IAEA/ANL
Interregional Training Course

Technical and Administrative Preparations Required for Shipment of Research Reactor Spent Fuel to Its Country of Origin

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Lecture L.3.3a

Spent Fuel Classification Data PHDOSE Program Package

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PHDOSE Program Package:
Example Input
Example Output
Input/Output Description
PHDOSE Program (Fortran)

PHDOSE Program

Calculates the photon dose rate of a line-source model (see attached figure) of spent fuel as a function of:

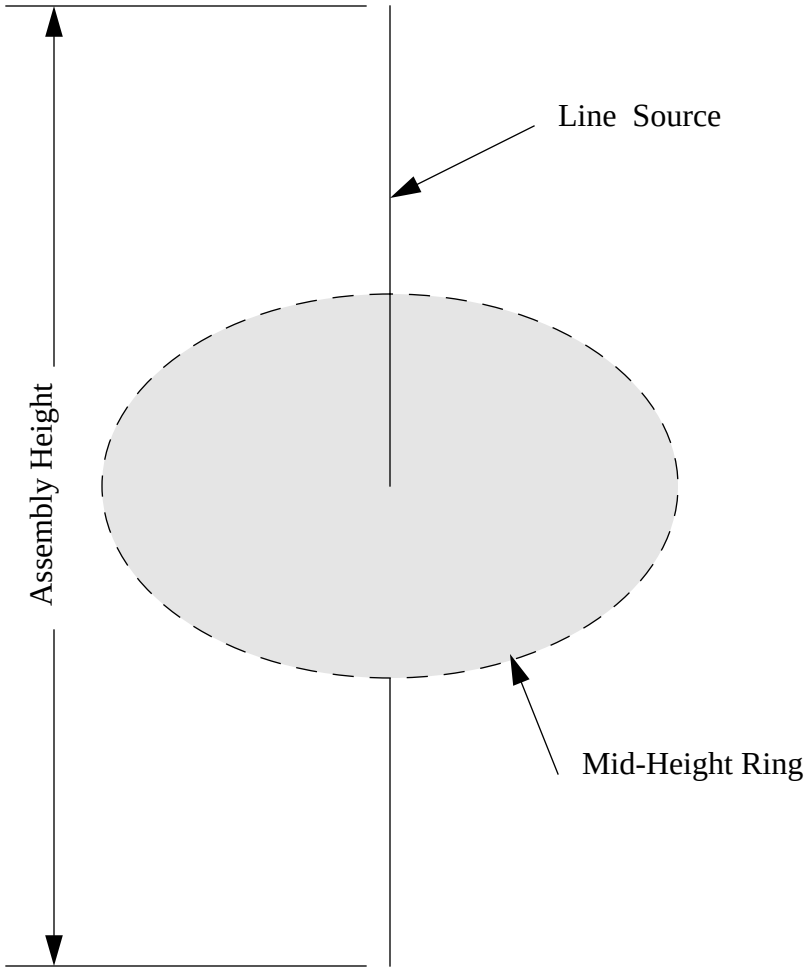
1. Fuel assembly power density, MW/kg^{235}U
    a. fuel assembly power, MW
    b. fuel assembly mass, kg^{235}U
2. U-235 Burnup, %
3. Fission product decay time, year

A dose rate estimate for an MTR-, TRIGA- or DIDO-type fuel assembly can be made based upon the line-source model dose rate. An MTR-type fuel assembly dose rate is a factor of ≈ 0.92 times the line-source model dose rate; a TRIGA-type fuel assembly is a factor of ≈ 1.04 times an MTR-type fuel assembly dose rate; and a DIDO-type fuel assembly is a factor of ≈ 1.05 times an MTR-type fuel assembly dose rate.

Calculates the photon source (ph/s), photon dose (rem/h), radioactivity (Curies) and gamma decay heat (Watts) of 12 fission products. The fission products are:

Sr-90	Y-90	Cs-133	Cs-134
Cs-137	Ba-137m	Ce-144	Pr-144
Ru-106	Rh-106	Zr-95	Nb-95

Similar data are also calculated for Co-60, since it is a possible photon source in spent fuel arising from the activation of Co-59.


Line Source
Assembly Height
Mid-Height Ring

PHDOSE PROGRAM

Purpose To calculate the photon dose rate from spent fuel.

Input (format 7D10.5)

ti	Irradiation time (d) ■ if ti = 0.0, ti is calculated from the powden and burnup parameters as: ti = burnup/powden*8, assuming 1.25 g^{235}U burned per MWd. ■ if ti ≥ 0.0, normal output is printed. ■ if ti < 0.0, ti = -ti and optional output is also printed. ■ note: if ti ≠ 0.0, ti must be within 1% of the calculated irradiation time. (≥ 1%, stop code 101)
power	Assembly power (MW)
powden	Assembly power density (MW/kg^{235}U)
td	Fission product decay time (y)
kg	Structural material mass (kg)
ppm	^{59}Co in structural material (ppm)
burnup	^{235}U burnup in fuel (%)

Normal Output

Record #1:
- Echo input (ti, power, powden, td, kg, ppm, burnup)
- Average neutron flux (n/cm^2-s)

Record #2:
- ^{235}U burned (g) [= power/powden*burnup*10]
- Fission product photon source rate (ph/s) per g^{235}U burned
- ^{60}Co photon source rate (ph/s)
- Self-protecting ^{235}U mass (g^{235}U burned)
- Fission product photon dose rate (rem/h) per g^{235}U burned
- ^{60}Co photon dose rate (rem/h)

Fission products (FP):
^{90}Sr, ^{90}Y, ^{134}Cs, ^{137}Cs, ^{137m}Ba, ^{144}Ce, ^{144}Pr, ^{106}Rh, ^{95}Zr, ^{95}Nb

Optional Output

- Material formation rates (atoms/s)
- Material loss rates (atoms/s)
- Material n0 present at time ti (atoms)
- Material n present at time td (atoms)
- Material disintegration rates (curies)
- Material/group photon source rates (ph/s)
- Material/group photon dose rates (rem/h)
- Group photon heat (watts)
- Group photon flux (ph/cm^2-s)
- Group photon source rate (ph/s)
- Group photon dose rate (rem/h)

Material (Group #) order:

^{90}Sr(1,2), ^{90}Y(1,2,3), ^{133}Cs, ^{134}Cs(2,3), ^{137}Cs(1,2), ^{137m}Ba(2), ^{144}Ce(1), ^{144}Pr(1,2,3), ^{106}Ru, ^{106}Rh(1,2,3), ^{95}Zr(2), ^{95}Nb(2), ^{60}Co(5)

Group:

#1=0.30 MeV, #2=0.63 MeV, #3=1.10 MeV,
#4=sum #1 – #3, #5=1.10 MeV (^{60}Co)

PHDOSE Example Input:

```
  -3584.0     0.025 0.0892857       3.0       4.0      10.0      40.0
```

