



The Use of Pro/Engineer CAD Software and Fishbowl Tool Kit in Ray-tracing Analysis

Hatem N. Nounu^{1,2}, Myung-Hee Y. Kim², Artem L. Ponomarev², and Francis A. Cucinotta³

¹*University of Houston, Texas 77004*

²*Universities Space Research Association, Houston, Texas 77058*

³*NASA Lyndon B. Johnson Space Center, Houston, Texas 77058*

THE NASA STI PROGRAM OFFICE . . . IN PROFILE

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program Office plays a key part in helping NASA maintain this important role.

The NASA STI Program Office is operated by Langley Research Center, the lead center for NASA's scientific and technical information. The NASA STI Program Office provides access to the NASA STI Database, the largest collection of aeronautical and space science STI in the world. The Program Office is also NASA's institutional mechanism for disseminating the results of its research and development activities. These results are published by NASA in the NASA STI Report Series, which includes the following report types:

- **TECHNICAL PUBLICATION.** Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA's counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.
- **TECHNICAL MEMORANDUM.** Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.
- **CONTRACTOR REPORT.** Scientific and technical findings by NASA-sponsored contractors and grantees.

- **CONFERENCE PUBLICATION.** Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.
- **SPECIAL PUBLICATION.** Scientific, technical, or historical information from NASA programs, projects, and mission, often concerned with subjects having substantial public interest.
- **TECHNICAL TRANSLATION** English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services that complement the STI Program Office's diverse offerings include creating custom thesauri, building customized databases, organizing and publishing research results . . . even providing videos.

For more information about the NASA STI Program Office, see the following:

- Access the NASA STI Program Home Page at <http://www.sti.nasa.gov>
- E-mail your question via the Internet to help@sti.nasa.gov
- Fax your question to the NASA Access Help Desk at (301) 621-0134
- Telephone the NASA Access Help Desk at (301) 621-0390
- Write to:
NASA Access Help Desk
NASA Center for AeroSpace Information
7115 Standard
Hanover, MD 21076-1320



The Use of Pro/Engineer CAD Software and Fishbowl Tool Kit in Ray-tracing Analysis

Hatem N. Nounu^{1,2}, Myung-Hee Y. Kim², Artem L. Ponomarev², and Francis A. Cucinotta³

¹*University of Houston, Texas 77004*

²*Universities Space Research Association, Houston, Texas 77058*

³*NASA Lyndon B. Johnson Space Center, Houston, Texas 77058*

Available from:

NASA Center for AeroSpace Information
7115 Standard Drive
Hanover, MD 21076-1320
301-621-0390

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
703-605-6000

This report is also available in electronic form at <http://ston.jsc.nasa.gov/collections/TRS/>

CONTENTS

ABSTRACT	1
1 Introduction	1
2 Pro/Engineer Installation and System requirements	3
2.1 Pro/E installation	3
2.2 Platform support and system requirements	4
2.2.1 <i>Platform Support</i>	4
2.2.2 <i>System requirements</i>	4
2.2.3 <i>Graphics information</i>	6
2.2.4 <i>Dual Monitor Support</i>	6
3 Fishbowl Toolkit Installation and launching from ProE	6
3.1 Installing Fishbowl tool kit	6
3.2 Launching ProE	6
3.3 Launching Fishbowl tool kit	7
4 Fishbowl operation within ProE	12
4.1 Before using fishbowl in ray tracing	12
4.1.1 <i>Assigning Material for parts (Individually or collectively)</i>	12
4.1.2 <i>Assigning same unit system for all parts</i>	14
4.1.3 <i>Setting the Coordinate system</i>	15
4.2 Ray tracing options in Fishbowl	17
4.2.1 <i>Dose Point</i>	17
4.2.2 <i>Batch Dose point</i>	18
4.2.3 <i>Ray Tracing Options</i>	18
4.2.4 <i>Ray Trace</i>	20
4.2.5 <i>Clear Rays</i>	20
4.2.6 <i>Analysis</i>	20
4.2.7 <i>Assign Material</i>	23
4.2.8 <i>Radiation Dose</i>	23
4.3 Troubleshooting error messages in ray tracing	23
4.3.1 <i>Ambiguous intersection</i>	23
4.3.2 <i>Rmat value is not set</i>	23
5 Definition of Terms and Parameters	23
References	25
Appendix	27

TABLES

Table 1. Platform support for Pro/Engineer CAD software.	4
Table 2. System requirements for Pro/Engineer CAD software.	5

FIGURES

Figure 1 shows a an example of ray tracing a lunar rover prototype, b the directional areal density color coded representation on a sphere with its center at the dose point.	3
Figure 2. Initial Window appears after launching Pro/E.	7
Figure 3. Selection of working directory	7
Figure 4. The choice of the working directory as the location of Fishbowl folder.	8
Figure 5. Starting the launch process of Fishbowl tool kit.	9
Figure 6. Registration of the Fishbowl tool kit.	9
Figure 7. Running the executable file of Fishbowl tool kit.	10
Figure 8. Starting the Fishbowl tool kit	11
Figure 9. Final stage of the launch process of Fishbowl tool kit.	11
Figure 10. Opening the file of a part from an assembly	12
Figure 11. Choosing Set up option to change part properties manually.	13
Figure 12. Changing part material properties such as mass density and emissivity.	14
Figure 13. Selecting the unit system of a part.	15
Figure 14. Selecting the Datum coordinate tool to start setting the coordinate system.	16
Figure 15. Selecting the desired coordinates in the coordinate system.	16
Figure 16. The display of newly selected coordinate system shown.	17
Figure 17. Fishbowl drop down menu shows all of its control options.	17
Figure 18. The color code chart shows the range of colors that will be linearly distributed over the selected range of T _{opt} values. If no range is selected, the default range is form the minimum value to the maximum one.	19
Figure 19. The Analysis options.	20
Figure 20. An example of the Ray History Table output.	21
Figure 21. An example of the Display T _{mat} Values Table output.	21

ACRONYMS

BRYNTRN	baryon transport computer code
CAD	computer-aided drafting
CAF	computerized anatomical female (model)
CAM	computerized anatomical male (model)
GCR	galactic cosmic radiation
GERM	GCR event-based risk model
HZE	high-charge and high-energy nuclei
HZETRN	high-charge-and-energy transport computer program
JSC	Johnson Space Center
LET	linear energy transfer
NCRP	National Council on Radiation Protection & Measurements
SPE	solar particle event
SRP	Space Radiation Program
3-D	three-dimensional

ABSTRACT

This document is designed as a manual for a user who wants to operate the Pro/ENGINEER (ProE) Wildfire 3.0 with the NASA Space Radiation Program's (SRP) custom-designed Toolkit, called "Fishbowl," for the ray tracing of complex spacecraft geometries given by a ProE CAD model. The analysis of spacecraft geometry through ray tracing is a vital part in the calculation of health risks from space radiation. Space radiation poses severe risks of cancer, degenerative diseases and acute radiation sickness during long-term exploration missions, and shielding optimization is an important component in the application of radiation risk models. Ray tracing is a technique in which 3-dimensional (3D) vehicle geometry can be represented as the input for the space radiation transport code and subsequent risk calculations. In ray tracing a certain number of rays (on the order of 1000) are used to calculate the equivalent thickness, say of aluminum, of the spacecraft geometry seen at a point of interest called the dose point. The rays originate at the dose point and terminate at a homogeneously distributed set of points lying on a sphere that circumscribes the spacecraft and that has its center at the dose point. The distance a ray traverses in each material is converted to aluminum or other user-selected equivalent thickness. Then all equivalent thicknesses are summed up for each ray. Since each ray points to a direction, the aluminum equivalent of each ray represents the shielding that the geometry provides to the dose point from that particular direction. This manual will first list for the user the contact information for help in installing ProE and Fishbowl in addition to notes on the platform support and system requirements information. Second, the document will show the user how to use the software to ray trace a Pro/E-designed 3-D assembly and will serve later as a reference for troubleshooting. The user is assumed to have previous knowledge of ProE and CAD modeling.

1 INTRODUCTION

One of the major challenges facing planners of long-term space exploration missions is the health risks associated with prolonged exposure to the complex space radiation environment. Space radiation related health risks range from risk of cancer, degenerative diseases such as central nervous system, heart and cataract risks, to acute radiation syndromes. Estimating these risks bear great uncertainties and many studies are underway to identify and improve the risk assessments [Cucinotta et al., 2001, Cucinotta et al., 2004]. The uncertainties in determining the biological effects of the space radiation on astronauts are largely related to uncertainties in the radiobiology of heavy ions in space and to a much lesser about the radiation environment and radiation transport in shielding and tissues. [Cucinotta and Durante, 2006; Cucinotta et al., 2001; NCRP, 2006] Models have been developed to statistically approximate the sporadic changes in the radiation environment such due to solar particle events (SPE's) [Kim et al., 2004].

The radiation environment consists mainly of galactic cosmic radiation (GCR) and high energy solar protons during solar particle events (SPE's). GCR includes high-energy heavy ions (HZE), which have high linear energy transfer (LET) – larger quantities of radiation per cell traversal—that can potentially cause more biological damages than the relatively low energy solar particles –protons—that have lower LET radiation [NCRP, 1989; 2006]. The high penetration depth of heavy ions from GCR requires much thicker shielding materials against heavy ions that make shielding cost-preventive. While solar particles in are one of the main sources of radiation risk

they are easier to shield against because of their relatively lower energies and shorter penetration depth compared to heavy ions from GCR. However, because of the high costs of launching mass into space (approximately \$300,000 per pound in 2009 dollars), optimization of the spacecraft design, shielding and placement of equipment inside the spacecraft is mandatory [Cucinotta et al., 2006].

The risks from space radiation is calculated using NASA-developed transport codes that calculate the organ dose at a certain point in the spacecraft—called the dose point—based on the areal density map of the space craft geometry and the organ in concern. The deterministic HZETRN code (Wilson et al., 2005) or BRYNTRN code (Cucinotta et al., 1994) and the stochastic GERMcode (Cucinotta et al., 2009) calculate energy spectra of high-energy (HZE) particles passing through the spacecraft material of a certain thickness taking into account fragments created by nuclear reactions. These codes evaluate the transport of protons, heavy ions and secondary nuclei through the astronaut’s tissues until reaching the critical organ tissues. Space transport codes calculate the organ dose from solar protons based on the material thicknesses provided by the spacecraft areal density map of the environment surrounding the astronaut and the distances inside the astronaut’s tissues through which protons pass to reach the organ in concern. The geometry of the astronaut is represented by the Computerized Anatomical Male (CAM) [Kase et al., 1970; Billings et al., 1873; Yucker et al., 1992] model or the Computerized Anatomical Female (CAF) model [Yucker et al. 1990; Yucker et al. 1992]. The calculated organ doses are used by NASA to model and estimate cancer risks to astronauts [Cucinotta and Durante, 2006], especially in interplanetary missions [Duranete and Cucinotta 2008] for the SPE’s energetic protons [Hu et al., 2008] and the heavy nuclei of the GCR [Cucinotta et al., 2006].

