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Aircraft Radiation Shield Experiments—Preflight Laboratory Testing

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Symbols

E_n	neutron energy, MeV
(n, 2n)	nuclear process in which one neutron enters a nucleus and two neutrons leave
y	linear energy, keV/μm
σ	cross section
σ_{el}	elastic scattering cross section, barns
σ_{in}	inelastic scattering cross section, barns

Abbreviations:

Cf-252	Californium isotope 252
FAA	Federal Aviation Administration
HSCT	High-Speed Commercial Transport
HSR	High-Speed Research
ICRP	International Commission on Radiobiological Protection
mb	millibarns, a measure of interaction probability between a projectile and a target. Barns are equal to 10^{-24} cm^2
MCNP	Monte Carlo *N*-Particle Transport Code
NCRP	National Council on Radiation Protection
NIOSH	National Institute for Occupational Safety and Health
PNL	Pacific Northwest Laboratory
TEPC	tissue-equivalent-proportional-counter dosimeter
USAF	United States Air Force

Abstract

In the past, measurements onboard a research Boeing 57F (RB57-F) aircraft have demonstrated that the neutron environment within the aircraft structure is greater than that in the local external environment. Recent studies onboard Boeing 737 commercial flights have demonstrated cabin variations in radiation exposure up to 30 percent. These prior results were the basis of the present study to quantify the potential effects of aircraft construction materials on the internal exposures of the crew and passengers. The present study constitutes preflight measurements using an unmoderated Cf-252 fission neutron source to quantify the effects of three current and potential aircraft materials (aluminum, titanium, and graphite-epoxy composite) on the fast neutron flux. Conclusions about the effectiveness of the three selected materials for radiation shielding must wait until testing in the atmosphere is complete; however, it is clear that for shielding low-energy neutrons, the composite material is an improved shielding material over aluminum or titanium.

1.0. Introduction

As a result of recent studies on cancer induction from radiation exposure due to the nuclear weapons detonations of World War II, both the National Council on Radiation Protection (NCRP) and the International Commission on Radiobiological Protection (ICRP) have lowered their recommended limits for radiation worker exposure from an annual basis of 5 rem to 2 rem (refs. 1 and 2). In addition, it has been recognized for many years that airline flight crews are the most highly exposed of any occupational group (ref. 3). The ICRP further recommended that for career planning, flight crew members should be treated as radiation workers and should be counseled on their individual exposures. Indeed, the exposures projected for some flight crew members approach and may, in usual circumstances, exceed the new recommended exposure limits. The NCRP has recently recommended that a new assessment of the radiation environment be made to improve the analysis of the radiation risks to flight crews.

Commercial airline flight crews have a unique working environment with exposures to known or suspected carcinogens or mutagens, particularly ionizing radiation, ozone, and jet engine emissions (refs. 4 through 7). Elevated hospitalization rates for malignant lymphomas and testicular cancers have been reported among U.S. Naval Aviators (ref. 8). However, they fly fewer hours and in a less hazardous radiation environment[1] than do commercial carriers[2]. Precise information about cancer risk in this environment is lacking, as is the environmental information necessary to assess its biological effects. However, many more studies of airline personnel are being conducted, including a recent Canadian study which observed increased brain and prostate cancers among Canadian airline pilots, but which did not note a cause (ref. 9). Measurement of the radiation environment at high altitudes has considerable uncertainties that compound the biological uncertainties. Part of the data used to derive and validate the ionizing-radiation predictive code used by the Federal Aviation Administration (FAA) was obtained on a B-36 bomber over 36 years ago. These data were acquired at geomagnetic latitudes much lower than commercial aircraft generally fly today and only at altitudes less than 41 000 ft (ref. 10). Furthermore,

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[1] 200 hr annually and usually less than 18 000 ft.

[2] Up to 1000 hr annually at up to 42 000 ft.

high-energy neutron radiation measurements were not made at that time because this radiation was not considered a problem.

Recently, *Aviation Week* reported (refs. 11 and 12) a controversy in Japan on commercial flight crew exposure to ionizing radiation on intercontinental flights. The Japanese flight crews are asking to be classified as radiation workers, which will give them some legal protection. A similar situation occurred in Europe a few years ago with Lufthansa and has yet to be resolved (ref. 13). The Commission for the European Community has been funding studies of radiation exposure of flight crews, but little progress has been made (private communication between Dr. Chris Hume, British Airways, and Donald Maiden, Langley Research Center, June 1996).

To study the ionizing radiation levels associated with the high-altitude flight of future High-Speed Commercial Transport (HSCT) aircraft, the High-Speed Research (HSR) office has initiated a project to measure the ionizing radiation environment by using a NASA ER-2 research aircraft. Assuming subsonic and supersonic flight crews fly the same annual block hours, the levels of ionizing radiation to which the HSCT crew will be subjected is estimated to be two to three times higher than that for crews on subsonic aircraft (ref. 14). Much effort has gone into expediting the HSR ER-2 flight project; however, the data from this experiment and its analysis will not be available for several years.

Because of the technology development time schedule, the results of the ER-2 flight data analysis cannot influence HSCT fuselage material selection; the data may affect only operational concerns. Therefore, a challenge exists for finding technologies that can reduce the levels of ionizing radiation exposure to flight crews and the public. Aside from reducing flight hours, there are presently no other solutions. Little radiation shielding materials research has been performed for aircraft application because the effect of radiation has only recently been elevated in concern, as prompted by the recommended lowering of radiation exposure limits from maturing medical studies of nuclear weapons and accident victims (refs. 1 and 2). These events, without proactive government regulatory action, have prompted NCRP criticism of the FAA for lack of attention to high-altitude radiation (ref. 15).

High-altitude radiation shields are not like terrestrial shields, such as lead and concrete, which are used to attenuate or moderate the radiation. Starting in 1964 and continuing through the mid-1970's, scientists at Langley Research Center conducted flight tests using USAF RB57-F aircraft and balloon flights (refs. 16 and 17). The results indicated that the dose measured in the RB57-F aircraft was 10 percent higher than that in the free atmosphere. It is believed that this higher dose was caused by the amplification of high-energy neutrons by the aluminum in the fuselage. Australian airline measurements have shown approximately a 30-percent decrease in the dose rate for the cabin, compared to the cockpit of a Boeing 737 (ref. 18). The authors of this study conjectured that the passengers in the cabin were absorbing the radiation before it could be detected.

Theoretical analyses suggest that high-altitude ionizing radiation shielding characteristics are a function of atomic number. The smaller the atomic number is, the better the overall shielding characteristics will be. This finding may make it possible to find a reasonable shielding material that can be incorporated in the acoustical linings and decor of the cabin, or more practically, integrated with the structural material itself.

Among the candidate material studies in a Langley Research Center program for deep space and lunar habitat radiation shielding, a polymer composite material having a boron-impregnated resin has had some success in absorbing low-energy neutrons (refs. 19 through 24), but the utility of the material is unknown. In Europe, radiation shielding materials research is being conducted on a boron-manganese shielding material, but the details are not available (private communication, Boeing and Deutsche

Airbus sponsored study by Dailmre-Benge, 1996). Even a marginally effective material would have wide application in aviation and might provide an environmental marketing incentive for new commercial transports. The present study is the beginning of a program to evaluate potential aircraft materials to quantify their effectiveness in reducing cabin radiation levels.

The purpose of this work is to begin a set of flight experiments for in situ measurements of the ionizing radiation shielding characteristics of current and potential aircraft materials. The candidate materials being preflight tested are a graphite-epoxy composite, an aluminum-lithium alloy with copper, and a titanium alloy with vanadium and aluminum. The candidate material specimens are designed to shield a tissue-equivalent-proportional-counter (TEPC) dosimeter. Two TEPC dosimeters will be used for comparison studies. The TEPC dosimeters are similar to those being flown on the Space Shuttle, those being used in an FAA-NIOSH epidemiological study of reproductive problems encountered by female U.S. airline flight attendants, and those recently flown on the Atmospheric Ionizing Radiation ER-2 flight measurements by the Boeing Airplane Company, Seattle, Washington, and the Defense Research Establishment, Ottawa, Canada.

2.0. Science Overview

Prior studies (refs. 16 and 17) in the late 1960’s observed that the neutron levels within the RB57-F were somewhat higher than the ambient levels. Researchers conjectured that the production of fast neutrons by aircraft materials was the primary contributing factor. In addition to the neutron environment, the direct knockout of nuclear clusters from the target material is observed in Space Shuttle measurements (ref. 25) and may prove an important source of secondary charged particles produced in the aircraft structures.

The atmospheric neutrons consist of a low-energy component (0.1 to 10 MeV) and a high-energy component (50 to 1000 MeV). The low-energy neutrons interact with the shield mainly through elastic scattering in which the neutron energy is reduced over many collisions; large-angle scattering can reduce the intensity through diffusion. The interaction of low-energy neutrons is well understood due to many years of research associated with the development of nuclear power. An important process is the elastic scattering of the neutrons wherein the neutron is scattered and a fraction of its energy is transferred to the shield and dissipated as harmless heat. Consequently, some of the neutrons are scattered by the shield, providing additional protection. The scattering cross sections (ref. 26) are shown in figure 1 for typical constituents of the shields being analyzed. In complex nuclei, neutrons can also excite nuclear states within the material, which ultimately de-excite with gamma ray emission. These secondary gamma rays are less damaging than the neutrons themselves and directly pose little hazard. The neutron inelastic cross sections (ref. 26) are shown in figure 2 and are seen to be zero up to the first excited state and somewhat less than the elastic cross sections in figure 1 in the higher energy region. As can be seen in figure 2, the thresholds decrease with increasing complexity of the nucleus so that inelastic processes will generally be more important in higher atomic number shields. Low-energy neutrons can be multiplied in the shield materials through (n, 2n) processes. These cross sections (ref. 26) are shown in figure 3. The thresholds for these processes lie above the single particle excitation energies, and only the upper energy bands of the low-energy neutrons in this environment participate as seen in the figure.

Most of the effectiveness of the materials in actual flight is expected to result from the collisions of high-energy neutrons producing more secondary particles in the materials. For example, the neutron production cross sections for 1-GeV neutrons on atomic constituents of the candidate materials are shown in table 1. It is apparent from the cross sections that neutron production in the shield is strongly dependent on the shield composition, with higher atomic numbers being far more prolific in the generation of secondary neutrons. Therefore, a significant increase in the neutron flux is expected from the metal alloys, while little change is expected in the polymeric composite because the gains of secondary neutrons will partly compensate for the reduction in the fast neutron flux in the polymeric composite.

Table 1. Neutron Production Cross Sections for Collisions of
1-GeV Neutrons With Various Nuclear Constituents (ref. 27)

Element	Cross section σ, mb
H	0
B	521
C	688
O	893
AL	1695
Ti	4328

3.0. Experimental Configuration and Theoretical Considerations

Before any flights of the TEPC dosimeters occur for the ER-2 shielding materials investigation, they need to be tested and evaluated against sources that can approximate aspects of the environment at high altitude. An unmoderated Cf-252 fission neutron source at the Pacific Northwest Laboratory (PNL) in Richland, Washington was used to simulate the low-energy component. This facility has a large room, shown in figure 4, where the object is exposed to the source. The source is remotely placed in the foreground structure, and the background structure is a platform that allows movement of the object during the exposure. The TEPC's are placed on a moveable cart, seen in figure 5, which can be manipulated from the control room. When not in use, the source is stored in the source well shown in the foreground of figure 6.

The TEPC's, built by Battelle at PNL, contain a 5-in. proportional counter and associated multichannel analyzer, as shown in figure 7. The proportional gas is contained in a tissue equivalent plastic sphere. The processor electronics and flash memory module are shown in figure 8. The entire package, with electronics module and counter, is shown in figure 9.

The three shield materials were all constructed to be 3 g/cm^2 thick. The first material is an aluminum alloy that is 95 percent aluminum, 4 percent copper, and 1 percent lithium and is approximately 0.5 in. thick. The second material is a lightweight titanium alloy that is 90 percent titanium, 6 percent vanadium, and 4 percent aluminum and is approximately 0.25 in. thick. The last material is a graphite-epoxy composite (AS4/3502, with a fiber volume of 0.68) approximately 0.75 in. thick. The shields are constructed as cylinders that fit around the TEPC's and are attached to the flange seen in figure 9. For flight qualification, the shields will be fitted to the TEPC with foam rubber filling and attached to a pallet with the various power and data couplings. For the Cf-252 exposures, the shields were loosely fitted around the TEPC and placed on the cart, as shown in figure 5.

As a secondary check on the Cf-252 exposure results, the Monte Carlo *N*-particle Transport Code (MCNP) (ref. 28) was used to model the source and shields. Figure 10 shows a comparison among the three shields and the ambient radiation environment. For the energies above 1 MeV, MCNP shows that the composite shield should reduce the number of neutrons, as compared to the other shields and the ambient environment. Below 1 MeV, the number of neutrons from the composite shield should increase to two orders of magnitude over the ambient environment. However, the importance of these neutrons to the overall dose is small compared with the higher energy neutrons and other particles, so this large rise is of little consequence. The transfer of the high-energy neutrons to lower energies in the composite shield has the effect of reducing the total dose equivalent behind the composite shield.