PHDOSE Example Output:

```
0input: irrad time (d), power (MW), pow den (MW/kgU-235), decay time (y),
     asby mass (kg), Co-59 (ppm), U-235 burnup (%), avg flux (n/cm**2-s)
 -3.58400D+03 2.50000D-02 8.92857D-02 3.00000D+00 4.00000D+00 1.00000D+01
  4.00000D-01 3.29464D+12
 output: U-235 burned (g), FP source (ph/s per g), Co-60 source (ph/s),
     self-pro U-235 mass (g), FP dose (rem/h per g), Co-60 dose (rem/h)
  1.12000D+02 1.34115D+11 6.39796D+10 8.94664D+01 1.11774D+00 8.73080D-01
 material formation rates, atoms/s
  4.52545D+13 0.00000D+00 5.21987D+13 0.00000D+00 4.82975D+13 0.00000D+00
  4.29138D+13 0.00000D+00 3.12880D+12 0.00000D+00 5.07162D+13 0.00000D+00
  5.34375D+10
 material loss rates, atoms/s
  7.84987D-10 3.00501D-06 3.40007D-10 1.10129D-08 7.30132D-10 4.53000D-03
  2.82139D-08 6.68400D-04 2.17415D-08 2.31800D-02 1.22500D-07 2.28512D-07
  4.19008D-09
 material n0, atoms (time=ti)
  1.24395D+22 3.23551D+18 1.53419D+22 4.02355D+20 1.33854D+22 2.15615D+15
  1.52072D+21 6.41825D+16 1.43736D+20 1.34806D+14 4.14010D+20 2.21942D+20
  9.97537D+18
 material n, atoms (time=td)
  1.15529D+22 3.00490D+18 1.53419D+22 1.46762D+20 1.24925D+22 2.01232D+15
  1.05430D+20 4.44971D+15 1.83788D+19 1.72371D+13 3.83499D+15 4.43184D+15
  6.71965D+18
 material disintegration rates, curies
  2.44047D+02 2.44047D+02 0.00000D+00 4.22834D+01 2.46373D+02 2.46373D+02
  8.03834D+01 8.03834D+01 1.07988D+01 1.07988D+01 1.26969D-02 2.73696D-02
  7.58412D-01
 material/group photon source rates, ph/s
  4.23494D+10 3.96405D+07 4.46069D+11 1.46282D+11 2.23937D+10 3.75476D+12
  4.84990D+10 9.20697D+10 3.86510D+08 9.57160D+12 2.97419D+11 2.23956D+11
  1.28485D+11 2.57862D+10 6.11319D+10 1.37047D+11 2.07769D+10 5.40254D+08
  1.23546D+09 6.39796D+10
 material/group photon dose rates, rem/h
  1.82942D-01 3.42041D-04 1.92694D+00 1.26220D+00 3.05590D-01 3.23983D+01
  6.61829D-01 3.97725D-01 3.33503D-03 8.25893D+01 1.28480D+00 9.67452D-01
  1.10864D+00 3.51884D-01 2.64079D-01 1.18252D+00 2.83526D-01 4.66162D-03
  1.06603D-02 8.73080D-01
 group photon heat, wt
  5.59001D-02 1.38693D+00 2.07005D-02 1.46353D+00 1.12758D-02
 group photon flux, ph/cm**2-s
  8.94575D+06 1.05691D+08 9.03470D+05 1.15540D+08 4.92131D+05
 group photon source rate, ph/s
  1.16299D+12 1.37404D+13 1.17456D+11 1.50208D+13 6.39796D+10
 group photon dose rate, rem/h
  5.02394D+00 1.18560D+02 1.60283D+00 1.25187D+02 8.73080D-01
```

```
 program phdose
c PC Version
c The code below has been compiled using a Pentium processor and a Lahey
c compiler.  It should work in most PC environments.
c hand calculation of photon dose rate
      real (kind=8) dk(13),yield(13),cap(13),r(13),k(13),n0(13),n(13),
     x mrate(13)
      real (kind=8) f2d(3),mev(3),gsour(5),gflux(5),gdose(5),gheat(5)
      real (kind=8) ph(20),srate(20),drate(20)
      real (kind=8) ti,power,powden,td,kg,ppm,burnup,jmev,bpc
      real (kind=8) bu,time,dm,pflux,nflux,sums,sumd,self
      common r,n0,powden,kg,ppm,bu,time
      common /comdat/dk,cap
c parameter order in data arrays:
c      material   t(1/2)     ph/dis   groups*
c     #01 Sr-90    28.1y    #01-#02    #1-#2
c     #02 Y-90     2.67d    #03-#05    #1-#3
c     #03 Cs-133
c     #04 Cs-134   2.06y    #06-#07    #2-#3
c     #05 Cs-137   30.1y    #08-#09    #1-#2
c     #06 Ba-137m  2.55m    #10        #2
c     #07 Ce-144   284.d    #11        #1
c     #08 Pr-144   17.3m    #12-#14    #1-#3
c     #09 Ru-106   1.01y
c     #10 Rh-106   29.9s    #15-#17    #1-#3
c     #11 Zr-95    65.5d    #18        #2
c     #12 Nb-95    35.1d    #19        #2
c     #13 Co-60    5.26y    #20        #5
c     *gps, MeV: #1=0.30, #2=0.63, #3=1.10, #4=sum #1-#3, #5=Co-60 (1.10)
c fission product yield
      data yield/5.8d-2,0.d0,6.69d-2,0.d0,6.19d-2,0.d0,5.5d-2,0.d0,
     x 4.01d-3,0.d0,6.5d-2,2*0.d0/
c photons/disintegration
      data ph/4.69d-3,4.39d-6,4.94d-2,1.62d-2,2.48d-3,2.4d0,3.1d-2,
     x 1.01d-2,4.24d-5,1.05d0,1.0d-1,7.53d-2,4.32d-2,8.67d-3,1.53d-1,
     x 3.43d-1,5.2d-2,1.15d0,1.22d0,2.28d0/
c photon flux
      data pflux/7.692d-6/
c conversion: joule=wt-s per mev
      data jmev/1.60219d-13/
c conversion: becquerel per curie
      data bpc/3.7d10/
c mean photon energy, mev/ph
      data mev/0.3d0,0.63d0,1.1d0/
c fluence-to-dose factor, sv-cm**2
      data f2d/1.56d-12,3.116d-12,4.928d-12/
c flux-to-dose conversion, rem/h
      do 105 i=1,3
  105 f2d(i)=f2d(i)*3.6d5
   10 format(7d10.5)
   11 format(1x,1p6d12.5)
      open(5,file='phdose.ft5')
      open(6,file='phdose.ft6')
c read input: irrad time (d); power (MW); pow den (MW/kgU-235);
c decay time (y); asby mass (kg); Co-59 (ppm); U-235 burnup (%)
c note: if ti=0, ti is calculated in the 'time' parameter below
  100 read(5,10,ee(i)=0.0d0
```

```
program phdose
c UNIX Version
c The code below has been compiled and run on a SUN workstation
c and should work in most UNIX environments.
c hand calculation of photon dose rate
      real*8 dk(13),yield(13),cap(13),r(13),k(13),n0(13),n(13),mrate(13)
      real*8 f2d(3),mev(3),gsour(5),gflux(5),gdose(5),gheat(5)
      real*8 ph(20),srate(20),drate(20)
      real*8 ti,power,powden,td,kg,ppm,burnup,jmev,bpc
      real*8 bu,time,dm,pflux,nflux,sums,sumd,self
      common dk,cap,r,n0,powden,kg,ppm,bu,time
c parameter order in data arrays:
c      material   t(1/2)     ph/dis   groups*
c     #01 Sr-90    28.1y    #01-#02    #1-#2
c     #02 Y-90     2.67d    #03-#05    #1-#3
c     #03 Cs-133
c     #04 Cs-134   2.06y    #06-#07    #2-#3
