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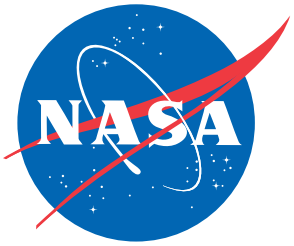

Evaluation of Multiple Methods for Calculating Gray Equivalent

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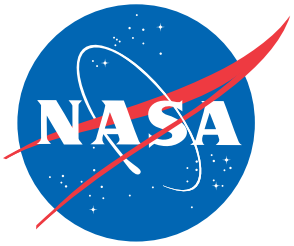

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Abstract

The assessment of different algorithms to determine the Gray-Equivalent as defined in NASA-STD-3001 from a source of space radiation has been evaluated in this paper. The Gray-Equivalent applies an RBE (Relative Biological Effectiveness) to the dose seen at the organ of interest in a human phantom. The current design basis solar particle event was used in the assessments along with the August 1972 event modeled by J.H. King and with idealized spheres and two vehicle designs. Three different algorithms were used and compared. One of the algorithms was the current OLTARIS algorithm. This algorithm is astronaut orientation averaged, which is not what happens in a storm shelter during a solar particle event. Two other algorithms were proposed to eliminate this issue. Either algorithm will be adequate to satisfy NASA-STD-3001 requirements. This work recommends the algorithm which applies the RBEs to the phantom points instead of at the surface of the phantom as with the current OLTARIS algorithm.

1 Introduction and Background

In NASA-STD-3001,[1] Table 3 lists astronaut dose limits for short-term and career non-cancer effects (deterministic effects). The radiation response function for those limits are given as dose in gray (Gy) and gray equivalent (Gy-Eq). 1 Gy is defined as the net absorption of 1 Joule of energy in 1 kilogram of any material.[2] Gy-Eq is defined as the dose in Gy multiplied by the RBE (relative biological effectiveness) for whatever tissue system, particle species, and particle energy are being analyzed. RBE is just the ratio, or comparison, of the dose for a standard effect on a tissue, like an LD-30[a] value, from a particular particle/energy combination, like X-ray photons at 250 keV, and the dose of another particle/energy combination to also cause an LD-30 effect in the same tissue. The RBE compares the same biological damage between two types of radiation and assigns a value to that difference as a ratio. Therefore, in the example presented, if a 100 MeV neutron had an RBE of 5.0, then 1 Gy of 100 MeV neutron causes the same effect as 5 Gy of 250 keV X-rays.

NCRP-132[2] estimates RBEs for space relevant particles and energies in Table 6.4; however, the RBEs have large uncertainties as seen in the range column of that table and are not fully defined over all particle types and energies. For computational purposes, these missing RBEs need to be defined. Wilson *et. al.*[3] suggested values to complete the RBEs for neutrons which were not defined below 1 MeV and above 50 MeV and for protons which were not defined below 2 MeV. This complete RBE definition enabled computational algorithms to determine Gy-Eq. A particular Gy-Eq algorithm is implemented in OLTARIS version 4.2[4,5] (On-Line Tool for the Assessment of Radiation In Space). The Off-line version of OLTARIS, abbreviated as TARIS and referred to as TARIS in this paper unless specifically noting the On-Line version, can be scripted to perform any Gy-Eq solution algorithm of interest. In this paper, potential Gy-Eq algorithms are compared and justifies one algorithm to be used to compare against the NASA-STD-3001 Table 3 standards.

OLTARIS and TARIS use HZETRN[6] as the particle transport engine with two different methods to determine the flux of particles at a point. Both methods start with a ray trace of the geometry at a point of interest inside the spacecraft. Since the Gy and Gy-Eq response functions depend on a human phantom, the ray directions in the CAD (computer aided design) model must be aligned with the detailed ray directions of the phantom hard-coded in TARIS by placing a shadow phantom (see Figure 1) in the CAD model. In the Thickness Distribution menu item of OLTARIS, explicit instructions show how to perform this alignment. The shadow phantoms can be downloaded and used in any CAD package available. Once these phantoms are placed within the CAD model containing the spacecraft design, the A, B, and C points in the chest of the phantom are used to align the coordinate system in the CAD design to the TARIS phantoms' coordinate systems. OLTARIS can be used to create a set of ray directions that align the CAD model and the phantom. Ray traces can then be generated in the CAD model using these ray directions. Each phantom contains over 1000 points with numerous points per organ or tissue so that a mass average dose can be calculated for each organ or tissue. In order to keep from ray tracing a spacecraft over 1000 times per phantom, all organs and tissue points are assigned to one of the five zones in which the phantom has been divided. Therefore, only five spacecraft ray traces need to be performed at the points in Figure 1 along the long axis of the phantom from the head to the feet. Of course, a single spacecraft ray trace point can be used with each of the phantom points assigned to that single zone.

[a]LD-30 is a dose associated with the radiation effect wanted, like cellular damage associated with the inability to undergo mitotic division, in 30 % of the cells being observed. LD used to stand for Lethal Dose but its understanding has been broadened.

Two transport methods can be employed by TARIS on the ray traces to calculate the flux of particles and other response functions at the point of interest within the spacecraft:

1. Interpolation (now called 1D (one dimension) in TARIS 5.0)
2. Ray-by-ray (now called 3D (three dimension) in TARIS 5.0)

For Item 1, a one, two, or three material flux database is generated in particles/cm^2-MeV at preset areal densities or thicknesses in g/cm^2 with the HZETRN transport code. The ray trace data must be consolidated by material along each ray. The consolidation happens by reordering all the materials in a ray so that all segments of the first material are summed together (considered the vehicle), all of the second (considered the shield), and all of the third (must be tissue if computing Gy-Eq). The computed flux database is then converted to dose at each database value to create a dose table. Then, each material thickness is interpolated for each ray trace to determine dose from each direction. The total dose is obtained by summing over the contributions from all ray directions. For Item 2, instead of a database, each ray with its original material configuration is executed within HZETRN to get the flux at each point and direction. The dose is computed at the point from each direction and the total dose at the point is the sum from all ray directions. Back-scattered light particles from the material on the other side of the ray trace point can be included in Item 2, but not in Item 1, or in the 3D algorithm in TARIS 5.0. However, the treatment of light particles in the 3D algorithm is multi-directional instead of just back-scattered. Because of the inclusion of multi-directional light particles and the accurate layering of materials on a ray, Item 2 is considered more accurate; however, even with crude multi-threading, it takes longer to complete an analysis when compared to Item 1.

To determine the RBEs, many space relevant dose measurements were reported in ICRP-58.[7] Most of the measurements were on small animals but some larger animals were used including humans. Appropriate effects seen in the animal models were folded into the RBE values and are a function of particle type and energy as reflected in NCRP-132 Table 6.4. RBEs are also reported for radiation induced effects, like reproductive cell death, early skin effects, and many other biological effects. ICRP-58 reports data mainly by the dose given to the animal to determine the wanted effect. Fortunately, dose is a linear function of flux by particles and energy; therefore, the application of the RBEs can be on the flux or the dose in a computational algorithm.

