Beam Transport Radiation Shielding for Branch Lines 2-ID-B and 2-ID-C

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Advanced Photon Source
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DISCLAIMER

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ABSTRACT

The x-ray radiation shielding requirements beyond the first optics enclosure have been considered for the beam transport of the 2-ID-B and 2-ID-C branch lines of Sector 2 (SRI-CAT) of the APS. The first three optical components (mirrors) of the 2-ID-B branch are contained within the shielded first optics enclosure. Calculations indicate that scattering of the primary synchrotron beam by beamline components outside the enclosure, such as apertures and monochromators, or by gas particles in case of vacuum failure is within safe limits for this branch. A standard 2.5-inch-diameter stainless steel pipe with 1/16-inch-thick walls provides adequate shielding to reduce the radiation dose equivalent rate to human tissue to below the maximum permissible limit of 0.25 mrem/hr. The 2-ID-C branch requires, between the first optics enclosure where only two mirrors are used and the housing for the third mirror, additional lead shielding (0.75 mm) and a minimum approach distance of 2.6 cm. A direct beam stop consisting of at least 4.5 mm of lead is also required immediately downstream of the third mirror for 2-ID-C. Finally, to stop the direct beam from escaping the experimental station, a beam stop consisting of at least 4-mm or 2.5-mm steel is required for the 2-ID-B or 2-ID-C branches, respectively. This final requirement can be met by the vacuum chambers used to house the experiments for both branch lines.

I. INTRODUCTION

The Sector 2 insertion device beamline consists of three branches sharing the same straight section of the storage ring, the same front end, and the same first optics enclosure (FOE).[1] Branching is achieved using several horizontally reflecting optics inside the FOE, including a first mirror (M1), a second mirror (M2B, or M2C depending on the branch in operation), and a third mirror (M3B) as shown in Fig. 1(a) and 1(b). A vertically deflecting third mirror (M3C) outside the FOE is used for the 2-ID-C branch. The 2-ID-B and 2-ID-C branch lines are designed to operate in the energy range of 0.5 to 4 keV, and a straight-through branch, 2-ID-E, will operate in the range from 2.5 to 40 keV.

The most important aspects of the radiation shielding for the Sector 2 insertion device beamlines and the beam transport shielding for the 2-ID-E branch line have already been considered.[2] It was concluded that the primary high-energy bremsstrahlung radiation (BR), produced by positron scattering from gas molecules and positron collision with the vacuum chamber wall, as well as the secondary bremsstrahlung radiation (SBR) and concomitant neutron production, will be stopped by the FOE.[2] These calculations have shown that lead shielding is not necessary outside the FOE for the 2-ID-B, 2-ID-C, and the 2-ID-E beamlines to handle the BR and SBR.[2] However, lead beam transport shielding is required on the 2-ID-E branch to reduce to within safe limits the radiation arising from the synchrotron beam striking beamline components. Since the operating energy ranges for the 2-ID-C and 2-ID-B branches are much lower than that of the 2-ID-E branch, the radiation due to scattering of the synchrotron beam is considerably lower. In this report, we examine the radiation shielding requirements for the 2-ID-B and 2-ID-C branches due to the synchrotron beam striking the beamline components.

The maximum permissible radiation exposure limits used here are the same as those required by the *RadCon Manual*.[3] In particular, the dose equivalent rate (DER) of **0.25 mrem/h** is used as the upper limit with the assumption of a 2000-hour working year and a maximum yearly dose of **500 mrem**. This DER is identical to that used in the "Guide to Beamline Radiation Shielding Design at the Advanced Photon Source".[4] For nonroutine situations in which the exposure is limited to a short time period, the maximum dose rate will be limited to **5 mrem/h** and the total annual duration of such a working condition will be limited to **100 hours**, in accordance with the *RadCon Manual*.[3]

II. SHIELDING CALCULATION

Our dose rate calculations were performed using a modified version of the PHOTON program,[5] which takes into account the reflectivities of the various mirrors inside and outside the FOE. These mirrors are M1, M2B, and M3B for the operation of the 2-ID-B branch line, or M1, M2C, and M3C for the 2-ID-C branch line. The APS wiggler A was used as the source, although the APS 3.3-cm-period (undulator A) and 5.5-cm-period undulators are actually planned for Sector 2. In PHOTON, the spectrum of a wiggler source is approximated by that of a bending magnet multiplied by the number of poles $2N$, where N is the number of periods of the wiggler. As we shall discuss later, this approach results in an overall higher radiation dose rate, which is taken as a safety factor. For comparison, we have calculated and plotted in Fig. 2 the angle-integrated flux for the bending magnet approximation of wiggler A, the 3.3-cm-period, and the 5.5-cm-period undulators working at their respective minimum gaps. The storage ring energy was assumed to be 7.5 GeV and the stored positron current was taken to be 200 mA.[4] The angular acceptance of the two branches was determined by a 4.5 mm x 2.9 mm aperture inside the FOE, located at 28.5 m from the source, that limits the horizontal and vertical acceptance angles to 158 μrad and 102 μrad, respectively. In the actual PHOTON calculation, the vertical acceptance was taken to be 109 μrad for the convenience of choosing an integer number of steps. All parameters for the calculation are summarized in Table I.

To calculate scattering of the synchrotron beam in the branch lines, two types of scatterers similar to those analyzed in Ref. 2 were modeled inside a 2.5-inch-diameter steel pipe with 1/16-inch-thick walls, namely a 30-cm copper block and a 30-cm air column at atmospheric pressure. Copper was selected as it is an efficient scatterer and because it can represent various optical components, such as mirrors, monochromators, and apertures. The 30-cm air column was used to represent vacuum failure within the beam transport. In either case, the scattered radiation was assumed to be shielded by a steel pipe. We did not consider the unlikely case of a *pink* beam (obtained by reflecting off the first mirror M1) directly hitting the transport pipe because the masks and apertures in the beamlines will not allow this situation to happen. Due to the large angles at which the 2-ID-B and 2-ID-C branch lines are oriented with respect to the storage ring, the synchrotron beam can only be directed into the transport pipe when properly reflected by the M2B/M3B and M2C mirrors, respectively.

Because only the first two mirrors of the 2-ID-C branch are inside the FOE, the radiation dose rate beyond the FOE will generally be much higher for this branch than for the 2-ID-B branch. We first considered the radiation shielding for the 2-ID-C branch, including the section between the FOE and the M3C mirror housing and the section beyond the M3C mirror housing. For the section between the FOE and the M3C mirror housing, we calculated the dose rate using different combinations of the first and second mirror, namely (i) M1(Pt)M2C(ML), (ii) M1(Si)M2C(ML), (iii) M1(Pt)M2C(Rh), and (iv) M1(Si)M2C(Rh), where Pt and Rh are platinum and rhodium coatings on the silicon mirrors, and ML stands for a Ni/Be multilayer coating. A rhodium-coated silicon mirror was used for M3C in series with the above four combinations to calculate the dose rate immediately downstream of the M3C mirror housing. The incidence angles of the first, second, and third mirrors are 0.15°, 1.25°, and 1.0°, respectively. The reflectivities of Pt (θ_{in} = 0.15°) and Si (θ_{in} = 1.25°) are shown in Fig. 3, and those of Rh at θ_{in} = 1.25° and 1.0° are shown in Fig. 4. A typical multilayer consisting of Ni and Be bilayers deposited on a Si mirror was chosen for the calculation. The layer thicknesses were 27 Å for the Ni layer and 63 Å for the Be layer. These parameters were selected because the first Bragg reflection of the multilayer is close to 4 keV, which is the upper limit for operation of both branch lines. The reflectivity of the Ni/Be multilayer at θ_{in} of 1.25° is plotted in Fig. 5. Because the XOP program[6] used to calculate the multilayer reflectivity does not extend beyond 100 keV, the reflectivity for energies higher than 100 keV was extrapolated using the inverse-quadratic dependence of the momentum transfer. Zero interfacial roughness was assumed in the calculation. This assumption resulted in an overestimation of the reflectivity and can be taken as an extra safety factor.

The incident angles used in the calculation are the nominal working values, not the "worst case" values at which the combined reflectivity of all mirrors would be higher. This will not pose major concerns because we plan to restrict the movement of these mirrors to 60 μrad from their working orientations after the commissioning of the beamline. The increase in the reflectivity due to possible mirror misalignment would be a few percent at most. This small effect is well within the safety margin of our calculations.

For the section between the FOE and the M3C mirror housing on the 2-ID-C branch line, the dose rate absorbed by human tissue due to the scattered synchrotron radiation was calculated on the outer surface of a steel pipe (3.2 cm from the center) and then for a more reasonable distance of 25 cm from the center. The results for the various mirror combinations are summarized in Table II. In Figs. 6 and 7, we have plotted the angle-integrated spectral flux after the first two mirrors. In Figs. 8 and 9, the spectral dose rate is plotted for the various combinations of the first two mirrors (M1 and M2C). It is apparent that the radiation dose comes mainly from x-rays in the 40 to 120 keV energy range. The flux of high energy x-rays ($E > 120$ keV) from the source is sufficiently reduced by the mirrors so that it presents little radiation hazard. From the analysis (see Table II), we find that a 1/16-inch steel pipe will provide adequate shielding for a twice-reflected synchrotron beam, if the minimum approach distance is 25 cm. This safe distance can be guaranteed by constructing exclusion zones surrounding the beam pipe and scattering centers, such as apertures and mirrors.

