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Benchmark Calculations for EGS5 *

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Abstract

In the past few years, EGS4 has undergone an extensive upgrade to EGS5, in particularly in the areas of low-energy electron physics, low-energy photon physics, PEGS cross section generation, and the coding from Mortran to Fortran programming. Benchmark calculations have been made to assure the accuracy, reliability and high quality of the EGS5 code system. This study reports three benchmark examples that show the successful upgrade from EGS4 to EGS5 based on the excellent agreements among EGS4, EGS5 and measurements. The first benchmark example is the 1969 Crannell Experiment to measure the three-dimensional distribution of energy deposition for 1-GeV electrons shower in water and aluminum tanks. The second example is the 1995 Compton-scattered spectra measurements for 20-40 keV, linearly polarized photon by Namito et. al., in KEK, which was a main part of the low-energy photon expansion work for both EGS4 and EGS5. The third example is the 1986 heterogeneity benchmark experiment by Shortt et. al., who used a monoenergetic 20-MeV electron beam to hit the front face of a water tank containing both air and aluminum cylinders and measured spatial depth dose distribution using a small solid-state detector.

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INTRODUCTION

In the past few years, EGS4 [1] has been upgraded to EGS5 in the following areas: low-energy electron physics[2,3], low-energy photon physics [4,5], the PEGS cross section generation, and the change of coding from Mortran to Fortran language (by Nelson). Therefore, benchmark calculations have been made in various transition phases to assure the accuracy, reliability and high quality of EGS5. This paper reports the three benchmark studies that show the successful upgrade from EGS4 to EGS5, based on the agreements among EGS4, EGS5 and the benchmark measurements. The three benchmark examples, which have been important in testing all versions of EGS4 Code System, are:

1) Shower Experiment, in which 1-GeV electrons hit water and aluminum tanks and three-dimensional distribution of energy deposition were measured [6].
2) Polarization/Doppler Experiment in which 20-40 keV, linearly polarized photons hit carbon and copper targets and the Compton-scattered spectra were measured [7].
3) Heterogeneity Experiment in which 10 and 20 MeV broad electron beam hit the front face of a water tank containing both air and aluminum cylinders. The depth dose distribution and lateral dose distribution at various depths were measured [8].

KEY PARAMETERS IN EGS CALCULATIONS

Table 1 summarizes the input values for the key EGS parameters in the three benchmark examples. The EFRACH, EFRACL, ESTEPE and ESTEPE2 are related to the new EGS5 electron transport mechanics [2]. In the polarization benchmark study [5], which involves the photon physics of polarization, bound Compton scattering, and Doppler broadening, the PEGS inputs for IBOUND / INCOH / ICPROF are 1 / 1 / -3, respectively.

Table 1. Values for the key EGS parameters in benchmark examples.

EGS5 Parameters	**EFRACH / EFRACL**	**ESTEPE / ESTEPE2**
Values	0.05 / 0.20	0.1 / 0.2
Benchmark	**AE / UE**	**AP / UP**
Shower	0.611 / 1000.1	0.001 / 1000
Polarization	0.512 / 0.711	0.001 / 0.200
Heterogeneity	0.711 / 21.0	0.100 / 20.0

1) In polarization benchmark, PEGS inputs for IBOUND / INCOH / ICPROF are 1 / 1 / -3.

BENCHMARK RESULTS

The three benchmark experiments and EGS comparison results, as well as the timing comparison, will be shown in the following sections. In the comparison figures, EGS4.4 is already a Fortran 77 version with PEGS4 cross generation on the fly and with low-energy photon physics included, while EGS5 is a version with the addition of low-energy electron physics.

Shower Experiment

In the Crannell shower experiment [6], a 1-GeV electron beam was incident on 8000 liters of distilled water in a stainless steel tank (140x140x460 cm^3) or an Al block. Measurements of the radial energy deposition (MeV/cm^3/electron) were made at various depths of the targets using a scintillation detector. This is an important benchmark to test shower development. EGS4 has been shown to be in excellent agreement, on an absolute basis, with the measurements [9].

Figure 1 shows the EGS5 user input file (using the format of getRTZ user code) for Shower experiment, which prescribes 2 media, the radii of cylinders, the parallel planes at various depths, the electron beam parameters, number of cases, and various transport and physics switches/values. Note the values of ESTEPE (0.1) and ESTEPE2 (0.2) in the last row.

Figure 2 shows the PEGS input for Shower experiment in EGS5 calculations. It is similar to EGS4, except the addition of EFRACH (0.05) and EFRACL (0.2) values for both media.

Figure 3 compares the depth dose profile in central axis (1-cm-radius) between the experiment, EGS4.4, and EGS5 for the phantom of water (top figure) and Al (bottom figure). The agreement is within the experimental uncertainty. A complete benchmark check of the radial energy deposition profiles has also been made successfully, but the results are not shown here.

Polarization Experiment

Figure 4 shows the set-up for the Polarization/Doppler Experiment [7], which is an important benchmark to test the low-energy photon physics. The 40-keV photons hit an inclined carbon or a copper disc and the scattered photon spectra at 90-degrees (both vertical and horizontal) were measured with High Purity Ge detectors (HPGe) at about 0.4 m. Because the photons from the wiggler are linearly polarized, the scattered photon intensities at vertical and horizontal planes are different and the average of the two spectra is used in the comparison.

Figure 5 shows the EGS5 user input file (using the format of getRTZ user code) for Polarization Experiment. Note that the three switches for polarization, Bound Compton and Doppler broadening effects (ipolarsw, incohrsw and iprofrsw), as well as those important for low-energy photon transport and physics, were activated.

Figure 6 shows the EGS5 PEGS input for Polarization Experiment Note that the three switches for Bound Compton and Doppler broadening effects (IBOUND=1, INCOH=1, ICPROF=-3) were activated.

Figure 7 shows the agreement of the 90^o-scattered Compton spectra for the targets of carbon (top figure) and copper (bottom figure) between the experiment, EGS4.4 and EGS5. Note that the calculated spectra have been broadened by the resolution of the HPGe using a post-processing routine.

Heterogeneity Experiment

Figure 8 shows the set-up for the Heterogeneity Experiment [8], which is one of the most critical benchmark problem in medical physics to test the low-energy electron physics and transport in a Monte Carlo code. The 20-MeV (or 10-MeV) electron broad beam hit the front face of the water phantom, in which a small cylinder disc (air or aluminum) may be inserted at a distance of 2-mm (or 2-cm) behind the front face. The EGS5 user input files and the PEGS file are similar to those shown for Shower and Polarization Experiments.

Figure 9a shows the agreement of the depth dose curves at central axis for the 3 cases of 20-MeV electron and 2-mm-gap between experiment, EGS4.4 and EGS5. The figure numbers indicated on the figures are those in the original paper [8] so readers can check easily if needed. Figure 9b shows the corresponding radial dose profiles at various depths behind the air disc, while Figure 9c compares the radial dose profiles at various depths behind the Al disc. The discrepancy between measurements and calculations for the dose near the boundary between water and inserted disc was due to the larger spatial bin in the EGS calculations than the detector size.

Similar to Figures 9a, 9b and 9c, Figures 10a, 10b and 10c show the benchmark results for the case of 10-MeV electron at 2-mm gap. Similar to Figure 9a (2-mm-gap), Figures 11 and 12 compares the depth dose curve for the cases of 20-MeV and 10-MeV electron, respectively, at 2-cm gap.