The next section explains the algorithmic variations that have been used in the past to calculate Gy-Eq along with their pros and cons. The last section justifies the choice of a Gy-Eq algorithm for use in comparing a spacecraft design against the limits in NASA-STD-3001.

2 Various Algorithms Used to Compute Gy-Eq

Three distinct Gy-Eq methods have been applied in TARIS for comparison in this paper. Wilson's[3] complete RBE estimates are summarized in Table 1. In this table, there are subtle assumptions and issues due to the manner in which the measurements were acquired and the algorithms in TARIS that do not comport with the measurement philosophy. The most obvious is that the dose was measured outside of the animal, and effects were determined inside the animal by organ/tissue. Dose values at the body surface of the animal are being applied to a specific organ/tissue for a specific effect and then integrated over all organs/tissues. The neutron RBE is mainly associated with proton recoils generated inside the animals. Therefore, the RBEs should be applied to the dose by particle type and energy that impinge on the body surface of the animal going to the specific organ/tissue. However, discontinuities are created within a calculational algorithm that must be addressed. Wilson found that for a uniform dose field (therefore, a uniform flux field) within the animal, finding effective field quantities and applying the average RBE to the whole dose field showed "little difference" compared to applying the RBEs to flux field values at the body surface of the animal and then finding the dose at the specific organ/tissue. The issue is that the flux field is not uniform inside a typical spacecraft and therefore cannot be uniform within the human. The dose at the surface of the human differs from point to point on the surface.

Since the animals in question are small and the flux field is uniform, the secondaries generated in the animal can be ignored. Secondaries generated inside humans cannot be ignored. A related issue is that the secondaries generated in the animal have already been weighted at the surface by the RBEs and should not be weighted by them again. Tryig not to double weight secondaries drives the algorithm suggested by Wilson

(see Section 2.1). Other algorithms have been put forward to solve other issues with the computational algorithms in TARIS (see Sections 2.2 and 2.3).

2.1 Method 1: Apply RBEs to flux outside the phantom

This method multiplies the flux values by the RBEs at the surface of the phantom before creating the dose table and interpolating the doses at each organ/tissue point. The procedure is as follows:

- Calculate the flux impinging on the phantom by calculating the flux at a single point within a spacecraft
- Weight the flux impinging on the phantom by the RBEs, and assume it is isotropic on the phantom
- Use the interpolation method to calculate the transport of the weighted flux through the phantom to organ/tissue points
- Calculate organ/tissue averaged dose for the relevant organ/tissue

This method has numerous pros and cons. The two important pros are that it is the method recommended in the Wilson work and it is the current method used by OLTARIS. From a radiation physics point of view, the low energy proton (<2 MeV) RBE value is immaterial as these particles do not even penetrate the skin to contribute to the dose in any organ/tissue of interest. This method is also consistent with the manner RBEs are used in terrestrial applications. Two important cons are the decoupling of the astronaut from the spacecraft and the much larger mass of the astronaut over a lab animal, which breaks the uniform dose field assumption used to determine the RBEs, and the application of the isotropic flux source on the phantom. The decoupled aspect of this method then prevents the ray-by-ray or any other 3D approximation from being used. This decoupling of the spacecraft and astronaut has been called the spinning astronaut approximation in many previous papers on this subject and represents the average exposure over time or a mission as the radiation field changes. Therefore, combined effects of the astronaut and spacecraft shielding, like in an SPE (solar particle event) shelter, is lost as the astronauts are in the same orientation while in a shelter; therefore, in an SPE shelter, the spinning astronaut approximation is violated.

2.2 Method 2: Apply RBEs to flux at phantom points

This method calculates the flux to each phantom point and then multiples the discontinuous RBEs before either creating a dose table (interpolation) or summing the dose value over each direction (ray-by-ray). The procedure is as follows:

- Use interpolation or ray-by-ray method to calculate the flux values at the phantom points in the relevant organ/tissue
- Weight the phantom point flux values using the RBEs
- Calculate averaged dose for the relevant organ/tissue

The pros for this method are that the calculation comports more on how other calculations work within TARIS and allows the normal 3D approximations used by other response functions in TARIS. The RBEs can easily be a function of particle type and energy. The cons for this methods are subtle, but important. From the measurements associated with determination of the RBEs, secondaries and target fragments generated inside the phantom have already been weighted by the RBEs outside the phantom and should not be weighted again. For example, if a secondary neutron is generated inside the phantom and it creates a recoil proton, that neutron has already been weighted by the RBEs and the recoil proton is now double weighted: once from the neutron's RBE and once from the proton's RBE. Creating such a solution within any computational framework is complex. Tagging the particles in a Monte Carlo solution might allow the computation to stop double counting these secondary and location-based relationships; however, MCNP6[8] is the only Monte Carlo code that allows particle tagging. The complexity of the secondary and location-based hierarchy would necessitate the Monte Carlo histories to be post processed as it is not part of a pre-programmed response function in MCNP6. For a deterministic solution, like HZETRN, particle tagging is possible, but the cross sections would need to be manipulated to allow the tagging. The low energy protons (<2 MeV), now that they are being weighted by the RBEs inside the phantom, contribute to the dose.

2.3 Method 3: Apply 1.5 (proton RBE) to total dose

This method calculates the dose for each phantom point and then multiples the proton's RBE before either creating a dose table (interpolation) or summing the dose value over each direction (ray-by-ray). The procedure is as follows:

- Use interpolation or ray-by-ray method to calculate the transport of the external environment through the shielding provided by the spacecraft and the human body to get fluxes at points in the relevant organ/tissue points
- Generate dose tables or points
- Multiple dose tables or points by 1.5 (the RBE for protons, but any constant could be used)
- Calculate organ/tissue averaged dose for the relevant organ

The pros for this method are that it is the simplest method to implement and comports most closely to other TARIS calculations for interpolation and ray-by-ray methods. It is the method used to estimate astronaut exposure from detector measurements. The 1.5 multiplication factor is an arbitrary factor and can be precalculated before being used. However, the 1.5 is the RBE for protons, the dominate particle in the flux field. This method has the same cons as method 2 (See Section 2.2); plus, if the proton RBE becomes a function of energy in the future, it will be difficult to implement.

3 Comparison of Methods in Spherical Geometry

To recommended which of these algorithms should be used to compare TARIS results to NASA-STD-3001, the pros and cons of each method must be compared and analyzed. The SPE fluences depicted in Figure 2 are the boundary conditions used for this analysis. The August 1972 event using King's fit[9] was the design basis for the Constellation Program. The combined October 1989 event using Tylka's coefficients to a band function fit[10] is recommended as the design basis for the Gateway and lunar missions.[10] The main difference between these design basis events are that the Constellation design basis SPE has the largest mid-energy flux of any historical event seen in the satellite era but has no data for the higher energy tail. The Gateway design basis SPE uses ground measured data to model the high energy tail. The higher energy tail particles penetrate deeper into the spacecraft and can generate a larger exposure.

