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Development of Graphical User Interface for ARRBOD (Acute Radiation Risk and BRYNTRN Organ Dose Projection)

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ACRONYMS

ALARA	as low as reasonably achievable
ARR	acute radiation risk
ARS	acute radiation sickness
ARRBOD	acute radiation risk and BRYNTRN organ dose projection
BFO	blood forming organ
BRYNTRN	baryon transport computer code
CAF	computerized anatomical female
CAM	computerized anatomical male
EVA	extra vehicular activity
FAX	female adult voxel (volumetric and pixel)
FW	fatigability and weakness
GCR	galactic cosmic radiation
GUI	graphical user interface
GERM	GCR event-based risk model
Gy	Gray
Gy-Eq	Gray-Equivalent
HZE	high-charge and -energy nuclei
HZETRN	high-charge and -energy transport computer program
ICRP	International Commission on Radiological Protection
ISS	International Space Station
JSC	Johnson Space Center
LEO	low Earth orbit
LET	linear energy transfer
MAX	male adult voxel (volumetric and pixel)
MOD	mission operations directorate
NASCA	NASA study of cataracts in astronauts
NCRP	National Council on Radiation Protection & Measurements
NSRL	NASA Space Radiation Laboratory
PEL	permissible exposure limit
PRA	probabilistic risk assessment
RBE	relative biological effectiveness
REID	risk of exposure-induced death
SPE	solar particle event
SRPE	Space Radiation Program Element
SUMDOSE	summation of dose
Sv	Sievert
UG	upper gastrointestinal distress
UI	user interface

Abstract

The space radiation environment, particularly solar particle events (SPEs), poses the risk of acute radiation sickness (ARS) to humans; and organ doses from SPE exposure may reach critical levels during extra vehicular activities (EVAs) or within lightly shielded spacecraft. NASA has developed an organ dose projection model using the BRYNTRN with SUMDOSE computer codes, and a probabilistic model of Acute Radiation Risk (ARR). The codes BRYNTRN and SUMDOSE, written in FORTRAN, are a Baryon transport code and an output data processing code, respectively. The ARR code is written in C. The risk projection models of organ doses and ARR take the output from BRYNTRN as an input to their calculations. BRYNTRN code operation requires extensive input preparation. With a graphical user interface (GUI) to handle input and output for BRYNTRN, the response models can be connected easily and correctly to BRYNTRN in friendly way. A GUI for the Acute Radiation Risk and BRYNTRN Organ Dose (ARRBOD) projection code provides seamless integration of input and output manipulations, which are required for operations of the ARRBOD modules: BRYNTRN, SUMDOSE, and the ARR probabilistic response model. The ARRBOD GUI is intended for mission planners, radiation shield designers, space operations in the mission operations directorate (MOD), and space biophysics researchers. The ARRBOD GUI will serve as a proof-of-concept example for future integration of other human space applications risk projection models. The current version of the ARRBOD GUI is a new self-contained product and will have follow-on versions, as options are added: 1) human geometries of MAX/FAX in addition to CAM/CAF; 2) shielding distributions for spacecraft, Mars surface and atmosphere; 3) various space environmental and biophysical models; and 4) other response models to be connected to the BRYNTRN. The major components of the overall system, the subsystem interconnections, and external interfaces are described in this report; and the ARRBOD GUI product is explained step by step in order to serve as a tutorial.

1. Introduction

The potential for exposure to large solar particle events (SPEs) is a major concern during extra-vehicular activities (EVAs) on the lunar surface and during Earth-to-Lunar or Earth-to-Mars transit. This includes the acute radiation syndrome from exposure to an intense SPE during an EVA or in a lightly shielded vehicle (< 5 g cm^{-2}), as well as the increased risk of radiation induced cancers and degenerative diseases due to the cumulative organ doses from galactic cosmic rays (GCR) and multiple SPEs with intense particle flux and high energy levels (Cucinotta, 1999; Cucinotta et al. 2001; Cucinotta and Durante 2006). Most SPEs would lead to small crew doses, although even a small SPE can disrupt mission operations and lead to excessive costs. A real concern for the health risk to astronauts would be from SPEs with large proton fluences and effective doses exceeding 50 mSv. The development of operational strategies and capabilities for the protection of astronauts from SPEs is an important consideration for the planning of future lunar surface scenarios, exploration of near Earth objects, and missions to Mars.

In NASA's operational radiation protection program, career doses are monitored for individual astronauts, who engage in the space shuttle missions and/or the International Space Station (ISS), and best efforts are used to keep the risk as low as reasonably achievable (ALARA) (NCRP, 2000 and 2003). Radiation exposures for astronauts corresponding to a 3% risk of exposure-induced death (REID) (NCRP, 2000, 2003, Cucinotta *et al*., 2006), as well as short-term limits to avoid detrimental effects (NRC/NAS, 2008) are given as dose limits in radiation protection practices for space missions.

NASA's space radiation transport model of organ dose projection, which includes the baryon transport code BRYNTRN (Cucinotta *et al.*, 1994; Wilson *et al*., 1989) and an output data processing code SUMDOSE, has been used to estimate the whole body effective dose for astronauts. The radiation shielding by body tissue at specific organ sites was accounted for by using ray tracing in the human phantom models of the Computerized Anatomical Male (CAM), (Kase et al., 1970; Billings and Yucker, 1973) and the Computerized Anatomical Female (CAF), (Yucker and Hudston, 1990; Yucker, 1992). For human exposure, the dose-equivalent is defined by the product of the absorbed dose and the radiation quality factor Q, which compares the biological damage incurred from any ionizing radiation to the damage produced by γ-rays. In general, Q is a function of linear energy transfer (LET). For dose equivalent calculations (in Sv), the quality factors used are those defined by the International Commission on Radiological Protection in 1990 (ICRP 60). The whole body effective dose, E, is defined as a weighted sum of organ dose equivalents over major sites for radiation cancer risks (ICRP, 2007; NCRP, 2000, 2003) using the tissue weighting factors, w_T (ICRP, 1991 & 2007).

For space missions beyond LEO, the clinically significant deterministic health effects, including performance degradation in-flight, from the exposure to large SPEs must be prevented. For the deterministic acute effects, the National Council for Radiological Protection (NCRP, 2000) has recommended that individual organ doses be made in terms of an alternate dose quantity denoted as the Gray-Equivalent (Gy-Eq), using the relative biological effectiveness (RBE), which is radiation-field dependent. Because biological effects are expected to increase significantly for dose-rates above 0.05 Gy/h, the current 30-day permissible exposure limits (PELs) have been approved by NASA for skin, eye, and BFO as 1.5, 1.0, and 0.25 Gy-Eq (NCRP 2000, 2006), respectively. For the estimation of deterministic acute effects from the intense SPEs during transition between and on the surface of the Moon or Mars missions, the new dosimetric quantity of organ dose (in Gy-Eq), was calculated using BRYNTRN with SUMDOSE by implementing the NCRP's RBE together with the full definition of neutron RBE suggested by Wilson et al. (2002). The resultant early radiation risks were assessed for the blood forming organ (BFO) dose by using an NASA-developed probabilistic model of acute radiation risk (ARR) (Anno et al. 1996; Hu et al. 2009).

The purpose of the graphical user interface (GUI) development for ARRBOD is to provide seamless integration of input and output manipulations for the operations of projection modules (BRYNTRN, SUMDOSE, and the ARR probabilistic response

model) in assessing the acute risk and the organ doses of significant SPEs. The ARRBOD GUI product will serve as a proof-of-concept for future integration of other risk projection models for human space applications. Future capabilities will include the ability of the user to supply a shield file of detailed geometry and SPE spectral measurement data of the radiation environment. Also, the blood kinetics and the cataract risk projections based on NASCA (NASA study of cataracts in astronauts) and NSRL (NASA Space Radiation Laboratory) data will be added into the acute risk model. The probabilistic risk assessment (PRA) approach using hazard functions will be added for SPE protection purposes. Eventually, the galactic cosmic ray (GCR) event-based risk model (GERM) (Cucinotta *et. al*. 2010) will be developed in order to provide stochastic-based estimates for GCR and SPE exposures.

2. Measures of Radiation Exposure, NASA Limits, and Acute Severity Levels

Quantities used to describe radiation include the absorbed dose (D), dose equivalent (H), quality factor (Q), linear energy transfer (L), gray equivalent ($Gy\text{-}Eq$), effective dose (E), and relative biological effectiveness (RBE). The absorbed dose is measured in Grays (Gy), energy absorbed per unit mass of material (1 Gy = 1 J per kg). Dose equivalent is measured in Sieverts (Sv), $H = DxQ = \int Q(L)\, D(L)\, dL$, where Q is the quality factor which represents the relative weighting of different types of radiation to produce stochastic biological effects compared to gamma-rays. Gray equivalent is calculated as $Gy\text{-}Eq = \Sigma\, (\mathrm{RBE})_i\, D_i$, where RBE_i is the relative biological effectiveness factor for deterministic effects produced as a result of exposure to type i particles, and D_i is the dose due to type i particles. The effective dose is measured in Sieverts (Sv), $E = \Sigma\, w_T\, H_T$, where w_T is a weighting factor for tissue or organ type T, and H_T is the dose equivalent averaged over tissue type T. Measures of radiation exposure quantity are summarized in Table 1.

Table 1. Measures of Exposure.

	Physical dose	Dosimetric quantity for deterministic effects (typically acute response)	Dosimetric quantity for stochastic (probabilistic) effects (typically cancer)
Point	Absorbed dose (D)	Absorbed dose (D) or Gray-Equivalent ($Gy\text{-}Eq$)[2]	Dose equivalent (H)[1]
Organ/tissue	Mean absorbed dose (D_T)	Gray-Equivalent ($Gy\text{-}Eq$)[2]	Organ dose equivalent ($\overline{H_T}$)[1] or Equivalent dose (H_T)[2]
Body			Effective dose (E)[3]

[1]Absorbed dose is weighted by a **quality factor** that is a function of particle LET.
[2]Absorbed dose is weighted by a **radiation weighting factor** that is a function of particle type. [3]Absorbed dose is *also* weighted by type of tissue or organ.

The possibility of acute risk exists for a blood-forming organ (BFO) dose over 500 mGy-Eq. Dose limits for non-cancer radiation effects at BFO occur at doses below the threshold for prodromal effects. The current NASA 30-day limits to BFO, lens, and skin for deterministic effects from space radiation and the minimum BFO dose for ARR are given in Table 2. Symptoms of the early radiation effects at each severity levels are listed in Table 3 for the NASA-developed probabilistic model of acute radiation risk (Anno et al. 1996; Hu et al. 2009).

