The Use of EGS for Monte Carlo Calculations in Medical Physics

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Lecture notes for Refresher Course RC7

First Inter-American Meeting of Medical Physics

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SLIDE 1

The Use of EGS for Monte Carlo Calculations in Medical Physics

Refresher Course RC7

First Inter-American Meeting of Medical Physics

Tuesday, July 17, 1984, Chicago

SLIDE 2

Course Outline

1) Introduction to EGS

2) Why Use EGS

3) A Simple Example of its Use

4) Parameter Selection

5) Variance Reduction Techniques

6) Benchmarks

Notes: The course assumes a basic familiarity with the Monte Carlo technique of radiation transport. The emphasis will be on the use of EGS to do medical physics related calculations in which electron transport is important. However, many of the considerations are valid with other codes.

SLIDE 3

Introduction to EGS

(Electron-Gamma-Shower)

Version 3: Developed at SLAC for High Energy Physics Applications

Version 4: Modified & corrected for applications down to 100 keV.

Uses condensed history technique of charged particle transport

Highly Structured and General Purpose

Written in an extended Fortran called MORTRAN

Notes: See Ford and Nelson,1978 and Nelson et al 1984, for detailed documentation or Rogers 1982,1984a,1984b for briefer descriptions. Write to Dr.W.R.Nelson, Stanford Linear Accelerator Center, P.O.Box 4349, Stanford CA94305 for SLAC report 210.

SLIDE 4

The Physics in the Simulation

Electron/Positron Transport

Bremsstrahlung Production
(no Elwert correction)

Positron annihilation in flight
and at rest

Moliere Multiple Scattering
(coulomb scatter from nuclei)

Moller & Bhabha Scattering
(scattering from electrons)

Continuous energy loss (restricted
Bethe-Bloch)

Photon Transport

Compton Scattering

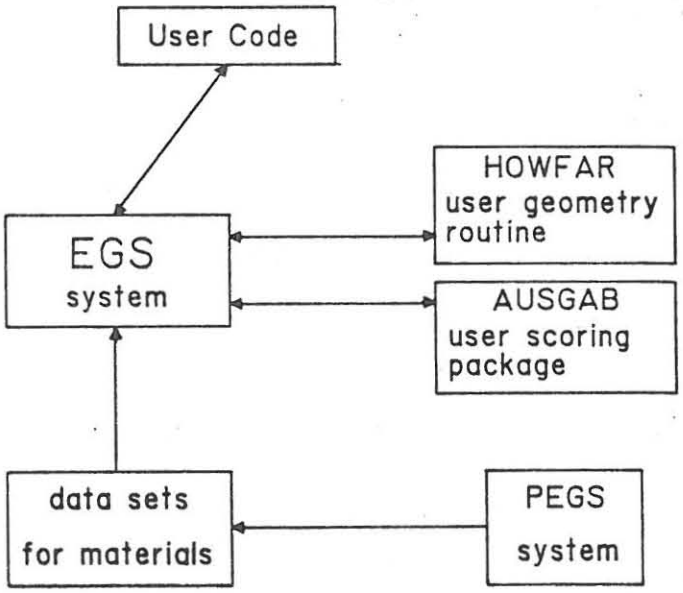
Rayleigh(coherent)Scattering
(Version 4 only)

Photo-electric effect
(K x-rays not followed)

Pair Production

Notes: Ford and Nelson,1978 give very clear and complete documentation.

SLIDE 5



Notes: The user writes a users code to handle input and output, to do a statistcal analysis of the results and to call, via a simple subroutine call, the EGS system to do the actual radiation transport simulation. The user also supplies two subroutines called HOWFAR and AUSGAB. HOWFAR basically specifies the users geometry and answers a few very specific questions. AUSGAB keeps track of the parameters of interest. It can be very simple or very sophisticated. It is called under a set of very well defined and selectable conditions (e.g. at the beginning of every electron step) and the user has access to a set of well defined parameters (e.g.position, direction,energy, energy deposited and pathlength traversed in this step etc).

The cross-secton preparation code called PEGS is much larger than EGS. It can prepare data sets for materials of arbitrary composition.

SLIDE 6

Why Use EGS?

1) Very Flexible - can handle virtually any problem

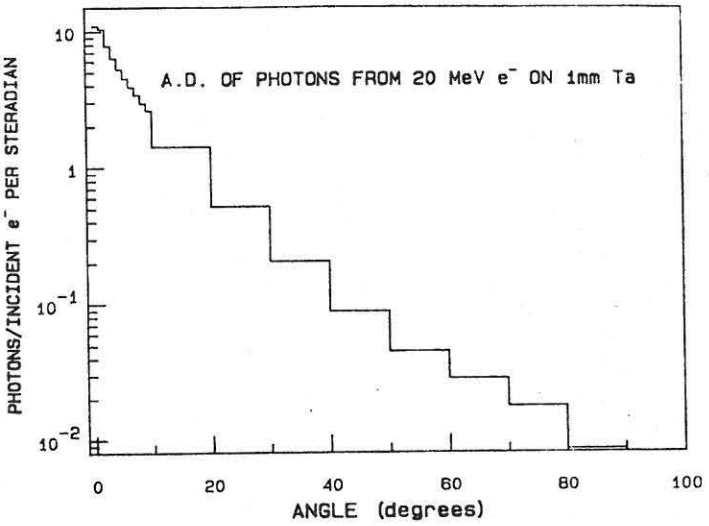
2) More accurate and easier than writing your own routines

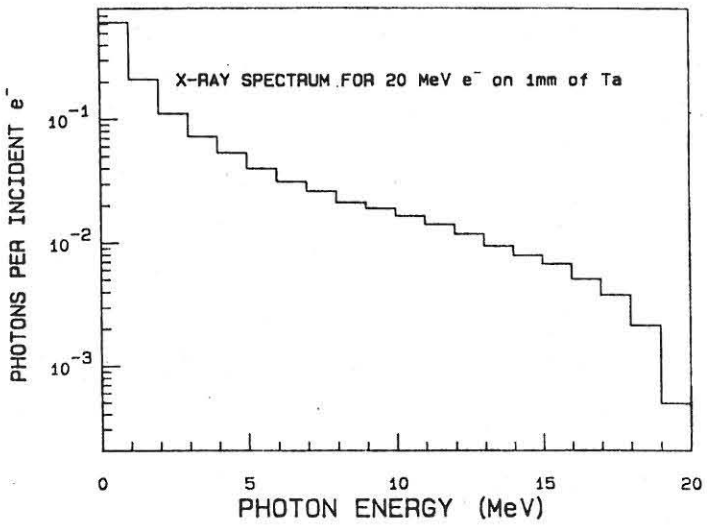
3) Well documented and benchmarked - you specify what you have done by using a standard code.

4) Your improvements and error corrections are a general contribution to the field.

Notes:The major competitor to EGS is Berger and Seltzer's ETRAN and its Sandia Labs extentions (CYLTRAN, ACCEPT, SANDYL). These codes are perhaps more sophisticated than EGS in their low energy electron transport and represent a benchmark for EGS. However ETRAN is not flexible (except for Berger and Seltzer!) and cannot be applied by others to problems other than those it is designed for. Its published documentation is poor although the range of published benchmark comparisons to experiment is still better than for EGS.

SLIDE 7





Notes: These results are for a fairly thin target; 95% of the electrons go through and exit with an average energy of 14.3 MeV. ECUT=AE=1.5 MeV(total energy), AP=PCUT=0.100 MeV, default ESTEPE.

```
0   *       AAPMS.MOR       AN UNCOMMENTED VERSION OF AAPM.MOR
    %Q1
    %C80
    %'$MXMED'='1'   %'$MXREG'='3'  %'$MXSTACK'='15'
    %';COMIN/GEOM/;'=';COMMON/GEOM/ZBOUND;'
0   ;COMIN/BOUNDS,GEOM,MEDIA,THRESH/;
0   INTEGER MEDARR(24) /$S'TA',22*' '/; DO I=1,24<MEDIA(I,1)=MEDARR(I);>
0   ZBOUND=0.1;
0   ;OUTPUT;(///'    START AAPM'//' CALL HATCH TO GET CROSS-SECTION DATA'/);
0   CALL HATCH;
0   ;OUTPUT AE(1)-0.511, AP(1);('0ELECTRONS CAN BE CREATED OR FOLLOWED DOWN TO',
0   F8.3,' MeV KINETIC ENERGY'/'   PHOTONS CAN BE CREATED OR FOLLOWED DOWN TO',
0   F8.3,' MeV ');ECUT(2)=1.5;PCUT(2)=0.1;
0   ;OUTPUT;('0',T19,'KINETIC ENERGY(MeV)',T40,'CHARGE',T48,
0   'ANGLE W.R.T. Z AXIS-DEGREES');IQIN=-1;EIN=20.511;/XIN,YIN,ZIN/=0.0;
0   /UIN,VIN/=0.0;WIN=1.0;IRIN=1;WTIN=1.0;INRCIN=0;
0   DO I=1,10<OUTPUT I;(' START HISTORY',I4);
1       CALL SHOWER(IQIN,EIN,XIN,YIN,ZIN,UIN,VIN,WIN,IRIN,WTIN,INRCIN);>
0   STOP;END;
0   SUBROUTINE AUSGAB(IARG);
0   COMIN/STACK/;IF(IARG.EQ.3)<ANGLE=ACOS(W(NP))*180./3.14159;
1       IF(IQ(NP).EQ.0)<EKINE=E(NP);> ELSE <EKINE=E(NP)-0.511;>
1       OUTPUT EKINE,IQ(NP),ANGLE;(T21,F10.3,T33,I10,T49,F10.1);>
0   RETURN;END;
0   SUBROUTINE HOWFAR;
0   COMIN/STACK,EPCONT,GEOM/;
0   IF(IR(NP).EQ.3)<IDISC=1;RETURN;>
0   ELSEIF(IR(NP).EQ.2)<IF(W(NP).GT.0.0)<
2           TVAL=(ZBOUND-Z(NP))/W(NP);IF(TVAL.GT.USTEP)<RETURN;>
2           ELSE<USTEP=TVAL;IRNEW=3;RETURN;>>
1       ELSEIF(W(NP).LT.0.0)<TVAL=-Z(NP)/W(NP);IF(TVAL.GT.USTEP)<RETURN;>
2           ELSE<USTEP=TVAL;IRNEW=1;RETURN;>>
1       ELSEIF(W(NP).EQ.0.0)<RETURN;>>
0   ELSEIF(IR(NP).EQ.1)<IF(W(NP).GT.0.0)<USTEP=00.00;IRNEW=2;RETURN;>
1       ELSE<IDISC=1;RETURN;>>
0   END;
    %Q0
    %%
```