While it cannot be shown in general, the Gy-Eq exposure to BFO (blood forming organs) drives the requirement process for these SPEs. Therefore, only BFO results will be shown for the comparisons. In NASA-STD-3001, the BFO PEL (personal exposure limit) is 250 mGy-Eq for 30 days. It is assumed that only one SPE of this magnitude will occur in any 30 day window.

The BFO Gy-Eq vs. depth plots for the three methods in aluminum and polyethylene for the Gateway design basis SPE are shown in Figure 3. The same data for the Constellation design basis SPE are shown in Figure 4. In TARIS, to perform any human phantom based response function, a 3D vehicle is needed with a ray trace. Therefore, the depth is the thickness of the sphere encompassing the phantom. The relative difference of Methods 2 and 3 to Method 1 in aluminum and polyethylene are shown in Figure 5 for the Gate Design Basis SPE and in Figure 6 for the Constellation design basis SPE.

Some observations about Method 2 relative to Method 1 for the Gateway design basis SPE are:

- Method 2 decreases more rapidly
- At 10 g/cm^2, where the Method 1 gray equivalent for aluminum is ≈250 mGy-eq, Method 2 is 3 % less
- At 20 g/cm^2, where the Method 1 gray equivalent for aluminum is ≈100 mGy-eq, Method 2 is 8 % less
- At 35 g/cm^2, where the Method 1 gray equivalent for aluminum is ≈50 mGy-eq, Method 2 is 15 % less

Some observations about Method 3 relative to Method 1 for the Gateway design basis SPE are:

- Method 3 decreases more rapidly than Method 2

- At 10 g/cm^2, where the Method 1 gray equivalent for aluminum is ≈250 mGy-eq, Method 3 is 5 % less
- At 20 g/cm^2, where the Method 1 gray equivalent for aluminum is ≈100 mGy-eq, Method 3 is 10 % less
- At 35 g/cm^2, where the Method 1 gray equivalent for aluminum is ≈50 mGy-eq, Method 3 is 18 % less

Some observations about Method 2 relative to Method 1 for the Constellation design basis SPE are:

- Method 2 decreases more rapidly
- At 7 g/cm^2, where the Method 1 gray equivalent for aluminum is ≈250 mGy-eq, Method 2 is 5 % less
- At 11 g/cm^2, where the Method 1 gray equivalent for aluminum is ≈100 mGy-eq, Method 2 is 11 % less
- At 16 g/cm^2, where the Method 1 gray equivalent for aluminum is ≈50 mGy-eq, Method 2 is 20 % less

Some observations about Method 3 relative to Method 1 for the Constellation design basis SPE are:

- Method 3 decreases more rapidly than Method 2
- At 7 g/cm^2, where the Method 1 gray equivalent for aluminum is ≈250 mGy-eq, Method 3 is 8 % less
- At 11 g/cm^2, where the Method 1 gray equivalent for aluminum is ≈100 mGy-eq, Method 3 is 15 % less
- At 16 g/cm^2, where the Method 1 gray equivalent for aluminum is ≈50 mGy-eq, Method 3 is 25 % less

In general, the results from the methods are within 10 % of each other for shielding thicknesses that meet the 250 mGy-Eq for BFO exposure limit. These differences are less than the current biological uncertainties. Therefore, any of these methods can be used to evaluate exposure limit requirements. The differences increase as the thickness increases. Methods 2 and 3 are less than Method 1 and therefore, Methods 2 and 3 do not give conservative estimates for Method 1. The differences between Method 2 and Method 3 are small and if Method 2 is recommended to replace Method 1, then Method 3 can also be recommended. During an ALARA (as low as reasonably achievable) analysis, as the thicknesses get larger, the differences between Method 1 and Methods 2 and 3 increases. While the absolute values between methods is different, as the thicknesses increase, the values decrease at the same rate. So, any method can be used to perform an ALARA analysis.

4 Comparison of Methods in Realistic Geometries

To test the spinning astronaut approximation used in Method 1, but not in Method 2 and 3, two realistic geometries were chosen for this paper. The first geometry is a version of the MPCV[11] (Multi-Purpose Crew Vehicle). There are two different configurations of the MPCV: seated and sheltered. The seated configuration is for normal operations and has a median thickness of approximately 31 g/cm^2. The sheltered configuration has been optimized according to ALARA for the Constellation design basis SPE and has a median thickness of approximately 36 g/cm^2. The second geometry is a Gateway module used for testing at NASA Langley Research Center (LaRC).[12] It was not designed as a flight vehicle, meaning as heavily shielded as the MPCV, but was used as a lightly shielded test bed for computational studies and has a median thickness of approximately 15 g/cm^2. The thinner the vehicle, the more susceptible the astronauts are to exposures larger than the regulatory limit from the design basis SPE. The MPCV results are in Table 2 for the Gateway design basis SPE and Table 3 for the Constellation design basis SPE. The LaRC test vehicle is in Table 4 for both design basis SPEs.

The results for the realistic geometries are mixed and not as clear when compared to the sphere analysis in Section 3. Methods 2 and 3 under and over-predict relative to Method 1. There does not also seem to be a discernible pattern. For the Gateway design basis SPE, the absolute differences are less than 10.3 %. The differences for the Constellation design basis SPE are quite large at a maximum of 50 %. For the lightly shielded LaRC design, the absolute Gy-Eq is quite large; however, the differences are less than 7 % with Methods 2 and 3 being greater than Method 1. For these thin vehicles (absolute mGy-Eq over 300), it appears that Methods 2 and 3 are greater than Method 1 and in thicker vehicles (mGy-Eq around 100 to 150), the predictions of Methods 2 and 3 do not show a consistent trend versus Method 1. The major take-away from this analysis is that orientation averaging, Method 1, does not represent Gy-Eq when using humans.

5 Recommendation of a Method to be Used in OLTARIS and for Comparison to NASA-STD-3001

The nature of design for a space vehicle is complex. Not only does the vehicle need to meet NASA-STD-3001 for deterministic effects, but ALARA principles must be considered during the design process and accommodations for SPE shelters. A consistent method to calculate the values for Table 3 in NASA-STD-3001 must be agreed upon by all parties at NASA and incorporated into OLTARIS. All methods at the BFO 30 day exposure limit of 250 mGy-Eq are very close to one another, <5 %. The ability to analyze without the spinning astronaut approximation is key in an ALARA analyses. As the shield gets thicker, Method 2 only deviates from Method 1 by at most 20 % and this is why the authors recommend that Method 2 be used.

References

[1] NASA STD 3001, "NASA Space Flight Human-System Standard, Volume 1, Revision B: Crew Health," 2022. Seen on July 28, 2022.

[2] NCRP Report No. 132, "Radiation Protection Guidance for Activities in Low-Earth Orbit," National Council on Radiation Protection and Measurements, 2000.