Timing Comparison

The new low-energy electron transport mechanics should make EGS5 run faster than EGS4 [2,3]. Table 2 summarizes the time comparison between EGS4.4 and EGS5 for the three benchmark examples. EGS5 takes less time than EGS4.4, particularly for the Heterogeneity Experiment, in which low-energy electron transport is important (a factor of 5 gain in speed for EGS5 in this case).

Table 2. Time comparison between EGS4.4 and EGS5 for three benchmark experiments.

Shower Experiment ($2.5x10^5$ cases for EGS4.4 & 10^6 cases for EGS5)			
Phantom	Water		Aluminum
EGS5 / EGS4.4	0.43		0.43
Polarization Experiment ($2x10^9$ cases)			
Scattering Target	Carbon		Copper
EGS5 / EGS4.4	0.58		0.73
Heterogeneity Experiment (10^5 cases, 20-MeV Beam)			
Inserted Disc with 2-mm-gap	None	Air	Aluminum
EGS5 / EGS4.4	0.16	0.18	0.18
Inserted Disc with 2-cm-gap	None	Air	Aluminum
EGS5 / EGS4.4	0.16	0.18	0.2
Heterogeneity Experiment (10^5 cases, 10-MeV Beam)			
Inserted Disc with 2-mm-gap	None	Air	Aluminum
EGS5 / EGS4.4	0.18	0.19	0.18
Inserted Disc with 2-cm-gap	None	Air	Aluminum
EGS5 / EGS4.4	0.18	0.24	0.20

CONCLUSIONS

EGS4 has undergone an extensive upgrade to EGS5, in the areas of low-energy electron physics and transport, as well as low-energy photon physics. The PEGS cross section can be generated on the fly. And the coding has changed from Mortran to Fortran 77. The EGS5 Code System is now more integrated than EGS4 and it also runs faster. This work, which compares EGS5 with three standard benchmark experiments, has assured the accuracy and high quality of EGS5.

REFERENCES

[1] W. R. Nelson, H. Hirayama and D. W. O. Rogers, "The EGS4 Code System", Stanford Linear Accelerator Center report SLAC-265 (1985).

[2] Alex Bielajew, Scott Wilderman, “New electron transport physics in EGS5”, This Proceedings (2004).

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[6] C. J. Crannell, H. Crannell, R. R. Whitney and H. D. Zeman, “Electron-induced cascade showers in water and aluminum”, Phys. Rev. 184, p426 (1969).

[7] Namito et. al, “Polarization/Doppler Experiment: 20-40 keV, linearly polarized photons hit carbon and copper targets. Measured Compton-scattered spectra”, KEK Proceedings 97-16, p32 (1997).

[8] Shortt et. al., “Heterogeneity Experiment: 10 and 20 MeV broad electron beam hit the front face of a water tank containing both air and aluminum cylinders. Measured depth dose distribution”, Phys. Med. Biol., Vol. 31, p235, (1986).

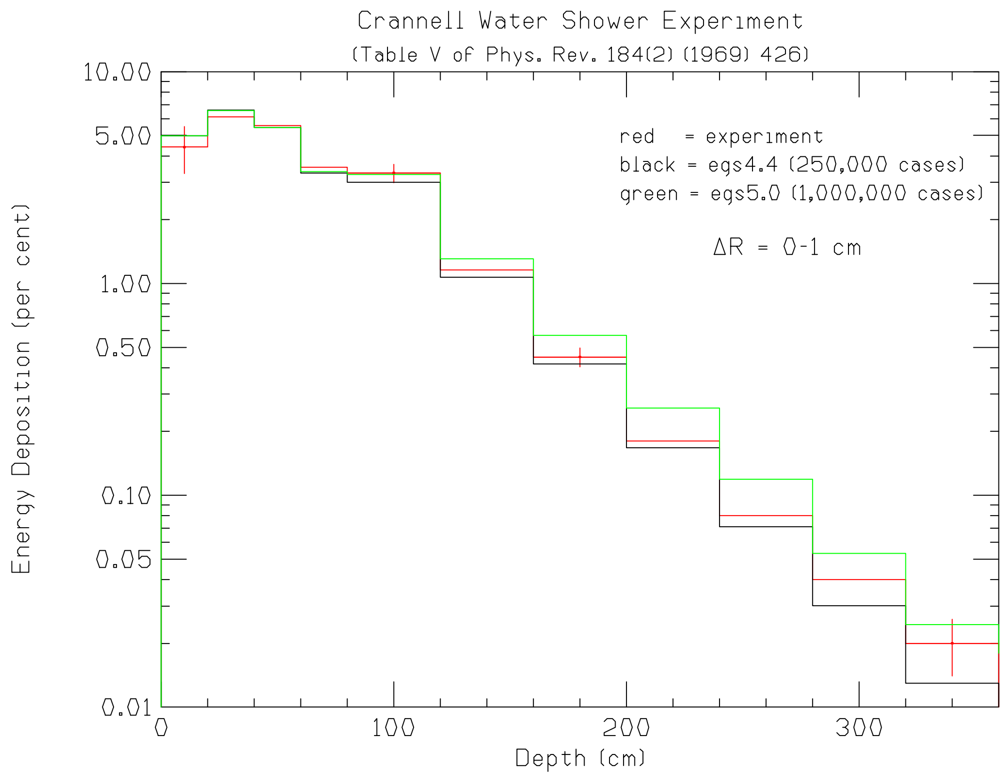
[9] W. R. Nelson and T. M. Jenkins, “Solution of the electromagnetic cascade shower problem by analog Monte Carlo methods - EGS”, Chapter 12 in *Computer Techniques in radiation Transport and Dosimetry*, Plenum Press (1980).

```
Crannell water shower experiment
         2                          nmed (I10)
WATER (CRANNELL)              media(j,1) (24A1)
AL (INTERFACE)
       0.1       0.1           ecutin,pcutin (Kinetic) (MeV)
        11         1        12 imax,jmax,kmax (3I10)
       1.0  i=1                cyrad (cm) (F10.0)
       2.0   =2
       3.0   =3
       4.0   =4
       6.0   =5
       8.0   =6
      12.0   =7
      16.0   =8
      20.0   =9
      24.0   =10
      68.8   =11=imax
       0.0  j=1=jmax           tpl (degrees) (F10.0)
       0.0  k=1                zpl (cm)
      20.0   =2
      40.0   =3
      60.0   =4
      80.0   =5
     120.0   =6
     160.0   =7
     200.0   =8
     240.0   =9
     280.0   =10
     320.0   =11
     360.0   =12=kmax
     460.0   =13=kmax+1
    1   11    1    1    1   12    1       0.0 WATER (CRANNELL)
                                           blank card (required EOF)
       0.0       0.0       0.0   xin,yin,zin (3F10.0)
         1         1         1   iin,jin,kin (3I10)
       0.0       0.0       1.0   uin,vin,win (3F10.0)
   1000000                       ncases (I10)
    1000.0        -1         0  ekein(mev),iqin,isamp (F10.0,2I10)
    1    1    1    0          ipeangsw,iedgesw,iraysw,iwatch (4I5)
    0    0    0    0          ipolarsw,incohrsw,iprofrsw,impacrsw (4I5)
    1    2    0    0          ibrdst,iprdst,ibrspl,nbrspl (4I5)
    0.10      0.20            estepe and estepe2 (2F10.0)
```

Figure 1. EGS5 user input (using format of getRTZ user code) for Shower experiment.

```
COMP
&INP NE=2, RHO=1.0, PZ=2,1, IAPRIM=1, EFRACH=0.05, EFRACL=0.20, IRAYL=1,
IBOUND=0, INCOH=0, ICPROF=0, IMPACT=0 /END
WATER (CRANNELL)              H2O
H  O
ENER
&INP AE=0.611, AP=0.001, UE=1001.0, UP=1000.0 /END
ELEM
&INP RHO=2.65, IRAYL=1, IBOUND=0, INCOH=0, ICPROF=0, IMPACT=0, IAPRIM=1,
EFRACH=0.05, EFRACL=0.20 /END
AL (INTERFACE)                AL
AL
ENER
&INP AE=0.611, AP=0.001, UE=1001.0, UP=1000.0 /END
```

Figure 2. EGS5 PEGS input for Shower experiment.



