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THE TRANSFER FUNCTION MODEL

A computer program for determination of jet engine test cell exhaust particulates and opacity

Clyde Richards
Atmospheric Physics, Inc.

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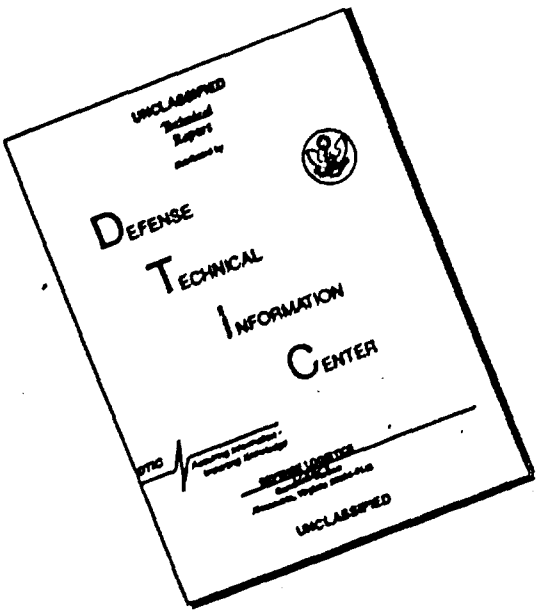

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The Transfer Function Model (TFM) is an extensive computer program which is capable of computing the downstream parameters of a jet engine exhaust plume for generalized initial conditions, duct system geometry, and liquid and/or gas dilution.

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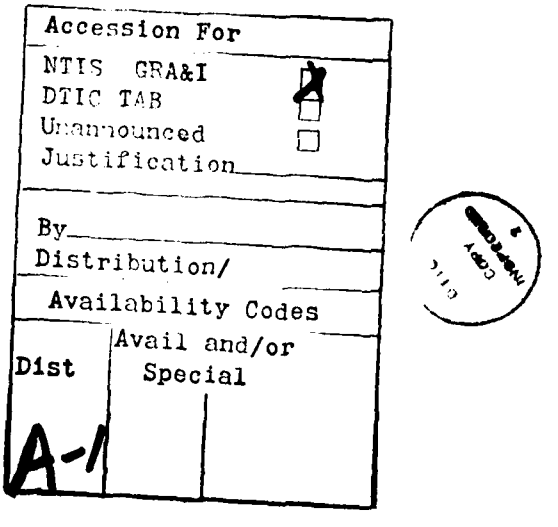

I. SUMMARY

The Transfer Function Model (TFM) is an extensive computer program which is capable of computing the downstream parameters of a jet engine exhaust plume for generalized initial conditions, duct system geometry, and liquid and/or gas dilution.

For example, the TFM can be used to predict the opacity of a plume at any distance from the engine exhaust plane, or the change in opacity as the engine load is changed.

More specifically, the following parameters of the exhaust plume can be calculated by the TFM at any arbitrary point downstream from the jet exhaust plane:

A. Particulate size distribution,

B. Gas temperature,

C. Gas density (and water vapor density),

D. Gas velocity,

E. Droplet size distribution (if condensation has occurred or if water has been injected),

F. Light scattered and absorbed by each of the various sized particulates, and

G. Total plume opacity.

The TFM can be used to determine the effects of changing any one of several control parameters. Some of the parameters which can be modified are:

At the exhaust plane:

A. Gas velocity (subsonic or supersonic)

B. Particulate size distribution

C. Mass flow rate

D. Gas temperature

E. Water vapor density

Within the test cell:

A. Injected air (or steam)

B. Injected liquid water

C. Variable test-cell cross section

The cost of running the TFM for a given situation is generally less than $100.00. Thus, the TFM should prove to be a very cost-effective tool for predicting jet test cell exhaust plume characteristics.

II. INTRODUCTION AND BACKGROUND

The U.S. Navy has a need to predict the opacity of jet engine test cell emissions and the parameters which affect the test cell exhaust opacity.

Because of the difficulty and cost in measuring the particulate size and opacity of jet engine emission plumes, a computer code has been developed which predicts the opacity. The code incorporates the basic laws of thermodynamics, hydrodynamics, and aerosol behavior, together with the laws which govern light scattering and absorption, to describe both the conditions inside the "smoke" as it moves away from the engine and the opacity of the plume itself.

Since the computer code describes the exhaust gas aerosol from the exhaust phase of the jet engine until the aerosol is transferred into the atmosphere, the code is called a Transfer Function Model (TFM).

In order to make the TFM as general as possible, allowance has been made for the injection of steam, air, other gases, or liquid water at arbitrary points downstream from the gas. This capability makes possible the study of the effect of such injections on the opacity of the plume as it rises into the atmosphere.

The original computer code upon which the TFM is based was a code used to simulate various pollution control devices. This aspect of the TFM would make it a valuable asset if, in the future, the Navy wanted to evaluate proposed test cell emissions control methods. The TFM could be used to simulate each of the proposed methods to determine energy costs, particulate removal efficiency, resultant plume opacity, etc.

Later sections of this report describe in detail the equations upon which the TFM is based and the computational techniques which are used. In short, the TFM follows a representative parcel of "smoke" from the time it leaves the jet engine exhaust until it rises into the atmosphere. As the TFM "steps" the parcel along, it calculates the changes in the intrinsic parameters (pressure, temperature, etc.) of the gas and the changes in the size distribution and number density of the aerosol particulates. If water has been injected, the TFM calculates (at each step) the amount of water which evaporates and the size distribution and number density of water droplets.

The second part of the TFM then uses the aerosol particulate and water droplet size distributions and number density to calculate the opacity of the plume. The second part of the TFM is based on the generalized scattering equations for electromagnetic radiation.

In developing the TFM, care was taken to make it as general as possible without increasing the computer time unnecessarily. The result is a model which can be easily modified or expanded as required.

The TFM should provide a very valuable, cost-effective tool for use in determining jet engine test facility emissions.

III. THEORETICAL BASIS AND COMPUTATIONAL TECHNIQUES

A. Exhaust Gas/Aerosol Dynamics

The TFM calculates the intrinsic parameters (temperature, pressure, density, velocity, etc.) of the exhaust gas as it moves away from a jet engine. These calculations are based on the basic principles of fluid dynamics and thermodynamics for compressible fluid flow (see references 1-4). Those basic principles include the following laws and assumptions:

1. Conservation of Mass
2. Newton's Second Law
3. First Law of Thermodynamics
4. Second Law of Thermodynamics
5. Equation of State for a Perfect Gas
6. Compressible Flow

The equations which represent these basic principles are formulated in the method outlined by Shapiro (reference 1). Using this method, a matrix of influence coefficients is formed, the elements of which can be used to calculate the change in each dependent variable due to changes in the independent variables.

In this method, the matrix elements of influence coefficients are first calculated using the initial values of the variables (i.e., the values specified at the jet engine exhaust plane). The TFM then calculates the changes in the independent variables between that point and a point lying a short distance downstream. The matrix of influence coefficients are then evaluated for the new point and then used to calculate the dependent variables at the new point. This process is repeated until the exhaust reaches a pre-specified point.

At each of the calculation points (dependent variable evaluation points), several other calculations are performed. References for the basis of each of these calculations can be found in the Appendix, which consists of a FORTRAN listing of the TFM with documentation. They fall under the following categories:

1. Liquid Injection. The TFM allows for the injection of liquid at arbitrary rates at arbitrary points downstream. The TFM checks to see if one of these ports has been passed in going from one calculation point to the next. If it has, the injected liquid is subjected to break-up into smaller droplets in a separate routine. The drag which the injected liquid exerts on the exhaust gas is calculated as is the cooling of the gas due to evaporation of the liquid and transfer of sensible heat from the gas to the liquid. The terms which arise from these calculations are added to the corresponding changes in the independent variables.

2. Gas Injection. The TFM also allows for the injection of any gas (or gas mixture) at arbitrary ports downstream. At each calculation point the TFM checks to see if a gas injection port has been passed, the gas mass injection rate is added to the exhaust gas mass flow rate, the momentum of the injected gas in the direction of the exhaust gas flow is added in, and the injected gas is assumed to be completely mixed with the exhaust gas to determine the resultant specific heat capacity and temperature. The injected gas may have arbitrary temperature and relative humidity.

3. Aerosol Agglomeration. The size, distribution, and number density of the aerosol particles can change in several ways. At present, the TFM assumes that they may change as follow:

(1) Particulate-particulate collisions

(2) Particulate-liquid droplet collisions

(3) Liquid droplet-liquid droplet collisions

(4) Liquid droplet evaporation (or condensation)

The particulate-particulate collisions are assumed to occur via random motion of the particulate (diffusional agglomeration).

The particulate-liquid droplet collisions are due to both diffusional agglomeration and the fact that injected liquid droplets may have an "ordered" velocity which is different from the exhaust gas, in which case the collisions are due to inertial impaction.

The liquid droplet-liquid droplet collisions are calculated using both diffusional agglomeration and inertial impaction.

All of these calculations are done at each time interval corresponding to each downstream calculation point.

4. Liquid Droplet Evaporation (or Condensation). The TFM, in its present form, assumes that there are no chemical reactions downstream of the jet engine exhaust. Thus, it assumes that a given chemical species is conserved. As it now stands, the TFM monitors only one evaporating or condensing species--water. At each computational point, the TFM calculates the partial pressure of the water vapor present in the gas. If that pressure is greater than the saturation vapor pressure condensation on the particulates, then pre-existing water droplets can occur; if the existing vapor pressure is less than the saturation vapor pressure, then evaporation can occur. The TFM calculates the amount of evaporation (or condensation) which occurs at each computational point for each size class of particulates and water droplets.