Table 2. Exposure Limit by NASA for Deterministic and Prodromal Effect.

Exposure limit	Organ dose, Gy-Eq
30-d limit to Skin	1.5
30-d limit to Lens	1.0
30-d limit to BFO	0.25
BFO dose limit without ARR	0.5

Table 3. ARR Sickness at Severity Level.

Severity	Upper Gastrointestinal Distress (UG)	Fatigability and Weakness (FW)
1	No effect	No effect
2	Upset stomach, clammy and sweaty, mouth waters	Somewhat tired with mild weakness
3	Nauseated, considerable sweating, swallows frequently to avoid vomiting	Tired with moderate weakness
4	Vomited once or twice, nauseated, and may vomit again	Very tired and weak
5	Vomited several times, including the dry heaves, severe nauseated, and will soon vomit again	Exhausted with almost no strength

3. Stimulus and Response Sequences of SPE/Beam Exposure

The sequences of user actions and system responses that stimulate the behavior defined in the GUI feature are illustrated in Fig.1. Shown is a flow chart of the calculation of physical dose from SPE exposure (label 1 in Fig. 1) using BRYNTRN and SUMDOSE modules. There are three major control components: Input File Control, BRYNTRN Execution Control, and SUMDOSE Execution Control. For radiation

exposure (label 2 in Fig. 1), those steps are entirely skipped to calculate directly ARR in the next step. Fig. 2 shows the flow chart in the calculation of severity of sickness for upper gastrointestinal distress (UG) and fatigability and weakness (FW) under ARR Execution Control.

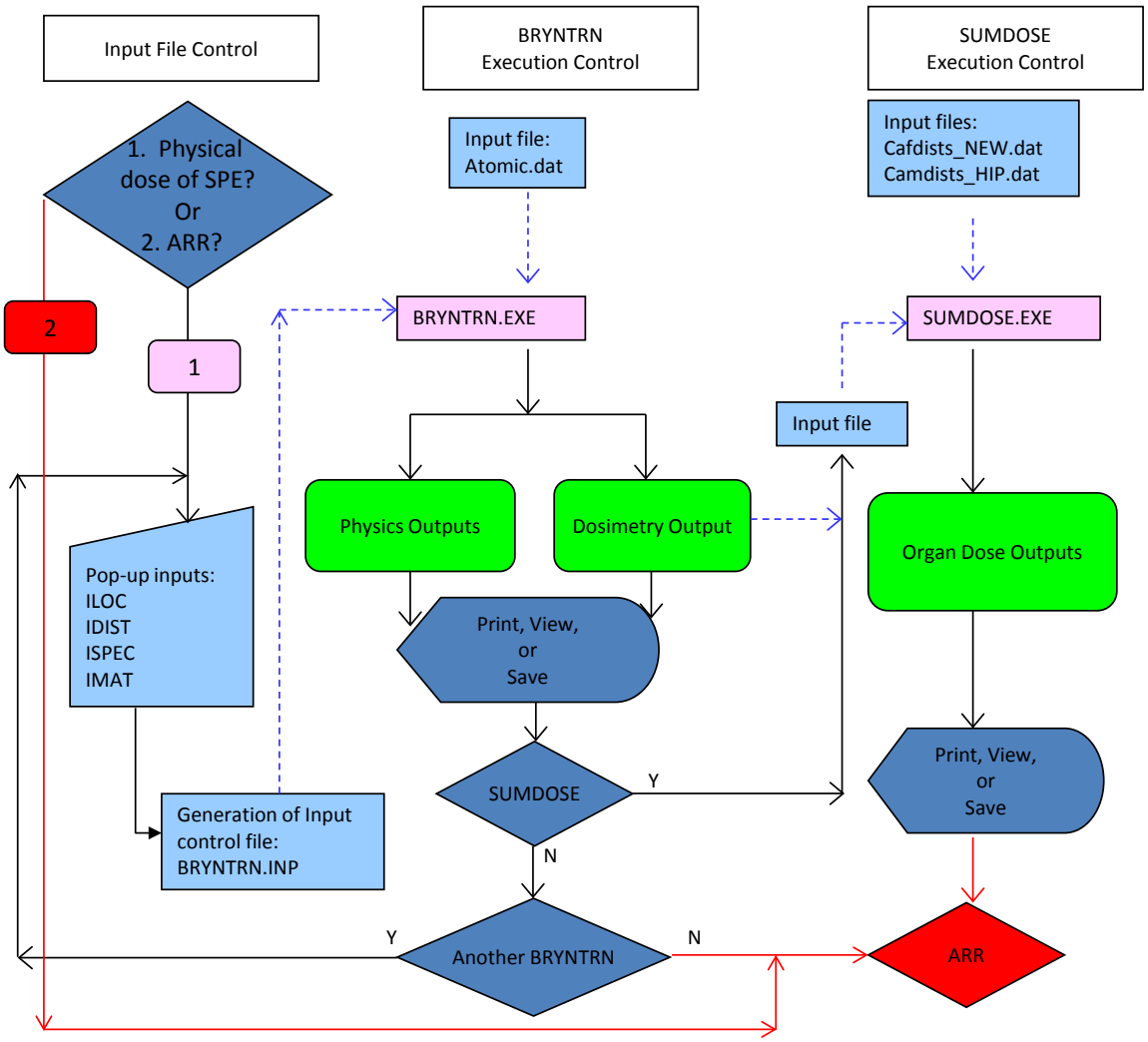


Figure 1. Flow chart of physical dose calculations using the BRYNTRN and SUMDOSE modules for SPE exposure (label 1). For the radiation exposure (label 2), go directly to the next step for the calculation of ARR.

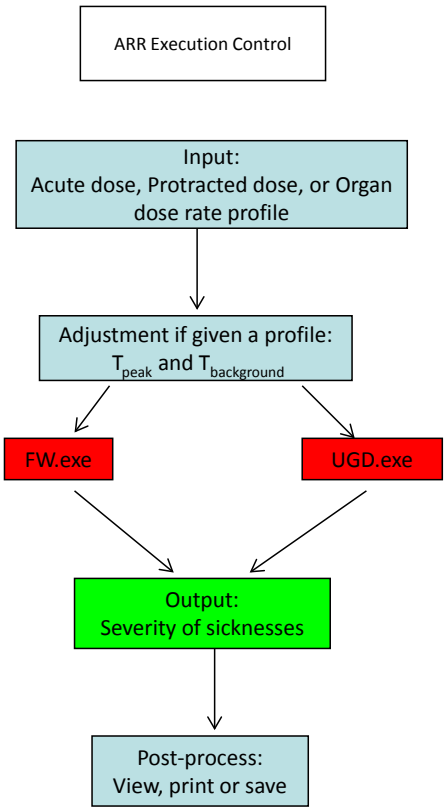


Figure 2. Flow chart of the ARR module.

3.1 Input Control Parameters of BRYNTRN.INP

Input control parameters of BRYNTRN.INP are location, radiation field, fluence distribution of historical SPEs, and shield material. Default values of input variables are listed in Table 4 for the pre-defined scenario. Possible values for the selection of each variable are listed in Table 5.

Table 4. Default Variables in Pre-defined Scenario

Location	Radiation Field	Fluence Distribution of Historical SPE		Shield Material
Interplanetary Space	SPE	Exponential Spectra	Aug 1972 King	Aluminum

Table 5. Input Parameters of BRYNTRN.INP

Location	Radiation Field	Fluence Distribution of Historical SPEs		Shield Material
Interplanetary Space Or Lunar Surface	SPE	Exponential Spectra	Feb 1956	Aluminum, Polyethylene, CO_2, Water, or Graphite Carbon
			Nov 1960	
			Aug 1972 King	
			Aug 1989	
			Sep 1989	
			Oct 1989	
		Weibull Spectra	Feb 1956	
			Nov 1960	
			Aug 1972	
			Oct 1989	
			Jul 2000	
			Oct 2003	
			Nov 2001	
			Nov 2000	
			Mar 1991	
			Aug 1989	
			Sep 1989	

3.2 Input Control Parameters of ARR.INP

There are 3 exposure types available for the calculation of ARR: 1) Acute beam exposure, 2) Protracted dose exposures of radiation beam, and 3) SPE exposure during EVA. Input control parameters for ARR.INP are: total BFO dose in acute dose exposure; total BFO dose and exposure time in protracted dose exposure; and EVA duration, gender of astronaut, and choice of spacecraft thickness with organ doses calculated from the selected SPE exposure. Table 6 summarizes the input control parameters of ARR for the 3 exposure types and the ranges of variables.

Table 6. Input Parameters of ARR.INP

<table>
<tr><td colspan="2">ARR Application Directly
due to the Exposure from Acute/Protracted Dose Defined by User</td><td>ARR Application with BRYNTRN+SUMDOSE
due to the Exposure from a Historically Large SPE</td></tr>
<tr><td>1) Acute Exposure</td><td>2) Protracted Exposure</td><td>3) SPE Exposure</td></tr>
<tr><td rowspan="3">Acute dose in Gy-eq:
[0.47* - 28.17]</td><td>Protracted dose in Gy-eq:
[0.47* - 28.17]</td><td>Male or Female:
→ Gender-specific total BFO dose inside spacesuit from the selected SPE exposure to be used.</td></tr>
<tr><td rowspan="2">Exposure time in hr:
[0.1 – 168.0]</td><td>EVA time in hr:
[0.0 – 10.0]</td></tr>
<tr><td>Shielding thickness:
[0.3, 1, 5, 10, 15, 20, or 30 g/cm^2]
→ Gender-specific BFO dose inside spacecraft at specified shielding thickness from the selected SPE exposure to be used.</td></tr>
</table>

*No acute radiation risk if total BFO dose < 0.47 Gy-Eq.

3.3 Overall I/O Sequences for ARR

Overall input/output sequences of ARR calculations are illustrated in Fig. 3 for 3 exposure types.