[3] Wilson, J.W.; Kim, M.Y.; de Angelis, G.; Cucinotta, F.A.; Yoshizawa, N.; Badavi, F.F., "Implementation of Gy-Eq for Deterministic Effects Limitation in Shield Design," J. Radiat. Res., Vol. 43, Suppl., S103-S106, 2002.

[4] Singleterry Jr.; R.C., Blattnig, S.R.; Clowdsley, M.S.; Qualls, G.D.; Sandridge, C.A.; Simonsen, L.C.; Norbury, J.W.; Slaba, T.C.; Walker, S.A.; Badavi, F.F.; Spangler, J.L; Aumann, A.R.; Zapp, E.N.; Rutledge, R.D.; Lee, K.T.; Norman, R.B., "OLTARIS: On-Line Tool for the Assessment of Radiation In Space," NASA Technical Paper 2010-216722, July 2010.

[5] OLTARIS 4.2 Website as seen on January 7, 2022 (oltaris.nasa.gov).

[6] Slaba, T.C.; Blattnig, S.R.; Badavi, F.F., "Faster and More Accurate Transport Procedures for HZETRN," NASA Technical Paper 2010-216213, March 2010.

[7] ICRP Report No. 58, "RBE for Deterministic Effects," Annals of the ICRP, Vol. 20, No. 4, 1989.

[8] C.J. Werner (Editor); "MCNP Users Manual - Code Version 6.2," Los Alamos National Laboratory, report LA-UR-17-29981, 2017.

[9] King, J.H., "Solar Proton Fluences for 1977 - 1983 Space Missions," Journal of Spacecraft and Rockets, Vol. 11, No. 6, pgs. 401-408, 1974.

[10] Townsend, L.W.; Adams, J.H.; Blattnig, S.R.; Clowdsley, M.S.; Fry, D.J.; Jun, I.; McLeod, C.D.; Minow, J.I.; Moore, D.F.; Norbury, J.W.; Norman, R.B.; Reames, D.V.; Schwadron, N.A.; Semones, E.J.; Singleterry, R.C.; Slaba, T.C.; Werneth, C.M.; Xapsos, M.A., "Solar Particle Event Storm Shelter Requirements for Missions Beyond Low Earth Orbit," Life Sciences in Space Research, Vol. 17, pgs. 32-39, 2018.

[11] Personal Communication from the Space Radiation Analysis Group at the National Aeronautics and Space Administration, 2019.

[12] Ewart, M.; Broyan, J.; Goofliff, K.; Clowdsley, M.; Singleterry, R., "Comparing Trash Disposal and Reuse Options for Deep Space Gateway and Mars Missions," AIAA SPACE Forum, Paper Number 2017-5126, Sep 2017.

Table 1: Summary of Wilson[3] RBEs as applied to TARIS.

Particle Type	Particle Energy	RBE
Neutrons	<1 MeV	5.0
	1 to 5 MeV	6.0
	>5 MeV	3.5
Protons	All	1.5
Heavy Ions (Z>1)	All	2.5

Table 2: MPCV mGy-Eq for each Astronaut in a Normal Seated Position and in the Sheltered Position for the Gateway Design Basis SPE.

Astronaut Position	Configuration	mGy-Eq BFO			Relative Difference to Method 1	
		Method 1	Method 2	Method 3	Method 2 (%)	Method 3 (%)
1	Seated	164.91	154.01	150.63	-6.61	-8.66
	Sheltered	163.53	157.52	154.11	-3.68	-5.76
2	Seated	146.18	150.22	147.03	2.76	0.58
	Sheltered	142.38	146.52	143.30	2.91	0.65
3	Seated	94.44	97.86	94.97	3.62	0.56
	Sheltered	103.50	97.14	94.23	-6.14	-8.96
4	Seated	99.94	97.82	94.88	-2.13	-5.06
	Sheltered	88.99	98.11	95.27	10.25	7.06

Table 3: MPCV mGy-Eq for each Astronaut in a Normal Seated Position and in the Sheltered Position for the Constellation Design Basis SPE.

Astronaut Position	Configuration	mGy-Eq BFO			Relative Difference to Method 1	
		Method 1	Method 2	Method 3	Method 2 (%)	Method 3 (%)
1	Seated	139.55	125.00	122.34	-10.42	-12.33
	Sheltered	135.28	130.58	127.88	-3.47	-5.47
2	Seated	121.32	144.50	141.96	19.10	17.01
	Sheltered	112.27	132.50	129.95	18.02	15.75
3	Seated	43.67	54.89	52.70	25.71	20.69
	Sheltered	46.80	38.35	36.19	-18.07	-22.68
4	Seated	43.84	40.29	38.10	-8.10	-13.09
	Sheltered	39.79	59.53	57.38	49.60	44.20

Table 4: A Central Location Inside a LaRC Designed Gateway, Unsheltered Position for both Design Basis SPEs.

Design Basis SPE	mGy-Eq			Rel. Dif. %	
	Method 1	Method 2	Method 3	1-2	1-3
Gateway	370.44	382.14	377.59	3.16	1.93
Constellation	492.28	524.55	520.54	6.56	5.74

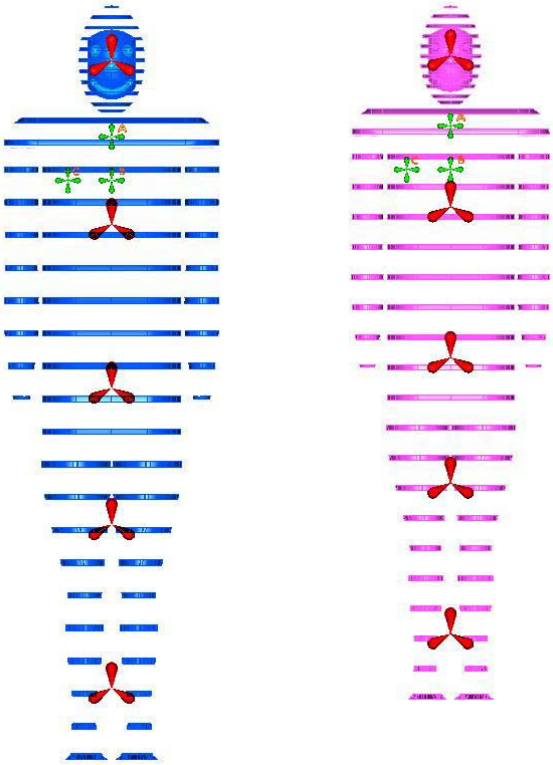


Figure 1: Shadow phantoms as shown on the OLTARIS website.

