL SETFLSH  
RETURN  
END
**** *IDENT FIX
**** *DELETE SV.23
   DATA LFIL4,KPR, NM/13D,5,500/
**** *INSERT SV.371
   IF (J, ,LE, 5) RH0(J)=RH0(J)+FL0AT(1D-4AX0(2+J))@0.25
**** *INSERT SV.26
   CALL UNDROP
| 41 | 33-2.80-2.90-2.33 |
| 42 | 34 - .79 -.79 -.77 - .79 -.50 -.73 - .62 - .47 - .30 -.10 .11 .33 .56 .81 |
| 43 | 35 1.05 1.32 1.09 1.05 2.12 2.33 2.64 2.76 1.71-3.11-2.62-2.62-2.62-2.62 ...
| 44 | 36-2.62-2.62-2.62-2.62 |
| 45 | 37 - .90 -.32 -.23 -.15 -.08 -.01 .07 .19 .33 .49 .67 .86 1.05 1.29 |
| 46 | 38 1.52 1.76 2.01 2.25 2.49 2.73 2.95 3.01 1.32-2.89-2.44-2.44-2.44-2.44 ...
| 47 | 39-2.44-2.44-2.44 |
| 48 | 40 -.44 -.28 -.07 .18 .42 .59 .74 .86 .97 1.10 1.24 1.39 1.55 1.76 |
| 49 | 41 1.97 2.15 2.40 2.62 2.33 3.05 3.25 3.19 1.92-2.66-2.26-2.26-2.26-2.26 ...
| 51 | 43 - .47 - .28 -.03 .22 .55 .89 1.19 1.39 1.54 1.65 1.77 1.90 2.05 2.21 |
| 52 | 44 2.33 2.33 2.73 2.97 3.17 3.36 3.52 3.33 2.02-2.44-2.03-2.08-2.08-2.08 ...
| 53 | 45-2.03-2.03-2.03-2.03 |
| 54 | 46 - .47 -.40 -.31 .01 .43 .86 1.28 1.62 1.90 2.09 2.24 2.37 2.53 2.63 |
| 55 | 47 2.73 2.95 3.12 3.31 3.49 3.67 3.80 3.49 2.12-2.22-1.90-1.90-1.90-1.90 ...
| 56 | 48-1.90-1.90-1.90-1.90 |
| 57 | 49 - .47 -.47 -.48 -.18 .24 .63 1.14 1.59 2.00 2.31 2.56 2.74 2.83 3.01 |
| 58 | 50 3.14 3.20 3.44 3.00 3.78 3.97 4.07 3.52 2.23-2.00-1.72-1.72-1.72-1.72 ...
| 59 | 51-1.72-1.72-1.72-1.72 |
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|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
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   DATA (RCV(J),J=1,200)/200*8.02232E-09/
*DELETE SV.370,SV.373
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   P(J)=1.99543E+03
   IF (J.LE.5) P(J)=5.37152E+14
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   CND(J)=0.5*(MUVISC(J-1)+MUVISC(J))/PR