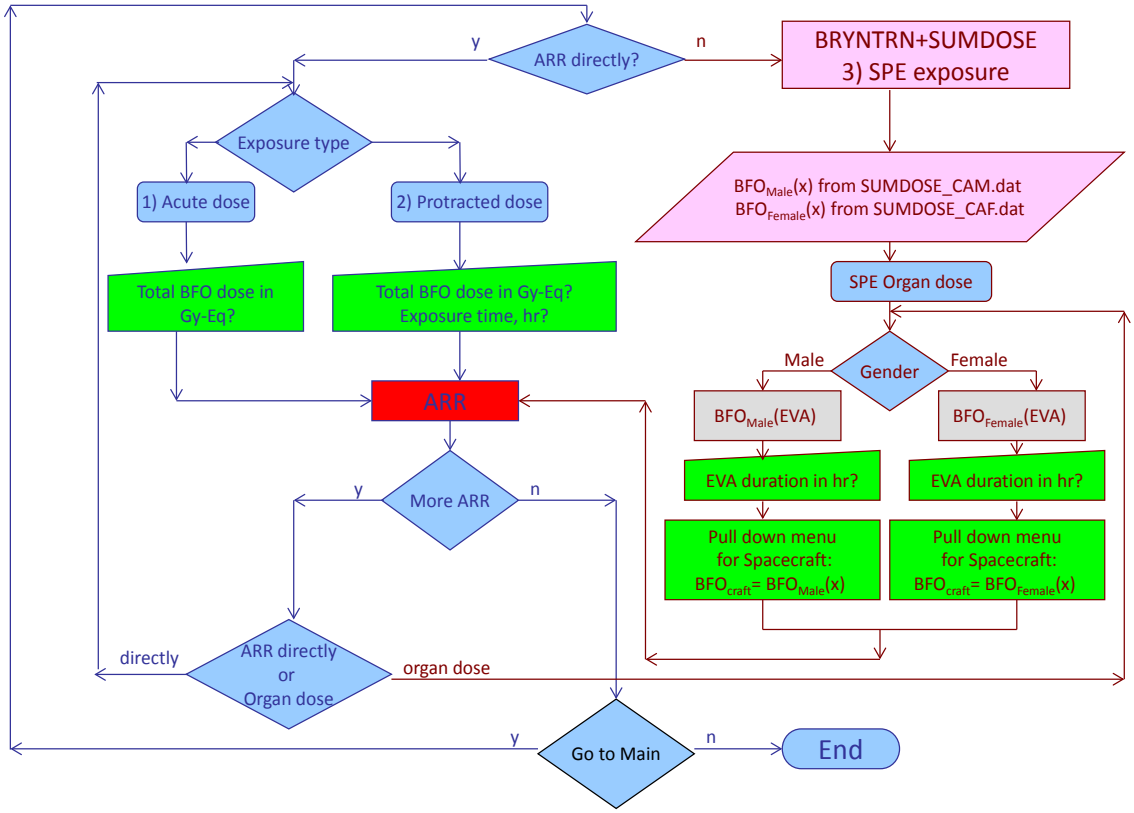
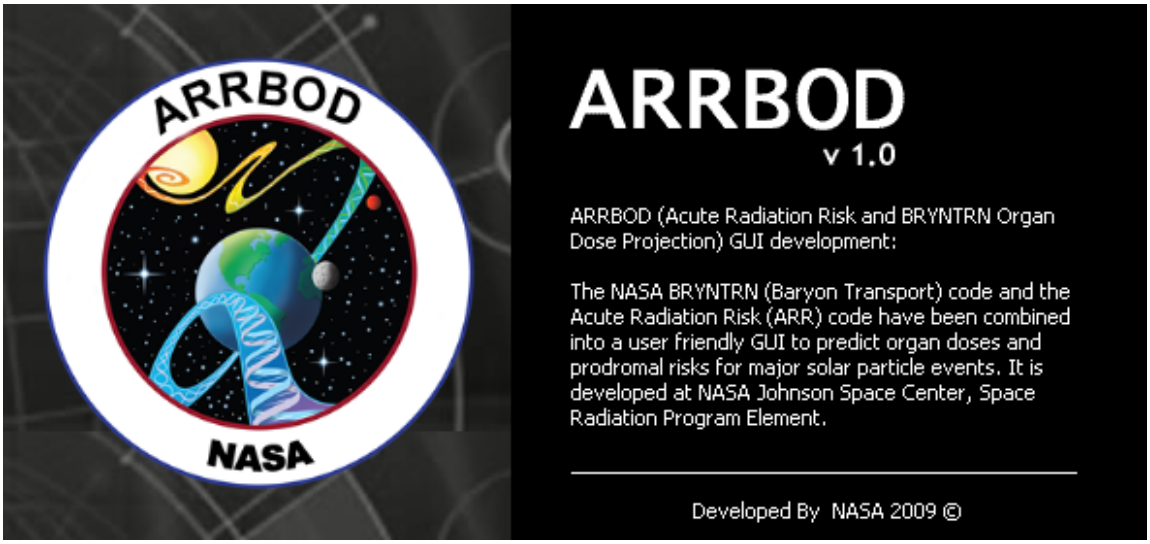


Figure 3. Overall input/output sequences of ARR calculations for 3 types of exposure: 1) Acute dose; 2) Protracted dose; and 3) SPE exposure during EVA.

4. Overview of ARRBOD GUI

As an application of ARRBOD GUI starts, it launches the banner below for a brief time period. It says that ARRBOD v 1.0 is developed at the NASA Johnson Space Center, Space Radiation Program Element (SRPE), in 2009.



The next screen is the main task user interface (UI) of ARRBOD application flow (Fig. 4). From this main task UI, the user has two options for the selection of either: (1) evaluation of physics and organ doses from historically large SPEs; or (2) do the acute risk analysis directly.

Figure 4. Main task UI

4.1 Option for SPE Exposure

4.1.1 Preparing of BRYNTRN Inputs to Generate the Physical Dose

For the selection of option 1 in the main task UI for the evaluation of physics and organ doses from historically large SPEs, the following input control UI of SPE (Fig. 5) appears. In this input control UI of SPE, the user can make either the selection of the default scenario of the August 1972 SPE (Table 4) or the manual selection for the input parameters listed in Table 5 to generate the BRYNTRN.INP file. By clicking "Generate Physics Dose", the BRYNTRN code is executed with the input variables selected by the user.

Figure 5. Input control UI of SPE

4.1.2 Viewing Options for Physical Quantities from SPE

Physical quantities generated from the execution of BRYNTRN code can be viewed for 1) physical dosimetry (*D*, *G*, *H*), or 2) LET spectra, by selecting the viewing option from the task UI in Fig. 6.

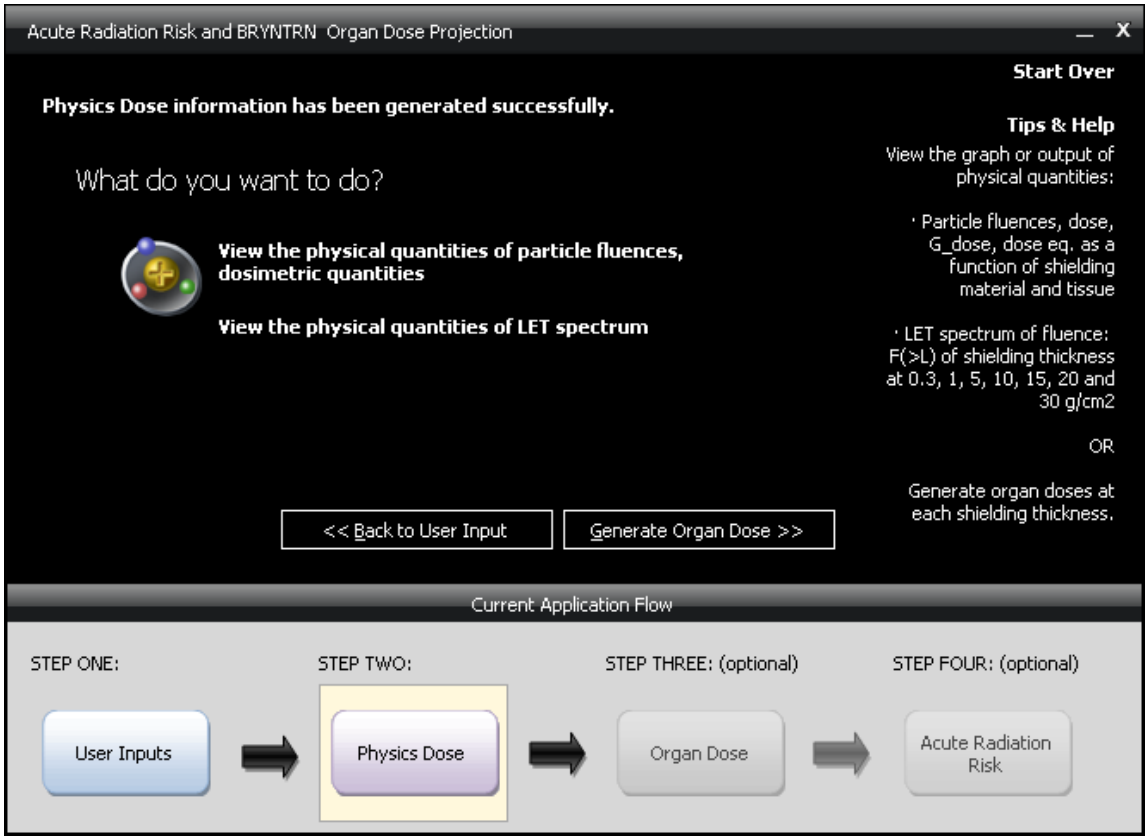


Figure 6. Task UI for the selection of physical quantities viewing options, or for the next application flow.

In the selection of viewing option "Physical Dosimetry" (Fig. 7), outputs of absorbed dose of physical dose (*D*), Gray-equivalent adjusted for acute risk (*G*), and dose-equivalent adjusted for long-term risk (*H*) are viewed as a function of tissue thickness at a given shielding thickness (x=0.3, 1, 5, 10, 15, 20 or 30 g/cm^2). In the "View Data" window, those output data are tabulated also in text format.

Linear energy transfer (LET) spectra at various shielding thicknesses can be viewed by clicking the corresponding tab "LET Spectra" in the same output window (in Fig. 7) or by clicking "Show Tasks" to go back to the previous task UI (Fig. 6), and then selecting the viewing option for LET in that task UI. In the current viewing option of "LET Spectra", data of LET spectra are viewed by clicking "View Data" and saving them as a text file. The graph can be printed directly and also can be saved separately in a working directory. The ARRBOD application for SPE is continued by clicking "Show Tasks" to go back to the task UI (Fig. 6) and then clicking "Generate Organ Dose" in the task UI for the next application flow of step three.