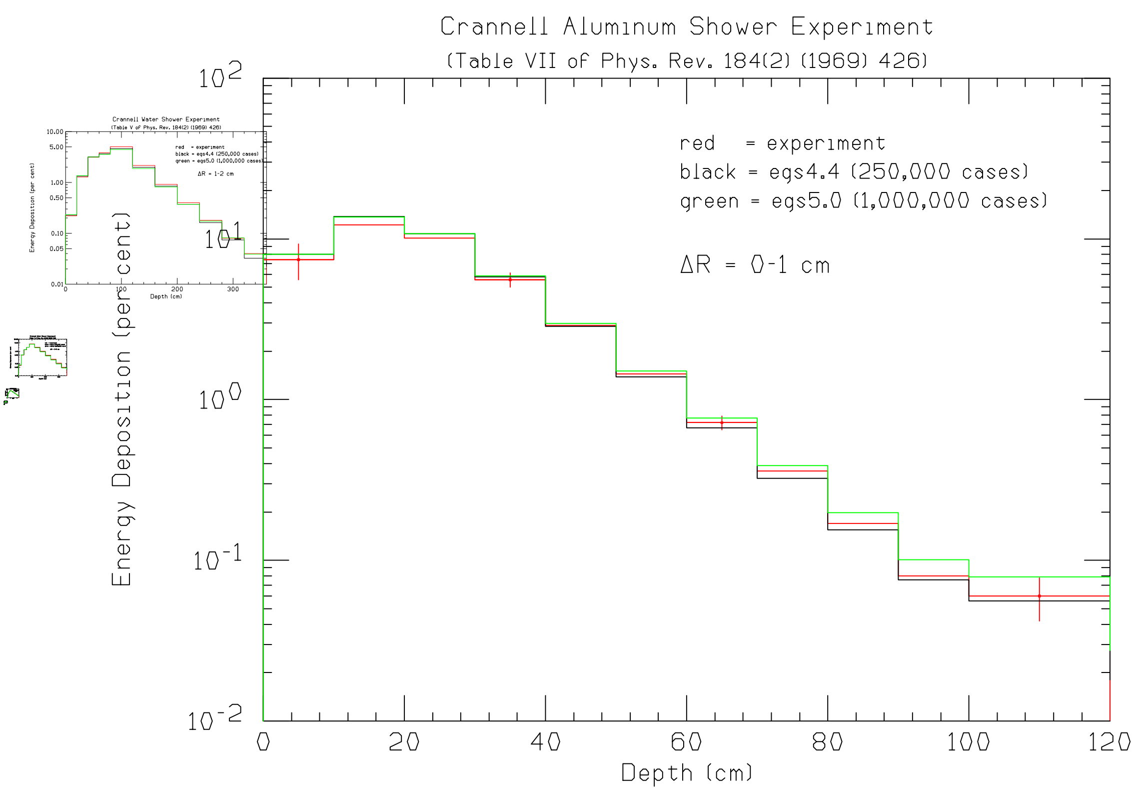
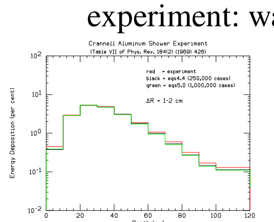


Figure 3. Benchmark results (depth dose profile in central axis, 1-cm-radius) for Shower experiment: water (top) and Al (bottom).