c     #05 Cs-137   30.1y    #08-#09    #1-#2
c     #06 Ba-137m  2.55m    #10        #2
c     #07 Ce-144   284.d    #11        #1
c     #08 Pr-144   17.3m    #12-#14    #1-#3
c     #09 Ru-106   1.01y
c     #10 Rh-106   29.9s    #15-#17    #1-#3
c     #11 Zr-95    65.5d    #18        #2
c     #12 Nb-95    35.1d    #19        #2
c     #13 Co-60    5.26y    #20        #5
c     *gps, MeV: #1=0.30, #2=0.63, #3=1.10, #4=sum #1-#3, #5=Co-60 (1.10)
c decay constant, s-1
      data dk/7.816d-10,3.005d-6,0.d0,1.066d-8,7.297d-10,4.530d-3,
     x 2.821d-8,6.684d-4,2.174d-8,2.318d-2,1.225d-7,2.285d-7,4.176d-9/
c fission product yield
      data yield/5.8d-2,0.d0,6.69d-2,0.d0,6.19d-2,0.d0,5.5d-2,0.d0,
     x 4.01d-3,0.d0,6.5d-2,2*0.d0/
c capture cross section, cm**2
      data cap/1.028d-24,2.740d-24,103.2d-24,107.1d-24,0.1310d-24,
     x 0.d0,1.172d-24,0.d0,0.4550d-24,2*0.d0,3.563d-24,4.275d-24/
c photons/disintegration
      data ph/4.69d-3,4.39d-6,4.94d-2,1.62d-2,2.48d-3,2.4d0,3.1d-2,
     x 1.01d-2,4.24d-5,1.05d0,1.0d-1,7.53d-2,4.32d-2,8.67d-3,1.53d-1,
     x 3.43d-1,5.2d-2,1.15d0,1.22d0,2.28d0/
c photon flux
      data pflux/7.692d-6/
c conversion: joule=wt-s per mev
      data jmev/1.60219d-13/
c conversion: becquerel per curie
      data bpc/3.7d10/
c mean photon energy, mev/ph
      data mev/0.3d0,0.63d0,1.1d0/
c fluence-to-dose factor, sv-cm**2
      data f2d/1.56d-12,3.116d-12,4.928d-12/
c flux-to-dose conversion, rem/h
      do 105 i=1,3
  105 f2d(i)=f2d(i)*3.6d5
   10 format(7d10.5)
   11 format(1x,1p6d12.5)
c read input: irrad time (d); power (MW); pow den (MW/kgU-235);
c decay time (y); asby mass (kg); Co-59 (ppm); U-235 burnup (%)
```

```
c note: if ti=0, ti is calculated in the 'time' parameter below
  100 read(5,10,end=999) ti,power,powden,td,kg,ppm,burnup
c burnup in percent
      burnup=1.0d-2*burnup
c calculate irradiation time and average neutron flux
      time=burnup/(1.25d-3*powden)
      if(ti.eq.0.0d0) ti=time
      dm=1.0d0 - 0.5d0*burnup
      nflux=2.952d13*powden/dm
c write input data plus nflux
      write(6,20)
   20 format('0input: irrad time (d), power (MW), pow den (MW/kgU-235),
     2decay time (y),'/5x,'asby mass (kg), Co-59 (ppm), U-235 burnup (%)
     3, avg flux (n/cm**2-s)')
      write(6,11) ti,power,powden,td,kg,ppm,burnup*1.0d2,nflux
c use ti as a flag for additional printout
      nskip=0
      if(ti.lt.0.0d0) then
       ti=-ti
       nskip=1
      endif
c check if ti is consistent (<1%) with burnup and power density
      if(dabs(ti/time - 1.0d0).ge.1.0d-2) stop 101
c irradiation time (ti) in days and decay time (td) in years
      ti=ti*8.64d4
      td=td*3.1536d7
c initialize arrays
      do 101 i=1,13
  101 r(i)=0.0d0
      do 103 i=1,5
      gsour(i)=0.0d0
      gflux(i)=0.0d0
      gdose(i)=0.0d0
  103 gheat(i)=0.0d0
c in subroutines, calculate nflux in 10 steps
      bu=burnup/10.0d0
      time=ti/10.0d0
c #1: sr-90
      r(1)=3.121d16*yield(1)*power
      k(1)=dk(1) + cap(1)*nflux
c     n0(1)=r(1)/k(1)*(1.0d0 - dexp(-k(1)*ti))
      call sr90
      n(1)=n0(1)*dexp(-dk(1)*td)
      mrate(1)=dk(1)*n(1)/bpc
      srate(1)=dk(1)*n(1)*ph(1)
      srate(2)=dk(1)*n(1)*ph(2)
      drate(1)=f2d(1)*srate(1)*pflux
      drate(2)=f2d(2)*srate(2)*pflux
      gsour(1)=gsour(1) + srate(1)
      gsour(2)=gsour(2) + srate(2)
      gflux(1)=gflux(1) + srate(1)*pflux
      gflux(2)=gflux(2) + srate(2)*pflux
      gdose(1)=gdose(1) + drate(1)
      gdose(2)=gdose(2) + drate(2)
c #2: y-90
      k(2)=dk(2) + cap(2)*nflux
      n0(2)=dk(1)/k(2)*n0(1)
```

```
       if(k(2)*ti.le.4.605170186d1) n0(2)=
      x dk(1)*r(1)/k(1)*((1.0d0 - dexp(-k(2)*ti))/k(2) -
      x (dexp(-k(1)*ti) - dexp(-k(2)*ti))/(k(2)-k(1)))
       n(2)=dk(1)/dk(2)*n(1)
       if(dk(2)*td.le.4.605170186d1) n(2)=
      x dk(1)*n0(1)*(dexp(-dk(1)*td) - dexp(-dk(2)*td))/
      x (dk(2) - dk(1)) + n0(2)*dexp(-dk(2)*td)
       mrate(2)=dk(2)*n(2)/bpc
       srate(3)=dk(2)*n(2)*ph(3)
       srate(4)=dk(2)*n(2)*ph(4)
       srate(5)=dk(2)*n(2)*ph(5)
       drate(3)=f2d(1)*srate(3)*pflux
       drate(4)=f2d(2)*srate(4)*pflux
       drate(5)=f2d(3)*srate(5)*pflux
       gsour(1)=gsour(1) + srate(3)
       gsour(2)=gsour(2) + srate(4)
       gsour(3)=gsour(3) + srate(5)
       gflux(1)=gflux(1) + srate(3)*pflux
       gflux(2)=gflux(2) + srate(4)*pflux
       gflux(3)=gflux(3) + srate(5)*pflux
       gdose(1)=gdose(1) + drate(3)
       gdose(2)=gdose(2) + drate(4)
       gdose(3)=gdose(3) + drate(5)
c #3: cs-133
       r(3)=3.121d16*yield(3)*power
       k(3)=dk(3) + cap(3)*nflux
       n0(3)=r(3)/k(3)*(1.0d0 - dexp(-k(3)*ti))
       n(3)=n0(3)*dexp(-dk(3)*td)
       mrate(3)=dk(3)*n(3)/bpc
c #4: cs-134
       k(4)=dk(4) + cap(4)*nflux
c      n0(4)=r(3)*((1.0d0 - dexp(-k(4)*ti))/k(4) -
c     x   (dexp(-k(3)*ti) - dexp(-k(4)*ti))/(k(4)-k(3)))
       call cs134
       n(4)=n0(4)*dexp(-dk(4)*td)
       mrate(4)=dk(4)*n(4)/bpc
       srate(6)=dk(4)*n(4)*ph(6)
       srate(7)=dk(4)*n(4)*ph(7)
       drate(6)=f2d(2)*srate(6)*pflux
       drate(7)=f2d(3)*srate(7)*pflux
       gsour(2)=gsour(2) + srate(6)
       gsour(3)=gsour(3) + srate(7)
       gflux(2)=gflux(2) + srate(6)*pflux
       gflux(3)=gflux(3) + srate(7)*pflux
       gdose(2)=gdose(2) + drate(6)
       gdose(3)=gdose(3) + drate(7)
c #5: cs-137
       r(5)=3.121d16*yield(5)*power
       k(5)=dk(5) + cap(5)*nflux
c      n0(5)=r(5)/k(5)*(1.0d0 - dexp(-k(5)*ti))
       call cs137
       n(5)=n0(5)*dexp(-dk(5)*td)
       mrate(5)=dk(5)*n(5)/bpc
       srate(8)=dk(5)*n(5)*ph(8)