Notes: This code + the EGS system does all the physics shown in slide 7, although it does not analyse the results. Its output is shown in the next slide. A commented version is given in slides 10,11,12. This version is presented to emphasize how simple it is to do physics with the EGS system.

```
  @AAPM
$ASSIGN NL: FOR008
$ASSIGN [DAVE.PEGS.DAT]EGSHI.DAT FOR012
$ASSIGN TT: FOR006
$RUN AAPM


   START AAPM

CALL HATCH TO GET CROSS-SECTION DATA


ELECTRONS CAN BE CREATED OR FOLLOWED DOWN TO   0.989 MeV KINETIC ENERGY
  PHOTONS CAN BE CREATED OR FOLLOWED DOWN TO   0.100 MeV

                KINETIC ENERGY(MeV)  CHARGE  ANGLE W.R.T. Z AXIS-DEGREES
START HISTORY   1
                      0.284           0            23.2
                      1.652           0            28.0
                     15.870          -1            25.0
START HISTORY   2
                      0.544           0             2.7
                      0.573           0            22.5
                     16.800          -1            19.6
START HISTORY   3
                      0.196           0             5.2
                      5.194           0            18.8
                      0.133           0            14.1
                     12.400          -1            17.3
START HISTORY   4
                      0.339           0             4.4
                      0.895           0            11.1
                     16.708          -1            19.6
START HISTORY   5
                      0.704           0             3.1
                     17.253          -1             6.8
START HISTORY   6
                     17.911           0            19.9
START HISTORY   7
                      0.561           0            16.9
                      0.113           0            17.5
                     17.249          -1            31.8
START HISTORY   8
                     17.746          -1            55.7
START HISTORY   9
                      5.878          -1            22.5
                     11.968           0             1.1
START HISTORY  10
                      0.701           0            81.0
                     17.142           0             3.7
FORTRAN STOP
$
```

Note: Total CPU time for the simulation was 150ms on a VAX 780.

SLIDE 10

```
    %Q1
    %C80    USE 80 COLUMNS
0   '*******************************************************************************
0   '
0   '                                ***********
0   '                                *         *
0   '                                * AAPM.MOR*
0   '                                *         *
0   '                                ***********
0   '
0   '       An EGS program which lists the particles escaping from
0   '       a 1 mm thick slab of Ta onto which a 20 MeV pencil beam of electrons
0   '       has been directed
0   '
0   '       Dave Rogers Feb 1984, NRCC
0   '
0   '*******************************************************************************
0
0   'set some user defaults
0
    %'$MXMED'='1'    'There is only 1 medium in the problem
    %'$MXREG'='3'    'There are only 3 geometric regions (defaults 2000)
    %'$MXSTACK'='15'         'less than 15 particles on the stack at once
0
0   'DEFINE A COMMON TO PASS INFORMATION TO THE GEOMETRY ROUTINE HOWFAR
    %';COMIN/GEOM/;'=';COMMON/GEOM/ZBOUND;'
0
0   ;COMIN/BOUNDS,GEOM,MEDIA,THRESH/;'NOTE WE NEED A ; TO START THE FIRST REAL LINE
0   '       BOUNDS CONTAINS ECUT AND PCUT
0   '       GEOM PASSES INFO TO OUR HOWFAR ROUTINE
0   '       MEDIA CONTAINS THE ARRAY MEDIA
0   '       THRESH CONTAINS AE AND AP
0
0   INTEGER MEDARR(24) /$S'TA',22*' '/; 'PLACE MEDIUM NAME IN AN ARRAY
0   DO I=1,24<MEDIA(I,1)=MEDARR(I);>'THIS IS TO AVOID A DATA STATEMENT FOR
0   '                                   A VARIABLE IN COMMON
0   ZBOUND=0.1;'    Plate is 1mm thick
0
0   ;OUTPUT;(///'    START AAPM'/// CALL HATCH TO GET CROSS-SECTION DATA'/);
0
0   CALL HATCH;'    PICK UP CROSS SECTION DATA FOR TA
0   '                DATA FILE MUST BE ASSIGNED TO UNIT 12
0
0   ;OUTPUT AE(1)-0.511, AP(1);('0ELECTRONS CAN BE CREATED OR FOLLOWED DOWN TO',
0   F8.3,' MeV KINETIC ENERGY'/'   PHOTONS CAN BE CREATED OR FOLLOWED DOWN TO',
0   F8.3,' MeV ');
0   ECUT(2)=1.5;'   TERMINATE ELECTRON HISTORIES AT 1.5 MEV IN THE PLATE
0   PCUT(2)=0.1;'   TERMINATE   PHOTON HISTORIES AT 0.1 MEV IN THE PLATE
0
    %E
```

Notes:i)Variables in common are carefully documented in SLAC 210.
ii) The numbers down the left indicate the current level of nesting, and are matched by automatic indentation (all level 0 here).
iii) ; ends all statements
iv) OUTPUT writes to unit 6 with the format following it.
v) %'TEXT1'='TEXT2' defines a macro substitution. This replaces all occurances of TEXT1 by TEXT2. It is used here to define some dimensions.

```
0   "PRINT HEADER FOR OUTPUT
0   ;OUTPUT;('0',T19,'KINETIC ENERGY(MeV)',T40,'CHARGE',T48,
0   'ANGLE W.R.T. Z AXIS-DEGREES');
0
0   "DEFINE INITIAL VARIABLES FOR 20 MEV BEAM OF ELECTRONS NORMALLY INCIDENT
0   "ON THE SLAB
0
0   IQIN=-1;"               INCIDENT CHARGE - ELECTRONS
0   EIN=20.511;"            20 MEV KINETIC ENERGY
0   /XIN,YIN,ZIN/=0.0;"     INCIDENT AT ORIGIN
0   /UIN,VIN/=0.0;WIN=1.0;" MOVING ALONG Z AXIS
0   IRIN=1;"                STARTS IN REGION 1, COULD BE 2
0   WTIN=1.0;"              INITIAL WEIGHT = 1 SINCE NO VARIANCE REDUCTION USED
0   INRCIN=0;"              NRC VARIABLE FOR TRACKING THE HISTORY -NOT USED HERE
0
0   "NOW INITIATE THE SHOWER 10 TIMES
0
0   DO I=1,10<OUTPUT I;(' START HISTORY',I4);
1
1       CALL SHOWER(IQIN,EIN,XIN,YIN,ZIN,UIN,VIN,WIN,IRIN,WTIN,INRCIN);
1
1       "NOTE THE OUTPUT IS DONE AT THE END OF EACH HISTORY IN SUBROUTINE AUSGAB">
0
0   STOP;END;
0
0
0
0
0   "*************************************************************************************
0   "
0   SUBROUTINE AUSGAB(IARG);
0   "
0   "       THIS ROUTINE WILL BE CALLED WITH IARG=3 WHENEVER A PARTICLE HAS
0   "       BEEN DISCARDED BY THE USER IN HOWFAR
0   "       WE GET IT TO PRINT THE REQUIRED INFORMATION AT THAT POINT
0   "
0   "*************************************************************************************
0
0   COMIN/STACK/;
0
0   IF(IARG.EQ.3)<
1       ANGLE=ACOS(W(NP))*180./3.14159;"ANGLE W.R.T. Z AXIS IN DEGREES
1
1       IF(IQ(NP).EQ.0)<EKINE=E(NP);> ELSE <EKINE=E(NP)-0.511;>"GET KINETIC ENERGY
1       OUTPUT EKINE,IQ(NP),ANGLE;(T21,F10.3,T33,I10,T49,F10.1);>
0   RETURN;END;
    %E
```

Notes: i) For a sophistcated program there would be a great deal of I/O and statistical analysis in the main program.
ii) AUSGAB is called under 21 well defined conditions which are specified by the value of IARG.

```
0   '*************************************************************************************
0   '
0   SUBROUTINE HOWFAR;
0   '
0   '
0   '       GIVEN A PARTICLE AT (X,Y,Z) IN REGION IR AND GOING IN DIRECTION
0   '       (U,V,W), THIS ROUTINE ANSWERS THE QUESTION, CAN THE PARTICLE GO
0   '       A DISTANCE USTEP WITHOUT CROSSING A BOUNDARY
0   '               IF YES, IT MERELY RETURNS
0   '               IF NO, IT SETS USTEP=DISTANCE TO BOUNDARY IN THE CURRENT
0   '               DIRECTION AND SETS IRNEW TO THE REGION NUMBER   ON THE
0   '               FAR SIDE OF THE BOUNDARY (THIS CAN IN GENERAL BE MESSY!)
0   '
0   '       THE USER CAN TERMINATE A HISTORY BY SETTING IDISC>0. HERE WE TERMINATE
0   '       ALL HISTORIES WHICH ENTER REGION 3 OR ARE GOING BACKWARDS IN REGION 1
0   '
0   '                       |               |
0   '       REGION 1        | REGION 2      |       REGION 3
0   '                       |               |
0   '       e- =========>   |               | e- or photon ====>
0   '                       |               |
0   '       vacuum          |       Ta      |       vacuum
0   '
0   '*************************************************************************************
0   COMIN/STACK,EPCONT,GEOM/;
0   '       COMMON STACK CONTAINS X,Y,Z,U,V,W AND IR
0   '       COMMON EPCONT CONTAINS IRNEW,USTEP AND IDISC
0   '       COMMON GEOM CONTAINS ZBOUND
0
0   IF(IR(NP).EQ.3)<IDISC=1;RETURN;'TERMINATE THIS HISTORY! IT IS PAST THE PLATE'>
0
0   ELSEIF(IR(NP).EQ.2)<'WE ARE IN THE Ta PLATE - CHECK THE GEOMETRY
1
1       IF(W(NP).GT.0.0)<'GOING FORWARD -CONSIDER THIS FIRST SINCE IT IS MOST FREQUENT
2           TVAL=(ZBOUND-Z(NP))/W(NP); 'TVAL IS DISTANCE TO BOUNDARY IN THIS DIRECTION
2           IF(TVAL.GT.USTEP)<RETURN;'CAN TAKE CURRENTLY REQUESTED STEP'>
2           ELSE<USTEP=TVAL;IRNEW=3;RETURN;>
2           >'END OF W(NP)>0 CASE
1
1       ELSEIF(W(NP).LT.0.0)<'GOING BACK TOWARDS ORIGIN
2           TVAL=-Z(NP)/W(NP); 'DISTANCE TO PLANE AT ORIGIN
2           IF(TVAL.GT.USTEP)<RETURN;'CAN TAKE CURRENTLY REQUESTED STEP'>
2           ELSE<USTEP=TVAL;IRNEW=1;RETURN;>
2           >'END W(NP)<0 CASE
1
1       ELSEIF(W(NP).EQ.0.0)<'CANNOT HIT BOUNDARY'RETURN;>
1       >'END OF REGION 2 CASE
0
0   ELSEIF(IR(NP).EQ.1)<'IN REGON WITH SOURCE
1       IF(W(NP).GT.0.0)<'THIS MUST BE A SOURCE PARTICLE ON Z=0 BOUNDARY
2           USTEP=00.00;IRNEW=2;RETURN;>
1       ELSE<'IT MUST BE A REFLECTED PARTICLE - DISCARD IT' IDISC=1;RETURN;>
1       >'END REGION 1 CASE
0
0   END;'END OF SUBROUTINE HOWFAR
```