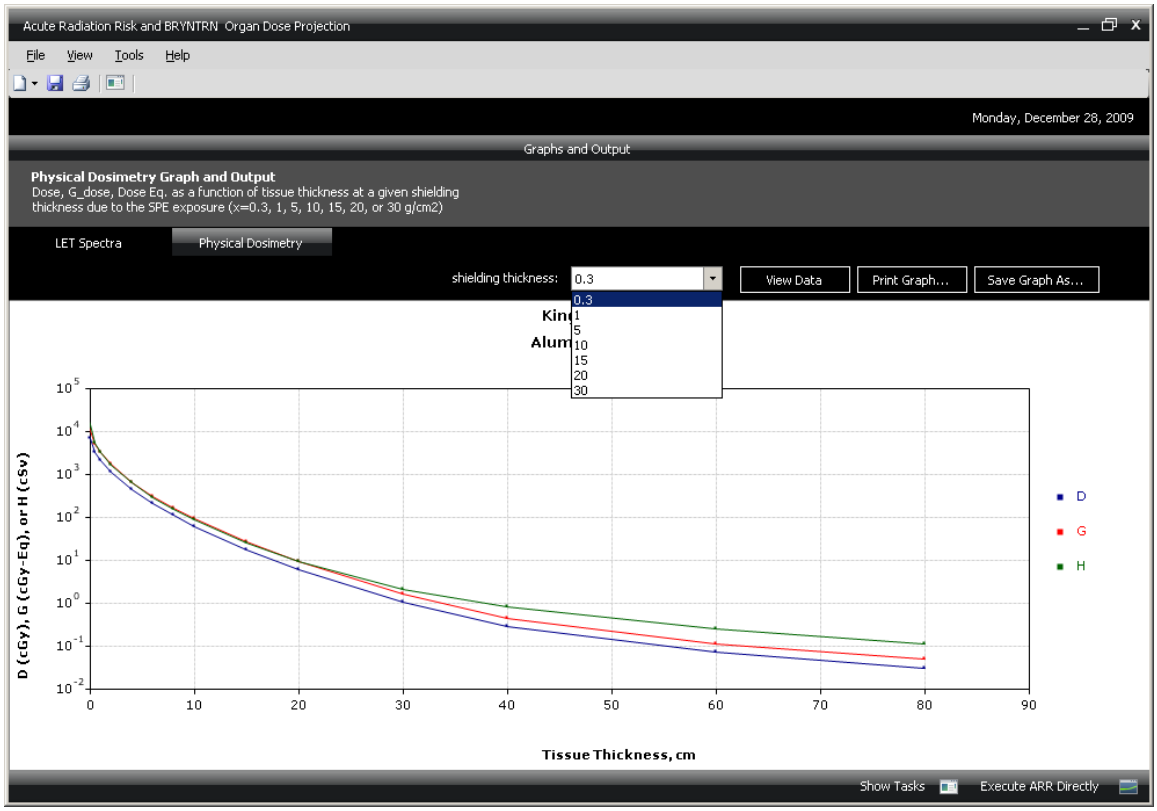


Figure 7. Graph and Output window for physical quantities

4.1.3 Viewing Organ Dose for Male or Female

Organ dose quantities for male or female can be viewed by selecting organ dose output for male or female in the SUMDOSE task UI in Fig. 8.

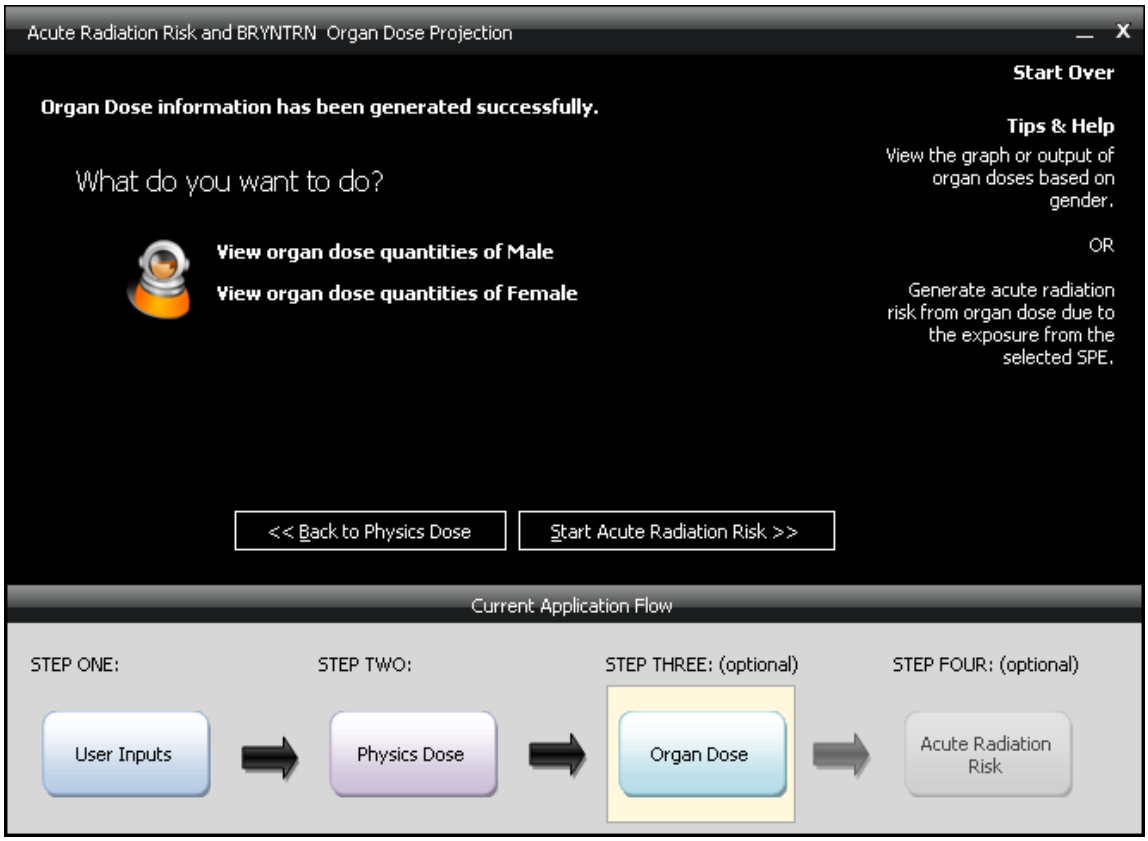


Figure 8. Task UI for the selection of viewing options of organ doses, or for the next application flow.

Organ doses at various organ/tissue sites, whole body effective dose, and point dose without body shielding are viewed in terms of absorbed dose (*D*), Gray-equivalent dose (*G*), and dose-equivalent (*H*) at a given shielding thickness. The result data are viewed and saved as text files for male or female. The graph can be printed directly and also saved in a separate working directory.

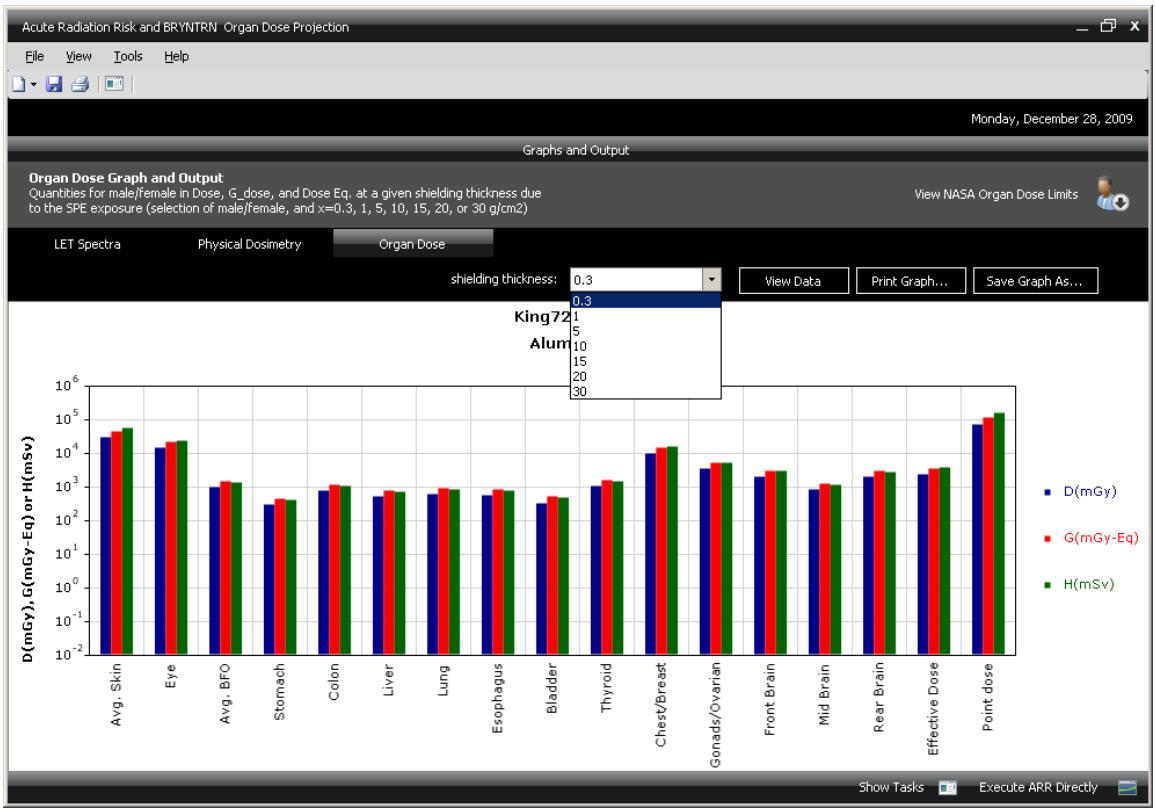


Figure 9. Graph and Output window for physical quantities and organ doses.

In the graph and output window for physical quantities and organ doses, an added feature is “View NASA Organ Dose Limits”. By clicking it, the organ doses of male or female for skin, eye, and blood forming organ (BFO) at each shielding thickness are easily compared to the color-coded parallel lines, which are NASA exposure limits for deterministic and prodromal effects (Table 2), as shown in Fig. 10.