       srate(9)=dk(5)*n(5)*ph(9)
       drate(8)=f2d(1)*srate(8)*pflux
       drate(9)=f2d(2)*srate(9)*pflux
```

```
      gsour(1)=gsour(1) + srate(8)
      gsour(2)=gsour(2) + srate(9)
      gflux(1)=gflux(1) + srate(8)*pflux
      gflux(2)=gflux(2) + srate(9)*pflux
      gdose(1)=gdose(1) + drate(8)
      gdose(2)=gdose(2) + drate(9)
c #6: ba-137m
      k(6)=dk(6) + cap(6)*nflux
      n0(6)=dk(5)/k(6)*n0(5)
      if(k(6)*ti.le.4.605170186d1) n0(6)=
     x dk(5)*r(5)/k(5)*((1.0d0 - dexp(-k(6)*ti))/k(6) -
     x (dexp(-k(5)*ti) - dexp(-k(6)*ti))/(k(6)-k(5)))
      n(6)=dk(5)/dk(6)*n(5)
      if(dk(6)*td.le.4.605170186d1) n(6)=
     x dk(5)*n0(5)*(dexp(-dk(5)*td) - dexp(-dk(6)*td))/
     x (dk(6) - dk(5)) + n0(6)*dexp(-dk(6)*td)
      mrate(6)=dk(6)*n(6)/bpc
      srate(10)=dk(6)*n(6)*ph(10)
      drate(10)=f2d(2)*srate(10)*pflux
      gsour(2)=gsour(2) + srate(10)
      gflux(2)=gflux(2) + srate(10)*pflux
      gdose(2)=gdose(2) + drate(10)
c #7: ce-144
      r(7)=3.121d16*yield(7)*power
      k(7)=dk(7) + cap(7)*nflux
c     n0(7)=r(7)/k(7)*(1.0d0 - dexp(-k(7)*ti))
      call ce144
      n(7)=n0(7)*dexp(-dk(7)*td)
      mrate(7)=dk(7)*n(7)/bpc
      srate(11)=dk(7)*n(7)*ph(11)
      drate(11)=f2d(1)*srate(11)*pflux
      gsour(1)=gsour(1) + srate(11)
      gflux(1)=gflux(1) + srate(11)*pflux
      gdose(1)=gdose(1) + drate(11)
c #8: pr-144
      k(8)=dk(8) + cap(8)*nflux
      n0(8)=dk(7)/k(8)*n0(7)
      if(k(8)*ti.le.4.605170186d1) n0(8)=
     x dk(7)*r(7)/k(7)*((1.0d0 - dexp(-k(8)*ti))/k(8) -
     x (dexp(-k(7)*ti) - dexp(-k(8)*ti))/(k(8)-k(7)))
      n(8)=dk(7)/dk(8)*n(7)
      if(dk(8)*td.le.4.605170186d1) n(8)=
     x dk(7)*n0(7)*(dexp(-dk(7)*td) - dexp(-dk(8)*td))/
     x (dk(8) - dk(7)) + n0(8)*dexp(-dk(8)*td)
      mrate(8)=dk(8)*n(8)/bpc
      srate(12)=dk(8)*n(8)*ph(12)
      srate(13)=dk(8)*n(8)*ph(13)
      srate(14)=dk(8)*n(8)*ph(14)
      drate(12)=f2d(1)*srate(12)*pflux
      drate(13)=f2d(2)*srate(13)*pflux
      drate(14)=f2d(3)*srate(14)*pflux
      gsour(1)=gsour(1) + srate(12)
      gsour(2)=gsour(2) + srate(13)
      gsour(3)=gsour(3) + srate(14)
      gflux(1)=gflux(1) + srate(12)*pflux
      gflux(2)=gflux(2) + srate(13)*pflux
      gflux(3)=gflux(3) + srate(14)*pflux
```

```
      gdose(1)=gdose(1) + drate(12)
      gdose(2)=gdose(2) + drate(13)
      gdose(3)=gdose(3) + drate(14)
c #9: ru-106
      r(9)=3.121d16*yield(9)*power
      k(9)=dk(9) + cap(9)*nflux
c     n0(9)=r(9)/k(9)*(1.0d0 - dexp(-k(9)*ti))
      call ru106
      n(9)=n0(9)*dexp(-dk(9)*td)
      mrate(9)=dk(9)*n(9)/bpc
c #10: rh-106
      k(10)=dk(10) + cap(10)*nflux
      n0(10)=dk(9)/k(10)*n0(9)
      if(k(10)*ti.le.4.605170186d1) n0(10)=
     x dk(9)*r(9)/k(9)*((1.0d0 - dexp(-k(10)*ti))/k(10) -
     x (dexp(-k(9)*ti) - dexp(-k(10)*ti))/(k(10)-k(9)))
      n(10)=dk(9)/dk(10)*n(9)
      if(dk(10)*td.le.4.605170186d1) n(10)=
     x dk(9)*n0(9)*(dexp(-dk(9)*td) - dexp(-dk(10)*td))/
     x (dk(10) - dk(9)) + n0(10)*dexp(-dk(10)*td)
      mrate(10)=dk(10)*n(10)/bpc
      srate(15)=dk(10)*n(10)*ph(15)
      srate(16)=dk(10)*n(10)*ph(16)
      srate(17)=dk(10)*n(10)*ph(17)
      drate(15)=f2d(1)*srate(15)*pflux
      drate(16)=f2d(2)*srate(16)*pflux
      drate(17)=f2d(3)*srate(17)*pflux
      gsour(1)=gsour(1) + srate(15)
      gsour(2)=gsour(2) + srate(16)
      gsour(3)=gsour(3) + srate(17)
      gflux(1)=gflux(1) + srate(15)*pflux
      gflux(2)=gflux(2) + srate(16)*pflux
      gflux(3)=gflux(3) + srate(17)*pflux
      gdose(1)=gdose(1) + drate(15)
      gdose(2)=gdose(2) + drate(16)
      gdose(3)=gdose(3) + drate(17)
c #11: zr-95
      r(11)=3.121d16*yield(11)*power
      k(11)=dk(11) + cap(11)*nflux
c     n0(11)=r(11)/k(11)*(1.0d0 - dexp(-k(11)*ti))
      call zr95
      n(11)=n0(11)*dexp(-dk(11)*td)
      mrate(11)=dk(11)*n(11)/bpc
      srate(18)=dk(11)*n(11)*ph(18)
      drate(18)=f2d(2)*srate(18)*pflux
      gsour(2)=gsour(2) + srate(18)
      gflux(2)=gflux(2) + srate(18)*pflux
      gdose(2)=gdose(2) + drate(18)
c #12: nb-95
      k(12)=dk(12) + cap(12)*nflux
      n0(12)=dk(11)*r(11)/k(11)*((1.0d0 - dexp(-k(12)*ti))/k(12) -
     x (dexp(-k(11)*ti) - dexp(-k(12)*ti))/(k(12)-k(11)))
      n(12)=dk(11)*n0(11)*(dexp(-dk(11)*td) - dexp(-dk(12)*td))/
     x (dk(12) - dk(11)) + n0(12)*dexp(-dk(12)*td)
      mrate(12)=dk(12)*n(12)/bpc
      srate(19)=dk(12)*n(12)*ph(19)
      drate(19)=f2d(2)*srate(19)*pflux
```

```
      gsour(2)=gsour(2) + srate(19)
      gflux(2)=gflux(2) + srate(19)*pflux
      gdose(2)=gdose(2) + drate(19)
c #13: co-60
      r(13)=1.197d10*kg*ppm*powden/dm
      k(13)=dk(13) + cap(13)*nflux
c     n0(13)=r(13)/k(13)*(1.0d0 - dexp(-k(13)*ti))
      call co60
      n(13)=n0(13)*dexp(-dk(13)*td)
      mrate(13)=dk(13)*n(13)/bpc
      srate(20)=dk(13)*n(13)*ph(20)
      drate(20)=f2d(3)*srate(20)*pflux
      gsour(5)=srate(20)
      gflux(5)=srate(20)*pflux
      gdose(5)=drate(20)
      gheat(5)=gsour(5)*mev(3)*jmev
c sum fission product photon source and dose rates
      sums=0.0d0
      sumd=0.0d0
      do 102 i=1,19
      sums=sums + srate(i)
  102 sumd=sumd + drate(i)
      burnup=power/powden*1.0d3*burnup
      sums=sums/burnup
      sumd=sumd/burnup
c mass of burned U-235 necessary for 100 rem/h dose rate
      self=1.0d2/sumd
c write output: U-235 burned, g;
c FP source, ph/s per gU-235 burned; Co-60 source, ph/s;
c self-protected U-235 mass burned, g
c FP dose,  rem/h per gU-235 burned; Co-60 dose,  rem/h
      write(6,21)
   21 format(' output: U-235 burned (g), FP source (ph/s per g), Co-60 s