The net water mass condensed between the two computational points is then calculated and the corresponding release of latent and sensible heat is added to the heat of the gas.

B. Opacity and Electromagnetic Scattering Calculations

The TFM can calculate the scattering (and absorption) by any arbitrary size spherical particle for a given wavelength of electromagnetic radiation and a given angle of scatter. Thus, by using these equations to calculate the extinction cross-section for each size-class particle (particulate or liquid droplet) in the jet exhaust (at a given point downstream from the exhaust plane), the total extinction cross-section can be obtained. Thus, the opacity of the plume can be found by knowing the number density of each size-class particle and the diameter of the plume.

The equations upon which the scattering and opacity calculations are based are the solutions to the general scattering theory (see references 5-10).

These solutions are in the form of a series of expansions, some of which are straightforward but others require evolved numerical techniques in order to assure rapid convergence.

The TFM must have the following parameters for each of the scattering calculations:

1. Diameter of the scattering particle
2. Wavelength of the electromagnetic radiation
3. Angle defined by light source : particle : observer
4. Imaginary and real components of the index of refraction of the particle or the conductivity and relative permittivity of the particle

Further documentation of and references for these calculations may be found in the Appendix.

IV. CONCLUSIONS

This model provides an ability to predict test facility particulate and opacity for any combination of gas turbine engine and test facility/control device configurations. The cost is estimated to 1/200th of the cost to measure the same parameters.

The TFM is a cost-effective tool for the determination of jet engine test cell particulate loading and exhaust opacity. It is both flexible and general. The flexibility manifests itself in the ease with which a specific situation (engine size and load, test cell geometry, liquid injection, etc.) can be modeled. It is general in the sense that other effects (such as chemical reactions, hydrocarbon condensation, etc.) can be added without modifying the theory and computational techniques upon which the TFM is based.

V. RECOMMENDATIONS

Two types of recommendations are pertinent concerning the model. First, the model must be validated using actual engine exhaust plane/top of the exhaust stack data. Validation will provide air pollution control districts with confidence of the model's accuracy. Second, the following additional efforts will make the model easier to use and more powerful when evaluating control devices.

A. Turbulent Agglomeration

As the TFM now exists, all agglomeration of the particulates is calculated using diffusional agglomeration equations only. However, turbulent agglomeration should be an important process in the modification of the size distribution and number density, especially for particulates greater than about 1 micron.

B. Entrainment of Air Into the Plume

As the TFM now exists, the amount of air entrained in the plume is an input parameter. However, more realistic method would be to have the TFM calculate the amount of air entrained in the plume after it leaves the test cell. The entrainment of air into the plume and the subsequent dispersion is required to predict opacity.

C. Condensation of Hydrocarbons

As the TFM now stands, water is the only liquid/vapor substance that is allowed to undergo phase transition. The evaporation/condensation of any other liquid can be added to the TFM if the saturation vapor pressure of the liquid is known.

D. Chemical Reactions

The TFM lends itself well to the addition of the effects of chemical reactions. If this feature were added, the TFM could model the effect of afterburning control devices on the plume opacity or injection of ammonia for NO_x control.