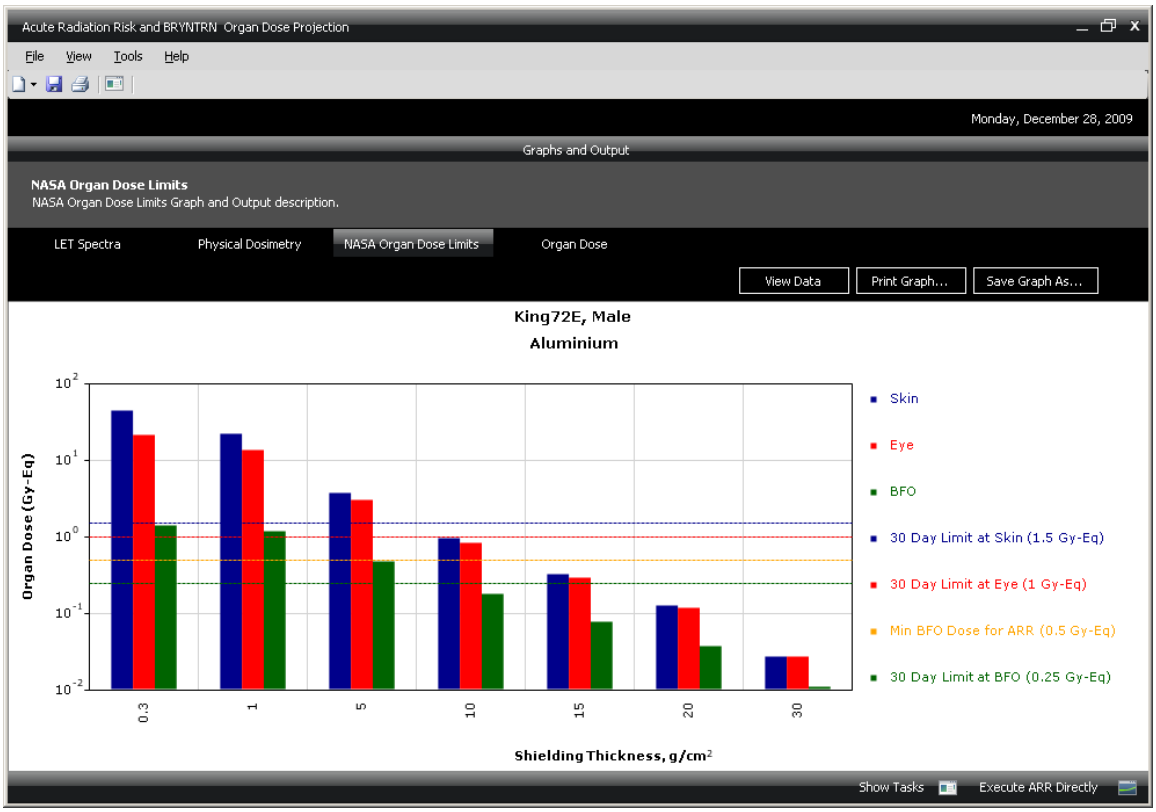


Figure 10. Graph and Output window of organ dose comparisons to the NASA limits at various thicknesses, which is displayed by clicking “View NASA Organ Dose Limits”.

The ARRBOD application for SPE is performed by clicking “Show Tasks” and then clicking “Start Acute Radiation Risk” in the task UI (Fig. 8), the next application in the flow of step four.

4.1.4 Preparing of ARR Inputs

Using the SPE exposure calculated from the previous three steps, gender-specific total BFO dose inside the spacesuit is assigned automatically to "BFO EVA dose" for the calculation of ARR, once the astronaut's gender is specified by the user. Additional input variables required are: 1) EVA duration, which ranges from 0 to 10 hours; and 2) the selection of a spacecraft shielding thickness to be used as a shelter against the SPE exposure during EVA far from the surface habitat. By the selection of a spacecraft thickness, gender-specific BFO dose inside a spacecraft of specified thickness is assigned for the calculation of ARR. BFO dose rates during the EVA and inside the spacecraft are assumed to be those at the peak fluence of the SPE for the 10-hour duration.

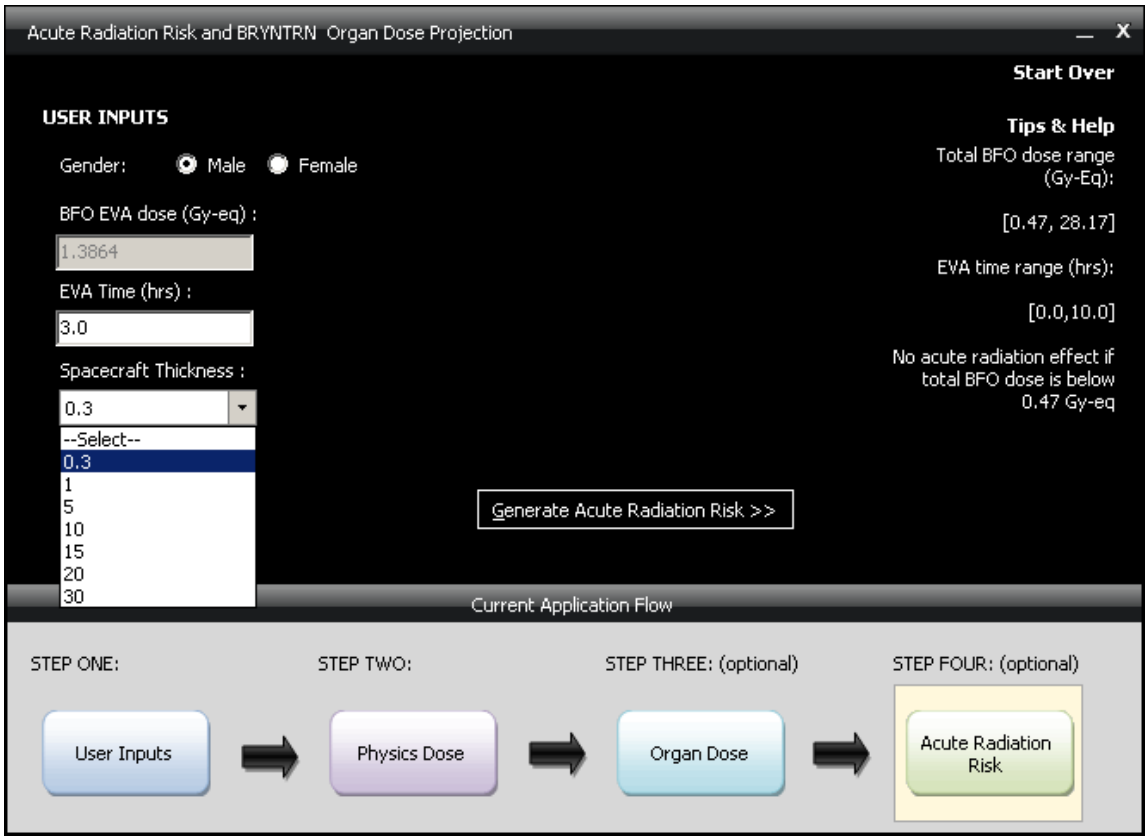


Figure 11. Input control UI of ARR for the selection of gender, EVA time, and spacecraft thickness.

By clicking “Generate Acute Radiation Risk” in the input control UI of ARR (Fig. 11), two outputs: “Exposure Summary” and “Acute Radiation Risk” are generated and added into the Graphs and Output window. The ARR results are represented as severity levels ranging from 1 to 5 for upper gastrointestinal distress (UG) and fatigability and weakness (FW), which are tabulated and added into the Graphs and Output window as “View ARR Sickness Severity Level Table”.

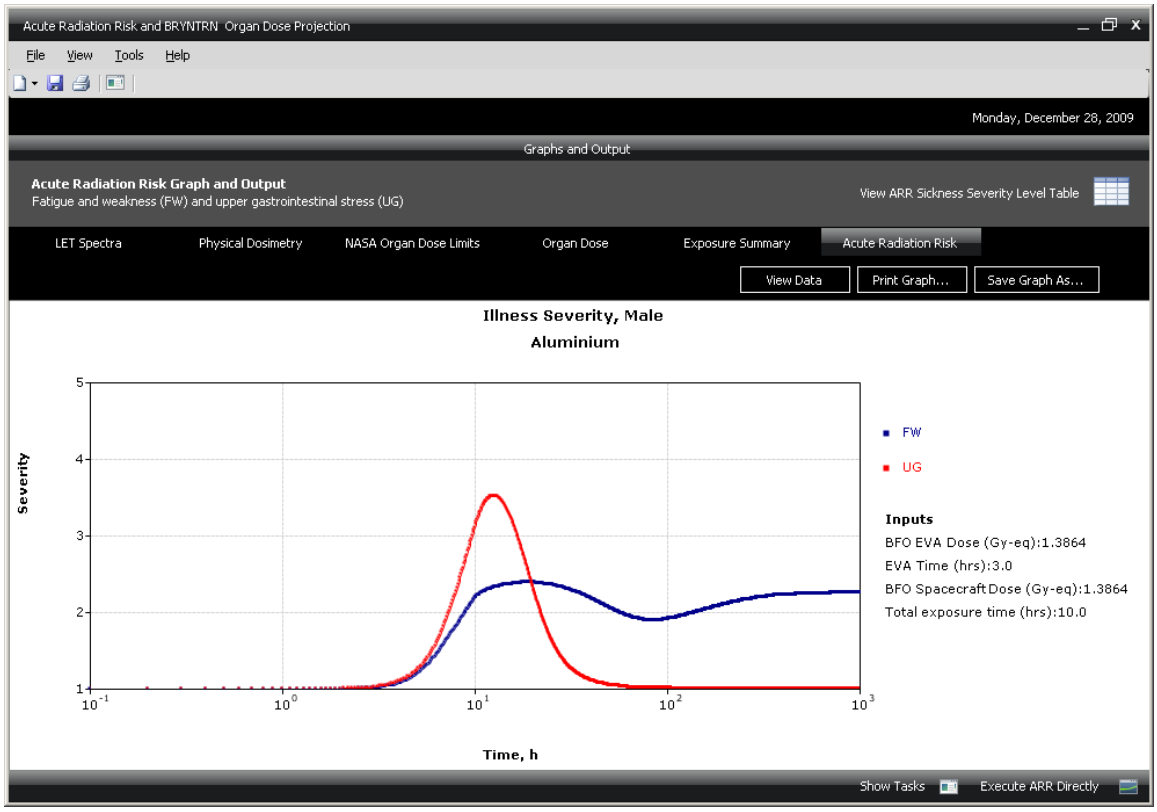


Figure 12. Graph and Output window for physical quantities, organ doses, and ARR. The tabulated information of ARR sickness of upper gastrointestinal distress (UG) and fatigability and weakness (FW) are added in this window and viewed by clicking “View ARR Sickness Severity Level Table”.

