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The Use of Pro/ENGINEER CAD Software and Fishbowl Toolkit in Ray-tracing Analysis

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ACRONYMS

CAD	computer-aided design
CGS	centimeter-gram-second (system)
GCR	galactic cosmic radiation
JSC	Johnson Space Center
ProE	Pro/ENGINEER
PTC	Parametric Technology Corporation
SPE	solar particle event
SRP	Space Radiation Program
3D	three-dimensional

ABSTRACT

This document is designed as a manual for a user who wishes to operate the Pro/ENGINEER (ProE) Wildfire 3.0 with the NASA Space Radiation Program (SRP) custom-designed toolkit, which is called “Fishbowl,” for ray-tracing of complex spacecraft geometries that are given by a ProE computer-aided design (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 three-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 1,000) are used to calculate the equivalent thickness (e.g., of aluminum) of the spacecraft geometry that is seen at a point of interest that is called the dose point. The rays originate at the dose point and terminate at a homogenously distributed set of points lying on a sphere that circumscribes the spacecraft and that has its center at the dose point. The distance that a ray traverses in each material is converted to aluminum or other user-selected equivalent thickness. All equivalent thicknesses are then 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 platform support and system requirements information. The document will then show the user how to use the software to ray-trace a ProE-designed 3D 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 that are associated with prolonged exposure to the complex space radiation environment. Space radiation-related health risks range from the risk of cancer to degenerative diseases such as those of the central nervous system, heart disease and cataracts, and to acute radiation syndromes. Estimating these risks bears great uncertainties, and many studies are under way to identify and improve the risk assessments (Cucinotta et al., 2001; 2004). Uncertainties in determining the biological effects of space radiation on astronauts are largely related to uncertainties in the radiobiology of the heavy ions in space and, to a much lesser extent, concerning 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 due to solar particle events (SPEs) (Kim et al., 2004).

The radiation environment consists mainly of galactic cosmic radiation (GCR) and high-energy solar protons that are generated during SPEs. GCR includes high-energy heavy ions, 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 GCR requires much thicker shielding materials, which makes shielding cost-preventive. While solar particles are one of the main sources of radiation risk, because of their relatively lower energies and comparatively shorter penetration depth, they are easier to shield against than the GCR. However, because of the high costs of launching mass into space (~$300,000 per pound in 2009), optimization of the spacecraft design and shielding as well as placement of equipment inside the spacecraft is mandatory (Cucinotta et al., 2006).

The risks from space radiation are calculated using NASA-developed transport codes that calculate the organ dose at a certain point in the spacecraft, which is called the dose point and which is based on the areal density map of the spacecraft geometry and the organ in concern. The deterministic HZETRN code (Wilson et al., 1995) or BRYNTRN code (Cucinotta et al., 1994) and the stochastic GERMcode (Cucinotta et al., 2009) calculate energy spectra of high charge and energy (HZE) nuclei that are passing through spacecraft material of a certain thickness, taking into account the fragments that are 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 organs. Space transport codes calculate the organ dose from space radiation that is based on the material thicknesses that are provided by the spacecraft areal density map of the environment that is surrounding the astronaut and the distances inside the astronaut's tissues through which protons pass to reach the organ of concern. The geometry of the astronaut is represented by the Computerized Anatomical Male (CAM) model (Kase, 1970; Billings and Yucker, 1973; Yucker, 1992a) or the Computerized Anatomical Female (CAF) model (Yucker and Huston, 1990; Yucker, 1992b). Calculated organ doses are used by NASA to model and estimate cancer risks to astronauts (Cucinotta and Durante, 2006), especially in interplanetary missions (Durante and Cucinotta, 2008), for the energetic protons of the SPEs (Hu et al., 2008) and the proton and heavy nuclei of the GCR (Cucinotta et al., 2006).

To quantify the shielding that is provided by the spacecraft structural components, the NASA Space Radiation Program at Johnson Space Center (JSC) developed a toolkit, which is referred to herein as "Fishbowl," that is used with the CAD tool ProE 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, which is a used to perform spacecraft shielding evaluations. This 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 in g/cm^3). It creates a specified number of homogenously spaced rays that originate from the dose point and end in the vacuum that is outside of the spacecraft.