The energy spectrum of the Cf-252 source, shown in figure 11, peaks at approximately 2.5 MeV with a low-energy cutoff at 1 keV because neutrons below this energy are not large contributors to biological interactions that could cause damage. Therefore, the spectrum, which rises smoothly above 10 keV to a maximum 2.5 MeV, is a good simulator of the evaporation source of low-energy atmospheric neutrons (ref. 10).

4.0. Results and Discussion

The TEPC's were exposed to PNL's Cf-252 source for approximately 11 hr, rotating the shields approximately every 2 hr between TEPC 1 and TEPC 2. The raw data were downloaded from the TEPC's and an integral spectrum was created. Figures 12 through 14 show these spectrums for TEPC 1 compared to the bare spectrum. Figures 15 through 17 are for TEPC 2. The ordinate has been modified by the square of the abscissa to accentuate and separate the neutron and gamma portions of the spectrum. The peak above 10 keV/μ is the neutron component, and the plateau below is the gamma component. Because background exposures were not taken, and the minute-by-minute spectrum data are not readily available, a counting statistics or noise reduction analysis cannot be performed on these spectral data.

To compare the three shield materials with one another, figures 18 and 19 show the relative difference between the shielded TEPC's and the bare TEPC's. These figures, along with the spectral figures, show that the composite shield is most effective, by an order of magnitude, in reducing the number of neutrons below the proton knockout region at approximately 200 keV/μm. The gamma ray shielding efficiency of the composite is not as great as that of titanium, but these fission-based gamma rays do not exist in the high-altitude environment. In another view of the data, figures 20 and 21 plot lineal energy versus the fraction of the flux for a specific shield over the bare TEPC. These figures show that below 200 keV/μm, the composite shield is most effective in reducing the counts from neutrons in the TEPC's.

To check the consistency of the two TEPC's, figure 22 shows the difference between TEPC 1 and TEPC 2 without a shield. It appears that TEPC 2 may be slightly more efficient in detecting neutrons than TEPC 1, but this will need to be confirmed in a more controlled environment.

These data contained a narrow peak at approximately 10 keV/μm. This narrow peak (four channels wide) cannot be caused by any external radiation source. Upon subsequent testing with these and other TEPC's with low and moderate strength sources, the peaks disappear. Therefore, it is reasoned that the extremely high count rate caused by the intense Cf-252 source is perturbing the electronics; this interference will not be a problem when these TEPC's are flown on the ER-2.

Within the context of the low-energy neutron test performed at the PNL's fast neutron test facility, the advantages of the composite shield are evident. These advantages result from the moderating effects of the hydrogen rich material and the resultant high threshold for (n, 2n) processes. The aluminum alloy is not as effective a moderator as the composite material, but the (n, 2n) reaction threshold is still sufficiently high, and the small copper content adds little to the total neutron field within the alloy. The titanium alloy is ineffective as a moderator, and the (n, 2n) threshold is relatively low. From the MCN analysis, the titanium alloy produced 2.8 times as many neutrons as the aluminum alloy and over 600 times more than the composite material.

The particle production processes will play a more important role for the atmospheric neutrons with their high-energy component than the testing performed so far. These processes can be seen in figure 3 and in table 1 for the (n, 2n) reaction channel, which grows in importance at the higher neutron energies. These energy ranges also open other reaction channels with high-particle multiplicities. These processes will be tested in the flight program, and the current results will allow some judgment on the relative importance of their contributions.

5.0. Concluding Remarks

The current results are consistent with the cross sections of the material constituents and demonstrate the importance of aircraft material choices on the neutron flux levels exposing the crew and passengers. Determination of the shielding characteristics of the test materials at high altitude must await in situ ER-2 flight measurements in the full-atmosphere environment. However, for neutrons with lineal energies below about 200 keV/μm and gross energies below 10 MeV, the composite test material shows an improved shielding response relative to aluminum and titanium. This response occurs because the composite material scatters higher energy neutrons to lower energies, making them less important in biological damage processes. The composite material also does not create as many secondary particles as aluminum or titanium, thus reducing the potential for biological damage.

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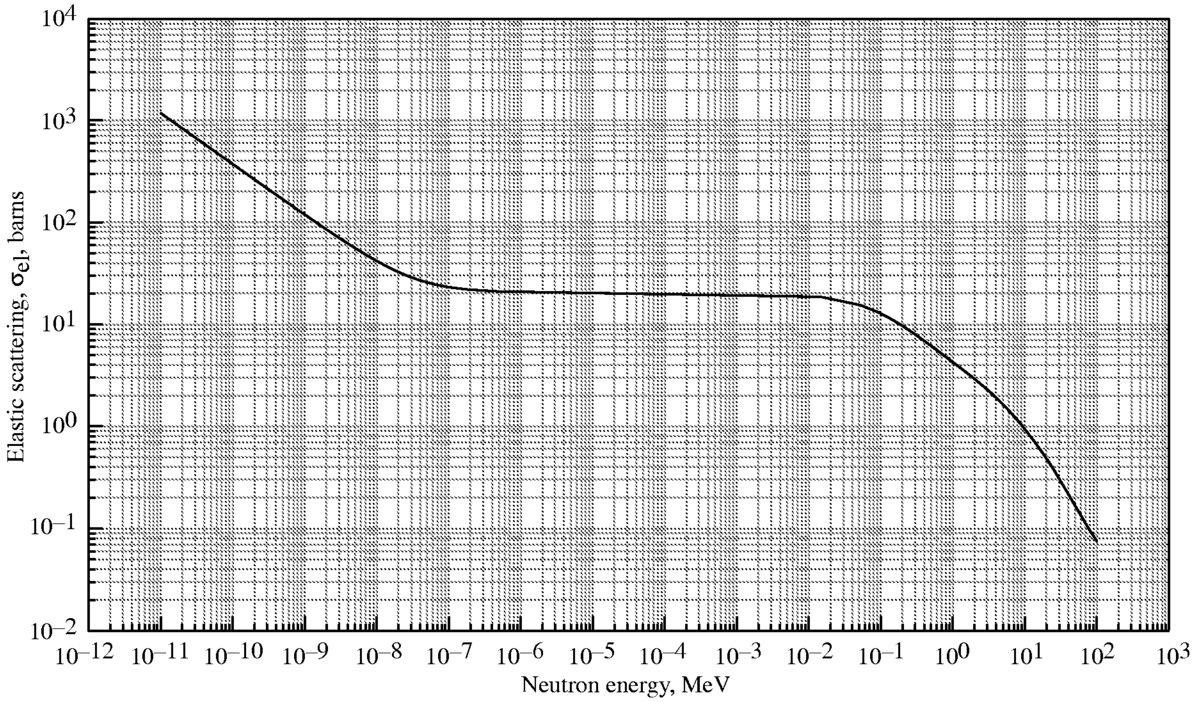
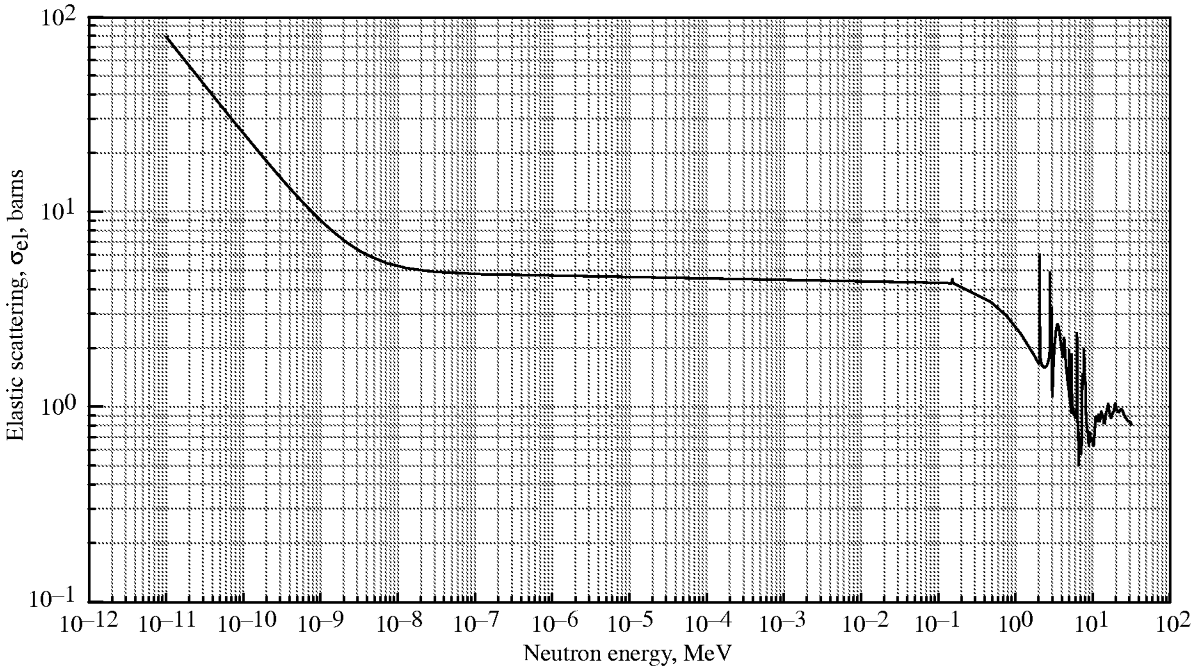
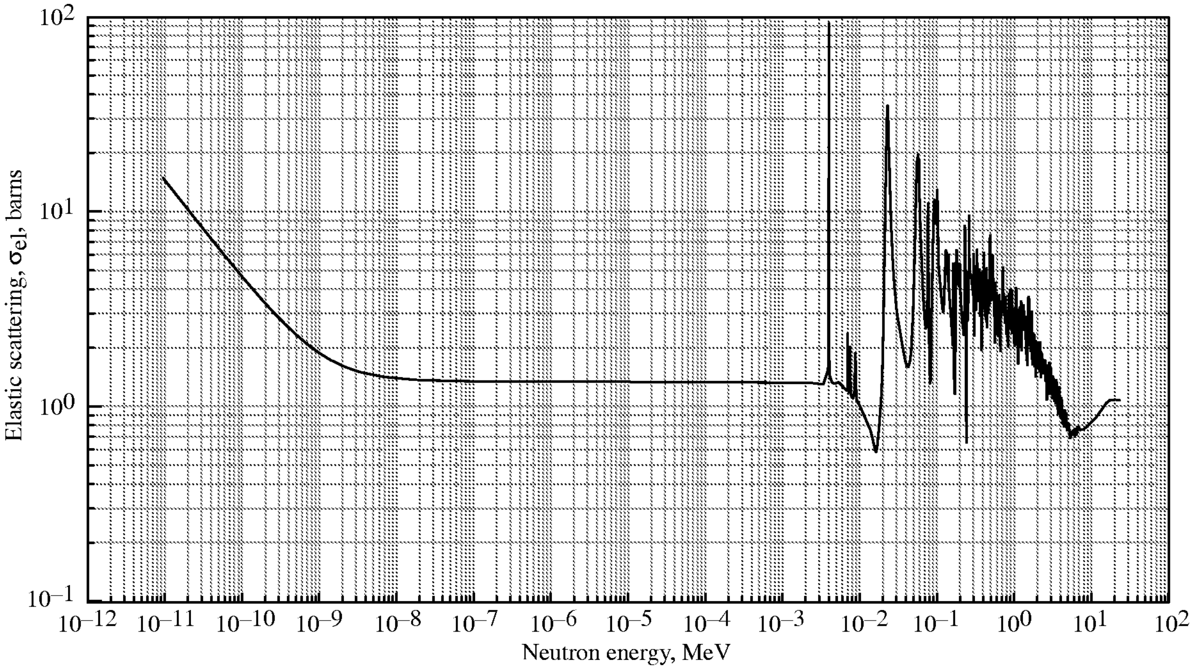


(a) In hydrogen.

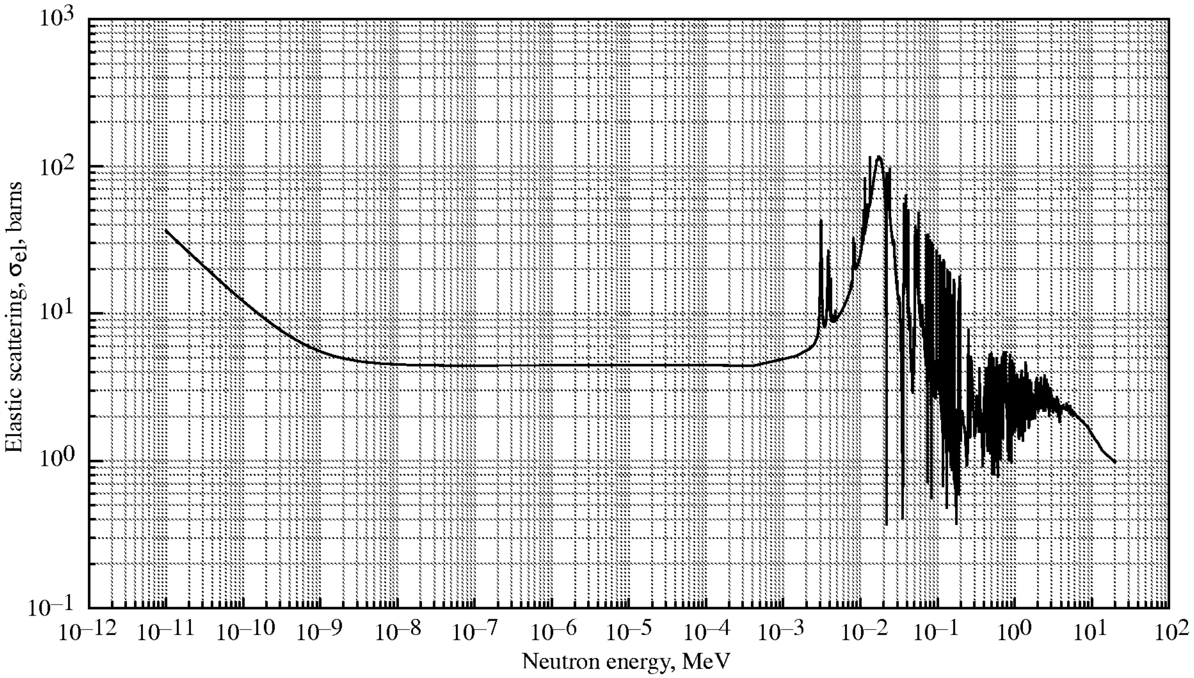


(b) In carbon.