Once all the results have been viewed in each step of the application flow after the execution of each module of BRYNTRN, SUMDOSE, and ARR, they are accumulated in the Graphs and Output window to be viewed/printed/saved at the end of the ARRBOD application flow. These result tabs are “LET Spectra” and “Physical Dosimetry” from the BRYNTRN module; “NASA Organ Dose Limits” and “Organ Dose” from the SUMDOSE module; “Exposure Summary” and “Acute Radiation Risk” from the ARR module; and “View ARR Sickness Severity Level Table” for the symptoms of quantified ARR severity level.

By clicking “Show Tasks”, the ARRBOD application for SPE can be continued by returning to the previous flow, or the entire application can be started over.

4.2 Option for Radiation Exposure

The second option of the ARRBOD application is the direct analysis of ARR. This option determines the calculation of ARR from the user-defined radiation dose. It is selected by clicking "Run Acute Radiation analysis directly" in the main task UI of ARRBOD application in Fig. 4.

In the input control UI of ARR, there are two options of radiation exposure type (Fig. 13): acute and protracted doses of radiation. Total BFO doses from 0.47 to 28.17 Gy-Eq are considered for the analysis of ARR for both acute and protracted exposure types. For the protracted dose exposure, possible exposure times can be inputted from 0.1 to 168 hours. However, dose rates ($\dot{D}$) of protracted exposure should be less than 5 Gy-Eq/hr from any combination of total dose (D_{total}) and exposure time ($t_{exposure}$).

$$\dot{D} = \frac{D_{total}}{t_{exposure}} < 5\ Gy - Eq/hr\ .$$

In the case that the dose rate exceeds 5 Gy-Eq/hr from the combination of total dose and exposure time, the ARRBOD application results in an error with the dummy outputs. Inclusion of the correct error message is planned. By definition, acute exposure is quite representative for these high dose rates, and the user is advised to select "Use Acute Dose" from the input control UI (Fig. 13) to get the appropriate ARR analysis for the given total BFO dose.

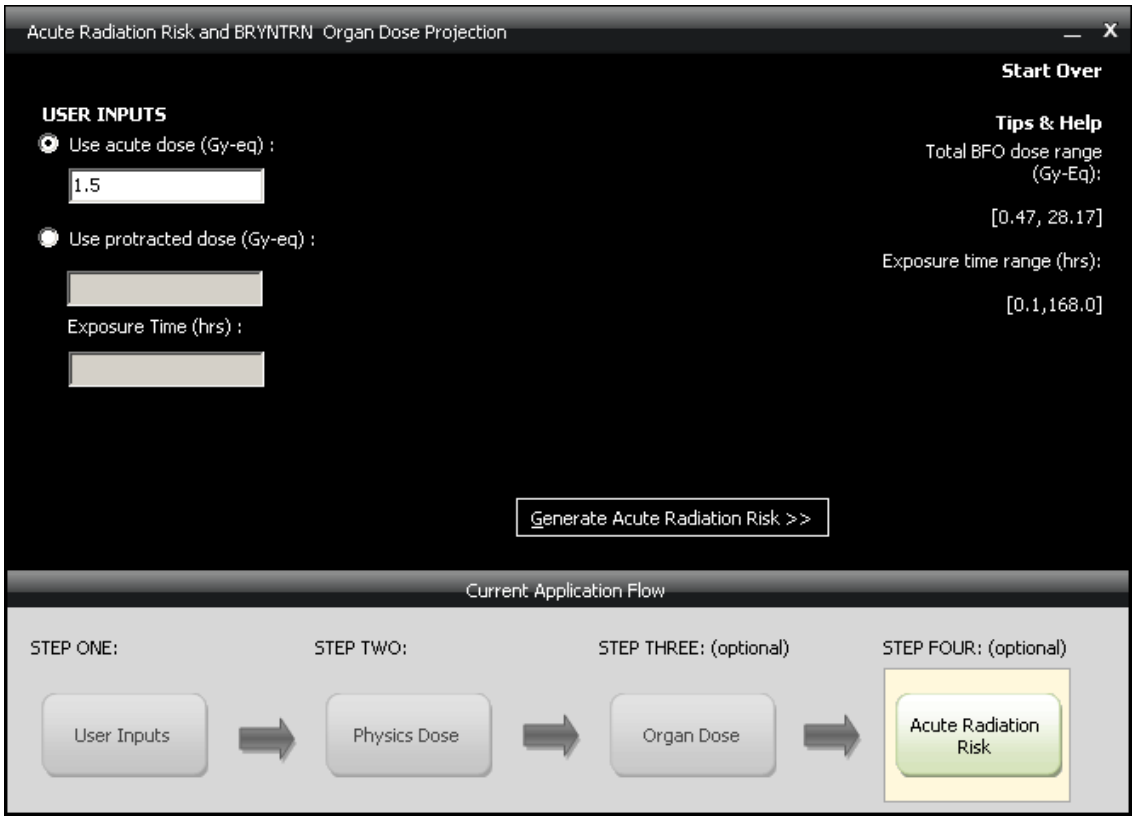


Figure 13. Input control UI of ARR for the selection of exposure types for acute and protracted doses of radiation.

After execution of the ARR module, two outputs, “Exposure Summary” and “Acute Radiation Risk”, are displayed in the Graphs and Output window. ARR results are represented as severity levels ranging from 1 to 5 for upper gastrointestinal distress (UG) and fatigability and weakness (FW). The symptoms at each severity levels are tabulated in the “View ARR Sickness Severity Level Table” and added into the Graphs and Output window. By clicking “View ARR Sickness Severity Level Table”, the table is viewed as in Fig. 14.

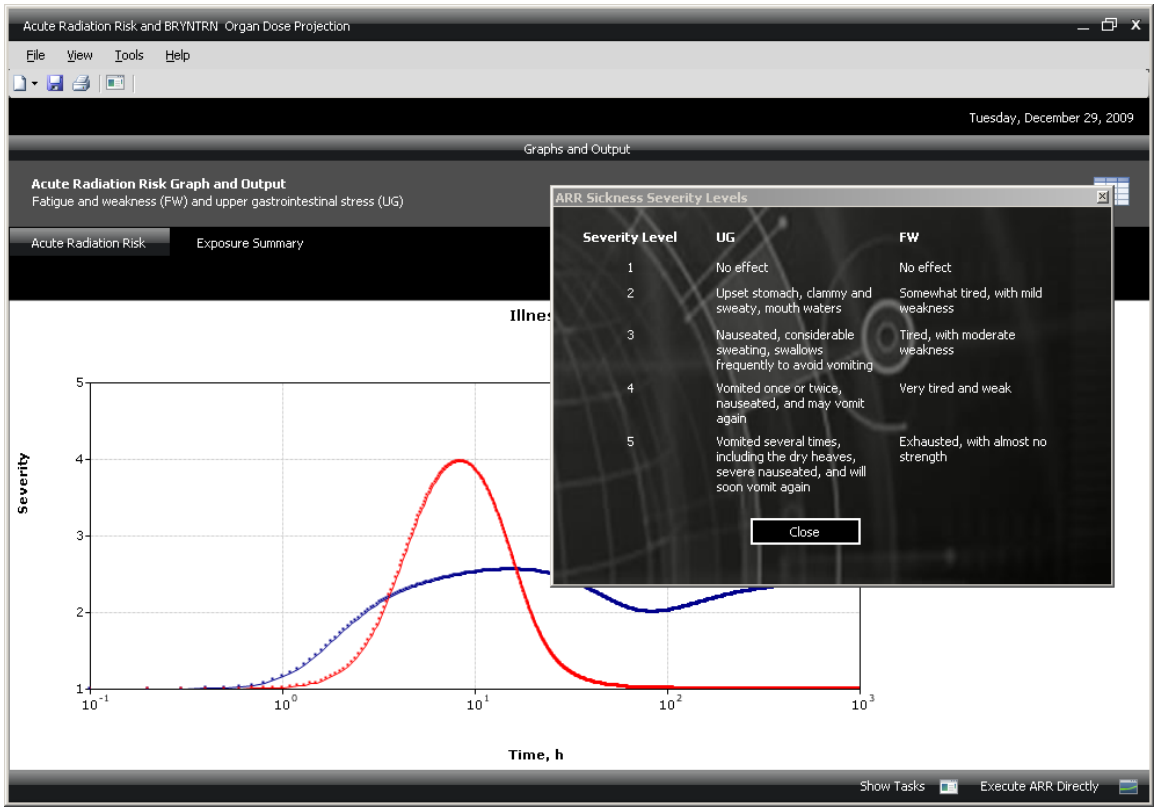


Figure 14. Graph and Output window of the ARR for the option of acute/protracted doses of radiation exposure. The tabulated information of ARR sickness of upper gastrointestinal distress (UG) and fatigability and weakness (FW) is viewed by clicking “View ARR Sickness Severity Level Table” in this window.

The ARR analysis of radiation exposure is continued by clicking “Execute ARR Directly” for different beams, or the entire application of ARRBOD can be started over by clicking “Show Tasks” to go back to the input control UI of ARR (Fig. 13) and then clicking “Start Over”.

5. Illustration of Sample Results for the Protection of Astronauts in Space Missions

5.1 Organ Doses from Pre-defined Scenario of SPE Exposure and Implication to Exposure Limits

In the pre-defined scenario of SPE exposure in ARRBOD application, it is assumed that a crew member is located inside an aluminum spacecraft in interplanetary space and exposed to an August 1972-type SPE, characterized by the exponential distribution of 1972 King spectrum.

The current NASA 30-day permissible exposure limits (PELs) are 1.5, 1.0, and 0.25 Gy-Eq (NCRP 2000, 2006) for skin, lens of the eye, and BFO, respectively. The threshold for prodromal effects is 0.5 Gy-Eq, because the possibility of acute risk exists for BFO dose over this level (Hu *et al*., 2009). Future research is needed to understand if microgravity effects modify this threshold value.