     2ource (ph/s),'/5x,'self-pro U-235 mass (g), FP dose (rem/h per g),
     3 Co-60 dose (rem/h)')
      write(6,11) burnup,sums,srate(20),self,sumd,drate(20)
      if(nskip.eq.0) go to 100
c formation rates, atoms/s
      write(6,31)
   31 format(1x,'material formation rates, atoms/s')
      write(6,11) r
c loss rates, atoms/s
      write(6,32)
   32 format(1x,'material loss rates, atoms/s')
      write(6,11) k
c atoms initially present, atoms (time=ti)
      write(6,33)
   33 format(1x,'material n0, atoms (time=ti)')
      write(6,11) n0
c atoms currently present, atoms (time=td)
      write(6,34)
   34 format(1x,'material n, atoms (time=td)')
      write(6,11) n
c material disintegration rates, curies
      write(6,35)
   35 format(1x,'material disintegration rates, curies')
      write(6,11) mrate
```

```
c photon source rates, ph/s
      write(6,36)
   36 format(1x,'material/group photon source rates, ph/s')
      write(6,11) srate
c photon dose rates, rem/h
      write(6,37)
   37 format(1x,'material/group photon dose rates, rem/h')
      write(6,11) drate
c photon heat, wt; =ph/s*mev/ph*j/mev where j=wt-s
      do 104 i=1,3
      gheat(i)=gsour(i)*mev(i)*jmev
  104 gheat(4)=gheat(4) + gheat(i)
      write(6,41)
   41 format(1x,'group photon heat, wt')
      write(6,11) gheat
c photon flux, ph/cm**2-s; sum fission product photon fluxes
      do 107 i=1,3
  107 gflux(4)=gflux(4) + gflux(i)
      write(6,42)
   42 format(1x,'group photon flux, ph/cm**2-s')
      write(6,11) gflux
c photon source rate, ph/s; sum fission product photon source
      do 106 i=1,3
  106 gsour(4)=gsour(4) + gsour(i)
      write(6,43)
   43 format(1x,'group photon source rate, ph/s')
      write(6,11) gsour
c photon dose rate, rem/h; sum fission product photon dose
      do 108 i=1,3
  108 gdose(4)=gdose(4) + gdose(i)
      write(6,44)
   44 format(1x,'group photon dose rate, rem/h')
      write(6,11) gdose
      go to 100
  999 stop
      end
c
      subroutine sr90
      real*8 dk(13),cap(13),r(13),n0(13)
      real*8 powden,kg,ppm
      real*8 bu,time,dm,nflux,t(10),c(10),n(10),k
      common dk,cap,r,n0,powden,kg,ppm,bu,time
      do 101 i=1,10
      t(i)=dfloat(i)*time
      dm=1.0d0-bu*(dfloat(i)-0.5d0)
      nflux=2.952d13*powden/dm
      k=dk(1) + cap(1)*nflux
      if(i.eq.1) c(1)=-r(1)/k
      if(i.ne.1) c(i)=(n(i-1) - r(1)/k)*dexp(k*t(i-1))
  101 n(i)=r(1)/k + c(i)*dexp(-k*t(i))
c     write(6,11) n
   11 format(1x,1p6d12.5)
      n0(1)=n(10)
      return
      end
c
      subroutine cs134
```

```
      real*8 dk(13),cap(13),r(13),n0(13)
      real*8 powden,kg,ppm
      real*8 bu,time,dm,nflux,t(10),c(10),n(10),k1,k2,del
      common dk,cap,r,n0,powden,kg,ppm,bu,time
      do 101 i=1,10
      t(i)=dfloat(i)*time
      dm=1.0d0-bu*(dfloat(i)-0.5d0)
      nflux=2.952d13*powden/dm
      k1=dk(3) + cap(3)*nflux
      k2=dk(4) + cap(4)*nflux
      del=k2-k1
      if(i.eq.1) c(1)=r(3)*(-1.0d0/k2 + 1.0d0/del)
      if(i.ne.1) c(i)=(n(i-1) - r(3)/k2)*dexp(k2*t(i-1)) +
     x r(3)/del*dexp(del*t(i-1))
  101 n(i)=r(3)*(1.0d0/k2 - dexp(-k1*t(i))/del) + c(i)*dexp(-k2*t(i))
c     write(6,11) n
   11 format(1x,1p6d12.5)
      n0(4)=n(10)
      return
      end
c
      subroutine cs137
      real*8 dk(13),cap(13),r(13),n0(13)
      real*8 powden,kg,ppm
      real*8 bu,time,dm,nflux,t(10),c(10),n(10),k
      common dk,cap,r,n0,powden,kg,ppm,bu,time
      do 101 i=1,10
      t(i)=dfloat(i)*time
      dm=1.0d0-bu*(dfloat(i)-0.5d0)
      nflux=2.952d13*powden/dm
      k=dk(5) + cap(5)*nflux
      if(i.eq.1) c(1)=-r(5)/k
      if(i.ne.1) c(i)=(n(i-1) - r(5)/k)*dexp(k*t(i-1))
  101 n(i)=r(5)/k + c(i)*dexp(-k*t(i))
c     write(6,11) n
   11 format(1x,1p6d12.5)
      n0(5)=n(10)
      return
      end
c
      subroutine ce144
      real*8 dk(13),cap(13),r(13),n0(13)
      real*8 powden,kg,ppm
      real*8 bu,time,dm,nflux,t(10),c(10),n(10),k
      common dk,cap,r,n0,powden,kg,ppm,bu,time
      do 101 i=1,10
      t(i)=dfloat(i)*time
      dm=1.0d0-bu*(dfloat(i)-0.5d0)
      nflux=2.952d13*powden/dm
      k=dk(7) + cap(7)*nflux
      if(i.eq.1) c(1)=-r(7)/k
      if(i.ne.1) c(i)=(n(i-1) - r(7)/k)*dexp(k*t(i-1))
  101 n(i)=r(7)/k + c(i)*dexp(-k*t(i))
c     write(6,11) n
   11 format(1x,1p6d12.5)
      n0(7)=n(10)
      return
```

```
      end
c
      subroutine ru106
      real*8 dk(13),cap(13),r(13),n0(13)
      real*8 powden,kg,ppm
      real*8 bu,time,dm,nflux,t(10),c(10),n(10),k
      common dk,cap,r,n0,powden,kg,ppm,bu,time
      do 101 i=1,10
      t(i)=dfloat(i)*time
      dm=1.0d0-bu*(dfloat(i)-0.5d0)
      nflux=2.952d13*powden/dm
      k=dk(9) + cap(9)*nflux
      if(i.eq.1) c(1)=-r(9)/k
      if(i.ne.1) c(i)=(n(i-1) - r(9)/k)*dexp(k*t(i-1))
  101 n(i)=r(9)/k + c(i)*dexp(-k*t(i))
c     write(6,11) n
   11 format(1x,1p6d12.5)
      n0(9)=n(10)
      return
      end
c
      subroutine zr95
      real*8 dk(13),cap(13),r(13),n0(13)
      real*8 powden,kg,ppm
      real*8 bu,time,dm,nflux,t(10),c(10),n(10),k
      common dk,cap,r,n0,powden,kg,ppm,bu,time
      do 101 i=1,10
      t(i)=dfloat(i)*time
      dm=1.0d0-bu*(dfloat(i)-0.5d0)
      nflux=2.952d13*powden/dm
      k=dk(11) + cap(11)*nflux
      if(i.eq.1) c(1)=-r(11)/k
      if(i.ne.1) c(i)=(n(i-1) - r(11)/k)*dexp(k*t(i-1))
  101 n(i)=r(11)/k + c(i)*dexp(-k*t(i))
c     write(6,11) n
   11 format(1x,1p6d12.5)
      n0(11)=n(10)
      return
      end
c
      subroutine co60
      real*8 dk(13),cap(13),r(13),n0(13)