Figure 1. Elastic scattering cross section σ_{el} for neutrons E_n at 300 K.

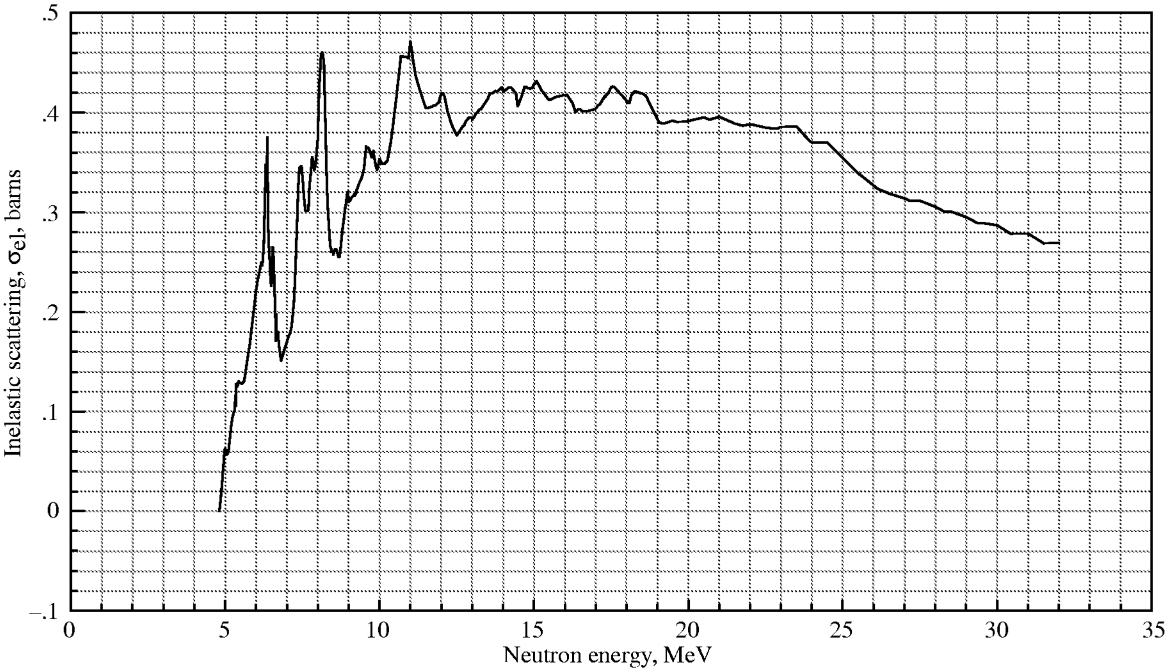


(c) In aluminum.

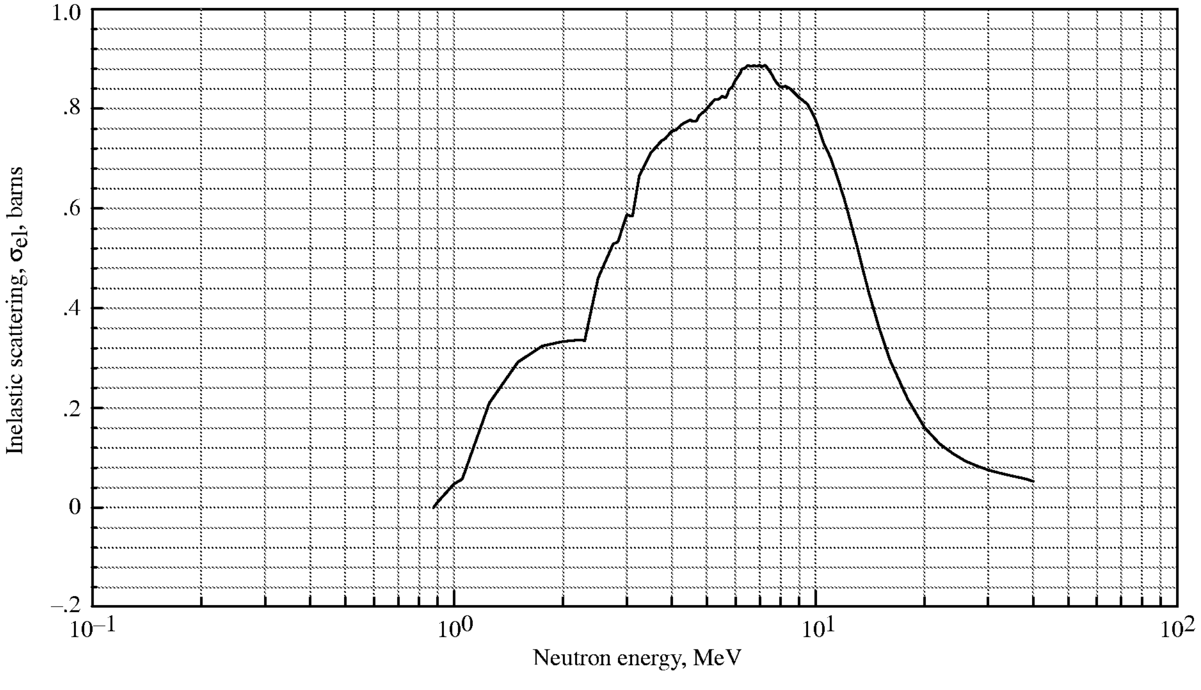


(d) In titanium.

Figure 1. Concluded.

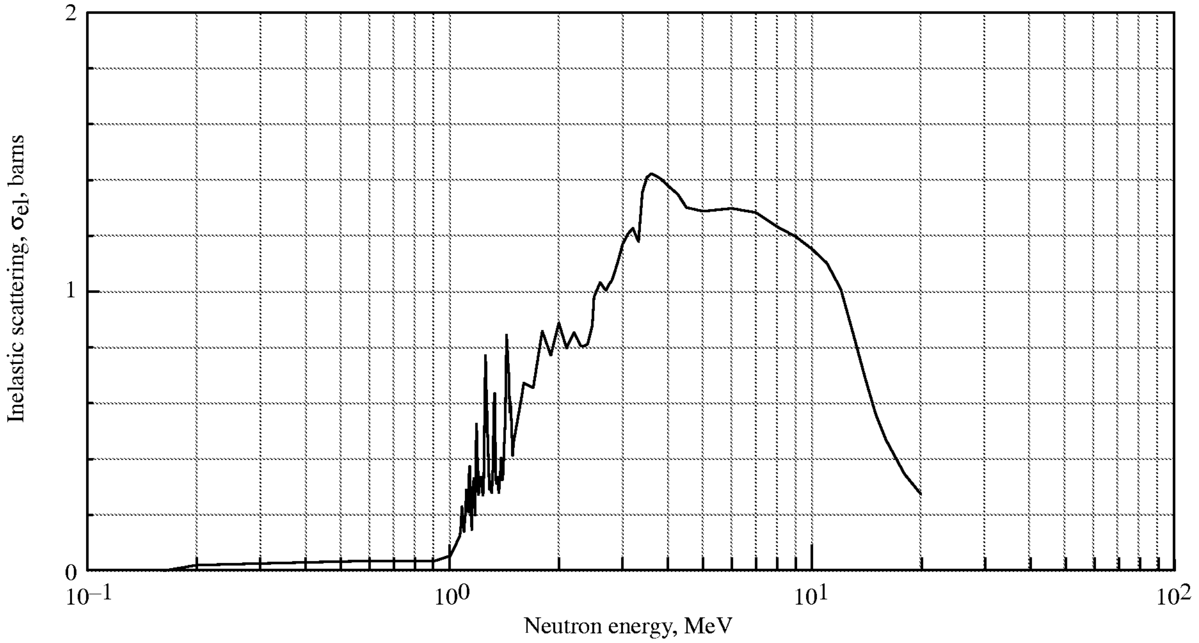


(a) In carbon.



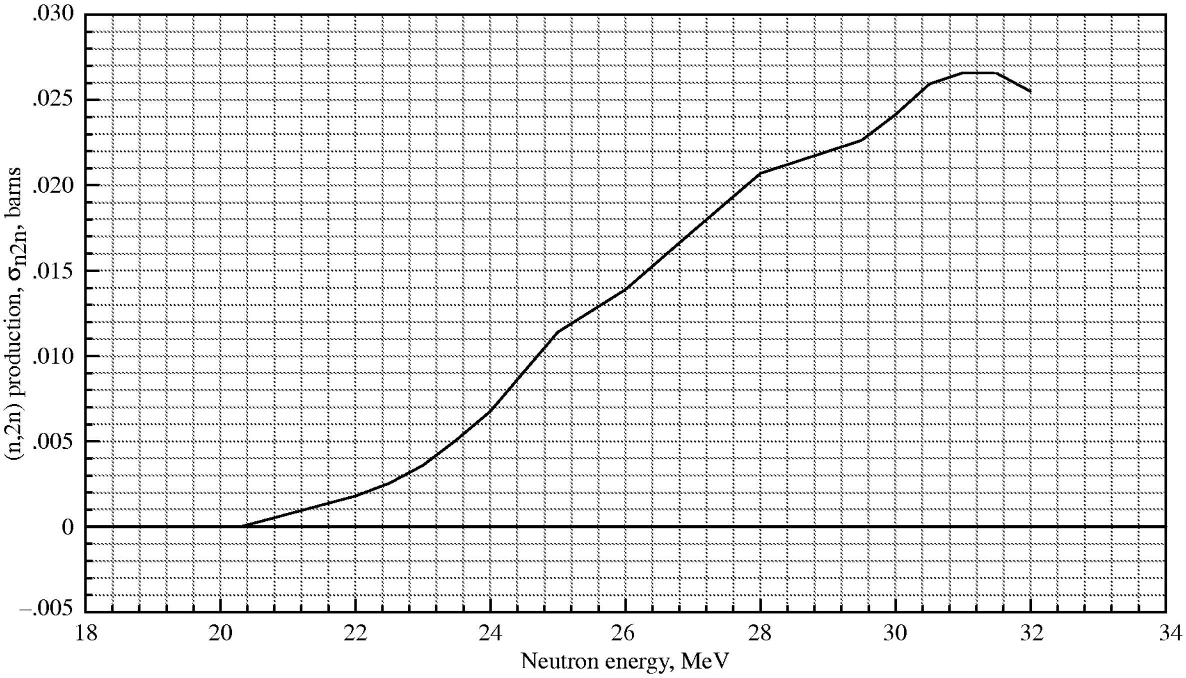
(b) In aluminum.

Figure 2. Inelastic scattering cross section for neutrons at 300 K.

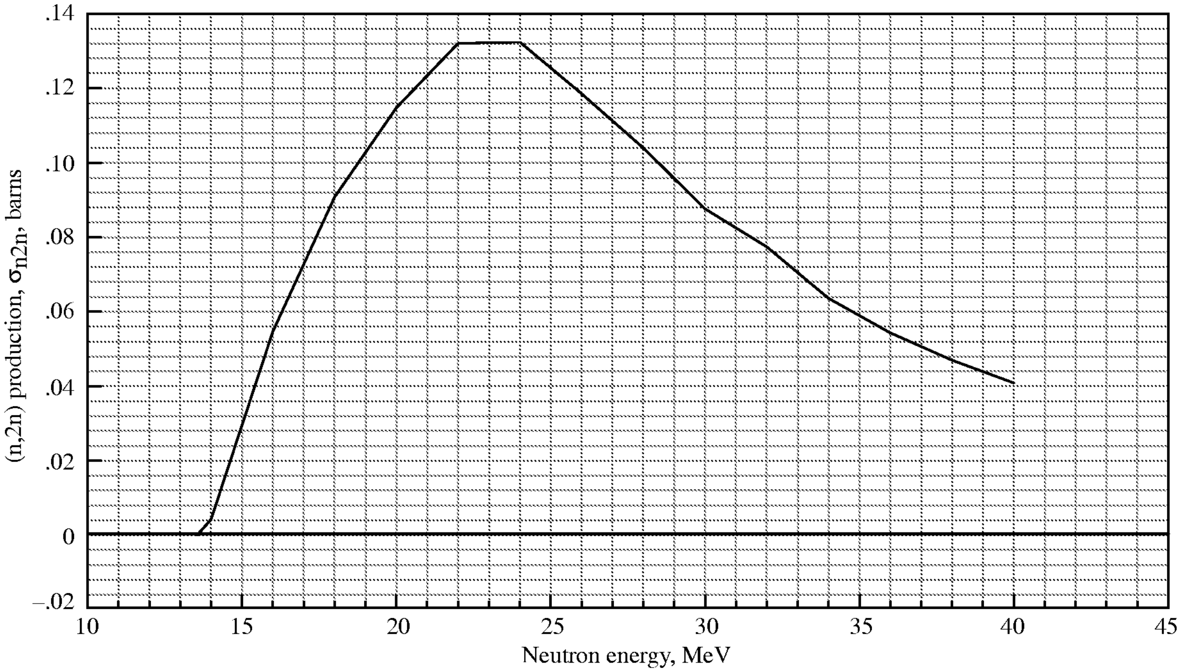


(c) In titanium.