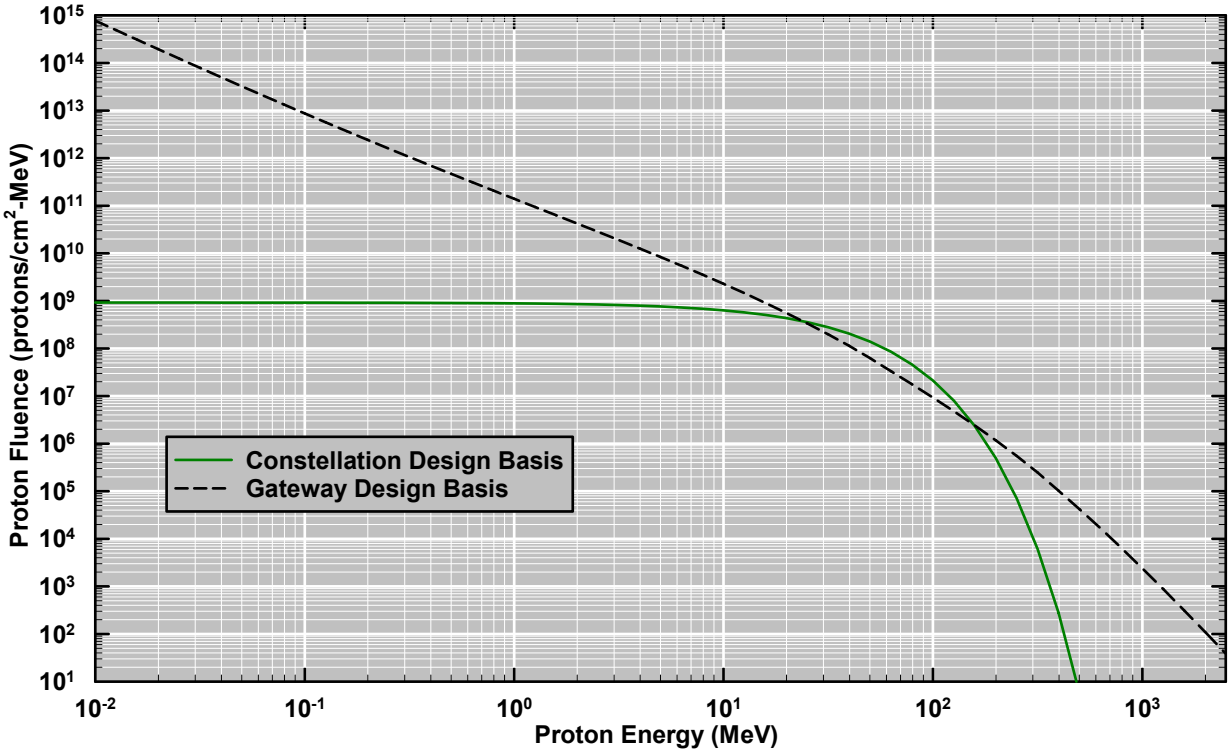
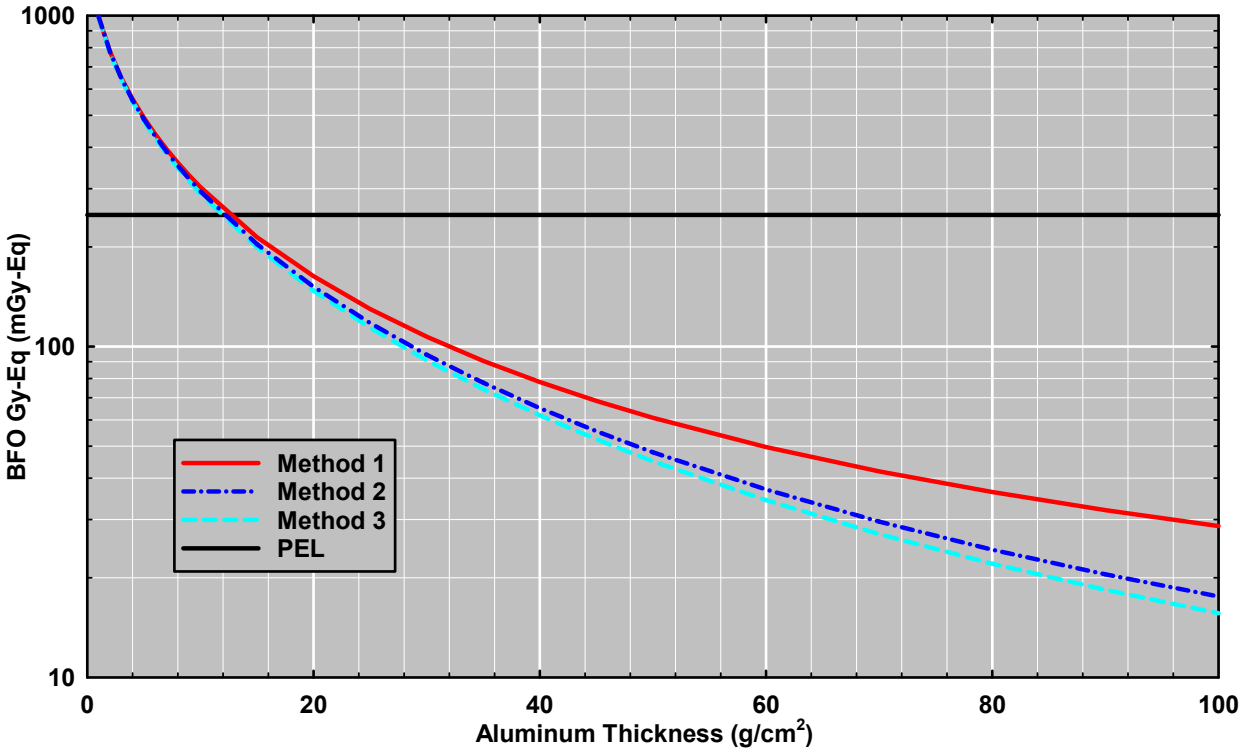
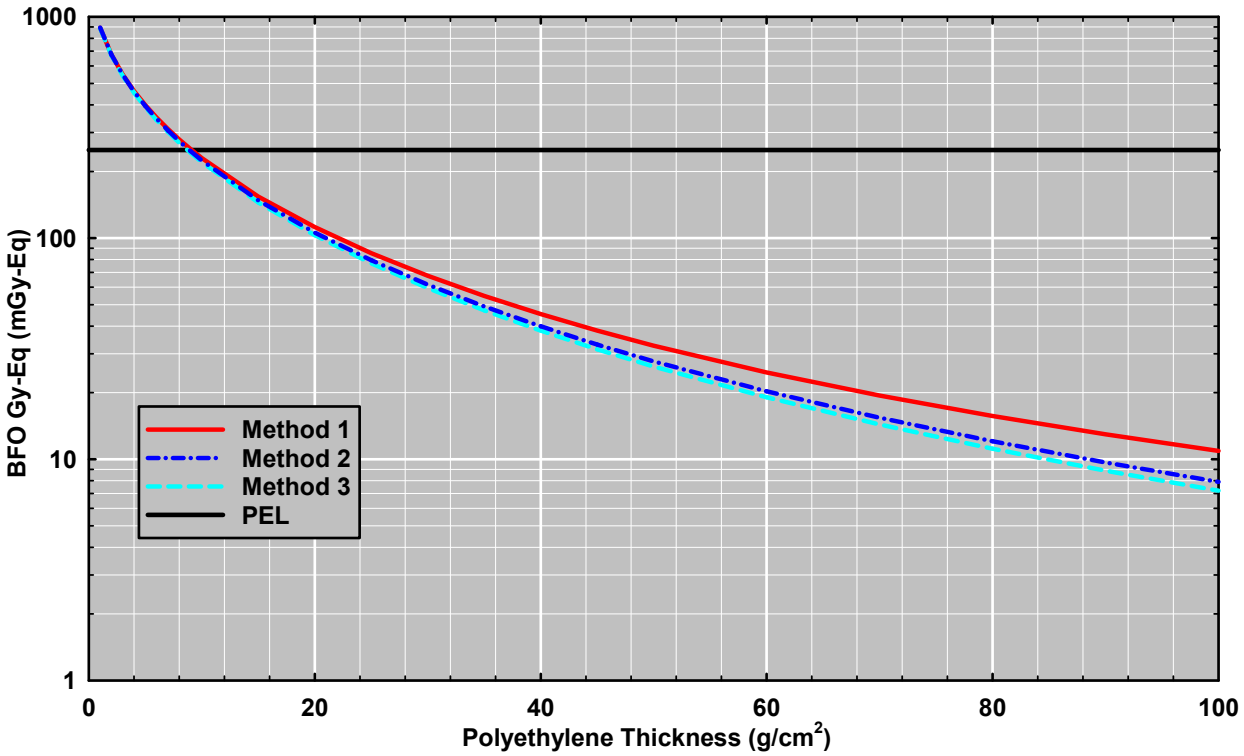