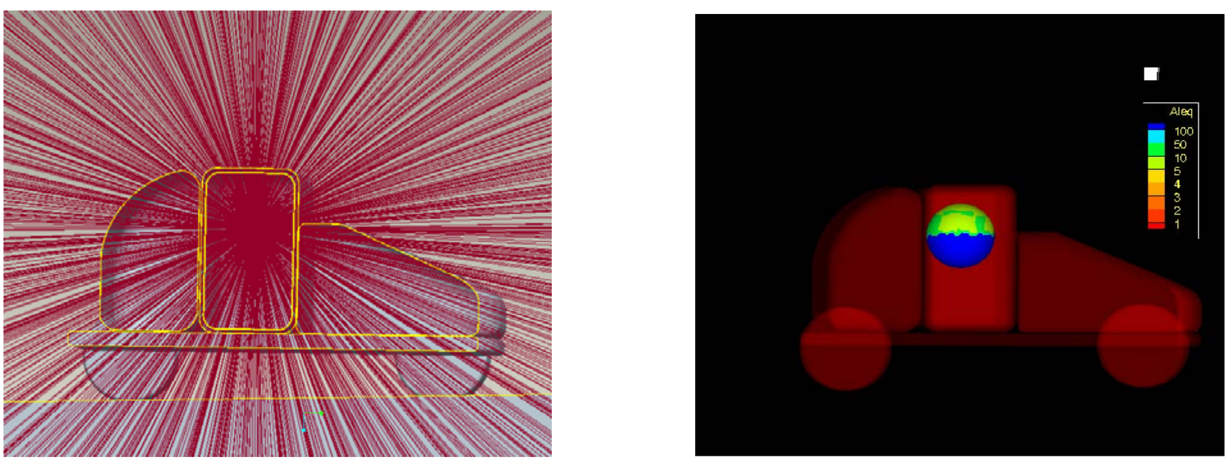
Traditionally, as aluminum is the most prevalent material in a spacecraft, it has been used to scale a diverse list of material types into a single material for ray-tracing. However, Fishbowl allows the user to select any material, not just aluminum, as an equivalent material for ray-tracing. The choice should be made based on spacecraft composition. The software calculates for each ray the directional distance that the ray travels inside every part of the spacecraft 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, which are traversed by the ray, is calculated according to the following equation (Kim et al., 2007):

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

where

$T_{Al\text{-}eq}$: 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
$R_{Al}(p_{50\ MeV})$: range of 50 MeV proton beam on aluminum, in g/cm^2
$R_{Mat}(p_{50\ MeV})$: 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 a ray-tracing image of a lunar rover prototype that was placed on a flat lunar surface with 1,024 homogenously distributed rays going out of the dose point that was chosen, in this case, to be inside the middle compartment. The rover image shows a cross section of the CAD to illustrate the rover structure. In figure 1(b), the resulting areal density is plotted on a sphere that has 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.



(a) (b)

Figure 1. (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 PROE INSTALLATION AND SYSTEM REQUIREMENTS

2.1 ProE installation

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 Parametric Technology Corporation (PTC) Website: http://www.ptc.com/WCMS/files/30890/en/30890en_file1.doc, which contains information for the minimum hardware requirements. The requirements may increase as the size of the assembly file increases, however. We found that for the large CEV files, large RAM –3 GB or more for 32-bit operating systems – is needed for a reasonable ray-tracing turnaround time (a 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 Table 1, which is shown below:

Table 1. Platform Support for Pro/ENGINEER CAD Software

Platform Support			
Partner	**Platform**	**Operating System levels**	**CPU**
Hewlett-Packard	HP-UX 11*i*		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; Windows XP (32-bit) Home Edition	Base OS, Service Pack 1 and 2	Intel Pentium/Xeon family
	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 shows 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 Microsoft® 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 that it will work normally. PTC will provide limited support to resolve issues that arise 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. Note that this list is not meant to be a comprehensive listing of cards with dual-monitor capabilities, and it does not represent a shift from the PTC 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 the 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 the Fishbowl toolkit

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 a **ProE** working directory. There is no license file to load or install for Fishbowl. The entire NASA JSC site is licensed to use Fishbowl. However, for other NASA sites, a license needs to be obtained before using Fishbowl.

3.2 Launching ProE

To launch the ProE software, double click on the **Pro Engineer M270** icon that is shown on the desktop. If the **Pro Engineer M270** icon is not visible on the desktop, you can start the software by clicking on **proe.exe** under the path **D:\PTC\M270\proe\bin**. ProE will launch, and the main window will open 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.