Figure 2. Concluded.

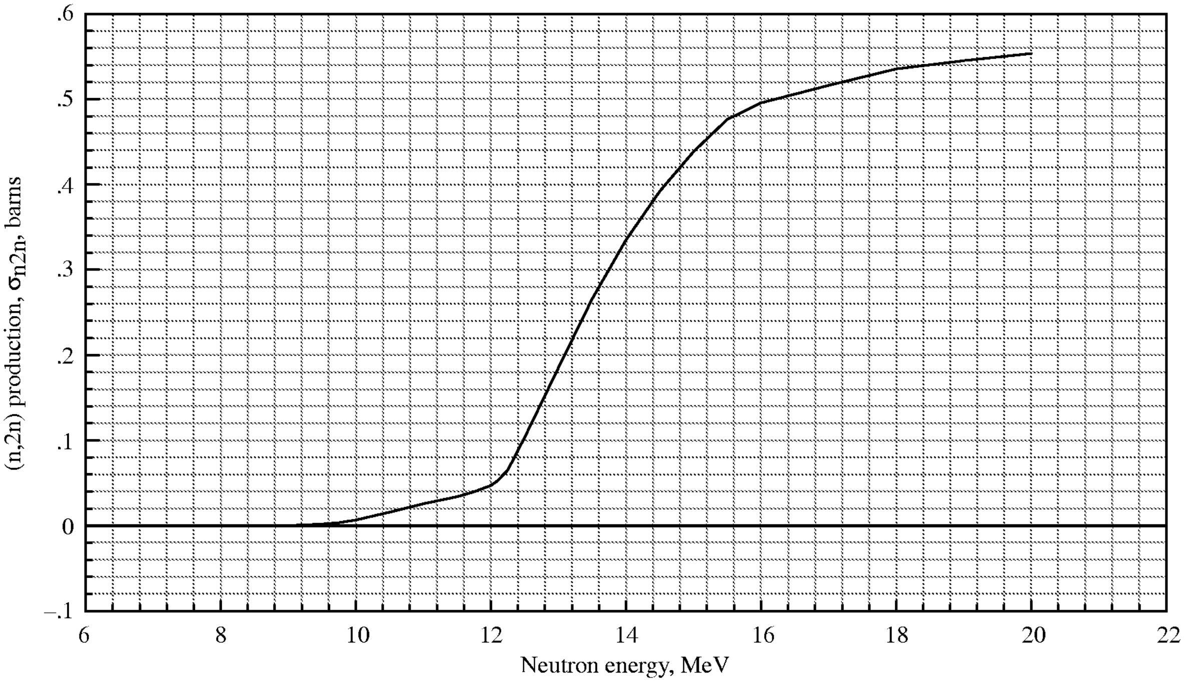


(a) In carbon.



(b) In aluminum.

Figure 3. The (n, 2n) production cross section for neutrons at 300 K.



(c) In titanium.

Figure 3. Concluded.

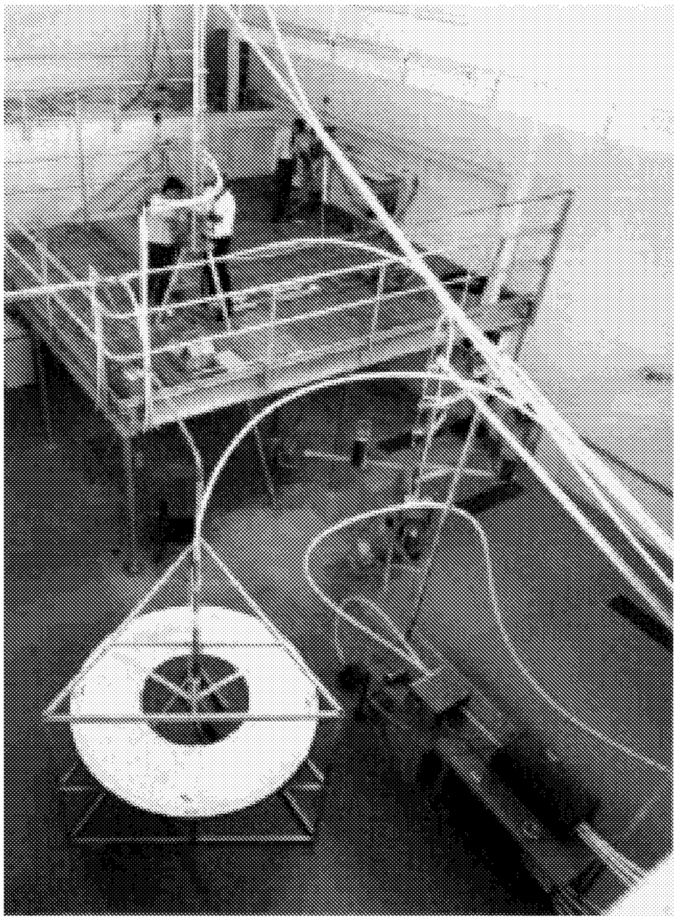


Figure 4. Exposure room with source in foreground and exposure platform in background.

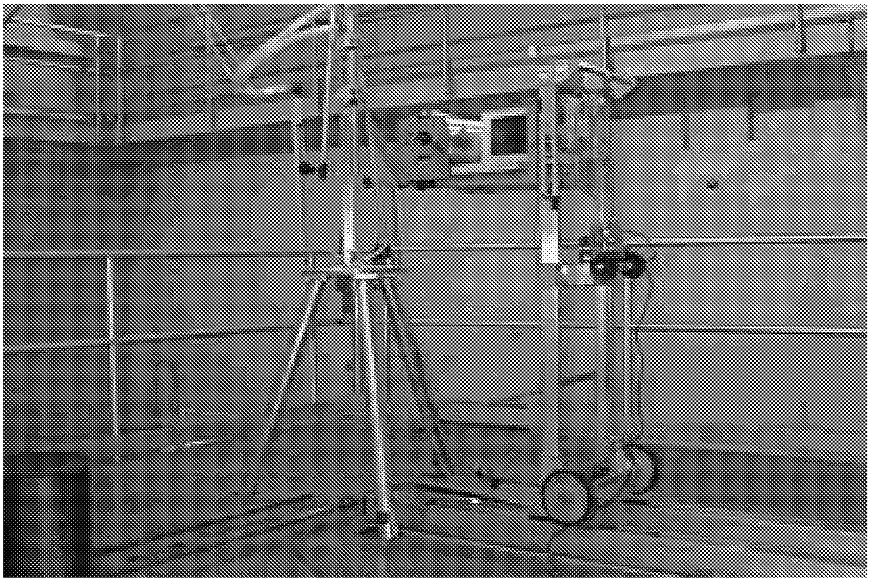


Figure 5. Moveable cart and TEPC dosimeter placement.

Figure 6. Source wells for the Cf-252 source facility.

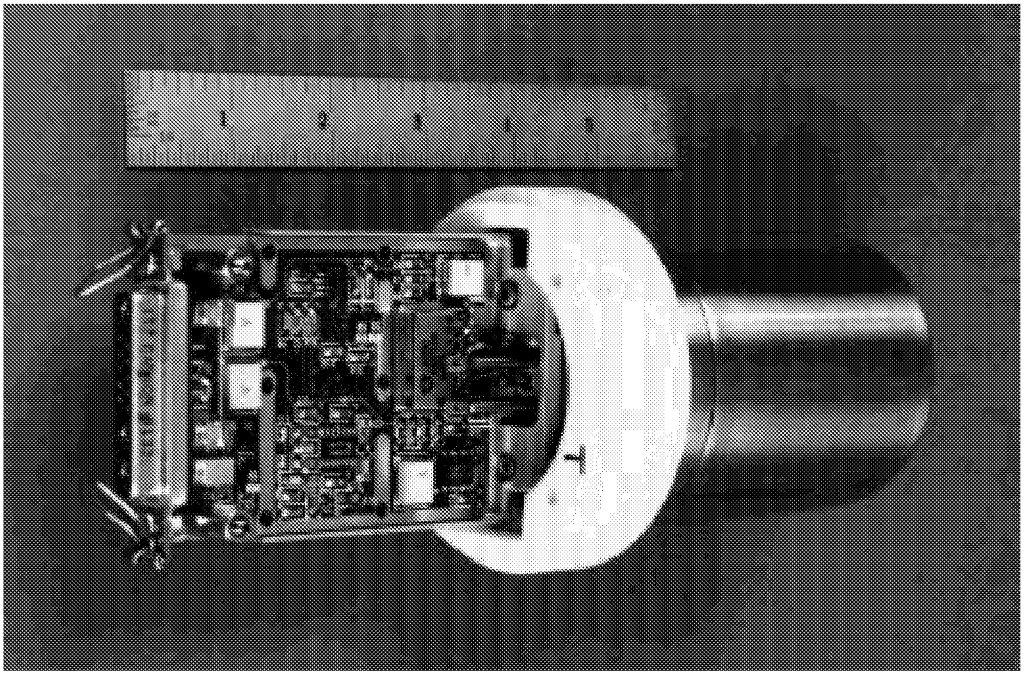


Figure 7. Containment for 5-in. proportional counter and multichannel analyzer.

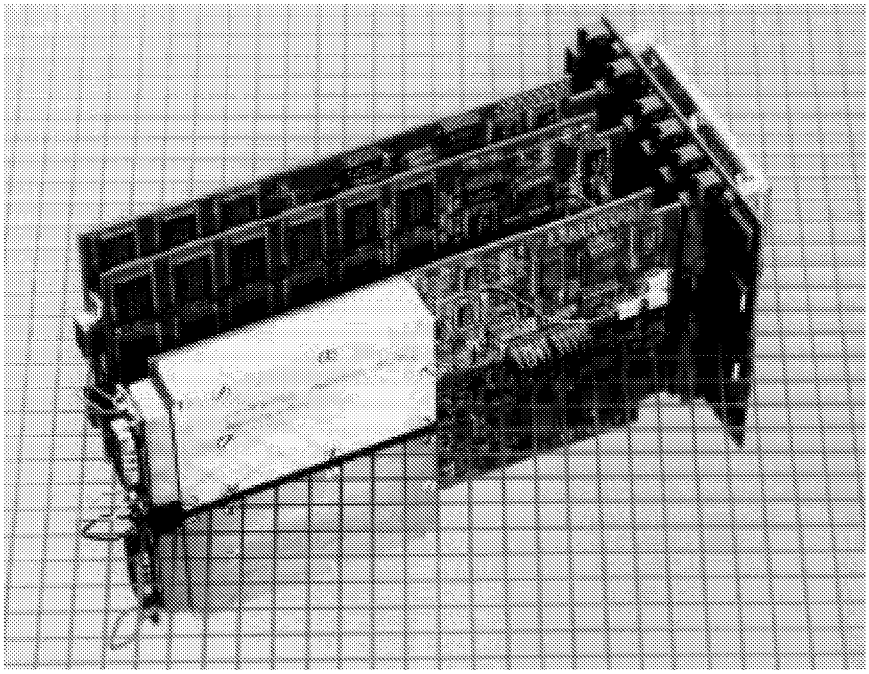


Figure 8. Electronics package for TEPC dosimeter.