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APPENDIX

FORTRAN LISTINGS OF TRANSFER FUNCTION MODEL (TFM)

```
      PROGRAM BUILD
      DIMENSION DAI(20),NAI(20),SLM(20),INSLM(20)
C       DAI(I) is the initial diameter of the aerosol particles in the
C      I th size class, assumed to have (initially) the same tempera-
C      ture as the jet exhaust.
C       NAI(I) is the number density of aerosol particles initially in
C      the I th size class.
C       SLM(I) is the water-soluble mass in each of the aerosol part-
C      icles in I th size class.
C       INSLM(I) is the water-insoluble solid mass in each of the aerosol
C      particles in the I th size class.
     1,DWI(20,20),NWI(20,20),TWI(20),NWIT(20)
C       DWI(I,J) , NWI(I,J) ,and TWI(J) are the diameter,number dens-
C      ity, and the temperature, respectively of the I th size injected
C      at the J th port.NWI(I,J) can be given J port,since it is normal-
C      ized later.
C       NWIT(I) is an approximation to a typical water spray.
     2,XWPORT(20),WMDOT(20),XAPORT(20),AMDOT(20),CONSOL(20)
C       XWPORT(J) is the distance to the J th water injection port.
C       WMDOT(J) is the mass injection water injection port.
C
C       XAPORT(J) is the distance to the J th air injection port.
C       AMDOT(J) is the mass injection rate of air at the J th port.
C       CONSOL(J) is the concentration of soluble salts in the injected water.
     3,TIAIR(20),VXAIR(20),SPHUMD(20),MASEQW(20),SPHTAR(20)
C      TIAIR(J) is the temperature of the air injected at the J th
C      port.
C       VXAIR(J) is the axial component of the velocity of the injected air
C      at the J th port.
C       SPHUMD(J) is the specific humidity of the gas being injected at
C      the J th port.It is defined as the ratio of the water vapor density to
C      the total density of the gas; thus a value of 1.0 corresponds
C      to steam.
C       MASEQW(J) is the mass equivilant weight(or kg./kmole)
C      of the gas injected at the J th port.
C       SPHTAR(J) is the specfic heat(at constant pressure) injected at the
C      J th port,(Joules/Kg-deg.Kelvin).
C
C       Now Dimension the working variable arrays.
     4,RA(20),RW(20,20),SOLUMA(20,20),INSOLM(20,20),H2OMAS(20,20)
C       RA(I) is the running radius of the aerosol particles.
C       RW(I,J) is the running radius of the injected water drops.
C       SOLUMA(I,J) is the running soluble mass in each of the(I,J) drops.
C       INSOLM(I,J) is the running insoluble mass in each of the(I,J) drops.
C       H2OMAS(I,J) is the mass of water in each of the(I,J) drops.
C
     5,TW(20,20),VXW(20,20),NW(20,20),NA(20),TA(20)
C       TW(I,J) is the running temperature of the water drops which were
C      injected at the J th and which were originally in the I th
C      size class.
C       VXW(I,J) is the running axial component of the velocity of the water
C      drops which were injected at the J th port and whicch were originally
C      in the I th size class.
C       NW(I,J) is the running number of water drops which were originally of
C      the I th size class and were injected at the J th port.(NW(I,J) mst be
C      less than NWI(I,J) due losses by collision or consulation with larger
C      drops or particles.)
```

```
C       NA(I,J) is the running number of aerosol particles which were orig-
C     inally in the I th size class.NA(I) will, in general, be less than NAI
C     (I) because of loses by collisions and coagulation with larger
C     particles or water drops.
C       TA(I) is the running temperature of the aerosol particles, which can
C     be different from the main gas flow because of condensation on the
C     particles.
     6,KWIJ(20),KAIJ(20),FNORM(20),DRDIF(20),WORKAR(20,20),TRW(20,20)
C       KWIJ(J) is a control array to determine if the J th water spray has
C     been injected; similarily, KAIJ(J) is for the air injection ports.
C       FNORM(J) is a normalization array for the drop size distribution
C     injected at the J th port.
C       DRDIF(I) is a typical drop diameter distribution to represent
C     the injected drops.
C       WORKAR(I,J) and TRW(I,J) are temporary storage arrays, used when
C     injecting hte water sprays.
C
     7,WATM(20),TYARDI(20),TYNUMD(20),DAPLOT(20)
C       WATM(I) is the array of the condensed water mass on each of the
C     I th size aerosol particles.
C       TYARDI(I) is a typical aerosol diameter array used to represen
C     the size distribution of the aerosol particles.
C       TYNUMD(I) is an un-normalized size distribution which, with
C     DAPLOT is the plotting array for the diameters, in microns.
     8,Aa(6),Bb(6,6),Cc(6),DA(20),DAIPLO(20)
C       Aa,Bb,Cc are the Shapiro matricies for the influence coefficients.
C      DA(I) is the 'running' diameter of the aerosol particles.
C     DAIPLO is the plotting array for the initial diameters, microns.
     9,PLTXXX(1000),T1YYY(1000),V1YYY(1000),RHYYY(1000)
C
      REAL  NAI,INSLM,NWI,MASEQW,INSOLM,NW,NA,NWIT,
     1Meaw,Loadin,Mix1,Mdot1,Mdot2,Msard1,Msard2,Molwt1,Molwt2,
     2NRBAR,INSLGN,MOWINA,L,MUH2O,NAMAX
C
C       DATA  Losnor /100,112.5,32,15,3.75,0.24,0.02,0,0,0/
      DATA DRDIF  /1.,2.,3.,5.,7.,10.,14.,20.,27.,35.,47.,65.,80.,100.
     1,140.,200.,300.,400.,700.,1000./
      DATA NWIT /0.1,0.2,0.4,1.5,1.7,2.5,4.0,6.0,7.0,10.0,15.0,20.0
     1,25.0,35.0,35.0,30.0,25.0,15.0,1.00,0.00/
      DATA XWPORT /0.50,2.00,3.00,4.00,5.00,6.00,7.00,8.00,9.00,10.00
     1,11.00,12.00,13.00,14.00,0.0,16.00,50.,50.,60.,79./
      DATA XAPORT /1.50,2.50,3.50,4.50,5.50,6.50,7.50,8.50,9.50,10.50
     1,11.00,12.00,13.00,14.00,15.00,15.00,17.00,58.00,0.0,56.00/
      DATA WMDOT /0.,0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00
     1,0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00/
      DATA AMDOT /00.0,0.00,0.00,00.00,0.0,0.00,0.0,0.00,0.00,000.0
     1,0.0,0.0,0.0,0.0,0.0,0.0,0.0,00.0,0.0,0.0/
      DATA CONSOL /0.0,0.0,0.0,0.00,0.0,0.00,0.0,0.0,0.0,0.0
     1,0.0,0.0,0.00,0.0,0.0,0.0,0.0,0.0,0.0,0.0/
      DATA TIAIR /150.0,20.,20.,20.,20.,20.,20.,20.,20.,
     1,20.0,20.0,20.0,20.0,20.0,20.0,20.0,20.0,20.0,20.0/
      DATA VXAIR /50.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0
     1,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0/
      DATA SPHUMD /0.10,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0
     1,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0/
      DATA MASEQW /30.,30.0,30.0,30.0,30.0,30.0,30.0,30.0,30.0,18.0
     1,30.,30.,30.,30.,30.,30.,30.,30.,30.,30./
      DATA SPHTAR /1006.,1006.,1006.,1006.,1006.,1006.,1006.,
```

```
     1,1006.,1980.,1006.,1006.,1006.,1006.,1006.,1006.,1006.,1006.,
     2,1006.,1006.,1006./
      DATA TWI /20.,20.,20.,20.,20.,98.,20.,20.,20.,20.,
     1,20.,20.,20.,20.,20.,20.,20.,20.,20.,20./
      DATA TYARDI /0.05,0.10,0.20,0.30,0.50,0.75,1.0,1.3,1.7,2.3,3.1