The radiation dose rate downstream of the M3C mirror housing that would be absorbed by human tissue was calculated on the outer surface of the steel pipe only. The total dose rates for each combination are summarized in Table III. It is obvious that a 1/16-inch steel pipe will provide adequate shielding regardless of the mirror combination and that the steel pipe itself will assure the minimum approach distance. Similar calculations were done for the 2-ID-B branch for the section beyond the FOE. In Figs. 10 and 11, we have plotted the angle-integrated spectral flux after the three mirrors (M1, M2B, and M3B). The spectral dose rate is plotted in Figs. 12 and 13. The total dose rates are given in Table IV. Again, we find that the 1/16-inch steel pipe will provide adequate shielding for the synchrotron beam regardless of the mirror combination and no exclusion zone needs to be constructed around the pipe.

Now we discuss several safety factors that have been built into the above calculations. First, PHOTON models wiggler A as a series of bending magnets with a fixed critical energy. This assumption ignores the fact that the critical energy for a wiggler source decreases with the horizontal observation angle and thus overestimates the flux of high energy x-rays.[6] In addition, the more sharply peaked spectra produced by undulator A and the 5.5-cm undulator source that will actually be used differ only for energies lower than 10 keV from the bending-magnet approximation used to model wiggler A, as shown in Fig. 2. At these energies, the radiation dose rate is in fact quite low due to the steel shielding, as indicated by Figs. 7 and 8. Therefore, the actual dose rates when using undulators should be even lower than those listed in Tables II, III and IV. Second, PHOTON assumes that the scattering occurs at a point instead of over an extended volume and hence is conservative for calculating scattering from air. Finally, the scattering is assumed to be isotropic. This tends to underestimate scattering in the forward direction but to overestimate that into angles near 90° from the direct beam. Consequently, our calculation for the shielding required to handle scattering of the synchrotron beam is conservative.

So far, we have considered the presence of a solid object or vacuum failure inside the beam transport that scatters the direct beam. Another potential hazard is the case in which the synchrotron beam (not the pink beam as we have stated on page 5) directly strikes the beam transport pipe. It is conceivable that this could happen accidentally or during initial alignment. If this should occur, direct x-ray transmission through the steel shielding is a major concern, even though the x-ray beam will be incident on the beam pipe at a grazing angle (10° or less) and will "see" an effectively thicker layer of steel. (For example, at 10° incidence angle the direct synchrotron beam sees 9.1 mm of steel.) This will not bring the dose rate down below the 0.25 mrem/hr limit. For example, for the M1(Pt)M2(ML) mirror combination, the dose rate directly behind the steel pipe was found to be 368 mrem/hr, much higher than the maximum permissible value. This high dose rate calls for additional shielding to the steel pipe alone. If lead (Pb) were to be used, a minimum thickness of 0.75 mm (effectively 4.3 mm due to the grazing incidence) would be needed to wrap around the steel pipe. With the lead layer, the total dose rate would be lowered to 0.01 mrem/hr, satisfying the 0.25 mrem/hr requirement. This additional lead layer will also bring the dose rates shown in Table II down to below the 0.25 mrem/hr limit even without requiring the 25 cm minimum approach distance using exclusion zones. For example, for the M1(Pt)M2(ML) mirror combination and the Cu scatterer, the dose rate on the outer surface of the steel pipe is now 0.12 mrem/hr, below the safe limit of 0.25 mrem/hr.

In addition, x-rays scattered from the steel and the fluorescent x-rays that result have a much shorter path through the steel, if they go through the steel almost normal to the surface. It can be assumed that most of the scattering and fluorescence occurs near the inner surface of the steel because of the grazing incidence angle. This allows the scattering and the shielding to be separated into two distinct processes in PHOTON, even though they occur within the same material. To model the situation, a thick steel target of 50 cm in length†, covered by a 1/16-inch-thick steel sheet, was used as an efficient scatterer. The dose rate immediately after the 1/16-inch of steel is 8200 mrem/hr for the M1(Pt)M2C(ML) configuration of the 2-ID-C branch. The

† the length of the steel is not critical but must be long enough to be an efficient scatterer.

increase in the dose rate is a consequence of the much shorter distance (1/16 inch) between the point where the scattering occurs and where the radiation exposure is measured. With the additional 0.75 mm Pb layer, the dose rate is reduced to 29 mrem/hr. If, however, we consider the exposure at a more reasonable distance of 25 cm from the center of the pipe, the dose rate now is reduced to 3.4×10^{-3} mrem/hr with the Pb layer. The maximum permissible dose rate of 0.25 mrem/hr requires a minimum approach distance of 2.6 cm with the additional Pb shielding layer. Considering the standard DOE practices of 25 cm approach distance, however, no exclusion zone is necessary. For the section downstream of the M3C, the dose rate is 0.024 mrem/hr for the M1(Pt)M2C(ML)M3C(Rh) mirror combination. For the 2-ID-B branch line with the M1(Pt)M2B(ML)M3B(ML) mirror combination, the dose rate is 0.31 mrem/hr due to the second multilayer, slightly higher than the 0.25 mrem/hr limit. However, in light of the safety factors in our calculations, we feel that no lead layer or exclusion zones are needed at all for the 2-ID-B branch line.

Finally, we consider the shielding requirements for preventing the direct beam from escaping the transport pipe and for stopping the direct beam at the end of the beamline. Immediately downstream of the M3C mirror, a beam stop is required to stop the direct beam reflected by the M1 and M2C mirrors in the event it is not intercepted by, or simply transmits through, the M3C mirror. When using a Pt first mirror and a multilayer second mirror, the radiation dose rate in the direct beam will be 1.0×10^{16} mrem/hr. If a Pb sheet is used as the beam stop, a minimum thickness of 4.5 mm is needed to bring the dose rate down to 0.11 mrem/hr. Downstream of the third mirror, i.e., M3B for 2-ID-B and M3C for 2-ID-C, the triply reflected beam, which is delivered to the perspective experimental stations, must also be properly stopped from escaping. For the 2-ID-B branch line when using a Pt first mirror, a multilayer second and a multilayer third mirror, the dose rate in the direct beam is still 4.4×10^{15} mrem/hr, which is comparable to that of the 2-ID-C direct beam immediately downstream of M2C when using a Pt and a multilayer mirror combination. The difference lies, however, in the spectral flux of the direct beam. For the 2-ID-B direct beam downstream of the M3B mirror, the x-ray flux in the 20-120 keV energy range, which produces the majority of the radiation dose when shielding with steel, is smaller than that in the 2-ID-C direct beam downstream of the M2C mirror by at least six orders of magnitude. As a result, we only need to use a steel sheet to stop the 2-ID-B direct beam from escaping the experimental chamber, and a thickness of 4 mm is sufficient to lower the dose rate to 0.14 mrem/hr. For the direct beam of the 2-ID-C branch downstream of the M3C mirror, the dose rate is 7.9×10^{15} mrem/hr with a combination of a Pt first mirror, a multilayer second mirror, and a Rh third mirror. To stop this direct beam from escaping the experimental station, a minimum of 2.5 mm of steel is required to lower the dose rate to 0.16 mrem/hr. This requirement of a steel beam stop downstream of the third mirror (M3B or M3C) can be met by the steel vacuum chamber used to house UHV experiments. These results are summarized in Table V.

III. SUMMARY

In conclusion, we find that a 2.5-inch-diameter steel pipe with 1/16-inch-thick walls will provide adequate shielding for the synchrotron beam for the 2-ID-B branch line everywhere outside the FOE and for the section beyond the M3C mirror housing of the 2-ID-C branch line. For the section between the FOE and the M3C mirror housing, additional shielding including 0.75 mm of Pb and a minimum of 2.6 cm approach distance is required. Downstream of the M3C mirror, a beam stop consisting of 4.5 mm of Pb is also required to prevent the direct beam reflected by the M1 and M2C mirrors from escaping. At the end of the branch lines, steel beam stops of at least 4.0 mm and 2.5 mm thick are need to handle the worst-case scenarios.

The authors wish to thank Z. Xu, S. D. Shastri, and D. R. Haeffner for useful discussions and comments. K. J. Randall's parameters were used to calculate the reflectivity of the Be/Ni multilayers.

Table I. Parameters used to calculate the beam transport shielding for scattered synchrotron radiation.

Source	Wiggler A
Positron Energy	7.5 GeV
Relativistic Parameter (γ)	14677
Positron Current	200 mA
Critical Energy	37.4 keV
Number of Poles	56
Vertical Acceptance	109 μrad (1.6/γ)
Horizontal Acceptance	158 μrad
Energy Range	1 - 300 keV
Scatterer	30 cm Cu or air*
Steel Beam Pipe	2.5" O.D. and 1/16" thick wall

* at 47.5 m from the source for 2-ID-B,
or at 40.5 and 45 m from the source for 2-ID-C.

Table II. Dose equivalent rate between the FOE and the M3C mirror housing for various combinations of the first and second mirrors for the 2-ID-C branch line.