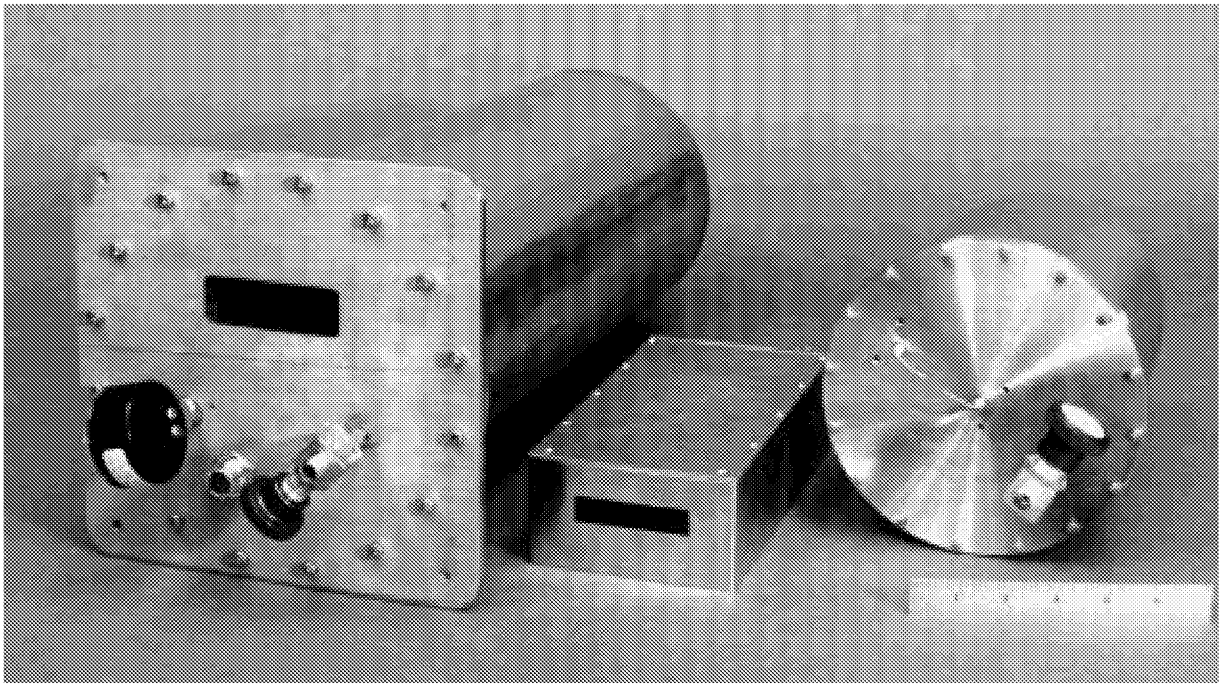


Figure 9. TEPC package and modules.

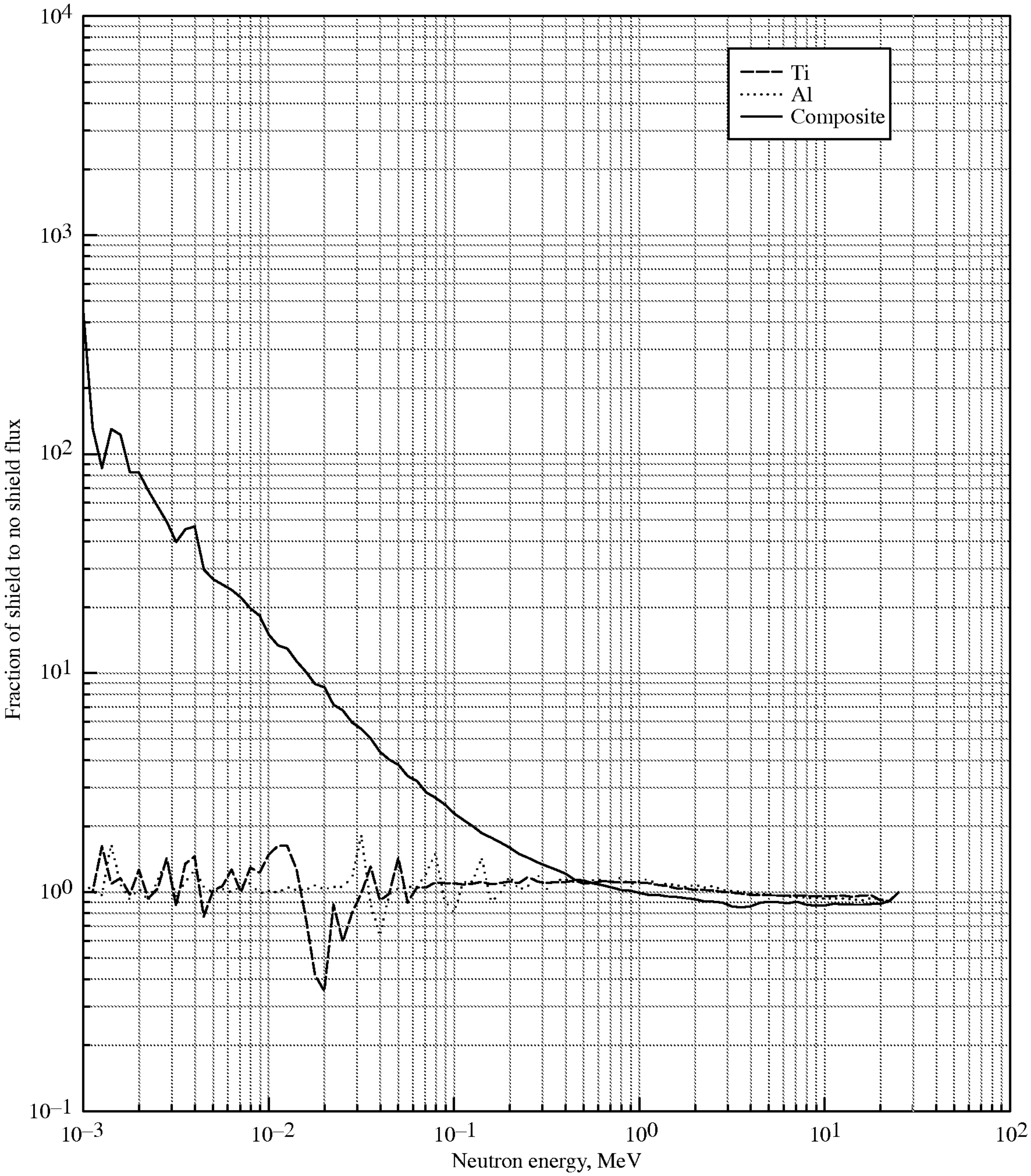


Figure 10. Comparison with MCNP of the neutron spectrums for aluminum, titanium, and graphite-epoxy composite shields.

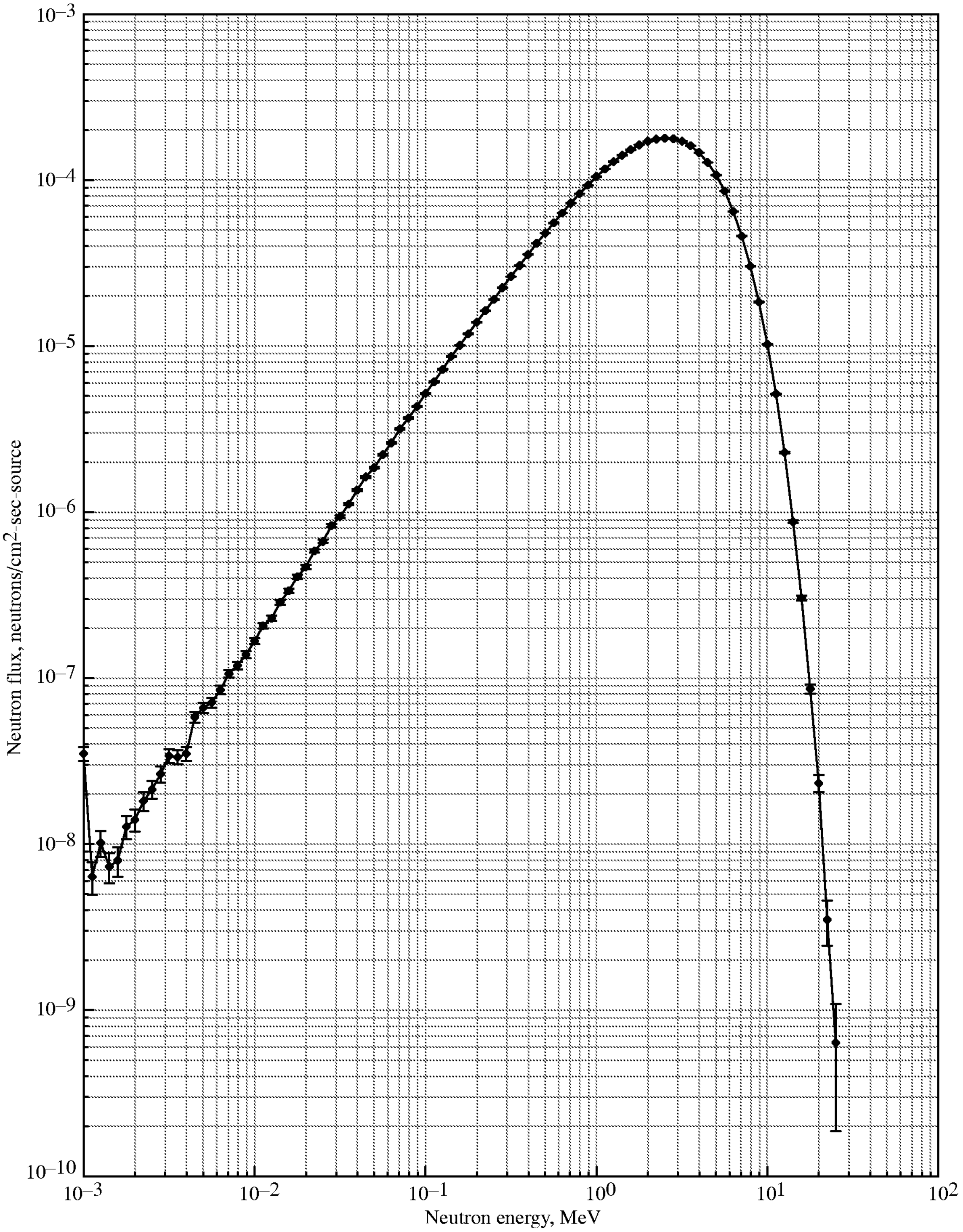


Figure 11. Neutron spectrum for generic Cf-252 source.

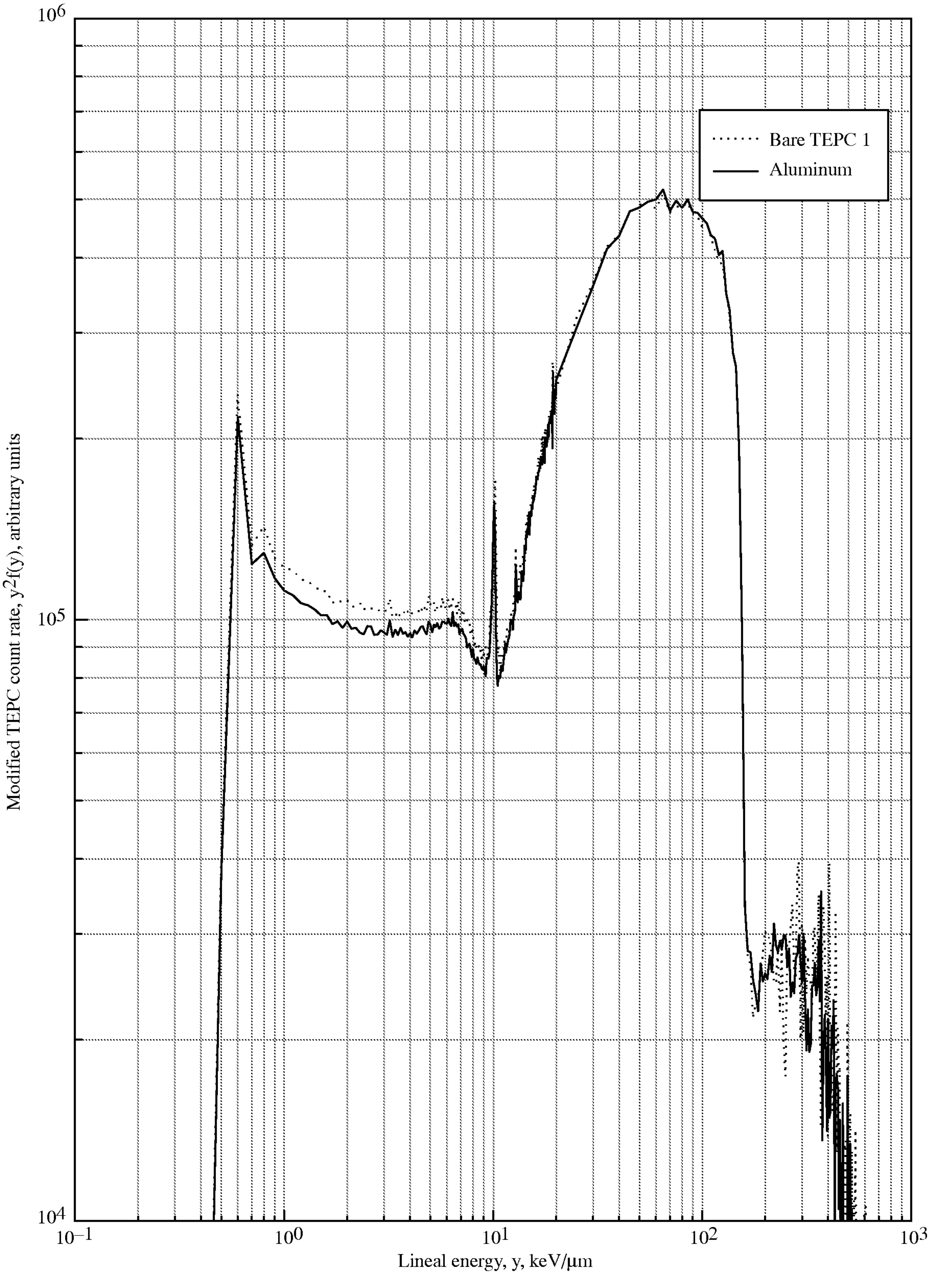


Figure 12. Lineal energy spectrum for TEPC 1 with and without 3-gm/cm^2 aluminum shield.