The results for males in this scenario are shown in Fig. 15. The resultant organ dose assessments are compared with the current NASA 30-day dose limits and the threshold for acute radiation sickness (ARS). From this figure, sufficient shielding can be determined to avoid ARS, and to stay within the NASA short-term limits. For example, a male crew member, located inside a spacecraft with 5 g/cm^2 aluminum shielding during interplanetary transit, may not experience any ARS, because the BFO dose is determined to be lower than the 0.5 Gy-Eq threshold. However, organ dose assessments of skin, lens of the eye, and BFO exceed the current NASA 30-day dose limits of these organs. Therefore, more than 5 g/cm^2 of aluminum shielding are required during interplanetary transit to protect astronauts against a large August 1972-type SPE.

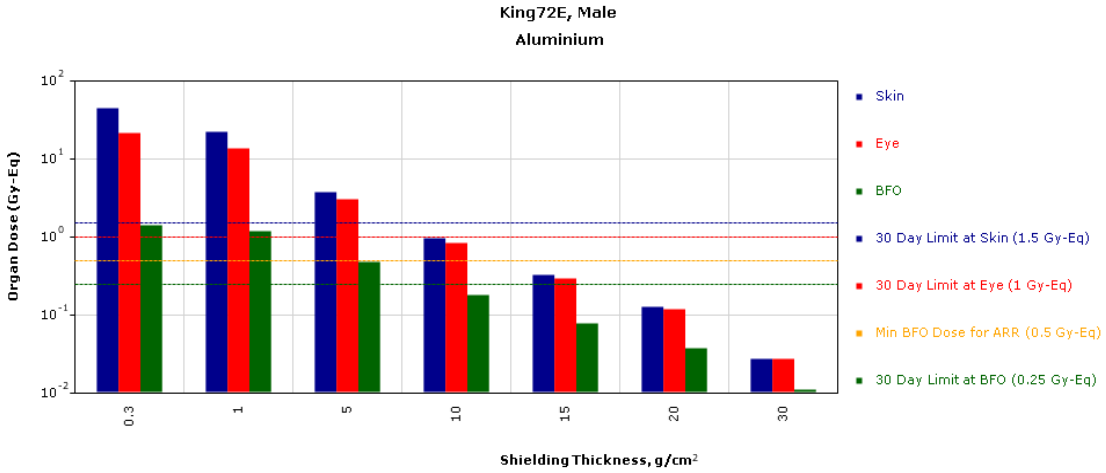


Figure 15. A sample result of the organ dose calculation for the pre-defined scenario for male (the same graph as in Fig. 10 as the one of the Graph and Output window).

5.2 ARS from SPE or Radiation Exposure

5.2.1 ARS from SPE Exposure during EVA

In the case of a male astronaut conducting 3 hours of EVA and then sheltering inside a 5 g/cm^2 aluminum spacecraft for 7 hours in this pre-defined scenario of SPE exposure, the input selection of the ARS analysis is shown in Fig. 16. It is assumed that the EVA occurs at the peak hours of the SPE, and that the total peak duration is 10 hours.

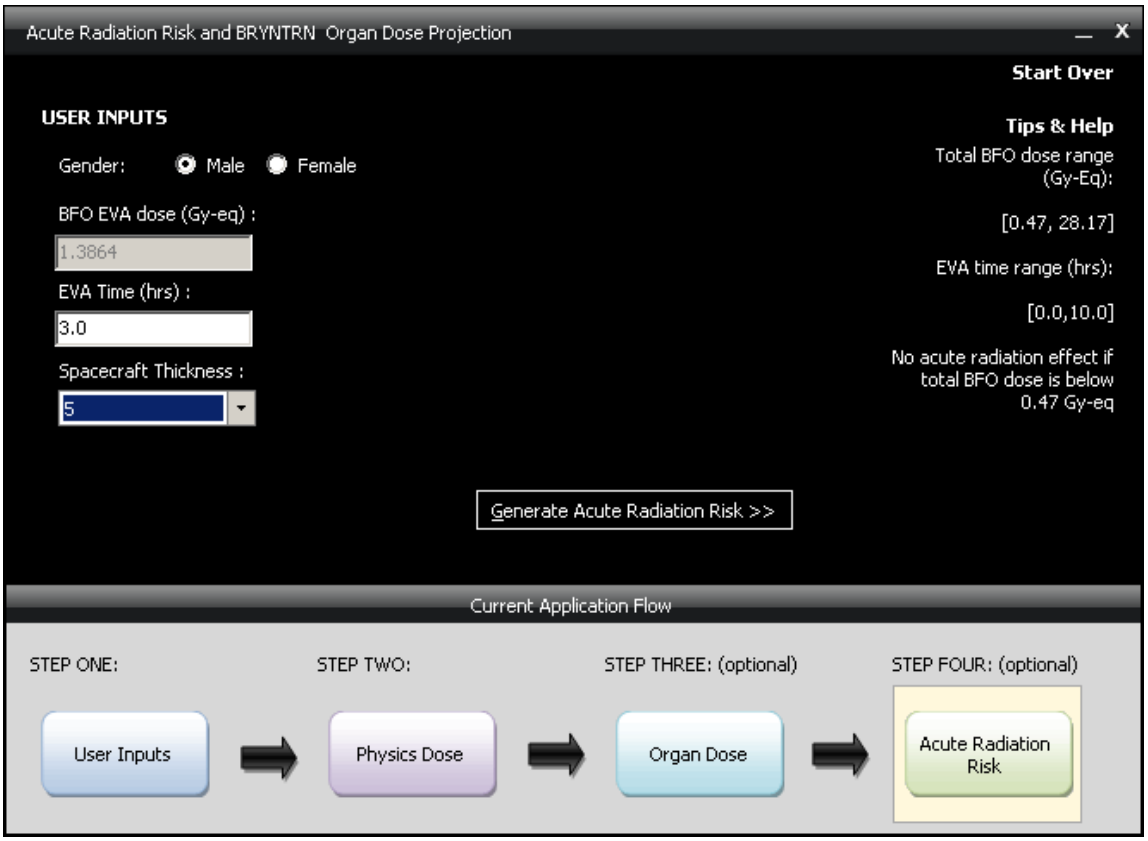


Figure 16. Input selection of ARR analysis in the case for a male astronaut who conducts 3 hours of EVA and stays the remainder of 7 hours inside a spacecraft of 5 g/cm^2 thickness in the pre-defined scenario of SPE exposure.

A male astronaut's time profile of BFO dose accumulation is shown in Fig. 17, which also provides an exposure summary. It shows that a total BFO dose of 74.03 cGy-Eq is accumulated at the end of the SPE, which is 10 hours after the initial exposure.

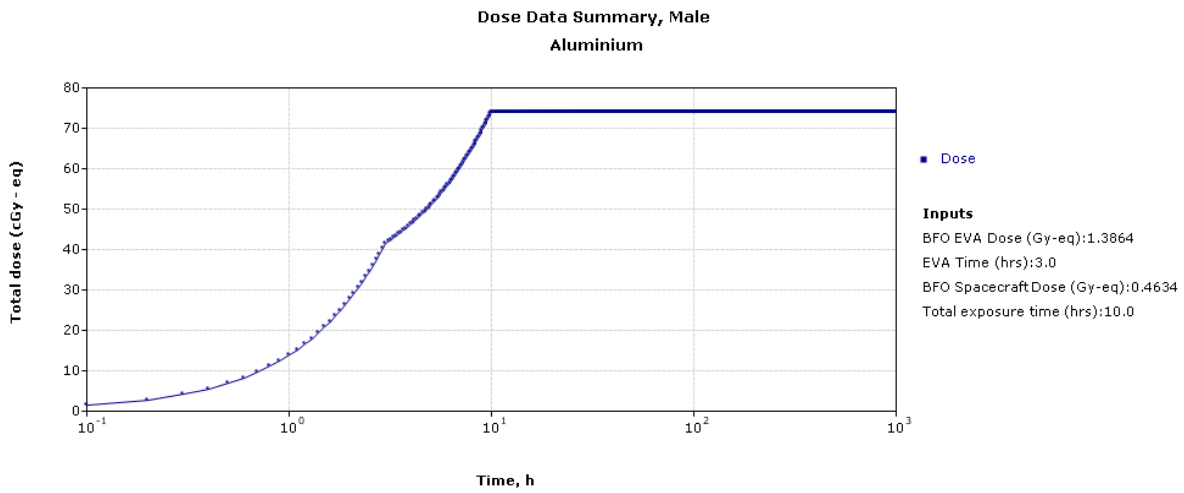


Figure 17. Time profile of BFO dose accumulation of a male astronaut after 3-hr EVA.

The resultant sickness levels for UG and FW are shown in Fig. 18 as acute radiation risk level. It shows that a male astronaut may not have any symptoms during the 3-hour EVA, however the initial ARR symptoms appear after he finds shelter. These symptoms include upset stomach, clammy and sweaty skin, and mouth watering (level 2 of UG distress). Long-lasting symptoms endure: tiredness and mild weakness (sub-level 2 of FW).

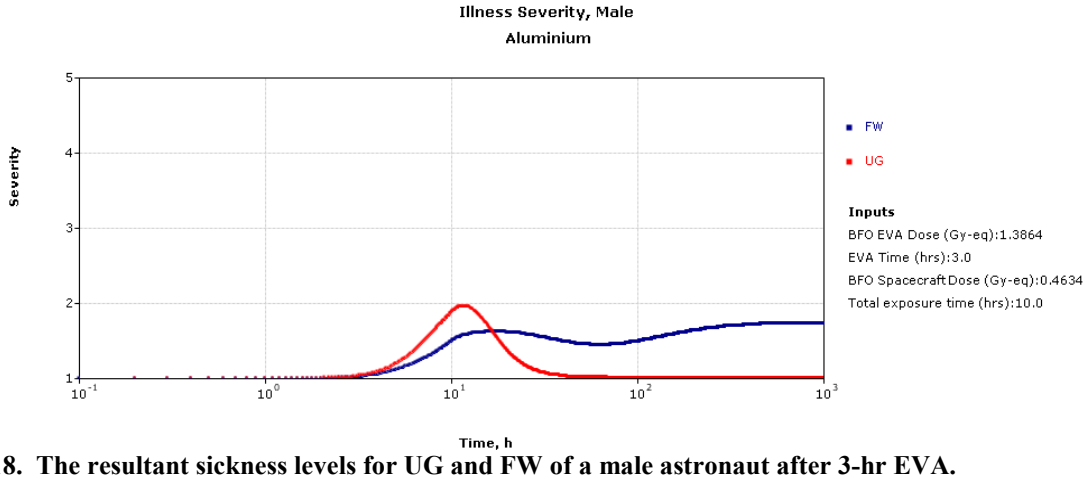


Figure 18. The resultant sickness levels for UG and FW of a male astronaut after 3-hr EVA.