(A) 30-cm Cu scatterer at 40.5 m from the source:

(i) on the outer surface of the 2.5-inch steel pipe (3.2 cm from the center)

Mirror Combination	Pt/Multilayer	Si/Multilayer	Pt/Rh	Si/Rh
Dose Rate (mrem/h)	14	0.16	2.3	2.8×10^{-2}

(ii) at a distance of 25 cm from the center

Mirror Combination	Pt/Multilayer	Si/Multilayer	Pt/Rh	Si/Rh
Dose Rate (mrem/h)	0.22	2.6×10^{-3}	3.7×10^{-2}	4.5×10^{-4}

(B) 30-cm air scatterer at 40.5 m from the source:

(i) on the outer surface of the 2.5-inch steel pipe (3.2 cm from the center)

Mirror Combination	Pt/Multilayer	Si/Multilayer	Pt/Rh	Si/Rh
Dose Rate (mrem/h)	1.0	1.0×10^{-2}	0.18	1.7×10^{-3}

(ii) at a distance of 25 cm from the center

Mirror Combination	Pt/Multilayer	Si/Multilayer	Pt/Rh	Si/Rh
Dose Rate (mrem/h)	1.6×10^{-2}	1.6×10^{-4}	2.9×10^{-3}	2.7×10^{-5}

Table III. Dose equivalent rate after the M3C mirror housing for various combinations of the first, second, and third mirrors for the 2-ID-C branch line (on the outer surface of the pipe, 3.2 cm from the center).

(i) 30-cm Cu scatterer at 45.0 m from the source:

Mirror Combination	Pt/Multi./Rh	Si/Multi./Rh	Pt/Rh/Rh	Si/Rh/Rh
Dose Rate (mrem/h)	4.0×10^{-5}	3.8×10^{-7}	7.2×10^{-6}	6.4×10^{-8}

(ii) 30-cm air scatterer at 45.0 m from the source:

Mirror Combination	Pt/Multi./Rh	Si/Multi./Rh	Pt/Rh/Rh	Si/Rh/Rh
Dose Rate (mrem/h)	4.8×10^{-6}	3.7×10^{-8}	8.9×10^{-7}	6.3×10^{-9}

Table IV. Dose equivalent rate for various combinations of the first, second, and third mirrors for the 2-ID-B branch line (on the outer surface of the pipe, 3.2 cm from the center).

(i) 30-cm Cu scatterer at 47.5 m from the source:

Mirror Combination	Pt/Multi./Multi.	Si/Multi./Multi.	Pt/Rh/Rh	Si/Rh/Rh
Dose Rate (mrem/h)	5.2×10^{-4}	4.7×10^{-6}	2.9×10^{-6}	2.8×10^{-8}

(ii) 30-cm air scatterer at 47.5 m from the source:

Mirror Combination	Pt/Multi./Multi.	Si/Multi./Multi.	Pt/Rh/Rh	Si/Rh/Rh
Dose Rate (mrem/h)	6.2×10^{-5}	4.8×10^{-7}	3.6×10^{-7}	2.6×10^{-9}

Table V. Dose equivalent rate in the direct beam before and after the beam stop.

Branch Line	2-ID-B	2-ID-C (before M3C)	2-ID-C (after M3C)
Mirror Combination	Pt/Multi./Multi.	Pt/Multi	Pt/Multi/Rh
Dose rate (mrem/h)	4.4×10^{15}	1.0×10^{16}	7.9×10^{15}
Beam Stop	4 mm steel	4.5 mm Pb	2.5 mm steel
Dose Rate (mrem/h)	0.14	0.11	0.16

REFERENCES:

[1]"*Preliminary Design Report for the SRI-CAT Sectors at the Advanced Photon Source*," June, 1994.

[2]W. Yun, B. Lai, K. J. Randall, S. C. Davey, E. Gluskin, D. R. Haeffner, P. K. Job, and D. Shu, "*Radiation Shielding of Insertion-Device Beamline of SRI-CAT Sector 2 Using a Mirror as the First Optical Element*," **ANL/APS/TB-21**, 1995.

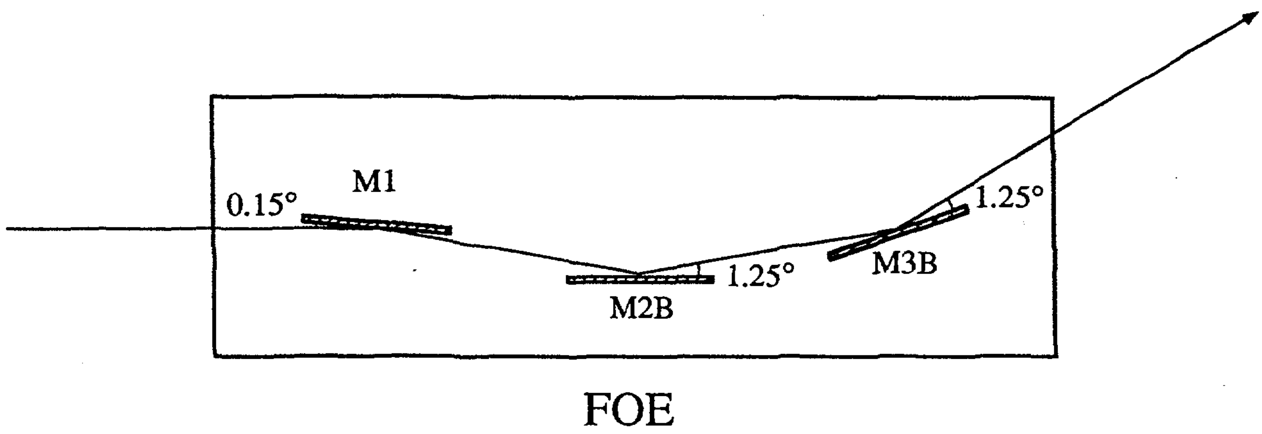
[3]*Radiological Control Manual*, Section 128.1.a., DOE N5480.6, U.S. Department of Energy, June 1992.

[4]N. Ipe, D. R. Haeffner, E. E. Alp, S. C. Davey, R. J. Dejus, U. Hahn, B. Lai, K. J. Randall, and D. Shu, "*Guide to Beamline Radiation Shielding Design at the Advanced Photon Source*," **ANL/APS/TB-7**, 1993.

[5]B. Lai and R. J. Dejus, Argonne National Laboratory, unpublished information, 1994.

[6]R. J. Dejus, Argonne National Laboratory, unpublished information, 1994.

(a) 2-ID-B branch line



(b) 2-ID-C branch line

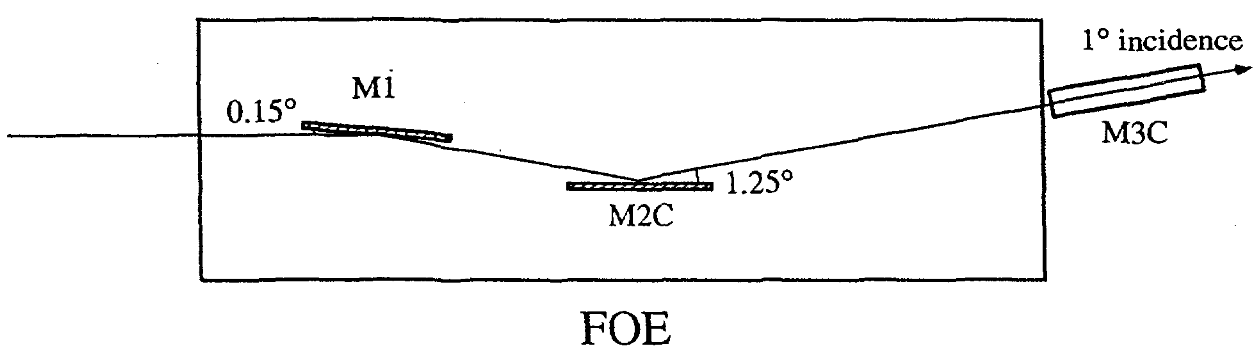


Fig. 1 Diagrams of the branch line optics. (a) The 2-ID-B branch line using mirrors M1, M2B, and M3B. (b) The 2-ID-C branch line using mirrors M1, M2C, and M3C (outside of the FOE).