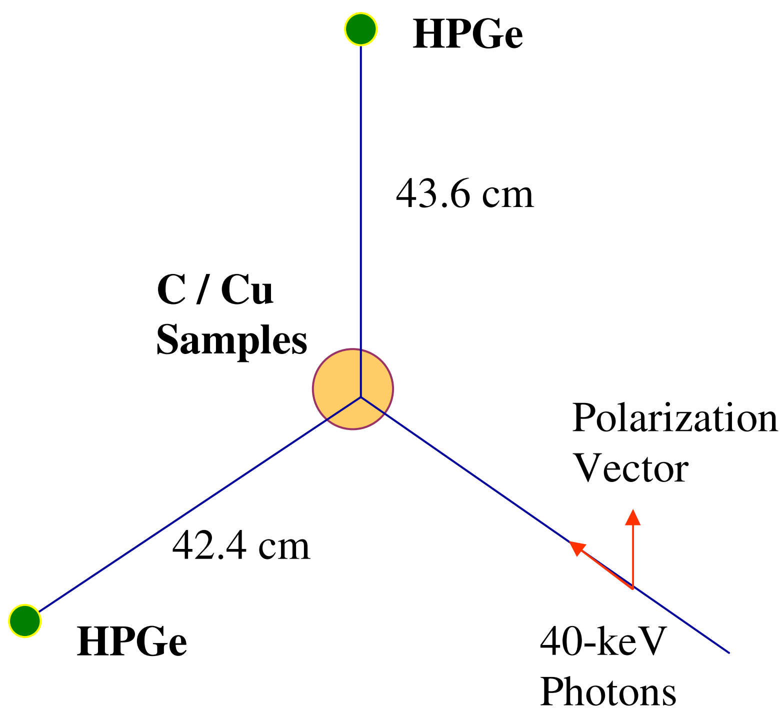


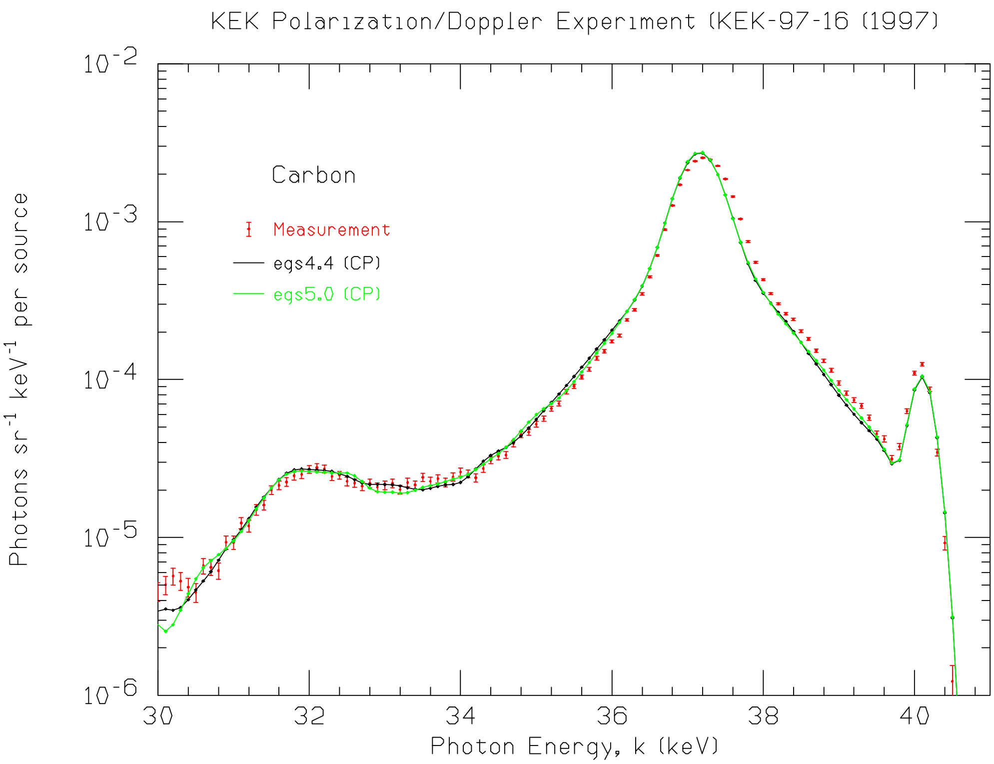
Figure 4. Set-up for Polarization/Doppler Experiement [7].

```
Check of KEK-LSCAT experiment (Fig.4 of KEK-97-16)
         2                    nmed (I10)
C-ICPROF3-PHOTX          media(j,1) (24A1)
CU-ICPROF3-PHOTX
       0.5        0.0         ecutin,pcutin (Kinetic) (MeV) (2F10.0)
         1          1       1 imax,jmax,kmax (3I10)
      2.26  i=1=imax          cyrad (cm) (F10.0)
       0.0  j=1=jmax          tpl (degrees) (F10.0)
       0.0  k=1=kmax          zpl (cm)
       0.2  =2=kmax+1         (actually, the "thickness" of the scatterer)
    1    1    1    1    1    1    2      0.0 CU-ICPROF3-PHOTX
                                          blank card (required EOF)
       0.0       0.0       0.0  xin,yin,zin (3F10.0)
         1         1         1  iin,jin,kin (3I10)
       0.0       0.0       1.0  uin,vin,win (3F10.0)
2000000000                      ncases (I10)
   0.04007         0         0  ekein(mev),iqin,isamp (F10.0,2I10)
    1    1    1    0            ipeangsw,iedgesw,iraysw,iwatch (4I5)
    1    1    1    0            ipolarsw,incohrsw,iprofrsw,impacrsw (4I5)
    1    2    0    0            ibrdst,iprdst,ibrspl,nbrspl (4I5)
      0.10      0.20            estepe and estepe2 (2F10.0)
     100.0                      sprad (cm) (F10.0) For scoring only
```

Figure 5. EGS5 user input (using format of getRTZ user code) for Polarization Experiment.

```
ELEM
&INP IRAYL=1, IBOUND=1, INCOH=1, ICPROF=-3, IAPRIM=0, EFRACH=0.05,
EFRACL=0.20 /END
C-ICPROF3-PHOTX          C
C
ENER
&INP AE=0.512, AP=0.001, UE=0.711, UP=0.200 /END
ELEM
&INP IRAYL=1, IBOUND=1, INCOH=1, ICPROF=-3, IAPRIM=0, EFRACH=0.05,
EFRACL=0.20 /END
CU-ICPROF3-PHOTX         CU
CU
ENER
&INP AE=0.512, AP=0.001, UE=0.711, UP=0.200 /END
```

Figure 6. EGS5 PEGS input for Polarization Experiment.



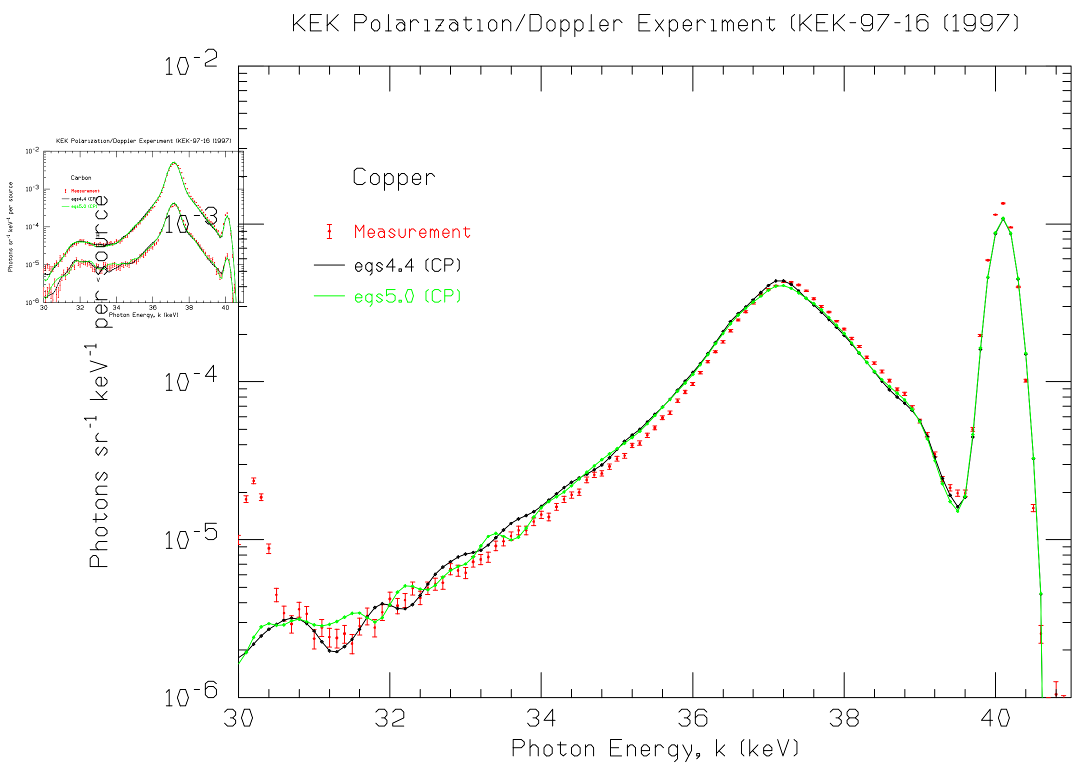
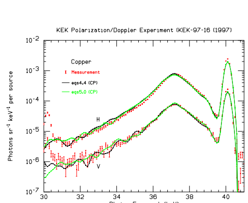


Figure 7. Benchmark results for Polarization Experiment: 90^{o}-scattered Compton spectra for carbon (top) and copper (bottom).



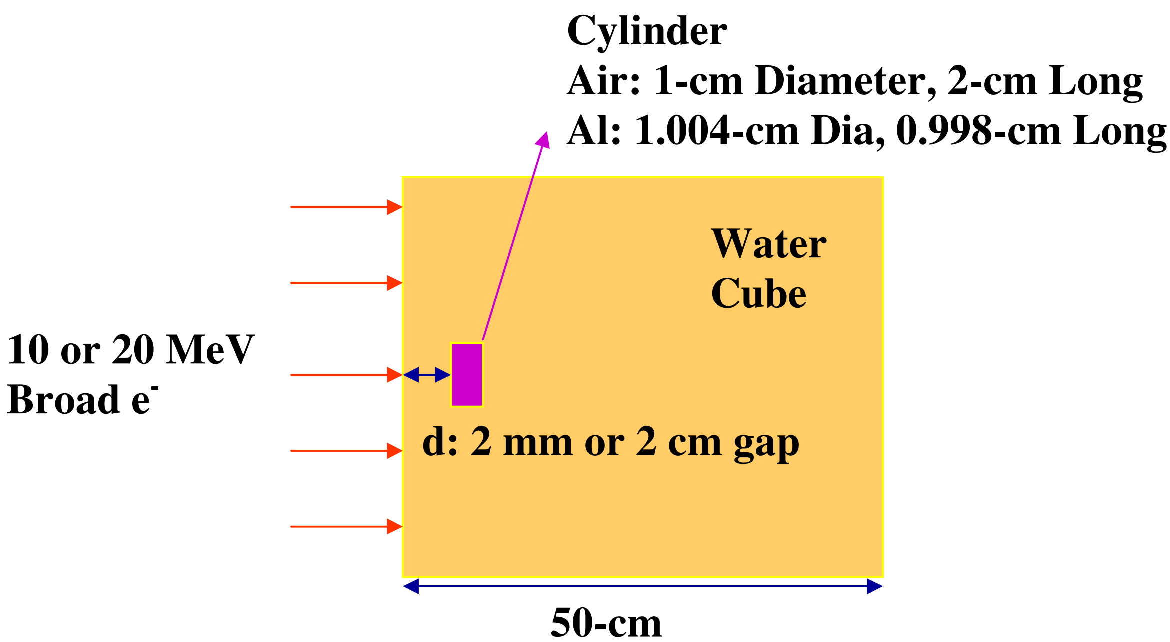


Figure 8. Set-up for Heterogeneity Experiement [8].