To quantify the shielding provided by the spacecraft structural components, NASA JSC developed a toolkit, referred to herein as *Fishbowl*, that is used with the CAD tool Pro/Engineer to create an areal density map of the spacecraft design [Ponomarev et al., 2007; Kim et al., 2007]. The areal density map is achieved using the ray tracing technique. Ray tracing is a technique used for spacecraft shielding evaluations. The technique creates a map of the areal mass density, t ($t=x\rho$ in units in g/cm^2 , where x is the physical distance in cm, and ρ is the material density g/cm^3). It creates a specified number of homogenously spaced rays that originate from the dose point and end in the vacuum outside of the spacecraft.

Traditionally, aluminum is the most prevalent material in a spacecraft, and has been used to scale a diverse list of material types into a single material for ray tracing. However, *Fishbowl* allows the user to select any material as the equivalent material for ray tracing. The choice should be made based on the spacecraft composition. The software calculates for each ray the directional distance it travels inside every part as it makes its way from the dose point to outside the spacecraft. Then, for each ray, the aluminum equivalent of the areal density for all parts, traversed by the ray, is calculated according to the following equation [Kim et al., 2007]:

$$\begin{aligned}
T_{Al-eq} &= T_{Mat} \times \frac{R_{Al}(p_{50MeV})}{R_{Mat}(p_{50MeV})} \\
&= X_{Mat} \times \rho_{Mat} \times \frac{R_{Al}(p_{50MeV})}{R_{Mat}(p_{50MeV})}
\end{aligned}
\tag{1}$$

where

T_{Al-eq} : Areal density of aluminum-equivalent, in g/cm^2

T_{Mat} : Areal density of a material, in g/cm^2

X_{Mat} : Linear thickness of a material, in cm

$R_{Al}(p_{50\text{ MeV}})$: Range of 50 MeV proton beam on aluminum, in g/cm^2

$R_{Mat}(p_{50\text{ MeV}})$: Range of 50 MeV proton beam on a target material, in g/cm^2

ρ_{Mat} : Bulk density of a material, in g/cm^3

Figure 1|a shows the image of ray tracing a lunar rover prototype placed on flat lunar surface with 1024 homogenously distributed rays going out of the dose point that is chosen to be inside the middle compartment in this case. The rover image shows a cross section of the CAD design to illustrate the rover structure. In figure 1|b, the resulting areal density is plotted on a sphere with its center located in the dose point to show the directional shielding that the rover structure is providing to the dose point and to indicate the location of hot spots if they exist.

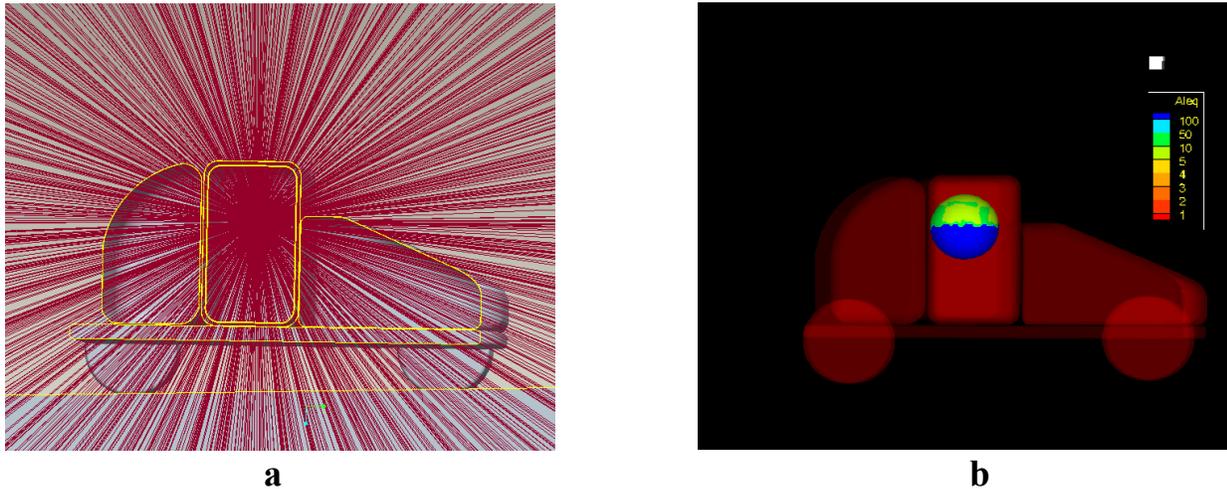


Figure 1 shows a| an example of ray tracing a lunar rover prototype, b| the directional areal density color coded representation on a sphere with its center in the dose point.

2 PRO/ENGINEER INSTALLATION AND SYSTEM REQUIREMENTS

2.1 Pro/E installation

The contact information for the installation of the **ProE** application software and its licensing on individual computers is:

MCAD Administrators:

Eloy De La Pena eloy.delapena-1@nasa.gov

Gary Stevens gary.f.stevens@nasa.gov

2.2 Platform support and system requirements

The following platform support and system requirements are obtained from the PTC (Parametric Technology Corporation) website: http://www.ptc.com/WCMS/files/30890/en/30890en_file1.doc, which contains information for the minimum hardware requirements. However, the requirements may increase as the size of the assembly file increases. We found that for the large CEV files, large RAM—3GB or more for 32 bit operating systems—is needed for a reasonable ray tracing turn around time. (64-bit architecture now allows up to 32 Gb of RAM for a DELL desktop)

2.2.1 Platform Support

The platform support information is summarized in the Table 1 shown below:

Table 1. Platform support for Pro/Engineer CAD software.

Platform Support			
Partner	Platform	Operating System levels	CPU
Hewlett-Packard	HP-UX 11i		PA8000 or later
	HP-UX 11	Quality Pack Bundle September 2002 Quality Pack Bundle March 2002	
	Linux	Red Hat 7.3	Intel Pentium/Xeon family
Microsoft ▪ Compaq ▪ Dell ▪ Fujitsu-Siemens ▪ Hewlett-Packard ▪ IBM ▪ NEC ▪ SGI	Windows XP (32-bit) Professional Edition;	Base OS, Service Pack 1 and 2	Intel Pentium/Xeon family
	Windows XP (32-bit) Home Edition		
	Windows 2000	Base OS, Service Pack 1, 2, 3 and 4.	
	Windows NT 4.0	Service pack 5 and 6a	
SGI	IRIX	6.5.10 (64-bit only)	Mips R8000 or later
Sun	Solaris	2.6, 7, 8 and 9	UltraSPARC II or later

2.2.2 System requirements

Table 2 has the system requirements as stipulated by PTC:

Table 2. System requirements for Pro/Engineer CAD software.

System Requirements					
		Windows (XP, 2000 and NT 4.0)		UNIX (including 64-bit) and Linux	
		Minimum	Recommended	Minimum	Recommended
Main Memory		128 MB	512 MB or higher	128 MB	512 MB or higher
Available Disk Space	ProE and Conferencing	900 MB	900 MB or higher	1.2 GB	1.2 GB or higher
	ProE and Conferencing with Pro/MECHANICA	1.2 GB	1.2 GB or higher	1.6 GB or higher	1.6 GB or higher
Swap Space		256 MB	1024 MB or higher	256 MB	1024 MB or higher
CPU speed		233 MHz	750 MHz or higher	See above table for individual vendor processor support	
Internal Browser Support		Microsoft Internet Explorer 5.5 SP2 or later		Browser (Mozilla 1.0.1) is embedded in ProE on the UNIX platform	
External Browser Support		Mozilla 1.0.1 Netscape 7.0 Netscape 6.2.x IE 5.5 SP2 and later Note: Netscape 4.x is NOT supported for the Help system.		Mozilla 1.0.1 Netscape 7.0 (when available) Netscape 6.2.x Note: Netscape 4.x is NOT supported for the Help system.	
Monitor		1024 x 768 (or higher) resolution support with 24-bit or greater color		1024 x 768 (or higher) resolution support with 24-bit or greater color	
Network		Microsoft TCP/IP Ethernet Network Adapter		TCP/IP Ethernet Network Adapter	
Mouse		Microsoft-approved 3-button mouse		3-button mouse	
File systems		NTFS		All vendor-supported file systems.	
Misc.		CD-ROM or DVD drive		CD ROM or DVD drive	

2.2.3 Graphics information

For 3D-hardware acceleration, an OpenGL graphics card must be used that has been tested in a PTC-certified configuration. To ensure the compatibility of a graphics driver with ProE, a PTC-certified hardware configuration is recommended.

2.2.4 Dual Monitor Support

Limited dual monitor support is provided in ProE Wildfire date code 2003100 and subsequent releases with Windows 2000 and XP *only*. PTC has successfully performed limited testing of some graphics card models from 3DLabs, ATI and NVIDIA that support dual monitor capabilities. If your graphics card is certified for ProE Wildfire and provides dual monitor support**, PTC expects it will work normally. PTC will provide limited support to resolve issues arising when running in dual monitor mode; however, the entire solution will not be submitted for formal certification as a complete configuration. PTC has tested and officially supports the following graphics cards. This list is not meant to be a comprehensive listing of cards with dual monitor capabilities and it does not represent a shift from PTC's policy of certifying complete systems.

Supported and tested graphics cards:

ATI FireGL X1

3DLabs Wildcat VP 990 Pro

NVIDIA Quadro4 900XGL, 980XGL and FX 2000

Note: in the event that dual monitor mode fails, we advise use of Span mode as a workaround.

** Please consult with 3DLabs, ATI, NVIDIA, or the hardware platform partner to confirm the availability of this functionality with a given graphics card that has been certified with ProE Wildfire.

3 FISHBOWL TOOLKIT INSTALLATION AND LAUNCHING FROM PROE

3.1 Installing Fishbowl tool kit

To install Fishbowl on your computer, copy the **SpaceHealth** folder in a known directory since you need to browse and find it later to set it as **ProE** working directory. There is no license file to load or install for Fishbowl. The entire NASA (JSC) site has a license to use Fishbowl. However, for other NASA sites, a license needs to be obtained before using Fishbowl.