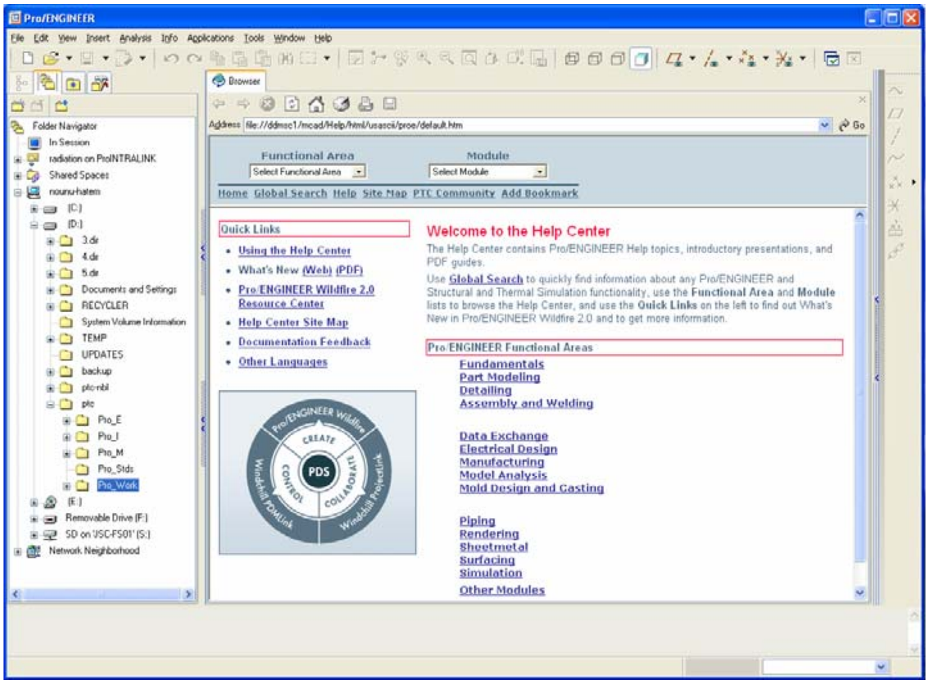


Figure 2. Main page appears after launching ProE.

3.3 Launching Fishbowl toolkit

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

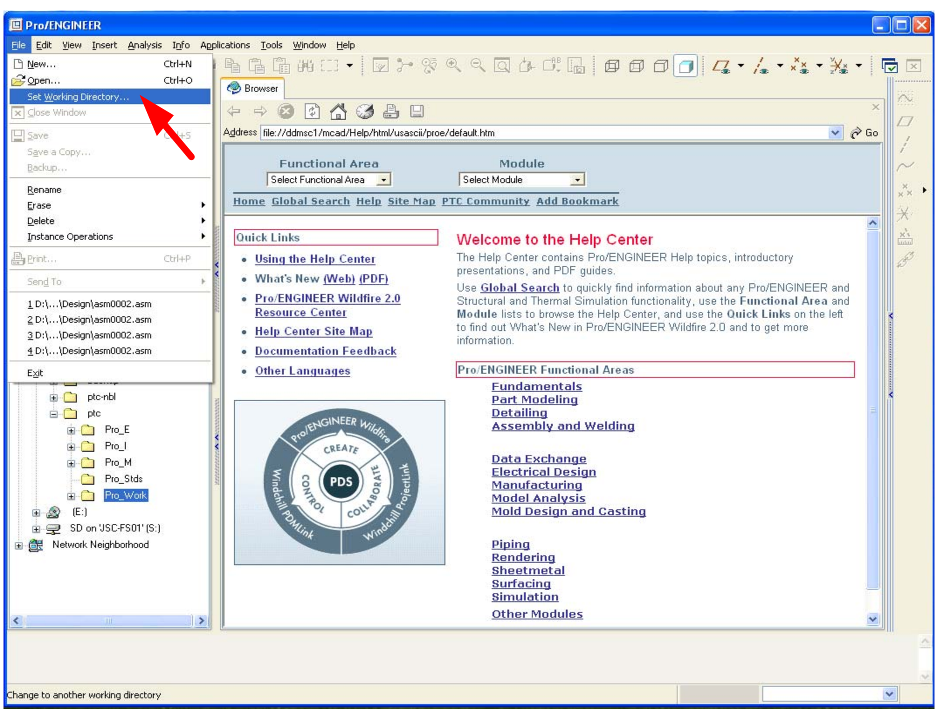


Figure 3. Selection of working directory.

Browse to the location in which 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.