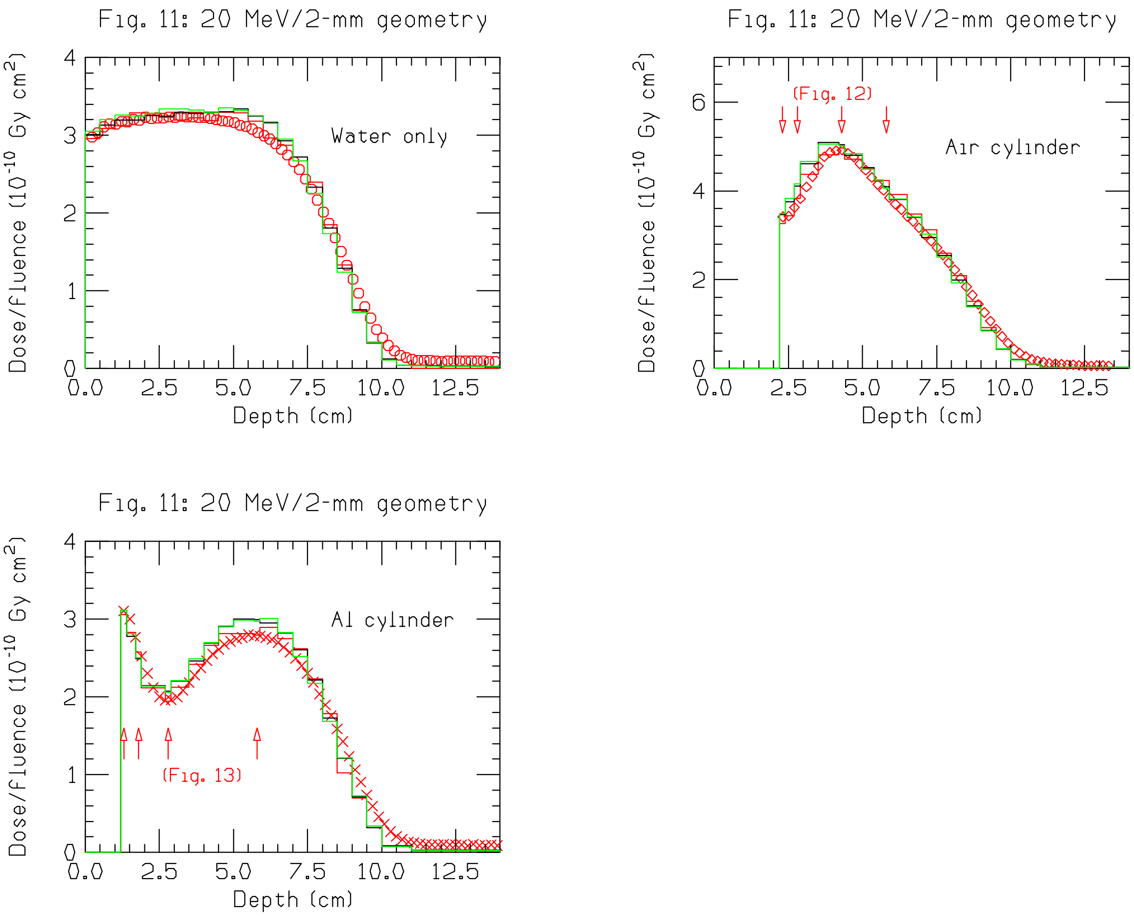
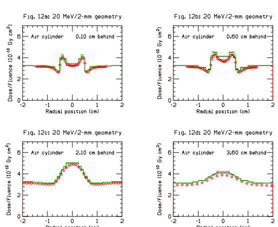
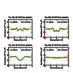


Figure 9a. Benchmark results for Heterogeneity Experiment (20-MeV electron; pure water, and water with air or Al disc at 2-mm gap; depth dose curves at central axis).





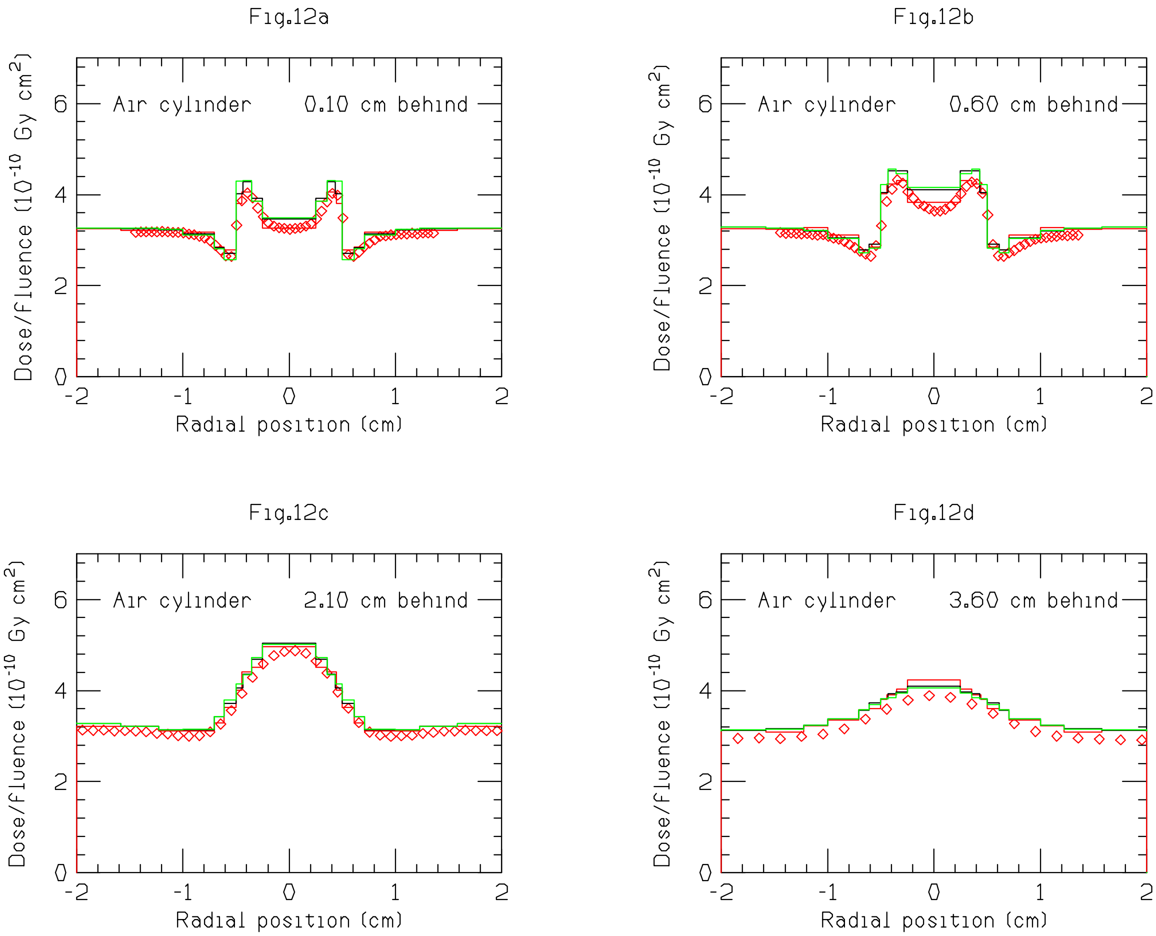


Figure 9b. Benchmark results for Heterogeneity Experiment (20-MeV electron; water with air disc at 2-mm gap; radial dose profiles at various depths behind the air disc).