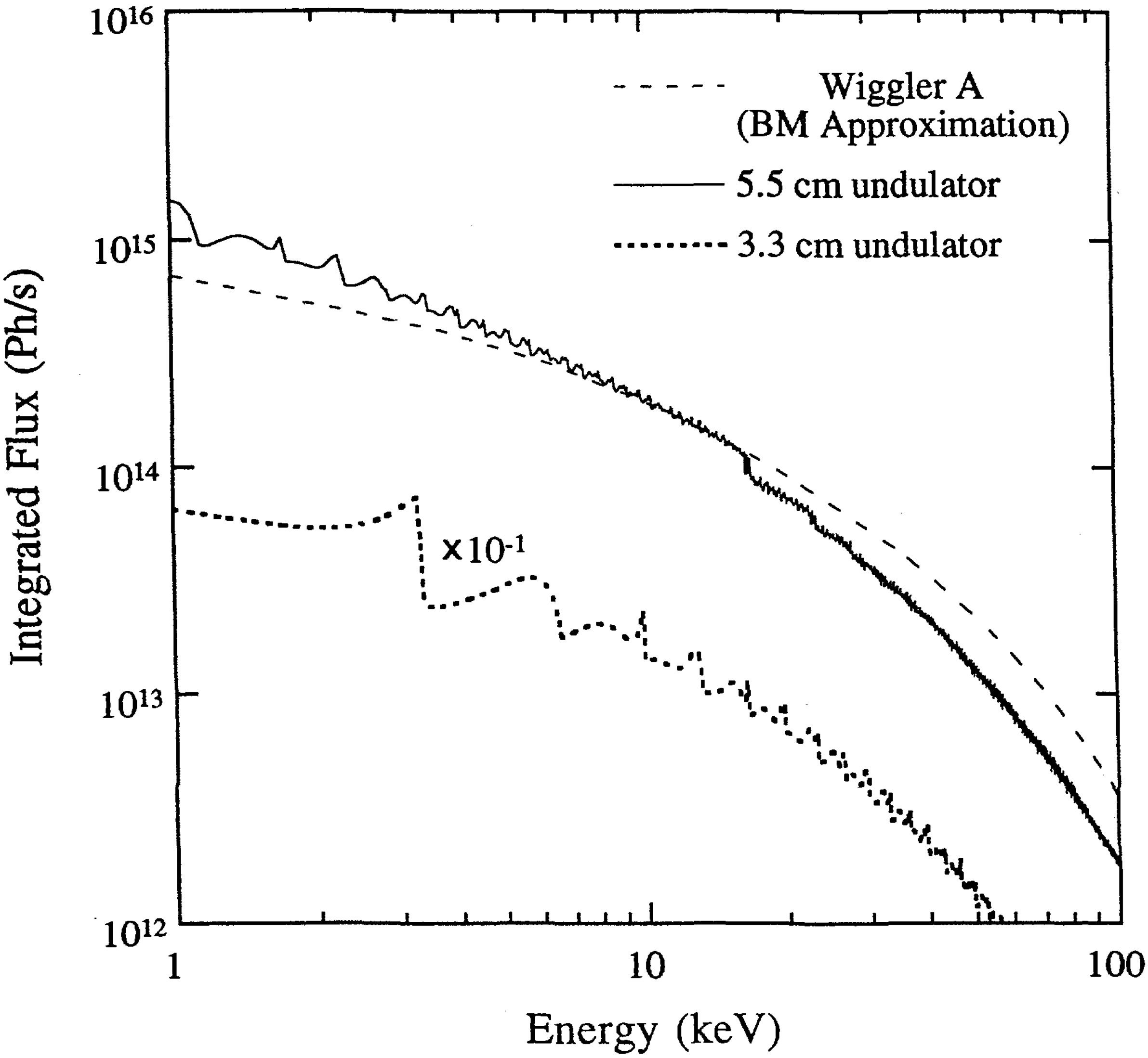


Fig. 2 Angle-integrated spectral flux produced by Wiggler A (calculated using the PHOTON program), the 3.3-cm Undulator A, and the 5.5-cm undulator (calculated using the XOP program).

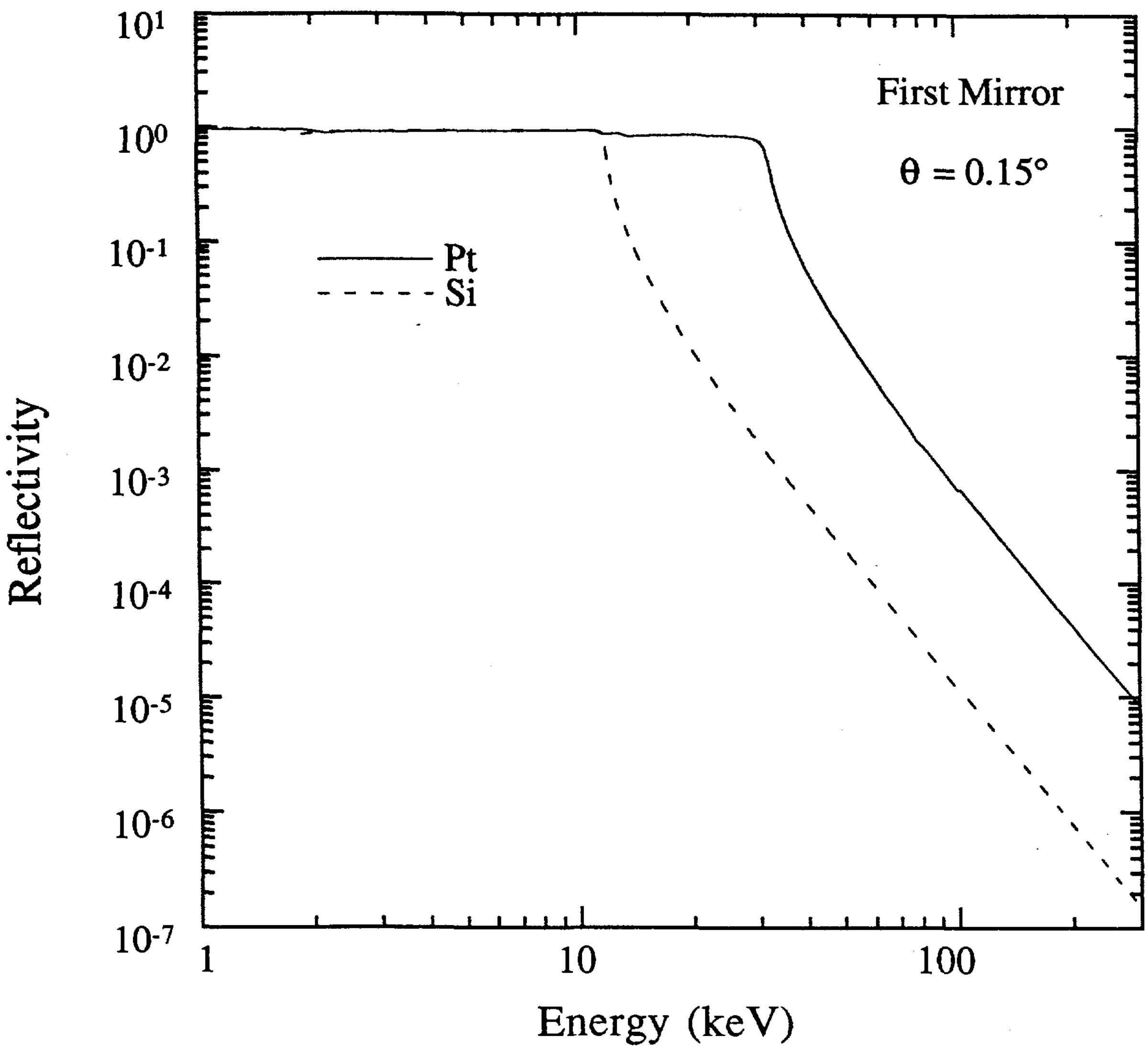


Fig. 3 Calculated reflectivity of the first mirror M1 using either the Si or the Pt reflecting coating. The incidence angle is 0.15°.

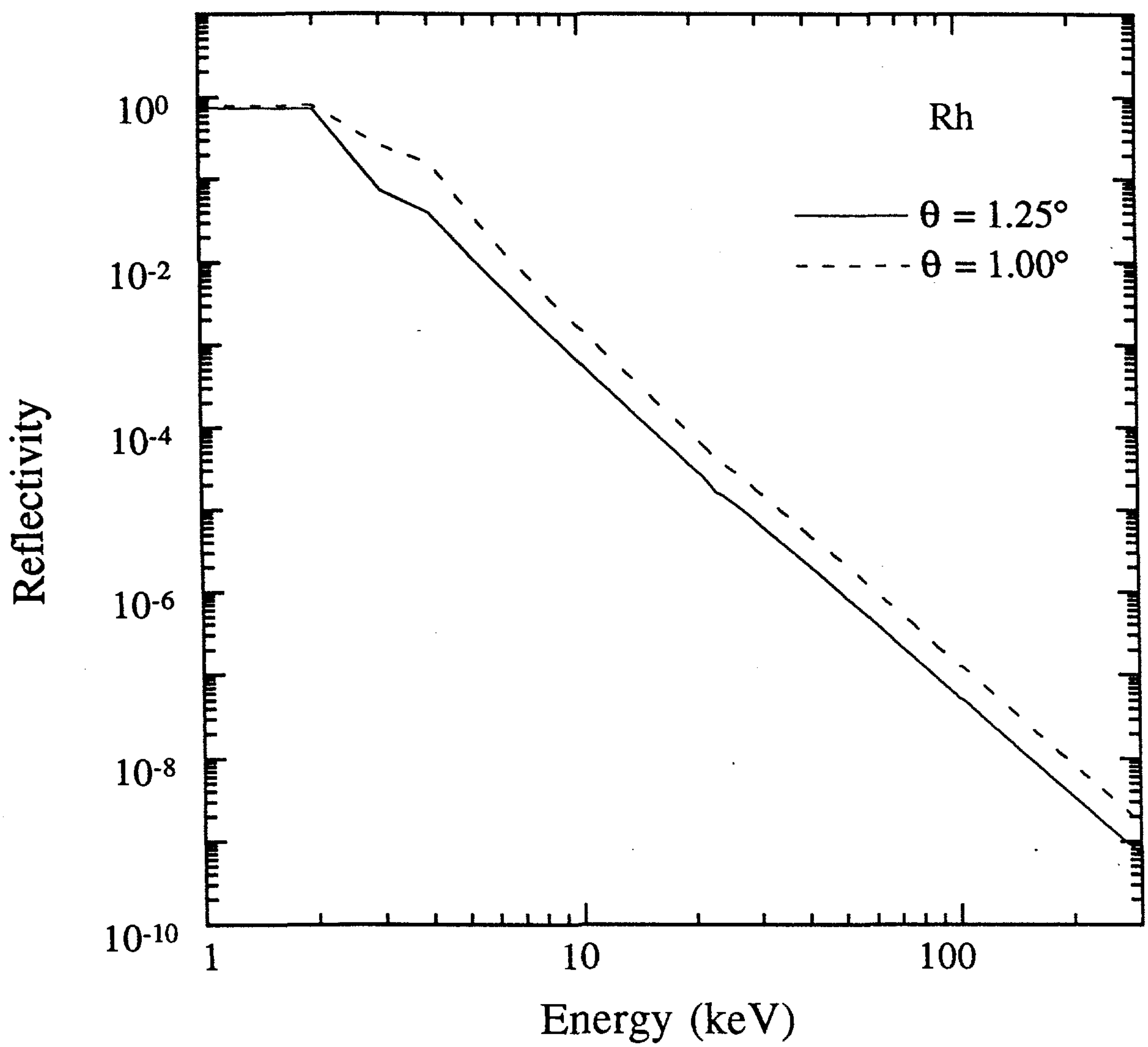


Fig. 4 Calculated reflectivity of the Rh coating on the M2B, M2C, and M3B mirrors at an incidence angle of 1.25° and on the M3C mirror at an incidence angle of 1°.