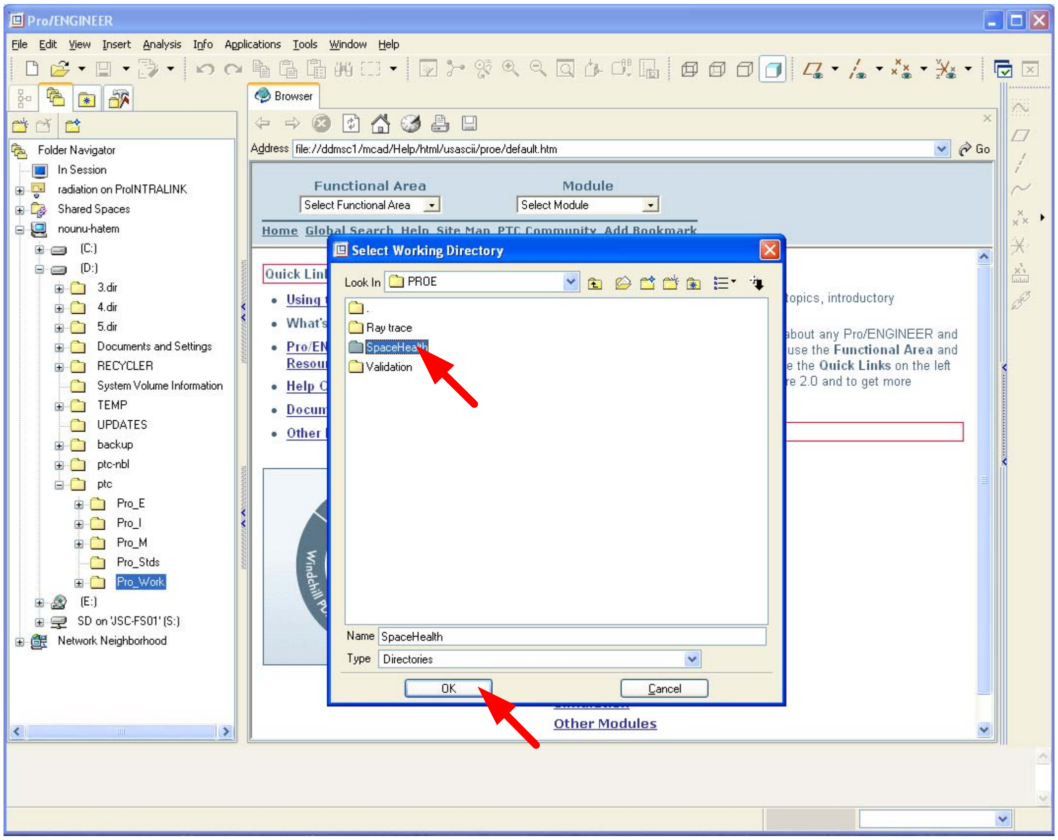


Figure 4. Choice of the working directory as the location of the Fishbowl folder.

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

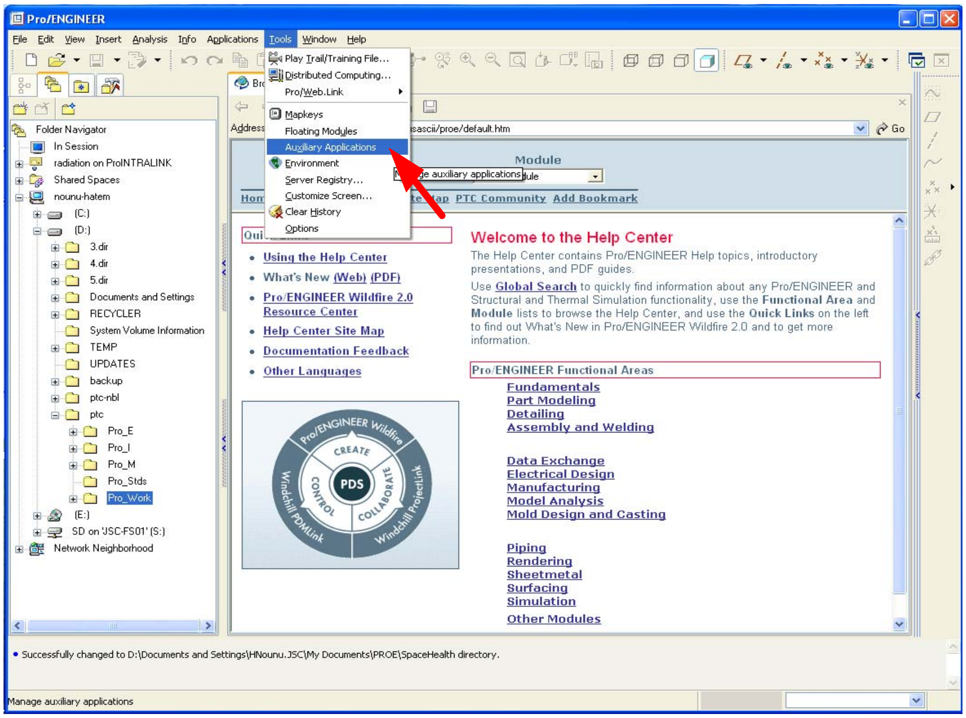


Figure 5. Starting the launch process of Fishbowl toolkit.