3.2 Launching ProE

To launch the Pro/E software, double click on the **Pro Engineer M270** icon shown on the desk top as in the figure below. If the **Pro Engineer M270** icon is not visible on the desk top, you can start the software by clicking on **proe.exe** under the path **D:\PTC\M270\proe\bin**. The ProE will launch and the main window opens on your desktop. The Navigator panel opens on the left. This sliding panel houses several navigation tools, links, and internet sites. Figure 2 shows the main page with the navigation panel.

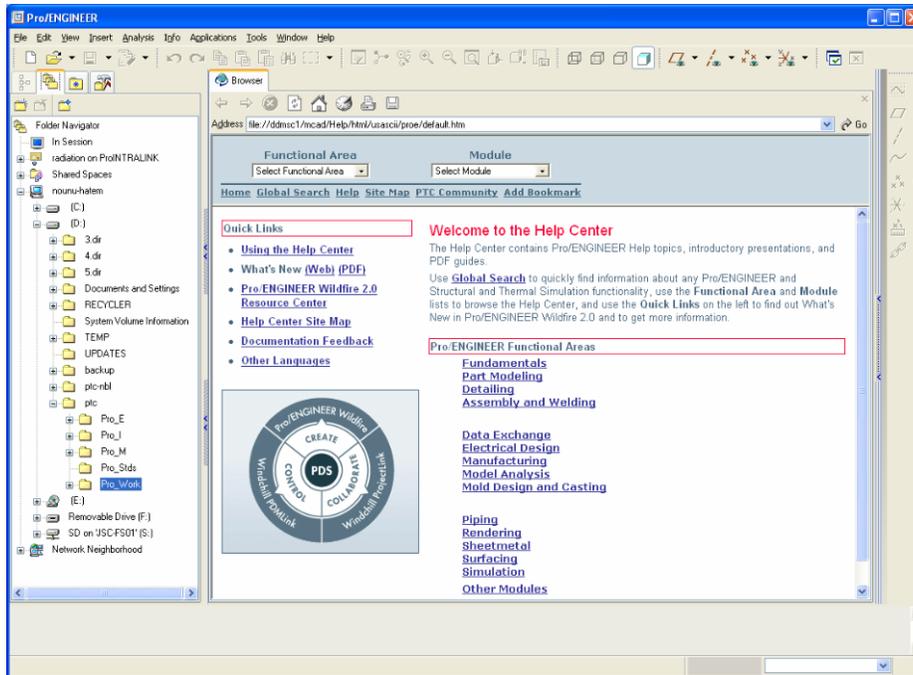


Figure 2. Main page appears after launching Pro/E.

3.3 Launching Fishbowl tool kit

Under **File**, choose **Set Working Directory**. A new window called **Select Working Directory** pops up. Figure 3 shows the working directory selection.

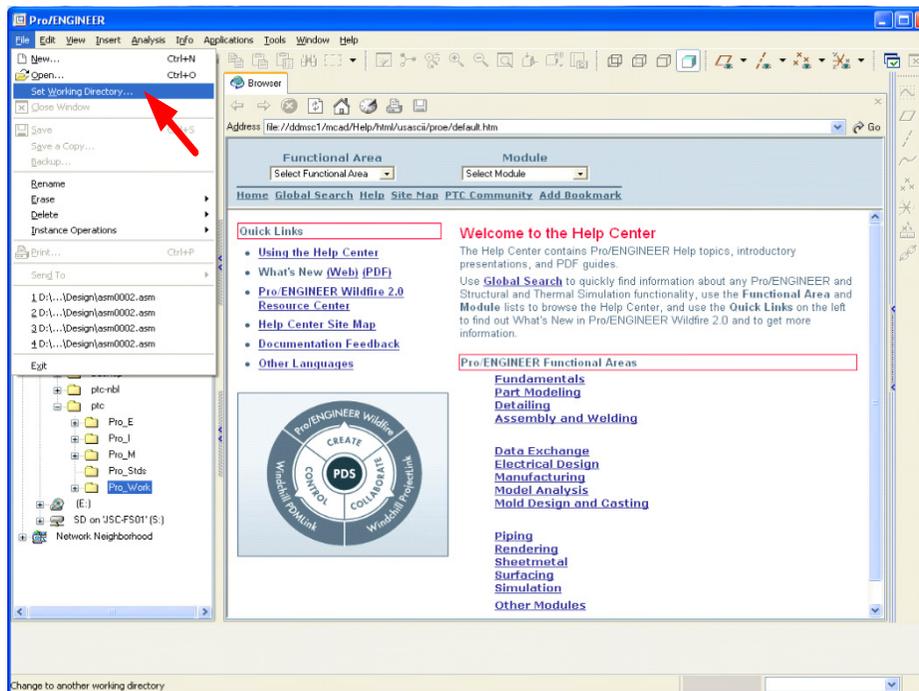


Figure 3. Selection of working directory

Browse to the location where you placed the “**SpaceHealth**” folder and click once on the folder name to highlight it. Press “**OK**” at the bottom of the window as shown in figure 4.

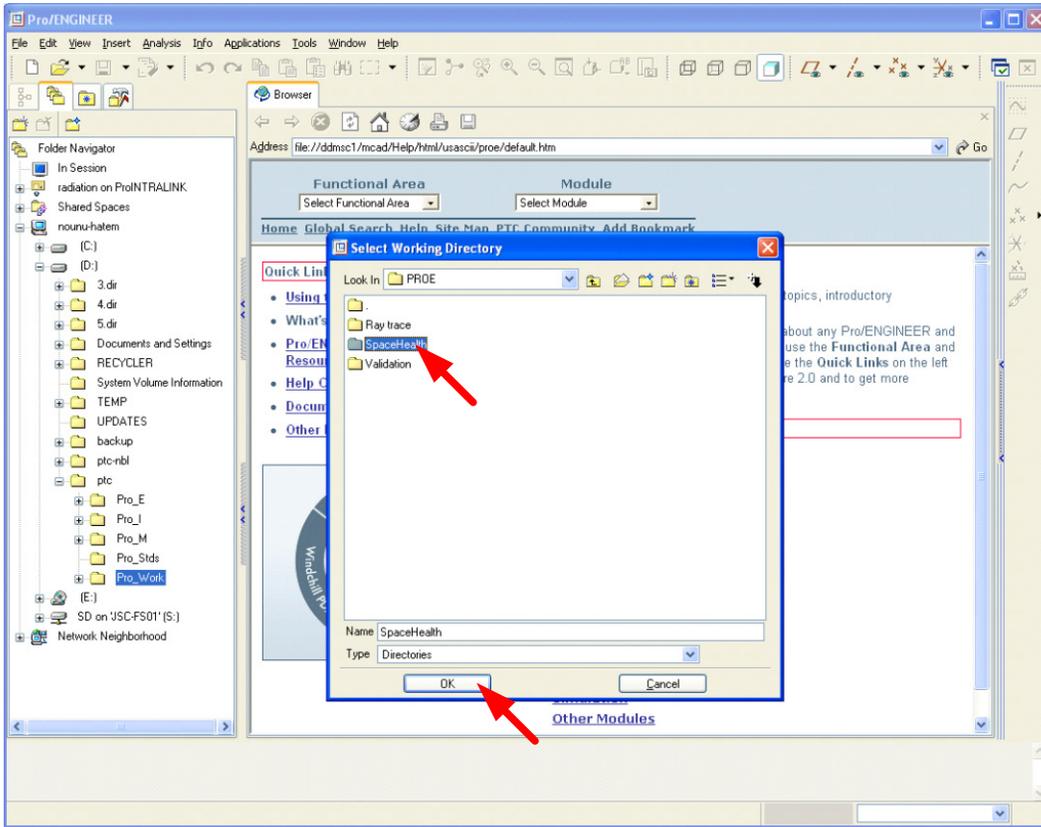


Figure 4. The choice of the working directory as the location of Fishbowl folder

Under **Tools** choose **Auxiliary Applications** as shown in figure 5.

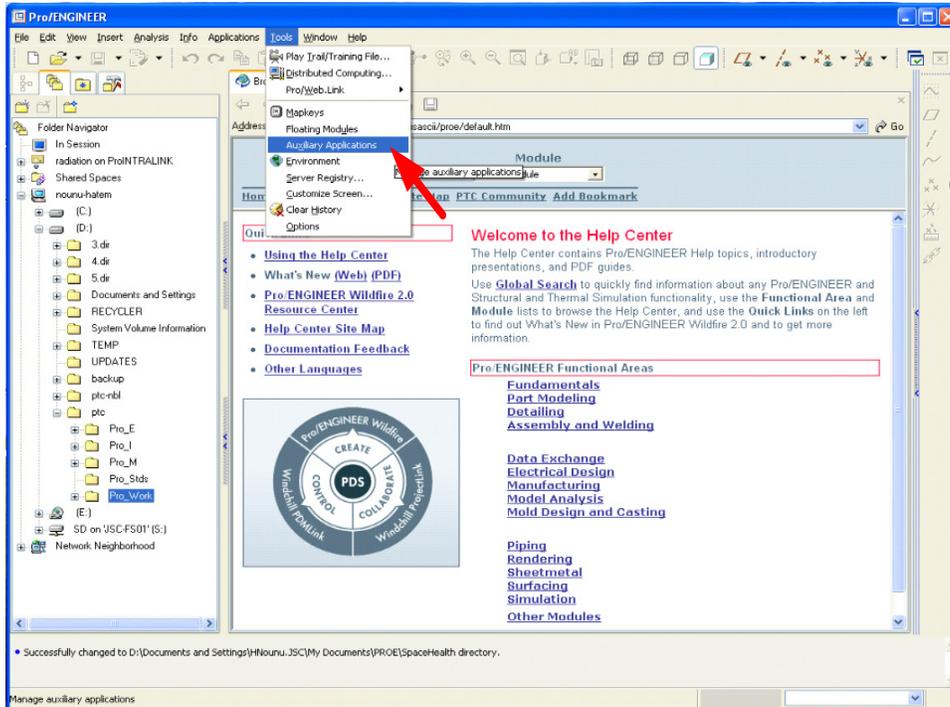


Figure 5. Starting the launch process of Fishbowl tool kit.

As shown in figure 6, when a window called **Auxiliary Applications** appears, click on **Register**.