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   DATA PR/100./
*DELETE SV.616,SV.617
   MUVISC(J)=2.4E+07
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*INSERT SV.26
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APPENDIX C
1 *IDENT PROB
2 *DELETE SV.23
3 DATA LFILM,KPR,NM/50,5,200/
4 *DELETE SV.313
5 DATA (RCV(J),J=1,200)/200*4.E-09/
6 *DELETE SV.259
7 U(JP2)=U(JP1)+DELU
8 U(JP3)=U(JP2)+DELU
9 RHO(1)=3.674E-21
10 EI(JP2)=2.*EI(JP1)-EI(JBAR)
11 *DELETE SV.261
12 EI(1)=2.65E+14
13 *DELETE SV.370,SV.373
14 RHO(J)=3.674E-21
15 EI(J)=2.65E+14
16 P(J)=(GAMMA-1.)*RHO(J)*EI(J)
17 *DELETE SV.375
18 *DELETE SV.618,SV.624
19 CND(J)=0.5*(MUVISC(J)+MUVISC(J-1))/PR
20 *DELETE SV.180
21 AA(K+1,L-5)=-1.
22 *DELETE SV.78
23 *DELETE SV.527
24 *DELETE SV.228
25 *DELETE SV.374
26 U(J)=UT1
27 *DELETE SV.87
28 SUM=1.33E+25
29 *DELETE SV.90
30 DPHI(JP2)=SUM/X(JP2)**2
31 *DELETE SV.204
32 RHO(1)=3.674E-21
33 EI(1)=2.65E+14
34 UT(JP2)=UT(JP1)+DELU
35 UT(JP3)=UT(JP2)+DELU
36 EI(JP2)=2.*EI(JP1)-EI(JBAR)
37 *DELETE SV.552
38 DO 10 J=2,JP3
39 *INSERT SV.296
40 SUBROUTINE ASOLN(X,P,EI,RHO,U,GAMMA,JP1)
DIMENSION X(1), P(1), EI(1), RHO(1), U(1)
JP2 = JP1 + 1
GNOT = 1.33E+26
ANA = RHO(1) * U(2) * X(2) * X(2)
ANB = EI(1) + D.5 * U(2) * U(2) + P(1) / RHO(1) - GNOT / X(2)
ANC = P(1) / RHO(1) ** GAMMA
D2 = GAMMA * ANC / (GAMMA - 1.)
D3 = GAMMA - 1.
D4 = SQRT(ANA ** 2 * 0.5)
WRITE (6, 6) ANA, ANB, ANC, D2, D3, D4
6 FORMAT (1X, *A AND D*, 7E15.6)
DO 1 J = 3, JPZ
ROLD = RHO(J)
1 CONTINUE
DO 2 IT = 1, 200
RHO(J) = 0.04 / (X(J) * X(J) * SQRT(ANB - D2 * RHO(J) ** D3 + GNOT / X(J))
2 CONTINUE
IF (ABS(RHO(J) - ROLD) .LE. 1.E-10 * ROLD) GO TO 3
3 CONTINUE
ROLD = RHO(J)
WRITE (6, 4) J, ROLD, RHO(J)
4 FORMAT (1X, *ITER FAILURE*, I5, 2E15.6)
CONTINUE
P(J) = ANC * RHO(J) ** GAMMA
EI(J) = P(J) / (D3 * RHO(J))
U(J) = ANA / (X(J) * X(J) * RHO(J))
WRITE (6, 5) J, RHO(J), P(J), EI(J), U(J)
5 FORMAT (1X, *A SOLN*, I5, 4E13.6)
END FILE 6
1 CONTINUE
RETURN
END
*INSERT SV.376
CALL ASOLN (X, P, EI, RHO, U, GAMMA, JP1)
*DELETE SV.511
DATA PR/1.E+05/
*INSERT SV.27
DELU = U(JP2) - U(JP1)
*DELETE SV.185
8(K+1) = DELU
*INSERT SV.617
$ *1.E-12
*DELETE SV.132
AA(4,7) = X(2) * X(2)
AA(4,12) = -X(3) * X(3)
*DELETE SV.229
*INSERT SV.210
                   RHOST = RHO(L(J))
                   EIT = EI(J)
IF (J NE. 2) GO TO 151
RHOST = RHO(L(1))
EIT = EI(1)
151 CONTINUE
*DELETE SV.214
1RHOST = UO(J+1) * AJ(J+1) * ((1. + DUB2) * RHO(L(J)) + (1. - DUB2) * RHO(L(J+1)))
*DELETE SV.215
1+(1. - DUB1) * RHOST * EIT - UO(J+1) * AJ(J+1) * ((1. + DUB2) * RHO(L(J)) * EIT(J)
*IDENT SHOK
*INSERT PROB.10
                   IF (T.LT.TSHOK OR T.GE.TSHOK+7560.) GO TO 1006
                   RHO(L(1)) = RHO(L(1)) * 3.864
                   EI(1) = EI(1) * 25.47
                   UT(2) = 1.57E+08
1006 CONTINUE
*INSERT PROB.26
                   IF (T.LT.TSHOK OR T.GE.TSHOK+7560.) GO TO 1007
                   RHO(L(1)) = RHO(L(1)) * 3.864
                   EI(1) = EI(1) * 25.47
                   UT(2) = 1.57E+08
1007 CONTINUE
*INSERT SV.22
DATA TSHOK/2.6E+05/
*IDENT RADCO
*DELETE PROB.22, PROB.23
U(JP3) = U(JP2)
*DELETE PROB.11, PROB.12
UT(JP3) = UT(JP2)
*DELETE PROB.7
AA(K+1,L-5) = -DT * U(JP2) / (X(JP2) - X(JP1))
*DELETE SV.184
AA(K+1,L) = 1. - AA(K+1,L-5)
*DELETE PROB.8
121 \quad B(k+1) = U(JP2)
122 \quad *INSERT SV* 26
123 \quad CALL UNDROP
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Note: Add $2.50 for each additional 100-page increment from 601 pages up.