Notes: i) In general this routine is the messy part - but it is conceptually simple. Its requirements in the general case have been completely specified by the in-line comments.

SLIDE 13

Parameters to be Set

AE,AP	thresholds for secondary electron and brem production
ECUT,PCUT	cutoffs for electron/positron and photon transport
ESTEPE	electron maximum fractional energy loss per step
SMAX	maximum length of electron step

Note: The last two parameters are not part of EGS but are essential at low energies as we see below. See Rogers 1984b.

SLIDE 14

Definitions of AE and AP

AE - for secondary or knock-on electrons if:

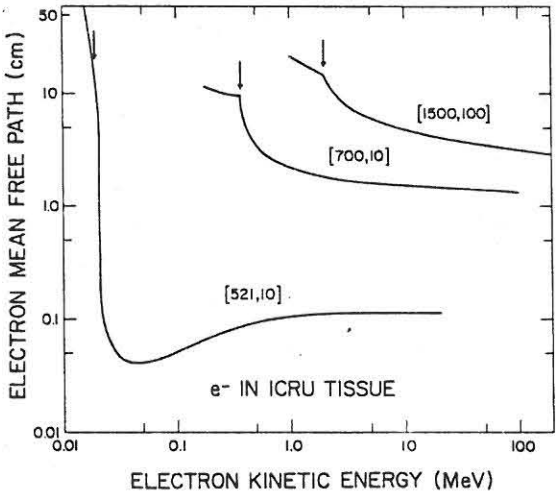
$E_{sec} > AE$	treat interactions discretely and follow secondaries
$E_{sec} < AE$	treat interactions as part of the continuous energy loss mechanism

AP - for bremsstrahlung generated photons if:

$E_{brem} > AP$	treat interaction discretely
$E_{brem} < AP$	treat as part of continuous energy loss mechanism

Notes: AE and AP are defined when calculating the cross-section data. One always has ECUT$\geq$AE and PCUT$\geq$AP.

SLIDE 15



Caption: Electron mean-free-paths in tissue between discrete interactions in which either knock-on electrons with total energies above AE keV or bremsstrahlung photons with energies above AP keV are created. The arrows denote the threshold energy for the production of knock-on electrons for that particular data set. The values were calculated by PEGS3.

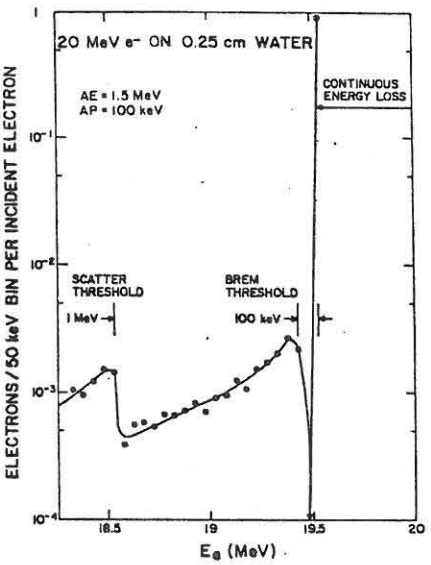
Notes:

i)AE is the total energy, including the rest mass

ii) lower values of AE mean more energy is lost via discrete events and hence the electron stopping power is smaller.

iii) The shape of the AE=521 keV curve makes one assumption used in EGS wrong since it doesn't decrease monotonically (see Rogers 1984b for a discussion - there appear to be no major consequences).

SLIDE 16

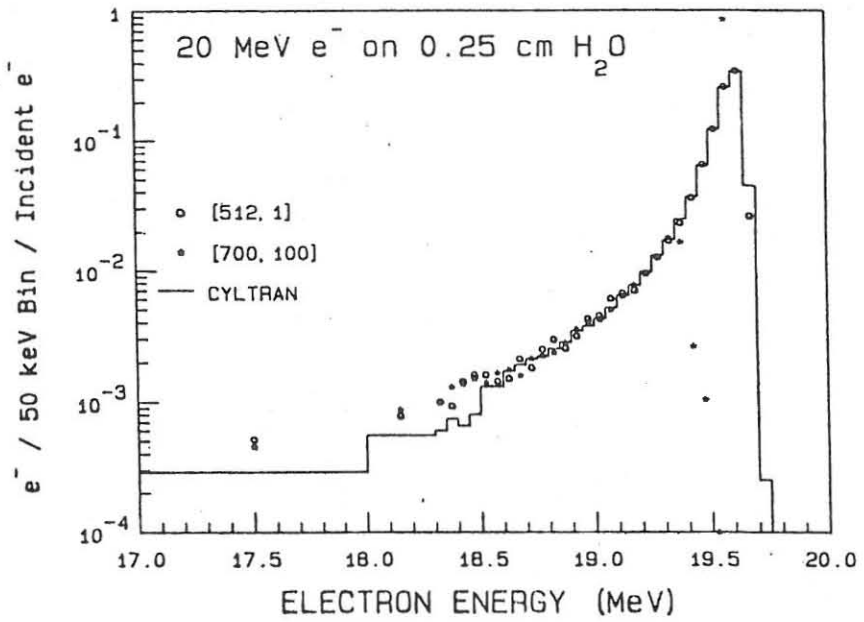


Caption: The electron energy spectrum as calculated by EGS after a beam of 20 MeV electrons has passed through an 0.25 cm slab of water. The data set used only allowed the creation of secondary electrons with kinetic energy greater than 1 MeV and hence there is a threshold 1 MeV below the peak corresponding to electrons which only lose energy in the slab via the continuous energy loss mechanism. A similar threshold occurs 100 keV below the peak. It corresponds to bremsstrahlung events creating 100 keV x-rays.

Note:

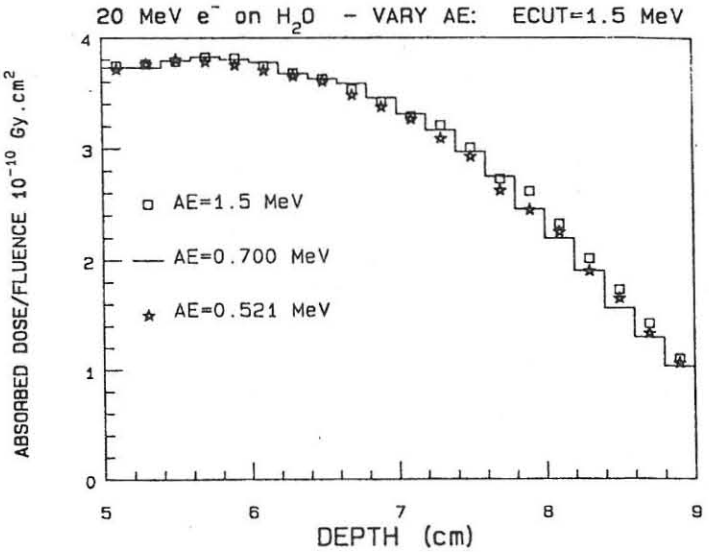
This spectrum is clearly not very realistic but in practice it often provides a sufficiently accurate model, see e.g. two slides on.

SLIDE 17



Caption: Electron spectra as in previous slide but for lower cutoff energies AE and AP and compared to the spectrum calculated with CYLTRAN (=ETRAN) which uses the Landau energy-loss straggling formalism. The EGS calculation for AE=512 keV, which explicitly includes all inelastic scatterings creating electrons greater than 1 keV, is in excellent agreement with the Landau approach to energy-loss straggling but takes considerably longer to calculate.
Note: The main concern when choosing values of AE and AP for a given value of ECUT is the effect on the energy-loss straggling.

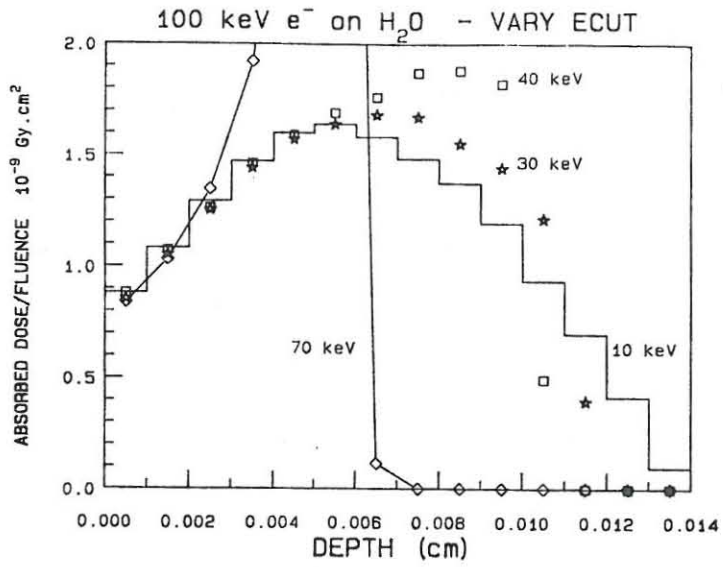
SLIDE 18



Caption: Depth-dose curve for broad parallel beams of 20 MeV electrons incident normally on a thick slab of water. In all cases electron histories were terminated when the energy fell below 1 MeV kinetic energy(ECUT=1.5 MeV). Different data sets with AE = 0.521, 0.700, and 1.5 MeV total energy were used. These data sets have considerably different energy loss straggling, as shown in the previous two slides; nonetheless the effect on the depth-dose curve is very little.