      real*8 powden,kg,ppm
      real*8 bu,time,dm,nflux,t(10),c(10),n(10),k1,k2,r59
      common dk,cap,r,n0,powden,kg,ppm,bu,time
      do 101 i=1,10
      t(i)=dfloat(i)*time
      dm=1.0d0-bu*(dfloat(i)-0.5d0)
      nflux=2.952d13*powden/dm
      k1=       39.67d-24*nflux
      k2=dk(13) + cap(13)*nflux
      r59=1.022d19*kg*ppm*k1
      if(i.eq.1) c(1)=-r59/k2
      if(i.ne.1) c(i)=(n(i-1) - r59/k2)*dexp(k2*t(i-1))
  101 n(i)=r59/k2 + c(i)*dexp(-k2*t(i))
c     write(6,11) n
   11 format(1x,1p6d12.5)
```

```
n0(13)=n(10)
return
end
```

```
  103 gheat(i)=0.0d0
c in subroutines, calculate nflux in 10 steps
      bu=burnup/10.0d0
      time=ti/10.0d0
c #1: sr-90
      r(1)=3.121d16*yield(1)*power
      k(1)=dk(1) + cap(1)*nflux
c     n0(1)=r(1)/k(1)*(1.0d0 - dexp(-k(1)*ti))
      call sr90
      n(1)=n0(1)*dexp(-dk(1)*td)
      mrate(1)=dk(1)*n(1)/bpc
      srate(1)=dk(1)*n(1)*ph(1)
      srate(2)=dk(1)*n(1)*ph(2)
      drate(1)=f2d(1)*srate(1)*pflux
      drate(2)=f2d(2)*srate(2)*pflux
      gsour(1)=gsour(1) + srate(1)
      gsour(2)=gsour(2) + srate(2)
      gflux(1)=gflux(1) + srate(1)*pflux
      gflux(2)=gflux(2) + srate(2)*pflux
      gdose(1)=gdose(1) + drate(1)
      gdose(2)=gdose(2) + drate(2)
c #2: y-90
      k(2)=dk(2) + cap(2)*nflux
      n0(2)=dk(1)/k(2)*n0(1)
      if(k(2)*ti.le.4.605170186d1) n0(2)=
     x dk(1)*r(1)/k(1)*((1.0d0 - dexp(-k(2)*ti))/k(2) -
     x (dexp(-k(1)*ti) - dexp(-k(2)*ti))/(k(2)-k(1)))
      n(2)=dk(1)/dk(2)*n(1)
      if(dk(2)*td.le.4.605170186d1) n(2)=
     x dk(1)*n0(1)*(dexp(-dk(1)*td) - dexp(-dk(2)*td))/
     x (dk(2) - dk(1)) + n0(2)*dexp(-dk(2)*td)
      mrate(2)=dk(2)*n(2)/bpc
      srate(3)=dk(2)*n(2)*ph(3)
      srate(4)=dk(2)*n(2)*ph(4)
      srate(5)=dk(2)*n(2)*ph(5)
      drate(3)=f2d(1)*srate(3)*pflux
      drate(4)=f2d(2)*srate(4)*pflux
      drate(5)=f2d(3)*srate(5)*pflux
      gsour(1)=gsour(1) + srate(3)
      gsour(2)=gsour(2) + srate(4)
      gsour(3)=gsour(3) + srate(5)
      gflux(1)=gflux(1) + srate(3)*pflux
      gflux(2)=gflux(2) + srate(4)*pflux
      gflux(3)=gflux(3) + srate(5)*pflux
      gdose(1)=gdose(1) + drate(3)
      gdose(2)=gdose(2) + drate(4)
      gdose(3)=gdose(3) + drate(5)
c #3: cs-133
      r(3)=3.121d16*yield(3)*power
      k(3)=dk(3) + cap(3)*nflux
      n0(3)=r(3)/k(3)*(1.0d0 - dexp(-k(3)*ti))
      n(3)=n0(3)*dexp(-dk(3)*td)
      mrate(3)=dk(3)*n(3)/bpc
c #4: cs-134
      k(4)=dk(4) + cap(4)*nflux
c     n0(4)=r(3)*((1.0d0 - dexp(-k(4)*ti))/k(4) -
c    x   (dexp(-k(3)*ti) - dexp(-k(4)*ti))/(k(4)-k(3)))
```

```
      call cs134
      n(4)=n0(4)*dexp(-dk(4)*td)
      mrate(4)=dk(4)*n(4)/bpc
      srate(6)=dk(4)*n(4)*ph(6)
      srate(7)=dk(4)*n(4)*ph(7)
      drate(6)=f2d(2)*srate(6)*pflux
      drate(7)=f2d(3)*srate(7)*pflux
      gsour(2)=gsour(2) + srate(6)
      gsour(3)=gsour(3) + srate(7)
      gflux(2)=gflux(2) + srate(6)*pflux
      gflux(3)=gflux(3) + srate(7)*pflux
      gdose(2)=gdose(2) + drate(6)
      gdose(3)=gdose(3) + drate(7)
c #5: cs-137
      r(5)=3.121d16*yield(5)*power
      k(5)=dk(5) + cap(5)*nflux
c     n0(5)=r(5)/k(5)*(1.0d0 - dexp(-k(5)*ti))
      call cs137
      n(5)=n0(5)*dexp(-dk(5)*td)
      mrate(5)=dk(5)*n(5)/bpc
      srate(8)=dk(5)*n(5)*ph(8)
      srate(9)=dk(5)*n(5)*ph(9)
      drate(8)=f2d(1)*srate(8)*pflux
      drate(9)=f2d(2)*srate(9)*pflux
      gsour(1)=gsour(1) + srate(8)
      gsour(2)=gsour(2) + srate(9)
      gflux(1)=gflux(1) + srate(8)*pflux
      gflux(2)=gflux(2) + srate(9)*pflux
      gdose(1)=gdose(1) + drate(8)
      gdose(2)=gdose(2) + drate(9)
c #6: ba-137m
      k(6)=dk(6) + cap(6)*nflux
      n0(6)=dk(5)/k(6)*n0(5)
      if(k(6)*ti.le.4.605170186d1) n0(6)=
     x dk(5)*r(5)/k(5)*((1.0d0 - dexp(-k(6)*ti))/k(6) -
     x (dexp(-k(5)*ti) - dexp(-k(6)*ti))/(k(6)-k(5)))
      n(6)=dk(5)/dk(6)*n(5)
      if(dk(6)*td.le.4.605170186d1) n(6)=
     x dk(5)*n0(5)*(dexp(-dk(5)*td) - dexp(-dk(6)*td))/
     x (dk(6) - dk(5)) + n0(6)*dexp(-dk(6)*td)
      mrate(6)=dk(6)*n(6)/bpc
      srate(10)=dk(6)*n(6)*ph(10)
      drate(10)=f2d(2)*srate(10)*pflux
      gsour(2)=gsour(2) + srate(10)
      gflux(2)=gflux(2) + srate(10)*pflux
      gdose(2)=gdose(2) + drate(10)
c #7: ce-144
      r(7)=3.121d16*yield(7)*power
      k(7)=dk(7) + cap(7)*nflux
c     n0(7)=r(7)/k(7)*(1.0d0 - dexp(-k(7)*ti))
      call ce144
      n(7)=n0(7)*dexp(-dk(7)*td)
      mrate(7)=dk(7)*n(7)/bpc
      srate(11)=dk(7)*n(7)*ph(11)
      drate(11)=f2d(1)*srate(11)*pflux
      gsour(1)=gsour(1) + srate(11)
      gflux(1)=gflux(1) + srate(11)*pflux
```

```
      gdose(1)=gdose(1) + drate(11)
c #8: pr-144
      k(8)=dk(8) + cap(8)*nflux
      n0(8)=dk(7)/k(8)*n0(7)
      if(k(8)*ti.le.4.605170186d1) n0(8)=
     x dk(7)*r(7)/k(7)*((1.0d0 - dexp(-k(8)*ti))/k(8) -
     x (dexp(-k(7)*ti) - dexp(-k(8)*ti))/(k(8)-k(7)))
      n(8)=dk(7)/dk(8)*n(7)
      if(dk(8)*td.le.4.605170186d1) n(8)=
     x dk(7)*n0(7)*(dexp(-dk(7)*td) - dexp(-dk(8)*td))/
     x (dk(8) - dk(7)) + n0(8)*dexp(-dk(8)*td)
      mrate(8)=dk(8)*n(8)/bpc
      srate(12)=dk(8)*n(8)*ph(12)
      srate(13)=dk(8)*n(8)*ph(13)
      srate(14)=dk(8)*n(8)*ph(14)
      drate(12)=f2d(1)*srate(12)*pflux
      drate(13)=f2d(2)*srate(13)*pflux
      drate(14)=f2d(3)*srate(14)*pflux
      gsour(1)=gsour(1) + srate(12)
      gsour(2)=gsour(2) + srate(13)
      gsour(3)=gsour(3) + srate(14)
      gflux(1)=gflux(1) + srate(12)*pflux
      gflux(2)=gflux(2) + srate(13)*pflux
      gflux(3)=gflux(3) + srate(14)*pflux
      gdose(1)=gdose(1) + drate(12)