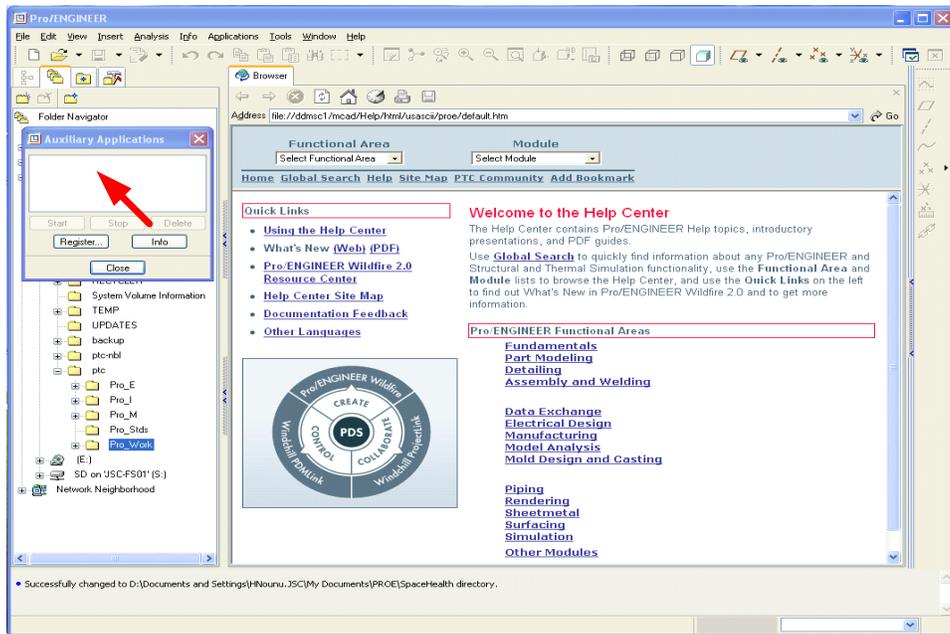


Figure 6. Registration of the Fishbowl tool kit.

A new window called **Register auxiliary application** will appear. Click once on the file **protk.dat** and then press **Open** at the bottom of the window as shown in figure 7.

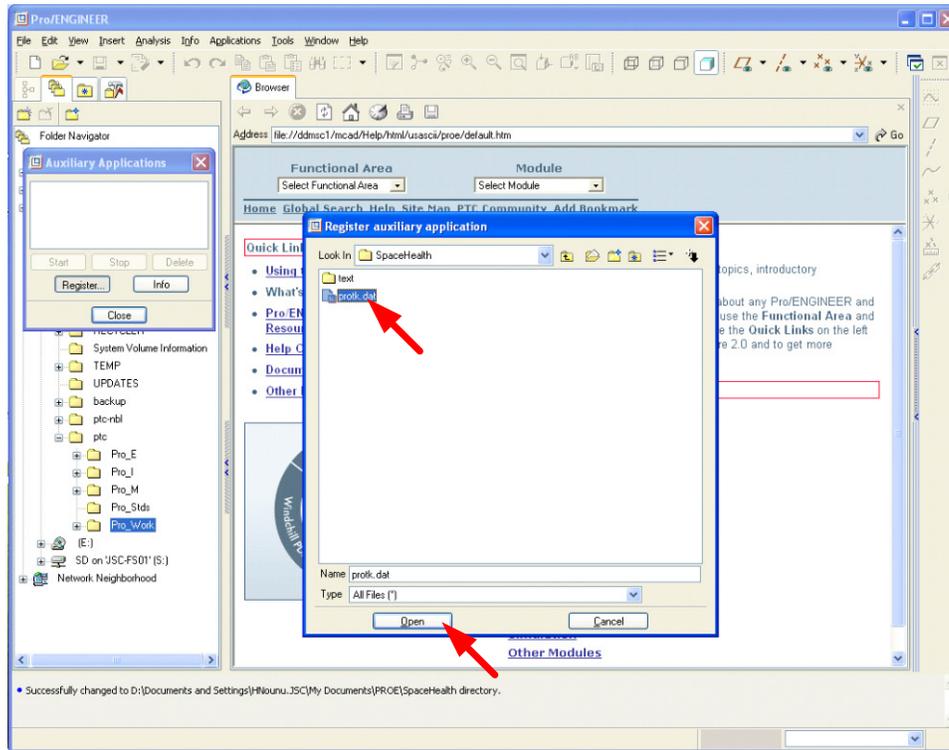


Figure 7. Running the executable file of Fishbowl tool kit.

The **Register auxiliary application** window will disappear and the statement **Space Radiation... Not Running** will show up in the window **Auxiliary Applications**. Click once on the statement **Space Radiation... Not Running** to highlight it and press the **Start** button as shown in figure 8.

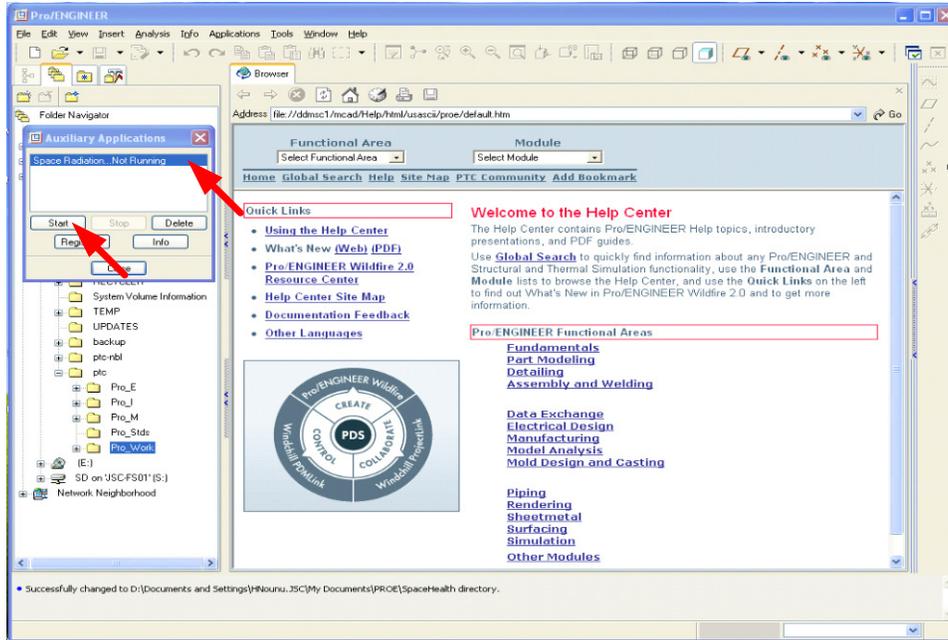


Figure 8. Starting the Fishbowl tool kit

When you see that the statement **Space Radiation... Not Running** is replaced by **Space Radiation Running**, press **Close**. The window **Auxiliary Applications** will disappear. Now we have Fishbowl ready to use. This process is shown in figure 9 below:

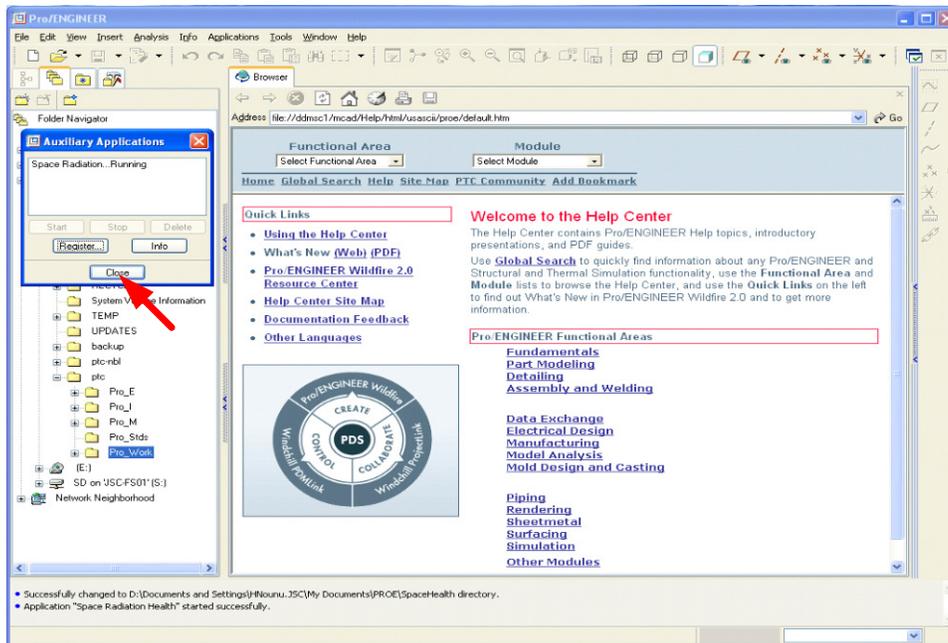


Figure 9. Final stage of the launch process of Fishbowl tool kit.

4 FISHBOWL OPERATION WITHIN PROE

The use of Fishbowl tool kit within Pro/E requires opening the CAD design file to be open. To do so, open the assembly which you want ray trace by clicking **File** then **Open**. Browse to the location where you have your assembly file and double-click on it.

4.1 Before using fishbowl in ray tracing

Before ray tracing, the material, unit system and coordinate system need to be defined to all parts and assemblies that make up the design. If not defined, the user can define them individually or collectively.

4.1.1 Assigning Material for parts (Individually or collectively)

The assignment can be performed individually on each part separately or can be assigned to all parts together.

4.1.1.1 Assigning material individually

Open the ProE file that you need to ray trace and ensure the parameters of all parts, such as mass density and emissivity, are set up correctly and all units are in the Centimeter-Gram-Second (CGS) system. To view and edit the part, right-click on the part name in the model tree and left-click on **Open**. As shown in figure 10.

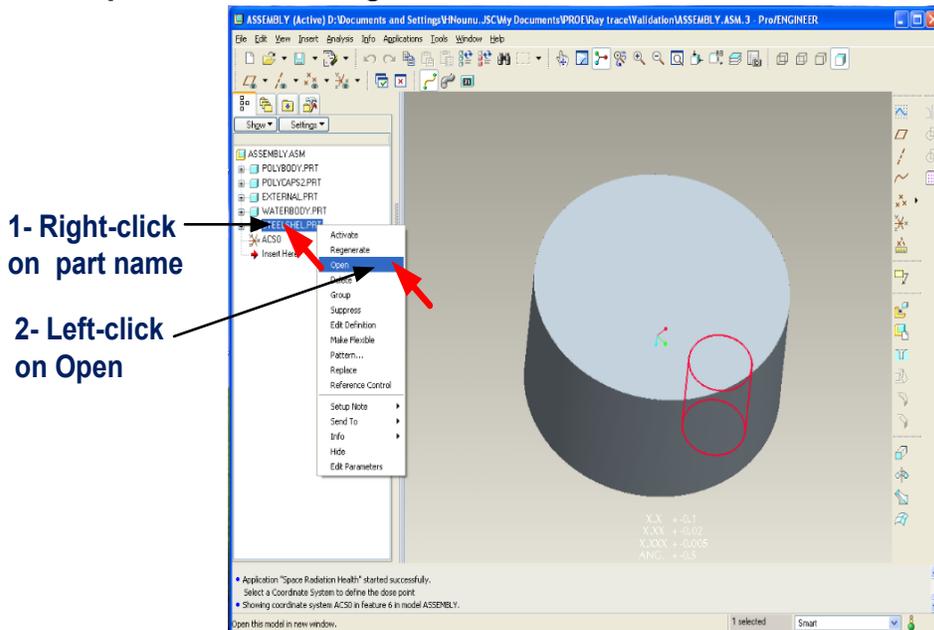


Figure 10. Opening the file of a part from an assembly

The file associated with a part will open in a separate window as shown in figure 11. On the new window, click **Edit** and choose **Setup** from the list under **Edit**.