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

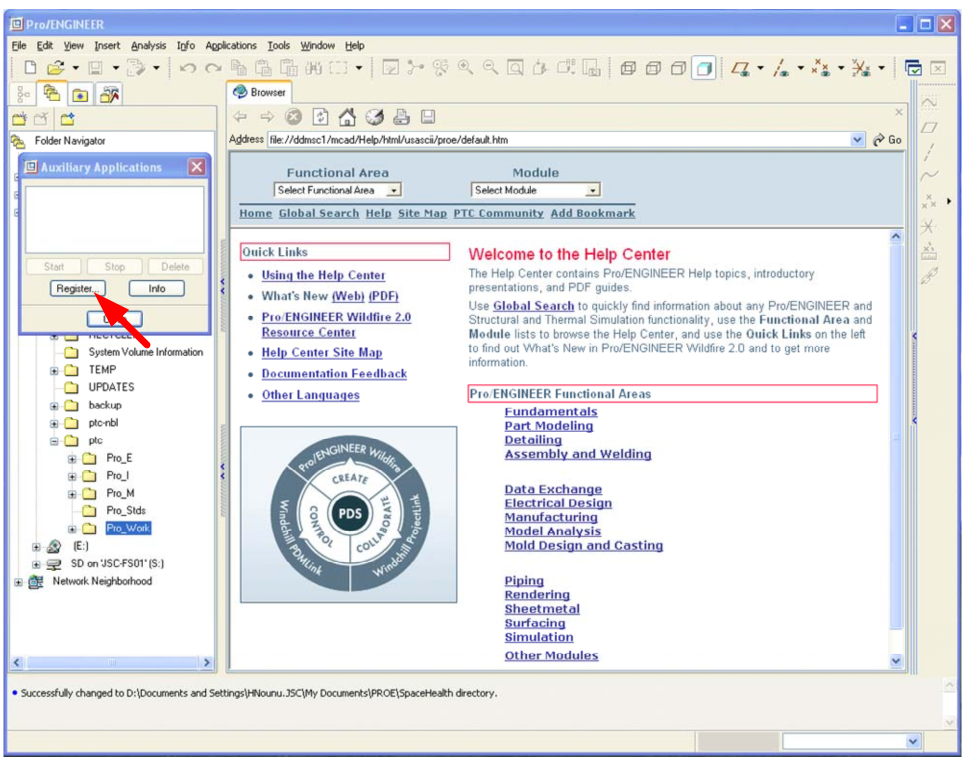


Figure 6. Registration of the Fishbowl toolkit.

A new window that is 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.

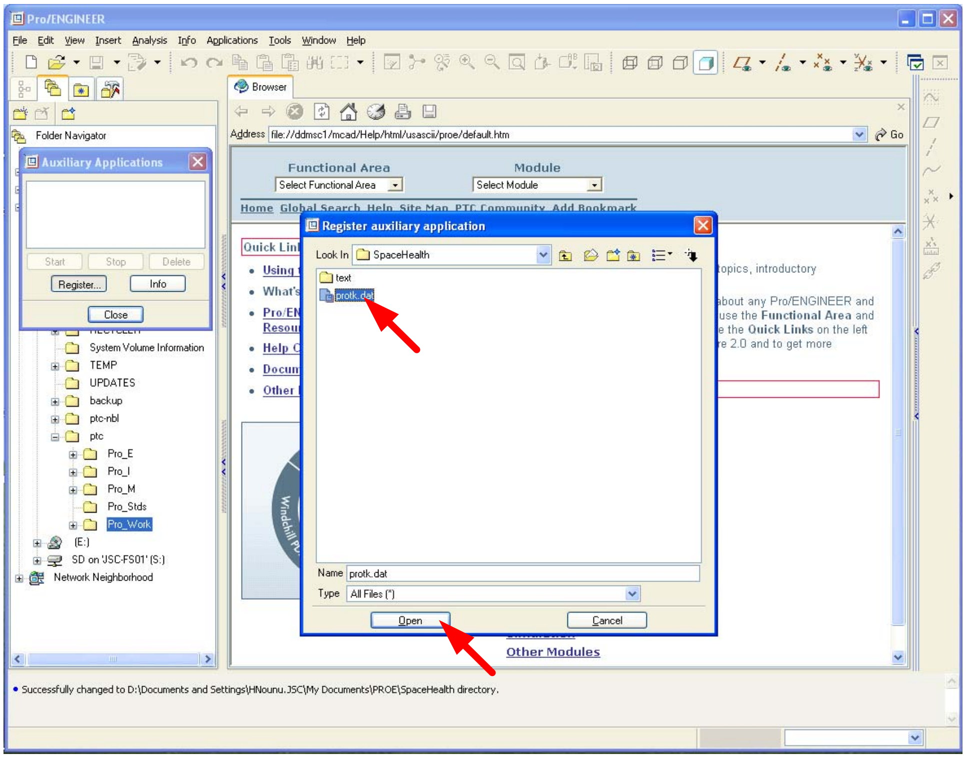


Figure 7. Running the executable file of Fishbowl toolkit.

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.