     1,4.0,5.0,7.0,10.0,15.0,20.0,30.0,50.0,100.0/
      DATA TYNUMD /500.,1000.,500.,200.,100.,50.,10.,7.,4.,2.,
     11.,0.1,0.01,0.001,0.001,0.0,0.0,0.0,0.0,0.0/
C       Now the Universal constants:
      Cva=766.4      @ specic heat at constant volume of dry air.
      Rgas=8314.34     @ universal gas constant.
      Rma=Rgas/29.98    @ gas constant/(mol. wt. of stack gas).
      Rmw=Rgas/18.015    @ specific gas constant for water vapor.
      PI=3.14159
      L=2.22583E6       @ latent heat of vaporization of water.
      Eps=Rma/Rmw
      Gama=1.37     @ Cp/Cv for dry gas.
      Cpa=Gama*Cva    @ Cp for dry air.
      Cpw=4186.      @ specfic heat for liquid water.
      Dif1=2.39E-5     @ water vapor diffusion coef. (m2/sec)
      Rhol=1.E3    @ density of liquid water.
      Cond=2.83E-2     @ Thermal diffusion coefficient in air.
C      The units of Cond are Joule/(meter-sec.-deg.Kelvin)
      Beta=0.036  @ Beta is  the condensation coefficient.
      Sig=0.072         @ Surface tension for water.
      Emob=2.2E-4         @ Ion mobility in air at 1 atm.
      Eta=1.66E-5      @ Kinematic coef. of viscosity for air (m2/sec)
      MUH20=1.143E-3       @ Viscosity of H20  (Kg/meter-sec.)
      ETAH20=1.143E-6       @ Kinematic coef. of vis. for liquid H20 (m2/sec.)
      TAYLRC=2.7  @ Taylor's constant for drop breakup in fast gas flows.
      BOLTZ=1.38E-23  @Boltzmann's constant ( Joules/deg)
      COAGC=(2./3.)*BOLTZ*293.16/Eta
      COLCON=(2./9.)*Rhol/Eta
      CWBRUP=2.5
      CPH20=1980.  @ Specific heat at constant pressure for H20 vapor.
C   Now the initial intrinsic parameters of the aerosol.
C
      Pdens=2.0E3    @ Particles' mass density.
      Meaw=58         @ Equiv. molecular wt. of NaCl.
      Ey=2.5          @ van't Hoff Factor.
      Loadin=5.000   @ Particulate loading (grains/cu ft.).
      P0=1.005E5     @ Initial pressure.
      Sphum1=0.10  @    "       specific humidity.
      T0=555.  @ Jet exhaust temperature in degs. Centigrade.
      V0=2600.  @ Jet exhaust velocity in ft/sec.
      W0=1597.  @ Mass flow rate through jet engine, lbs/sec.
      Xtot=350.
      A0=4.0    @ The initial cross-sectional area of the flow duct,sq.meter.
      Ratio=2.5    @Ratio is the ratio of the max. to min. cross sect.
C
C      Now some of the injected spray parameters.
      RHOSOL=1.05E3    @ Density of liquid to be injected (kg/cu.meter)
C    Calculate constants coefficients and convert all parameters to MKS
C   System of units.
      P1=P0
      Ac=2.0*Sig/(Rhol*Rmw)
      Bc=3*18.015/(4*PI*Rhol)
      C3=L*L*Dif1/(Cond*Rmw*Rmw)
```

```
      C4=4*PI*Diff/Rmw
      C5=4.*PI/3.
C      C11=0.018*Emlode*2.4E19/(Pdens*4*PI)
      C12=3/(Rhol*Cpw)
      C13=L/(4*PI)
      C14=4*PI*Cond
C
C     Initialize particulate parameter arrays.
C
C
      V1=V0/3.2808
      DO 2 J=1,20
      TWI(J)=273.16+TWI(J)
      TIAIR(J)=TIAIR(J)+273.16
      TA(J)=T0+273.16
 2    CONTINUE
      SUMNUM=0.0
      PLDMKS=Loadin*2.293E-3   @ Convert particle loading into Kg/cu.meter
      DO 9 I=1,20
      DAI(I)=TYARDI(I)*1.E-6
      RA(I)=DAI(I)/2      @ Calculate initial particle radii in MKS.
      DA(I)=DAI(I)
      SLM(I)=0.
      WATM(I)=0.
      SMFACT=C5*RA(I)**3*Pdens
      INSLM(I)=SMFACT-SLM(I)
      SUMNUM=SUMNUM+SMFACT*TYNUMD(I)
      DO 10 J=1,20
      NWI(I,J)=NWIT(I)
      NW(I,J)=0.0
      DWI(I,J)=DRDIF(I)*1.0E-6
      RW(I,J)=(DWI(I,J)/2.)
      DMASSE=C5*RW(I,J)**3*RHOSOL
      SOLUMA(I,J)=CONSOL(J)*DMASSE
      H2OMAS(I,J)=DMASSE-SOLUMA(I,J)
      INSOLM(I,J)=0.
      TW(I,J)=TWI(J)
      VXW(I,J)=0.
      WORKAR(I,J)=0.
      TRW(I,J)=0.
10    CONTINUE
 9    CONTINUE
      FACNRM=SUMNUM/PLDMKS
      DO 7 J=1,20
      FNORM(J)=0.
      KWIJ(J)=0.
      KAIJ(J)=0.
      DO 8 I=1,20
      FNORM(J)=FNORM(J)+NWI(I,J)*C5*RHOSOL*RW(I,J)**3
 8    CONTINUE
 7    CONTINUE
      DO 6 I=1,20
      NAI(I)=TYNUMD(I)/FACNRM
      NA(I)=NAI(I)
 6    CONTINUE
      Condw=0
      Time=0
      Dtmax=1.00E-4
```

```
      Dt=5.0E-3
      Deltim=Dt
      X=0
      KKK=1
      Count=0
      Lmn=0
C     Initialize the plot parameters :
      DXPLOT=50.0
      XPLOT=0.0
      KPLOT=0
      T1=T0+273.16
      WDOTO=W0/2.2
C     E1=RH*Esat(T1)
C     Mix1=Eps*E1/(P1-E1)
C     Sphum1=Mix1/(1+Mix1)  @ Specific humidity.
      Mix1=Sphum1/(1.-Sphum1)
      E1=Mix1*P1/(Eps+Mix1)
      Cv=(1+1.02*Sphum1)*Cva
      Cp=(1+0.9*Sphum1)*Cpa
      Gam1=Cp/Cv
      PrVapf=(Eta/Dif1)**(1./3.)
C
C   Begin stepping.
C
 30   CONTINUE
      KKK=KKK+1
      Lmn=Lmn+1
      Rm=Rma/(1-(1-Eps)*E1/P1)     @  Gas constant for moist air.
      IF  (Lmn.GT.1)  GO TO 11
      Gasdn1=P1/(Rm*T1)  @ Gas mass density.
C     Mdot1=Gasdn1*V1*A0      @ Gas mass flow rate.
      Mdot1=WDOTO
      V1=Mdot1/(Gasdn1*A0)
      Csqrd1=Gam1*P1/Gasdn1
      Msqrd1=V1*V1/Csqrd1
      Snspd1=Csqrd1**.5     @ Speed of sound in gas.
      Rhow1=E1/(Rmw*T1)
      Rhoda1=Gasdn1-Rhow1
      Molwt1=Gasdn1/(Rhoda1/29.98+Rhow1/18.015)
      Area1=A0
 11   CONTINUE
C      Calculate factors for diffusion rate on small droplets.
      Freth=Dif1/Beta*(2.*PI/(Rmw*T1))**(0.5)
C      Set values for heat ventilation factors.
      PrHeat=(Eta*Cp*Gasdn1/Cond)**(1./3.)
      IF  (X.LT.XPLOT) GO TO 3
      XPLOT=XPLOT+DXPLOT
      KPLOT=KPLOT+1
      IF (KPLOT.GT.1000) GO TO 100
      PLTXXX(KPLOT)=X
      T1YYY(KPLOT)=T1-273.16
      V1YYY(KPLOT)=V1
      RHYYY(KPLOT)=Gasdn1
      PRINT 202
C     PRINT *,  (PLTOUT(MPI,KPLOT),MPI=1,5)
C     PRINT *,  (PLTOUT(MPI,KPLOT),MPI=6,8)
C     PRINT *,  (PLTOUT(MPI,KPLOT),MPI=9,10)
      IF (KPLOT.GT.1) GO TO 333
```

```
C       First see if liquid injection port was passed during last time step.
        DO 40 J=1,20
        IF(X.LT.XWPORT(J)) GO TO 40  @ See if J th port has been reached.
        IF(KWIJ(J).NE.0) GO TO 40  @ Check to see if injected on previous step.
        KWIJ(J)=J          @ Set this water port flag non zero.
C           Now inject J th spray and shatter drops.
        DO 41 I=1,20
        NWI(I,J)=NWI(I,J)/FNORM(J)
C           In order to obtain the number density of drops in the I th size
C         range,injected at the J th port, multiply NWI(I,J) by the water
C         mass injection rate at the J th port, and divide by the total
C         (aerosol gas plus injected gas plus evaporated gas) volume flow
C         rate of the gas ( cu. meters/sec.)
        NW(I,J)=NWI(I,J)*WMDOT(J)/(Mdot1/Rhow1)
C        NW(I,J)=NWI(I,J)*WMDOT(J)/(Mdot1/Rhow1)
C           Check Taylor's criteria for drop breakup.
        VREL=V1-VXW(I,J)
        TEST=Rhow1*VREL**2/(2.*Sig/RW(I,J))
        IF (TEST.LT.TAYLRC) GO TO 44
C           Drop passes criteria; break it up.
        VOLIJ=C5*RW(I,J)**3*NW(I,J)
        RBAR=CWBRUP*(2.*RW(I,J))**(.5)*(MUH20*(Sig/Rho1)**.5
       1/(Gasdn1*VREL**2))**(1./3.)
        NRBAR=VOLIJ/(C5*RBAR**3)
        DO 42 K=1,19
        TRCE=(RW(K,J)+RW(K+1,J))/2.