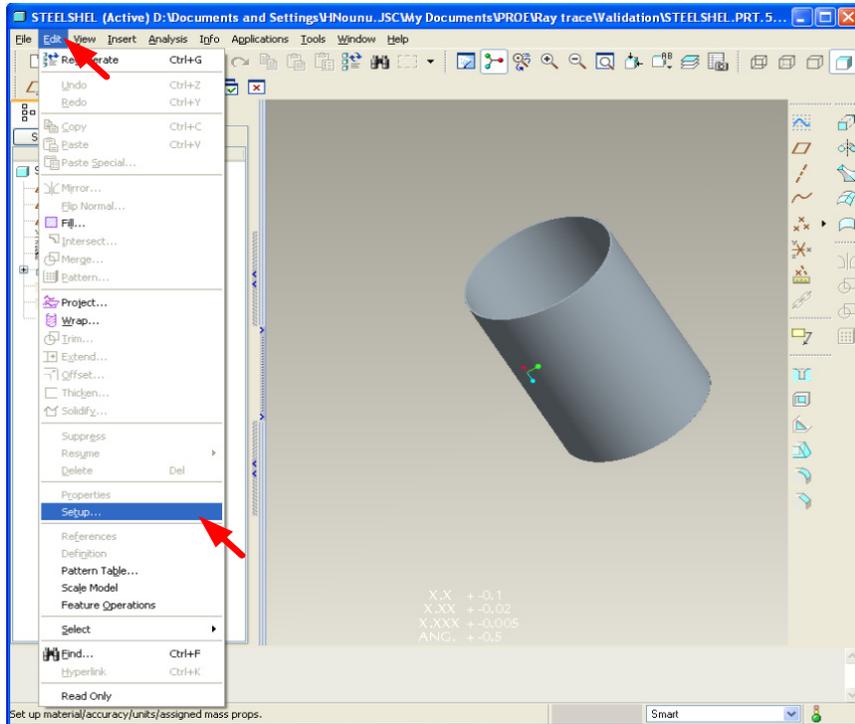


Figure 11. Choosing Set up option to change part properties manually.

A narrow window called **Menu Manager** will open. Click on **Material** under the **PART SETUP** option. A small window called **MATRL MGT** will open. Choose **Edit** followed by the material type (e.g., **STEEL**) and at the end choose **Accept**. A new window called **INFORMATION WINDOW (temppromatname.mat)** will open. Check the values of the **MASS_DENSITY**, which is the bulk material density and **EMISSIVITY** which represents the range of 50 MeV proton beam in the material and edit them if needed and click **Close** when you are done. This process is illustrated in figure 12.

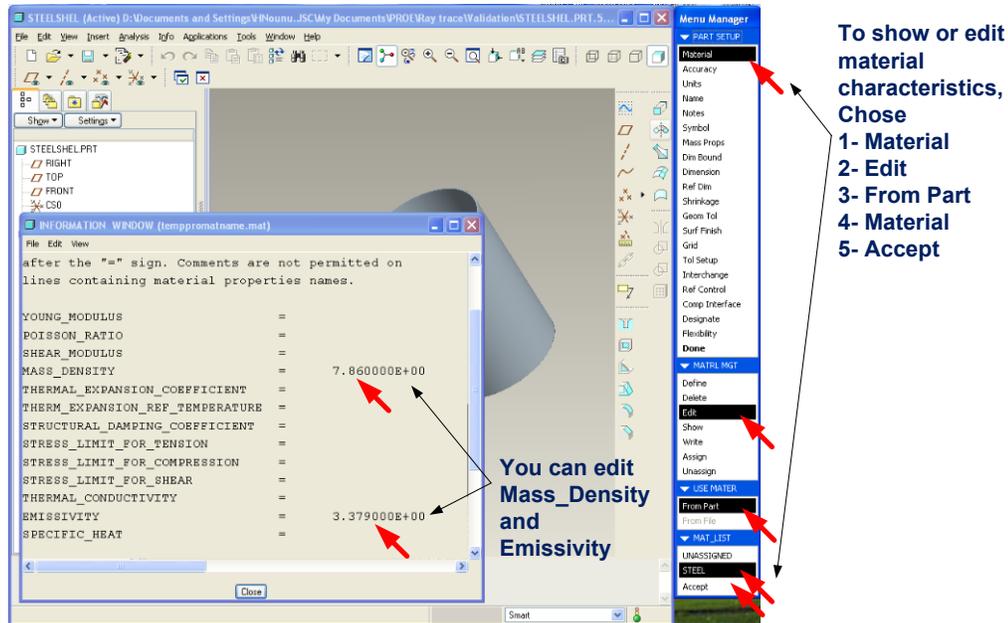


Figure 12. Changing the material properties of a part, such as mass density and emissivity.

4.1.1.2 Assigning material collectively

This option will be explained in the Tool kit applications in the next section.

4.1.2 Assigning same unit system for all parts

As shown in figure 13, to assign the units, choose “units” from the **Menu Manager**. A new window called **Units Manager** will open. If the units are on **Centimeter Gram Second (CGS)**, click **Close**. If the units are otherwise, you need to edit them by clicking on **Centimeter Gram Second (CGS)**, then click on **Set**. A window called **Changing model units** will open. Choose **Convert dimensions (for example 1” becomes 25.4mm)**. After you finish, click **Close**.

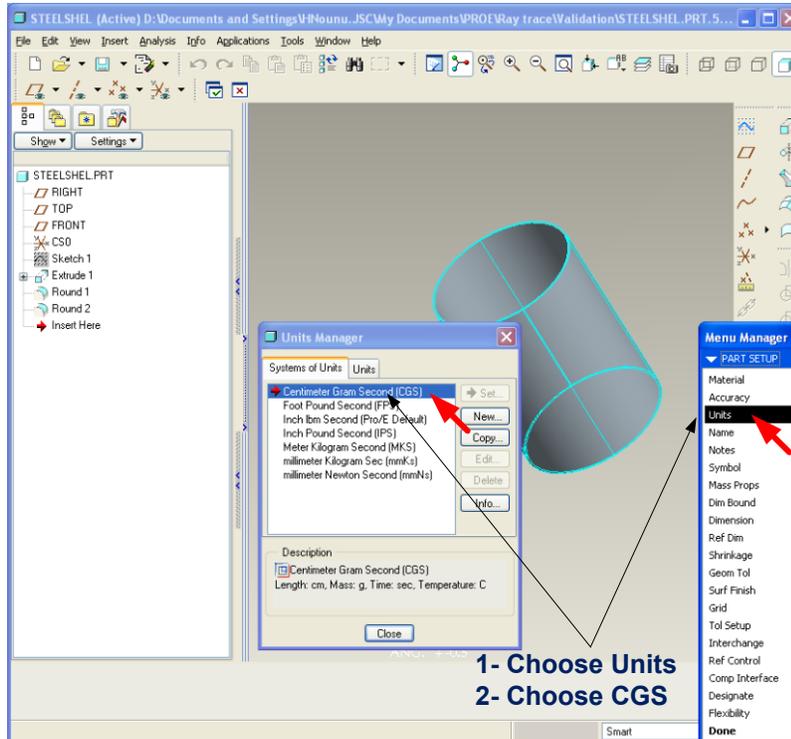


Figure 13. Selecting the unit system of a part.

After you finish choosing the material characteristics and units, click **Done** which is at the bottom of the **Menu Manager**.

4.1.3 Setting the Coordinate System

From the side panel, click on **Datum Coordinate System Tool** as shown in the figure 14. A small window called **COORDINATE SYSTEM** will open.

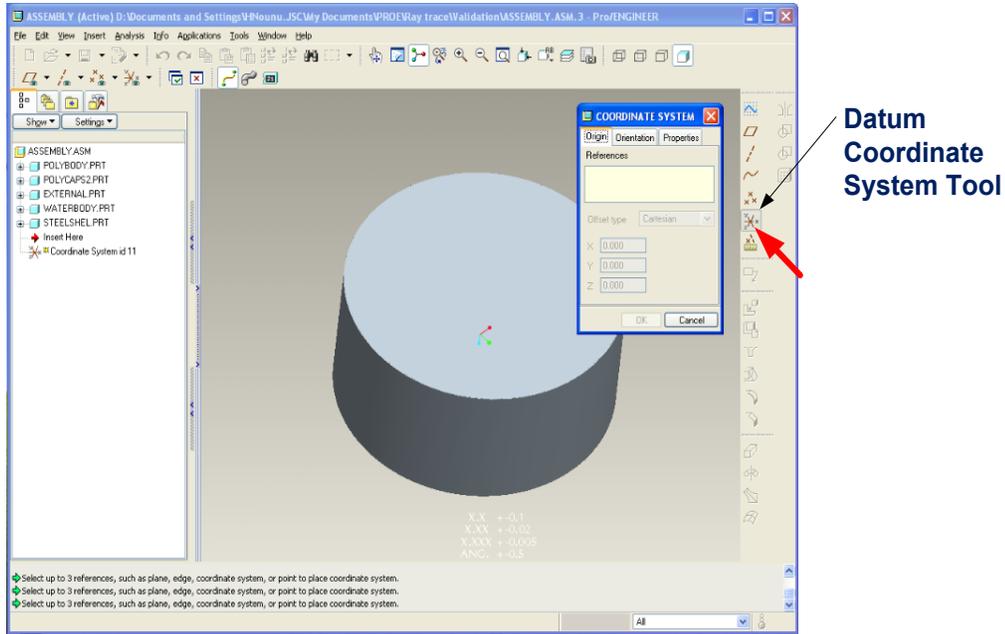


Figure 14. Selecting the Datum Coordinate Tool to start setting the coordinate system.

Go to the model tree on the left panel to choose the references. Click on the “+” sign next to any part name to show the list of items in that part file. The Datum planes of that part will be in the list. To enter these planes as references in the **COORDINATE SYSTEM** window, just click on each of the three planes while holding the **Shift** button. Click **OK** to apply the coordinate system. Figure 15 shows the plane selection process.