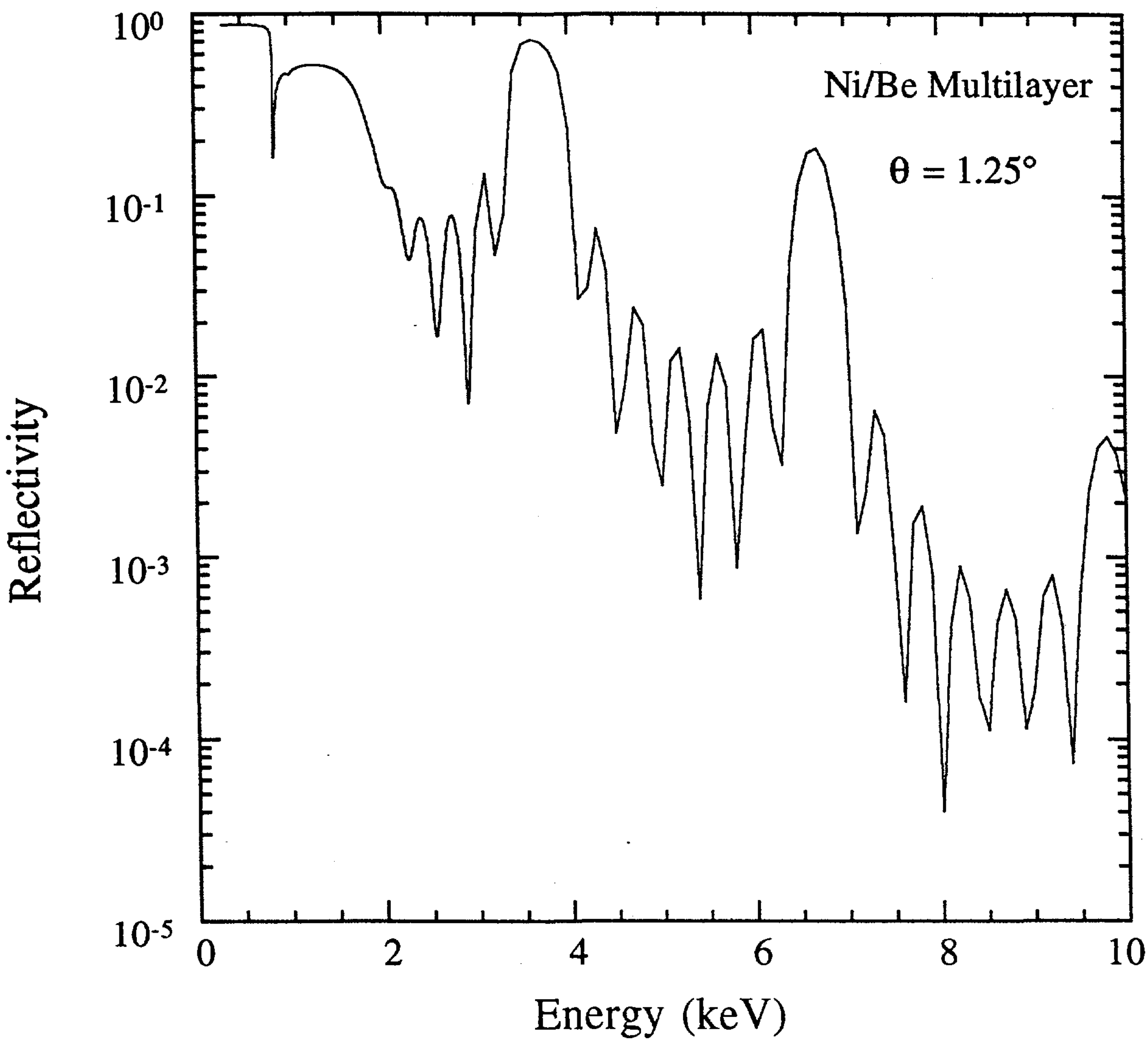


Fig. 5 Calculated reflectivities of a Ni/Be multilayer coating on the second (M2C and M2B) or third mirror (M3B). The multilayer parameters are given in the text. The incidence angle is 1.25°.

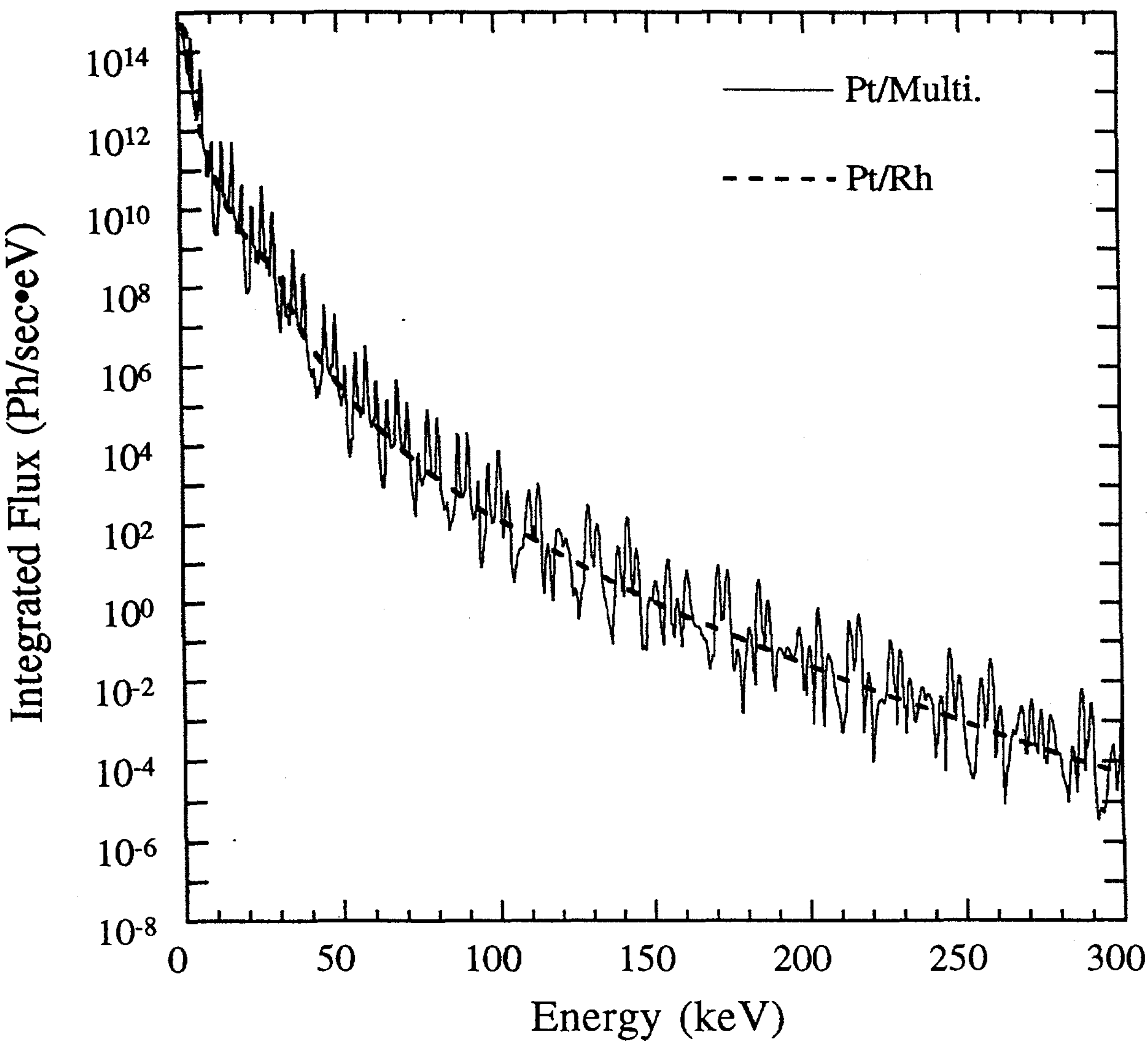


Fig. 6 Calculated angle-integrated spectral flux from APS Wiggler A after reflecting off the first (Pt) and second (multilayer or Rh) mirrors at $\theta_{in} = 0.15°$ and 1.25°, respectively, for the 2-ID-C branch line.