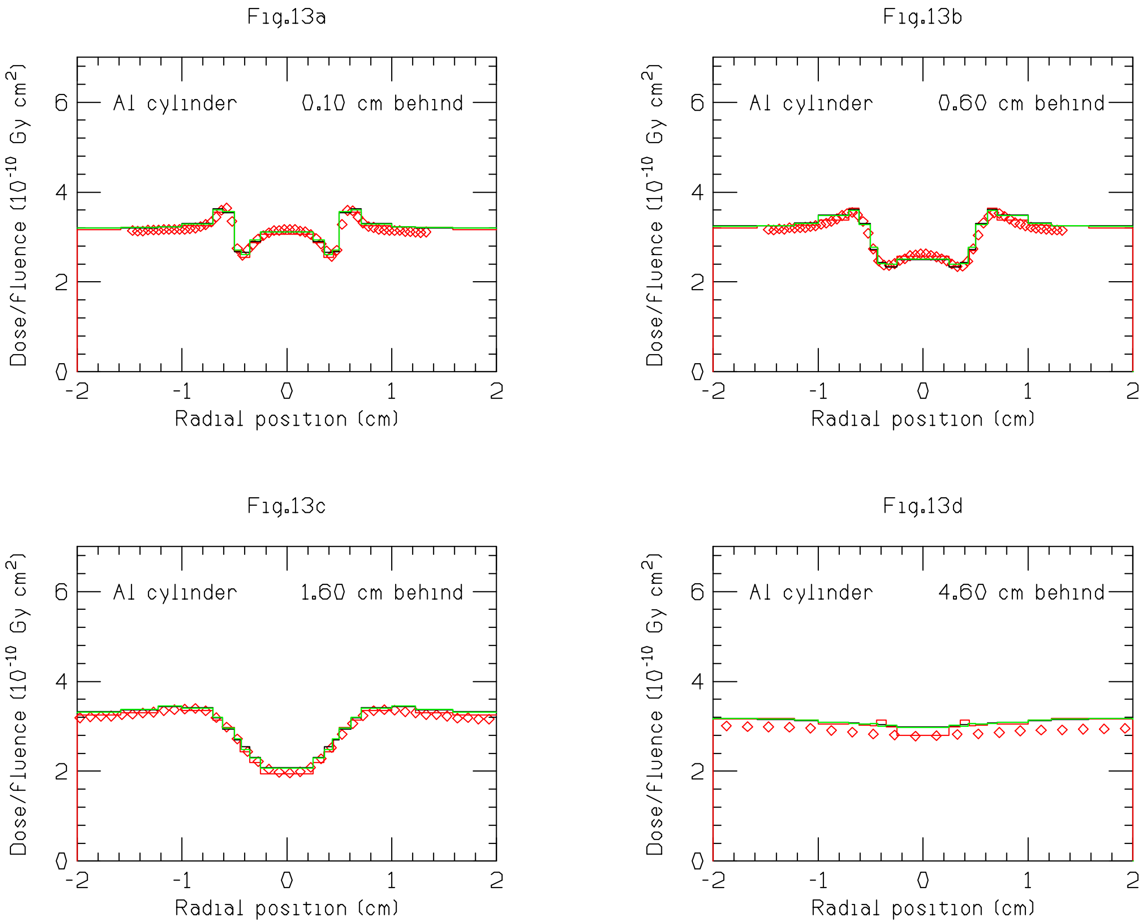


Figure 9c. Benchmark results for Heterogeneity Experiment (20-MeV electron; water with Al disc at 2-mm gap; radial dose profiles at various depths behind the Al disc).

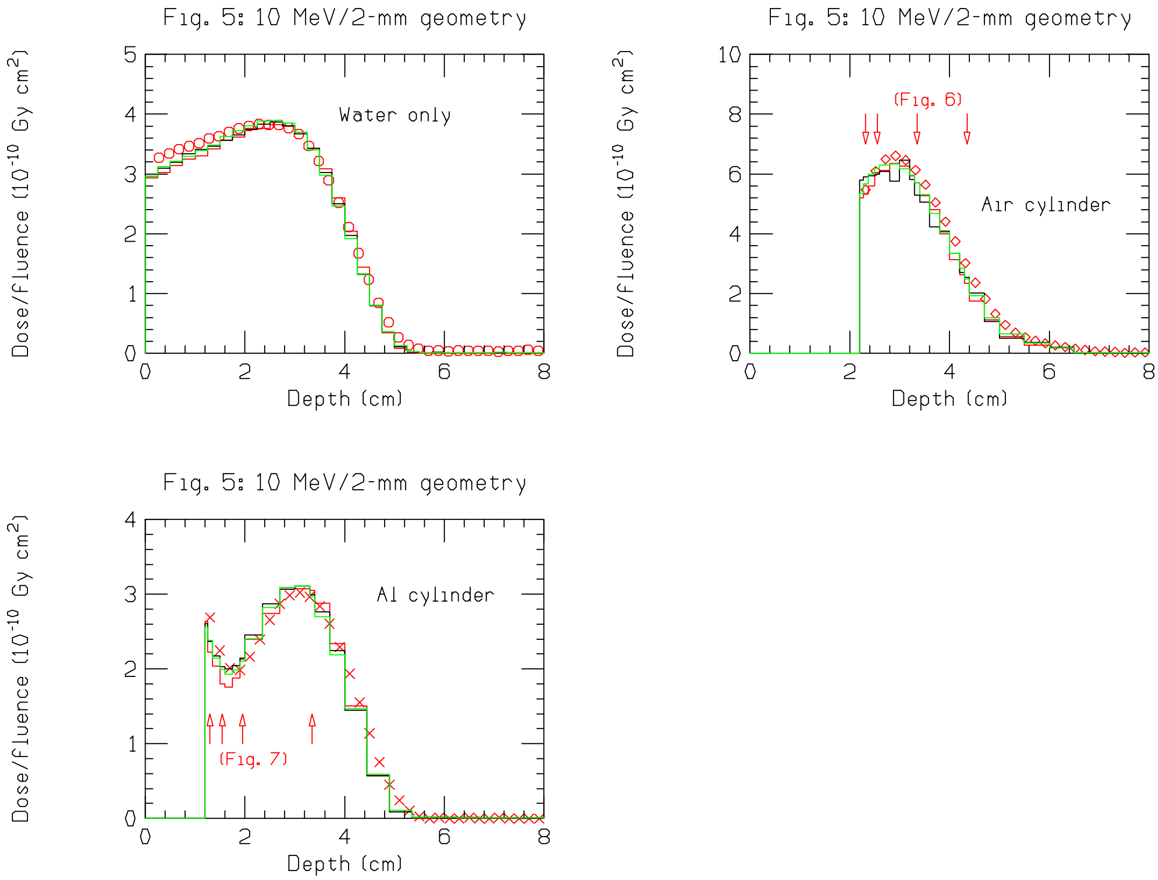
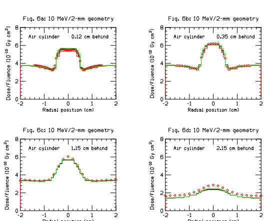
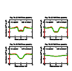


Figure 10a. Benchmark results for Heterogeneity Experiment (10-MeV electron; pure water, and water with air or Al disc at 2-mm gap; depth dose curves at central axis).