        IF (RBAR.GT.TRCE) GO TO 42
        JAY=K
        GO TO 43
  42    CONTINUE
        JAY=20
  43    CONTINUE
        TRW(JAY,J)=((C5*WORKAR(JAY,J)*TRW(JAY,J)**3+VOLIJ)/
       1((WORKAR(JAY,J)+NRBAR)*C5))**(1./3.)
        WORKAR(JAY,J)=WORKAR(I,J)+NRBAR
        GO TO 41
  44    CONTINUE
        TRW(I,J)=((WORKAR(I,J)*TRW(I,J)**3*NW(I,J)*RW(I,J)**3)/
       1(WORKAR(I,J)+NW(I,J)))**(1./3.)
        WORKAR(I,J)=WORKAR(I,J)+NW(I,J)
  41    CONTINUE
        DO 45 I=1,20
        NW(I,J)=WORKAR(I,J)
        RW(I,J)=TRW(I,J)
        DMASSE=C5*RHOSOL*RW(I,J)**3
        SOLUMA(I,J)=DMASSE*CONSOL(J)
        H2OMAS(I,J)=DMASSE-SOLUMA(I,J)
  45    CONTINUE
  40    CONTINUE
C         Set Dt for this iteration.
C       Dt=AMAX1(Dtmax,Dt)
C       DO 200 J=1,20
C       IF (KWIJ(J).EQ.0) GO TO 200
C       IF (WMDOT(J).EQ.0.0) GO TO 200
C       DO 201 I=1,20
C       IF (NW(I,J).EQ.0.0) GO TO 201
C       VPRSR=Esat(TW(I,J))*(1.+Ac/RW(I,J))
C       DMDTR=C4*RW(I,J)*(E1/T1-VPRSR/TW(I,J))
```

```
C       HTRACN=C14*RW(I,J)*(TW(I,J)-TL)
C       DTRDT=ABS((L*DMDTR-HTRACN)/(C5*Cpw*RW(I,J)**3))
C       Dtuc=Dtemp*X/DTRDT
C       Dt=AMIN1(Dt,Dtuc,Dt)
C201    CONTINUE
C200    CONTINUE
C       Deltim=Dt
C          Now calculate the coagulation.
        DO 49 J1=1,20
        IF (NWIJ(J1).EQ.0) GO TO 49
        DO 50 J2=J1,20
        IF (NWIJ(J2).EQ.0) GO TO 50
C          The coagulation rate is calculated by -dn1/dt=K(r1,r2)n1n2,
C        where n1 is the number density of the smaller particle; r1 is the
C        radius of the smaller particle; n2 and r2 are the same parameters for
C        the larger size particles.  K(r1,r2) is given by:
C            K(r1,r2)=(2/3)*k*t/Eta*((r1+r2)**2/(r1*r2)), where k is the
C        Boltzman constant, Eta is the viscsity of air at temperature T.
        DO 51 I1=1,20
        IF(NW(I1,J1).EQ.0) GO TO 51
        DO 52 I2=I1,20
        IF(NW(I2,J2).EQ.0) GO TO 52
        DN1DT=-COAGC*(RW(I1,J1)+RW(I2,J2))**2/(RW(I1,J1)*RW(I2,J2))
       1*NW(I1,J1)*NW(I2,J2)
        IF (RW(I2,J2).LT.RW(I1,J1)) THEN
        ILOS=I2
        JL=J2
        IGANE=I1
        JG=J1
        ELSE
        ILOS=I1
        JL=J1
        IGANE=I2
        JG=J2
        END IF
        VLMCOA=DN1DT*RW(ILOS,JL)**3*C5*Dt
        NW(ILOS,JL)=NW(ILOS,JL)+DN1DT*Dt
        RW(IGANE,JG)=((C5*NW(IGANE,JG)*RW(IGANE,JG)**3-VLMCOA)/
       1(NW(IGANE,JG)*C5))**(1./3.)
        SLMGAN=-DN1DT*Dt*SOLUMA(ILOS,JL)
        SOLUMA(IGANE,JG)=SOLUMA(IGANE,JG)+SLMGAN/NW(IGANE,JG)
        INSLGN=-DN1DT*Dt*INSOLM(ILOS,JL)
        INSOLM(IGANE,JG)=INSOLM(IGANE,JG)+INSLGN/NW(IGANE,JG)
        H2OGAN=-DN1DT*Dt*H2OMAS(ILOS,JL)
        H2OMAS(IGANE,JG)=H2OMAS(IGANE,JG)+H2OGAN/NW(IGANE,JG)
 52     CONTINUE
 51     CONTINUE
C            Now coagulate the water drops and the aerosol particles.
        DO 53 I2=1,20
        IF(NW(I2,J).EQ.0) GO TO 53
        DO 54 I1=1,20
        IF (NA(I1).EQ.0) GO TO 54
        DNARDT=-COAGC*(RA(I1)+RW(I2,J))**2/(RA(I1)*RW(I2,J))*NA(I1)
       1*NW(I2,J)
        VOLAER=DNARDT*RA(I1)**3*C5*Dt
        NA(I1)=NA(I1)+DNARDT*Dt
        RW(I2,J)=((C5*NW(I2,J)*RW(I2,J)**3-VOLAER)/(NW(I2,J)*C5))
       1**(1./3.)
```

```
      SOLUMA(I2,J)=SOLUMA(I2,J)-DNARDT*Dt*SLM(I1)/NA(I2)
      INSOLM(I2,J)=INSOLM(I2,J)-DNARDT*Dt*INSLM(I1)/NA(I2)
      H2OMAS(I2,J)=H2OMAS(I2,J)-DNARDT*Dt*WATM(I1)/NA(I2)
   54 CONTINUE
   53 CONTINUE
   50 CONTINUE
   49 CONTINUE
C          Now coagulate the aerosol particles with themselves.
      DO 55 I1=1,20
      IF (NA(I1).EQ.0.0) GO TO 55
      DO 56 I2=I1,20
      IF (NA(I2).EQ.0) GO TO 56
      DNARDT=-COAGC*(RA(I1)+RA(I2))**2/(RA(I1)*RA(I2)+.NA(I1)=NA(I2)
      NA(I1)=NA(I1)+DNARDT*Dt
      RA(I2)=((NA(I2)*RA(I2)**3-DNARDT*Dt*RA(I1)**3)/(NA(I2)))
     1**(1./3.)
      SLM(I2)=SLM(I2)-DNARDT*Dt*SLM(I1)/NA(I2)
      INSLM(I2)=INSLM(I2)-DNARDT*Dt*INSLM(I1)/NA(I2)
      WATM(I2)=WATM(I2)-DNARDT*Dt*WATM(I2)/NA(I2)
   56 CONTINUE
   55 CONTINUE
      DNTHLA=0.
C        DNTHLA is the energy added to the gas (per unit mass of gas)
C       by the injected air during Dt.
      DMDOTA=0.
C        DMDOTA is the total mass rate of dry air which is injected at
C       a given port.
      MOWINA=0.
C        MOWINA is the weighted molecular weight of the injected air
C       during Dt.
      DMOMIA=0.
C         DMOMIA is the total momentum (per momentum of the gas) which
C       is added to the gas by the injecter.
      VAPINJ=0.0
C        VAPINJ is the mass rate of water vapor injected during Dt.
      DO 60 J=1,20
      IF (X.LT.XAPORT(J)) GO TO 60
      IF (KAIJ(J).NE.0) GO TO 60
C
C        Inject air at J th port.
C
      KAIJ(J)=J
      DNTHLA=DNTHLA+(SPHTAR(J)*(T1-TIAIR(J))+V1*V1/2.)*AMDOT(J)/Mdot1
      DMDOTA=DMDOTA+(1.0-SPHUMD(J))*AMDOT(J)
      VAPINJ=VAPINJ+SPHUMD(J)*AMDOT(J)
      MOWINA=MOWINA+AMDOT(J)*MASEQW(J)*Gasdn1/Mdot1
      DMOMIA=DMOMIA+(2.*VXAIR(J)/V1)*(AMDOT(J)/Mdot1)
   60 CONTINUE
C          Now calculate the collisions of injected water drops with
C        the injected air at other ports.
      DO 70 J1=1,19
      IF (NWIJ(J1).GT.0) GO TO 70
      IF (WMDOT(J1).EQ.0.0) GO TO 70
      J3=J1+1
      DO 71 J2=J3,20
      IF (NWIJ(J2).EQ.0) GO TO 71
      IF (WMDOT(J2).EQ.0.0) GO TO 71
      GO TO 71
```

```
      DAMAX=0.0
      NAMAX=0.0
      DO 99 I=1,20
      IF (NA(I).EQ.0.0) GO TO 99
      DA(I)=2.*RA(I)
      DAIPLO(I)=DA(I)*1.E6
      NAMAX=AMAX1(NAMAX,NA(I))
      DAMAX=AMAX1(DAMAX,DA(I))
 99   CONTINUE
      PLOZZZ=ALOG10(NAMAX)*10.
      NPLOZZ=INT(PLOZZZ+0.5)
      MMMOD=MOD(NPLOZZ,5)
      NPLOZZ=NPLOZZ+5-MMMOD
      PLOZZZ=NPLOZZ/10.
      NAMAX=10.**PLOZZZ
      DAMAX=DAMAX*1.E6
      XXSTP=DAMAX/10.
      YYSTP=NAMAX/10.
      PRINT *, NAMAX,DAMAX,XXSTP,YYSTP
      CALL BGNPL(KPLOT)
      CALL PAGE (12.,9.0)
      CALL NOBRDR
      CALL AREA2D(10.,7.5)
      CALL XNAME('PARTICULATE DIAMETER,(Microns)$',100)
      CALL YNAME('NUMBER OF PARTICULATES/CUBIC METER IN SIZE RANGE$'
     1,100)
C     CALL HEADIN ('SIZE DISTRIBUTION $',100,1.0,1)
      CALL MESSAG('DISTANCE FROM ENGINE IS  $',100,5.5,7.0)
      CALL REALNO(X,2,'ABUT','ABUT')
      CALL MESSAG('  METERS$',100,'ABUT','ABUT')
      CALL GRAF(0.0,XXSTP,DAMAX,0.0,YYSTP,NAMAX)
C     CALL YLOG(0.0,XXSTP,0.0,7.5)
C     CALL VBARS(DA,'BASE',NA,20)
      CALL CURVE (DAIPLO,NA,20,1)
      CALL ENDPL(KPLOT)
      GO TO 334
 333  CONTINUE
      CALL BGNPL(KPLOT)
      CALL PAGE(12.,9.)
      CALL NOBRDR
      CALL AREA2D(10.,7.5)
      CALL XNAME('PARTICULATE DIAMETER,(Microns)$',100)
      CALL YNAME('NUMBER OF PARTICULATES/CUBIC METER IN SIZE RANGE$'
     1,100)
      CALL HEADIN ('SIZE DISTRIBUTION OF PARTICULATES$',100,1.5,1)
      CALL MESSAG ('DISTANCE FROM ENGINE IS $',100,5.5,7.0)
      CALL REALNO (X,2,'ABUT','ABUT')
      CALL MESSAG ('  METERS$',100,'ABUT','ABUT')
      CALL GRAF (0.0,XXSTP,DAMAX,0.0,YYSTP,NAMAX)
      CALL MARKER (0)
      CALL CURVE (DAIPLO,NAI,20,1)
      CALL MARKER (2)