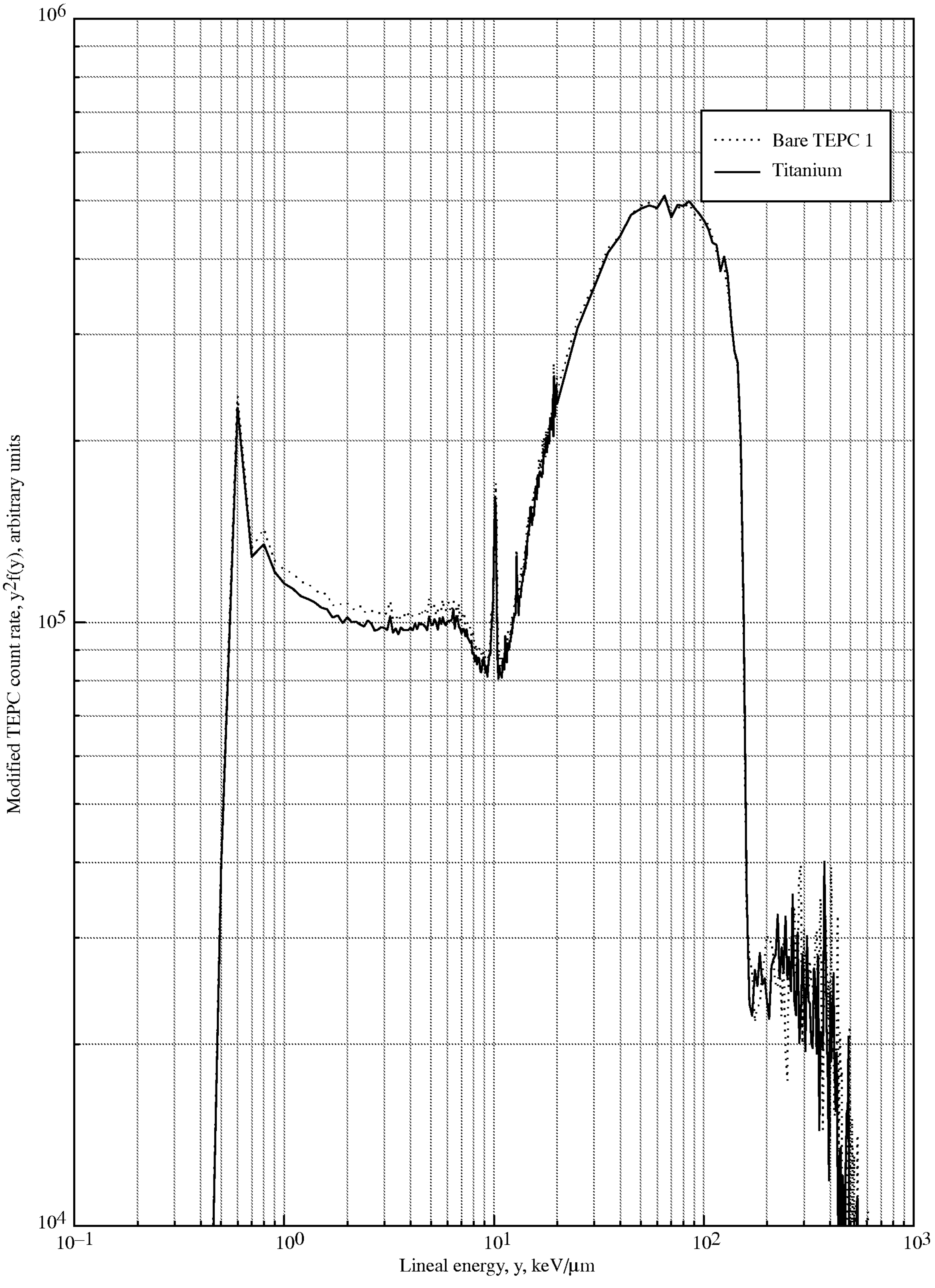


Figure 13. Lineal energy spectrum for TEPC 1 with and without 3-gm/cm^2 titanium shield.

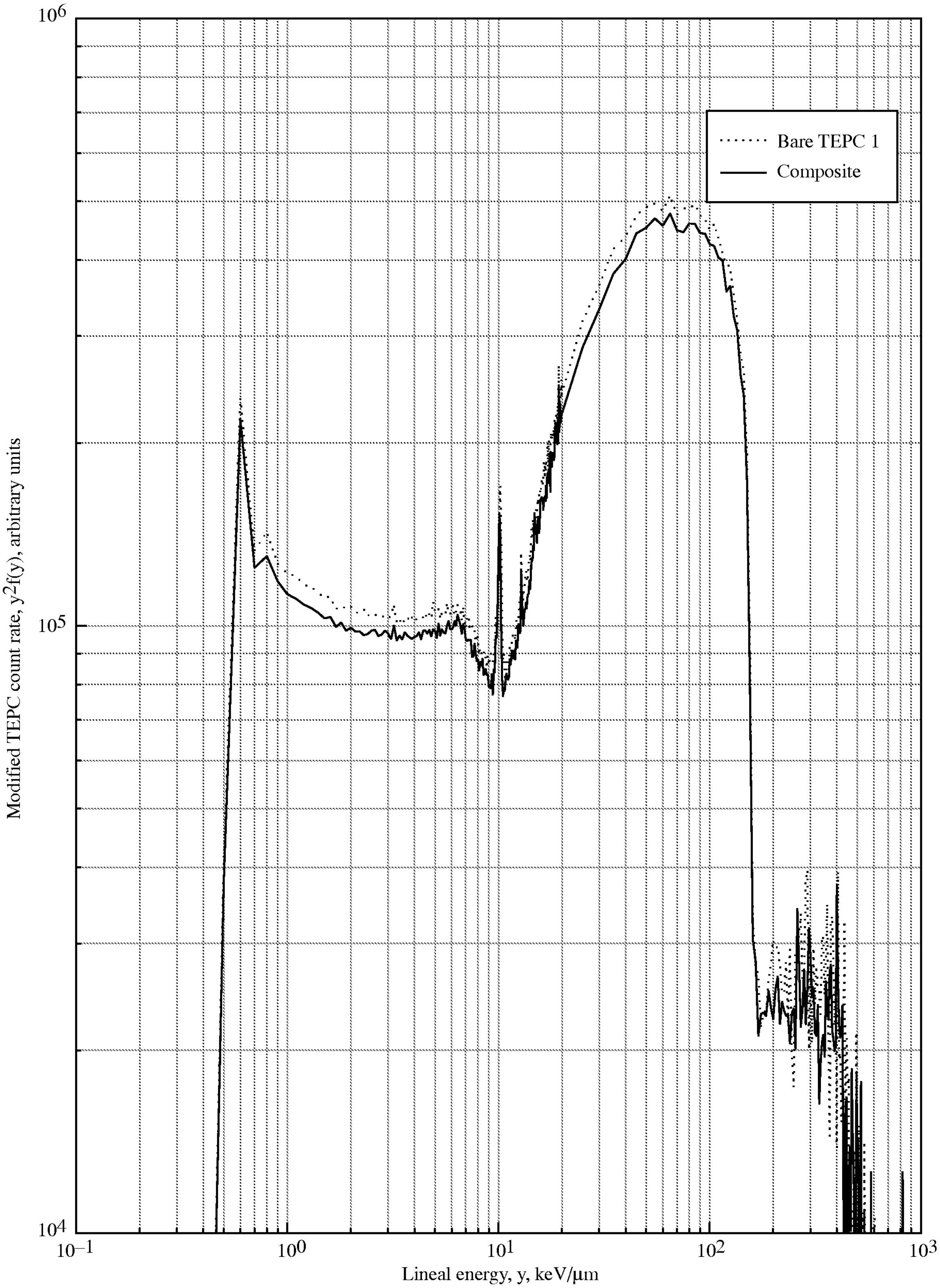


Figure 14. Lineal energy spectrum for TEPC 1 with and without 3-gm/cm^2 graphite-epoxy composite shield.

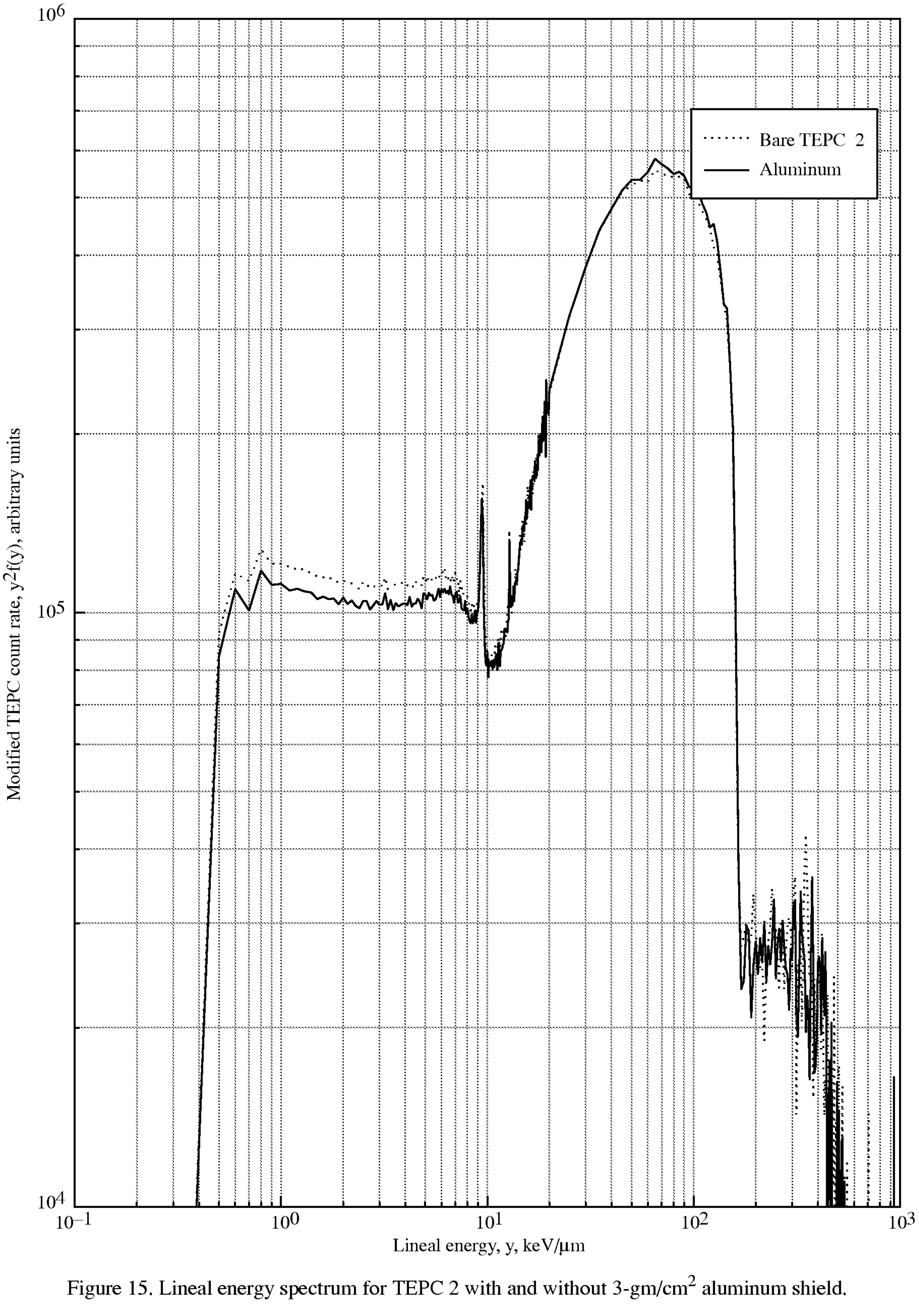


Figure 15. Lineal energy spectrum for TEPC 2 with and without 3-gm/cm^2 aluminum shield.