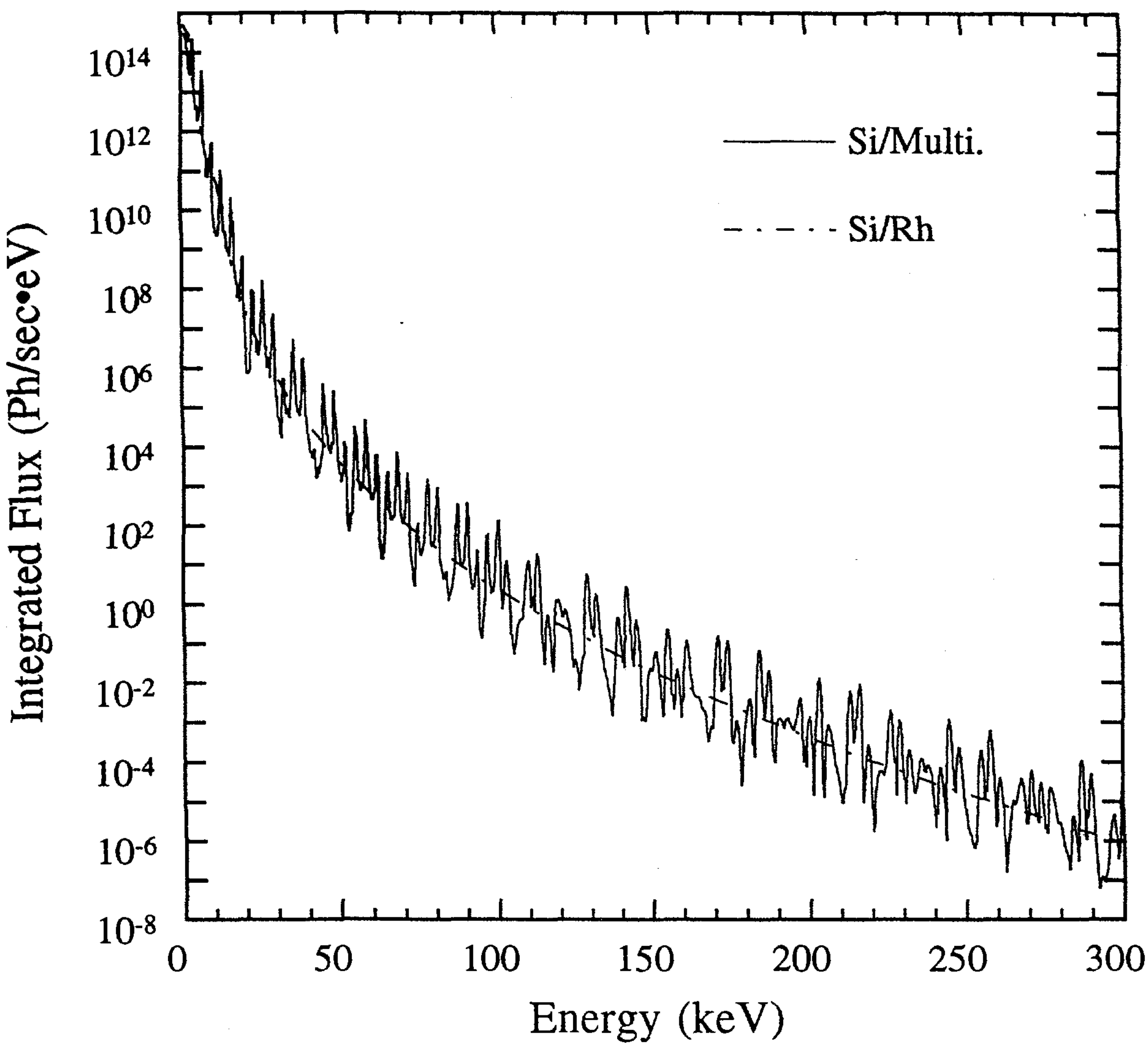


Fig. 7 Calculated angle-integrated spectral flux from APS Wiggler A after reflecting off the first (Si) and second (multilayer or Rh) mirrors at $\theta_{in} = 0.15°$ and $1.25°$, respectively, for the 2-ID-C branch line.

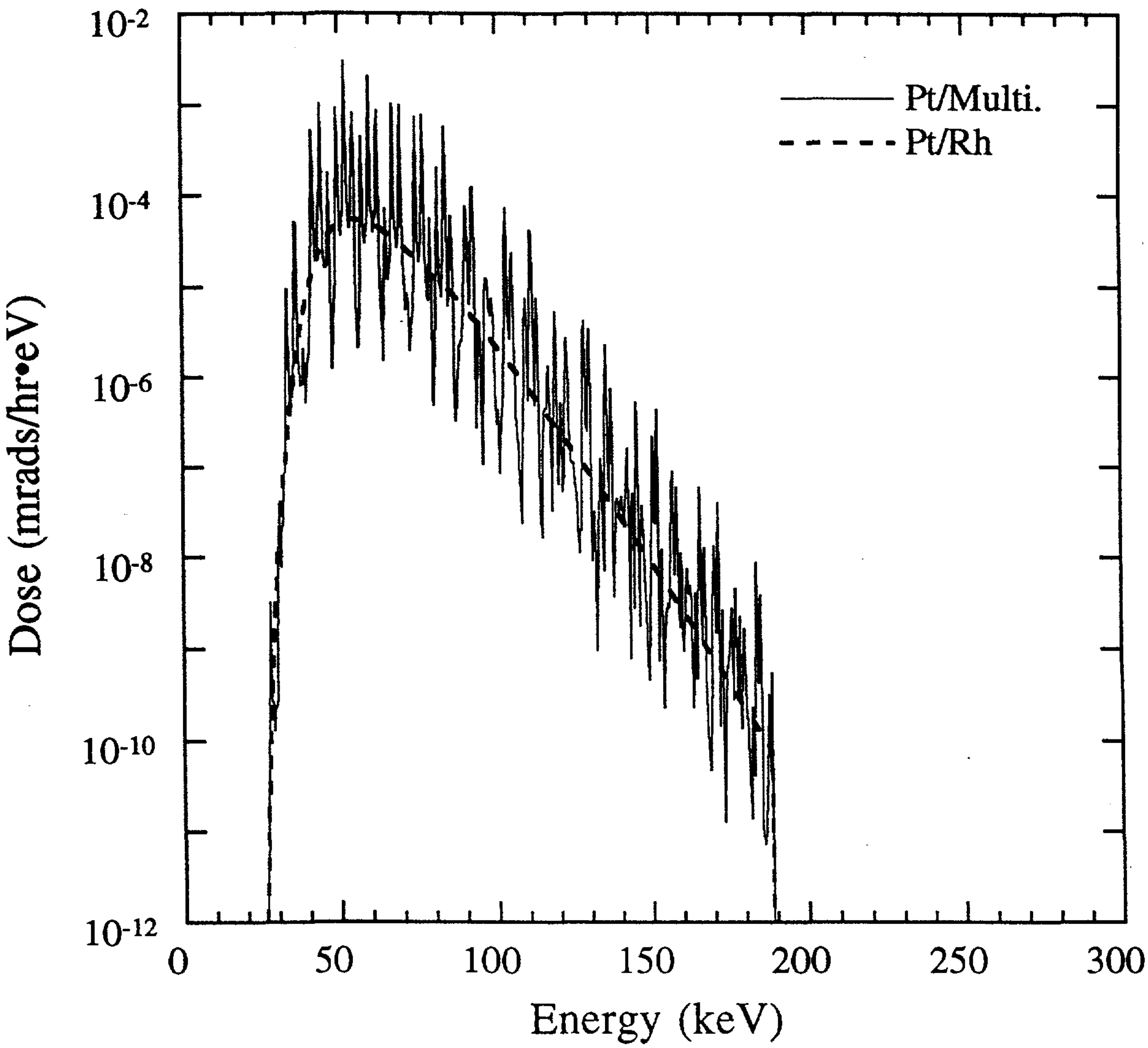


Fig. 8 Calculated spectral dose rate received by human tissue using the first (Pt) and the second (multilayer or Rh) mirrors for the 2-ID-C branch line. A 30-cm-thick Cu scatterer was assumed, and dose rate is calculated on the outer surface of a steel pipe of 2.5 inch in diameter and 1/16-inch wall thickness.