      CALL CURVE (DAPLOT,NA,20,1)
      CALL ENDPL (KPLOT)
 334  CONTINUE
C     IF (KPLOT.GE.1) GO TO 100
  3   CONTINUE
C
```

```
C             E=0
              VRELI2=ABS(VXW(I1,J1)-VXW(I2,J2))
              COLCON=COLCON*RW(I1,J1)*RW(I1,J1)*VRELI2/(RW(I1,J1)
              IF (COLPAR.LE.1.214) GO TO 73
              COLEFF=(1+0.75*ALOG(2.*COLPAR)/(COLPAR-1.214))**(-2)
              DN1DT=VRELI2*PI*(RW(I1,J1)*RW(I1,J1)*RW(I2,J2)*RW(I2,J2)
             1*NW(I1,J1)*NW(I2,J2)*COLEFF
              IF (RW(I1,J1).LT.RW(I2,J2))  THEN
              IL=I1
              JL=J1
              IG=I2
              JG=J2
              ELSE
              IL=I2
              JL=J2
              IG=I1
              JG=J1
              END IF
              DELNW1=DN1DT*Dt
              IF (DELNW1.GT.NW(IL,JL))  DELNW1=NW(IL,JL)
              NW(IL,JL)=NW(IL,JL)-DELNW1
              COLVOL= C5*DELNW1*RW(IL,JL)**3
              SOLUMA(IG,JG)=SOLUMA(IG,JG)+DELNW1*SOLUMA(IL,JL)/NW(IG,JG)
              INSOLM(IG,JG)=INSOLM(IG,JG)+DELNW1*INSOLM(IL,JL)/NW(IG,JG)
              H2OMAS(IG,JG)=H2OMAS(IG,JG)+DELNW1*H2OMAS(IL,JL)/NW(IG,JG)
              RW(IG,JG)=((C5*NW(IG,JG)*RW(IG,JG)**3+COLVOL)/(C5*NW(IG,JG)))
             1**(1./3.)
   73         CONTINUE
   72         CONTINUE
   71         CONTINUE
   70         CONTINUE
C               Now calculate the collisions between the aerosol particles and the
C              injected liquid drops due to the difference in their directed motion,
C              using the same method as above for the collisions of water drops with
C              themselves.
              DO 74 J2=1,20
              IF (KWIJ(J2).EQ.0) GO TO 74
              IF (WMDOT(J2).EQ.0) GO TO 74
              DO 75 I2=1,20
              IF (NW(I2,J2).EQ.0) GO TO 75
              DO 76 I=1,20
              IF (NA(I).EQ.0.0) GO TO 76
              VRELAW=ABS(V1-VXW(I2,J2))
```

```
      COLPAR=COLCON*RA(I)*RA(I)*VRELAW/RW(I2,J2)
      IF (COLPAR.LE.1.214) GO TO 76
      COLEFF=(1+0.75*ALOG(2.*COLPAR)/(COLPAR-1.214))**(-2)
      DNARDT=VRELAW*PI*(RA(I)*RA(I)+RW(I2,J2)*RW(I2,J2))*NA(I)*
     1NW(I2,J2)*COLEFF
      DELAER=DNARDT*Dt
      IF (DELAER.GT.NA(I)) DELAER=NA(I)
      NA(I)=NA(I)-DELAER
      COLAVO=C5*DELAER*RA(I)**3
      SOLUMA(I2,J2)=SOLUMA(I2,J2)+DELAER*SLM(I)/NW(I2,J2)
      INSOLM(I2,J2)=INSOLM(I2,J2)+DELAER*INSLM(I)/NW(I2,J2)
      H2OMAS(I2,J2)=H2OMAS(I2,J2)+DELAER*WATM(I)/NW(I2,J2)
      RW(I2,J2)=(C5*NW(I2,J2)*RW(I2,J2)**3*COLAVO)**(C5*NW(I2,J2))**
     1(1./3.)
      GO TO 76
   75 DNARDT=0.
      DELAER=0.
   76 CONTINUE
C
C     Now calculate the evaporation, the release of latent heat, and the
C     conduction of heat from the drops to the gas flow.
C     The equations used for these calculations are as follows:
C
C     1.)  (VAP.PRES.at drop surf.)=(sat.vap. at Tr)[1+A/r-iBM/(r**3)]
C
C     2.)  dm/dt=(4*Pi*r*Difl/Rmw)(Eo/To-Er/Tr)
C
C     3.)  L(dm/dt)=(4/3)*Pi*Rhol*Cpw*(r**2)*(dTr/dt) + 4*Pi*Cond*r*(Tr-To)
C
C      where A is proportional to the surface tension of the droplet,
C      B is a term which is proportional to the amount of soluble salts in
C     the droplet, dm/dt is the mass rate of growth of a droplet of radius r,
C     Difl is the water vapor diffusion coefficient, Rmw is the gas constant
C     for water vapor, Eo is the vapor pressure far from the drop, To is the
C     temperature far from the drop, Er and Tr are the corresponding quanti-
C     ties at the surface of the droplet, L is the latent heat of vaporiza-
C     tion of the liquid, Cpw is the specific heat capacity of the liquid
C     phase, and Cond is the thermal diffusion coefficient in air.
C
      THFCON=0.
C       THFCON is the total amount of heat(per mass of gas) conducted
C      via thermal diffusion) from the aerosol particles and injected
C      water drops to the gas during the time.
      TMOM=0.0
C       TMOM is total momentum per unit momentum of gas
C     which is added to the gas by evaporation of liquid during
C     dt.  (Shapiro's 2.*esubl*(dwsubL/w) )
      TCNMAS=0.
C       TCNMAS is the total mass condensed (per unit mass of the gas)
C     during dt.
      TEVPEN=0.
C       TEVPEN is the energy (per unit mass of the gas) added to the gas
C     by the evaporated liquid during dt.
      DO 80 I=1,20
      IF (NA(I).EQ.0.0) GO TO 80
      VPRSR=Esat(TA(I))*(1.+Ac/RA(I)-Cs*Sc*SLM(I)/(RA(I)**3*MW))
      DMDTR=C4*RA(I)*(E1/T1-VPRSR/TA(I))
C     Modify the evaporation rate for small droplets:
      DTR=DMDTR*(RA(I)/(RA(I)+Fmeanh))
      THFCN=C1*RA(I)*(TA(I)-T1)
```

```
      EVAPMS=-CO
      IF (EVAPMS
      CONDNM=-WATM(I)
      WATM(I)=0.
      RA(I)=DAI(I)/2.
      DMDTR=CONDNM/Dt
      ELSE
      WATM(I)=WATM(I)+CONDNM
      RA(I)=((SLM(I)+INSLM(I)
      END IF
      TCNMAS=TCNMAS+CONDNM*NA(I)/Gasdnl
      THTCON=THTCON+HTRACN*NA(I)*Dt/Gasdnl
      TEVPEN=TEVPEN-CONDNM*(CPH2O*(TA(I)-T1)-L)*NA(I)/Gasdnl
      DTRDT=(L*DMDTR-HTRACN)/(C5*Rhol*Cpw*RA(I)**3)
      TA(I)=TA(I)+DTRDT*Dt
C     IF (TA(I).LT.Dtempx) TA(I)=Dtempx
 80   CONTINUE
      DO 81 J=1,20
      IF (KWIJ(J).EQ.0) GO TO 81
      IF (WMDOT(J).EQ.0.) GO TO 81
      DO 83 I=1,20
      IF (NW(I,J).EQ.0.0) GO TO 83
      VPRSR=Esat(TW(I,J))*(1.+Ac/RW(I,J)-Ey*Bc*SOLUMA(I,J)
     1/(RW(I,J)**3))
      DMDTR=C4*RW(I,J)*(E1/T1-VPRSR/TW(I,J))
C     Modify the evaporation rate for small droplets and ventilation:
      SqRey=(2.*RW(I,J)*ABS(V1-VXW(I,J))/Eta)**(0.5)
      Fross1=1.0+0.276*SqRey*PrVapf
      DMDTR=DMDTR*(RW(I,J)/(RW(I,J)+Frepth))*Fross1
      HTRACN=C14*RW(I,J)*(TW(I,J)-T1)
C      Modify the heat flow rate caused by ventilation:
      Fross2=1.0+0.276*SqRey*PrHeat
      HTRACN=HTRACN*Fross2
      CONDNM=DMDTR*Dt
      EVAPMS=-CONDNM
      IF (EVAPMS.GT.H2OMAS(I,J)) THEN
      CONDNM=-H2OMAS(I,J)
      EVAPMS=-CONDNM
      H2OMAS(I,J)=0.0
      RW(I,J)=((SOLUMA(I,J)+INSOLM(I,J))/(Pdens*C5))**(1./3.)
      DMDTR=CONDNM/Dt
      ELSE
      H2OMAS(I,J)=H2OMAS(I,J)+CONDNM
      RW(I,J)=(((SOLUMA(I,J)+INSOLM(I,J))/Pdens+H2OMAS(I,J)/Rhol)/C5)
     1**(1./3.)
      END IF
      TCNMAS=TCNMAS+CONDNM*NW(I,J)/Gasdnl
      THTCON=THTCON+HTRACN*NW(I,J)*Dt/Gasdnl
      TEVPEN=TEVPEN-CONDNM*(CPH2O*(TW(I,J)-T1)-L+
     1(V1*V1-VXW(I,J)*VXW(I,J))/2.)*NW(I,J)/Gasdnl
      TEVMOM=TEVMOM+(2.*VXW(I,J)/V1)*(EVAPMS*NW(I,J)/Gasdnl)
      DTRDT=(L*DMDTR-HTRACN)/(C5*Cpw*Rhol*RW(I,J)**3)
      TW(I,J)=TW(I,J)+DTRDT*Dt
C     IF (TW(I,J).LT.Dtempx) TW(I,J)=Dtempx
 83   CONTINUE
 81   CONTINUE
```

```
      TEVPMS=-TCNMAS
C      TEVPMS is the total liquid mass (per gas mass) evaporated
C      during Dt.
C
C      Now calculate and collect all of the changes in the independent
C     variables for input into the Shapiro matrix.
C
C      First calculate the work done on dragging injected water.
      SHPDWX=0.0
C      SHPDWX is the total work done by the gas (per unit mass of gas)
C     on the injected water via drag forces during Dt.