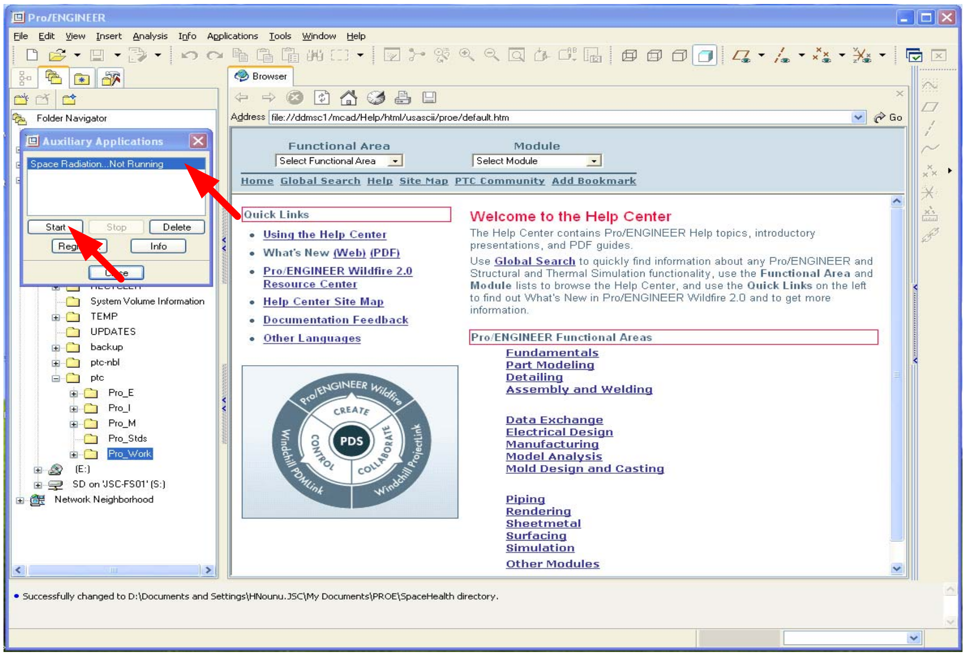


Figure 8. Starting the Fishbowl toolkit.

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.

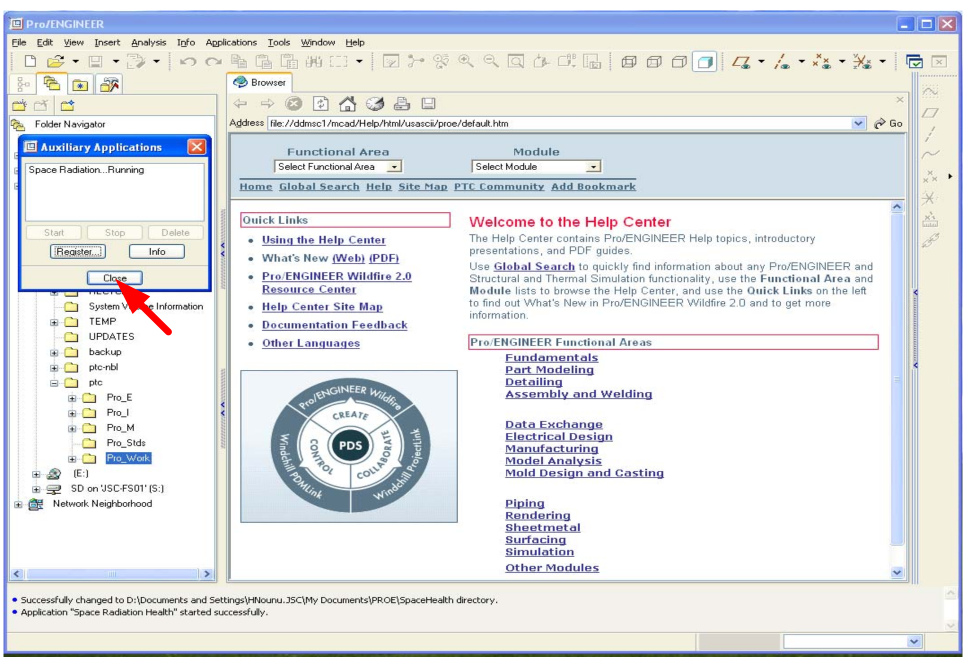


Figure 9. Final stage of the launch process of Fishbowl toolkit.

4 FISHBOWL OPERATION WITHIN PROE

To use the Fishbowl toolkit within ProE, open the CAD design file by opening the assembly that you want to ray-trace by clicking **File** and 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 these are 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 on each part separately or on all parts together.

4.1.1.1 Assigning material individually

Open the ProE file that you need to ray-trace and ensure that the parameters of all the 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.

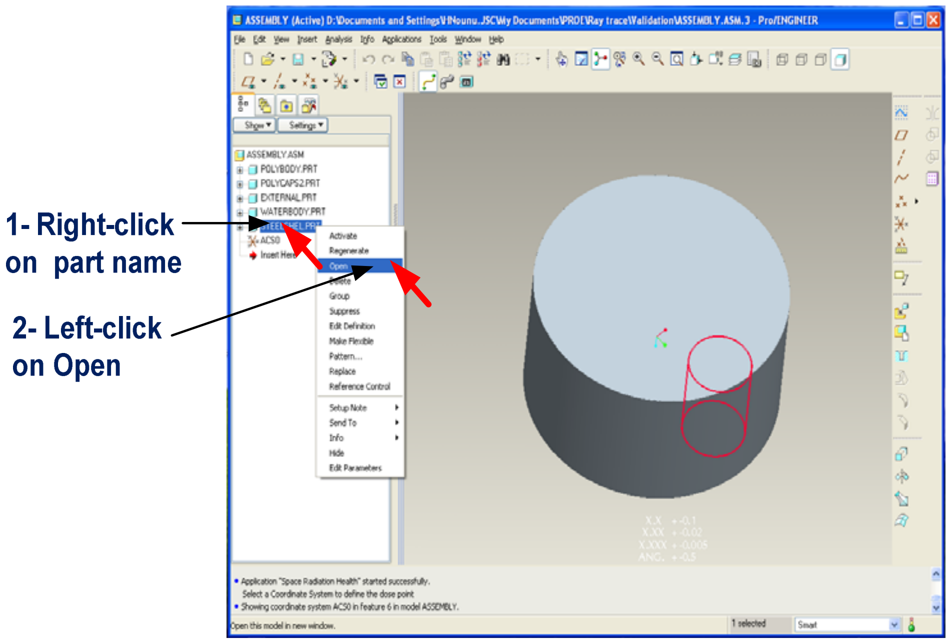


Figure 10. Opening the file of a part from an assembly.