      gdose(2)=gdose(2) + drate(13)
      gdose(3)=gdose(3) + drate(14)
c #9: ru-106
      r(9)=3.121d16*yield(9)*power
      k(9)=dk(9) + cap(9)*nflux
c     n0(9)=r(9)/k(9)*(1.0d0 - dexp(-k(9)*ti))
      call ru106
      n(9)=n0(9)*dexp(-dk(9)*td)
      mrate(9)=dk(9)*n(9)/bpc
c #10: rh-106
      k(10)=dk(10) + cap(10)*nflux
      n0(10)=dk(9)/k(10)*n0(9)
      if(k(10)*ti.le.4.605170186d1) n0(10)=
     x dk(9)*r(9)/k(9)*((1.0d0 - dexp(-k(10)*ti))/k(10) -
     x (dexp(-k(9)*ti) - dexp(-k(10)*ti))/(k(10)-k(9)))
      n(10)=dk(9)/dk(10)*n(9)
      if(dk(10)*td.le.4.605170186d1) n(10)=
     x dk(9)*n0(9)*(dexp(-dk(9)*td) - dexp(-dk(10)*td))/
     x (dk(10) - dk(9)) + n0(10)*dexp(-dk(10)*td)
      mrate(10)=dk(10)*n(10)/bpc
      srate(15)=dk(10)*n(10)*ph(15)
      srate(16)=dk(10)*n(10)*ph(16)
      srate(17)=dk(10)*n(10)*ph(17)
      drate(15)=f2d(1)*srate(15)*pflux
      drate(16)=f2d(2)*srate(16)*pflux
      drate(17)=f2d(3)*srate(17)*pflux
      gsour(1)=gsour(1) + srate(15)
      gsour(2)=gsour(2) + srate(16)
      gsour(3)=gsour(3) + srate(17)
      gflux(1)=gflux(1) + srate(15)*pflux
      gflux(2)=gflux(2) + srate(16)*pflux
      gflux(3)=gflux(3) + srate(17)*pflux
```

```
      gdose(1)=gdose(1) + drate(15)
      gdose(2)=gdose(2) + drate(16)
      gdose(3)=gdose(3) + drate(17)
c #11: zr-95
      r(11)=3.121d16*yield(11)*power
      k(11)=dk(11) + cap(11)*nflux
c     n0(11)=r(11)/k(11)*(1.0d0 - dexp(-k(11)*ti))
      call zr95
      n(11)=n0(11)*dexp(-dk(11)*td)
      mrate(11)=dk(11)*n(11)/bpc
      srate(18)=dk(11)*n(11)*ph(18)
      drate(18)=f2d(2)*srate(18)*pflux
      gsour(2)=gsour(2) + srate(18)
      gflux(2)=gflux(2) + srate(18)*pflux
      gdose(2)=gdose(2) + drate(18)
c #12: nb-95
      k(12)=dk(12) + cap(12)*nflux
      n0(12)=dk(11)*r(11)/k(11)*((1.0d0 - dexp(-k(12)*ti))/k(12) -
     x (dexp(-k(11)*ti) - dexp(-k(12)*ti))/(k(12)-k(11)))
      n(12)=dk(11)*n0(11)*(dexp(-dk(11)*td) - dexp(-dk(12)*td))/
     x (dk(12) - dk(11)) + n0(12)*dexp(-dk(12)*td)
      mrate(12)=dk(12)*n(12)/bpc
      srate(19)=dk(12)*n(12)*ph(19)
      drate(19)=f2d(2)*srate(19)*pflux
      gsour(2)=gsour(2) + srate(19)
      gflux(2)=gflux(2) + srate(19)*pflux
      gdose(2)=gdose(2) + drate(19)
c #13: co-60
      r(13)=1.197d10*kg*ppm*powden/dm
      k(13)=dk(13) + cap(13)*nflux
c     n0(13)=r(13)/k(13)*(1.0d0 - dexp(-k(13)*ti))
      call co60
      n(13)=n0(13)*dexp(-dk(13)*td)
      mrate(13)=dk(13)*n(13)/bpc
      srate(20)=dk(13)*n(13)*ph(20)
      drate(20)=f2d(3)*srate(20)*pflux
      gsour(5)=srate(20)
      gflux(5)=srate(20)*pflux
      gdose(5)=drate(20)
      gheat(5)=gsour(5)*mev(3)*jmev
c sum fission product photon source and dose rates
      sums=0.0d0
      sumd=0.0d0
      do 102 i=1,19
      sums=sums + srate(i)
  102 sumd=sumd + drate(i)
      burnup=power/powden*1.0d3*burnup
      sums=sums/burnup
      sumd=sumd/burnup
c mass of burned U-235 necessary for 100 rem/h dose rate
      self=1.0d2/sumd
c write output: U-235 burned, g;
c FP source, ph/s per gU-235 burned; Co-60 source, ph/s;
c self-protected U-235 mass burned, g
c FP dose,  rem/h per gU-235 burned; Co-60 dose,  rem/h
      write(6,21)
   21 format(' output: U-235 burned (g), FP source (ph/s per g), Co-60 s
```

```
     2ource (ph/s),'/5x,'self-pro U-235 mass (g), FP dose (rem/h per g),
     3 Co-60 dose (rem/h)')
      write(6,11) burnup,sums,srate(20),self,sumd,drate(20)
      if(nskip.eq.0) go to 100
c formation rates, atoms/s
      write(6,31)
   31 format(1x,'material formation rates, atoms/s')
      write(6,11) r
c loss rates, atoms/s
      write(6,32)
   32 format(1x,'material loss rates, atoms/s')
      write(6,11) k
c atoms initially present, atoms (time=ti)
      write(6,33)
   33 format(1x,'material n0, atoms (time=ti)')
      write(6,11) n0
c atoms currently present, atoms (time=td)
      write(6,34)
   34 format(1x,'material n, atoms (time=td)')
      write(6,11) n
c material disintegration rates, curies
      write(6,35)
   35 format(1x,'material disintegration rates, curies')
      write(6,11) mrate
c photon source rates, ph/s
      write(6,36)
   36 format(1x,'material/group photon source rates, ph/s')
      write(6,11) srate
c photon dose rates, rem/h
      write(6,37)
   37 format(1x,'material/group photon dose rates, rem/h')
      write(6,11) drate
c photon heat, wt; =ph/s*mev/ph*j/mev where j=wt-s
      do 104 i=1,3
      gheat(i)=gsour(i)*mev(i)*jmev
  104 gheat(4)=gheat(4) + gheat(i)
      write(6,41)
   41 format(1x,'group photon heat, wt')
      write(6,11) gheat
c photon flux, ph/cm**2-s; sum fission product photon fluxes
      do 107 i=1,3
  107 gflux(4)=gflux(4) + gflux(i)
      write(6,42)
   42 format(1x,'group photon flux, ph/cm**2-s')
      write(6,11) gflux
c photon source rate, ph/s; sum fission product photon source
      do 106 i=1,3
  106 gsour(4)=gsour(4) + gsour(i)
      write(6,43)
   43 format(1x,'group photon source rate, ph/s')
      write(6,11) gsour
c photon dose rate, rem/h; sum fission product photon dose
      do 108 i=1,3
  108 gdose(4)=gdose(4) + gdose(i)
      write(6,44)
   44 format(1x,'group photon dose rate, rem/h')
      write(6,11) gdose
```

```
      go to 100
  999 stop
      end
c
      block data
      real (kind=8) dk(13),cap(13)
      common /comdat/dk,cap
c decay constant, s-1
      data dk/7.816d-10,3.005d-6,0.d0,1.066d-8,7.297d-10,4.530d-3,
     x 2.821d-8,6.684d-4,2.174d-8,2.318d-2,1.225d-7,2.285d-7,4.176d-9/
c capture cross section, cm**2