5.2.2 ARS from Acute/Protracted Exposure

The input selection for ARS analysis from acute exposure is shown in Fig. 13. For acute dose exposure, the user-supplied total BFO dose ranges from 0.47 to 28.17 Gy-Eq. The output results of the acute doses are summarized in Fig. 19a for UG and Fig. 19b for FW, respectively. In these figures, the BFO dose ranges are 0.5 - 1.0 Gy-Eq with increments of 0.1 Gy-Eq and 1.0 – 3.0 Gy-Eq with increment of 0.5 Gy-Eq. As the acute BFO dose increases to 3 Gy-Eq, the possible symptoms for UG level 5 include vomiting several times, showing dry heaves, severe nausea, and vomiting again shortly after 7 hours following the exposure. Long-lasting symptoms of FW from the acute exposure dose of 3 Gy-Eq are at the levels between 2 and 4, which include being somewhat tired with mild weakness, to being tired with moderate weakness, and to being very tired and weak.

In the protracted exposure for 10 hours of time, the results for the same doses as those of acute exposure are summarized in Fig. 20a for UG and Fig. 20b for FW, respectively. In this uniform exposure of 10 hour duration, dose rates vary between 0.05 – 0.1 Gy-Eq/hr with increments of 0.01 Gy-Eq/hr, and 0.1 – 0.3 Gy-Eq/hr with increments of 0.05 Gy-Eq/hr. Maximum severities of UG and FW for 10-hour uniform exposures are similar to those of acute exposures. The delayed response is shown to be significantly shorter for the 10 hour uniform exposure, when the time profiles are compared.

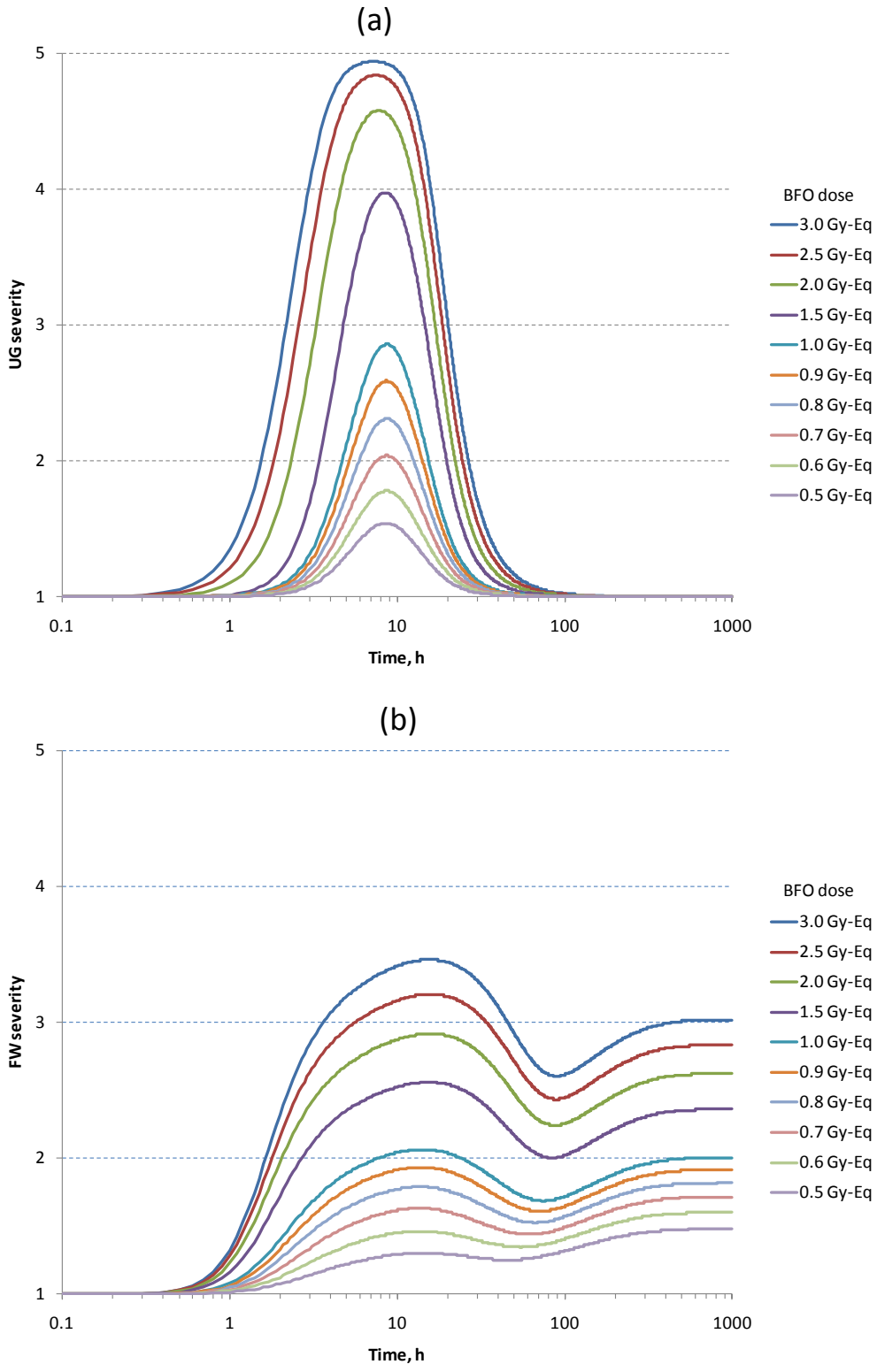


Figure 19. Acute radiation risk for the acute exposure to a given BFO dose: (a) upper GI distress (UG); and (b) fatigability and weakness (FW).

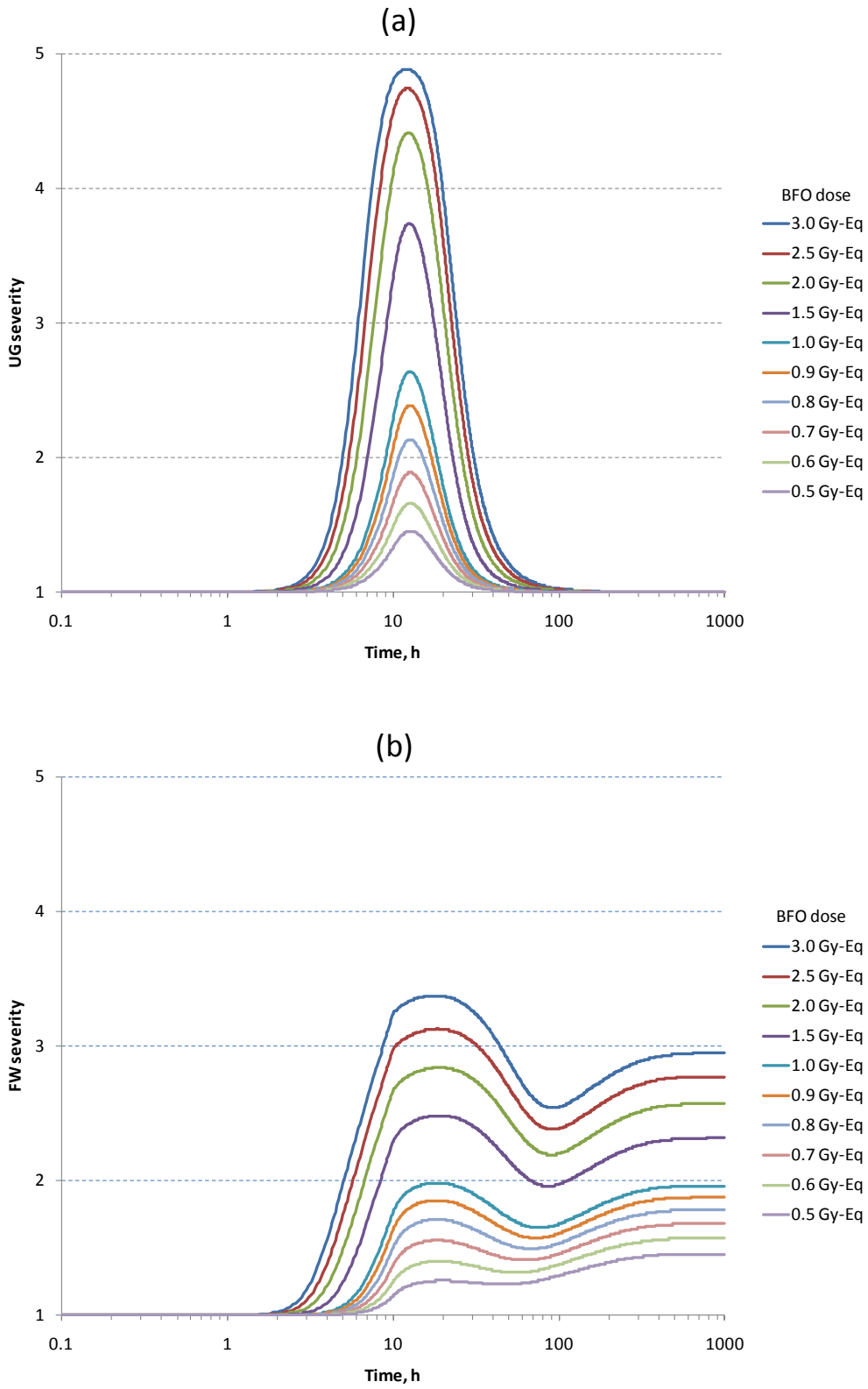


Figure 20. Acute radiation risk from the uniform exposure to a given BFO dose for a 10- hour period: (a) upper GI distress (UG); and (b) fatigability and weakness (FW).

6. Conclusions

The assessment of astronauts' radiation risk from SPE is an important goal in support of mission design and operational planning to manage radiation risks in future space missions. The first version of the ARRBOD GUI is developed for the purpose of NASA trade studies of mission scenarios, including studies of shielding materials, masses and topologies from exposure to historically recorded large SPEs. In the current ARRBOD version, proper shielding solutions can be identified from the gender-specific organ dose assessments to avoid ARR symptoms, and to stay within the current NASA short-term dose limits. Furthermore, the quantified evaluation of ARR severities based on any given shielding configuration and a specified EVA or other mission scenario can be made to guide alternative solutions for attaining determined objectives set by mission planners.

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