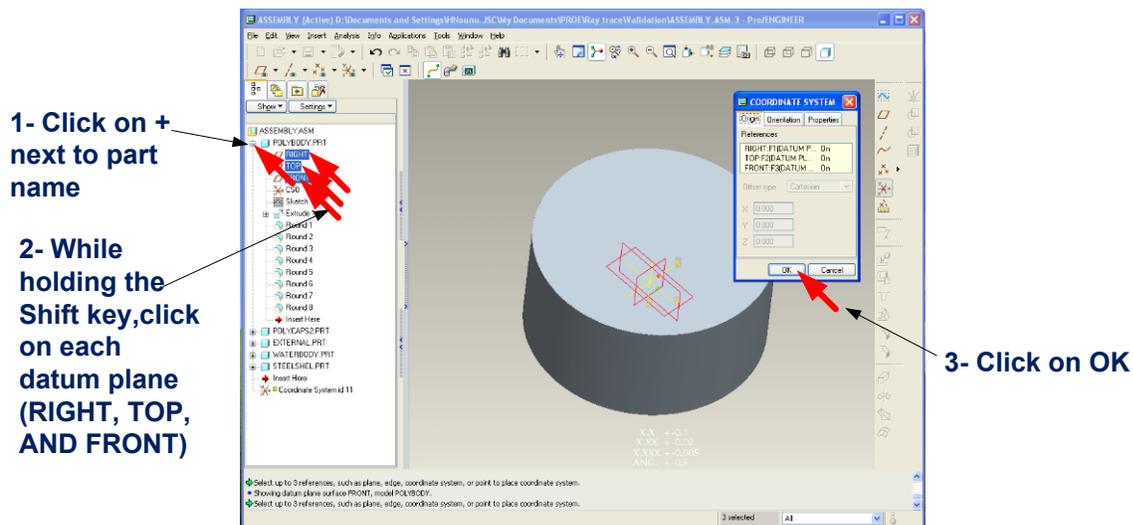


Figure 15. Selecting the desired coordinates in the coordinate system.

The new coordinate system name, **ACS0** in this case, will show up at the bottom of the model tree as shown in figure 16. Once you have **ACS0**, you can use it as the **Dose Point** from which ray tracing can be made.

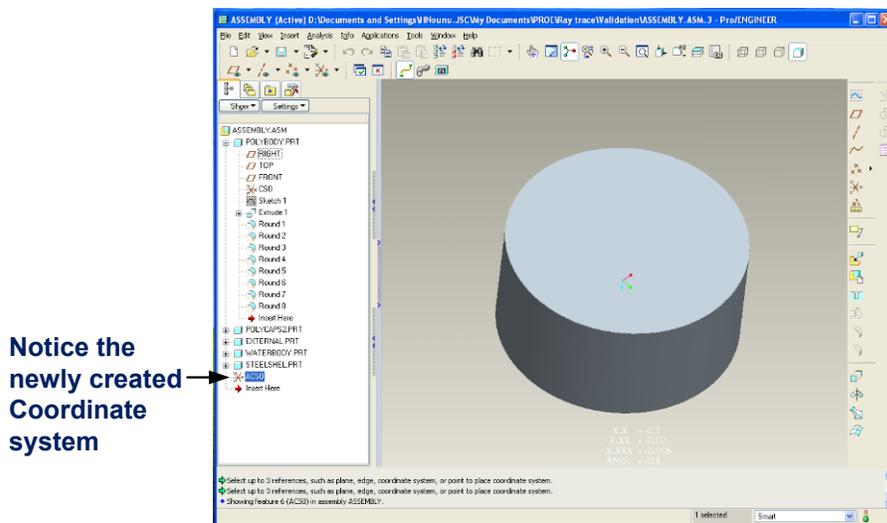


Figure 16. The display of newly selected coordinate system shown.

4.2 Ray tracing options in Fishbowl

After opening your assembly, click on **Applications** and choose **Space Radiation Health**. A side window will open showing all available choices as shown in figure 17.

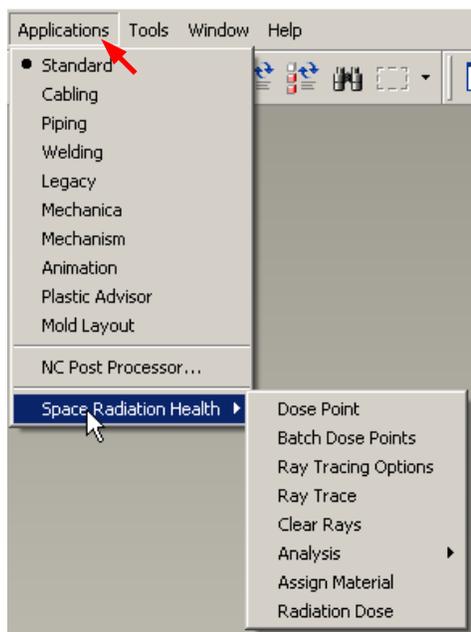


Figure 17. Fishbowl drop down menu shows all of its control options.

4.2.1 Dose Point

This option allows the user to select the dose point of interest. Selecting this option will prompt the user to select a Coordinate System defining the dose point. This selection is “saved” while the Assembly is in session. The user may select a new dose point by reselecting this menu item.

4.2.2 Batch Dose point

This option allows the user to select up to 200 dose points of interest for analysis. The coordinate systems for the dose points have to be pre-assigned before their selection using the coordinate system selection method explained earlier

4.2.3 Ray Tracing Options

From this option the user can select the ray tracing options. When this option is selected, a dialog will be presented as shown in the figure below. The selections are “saved” while the Assembly is in session. The options under this item are listed below:

4.2.3.1 Uniform

The user has the option of using predefined uniformly distributed rays (from 512 to 100,000 rays), or define his or her own rays. To use the predefined uniform rays, click on this option and enter the number of rays (from 512 to 100,000) in the space under **Count**. A ray count on the order of 1,000 is sufficient for much application, however a larger number should be used for higher fidelity including when a larger number of small parts are considered in the ProE model.

4.2.3.2 User defined

Additionally, you can specify certain rays, up to 100,000 rays, by entering their **Azimuth Phi** and the **Polar Theta** angles in radians. After entering the angles for each ray, click **Add**. When you are done adding all rays, click on **Save** to save all added angles in a ***.ray** file which you can access later. To delete an angle, highlight the angle and click on “**Delete**”. If the list of rays is large, the list can be copied in a **Notepad** file and saved as a text file under a name ending with **.ray**. The file can be loaded using the **Load** button. After all options are chosen, click **OK**.

4.2.3.3 Roptional

This option is set to the value of 2.921000 which is the range of 50 MeV protons in aluminum. If you want to ray trace a CAD drawing to calculate the equivalent thickness for another material, say polyethylene, you need to change the value of **Roptional** to the range of 50 MeV protons in polyethylene.

4.2.3.4 Vector Accuracy

The accuracy is the allowable movement in the origin of the ray and is in the current model units. The origin is allowed to “wobble” within this amount in order to try to resolve ambiguous intersections. The default value of this option is set to 0.001 which is the maximum ray accuracy. Note this value will increase computer running time. This values can be changed to any one of the following values [0.001, 0.010, 0.100, 1.000, 10.000] offered by this option.

4.2.3.5 Default Rmat

Rmat may be defined for any part by setting it in the POISSON_RATIO parameter in the part material file. For cases where this is not set, the default Rmat value may be used.

4.2.3.6 Default Density

Density may be defined for any part by setting it in the DENSITY parameter in the part material file. For cases where this is not set, the default Density value may be used.

4.2.3.7 Use default Rmat & Density

When this option is checked the default Rmat and Density values will be used for all parts.

4.2.3.8 Ambiguity Resolution

The application will attempt to resolve ambiguous intersections by moving the origin first in the X then in the Y then XY then XZ, etc. up to the value specified for Vector Accuracy. Higher resolutions iterate through more attempts and longer run times. This option has 4 choices:

Disabled, Minimal, Standard, and Aggressive.

“No Warning for Ambiguities” and “No Warning for Interferences” can be selected for the cases when operator interaction or intervention is not wanted or possible such as in cases of very long runs.

4.2.3.9 Autoscale ray Color Range

This option is used in color coding the rays that are used to ray trace the design. The color coding is coloring the each ray with a color that represents the aluminum equivalent thickness. The purpose of this option is to produce a 3-D color image that shows hot spots of the CAD thicknesses-weak areas by coloring them in different colors. When checked the minimum and maximum values found during the *Tmat* analysis will be used. If unchecked, the user may define the minimum and maximum and choose the number of colors to be used. The numbers need to be of the order $(2)^n$ where n is 1, 2, 3, 4, and 5. The range between the maximum and minimum is transformed into the range between 60 and 360 where the range then is divided linearly over the number of colors.

The colors will be determined according to the following example:

If number of colors is 4 (remember, available numbers of colors are 2,4,8,16,32 and 64) then colors would be 60 160 260 360, or yellow, green, blue and red according to the color chart shown in figure 18.

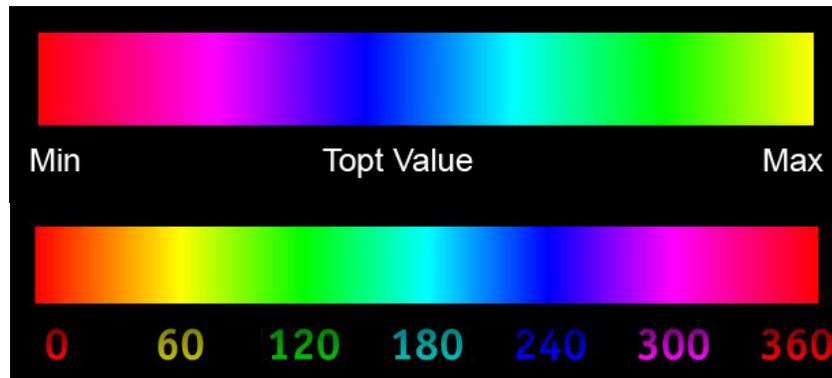


Figure 18. The color code chart shows the range of colors that will be linearly distributed over the selected range of *Topt* values. If no range is selected, the default range is from the minimum value to the maximum one.

4.2.3.10 Draw Rays From Origin

When checked, the color rays generated using Analysis - Display *Topt* Values - Draw Rays will be displayed from the Dose Point origin. By default, the rays are only shown in the area they intersect a part.

4.2.3.11 Number of Colors

This specifies the number of colors to be used for the color rays generated using **Analysis → Display Topt Values → Draw Rays**.