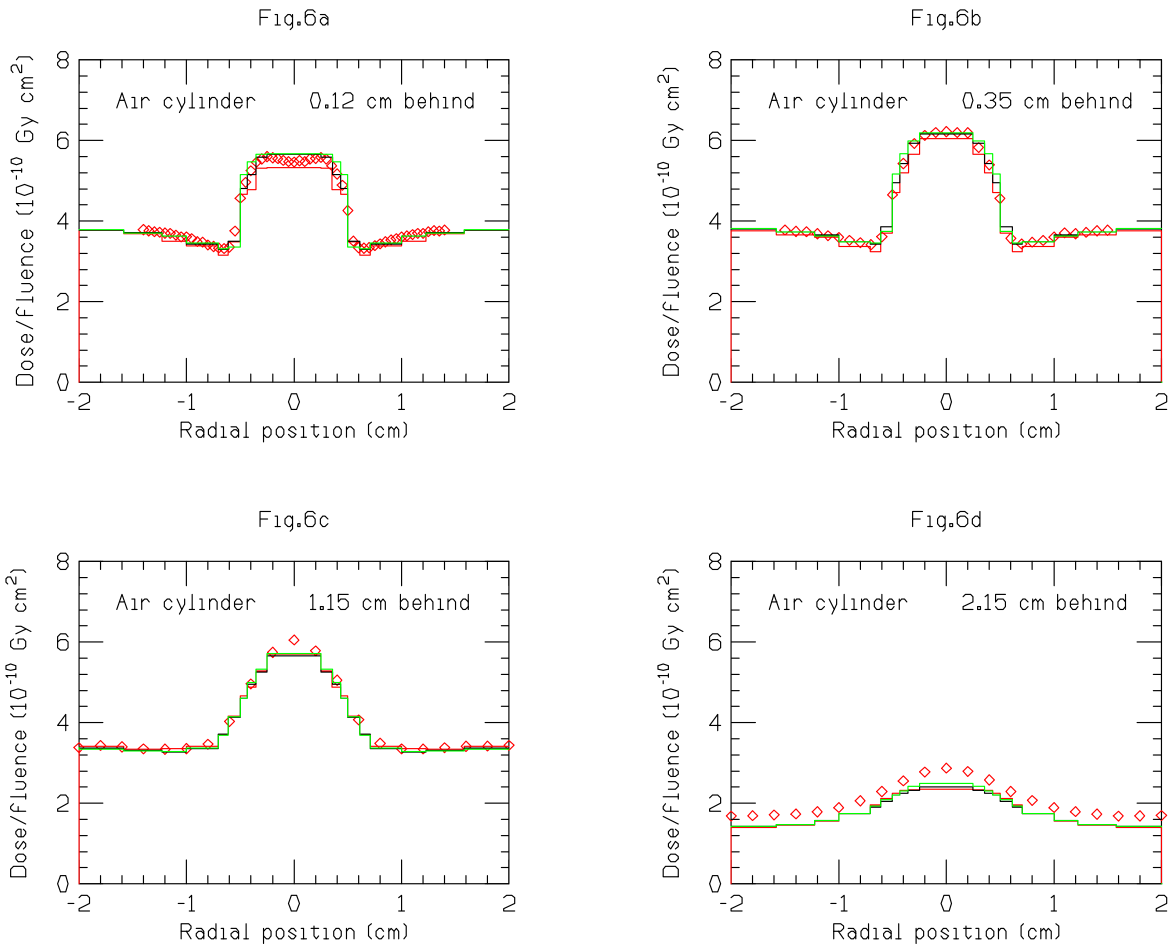


Figure 10b. Benchmark results for Heterogeneity Experiment (10-MeV electron; water with air disc at 2-mm gap; radial dose profiles at various depths behind the air disc).

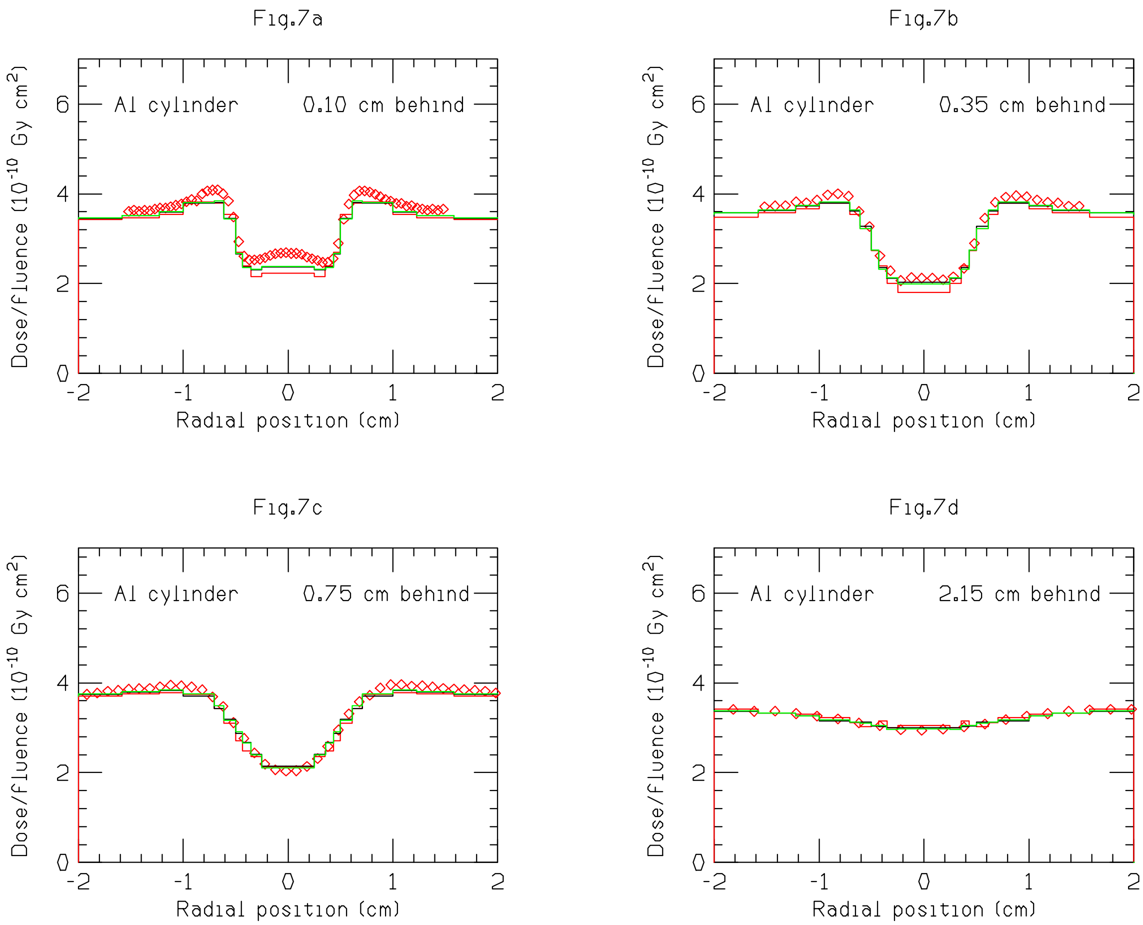


Figure 10c. Benchmark results for Heterogeneity Experiment (10-MeV electron; water with Al disc at 2-mm gap; radial dose profiles at various depths behind the Al disc).