      data cap/1.028d-24,2.740d-24,103.2d-24,107.1d-24,0.1310d-24,
     x 0.d0,1.172d-24,0.d0,0.4550d-24,2*0.d0,3.563d-24,4.275d-24/
      end
c
      subroutine sr90
      real (kind=8) dk(13),cap(13),r(13),n0(13)
      real (kind=8) powden,kg,ppm
      real (kind=8) bu,time,dm,nflux,t(10),c(10),n(10),k
      common r,n0,powden,kg,ppm,bu,time
      common /comdat/dk,cap
      do 101 i=1,10
      t(i)=dfloat(i)*time
      dm=1.0d0-bu*(dfloat(i)-0.5d0)
      nflux=2.952d13*powden/dm
      k=dk(1) + cap(1)*nflux
      if(i.eq.1) c(1)=-r(1)/k
      if(i.ne.1) c(i)=(n(i-1) - r(1)/k)*dexp(k*t(i-1))
  101 n(i)=r(1)/k + c(i)*dexp(-k*t(i))
c     write(6,11) n
   11 format(1x,1p6d12.5)
      n0(1)=n(10)
      return
      end
c
      subroutine cs134
      real (kind=8) dk(13),cap(13),r(13),n0(13)
      real (kind=8) powden,kg,ppm
      real (kind=8) bu,time,dm,nflux,t(10),c(10),n(10),k1,k2,del
      common r,n0,powden,kg,ppm,bu,time
      common /comdat/dk,cap
      do 101 i=1,10
      t(i)=dfloat(i)*time
      dm=1.0d0-bu*(dfloat(i)-0.5d0)
      nflux=2.952d13*powden/dm
      k1=dk(3) + cap(3)*nflux
      k2=dk(4) + cap(4)*nflux
      del=k2-k1
      if(i.eq.1) c(1)=r(3)*(-1.0d0/k2 + 1.0d0/del)
      if(i.ne.1) c(i)=(n(i-1) - r(3)/k2)*dexp(k2*t(i-1)) +
     x r(3)/del*dexp(del*t(i-1))
  101 n(i)=r(3)*(1.0d0/k2 - dexp(-k1*t(i))/del) + c(i)*dexp(-k2*t(i))
c     write(6,11) n
   11 format(1x,1p6d12.5)
      n0(4)=n(10)
      return
      end
```

```
c
      subroutine cs137
      real (kind=8) dk(13),cap(13),r(13),n0(13)
      real (kind=8) powden,kg,ppm
      real (kind=8) bu,time,dm,nflux,t(10),c(10),n(10),k
      common r,n0,powden,kg,ppm,bu,time
      common /comdat/dk,cap
      do 101 i=1,10
      t(i)=dfloat(i)*time
      dm=1.0d0-bu*(dfloat(i)-0.5d0)
      nflux=2.952d13*powden/dm
      k=dk(5) + cap(5)*nflux
      if(i.eq.1) c(1)=-r(5)/k
      if(i.ne.1) c(i)=(n(i-1) - r(5)/k)*dnd=999) ti,power,powden,td,kg,ppm,burnup
c burnup in percent
      burnup=1.0d-2*burnup
c calculate irradiation time and average neutron flux
      time=burnup/(1.25d-3*powden)
      if(ti.eq.0.0d0) ti=time
      dm=1.0d0 - 0.5d0*burnup
      nflux=2.952d13*powden/dm
c write input data plus nflux
      write(6,20)
   20 format('0input: irrad time (d), power (MW), pow den (MW/kgU-235),
     2decay time (y),'/5x,'asby mass (kg), Co-59 (ppm), U-235 burnup (%)
     3, avg flux (n/cm**2-s)')
      write(6,11) ti,power,powden,td,kg,ppm,burnup*1.0d2,nflux
c use ti as a flag for additional printout
      nskip=0
      if(ti.lt.0.0d0) then
       ti=-ti
       nskip=1
      endif
c check if ti is consistent (<1%) with burnup and power density
      if(dabs(ti/time - 1.0d0).ge.1.0d-2) stop 101
c irradiation time (ti) in days and decay time (td) in years
      ti=ti*8.64d4
      td=td*3.1536d7
c initialize arrays
      do 101 i=1,13
  101 r(i)=0.0d0
      do 103 i=1,5
      gsour(i)=0.0d0
      gflux(i)=0.0d0
      gdosexp(k*t(i-1))
  101 n(i)=r(5)/k + c(i)*dexp(-k*t(i))
c     write(6,11) n
   11 format(1x,1p6d12.5)
      n0(5)=n(10)
      return
      end
c
      subroutine ce144
      real (kind=8) dk(13),cap(13),r(13),n0(13)
      real (kind=8) powden,kg,ppm
      real (kind=8) bu,time,dm,nflux,t(10),c(10),n(10),k
      common r,n0,powden,kg,ppm,bu,time
```

```
      common /comdat/dk,cap
      do 101 i=1,10
      t(i)=dfloat(i)*time
      dm=1.0d0-bu*(dfloat(i)-0.5d0)
      nflux=2.952d13*powden/dm
      k=dk(7) + cap(7)*nflux
      if(i.eq.1) c(1)=-r(7)/k
      if(i.ne.1) c(i)=(n(i-1) - r(7)/k)*dexp(k*t(i-1))
  101 n(i)=r(7)/k + c(i)*dexp(-k*t(i))
c     write(6,11) n
   11 format(1x,1p6d12.5)
      n0(7)=n(10)
      return
      end
c
      subroutine ru106
      real (kind=8) dk(13),cap(13),r(13),n0(13)
      real (kind=8) powden,kg,ppm
      real (kind=8) bu,time,dm,nflux,t(10),c(10),n(10),k
      common r,n0,powden,kg,ppm,bu,time
      common /comdat/dk,cap
      do 101 i=1,10
      t(i)=dfloat(i)*time
      dm=1.0d0-bu*(dfloat(i)-0.5d0)
      nflux=2.952d13*powden/dm
      k=dk(9) + cap(9)*nflux
      if(i.eq.1) c(1)=-r(9)/k
      if(i.ne.1) c(i)=(n(i-1) - r(9)/k)*dexp(k*t(i-1))
  101 n(i)=r(9)/k + c(i)*dexp(-k*t(i))
c     write(6,11) n
   11 format(1x,1p6d12.5)
      n0(9)=n(10)
      return
      end
c
      subroutine zr95
      real (kind=8) dk(13),cap(13),r(13),n0(13)
      real (kind=8) powden,kg,ppm
      real (kind=8) bu,time,dm,nflux,t(10),c(10),n(10),k
      common r,n0,powden,kg,ppm,bu,time
      common /comdat/dk,cap
      do 101 i=1,10
      t(i)=dfloat(i)*time
      dm=1.0d0-bu*(dfloat(i)-0.5d0)
      nflux=2.952d13*powden/dm
      k=dk(11) + cap(11)*nflux
      if(i.eq.1) c(1)=-r(11)/k
      if(i.ne.1) c(i)=(n(i-1) - r(11)/k)*dexp(k*t(i-1))
  101 n(i)=r(11)/k + c(i)*dexp(-k*t(i))
c     write(6,11) n
   11 format(1x,1p6d12.5)
      n0(11)=n(10)
      return
      end
c
      subroutine co60
      real (kind=8) dk(13),cap(13),r(13),n0(13)
```

```
      real (kind=8) powden,kg,ppm
      real (kind=8) bu,time,dm,nflux,t(10),c(10),n(10),k1,k2,r59
      common r,n0,powden,kg,ppm,bu,time
      common /comdat/dk,cap
      do 101 i=1,10
      t(i)=dfloat(i)*time
      dm=1.0d0-bu*(dfloat(i)-0.5d0)
      nflux=2.952d13*powden/dm
      k1=       39.67d-24*nflux
      k2=dk(13) + cap(13)*nflux
      r59=1.022d19*kg*ppm*k1
      if(i.eq.1) c(1)=-r59/k2
      if(i.ne.1) c(i)=(n(i-1) - r59/k2)*dexp(k2*t(i-1))
  101 n(i)=r59/k2 + c(i)*dexp(-k2*t(i))
c     write(6,11) n
   11 format(1x,1p6d12.5)
      n0(13)=n(10)
      return
      end
```