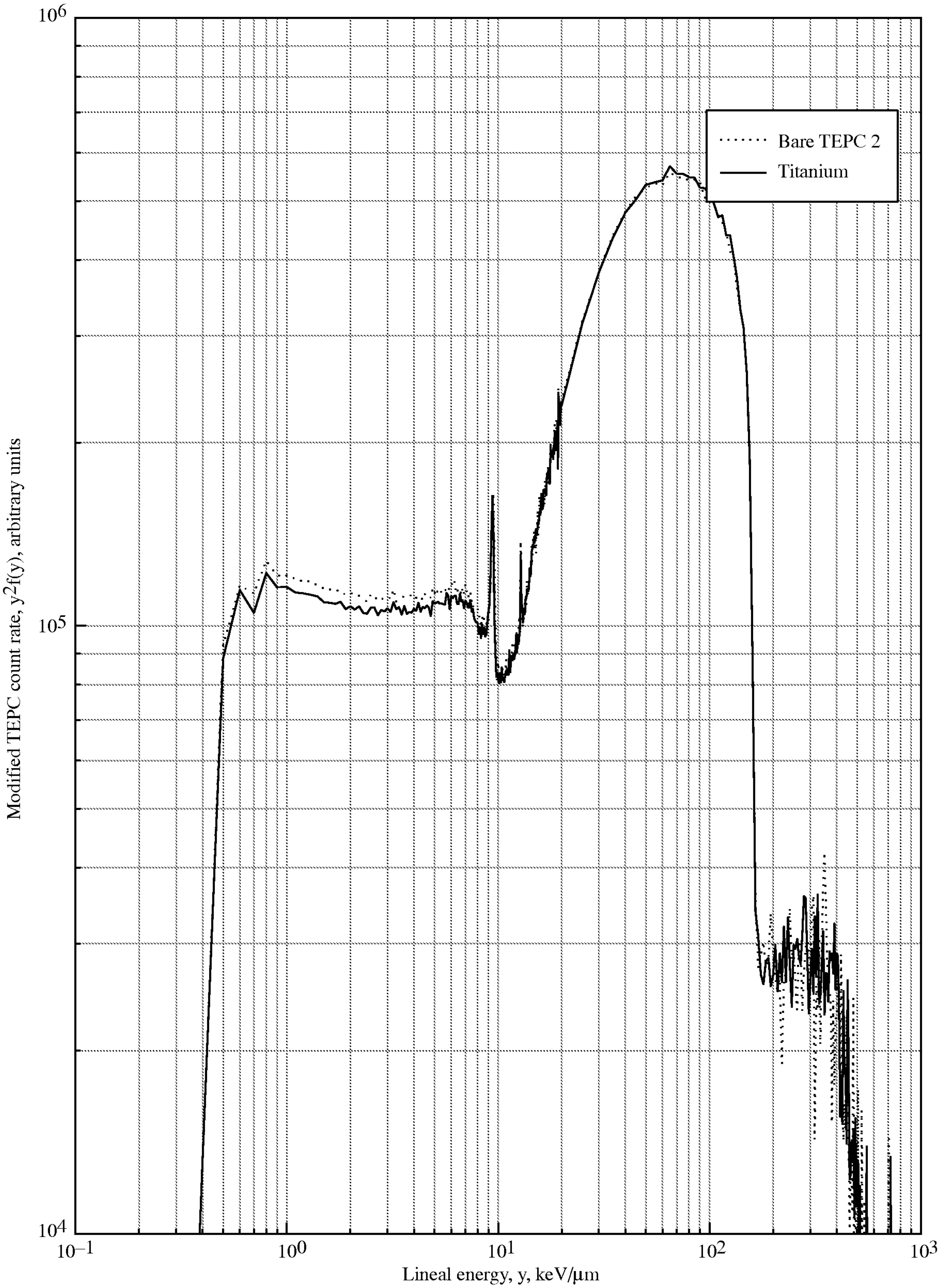


Figure 16. Lineal energy spectrum for TEPC 2 with and without 3-gm/cm^2 titanium shield.

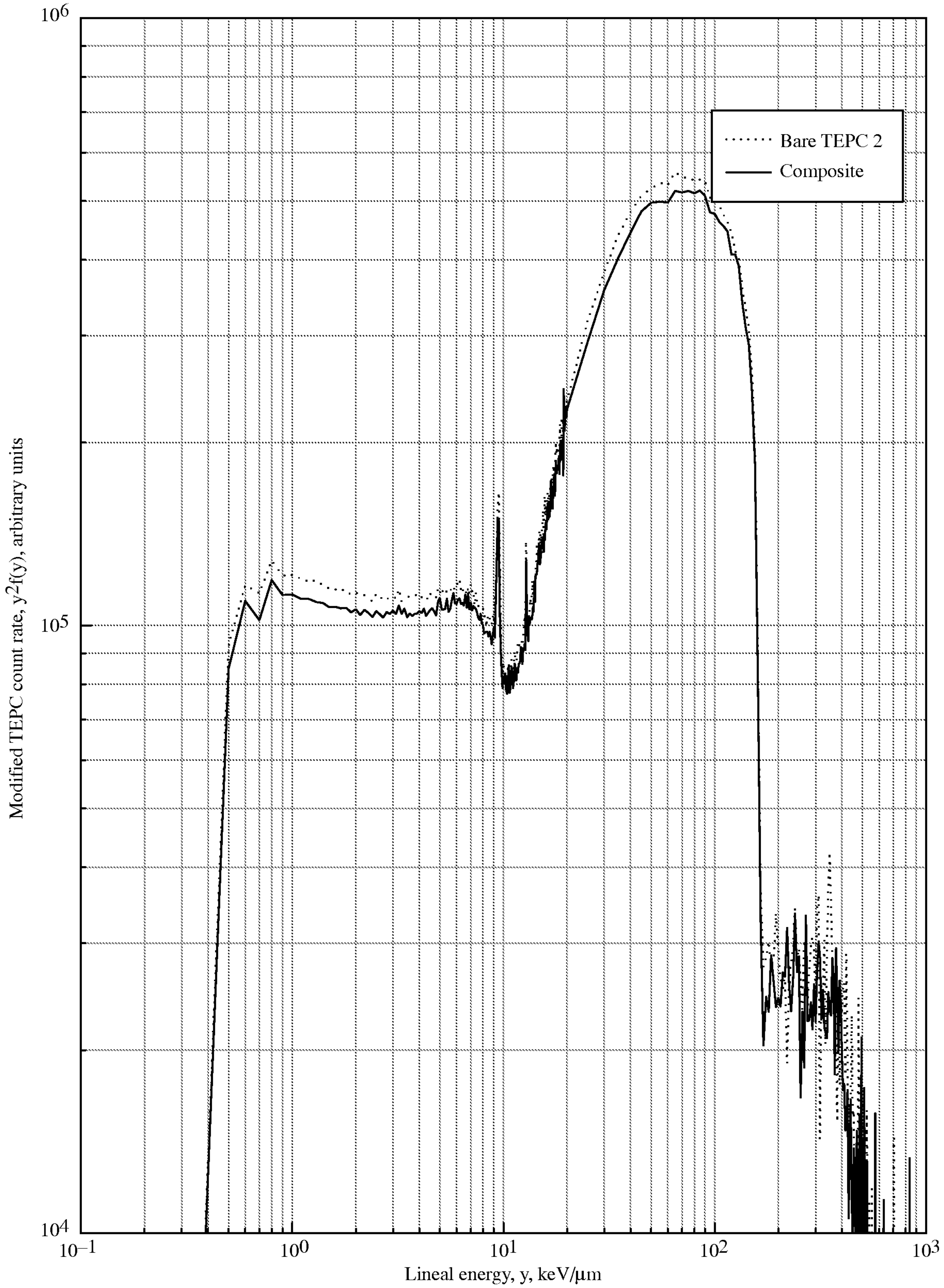


Figure 17. Lineal energy spectrum for TEPC 2 with and without 3-gm/cm^2 graphite-epoxy composite shield.

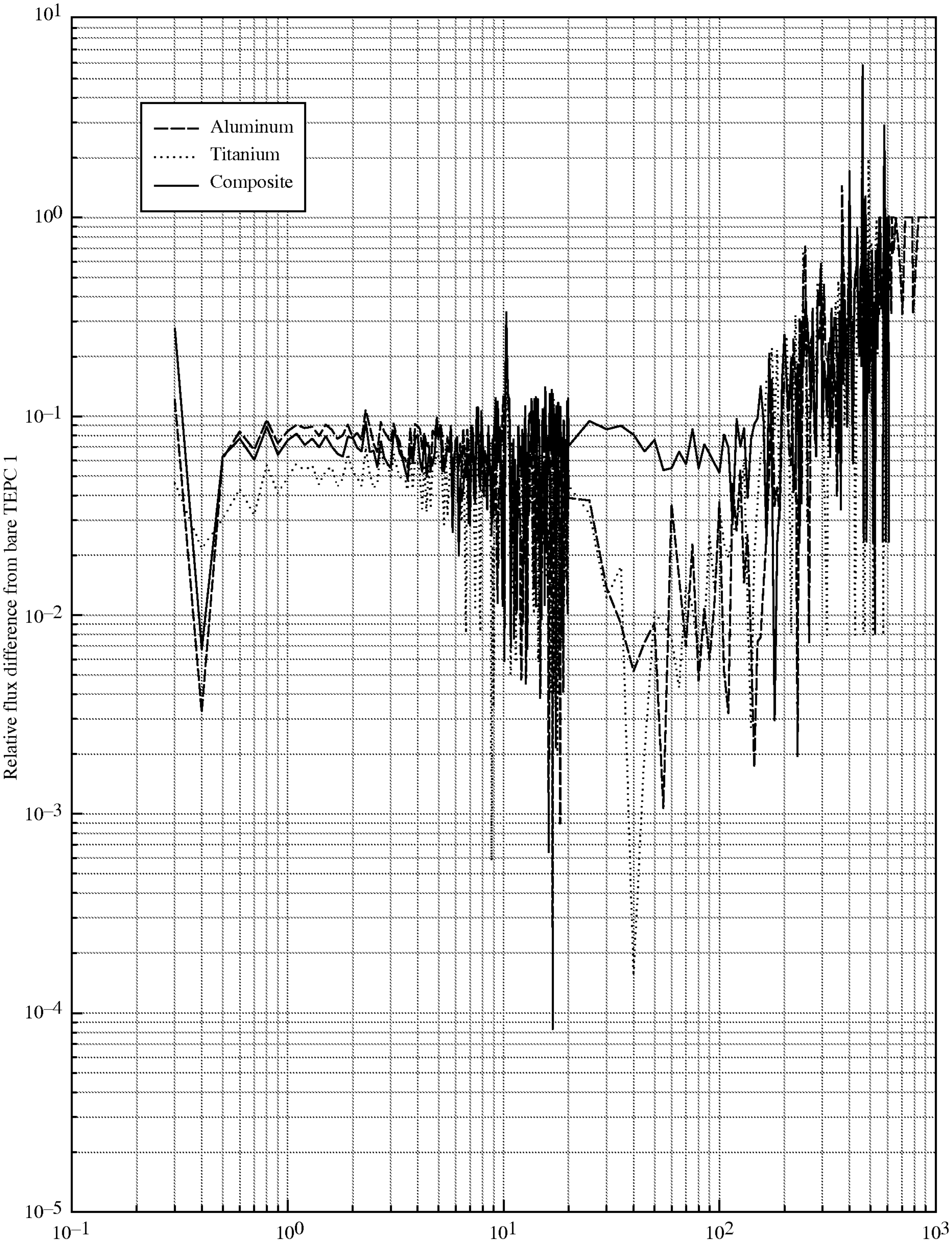


Figure 18. Relative difference from bare TEPC 1 for three shield materials.

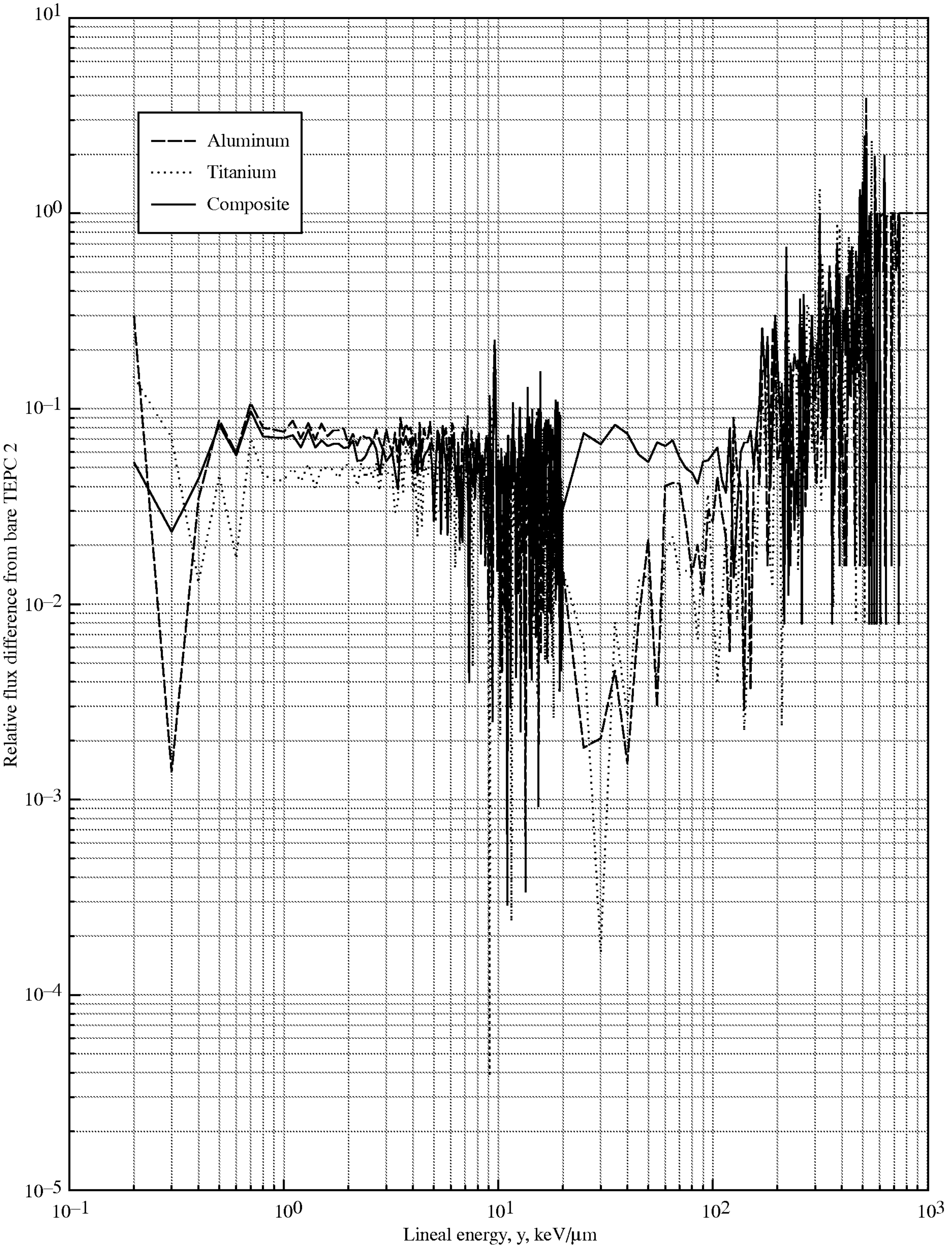


Figure 19. Relative difference from bare TEPC 2 for three shield materials.