The file that is 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 that is under **Edit**.

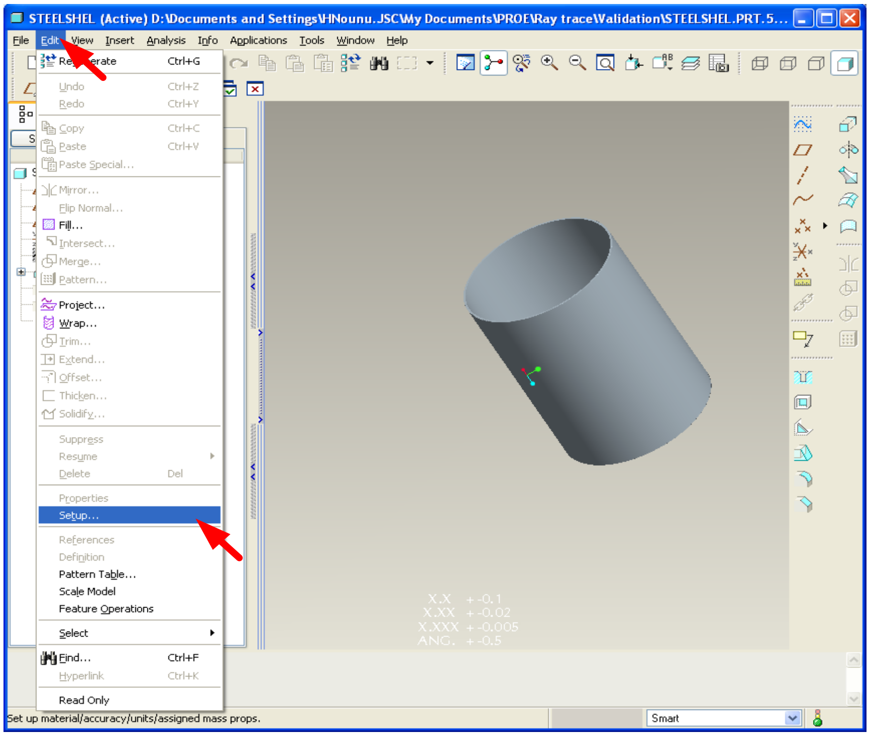


Figure 11. Choosing setup option to change part properties manually.

A narrow window that is called **Menu Manager** will open. Click on **Material** under the **PART SETUP** option. A small window that is called **MATRL MGT** will open. Choose **Edit** followed by the material type (e.g., **STEEL**) and, at the end, choose **Accept**. A new window that is 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; click **Close** when you are done. This process is illustrated in figure 12.

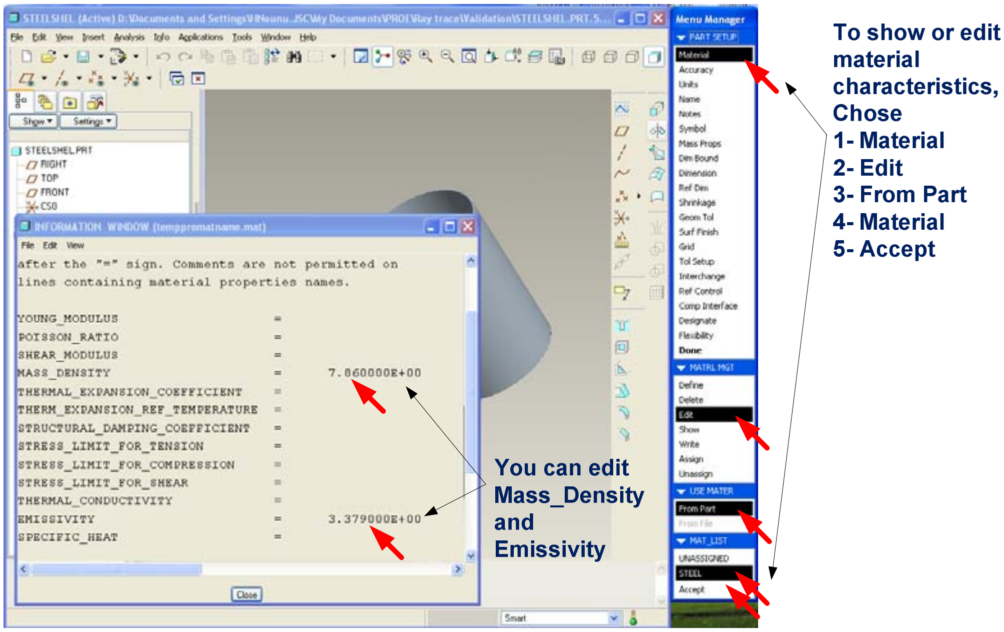


Figure 12. Changing the material properties of a part, such as mass density and emissivity.