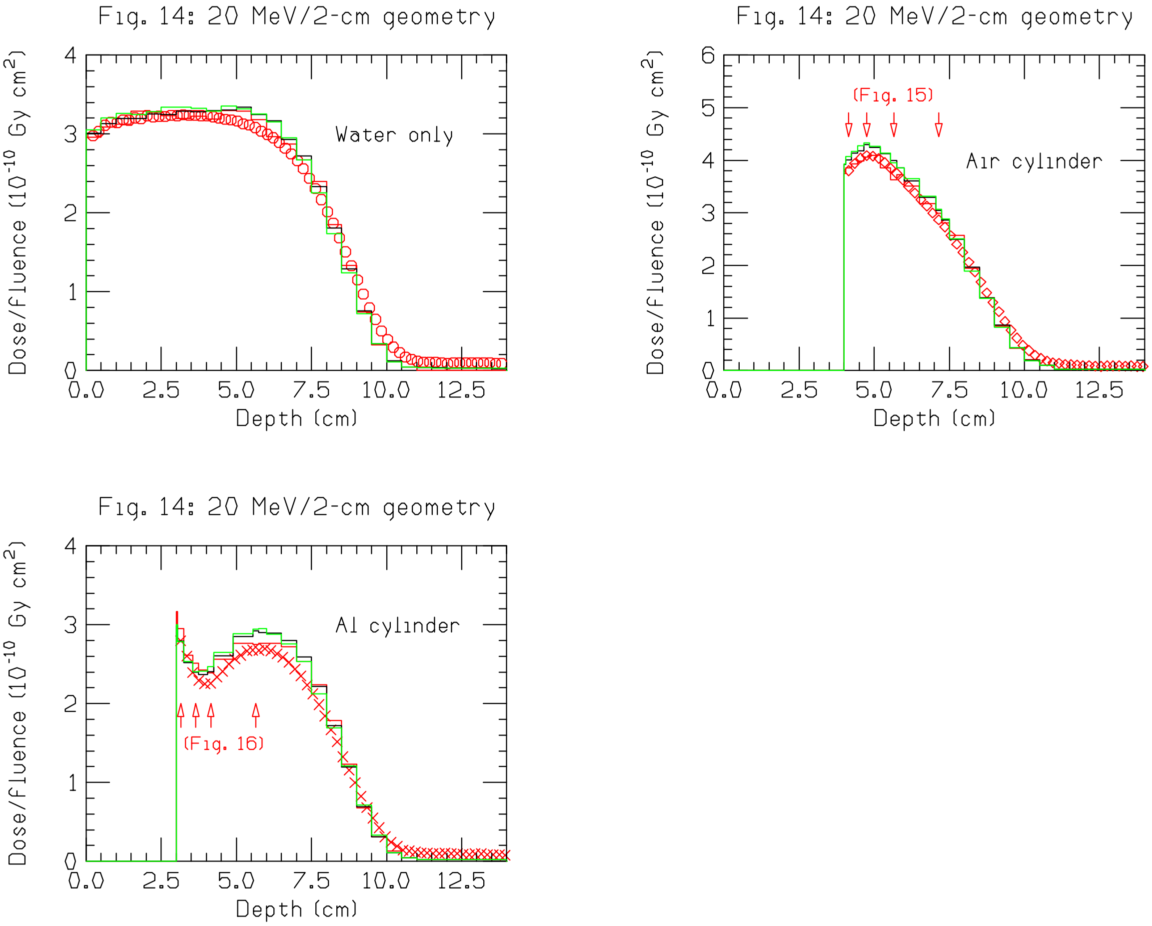
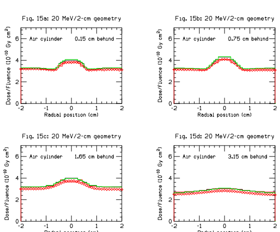
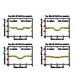


Figure 11. Benchmark results for Heterogeneity Experiment (20-MeV electron; pure water, and water with air or Al disc at 2-cm gap; depth dose curves at central axis).





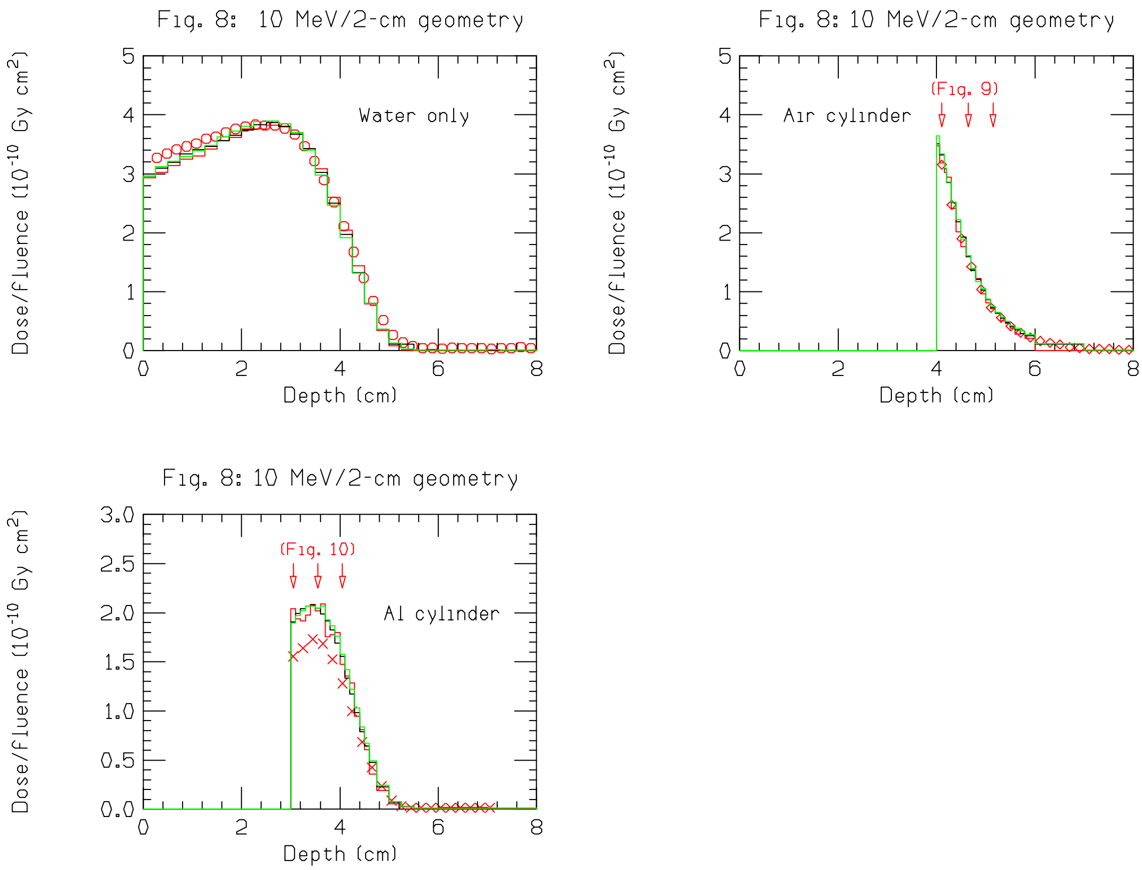


Figure 12. Benchmark results for Heterogeneity Experiment (10-MeV electron; pure water, and water with air or Al disc at 2-cm gap; depth dose curves at central axis).