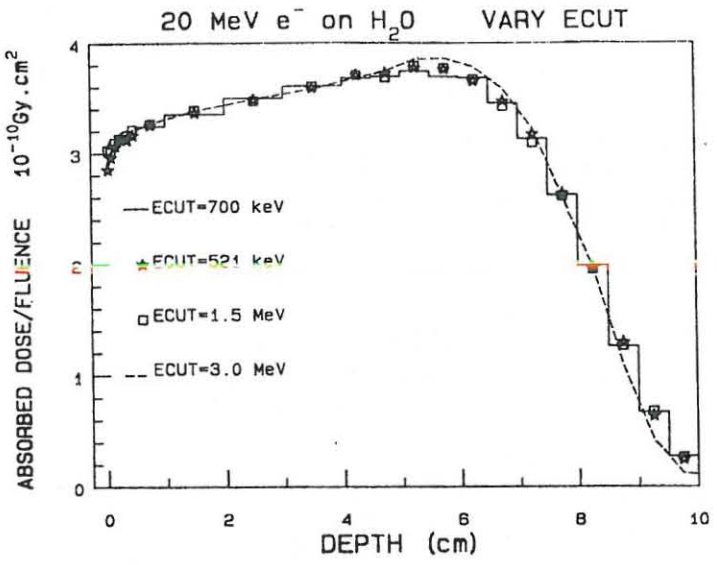
However, there are situations in which the results are very dependent on the energy-loss straggling and hence to AE. For example, for 100 keV electrons incident on a foil which has a thickness equal to 70% of the electrons CSDA range, the calculated number of electrons which get through the foil changes from 8.2+-0.3% for AE=512 keV to 18.6+-0.4% for AE=521 keV which has much less energy straggling.

SLIDE 19



Caption: Variation as a function of ECUT in the calculated depth-dose curve for 100 keV electrons incident normally on a slab of water. As an electron's energy falls below ECUT the history is terminated and thus when the residual range at the energy ECUT becomes significant with respect to the depth bins being used, the depth-dose curve becomes compressed. In all cases AE = 10 keV kinetic energy, ESTEPE=4%, EGS3.

SLIDE 20



Caption: Variation in the depth-dose curve as a function of ECUT for a 20 MeV broad parallel beam of electrons incident normally on a slab of water. AE=521 keV (total energy) for all cases. There appears to be no statistically significant variation until ECUT is greater than 1.5 MeV.

Selection of ESTEPE

ESTEPE the maximum fractional energy loss per electron step.

Not defined in EGS but can be set by adjusting the array TMXS.

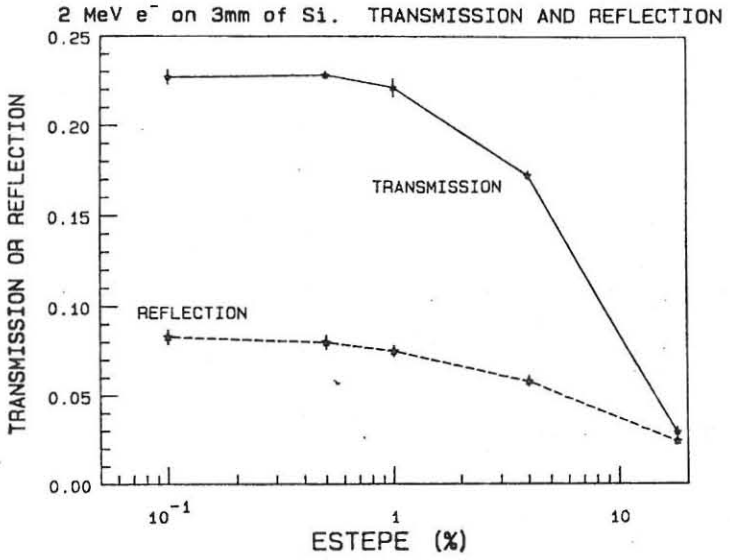
The default for low energy e^- in low Z materials is about 20%.

For completely accurate results, about 1% is needed for low Z materials.

The following subroutine should be called from the users code after HATCH has been called in order to set TMXS for a specified value of ESTEPE.

```
0  *                                                                      *
0  *                          $$$$$$$$$$                                  *
0  *                          $        $                                  *
0  *                          $ FIXTMX $                                  *
0  *                          $        $                                  *
0  *                          $$$$$$$$$$                                  *
0  *                                                                      *
0  SUBROUTINE FIXTMX(ESTEP,MEDIUM)$
0  *                                                                      *
0  *      THIS ROUTINE CHANGES THE STEP SIZE ALGORITHM USED IN EGS SO THAT *
0  *      THE STEP SIZE ARRAYS FOR TMXS CORRESPOND TO AN ARBITRARY, BUT    *
0  *      FIXED FRACTIONAL ENERGY LOSS ESTEP. ESTEP IS TYPICALLY 0.04.     *
0  *      THIS IS THE STEP SIZE ALGORITHM USED BY BERGER AND SELTZER IN ETRAN *
0  *      IT IS ONLY NECESSARY FOR LOW ENERGY ELECTRON PROBLEMS SINCE      *
0  *      TYPICALLY THE 200*TEFFO RESTRICTION ON TMXS IS MORE STRINGENT    *
0  *      THAN THIS 4% ENERGY LOSS FOR ELECTRONS WITH ENERGIES ABOVE A FEW MEV *
0  *                                                                      *
0  *      NOTE THAT THE $TMXS-OVER-RIDE MACRO IS STILL IN FORCE IN EGS. IT *
0  *      MAY BE DESIRABLE TO REMOVE IT?                                  *
0  *                                                                      *
0  *      THE ROUTINE CHANGES THE VALUES ONLY FOR THE MEDIUM 'MEDIUM'     *
0  *      AND IT SHOULD PROBABLY BE USED FOR ALL MEDIA IN A PROBLEM.      *
0  *                                                                      *
0  *      THE ROUTINE MUST BE CALLED AFTER HATCH HAS BEEN CALLED AND BEFORE *
0  *      THE SIMULATION IS BEGUN.                                        *
0  *                                                                      *
0  *      THE ROUTINE IS INDEPENDENT OF WHAT UNITS ARE BEING USED, AS LONG *
0  *      AS THEY ARE CONSISTENT( E.G. CM, RL OR GM/CM**2 )               *
0  *                                                                      *
0  *      NOTE THE ROUTINE WAS WRITTEN FOR THE 3/8/78 VERSION OF EGS3.    *
0  *      IN PARTICULAR, THIS MEANS THE SET INTERVAL MACRO HAS A DUMMY THIRD *
0  *      ARGUMENT AND THE MAPPING FEATURE HAS NOT BEEN IMPLEMENTED.      *
0  *                                                                      *
0  *      V01     DEC 10,1981 DAVE ROGERS NRCC                            *
0  *                                                                      *
0  '**********************************************************************'
0  ICOMIN/MEDIA,ELECIN/$
0  IF(MEDIUM.GT.$MXMED)<'ERROR'
1      OUTPUT MEDIUM!(///'0********* MEDIUM=',I4,' IN FIXTMX IS TOO LARGE')$
1      RETURN$>
0
0  'SET UP SOME VARIABLES FOR FIRST PASS THROUGH LOOP'
0
0  EI = EXP( (1.-EKE0(MEDIUM))/EKE1(MEDIUM))$'ENERGY OF FIRST TABLE ENTRY'
0  EIL = ALOG(EI)$
0  LEIL=1$'THIS IS EQUIVALENT TO $SETINTERVAL EIL,EKE,DUMMY$BUT AVOIDS ROUNDOFF'
0  $EVALUATE EDEDX USING EDEDX(EIL)$'PICK UP THE ELECTRON STOPPPING AT EI'
0  'NOW CALCULATE THE STEP REQUIRED TO CAUSE AN ESTEP REDUCTION IN ENERGY'
0  SI=ESTEP*EI/EDEDX$
0
0  'TABULATED ENERGIES ARE IN A FIXED RATIO - CALC LOG OF THE RATIO'
0  ERATIO=-1./EKE1(MEDIUM)$
0
0  NEKE=NEKE(MEDIUM)$'NUMBER OF ELEMENTS IN STORAGE ARRAY'
0  DO I=1,NEKE-1<
1      EIP1=EXP((FLOAT(I+1)-EKE0(MEDIUM))/EKE1(MEDIUM))$'ENERGY AT I+1'
1      EIP1L=ALOG(EIP1)$LEIP1L=I+1$'DESIGNED THIS WAY=$SETINTERVAL'
1      $EVALUATE EDEDX USING EDEDX(EIP1L)$SIP1=ESTEP*EIP1/EDEDX$
1
1      'NOW SOLVE THESE EQUATIONS                                       *
1      *                                                                *
1      *   SI   = TMXS1 * EIL   + TMXS0                                 *
1      *   SIP1 = TMXS1 * EIP1L + TMXS0                                 *
1      *                                                                *
1      *   FOR TMXS0(I,MEDIUM) AND TMXS1(I,MEDIUM)                      *
1
1      TMXS1(I,MEDIUM)=(SI-SIP1)/ERATIO$
1      TMXS0(I,MEDIUM)=SI-TMXS1(I,MEDIUM)*EIL$
1
1
1      'TRANSFER VALUES FOR NEXT LOOP'
1      EIL=EIP1L$SI=SIP1$
1      >
0  'NOW PICK UP LAST TABLE ENTRY WHICH APPLIES ONLY TO LAST ENERGY'
0  TMXS0(NEKE,MEDIUM)=TMXS0(NEKE-1,MEDIUM)$
0  TMXS1(NEKE,MEDIUM)=TMXS1(NEKE-1,MEDIUM)$
0  RETURN$END$
```

SLIDE 22



Caption: Transmission and reflection factors for a 2 MeV beam of electrons incident normally on a 3 mm thick slab of silicon as a function of ESTEPE. The default EGS case is shown as 18%. The default calculations take 0.08 s/history whereas the 1% calculations take 0.55 s/history and the 0.1% calculations take 4.8 s/history.