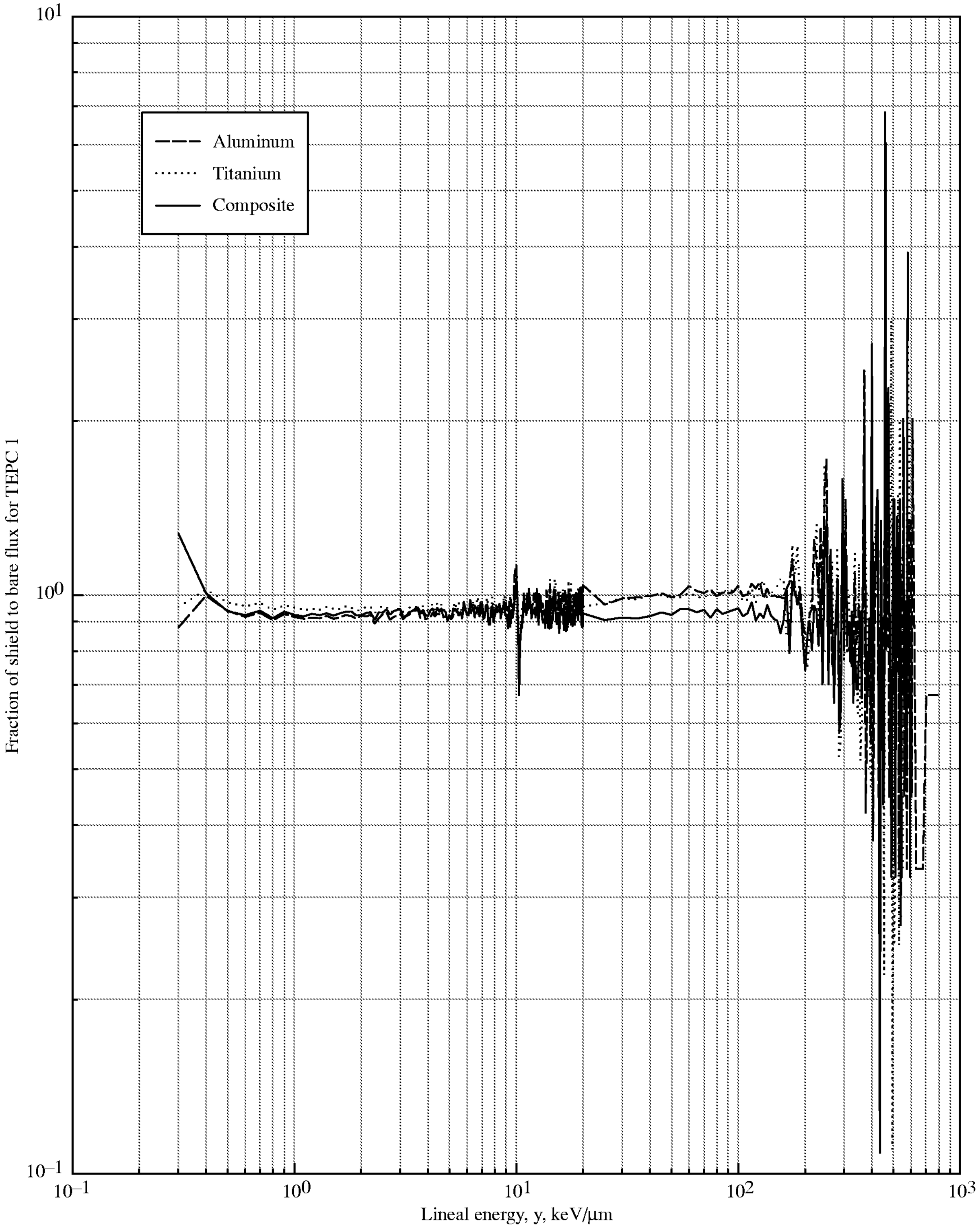


Figure 20. Fractional change in flux from shield material with respect to bare TEPC 1.

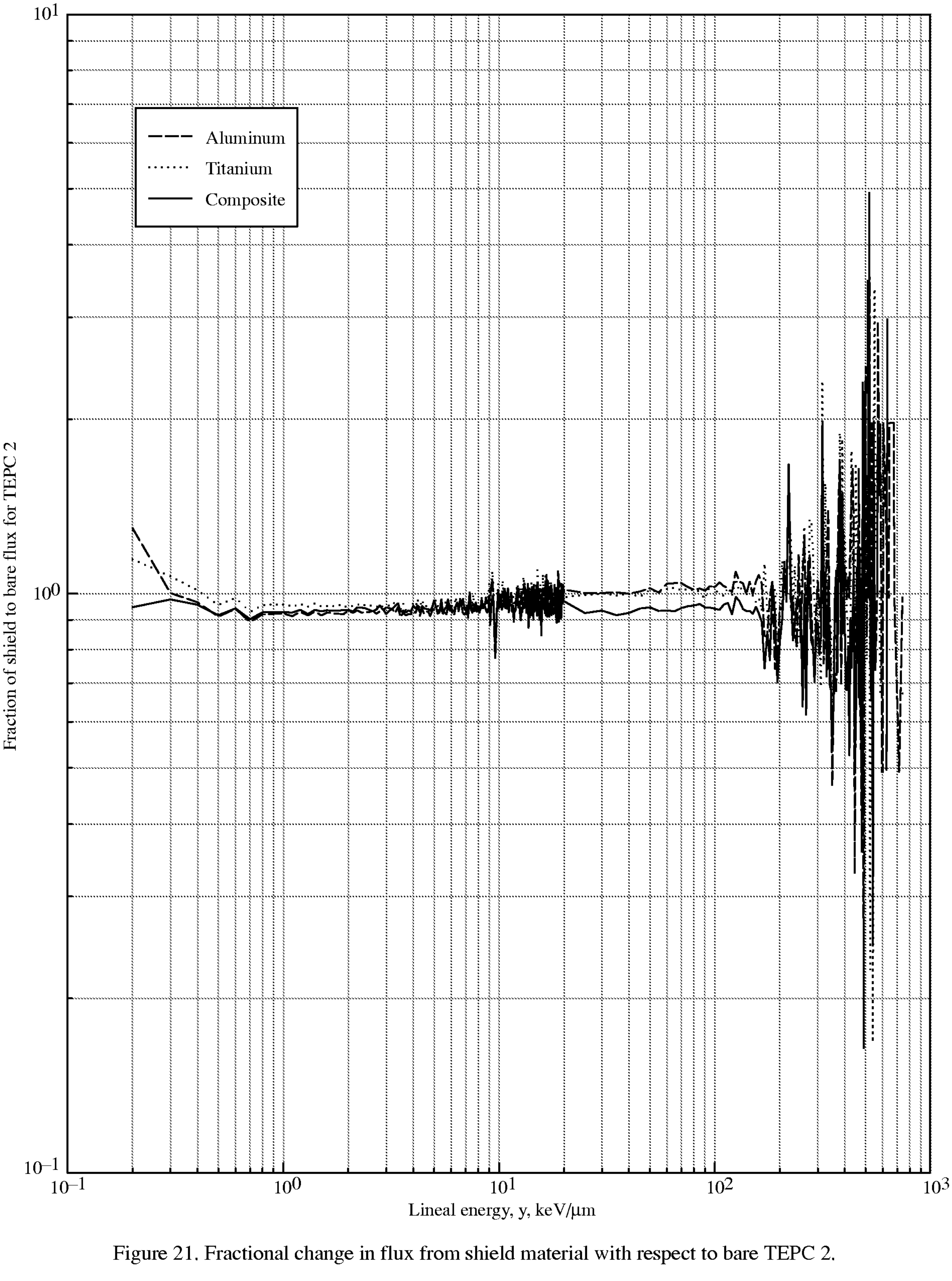


Figure 21. Fractional change in flux from shield material with respect to bare TEPC 2.

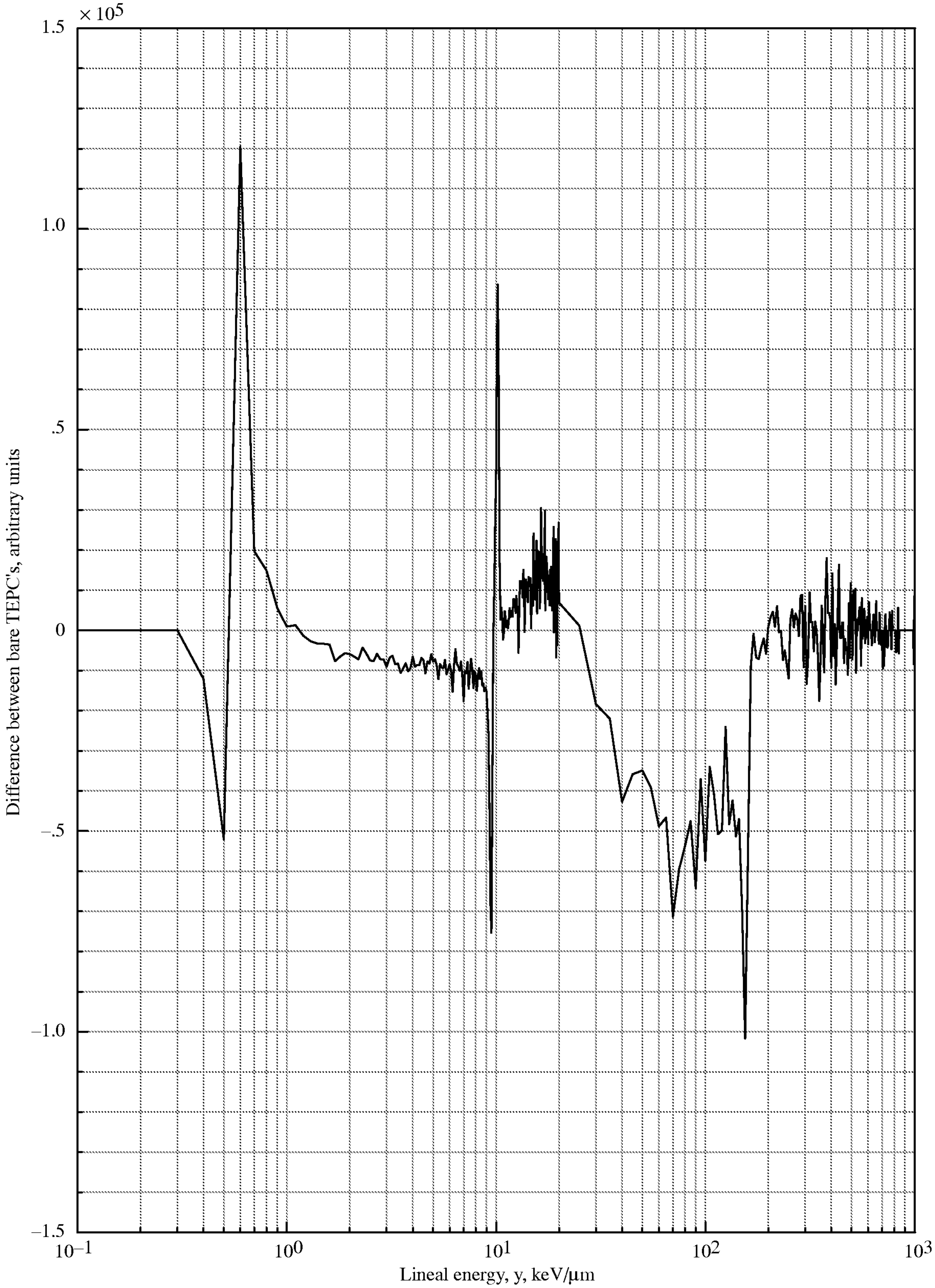


Figure 22. Flux difference between bare TEPC 1 and TEPC 2.

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13. ABSTRACT *(Maximum 200 words)*

In the past, measurements onboard a research Boeing 57F (RB57-F) aircraft have demonstrated that the neutron environment within the aircraft structure is greater than that in the local external environment. Recent studies onboard Boeing 737 commercial flights have demonstrated cabin variations in radiation exposure up to 30 percent. These prior results were the basis of the present study to quantify the potential effects of aircraft construction materials on the internal exposures of the crew and passengers. The present study constitutes preflight measurements using an unmoderated Cf-252 fission neutron source to quantify the effects of three current and potential aircraft materials (aluminum, titanium, and graphite-epoxy composite) on the fast neutron flux. Conclusions about the effectiveness of the three selected materials for radiation shielding must wait until testing in the atmosphere is complete; however, it is clear that for shielding low-energy neutrons, the composite material is an improved shielding material over aluminum or titanium.

14. SUBJECT TERMS
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