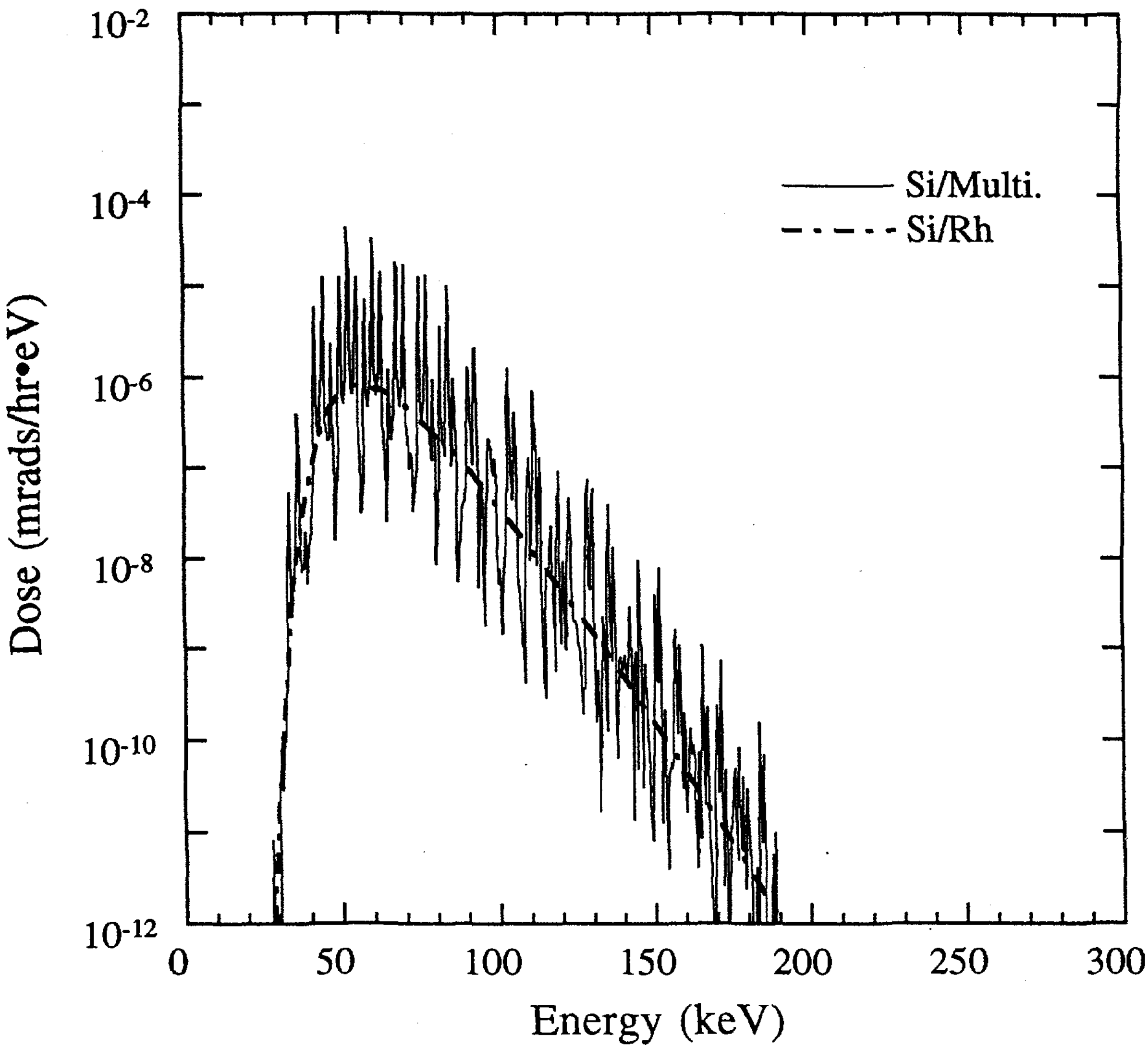


Fig. 9 Calculated spectral dose rate received by human tissue using the first (Si) and the second (multilayer or Rh) mirrors for the 2-ID-C branch line. A 30-cm-thick Cu scatterer was assumed, and dose rate is calculated on the outer surface of a steel pipe of 2.5 inch in diameter and 1/16-inch wall thickness.

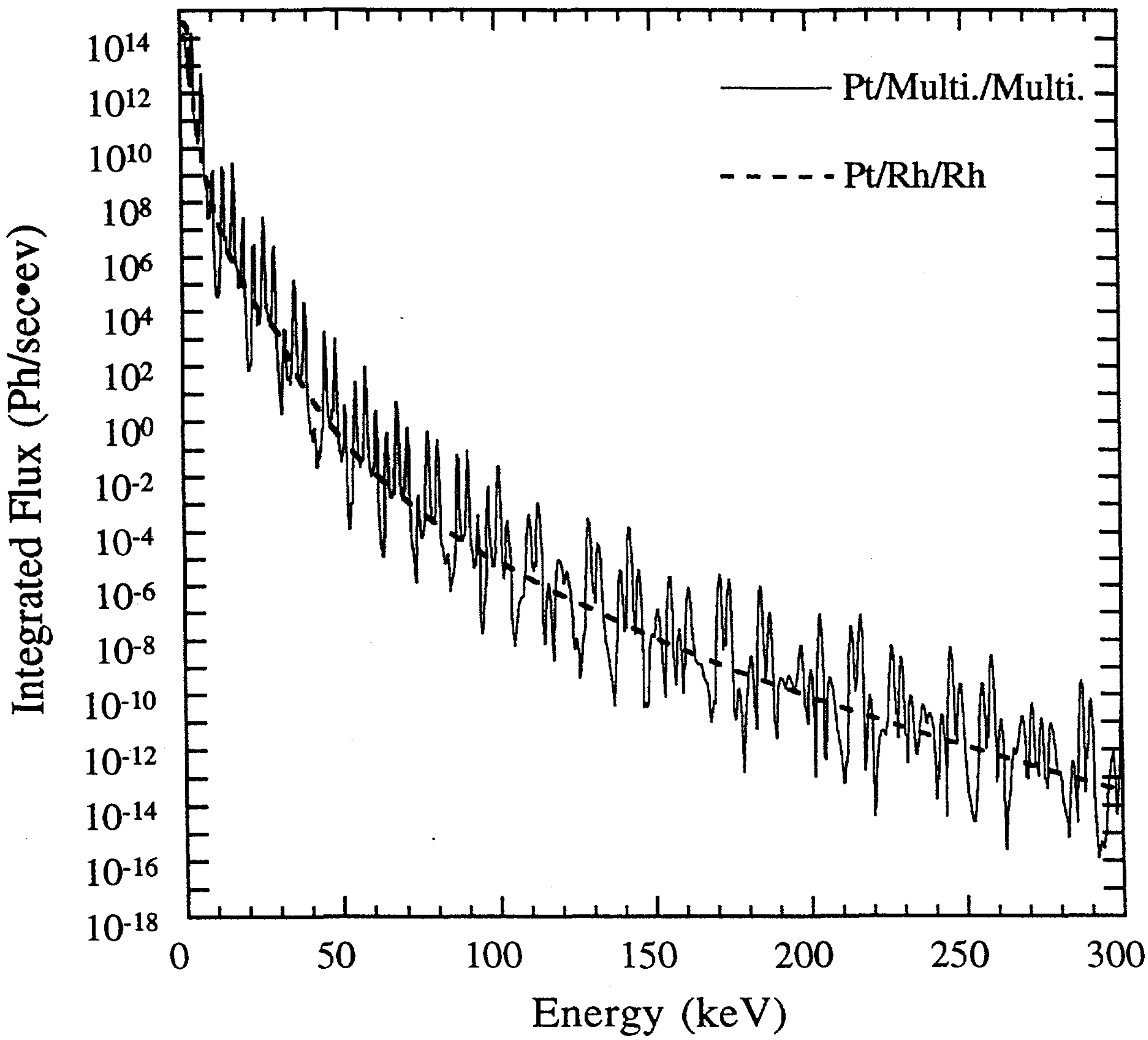


Fig. 10 Calculated angle-integrated spectral flux from APS Wiggler A after reflecting off the first (Pt), second (multilayer or Rh), and third (multilayer or Rh) mirrors for the 2-ID-B branch line.

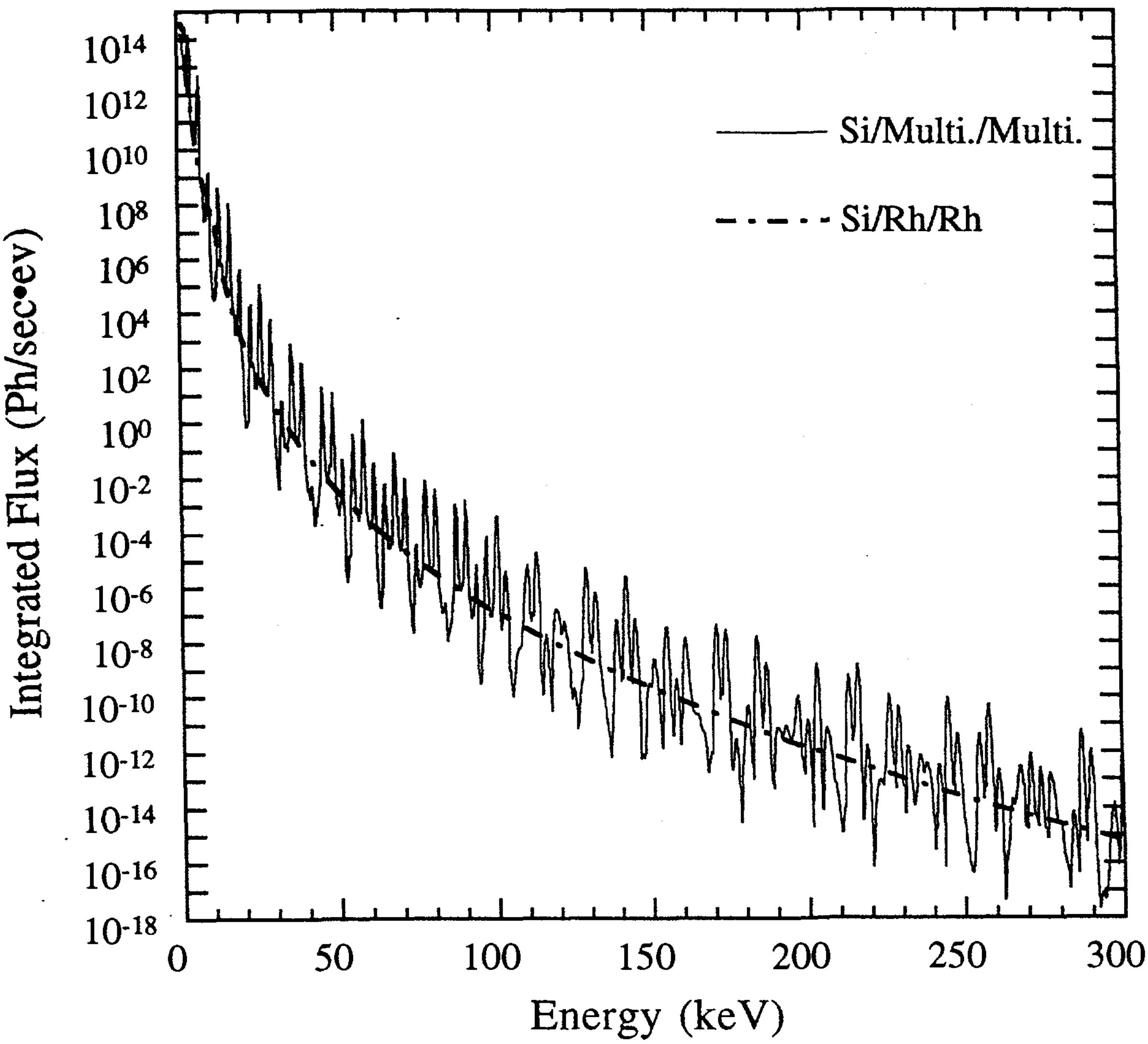


Fig. 11 Calculated angle-integrated spectral flux from APS Wiggler A after reflecting off the first (Si), second (multilayer or Rh), and third (multilayer or Rh) mirrors for the 2-ID-B branch line.