Notes:

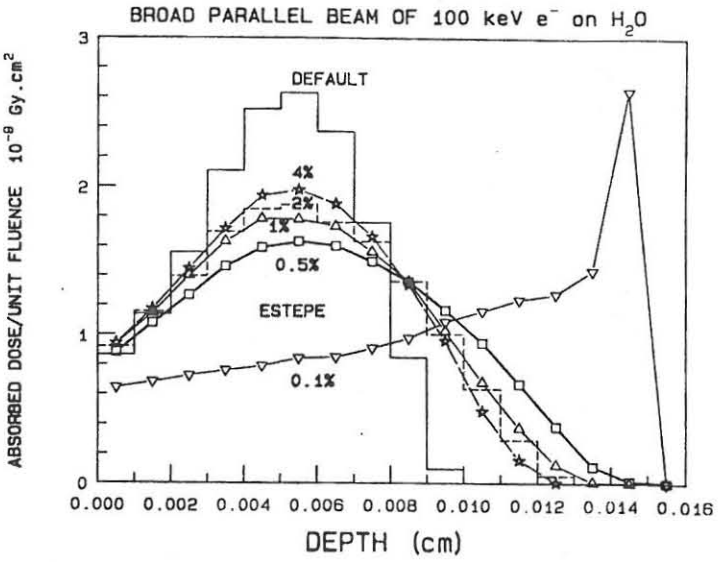
i) ESTEPE clearly has a dramatic effect on the results and the timing.

ii) ETRAN uses a comparable algorithm and energy loss per scattering step of around 1% or less.

iii) The basic cause of this ESTEPE dependence appears to be related to the difference between the curved pathlength and straight pathlength taken by the electron in the simulation. The approximate correction technique used in EGS appears to be wrong. By going to suffciently small steps the problem is avoided since there is no difference between the true curved pathlength and the straightline pathlength. ETRAN and other Monte Carlo codes make no correction for this difference and so they must use very short steps too.

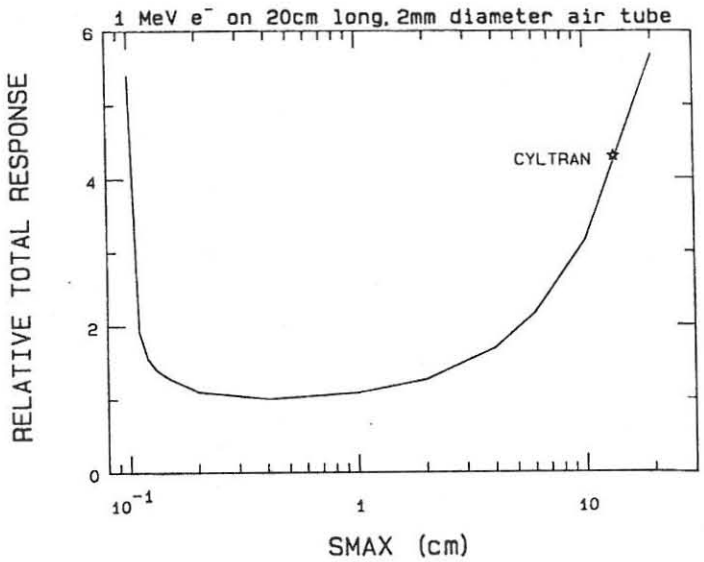
See Rogers 1984b for more discussion.

SLIDE 23



Caption: Absorbed dose to water vs depth as a function of the maximum continuous energy loss per step for 100 keV electrons incident on a water slab. The step-size has a 50% effect on the peak value in the depth-dose curve. As ESTEPE goes below about 1% the multiple scattering formalism is turned off more and more until it is completely turned off for ESTEPE=0.1%.
Note:
The problem of turning off the multiple scattering if too small a step-size is used makes life difficult in high precison work since there is only a narrow range of ESTEPE values which give the "correct" result. See Rogers 1984b for a discussion of this problem.

SLIDE 24



Caption: Dose delivered to a 2mm diameter, 20cm long tube of air by a pencil beam of 1 MeV electrons incident on the axis as a function of SMAX, the maximum length of each electron step. The values are normalized to the dose for SMAX=2mm. The value calculated with CYLTRAN (=ETRAN) is shown on the same curve although there is no corresponding parameter.
Note:
This is a dramatic demonstration of the "thin slice effect" discussed by Bielajew et al,1984. It is related to the difference between the curved pathlength and the straight line pathlength and is only important whenever one or two dimensions of the volume of interest are comparable to the electron step-size, e.g. very thin slices in a phantom or an ion chamber cavity.

SLIDE 25

Considerations in Parameter Selection

AE,AP -energy loss straggling, lower limit on ECUT,PCUT

ECUT,PCUT-residual range of particles

ESTEPE -pathlength correction, multiple scattering

SMAX -to avoid thin slice effect

SLIDE 26

Variance Reduction Techniques

i) exponential transformation of photon pathlength

ii) forced photon interactions

iii) range rejection of electrons

iv) use of stored pre-computed results

v) optimize ECUT

Note: For certain cases, a smaller ECUT can increase the efficency of the calculation (e.g. ion chamber response -see Bielajew et al,1984).

SLIDE 27

i)Exponential Transformation of Photon Pathlength

use:

$$mfp = - B.\ln R_i$$

$$WT' = WT.B.e^{-mfp.C.\cos Z}$$

with

$$B = 1./(1.-C.\cos Z)$$

where C is an input variable, mfp is the number of photon mean free paths, R_i is a random number from 0 to 1, and cosZ is the direction cosine w.r.t. the Z axis.

$C < -1$ pathlength shortening -Study Buildup

$0 < C < 1$ pathlength stretching -shielding

SLIDE 28

Calculational Efficiency vs C for 7-MeV Photons on a 30cm slab of Water

C	Histories 10^3	Relative Efficiency on Calculated Dose 0-0.25cm	6-7cm	10-30cm
0	100	11	1.4	0.16
-1	70	11	1.4	0.04
-3	55	7.8	1.2	0.25
-6	50	4.0	0.5	2.3

Notes:
i) Calculational efficiency is taken here as the square of the uncertainty on the calculated doses for a series of calculations using the same CPU time.
ii) This is a very common technique in neutron monte carlo work.
iii) $C < -1$ increases the number of photon interactions near the surface but reduces their weight. For a depth-dose curve we score the weightxenergy deposited. The effect of scoring more electrons, each with a reduced weight, is to reduce the statistical variation although we also increase the computing time per history. It is not always clear how much improvement there will be.
iv) Its effectiveness is very problem dependent. Here the efficiency increases by a factor of 3 near the surface as C increases but the efficiency at depth worsens since we are decreasing the number of interactions there.
v) $0 < C < 1$ is very useful in deep shielding problems.

SLIDE 29

ii) Force Photon Interactions

For a photon with a given energy, location and direction, find X, the number of mean free paths it must traverse before leaving the object of interest. Then use:

$$mfp = -\ln(1-R_i(1-e^{-X}))$$

$$WT' = WT \cdot (1-e^{-X})$$

where R_i is a random number from 0 to 1 and mfp is the number of mean free paths to traverse before interaction (note mfp $\neq$ X).

Note:
i) In general the only difficulty is finding X. However we have developed a general purpose macro which can be used in any EGS geometry to determine X and then mfp and WT'. This works in the general case because it calls the users routine HOWFAR to determine certain characteristics of the geometry (see next page)
ii) The improvements in calculational efficiency are very problem dependent. Define efficiency as the total computing time required to achieve a certain statistical uncertainty on the result of interest.

a)In calculating the response to ^{60}Co of an ion chamber in which 6% of photons would normally interact, forcing improves efficiency by 60% (see Bielajew et al,1984).

b)In calculating the dose from ^{60}Co in an 0.001cm slice of tissue in which 6×10^{-5} of the photons interact, the efficiency improves by a factor of 2600 (see Rogers and Bielajew, 1984).

c)In calculating the dose from ^{60}Co interacting in 100 cm of air the efficiency improves by a factor of 7.

SLIDE 30

iii) Range Rejection of Electrons

Terminate any electron which is greater than its CSDA range from:

a)the region of interest (e.g. an ion chambers cavity)

or b)any region boundary (specified by DNEAR).