Figure 2: The Two Historical SPE Fluences used as Boundary Conditions for this Analysis (Constellation[9] and Gateway.[10])

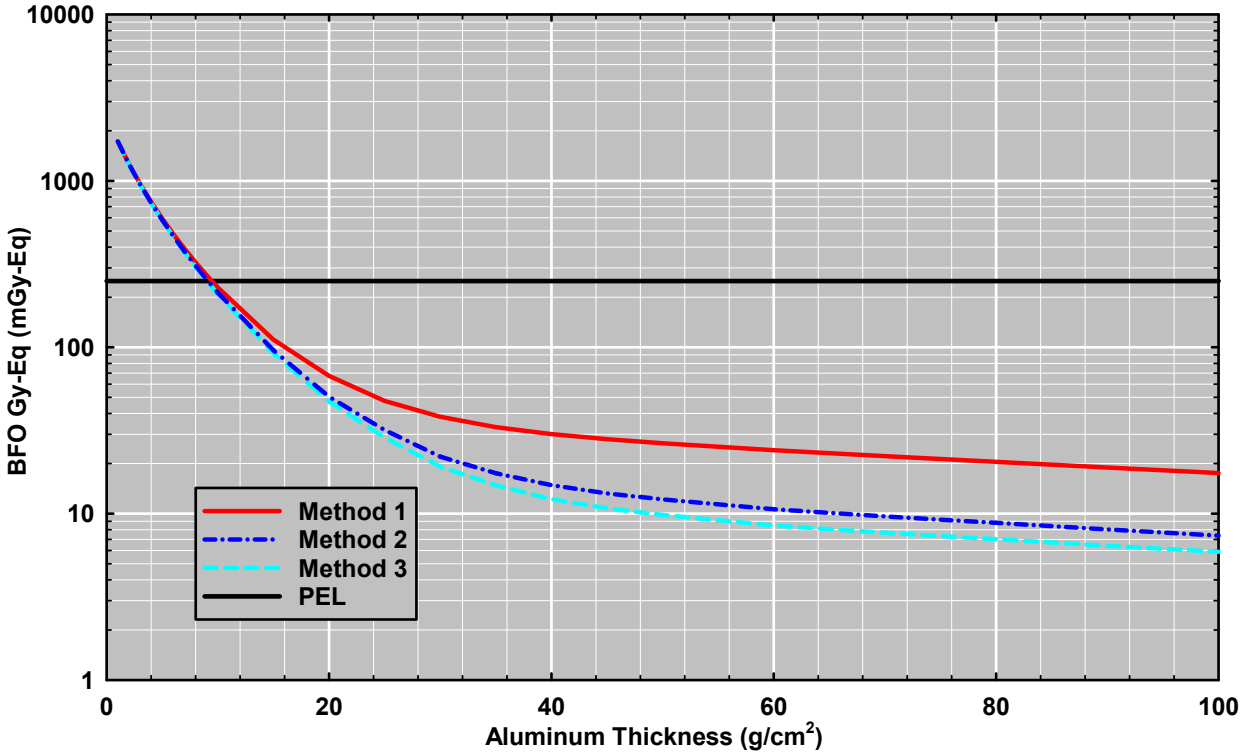


(a) Aluminum Spheres.

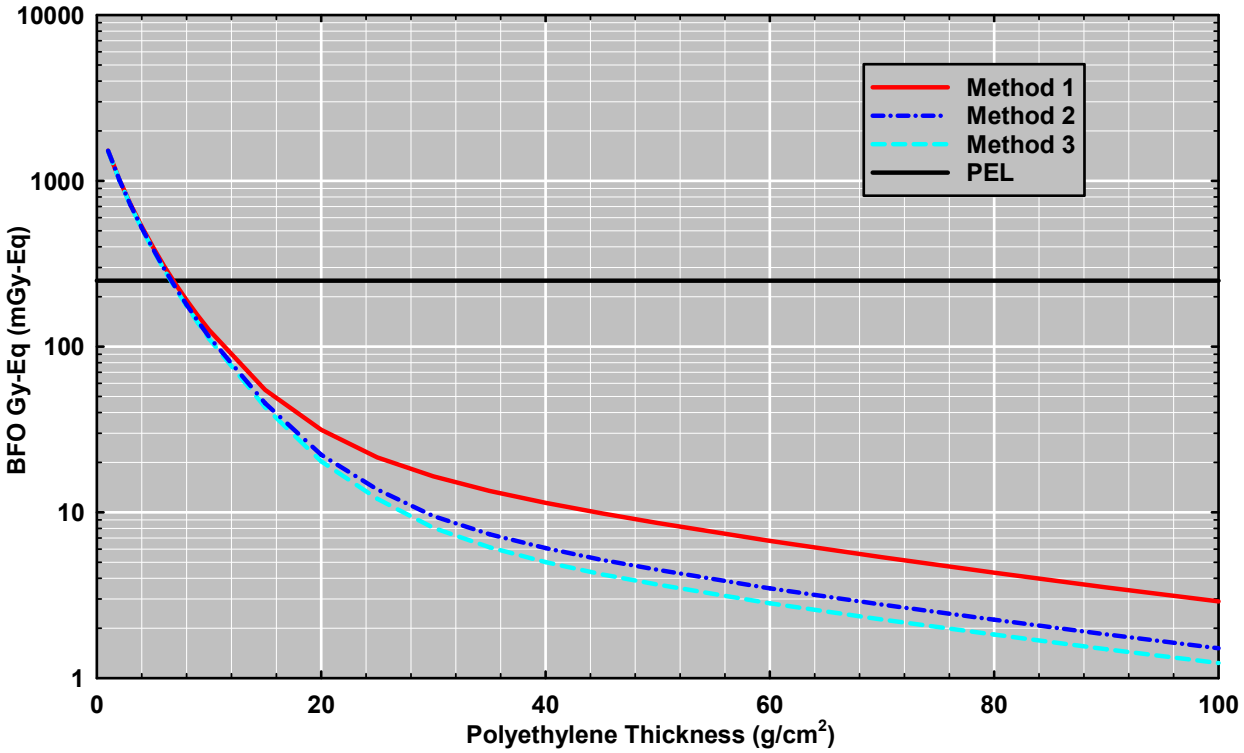


(b) Polyethylene Spheres.