4.2.4 Ray Trace

This option allows the user to start ray tracing and to display the rays on the screen.

4.2.5 Clear Rays

You can graphically remove the shown rays by choosing **Clear Rays** from under **Space Radiation Health**. The rays will be cleared graphically but all ray tracing results remain available when called.

4.2.6 Analysis

The analysis menu has 4 selections as shown in figure 19 below:

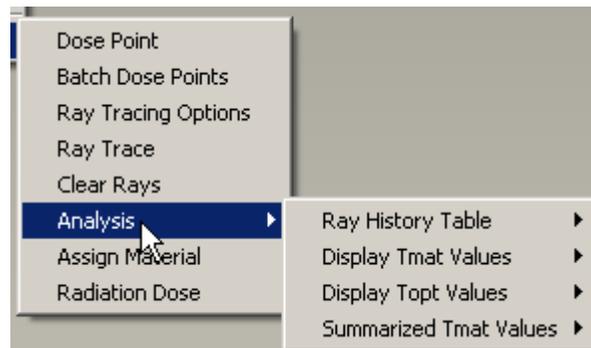


Figure 19. The Analysis options.

All output files are saved in a CSV format and have the following header information: The Analysis submenu is described below.

4.2.6.1 Ray History Table

This analysis will record every location a ray will hit. The user may choose one of the two following options.

4.2.6.1.1 To Screen

This option will display the results in a ProE Information window.

4.2.6.1.2 To File

This option will save the results to an output file similar to the example shown in figure 20.

```

Summary of mass distribution information generated from Space Radiation Health
NASA, JSC

Date / Time = Thu Nov 15 14:59:06 2007
Assembly Name = CM606_LIDS_MECHANISM_INSTL_R
Ray Vector Start Point = (0.000000, 0.000000, 0.000000)
Number of Ray Vectors = 20

Start Ray Number 1
Ray Node X Pos.    Y Pos.    Z Pos.    Phi      Theta    Parts          Xmat(cm)

Start Ray Number 2
Ray Node X Pos.    Y Pos.    Z Pos.    Phi      Theta    Parts          Xmat(cm)

Start Ray Number 3
Ray Node X Pos.    Y Pos.    Z Pos.    Phi      Theta    Parts          Xmat(cm)
1  18.708351    8.970412  -21.58868  0.447103  2.376054  58_TUNNEL_R    0.453846
2  18.99192     9.10638  -21.915907  0.447103  2.376054  58_TUNNEL_R    0
3  15.520983    7.44211  -17.910586  0.447103  2.376054  58_SOFTCAPTURE_RING_R  0.125777
4  15.59957     7.479792 -18.001272  0.447103  2.376054  58_SOFTCAPTURE_RING_R  0

```

Figure 20. An example of the Ray History Table output.

4.2.6.1.3 Batch Analysis

See Item 3. **Batch Analysis:** under **Summarized Tmat Values**

4.2.6.2 Display Tmat Values

This analysis will record the number of Areal Densities (T_{Mat}) values is equal the number of rays. The user may choose one of the two following options:

4.2.6.2.1 To Screen

This option will display the results in a ProE information window.

4.2.6.2.2 To File

This option will save the results to an output file similar to the example shown in figure 21.

```

Summary of mass distribution information generated from Space Radiation Health
NASA, JSC

Date / Time = Thu Nov 15 15:03:33 2007
Assembly Name = CM606_LIDS_MECHANISM_INSTL_R
Ray Vector Start Point = (0.000000, 0.000000, 0.000000)
Number of Ray Vectors = 20

Start Ray Number 1
Ray Node X Pos.    Y Pos.    Z Pos.    Phi      Theta    Parts          Xmat(cm)  Density(g/cm3)  Tmat
                                                                                                                                0

Start Ray Number 2
Ray Node X Pos.    Y Pos.    Z Pos.    Phi      Theta    Parts          Xmat(cm)  Density(g/cm3)  Tmat
                                                                                                                                0

Start Ray Number 3
Ray Node X Pos.    Y Pos.    Z Pos.    Phi      Theta    Parts          Xmat(cm)  Density(g/cm3)  Tmat
1  18.70835    8.970412  -21.58868  0.447103  2.376054  58_TUNNEL_R    0.453846    0.0975    0.04425
2  18.99192     9.10638  -21.91591  0.447103  2.376054  58_TUNNEL_R    0            0.0975    0
3  15.52098    7.44211  -17.91059  0.447103  2.376054  58_SOFTCAPTURE_RING_R  0.125777    0.0975    0.012263
4  15.59957     7.479792 -18.00127  0.447103  2.376054  58_SOFTCAPTURE_RING_R  0            0.0975    0
                                                                                                                                0.056513

```

Figure 21. An example of the Display Tmat Values Table output.

4.2.6.2.3 Batch Analysis

See Item 3. **Batch Analysis:** under **Summarized Tmat Values.**

4.2.6.3 Display Topt Values

The number of $T_{Optional}$ values is equal to the number of rays.

For every ray:

$$T_{Optional} = \sum T_{Mat} \times \frac{R_{Optional}(50MeV)}{R_{Mat}(50MeV)} = \sum X_{Mat} \times \rho_{Mat} \times \frac{R_{Optional}(50MeV)}{R_{Mat}(50MeV)} \quad (2)$$

The user may choose one of the three following options:

4.2.6.3.1 To Screen

This option will display the results in a ProE information window.

4.2.6.3.2 To File

This option will save the results to an output file similar to the following sample.

4.2.6.3.3 Batch Analysis

See Item 3. **Batch Analysis:** under **Summarized T_{mat} Values**

4.2.6.3.4 Show rays

When this option is selected the application will show a color rendered display of the T_{mat} values when the analysis is completed. The number of colors and T_{mat} range are controlled by the corresponding settings in the **Ray Tracing Option** dialog. The T_{mat} values are scaled and described in the **Autoscale Ray Color Range** section.

4.2.6.4 Summarized T_{mat} Values

This option provides the T_{mat} values in a summarized format.

4.2.6.4.1 To Screen

This option will save the results to an output file similar to the following sample.

4.2.6.4.2 To File

This option will save the results to an output file similar to the following sample.

4.2.6.4.3 Batch Analysis

This option allows the user to define a batch analysis for multiple coordinate systems. The user will be prompted to select any number of Coordinate Systems defining the dose points. Once the dose points are assigned the user start a batch analysis through any of the above analysis menus. Separate csv files will be written for each dose point. The naming convention will be partname_cs_analysisname.csv. For example, if the coordinate system dose_point_1 from the assembly module_1 was selected the following files will be created:

module_1_dose_point_1_ray.csv
module_1_dose_point_1_tmat.csv
module_1_dose_point_1_topt.csv

4.2.7 Assign Material

This selection allows the user to assign a material file to any number of parts in the current assembly. The config.pro setting PRO_MATERAIL_DIR must be set.

To do so follow these steps:

Tools → options → (under Option type: pro_material_dir) → (under Value: Browse and find the material library) → click Add/Change → click save on the two disks icon on the top next to Sort → click OK

4.2.8 Radiation Dose

This option is not activated yet.

4.3 Troubleshooting error messages in ray tracing

4.3.1 Ambiguous intersection

In case, you get an **Ambiguous intersection found** error message, you can eliminate this problem by going back to the **Ray Tracing Options** and set the **Vector Accuracy** to a higher number. You can increase it a maximum value of 10. If the **Ambiguous intersection found** error is not solved by increasing the **Vector Accuracy** number, you need to check the CAD design for any parts that have no thicknesses such as surface type parts.

4.3.2 Rmat value is not set

If **Rmat value is not set for part <part name>** error shows up, that means the part named in the error message was not assigned a material name and characteristics. You need to open the part in question and assign the right material and define the corresponding characteristics such as **MASS_DENSITY** and **EMISSIVITY**. A large scale part assignment is possible as in the Assign material option in the Ray tracing Options mentioned earlier using a file that assigns multiple part materials.

5 DEFINITION OF TERMS AND PARAMETERS

- 1- **Start Ray Number**: (the ray number)
- 2- **Ray Node**: (the number of the entry or exit that the ray makes in any part surface it faces— Number 1 means the first entry or exit the rays makes in or out of a part.)
- 3- **X POS.**: (the x-coordinate of the ray entry or exit of the part surface)
- 4- **Y POS.**: (the y-coordinate of the ray entry or exit of the part surface)
- 5- **Z POS.**: (the z-coordinate of the ray entry or exit of the part surface)
- 6- **Phi**: (the angle between the ray and the z-axis)
- 7- **Theta**: (the angle between the rays projection in the x-y plane and the x axis)
- 8- **Parts**: (the part's name)
- 9- **Xmat**: (cm): (the distance in centimeter the ray travels in this part.)
- 10- **Density**: (g/cm^3): (the density of the part's material in g/cm^3 .)
- 11- **Tmat**: (g/cm^2): (areal density of the part's material in g/cm^2 — which is $\text{Xmat} * \text{Density}$)

- 12- **Ral**": (the range of 50 MeV proton in aluminum)
- 13- **Rmat**: (the range of 50 MeV proton in the part's material)
- 14- **Ral/Rmat**: (conversion factor that converts the part's material into its aluminum equivalent.)
- 15- **T-aleq**: (Aluminum equivalent thickness of the part for this ray.)
- 16- **Total Tal-eq**: (the total equivalent aluminum thickness for this ray)
- 17- **Tmat(x)**: (the areal density in g/cm^2 of all parts that the ray passes through that have the same density x.

As shown above, the **Ray History Table** includes items 1 to 9. The **Display Tmat Values** includes items 1 to 11, and the **Display Topt Values** includes items 1 to 16.

Summarized Tmat Values table shows the items 1, 6, 7, and as many of item 17 as the number of materials used in the design.