Notes:
i) For ion chamber calculations, method a) improves the calculational efficiency by a factor of 4 when a good estimate of the CSDA residual range is used.
ii) Technique b) can be crudely implemented in EGS in a general fashion for low energy electrons. Since the electron stopping power dE/dx is initially monotonically decreasing with energy, then the range is always less than 1/(dE/dx). Thus one can safely terminate the electron history whenever 1/(dE/dx) is less than DNEAR (the distance to the nearest boundary as returned by HOWFAR).
iii) Implementing these techniques ignores the possibility of bremsstrahlung emmission by the terminated electron if it were allowed to slow down.

```
"MACRO WHICH FORCES A PHOTON INTERACTION TO OCCUR WITHIN THE VOLUME"
"OF INTEREST WITH THE BOUNDARY BEING DEFINED AS INSIDE REGION 1,I.E."
"THE PHOTON IS FORCED TO INTERACT BEFORE HITTING REGION 1"
"INSERT THE MACRO RIGHT AFTER THE $RANDOMSET RNNO35; STATEMENT IN PHOTON"
"***** WARNING! DELETE ALL COMMENTS INSIDE THE MACRO BEFORE USING.*****"

%'$SELECT-MEAN-FREE-PATHS;'=';

"FIRST STORE ANY VARIABLE THAT CAN BE CHANGED BY SUBROUTINE HOWFAR."
DUMU=USTEP;
DUMX=X(NP);DUMY=Y(NP);DUMZ=Z(NP);
IRODUM=IROLD;IRNDUM=IRNEW;IRDUM=IR(NP);MEDDUM=MEDIUM;
IDUM=IDISC;

PATHL=0.0; "ZERO THE MEAN FREE PATH COUNTER"
MEDTMP=0; "ASSUME THE INITIAL MEDIUM IS VACUUM"

"NOW LOOP THROUGH ALL REGIONS ALONG THE PHOTON'S LINE OF FLIGHT"
LOOP<
USTEP=VACDST; "ASSUME A LARGE DISTANCE TO THE NEXT REGION, HOWFAR WILL TRUNCATE"
IROLD=IR(NP);MEDIUM=MED(IROLD); "STORE THE REGION & MEDIUM NUMBERS THAT MAY"
                                "BE CHANGED BY HOWFAR"
IF(MEDTMP.NE.MEDIUM)<"THE MACROSCOPIC CROSS SECTION CHANGES ONLY IF THE"
                     "MEDIUM CHANGES"
MEDTMP=MEDIUM;
IF(MEDTMP.NE.0)<"TRANSPORT THROUGH VACUUM DOES NOT INCREMENT THE NUMBER"
"OF MEAN FREE PATHS TRAVERSED-DELTAP IS GAMMA MEAN FREE PATH IN THIS MEDIUM"
$SET INTERVAL GLE,GE,GEM;$EVALUATE DELTAP USING GMFP(GLE);;>
>
CALL HOWFAR; "SET USTEP AND SWITCH IRL,MEDIUM TO THE NEXT REGION"
IF(MEDTMP.NE.0)PATHL=PATHL+USTEP/DELTAP; "INCREMENT THE # OF MEAN FREE PATHS"
IF(IRNEW.EQ.1) EXIT; "EXIT THE LOOP IF THE PARTICLE IS LEAVING THE GEOMETRY"

"DO A FAKE TRANSPORT TO GET THE CORRECT COORDINATES FOR THE NEXT PASS THROUGH"
"THE LOOP"
IR(NP)=IRNEW;
X(NP)=X(NP)+USTEP*U(NP);
Y(NP)=Y(NP)+USTEP*V(NP);
Z(NP)=Z(NP)+USTEP*W(NP);
> "END OF THE PATHLENGTH SUMMATION LOOP"

"RESTORE THE VARIABLES THAT MAY HAVE BEEN ALTERED BY HOWFAR"
USTEP=DUMU;
X(NP)=DUMX;Y(NP)=DUMY;Z(NP)=DUMZ;
IROLD=IRODUM;IRNEW=IRNDUM;IR(NP)=IRDUM;MEDIUM=MEDDUM;
IDISC=IDUM;

"CALCULATE THE PROBABILITY THAT THE PHOTON INTERACTS"
GWAIT=1.-EXP(-PATHL);

"ADJUST THE PHOTON'S WEIGHT SO THAT PROBABILITY IS CONSERVED"
WT(NP)=WT(NP)*GWAIT;

"RANDOMLY SELECT THE NUMBER OF MEAN FREE PATHS UNTIL THE INTERACTION THAT"
"IS GUARANTEED TO BE IN THE GEOMETRY"
DPMFP=-ALOG(1.-RNNO35*GWAIT); "THE # OF MEAN FREE PATHS CORRECTLY SAMPLED"
 "RNNO35 IS A RANDOM NUMBER BETWEEN 0 AND 1"

' "END OF THE FORCING-INTERACTIONS MACRO"
$
```

iv) Fold Pre-computed Results

$$\text{Dose}(d) = \int^{E_{max}} \Phi(E)\, K_E(d)\, dE$$

$\Phi(E)$: incident planar fluence

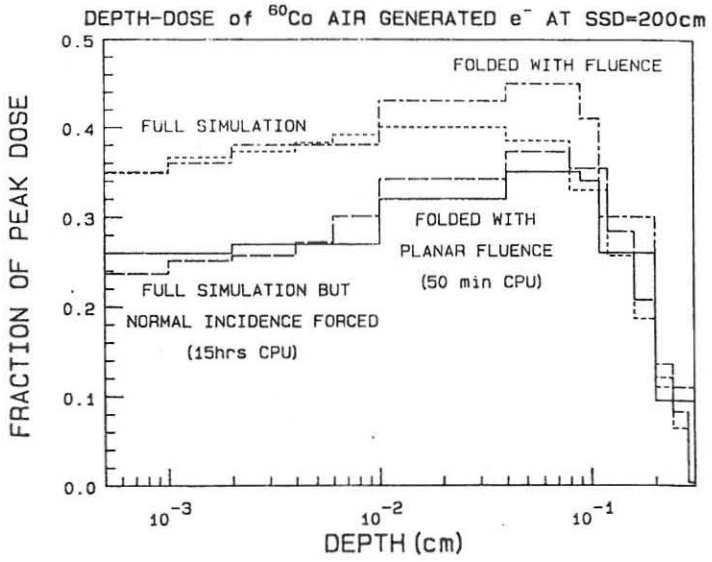
$K_E(d)$: precomputed conversion factors from incident fluence to absorbed dose at depth.

Notes:

In many calculatons we want the dose at a depth in a phantom due to electrons and photons generated in a complex geometry. Only a few particles get to the phantom so the dose calculated by tracking them in the phantom is very inaccurate. By just scoring the particle fluence as it reaches the phantom surface, and later folding it with pre-computed depth-dose curves, one makes an large gain in computing efficiency; the statistical uncertainty in the dose becoming comparable to the statistical uncertainty in the fluence.

The method introduces several approximations because it uses pre-computed conversion factors $K_E(d)$ (e.g. from Rogers,1984a) which are for broad parallel beams of particles incident normally on a tissue phantom. As we have implemented this procedure, we have not considered electrons below 100 keV and so we underestimate the dose in the first 12 $mg.cm^{-2}$.

SLIDE 32



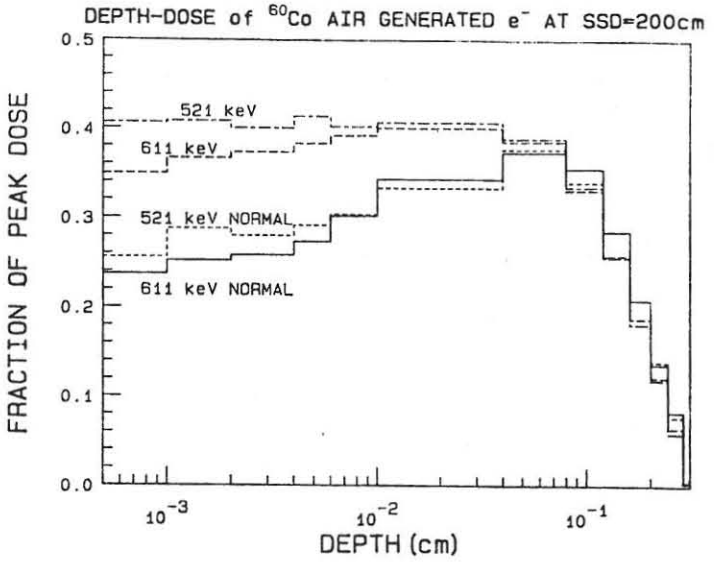
Caption: Comparison of various methods of computing the central axis dose in a tissue phantom due to electrons generated by a point source ^{60}Co beam hitting the phantom at SSD = 200 cm (beam diameter=35 cm at SSD=80cm). ECUT=611 keV total energy in all cases. The curves labelled "Full Simulation" tracked the electrons and photons through the air and into the phantom. In the lower of these, the electrons were artificially adjusted to have normal incidence at the phantom surface, thus reducing the surface dose, much of which is due to highly scattered low energy electrons. The curves marked "Folded" were done simulating the electron transport in the air and scoring either the planar fluence or the true particle fluence (which includes a 1/cosZ weighting factor) at the phantom surface.

Notes:

The curve we usually use is that folded with the planar fluence and it is, as expected, in excellent agreement with the normally incident full simulation. The result obtained by folding with the true fluence is more accurate near the surface since there it more properly accounts for the angular incidence; however it does not take into account the contraction of the depth-dose curves due to the angular incidence and hence substantially overestimates the dose at depth.

The statistical uncertainties are smaller for the folded calculations than for the full simulation and thus the ratio of calculational efficiencies is even greater than shown by the ratio of CPU times.

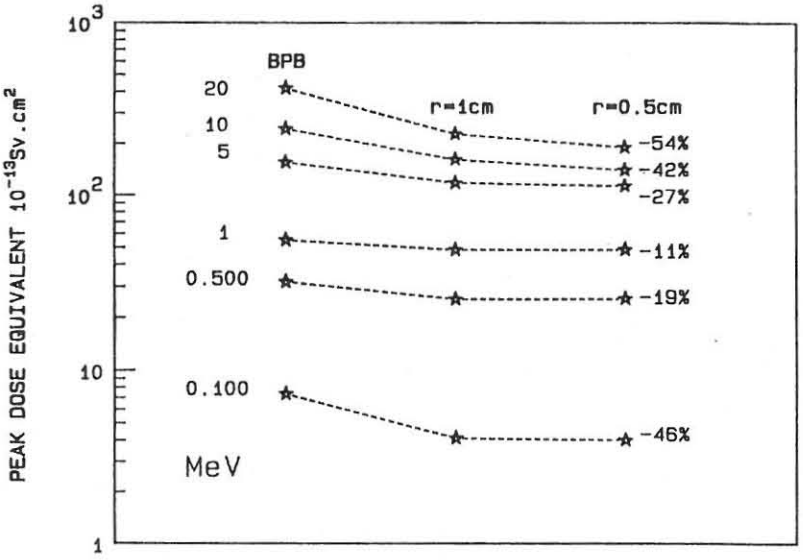
SLIDE 33



Caption: Same physical situation as in the previous slide but here we look at results of the full simulation as we change ECUT. The inclusion of electrons with kinetic energies between 10 and 100 keV increases the dose for depths down to 10mg.cm^{-2}, making less difference when normal incidence is forced at the phantom surface. Note that only 100 keV electrons generated within 13 cm of the phantom can reach it.