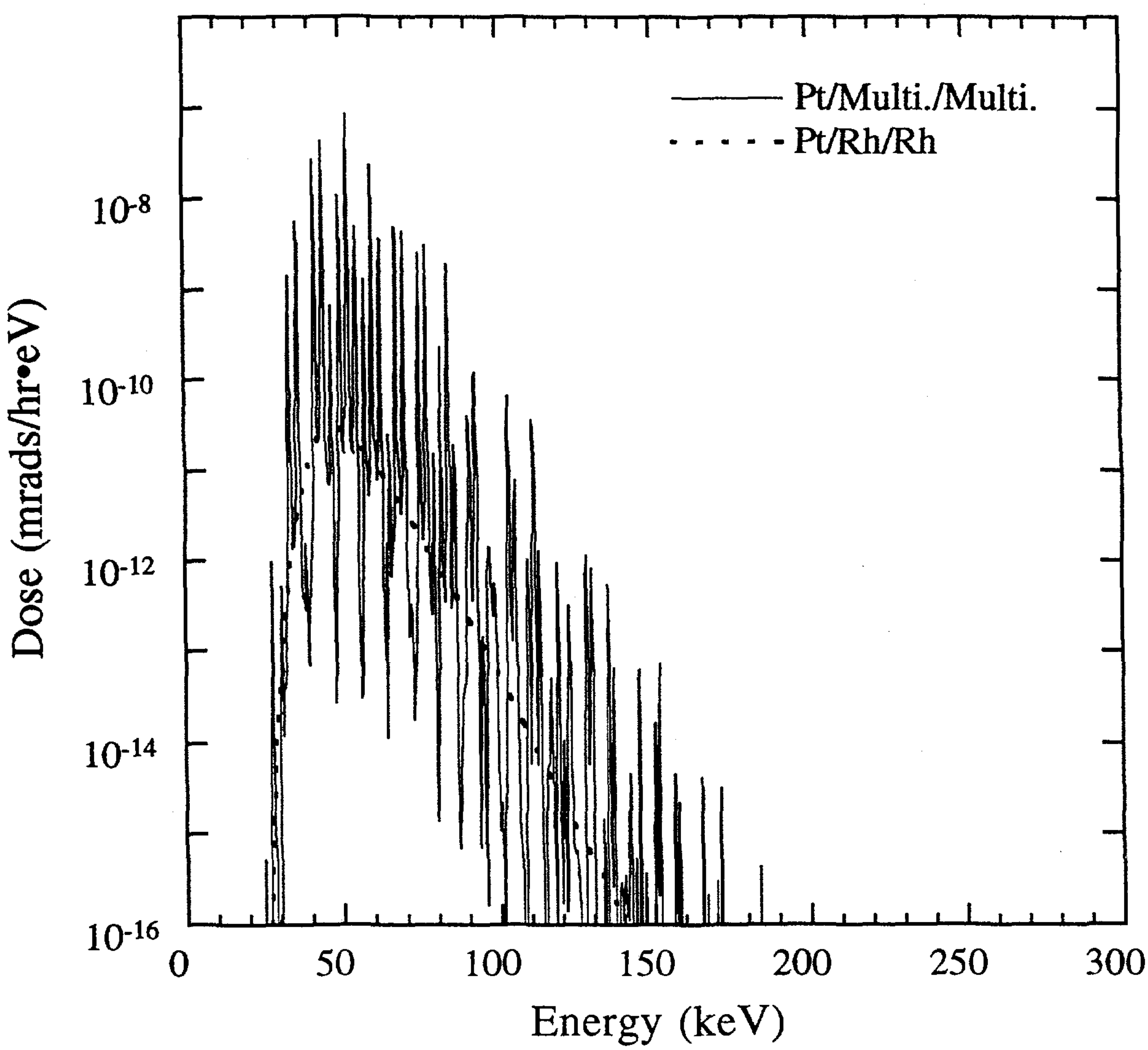


Fig. 12 Calculated spectral dose rate received by human tissue using the first (Pt), second (multilayer or Rh), and third (multilayer or Rh) mirrors for the 2-ID-B branch line. A 30-cm-thick Cu scatterer was assumed, and dose rate is calculated on the outer surface of a steel pipe of 2.5 inch in diameter and 1/16-inch wall thickness.

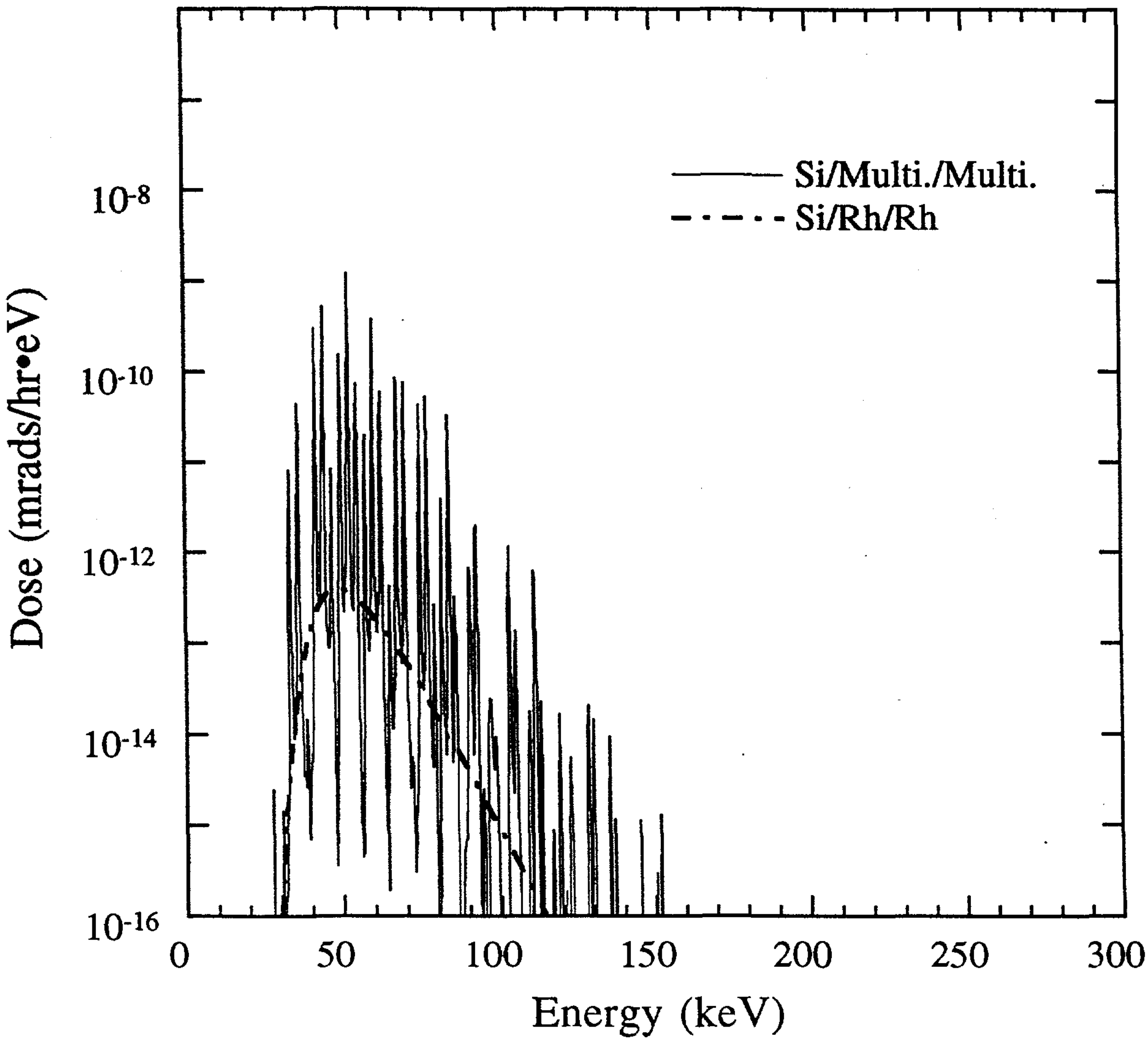


Fig. 13 Calculated spectral dose rate received by human tissue using the first (Si), second (multilayer or Rh), and third (multilayer or Rh) mirrors for the 2-ID-B branch line. A 30-cm-thick Cu scatterer was assumed, and dose rate is calculated on the outer surface of a steel pipe of 2.5 inch in diameter and 1/16-inch wall thickness.