Figure 3: Comparison of Methods 1, 2, and 3 BFO Gy-Eq and the PEL for the Gateway Design Basis SPE for Different Materials (Aluminum and Polyethylene).

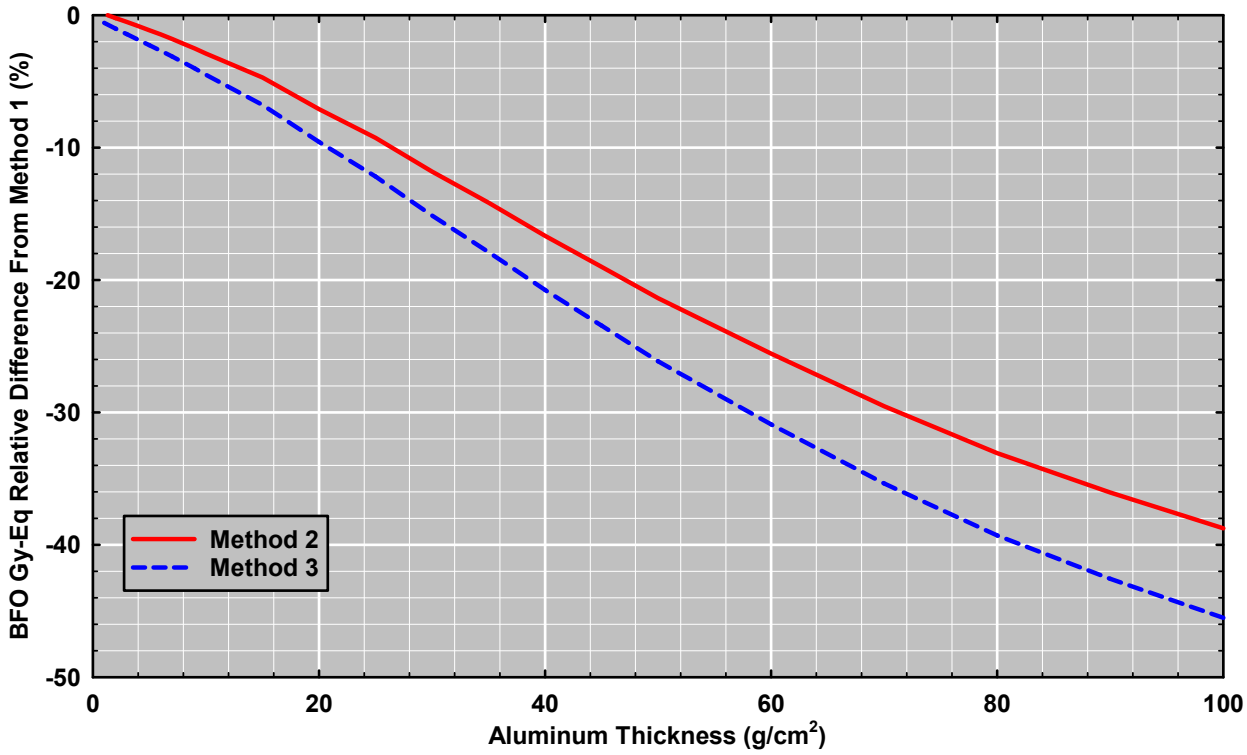


(a) Aluminum Spheres.

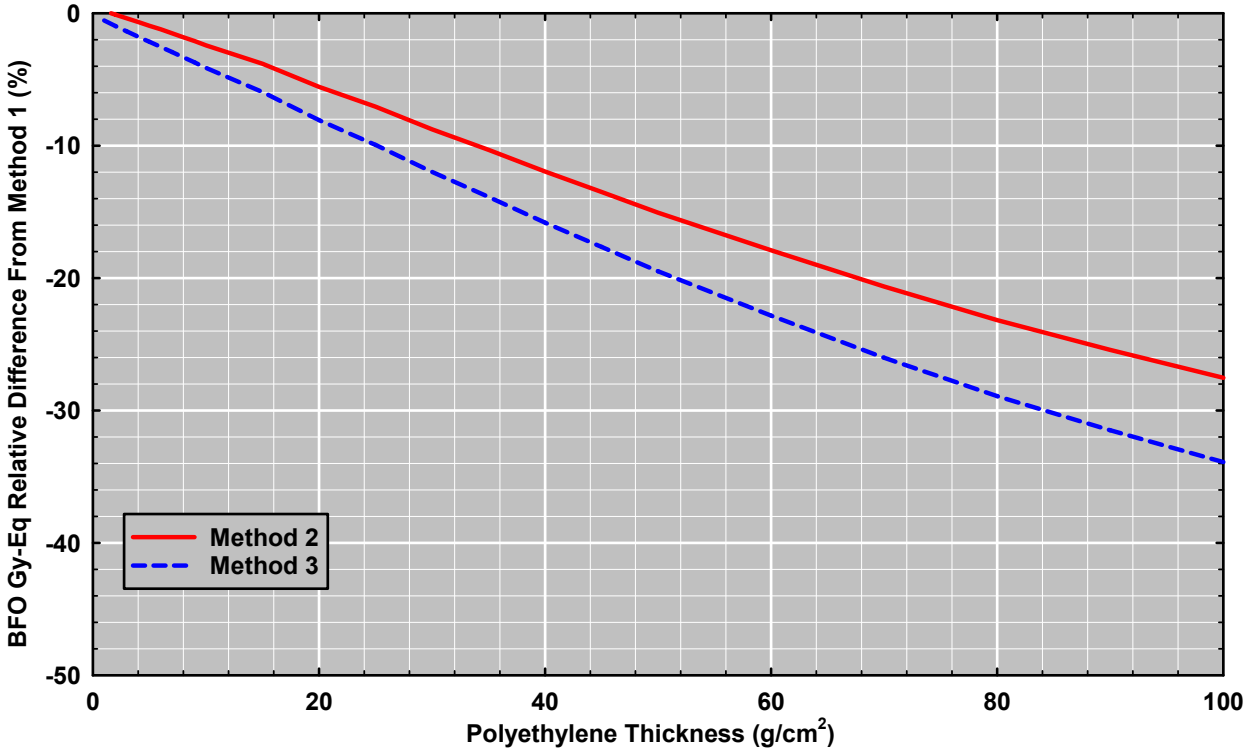


(b) Polyethylene Spheres.