SLIDE 34

DECREASE IN PEAK DOSE FOR NARROW BEAMS



INCIDENT BEAM RADIUS

Caption: The percentage values on the right are the decrease at that photon energy between the peak dose in a broad parallel beam and that in a beam of radius 0.5 cm. This shows that using coefficients for broad beams can introduce overestimates of up to a factor of 2 when the beam is actually very narrow.

SLIDE 35

Summary of Variance Reduction Techniques

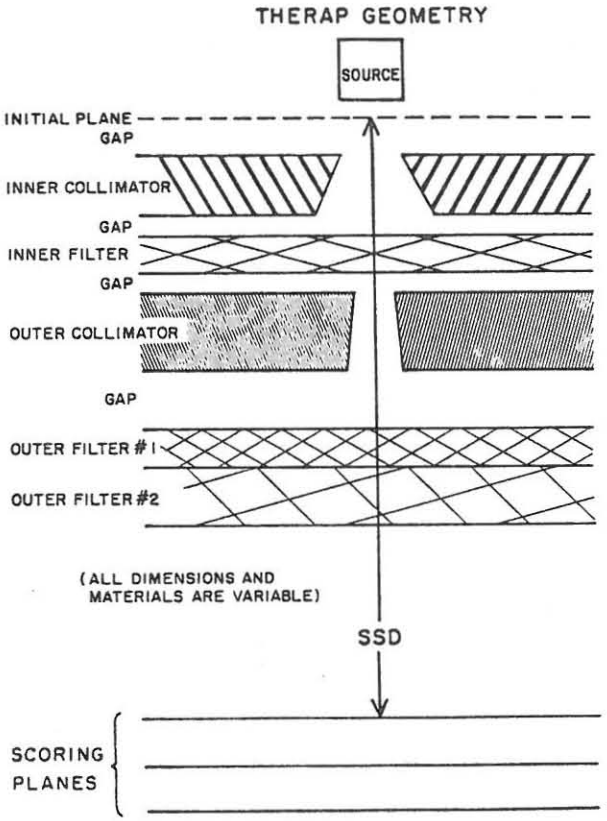
i) Exponential transformation of photon pathlength -factor of 2 or 3 in the buildup region

ii) Force photon interactions -2,7 or 2600 times more efficient

iii) Range rejection of Electrons - factor of 4 in a cavity chamber cal'n.

iv) Fold pre-computed results - more than 10 times as efficient but introduces approximations.

SLIDE 36



This is the geometry we have modeled to study electron contamination from a ^{60}Co therapy source. We have implemented most of the variance reduction techniques discussed above and added a few further tricks. We start with the encapsulated ^{60}Co source. By compressing into one 32 bit integer all the information concerning each particle leaving the front face of the capsule, we store the results of a 24 hour simulation of the source capsule and reuse the 2×10^6 electron and photon histories as an input to the second stage of the calculation which simulates the therapy head. Range rejection is done in all the filters and collimators. All primary photons leaving the source can be optionally forced to interact before leaving the outer filter. This is used as a break point. The particles leaving the head are reused as inputs for the simulation of the transport to the scoring surfaces at different SSDs. Once again primary photons can be forced in this last stage through the air. The fluence (planar or true) is determined at each SSD as a function of radius and depth-dose curves are determined using pre-computed depth dose curves.

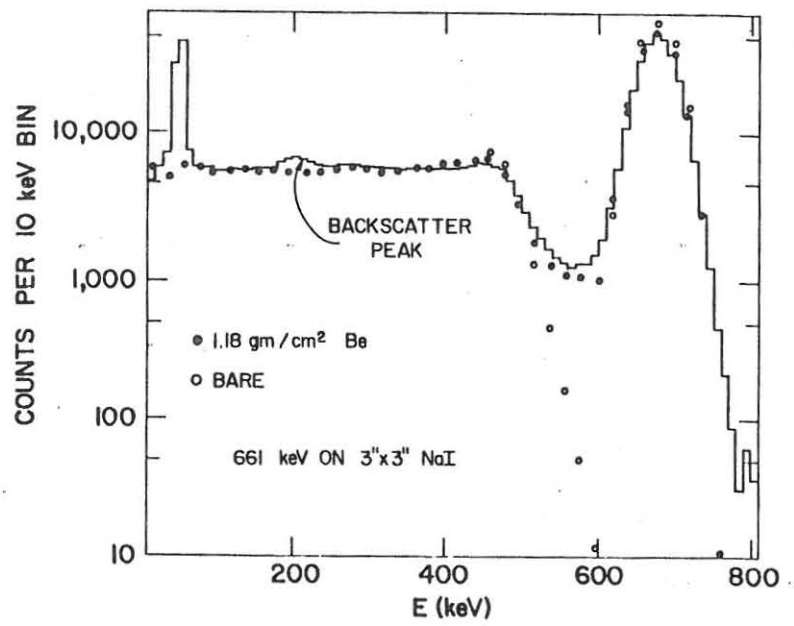
SLIDE 37

Benchmark Comparisons

A major advantage of using a standard code is that benchmark comparisons which have been done for it produce confidence in its ability to give accurate results for your problem. Unfortunately they don't guarantee that you have used it accurately.

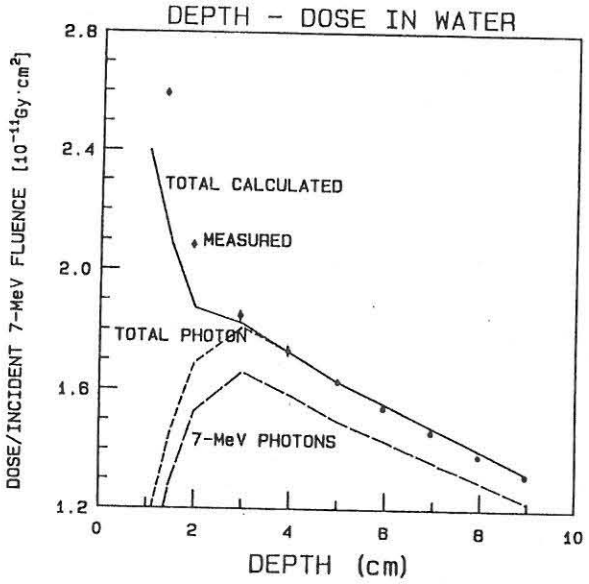
Note:
In the following slides we present a series of benchmark comparisons of EGS against experimental data or other calculations. They are drawn from our work at NRCC and involve low energy applications in which electron transport plays an important role. There are many other benchmark examples for higher energies. We would appreciate having our attention drawn to other comparisons.

SLIDE 38



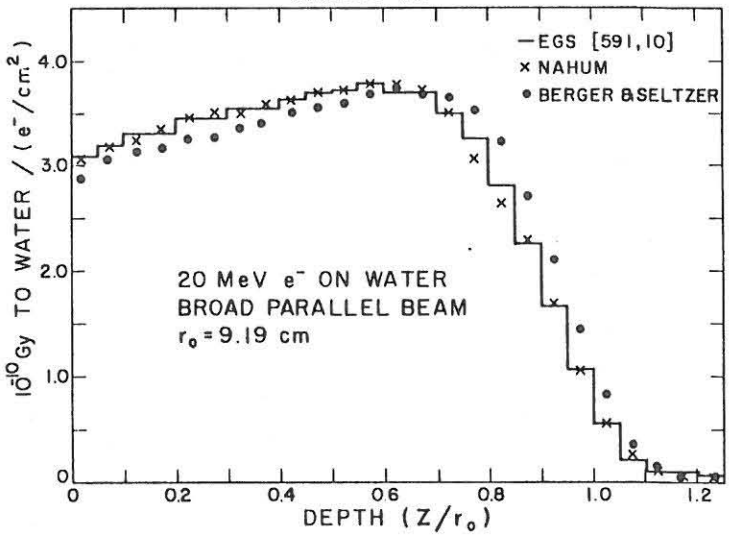
Caption: Measured and calculated response of a 3"x3" NaI detector with a $1.18 g.cm^{-2}$ beta absorber on its face to 3.07×10^{7} 661-keV photons from an isotropic source 10 cm away in a lead box. The open circles represent the calculations with no absorber. The inclusion of the absorber accounts for the filling in of the valley. There are no free parameters in the comparison. The calculations did not take into account the lead box and thus did not produce a backscatter peak. The low energy peak is from an associated X-ray peak in the source which was not included in the calculations (taken from Rogers, 1982). Agreement within 2% has also been obtained between the measured and calculated efficiency of a 5"x4" NaI to 6.13 MeV photons (Mach and Rogers 1983).

SLIDE 39



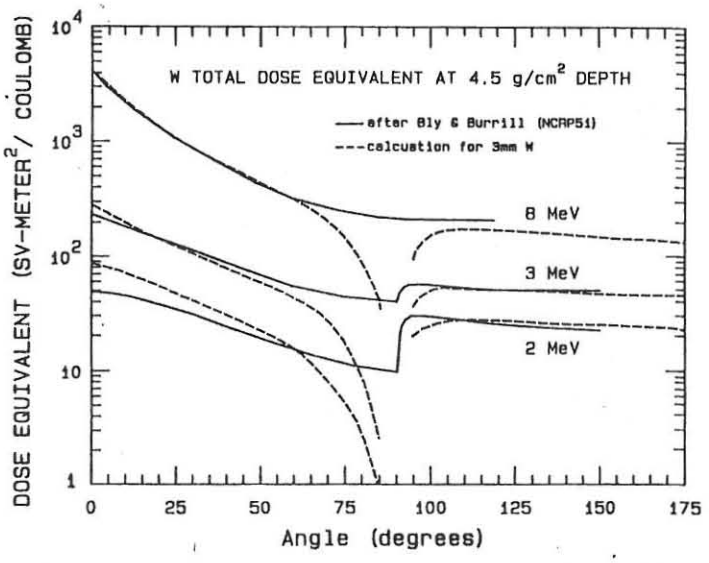
Caption: A comparison of the measured absorbed dose vs depth in a 16x16x30 cm water phantom and that calculated with EGS for a nearly monoenergetic 7-MeV photon beam and the associated electron contamination. The ion chamber calibration factor was assumed to be depth independent. The comparison at 5 cm is absolute and there is agreement within 1+-3%.
The details of the comparison are complex but basically confirm the fluence to absorbed dose factors calculated with EGS for 7-MeV photons.
(Taken from Mach and Rogers,1984).