REFERENCES

- Billings, M.P., Yucker, W.R., The computerized anatomical man (CAM) model. Final summary. Final Report, NASA-CR-134043, MDC-G4655, Contract NAS9-I3228. McDonnell-Douglas Corp., Saint Louis, MO. September 1973.
- Cucinotta, F.A. Durante, M. Cancer risk from exposure to galactic cosmic rays: Implications for Space Exploration by Human Beings. *Lancet Oncology*. **7(5)**; 2006:431-435.
- Cucinotta, F.A., Kim, M.-H., Ren, L., Evaluating shielding effectiveness for reducing space radiation cancer risks. *Radiation Measurements* **41**; 2006:1173-1185.
- Cucinotta, F.A., Ponomarev, A., Plante, I., Carra, C., and Kim, M.Y., Development of a GCR Event-based Risk Model. To be presented at the 5th International Workshop on Space Radiation Research. Cologne, Germany, 2009.
- Cucinotta, F.A., Schimmerling, W., Wilson, J.W., Peterson, L.E., Saganti, P., Badhwar, G.D., and Dicello, J.F. Space radiation cancer risks and uncertainties for Mars missions. *Radiation Research* **156**; 2001:682-688.
- Cucinotta, F.A., Schimmerling, W., Wilson, J.W., Peterson, L.E., and Saganti, P.B. Uncertainties in estimates of the risks of late effects from space radiation. *Advances in Space Research* **34(6)**; 2004:1383-1389.
- Cucinotta, F.A., Wilson, J.W., Badavi, F.F. Extension to the BRYNTRN code to monoenergetic light ion beams. NASA TP-1994-3472.
- Durante, M., Cucinotta, F.A., Heavy ion carcinogenesis and human space exploration, *Nature. Reviews* **8**; 2008:465-472.
- Hu, S., Kim, M.-H., McClellan, G.E., Cucinotta, F.A., Modeling the acute health effects of astronauts from exposure to large solar particle events, *Health Physics* **96(4)**; 2008:465-476.
- Kase, P. G. Computerized anatomical model man. Technical Report, AD-868927, MCR-69-409, AFWL-TR-69-161, Contract F29601-69-C-0052. Martin Marietta Corp., Denver, CO. January 1970.
- Kim, M.-H., Ponomarev, A.L., Nounu, H.N., Hussein, H.F., Cucinotta, F.A., Improvement of risk assessment from space radiation for future space exploration missions, ICES 2007-01-3116.
- Kim, M.-H., Wilson, J., Cucinotta, F.A., An improved solar cycle statistical model for the projection of near future sunspot cycles. NASA/TP-2004-212070.
- National Council of Radiation Protection and Measurements, NCRP. Guidance on Radiation Received in Space Activities. NCRP Report 98, Bethesda, MD; 1989.

National Council on Radiation Protection and Measurements, Information needed to make radiation protection recommendations for space missions beyond Low-Earth Orbit. NCRP Report No. 153, Bethesda, MD, 2006.

Ponomarev, A.L., Nounu, H.N., Hussein, H.F., Kim, M.-H., Cucinotta, F.A., NASA-developed ProE-based tool for the ray-tracing of spacecraft geometry to determine radiation doses and particle fluxes in habitable areas of spacecraft and in the human body. NASA/TP-2007-214770.

Wilson, J.W., Badavi, F.F., Cucinotta, F.A., Shinn J.L., Badhwar, G.D., Silberberg, R., Tsao, C.H., Townsend, L.W., Tripathy, R.K. HZETRN: Description of a free-space ion and nucleon transport and shielding computer program. NASA TP-3495.

Yucker, W.R. Body self-shielding distributions using the computerized anatomical male and female (CAM/CAF) Models. Report MDC-92H0940. McDonnell Douglas Space Systems Company, Huntington Beach, CA. September 1992.

Yucker, W.R. Computerized anatomical female body self-shielding distributions. Report MDC-92H0749. McDonnell Douglas Space Systems Company, Huntington Beach, CA. March 1992.

Yucker, W.R., and Huston, S.L. Computerized anatomical female. Final report, MDC-H-6107. McDonnell Douglas Corporate Report, Huntington Beach, CA. September 1990.

APPENDIX: Physical Constants and Conversion Formulas

1. Conversion to the aluminum equivalent thickness (T_{Al-eq} in g/cm^2) from the material's linear thickness (X_{Mat} in cm)

$$T_{Al-eq} = T_{Mat} \times \frac{R_{Al}(50\text{MeV})}{R_{Mat}(50\text{MeV})} = X_{Mat} \times \rho_{Mat} \times \frac{R_{Al}(50\text{MeV})}{R_{Mat}(50\text{MeV})} \quad (\text{A.1})$$

where the range of 50 MeV protons is used for various materials.

2. Basic materials

Material	$R_{Mat}(50 \text{ MeV}), \text{g}/\text{cm}^2$	Bulk Density (ρ_{Mat}), g/cm^3
Water (Tissue)	2.205	1.0
Aluminum (Standard Spacecraft)	2.921	2.7
Carbon Dioxide (Martian Atmosphere)	2.548	1.977E-3
Liquid Hydrogen (Fuel)	1.029	0.07
Liquid Deuterium	2.041	0.14
^7Li	2.696	0.534
^9Be	2.705	1.850
^{11}B	2.723	2.350
Graphite Carbon (Heat Shield)	2.485	1.67
Liquid ^{14}N	2.528	0.808
Liquid ^{16}O (Fuel)	2.578	1.149
Ethanol (Ethyl Alcohol as Fuel)	2.113	0.789
^{19}F	2.810	1.580
^{24}Mg	2.785	1.74
^{28}Si (Electronic Equipment)	2.822	2.33
^{31}P	2.942	1.82
^{32}S	2.869	2.07
^{40}Ca	2.902	1.54
^{48}Ti	3.284	4.5
^{51}V	3.352	5.96
^{56}Fe (Steel)	3.379	7.86
^{64}Co	3.557	8.92

3. Most widely used polymers for engineering design

Material	$R_{Mat}(50 \text{ MeV}), \text{g/cm}^2$	Bulk Density (ρ_{Mat}), g/cm^3
High Density Polyethylene	2.063	0.95
Polytetrafluoroethylene (Teflon)	2.735	2.17
Polysulfone (P1700)	2.351	1.24
Polyetherimide (Ultem)	2.365	1.27
Epoxy	2.310	1.30
Polyethylene Terephthalate Polyester (Mylar)	2.372	1.333 (amorphous polymer: 0 % crystallinity) 1.455 (100 % crystallinity)
Polyvinylfluoride (Tedlar)	2.375	1.38~1.72
Polyetheretherketone (PEEK)	2.360	1.32
Polyamideimide (Torlon)	2.367	1.38
Poly (<i>m</i> -phenylene isophthalamide) (Nomex), Poly (<i>p</i> -phenylene terephthalamide) (Kevlar)	2.360	Nomex:1.38 Kevlar:1.45
Polycyanate Ester (Cyanate)	2.405	1.24
Polystyrene	2.239	1.05 Styrofoam (Expandable Polystyrene): < 0.048
Polyimide (Kapton)	2.414	1.42
Phenylethynyl terminated imide oligomer (PETI-5)	2.408	1.37
Thermoplastic Polyimide (K3B)	2.369	1.337
Polyarylene Ether Benzimidazole - Polyphosphine Oxide (phosphine oxide gives AO resistance)	2.368	1.3 TOR: Triton Oxygen Resistant
Polyarylene Ether - Polyphosphine Oxide	2.334	1.3 COR: Clear Oxygen Resistant
Polyimide (TOR-RC)	2.514	1.3 TOR-RC (TOR-Reduced Color for thermal control)
LaRC-SI	2.400	1.379 LaRC-Soluble Imide

4. Polymer matrix composites

(60/40 vol. Fraction)

Composites	$R_{Mat}(50 \text{ MeV}),$ g/cm^2	Bulk Density (ρ_{Mat}), g/cm^3
Glass/Epoxy	2.573	2.008
HDPE/Epoxy	2.172	1.102
Kevlar/Epoxy	2.340	1.39
Graphite/Epoxy	2.422	1.522
Graphite/Polysulfone	2.438	1.498
Graphite/PEEK	2.439	1.53
Graphite/PETI-5	2.460	1.55
Graphite/K3B	2.437	1.671
Graphite/Ultem	2.442	1.51
Graphite/Polycyanate Ester (Cyanate)	2.458	1.498

5. Metal matrix composites

(30/70 vol. fraction)

Composites	$R_{Mat}(50 \text{ MeV}),$ g/cm^2	Bulk Density (ρ_{Mat}), g/cm^3
SiC/Aluminum	2.853	2.655
Graphite/Aluminum	2.821	2.39
Graphite/Magnesium	2.691	1.72
Alumina/Aluminum ($\text{Al}_2\text{O}_3/\text{Al}$)	2.855 (FP DuPont Alumina)	3.00 *FP DuPont Alumina (3.71 g/cm^3)
	2.860 (Kaowool Babcock & Wilcox Co. Alumina)	2.7 *Kaowool Babcock & Wilcox Co. Alumina (2.7 g/cm^3)
B-fiber/Aluminum	2.881	2.664

6. Ceramic composites

Composites	$R_{Mat}(50 \text{ MeV}),$ g/cm^2	Bulk Density (ρ_{Mat}), g/cm^3
Carbon-Carbon composite	2.485	1.67 Same as graphite carbon
SiC-SiC composite	2.703	2.55

7. Microcomposites

(20/80 weight fraction)

Composites	$R_{Mat}(50 \text{ MeV}),$ g/cm^2	Bulk Density $(\rho_{Mat}), \text{g/cm}^3$
Boron/Epoxy	2.382	1.43
B ₄ C/Epoxy	2.369	1.44
Epoxy/ Lunar Regolith	2.675	1.46

(90/10 wt. fraction)

Composites	$R_{Mat}(50 \text{ MeV}),$ g/cm^2	Bulk Density $(\rho_{Mat}), \text{g/cm}^3$
NZP/LaRC-SI (Ceramic/LaRC -Soluble Imide) *Coefficient of Thermal Expansion of NZP=0	3.085 with BS25 NZP (3.5 g/cm^3)	3.033
	2.988 with CS50 NZP (3.32 g/cm^3)	2.91

8. Metal alloys

Alloys	$R_{Mat}(50 \text{ MeV}),$ g/cm^2	Bulk Density $(\rho_{Mat}), \text{g/cm}^3$	
Al-Li alloy	2.937	2.67	1 % Li 4 % Cu 95 % Al by weight
Ti light weight alloy	3.258	4.46	4 % Al 6 % V 90 % Ti by weight

9. Planetary regoliths

Material	$R_{Mat}(50 \text{ MeV}),$ g/cm^2	Bulk Density $(\rho_{Mat}), \text{g/cm}^3$
Lunar Regolith	2.782	1.5
Martian Regolith	2.784	1.4

Composite	Wt fraction	$R_{Mat}(50 \text{ MeV}),$ g/cm^2	Bulk Density $(\rho_{Mat}), \text{g/cm}^3$
Martian Regolith/Epoxy	90/10 wt %	2.724	1.39
	80/20 wt %	2.669	1.38
	70/30 wt %	2.621	1.37
Martian Regolith/LaRC-SI	90/10 wt %	2.735	1.398
	80/20 wt %	2.696	1.396
	70/30 wt %	2.655	1.394
	60/40 wt %	2.612	1.392