Figure 4: Comparison of Methods 1, 2, and 3 BFO Gy-Eq and the PEL for the Constellation Design Basis SPE for Different Materials (Aluminum and Polyethylene).

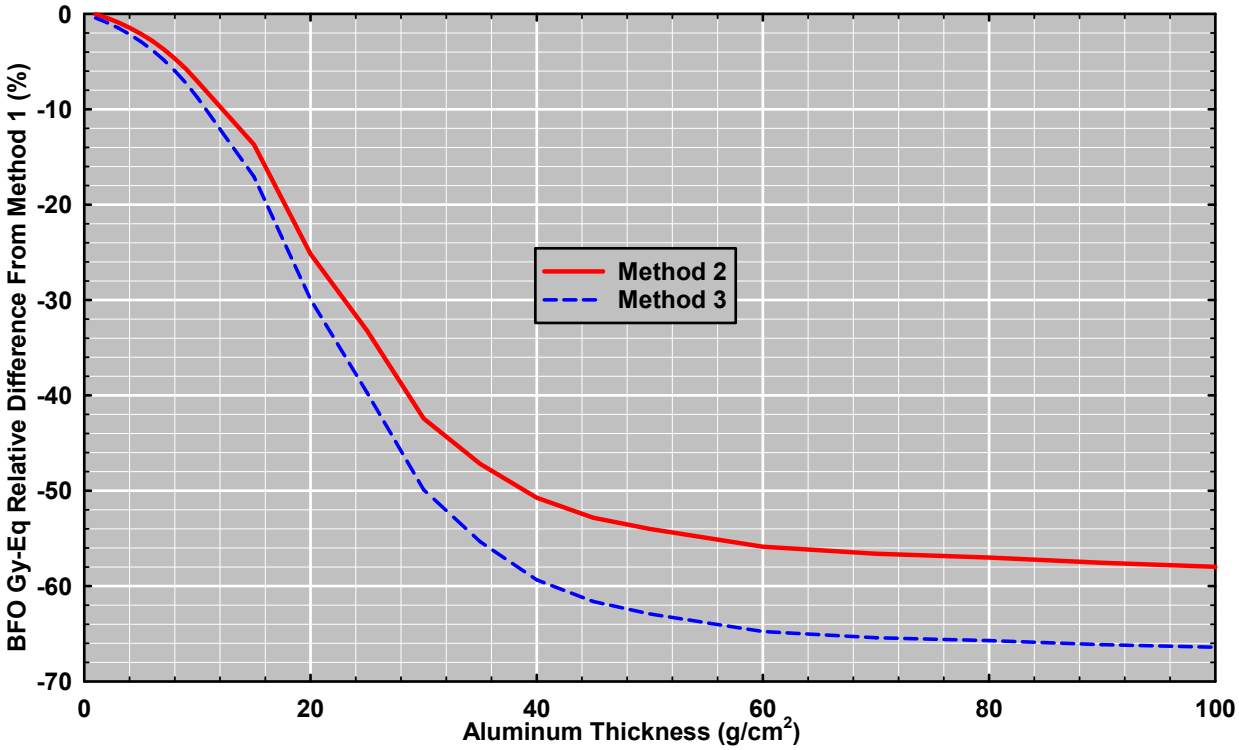


(a) Aluminum Spheres.

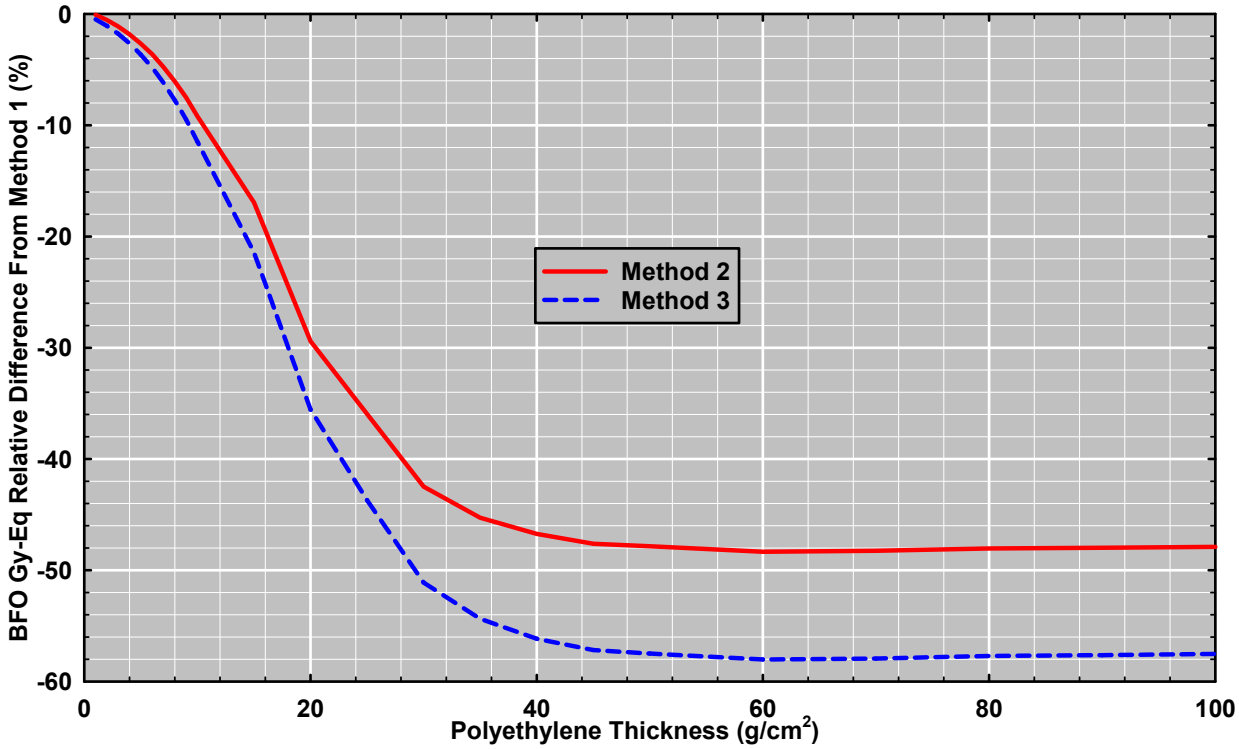


(b) Polyethylene Spheres.

Figure 5: Relative Difference between Method 1 and Methods 2, and 3 for Different Materials (Aluminum and Polyethylene) for the Gateway Design Basis SPE.



(a) Aluminum Spheres.



(b) Polyethylene Spheres.

Figure 6: Relative Difference between Method 1 and Methods 2, and 3 for Different Materials (Aluminum and Polyethylene) the Constellation Design Basis SPE.