      DXAKPM=0.0
C      DXAKPM is the total drag force exerted by the gas on the
C     injected water during Dt.
      DO 90 J=1,20
      IF (KWIJ(J).EQ.0) GO TO 90
      IF (WMDOT(J).EQ.0.0) GO TO 90
      DO 91 I=1,20
      IF (NW(I,J).EQ.0.0) GO TO 91
      FORSIJ=DRAGF(RW(I,J),V1,VXW(I,J),Gasdn1)
      SHPDWX=SHPDWX+FORSIJ*VXW(I,J)*Dt*NW(I,J)/Gasdn1
      DXAKPM=DXAKPM+FORSIJ
      DMASSE=INSOLM(I,J)+SOLUMA(I,J)+H2OMAS(I,J)
      VXW(I,J)=VXW(I,J)+FORSIJ*Dt/DMASSE
 91   CONTINUE
 90   CONTINUE
      DXAKPM=DXAKPM/(Area1*Gasdn1*V1*V1/2.)
C      Now sum Shapiro's energy terms.
      DQDWDH=THTCON-SHPDWX+(DNTHLA+TEVPEN)
C      Nex collect Shapiro's momentum terms.
      SHPMOM=DXAKPM-(DMOMIA+TEVMOM)
C        Sum injected and evaporated mass.
      SHAPDW=(VAPINJ+DMDOTA)/Mdot1+TEVPMS
C        Calculate the change in the density and molecular wt.
      DRGSIN=DMDOTA*Gasdn1/Mdot1
      INDENS=VAPINJ*Gasdn1/Mdot1
      EVDENS=TEVPMS*Gasdn1
      Gasdn2=Gasdn1+EVDENS+INDENS+DRGSIN
      Molwt2=(Gasdn1*Molwt1+EVDENS*18.015+MOWINA)/Gasdn2
      Rhow2=Rhow1+EVDENS+INDENS
      Rhoda2=Gasdn2-Rhow2
      Mdot2=Mdot1+SHAPDW*Mdot1
C        Now set up the matrix coefficients and calculate the independ-
C     ent variables.  Calculate deltas of the independent variables to
C     set to state 2.
C
      Condw=Condw+Tdeltm
      Time =Time+Deltim
      Delx=V1*Deltim
      X=X+Delx
      IF  (X.GT.Xtot) GO TO 100
      Area2=FNAREA(X,A0,Ratio)
      W2=Rhow2/Rhoda2
      U2=W2/(1.+W2)
      Gam2=(1.+0.90*U2)/(1.+1.02*U2)*Gama
C
C   Calculate the independent variables.
C
```

```
      Cc(1)=2.*(Area2-Area1)/(Area2+Area1)
      Cc(2)=DQDWDH/(Cp*T1)
      Cc(3)=SHPMOM
      Cc(4)=SHAPDW
      Cc(5)=2.*(Molwt2-Molwt1)/(Molwt1+Molwt2)
      Cc(6)=2.*(Gam2-Gam1)/(Gam2+Gam1)
      A7=Msqrd1
      B7=Gam1
      C7=B7*A7
      D7=1.-A7
      E7=B7-1.
      F7=1.+C7
      G7=1.+E7*A7/2.
      H7=1.-C7
      Bb(1,1)=-2.*G7/D7
      Bb(1,2)=F7/D7
      Bb(1,3)=C7*G7/D7
      Bb(1,4)=2.*F7*G7/D7
      Bb(1,5)=-F7/D7
      Bb(1,6)=-1.
      Bb(2,1)=-1./D7
      Bb(2,2)=1./D7
      Bb(2,3)=C7/(2.*D7)
      Bb(2,4)=F7/D7
      Bb(2,5)=-1./D7
      Bb(2,6)=0.0
      Bb(3,1)=E7*A7/(2.*D7)
      Bb(3,2)=H7/(2.*D7)
      Bb(3,3)=-B7*E7*A7*A7/(4.*D7)
      Bb(3,4)=-E7*A7*F7/(2.*D7)
      Bb(3,5)=-H7/(D7*2.)
      Bb(3,6)=0.5
      Bb(4,1)=E7/D7*A7
      Bb(4,2)=H7/D7
      Bb(4,3)=-B7*E7*A7/(2.*D7)
      Bb(4,4)=-E7*A7*F7/D7
      Bb(4,5)=E7*A7/D7
      Bb(4,6)=0.0
      Bb(5,1)=A7/D7
      Bb(5,2)=-1./D7
      Bb(5,3)=-C7/(2.*D7)
      Bb(5,4)=-(B7+1.)*A7/D7
      Bb(5,5)=1./D7
      Bb(5,6)=0.0
      Bb(6,1)=C7/D7
      Bb(6,2)=-C7/D7
      Bb(6,3)=-C7*(1.+E7*A7)/(2.*D7)
      Bb(6,4)=-2.*C7*G7/D7
      Bb(6,5)=C7/D7
      Bb(6,6)=0.0
      DO 20 I=1,6
      Aa(I)=0.0
      DO 21 J=1,6
      Aa(I)=Bb(I,J)*Cc(J)+Aa(I)
 21   CONTINUE
 20   CONTINUE
C
C       Calculate the new values of the intrinsic parameters of the gas.
```

```
C
      Msard2=Msard1*(1.+Aa(1))
      V2=V1*(1.+Aa(2))
      Smspd2=smspd1*(1.+Aa(3))
      T2=T1*(1.+Aa(4))
      Gasdn2=Gasdn1*(1.+Aa(5))
      P2=P1*(1.+Aa(6))
C
C   Re-initialize with the new values.
C
      Msard1=Msard2
      V1=V2
      Smspd1=Smspd2
      T1=T2
      Gasdn1=Gasdn2
      Mix1=W2
      P1=P2
      Rhow1=Rhow2
      Rhoda=Gasdn1-Rhow1
      E1=Rmw*Rhow1*T1
      Rm=Rma/(1.-(1.-Eps)*E1/P1)
      Cv=(1.+1.02*U2)*Cva
      Cp=(1.+0.90*U2)*Cpa
      Gam1=Gam2
      Area1=Area2
      Mdot1=Mdot2
      DO 93 I=1,20
      DAPLOT(I)=RA(I)*2.0E6
 93   CONTINUE
      GO TO 30
 100  CONTINUE
      IF (KPLOT.LE.1) GO TO 101
      T1MAX=-1.E6
      V1MAX=-1.E6
      RHOMAX=-1.E6
      T1MIN=1.E6
      V1MIN=1.E6
      RHOMIN=1.E6
      DO 350 I=1,KPLOT
      T1MAX=AMAX1(T1MAX,T1YYY(I))
      T1MIN=AMIN1(T1MIN,T1YYY(I))
      V1MAX=AMAX1(V1MAX,V1YYY(I))
      RHOMAX=AMAX1(RHOMAX,RHYYY(I))
      V1MIN=AMIN1(V1MIN,V1YYY(I))
      RHOMIN=AMIN1(RHOMIN,RHYYY(I))
 350  CONTINUE
      INT1MX=INT(T1MAX+0.5)
      IDEL=MOD(INT1MX,5)
      T1MAX=INT1MX+5-IDEL
      INT1MN=INT(T1MIN-0.5)
      IDEL=MOD(INT1MN,5)
      T1MIN=T1MIN-5+IDEL
      INV1MX=INT(V1MAX+0.5)
      IDEL=MOD(INV1MX,5)
      V1MAX=INV1MX+5-IDEL
      INV1MN=INT(V1MIN-0.5)
      IDEL=MOD(INV1MN,5)
      V1MIN=INV1MN-5+IDEL
```

```
      INRHMX=INT(RHOMAX+0.5)
      IDEL=MOD(INRHMX,5)
      RHOMAX=INRHMX+5-IDEL
      INRHMN=INT(RHOMIN-0.5)
      IDEL=MOD(INRHMN,5)
      RHOMIN=INRHMN-5+IDEL
      INPLOX=INT(PLTXX(KPLOT)+0.5)
      IDEL=MOD(INPLOX,10)
      PLOXMX=INPLOX+10-IDEL
      XXSTP=PLOXMX/10.
      V1STP=(V1MAX-V1MIN)/10.
      T1STP=(T1MAX-T1MIN)/10.
      ROSTP=(RHOMAX-RHOMIN)/10.
      CALL BGNPL(KPLOT+1)
      CALL PAGE (12.,9.)
      CALL NOBRDR
      CALL AREA2D(10.,7.5)
      CALL XNAME ('DISTANCE FROM ENGINE,(Meters)$',100)
      CALL YNAME ('TEMPERATURE,(Degrees Centigrade)$',100)
      CALL GRAF (0.0,XXSTP,PLOXMX,T1MIN,T1STP,T1MAX)
      CALL CURVE (PLTXXX,T1YYY,KPLOT,1)
      CALL ENDPL (KPLOT+1)
      CALL BGNPL(KPLOT+2)
      CALL PAGE (12.,9.)
      CALL NOBRDR
      CALL AREA2D (10.,7.5)
      CALL XNAME ('DISTANCE FROM ENGINE,(Meters)$',100)
      CALL YNAME ('EXHAUST GAS SPEED,(Meters/Sec.)$',100)
      CALL GRAF (0.0,XXSTP,PLOXMX,V1MIN,V1STP,V1MAX)
      CALL CURVE (PLTXXX,V1YYY,KPLOT,1)
      CALL ENDPL (KPLOT+2)
      CALL BGNPL (KPLOT+3)
      CALL PAGE (12.,9.)
      CALL NOBRDR
      CALL AREA2D (10.,7.5)
      CALL XNAME ('DISTANCE FROM ENGINE,(Meters)$',100)
      CALL YNAME ('GAS DENSITY,(Kg./Cubic Meter)$',100)
      CALL GRAF (0.0,XXSTP,PLOXMX,RHOMIN,ROSTP,RHOMAX)
      CALL CURVE (PLTXXX,RHYYY,KPLOT,1)
      CALL ENDPL(KPLOT+3)
  101 CONTINUE
      CALL DONEPL
  202 FORMAT (/)
      STOP
      END
      FUNCTION Esat(T)
C     DATA Ts /373.16/
C     DATA D5 /3.0057149/
C      D5=ALOG(EWS) , where EWS=1013.246 millibars.
C     IF (T.GT.Ts) GO TO 1
C     A=Ts/T
C     B=(1.-1./A)*11.344
C     C=-3.49149*(A-1.)
C     D1=-7.90298*(A-1.)
C     D2=5.02808*ALOG10(A)
C     D3=-1.3816E-7*10.**(B-1.)
C     D4=8.1328E-8*10.**(C-1.)
C     Tt=D1+D2+D3+D4+D5
```

```
C       E=10.**ATt
C       GO TO 2
C1      CONTINUE
        E=EXP(19.3450?2-4222.8246/T)
C2      CONTINUE
        Esat=100.*E
        END
        FUNCTION FNAREA(Z,A0,Ratio)
        ZZZZ=Z
        RATTT=Ratio
        FNAREA=A0
        END
        FUNCTION DRAGF(R,VAIR,VDROP,RHO)
        VR=VAIR-VDROP
        DRAGF=3.129E-4*R*VR*(1.+2.249E4*RHO*R*VR)
C          The drag force is calculated from Oseen flow approximation:
C       (drag force) = 6*PI*Eta*R*V*(1+(3/16)Re), where Eta is the vis-
C       cosity,R is the radius of the drop, V is its velocity relative
C       to the air flow; Re is the Reynold's number, defined by
C       Re=2*Rho*V/Eta, where Rho is the density of the air.
        END
c       PROGRAM MIESCAT
c       DIMENSION JAY(300),WHY(300),SIGH(300),CJAYPM(300),SIGHPM(300),
C