SLIDE 40



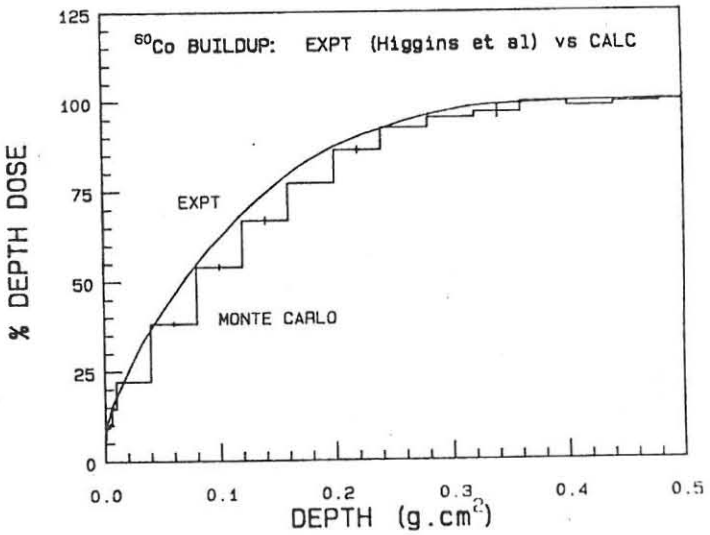
Caption: A comparison of various calculations of the depth-dose curve for broad parallel beams of 20 MeV electrons incident on a water phantom. The differences between the ETRAN and EGS results persist at other energies in water (but not, e.g. in copper) and the good agreement with Nahum's results also persists at other energies. (Figure from Rogers,1984a, other results from Berger and Seltzer 1969 and Nahum, 1975).

SLIDE 41



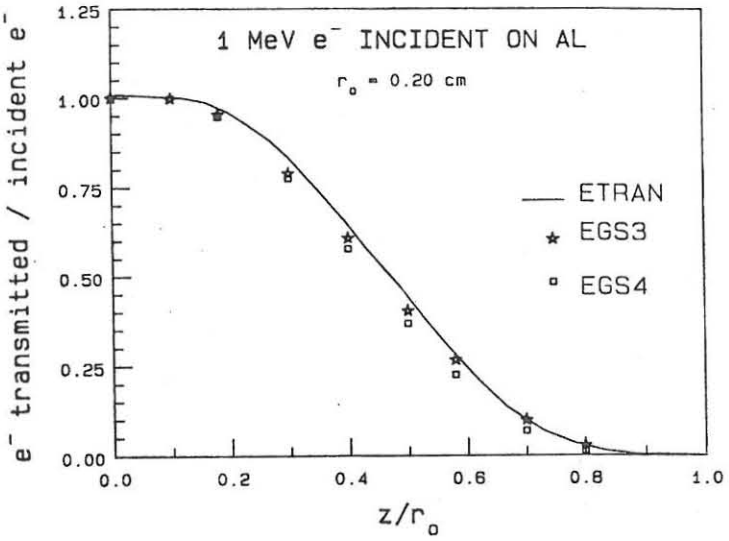
Caption: Comparison of calculated results to experimental results presented in NCRP Report 51 for the angular distribution of dose from 8,3 and 2 MeV electrons incident on 5.79 $g.cm^{-2}$ of W. EGS is known to overestimate the bremsstrahlung cross-section for low-energy electrons because it ignores the Elwert correction factor. The agreement here for 8 MeV and at higher energies as well is very satisfactory. The dip at 90^{o} is because the calculations are for a semi-infinite target. (Taken from Ewart and Rogers 1983).

SLIDE 42



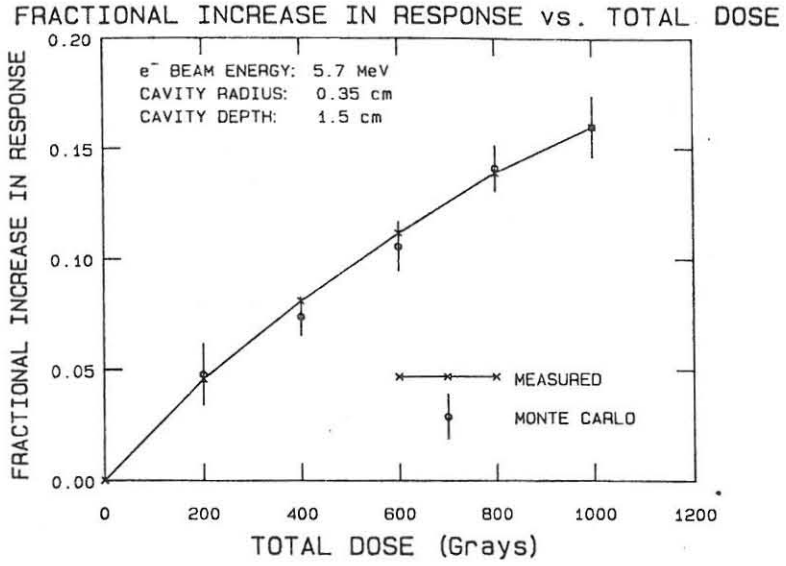
Caption: Comparison of a measured contaminant free buildup curve for a zero area ^{60}Co beam incident normally on a phantom (from Higgins et al,1984) with the calculated depth-dose curve for a broad parallel beam of ^{60}Co incident on a water phantom (radiation scattered in the source is not included in the calculations, from Rogers and Bielajew,1984).

SLIDE 43



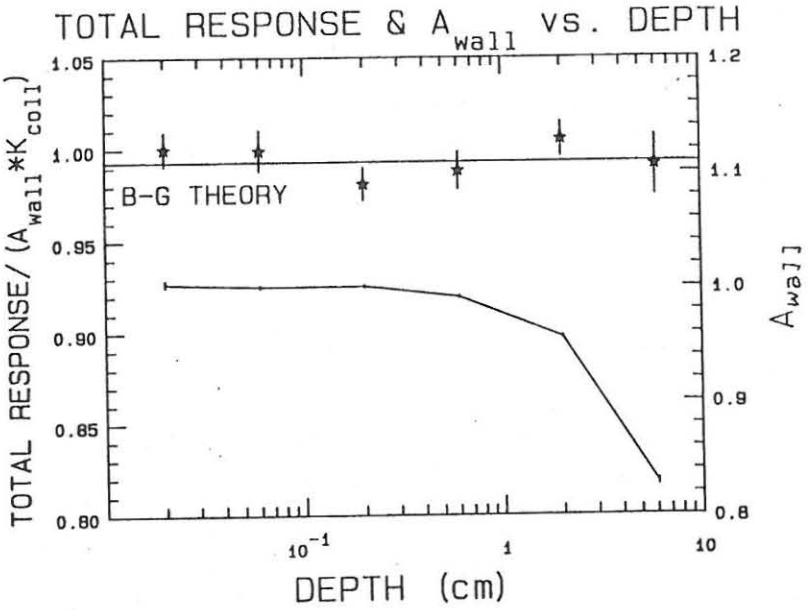
Caption: The fraction of 1 MeV electrons transmitted by various thicknesses of aluminium as calculated by EGS3 and EGS4 (with AE=521 keV,ECUT=551 keV) and ETRAN (Seltzer and Berger, 1974). The slight difference between EGS and ETRAN for calculated transmission factors persists in other cases as well. The experimental data is somewhat scattered but with a slight preference for the ETRAN results.

SLIDE 44



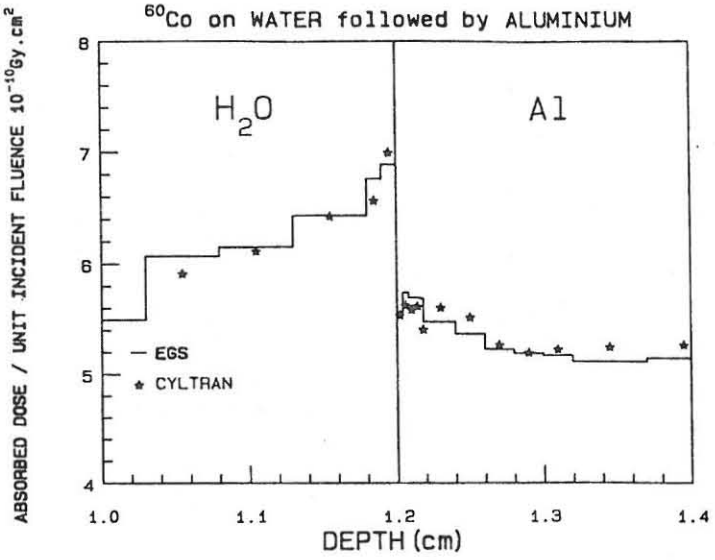
Caption: A comparison of the measureed and calculated increase in response measured in a cavity inside a PMMA phantom vs the total amount of irradiation by electrons. Because the phantom is an insulator, the incident electrons can remain in the phantom after they lose their energy. This sets up electric fields that can focus the electrons into the cavity producing an extra dose there. The EGS system has been modified to allow for transport in an electric field. In this case the electron beam energy is 5.7 MeV, the cavity is 0.35 cm in radius at a depth of 1.5 cm in the phantom (from Rawlinson et al,1984).

SLIDE 45



Caption: Calculated response to a ^{60}Co beam incident on the flat face of an 0.5 $g.cm^{-2}$ carbon walled pancake ion chamber, 1 cm radius, as a function of chamber depth. The calculated values agree within 1% with the values predicted by Bragg-Gray cavity theory (from Rogers et al, 1984). AE=ECUT=521 keV total energy, ESTEPE=1%.

SLIDE 46



Caption: Comparison of dose deposition at an aluminium-water interface irradiated by ^{60}Co as calculated by EGS and CYLTRAN (ETRAN). These type of interface calculations are very sensitive to ESTEPE which was 1% in this case.

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