C        The nomenclature used in the documentation of this program
C       follows that used in 'HANDBOOK OF MATHEMATICAL FUNCTIONS',edited
C       by ABRAMOWITZ and STEGUN, published by NATIONAL BUREAU OF STAND-
C       ARDS, December,1965.
C
C        JAY(N) are the Spherical Bessel Functions of the first kind,
C        WHY(N) are the Spherical Bessel Functions of the second kind,
C        SIGH(N) are the Riccati-Bessel Functions (with real argument),
C        CJAYPM(N) are the first derivatives of the Spherical Bessel
C         Functions of the first kind,
C        SIGHPM(N) are the first derivatives of the Riccati-Bessel
C         Functions.
C
C      1CPI(300),CTAU(300),CDPI(300)
C
C        CPI(N) are the Nth order Legendre Functions divided by the
C       Sine of the scattering angle,THETA ,
C        CTAU(N) are the first derivatives of the Legendre Functions
C       with respect to the scattering angle THETA,
C        CDPI(N) are the first derivatives of the Legendre Functions
C       with respect to the Cosine of the scattering angle THETA,
C
c       COMPLEX CH1(300),ETA(300),CH1PRM(300),ETAPRM(300),CSIGHR(300),
C
C        CH1(N) are the Spherical Bessel Functions of the third kind,
C        ETA(N) are the complex Riccati-Bessel Functions with complex
C         arguments,
C        CH1PRM(N) are the first order derivatives of the Spherical Bessel
C         Functions of the third kind,
C        ETAPRM(N) are the first order derivatives of the Riccati-Bessel
C         Functions,
C        CSIGHR(N) are the ratios of SIGHPM(N) to SIGH(N) for complex
C         arguments.
C
```

```
c     1CS1TH,CS2TH,CCEXT,CEM,CXM
C
C       CS1TH is the S sub 1 element of the amplitude scattering matri
C        ( See 'ATMOSPHERIC RADIATION',vol.1,by R.M.GOODY for the defini-
C        tion and nomenclature of the scattering equations. )
C       CS2TH is the S sub 2 element of the scattering matrix,
C       CCEXT is the extinction cross-section,
C       CEM is the complex index of refraction of the scatterer,
C       CXM is the complex wave number ( =CEM*KOA )
C
c      REAL JAY,JAY0,KOA,KO,LAMBDA,MMM1,MMM2
C
C       KOA is the wavenumber ( =2*PI/LAMBDA ),
C       KO is 2*PI/LAMBDA,
C       LAMBDA is the wavelength (in meters) of the incident radiation,
C       MMM1 is the real part of the index of refraction,
C       MMM2 is the imaginary part of the index of refraction.
c      DATA CPI(1),CDPI(1),CDPI(2)  /-1.0,0.0,-3.0/
c      DATA PI,EPS0,CSPLGT  /3.1415927, 8.8419413E-12, 3.00E8 /
c      DATA RADIUS,LAMBDA  / 1.00E-6, 4123.0E-10 /
c      DATA MMM1,MMM2  / 1.50 , -0.01 /
c      DATA  THETA  / 0.000000  /
c      DATA RNDERR  / 1.00E-8  /
c      KO=2.*PI/LAMBDA
c      KOA=KO*RADIUS
c      CEM=CMPLX(MMM1,MMM2)
c      CXM=KOA*CEM
c      TEST1=CABS(CXM)
c      IF ((KOA.LT.0.5).AND.(TEST1.LT.0.5)) GO TO 50
c      IF (KOA.LE.1.0) GO TO 60
c      RNDA=-ALOG(10.**(-RNDERR))
c      RNDA323=(3.*RNDA)*(2./3.)
c      B=RND323/10.
c      NMAX=RND323
c      IF (KOA.GT.B) NMAX=(RND323+(RND323**2+(2.0*KOA)**2)**(0.5))/2.
c      UNEVNN=NMAX+0.5
c      TANHAL=(1.-(KOA/UNEVNN)**2)**(0.5)
c      ALPHA=0.5*ALOG((1.+TANHAL)/(1.+TANHAL))
c      JAY(NMAX)=EXP(UNEVNN*(TANHAL-ALPHA))/(2.0*(KOA*TANHAL*UNEVNN)
c     1**(0.5))
c      KMAX=NMAX-1
c      IF (NMAX.GT.299) GO TO 100
c      JAY(NMAX+1)=0.0
c      SUMJ=(2*NMAX+1)*JAY(NMAX)*JAY(NMAX)
c      DO 1 I=1,KMAX
c      N2N1=2*(NMAX-I+1)+1
c      JAY(NMAX-I)=N2N1*JAY(NMAX-I+1)/KOA-JAY(NMAX-I+2)
c      SUMJ=SUMJ+JAY(NMAX-I)*JAY(NMAX-I)*N2N1
c 1    CONTINUE
c      JAY0=2.0*JAY(1)/KOA-JAY(2)
c      SUMJ=SUMJ+JAY0*JAY0
c      SUMJ=SUMJ**(0.5)
c      JAY(1)=JAY(1)/SUMJ
c      WHY0=-COS(KOA)/KOA
c      WHY(1)=WHY0/KOA-SIN(KOA)/KOA
c      CH1(1)=CMPLX(JAY(1),WHY(1))
c      WHY(2)=3.*WH(1)/KOA-WHY0
c      COSTH=COS(THETA)
```

```
c      SINTH=(1.-COSTH*COSTH)**(0.5)
c      SINTH=SIN(THETA)
c      CPI(2)=-3.*COSTH
c      SINTH2=SINTH*SINTH
c      CTAU(1)=-COSTH
c      DO 2 N=2,NMAX
c      WHY(N+1)=(2*N+1)*WHY(N)/KOA-WHY(N-1)
c      JAY(N)=JAY(N)/SUMJ
c      CH1(N)=CMPLX(JAY(N),WHY(N))
c      CPI(N+1)=((2*N+1)/N)*COSTH*CPI(N)-((N+1)/N)*CPI(N-1)
c      CTAU(N)=COSTH*CPI(N)-SINTH2*CDPI(N)
c      CDPI(N+1)=((2*N+1)/(N-1))*COSTH*CDPI(N)-((N+2)/(N-1))*CDPI(N-1)
c 2    CONTINUE
c      CH1(NMAX+1)=CMPLX(JAY(NMAX+1),WHY(NMAX+1))
c    CHECK ACCURACY OF JAY'S HERE BY JAY0 AND JAY1
c      CEM=CMPLX(MMM1,MMM2)
c      CXM=KOA*CEM
c      DO 3 N=1,NMAX
c      SIGH(N)=KOA*JAY(N)
c      ETA(N)=KOA*CH1(N)
c      CJAYPM(N)=(N*JAY(N-1)-(N+1)*JAY(N+1))/(2*N+1)
c      CH1PRM(N)=(N*CH1(N-1)-(N+1)*CH1(N+1))/(2*N+1)
c      SIGHPM(N)=JAY(N)+KOA*CJAYPM(N)
c      ETAPRM(N)=CH1(N)+KOA*CH1PRM(N)
c      CSIGHR(N)=FMCALC(CXM,N,RNDERR)+N/CXM
c 3    CONTINUE
c      CS1TH=(0.0,0.0)
c      CS2TH=(0.0,0.0)
c      CCEXT=(0.0,0.0)
c      DO 4 N=1,NMAX
c      NFAC21=2*N+1
c      NFAC12=NFAC21/(N*(N+1))
c      CS1TH=CS1TH+NFAC12*(CAMIE(N)*CPI(N)+CBMIE(N)*CTAU(N))
c      CS2TH=CS2TH+NFAC12*(CAMIE(N)*CTAU(N)+CBMIE(N)*CPI(N))
c      CCEXT=CCEXT+(2*N+1)*(CAMIE(N)+CBMIE(N))
c      QSCA=QSCA+NFAC21*(CAMIE(N)*CONJG(CAMIE(N)+
c     1CBMIE(N)*CONJG(CBMIE(N))
c 4    CONTINUE
c      CS1TH=CS1TH*ELECO*(0.0,-1.0)
c      CS2TH=CS2TH*ELECO*(0.0,-1.0)
c      CEXT=(2.*PI/(KO*KO))*REAL(CCEXT)
c      QEXT=(2./(KOA*KOA))*REAL(CCEXT)
c      QSCA=QSCA*(2./(KOA*KOA))
c      QABS=QEXT-QSCA
cccPUT IN PRINT STATEMENTS HERE
c      GO TO 200
c 50   CONTINUE
c      CMPLF1=(CEM*CEM-1.)/(CEM*CEM+2.)
c      CS1TH=KOA**3*CMPLF1
c      CS2TH=CS1TH*COS(THETA)
c      REEL=CABS(CMPLF1)
c      QSCA=(8./3.)*KOA**4*REEL*REEL
c      QABS=4.*AIMAG(CMPLF1)
CCC PRINT out RAYLEIGH scattering here.
c      GO TO 200
c 60   CONTINUE
c      A=MMM1
c      B=MMM2**2
```

```
c      Z1=(A+B)**2+4.*(A-B)+4.
c      Z2=4.*(A+B)**2+12.*(A-B)+7.
c      QSCA=8.*(((A+B)**2+A-B-2.)**2+36.*A*B)*KOA**4
c     1*(1.+(1.2/Z1)*(A+B-4.)*KOA**2-8.*MMM1*MMM2*KOA**3/Z1)/(3.*Z1**2)
c      QEXT=(24.*MMM1*MMM2*KOA/Z1)+((4./15.)+(20./(3.*Z2))*(32/Z1**2))*
c     1(7.*(A+B)**2+4.*(A-B-5.)))*MMM1*MMM2*KOA**3
c     2+(8./(3.*Z1**2))*(((A+B)**2+A-B-2.)**2+36.*A*B)*KOA**4
c      QABS=QEXT-QSCA
ccccccc PRINT OUT HIGHER ORDER EXPANSION RESULTS HERE
c      GO TO 200
c 100 CONTINUE
ccccPRINT *NUMBER OF TERMS REQUIRED TO CALCULATE THE MIE COEFS,TOO LARGE*
c 200 CONTINUE
c      COMPLEX FUNCTION FMCALC(X,N,RNDERR)
c      COMPLEX CIX,X,CNUM(300),CDEN(300),CAM(300),FMCALC,CNUF
c      DATA  CDEN(1) / (1.0,0.0)/
c      CIX=CMPLX(0.0,1.0)/X
c      DO 1 M=1,300
c      CAM(M)=-(2*(N+M)  )*CIX
c 1    CONTINUE
c      CNUM(1)=CAM(1)
c      CNUM(2)=CAM(2)+1./CAM(1)
c      CDEN(2)=CAM(2)
c      FMCALC=CNUM(1)*CNUM(2)/CDEN(2)
c      DO 2 M=3,300
c      CNUM(M)=CAM(M)+1./CNUM(M-1)
c      CDEN(M)=CAM(M)+1./CDEN(M-1)
c      CNUF=CNUM(M)/CDEN(M)
c      FMCALC=FMCALC*CNUF
c      F=CABS(CNUF)
c      ABSF=ABS(F-1.0)
c      IF (ABSF.LT.RNDERR) GO TO 3
c 2    CONTINUE
c 3    CONTINUE
c      RETURN
c      END
```