4.1.1.2 Assigning material collectively

This option will be explained in the toolkit applications that are addressed 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 that is called **Units Manager** will open. If the units are on **Centimeter Gram Second (CGS),** click **Close**. If the units are otherwise, edit them by clicking on **Centimeter Gram Second (CGS)**, then clicking on **Set**. A window that is called **Changing model units** will open. Choose **Convert dimensions** (for example, 1" becomes 25.4mm). After you finish, click **Close**.

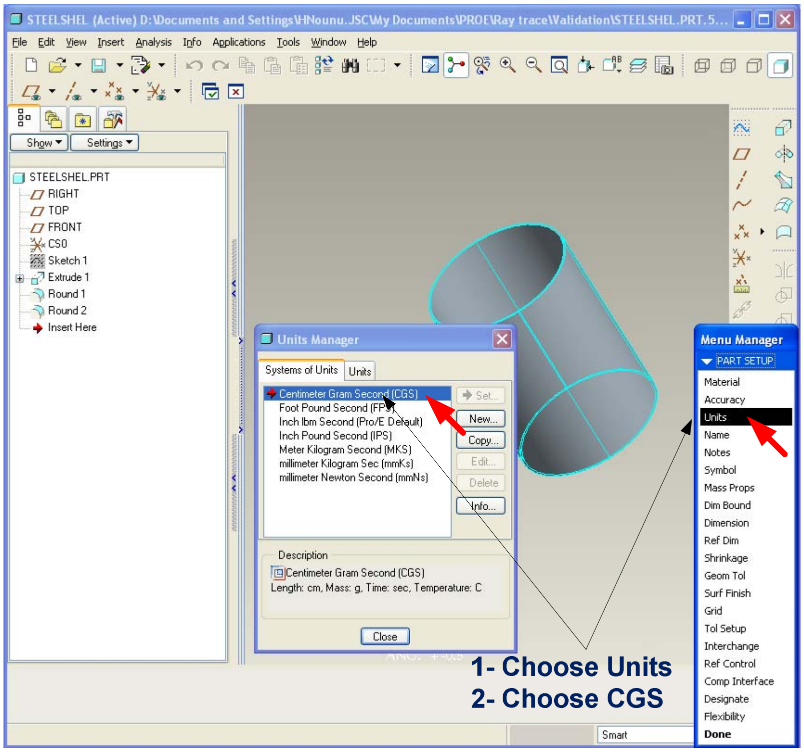


Figure 13. Selecting the unit system of a part.

After you finish choosing the material characteristics and units, click **Done** 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 that is called **COORDINATE SYSTEM** will open.

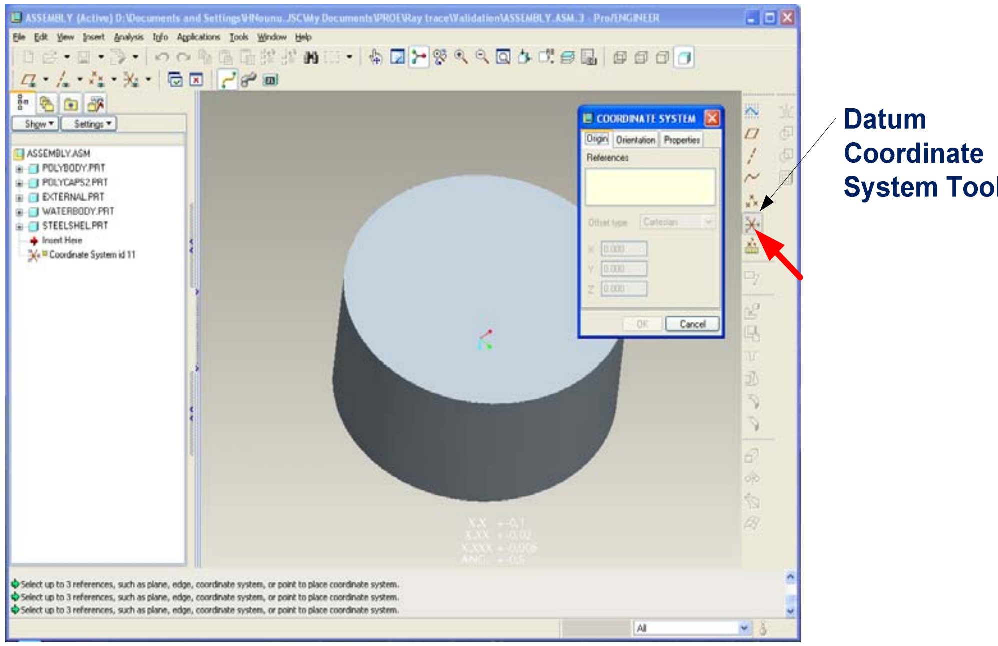


Figure 14. Selecting the Datum Coordinate Tool to start setting the coordinate system.

Go to the model tree that is on the left panel to choose the references. Click on the "+" sign that is 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, 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.

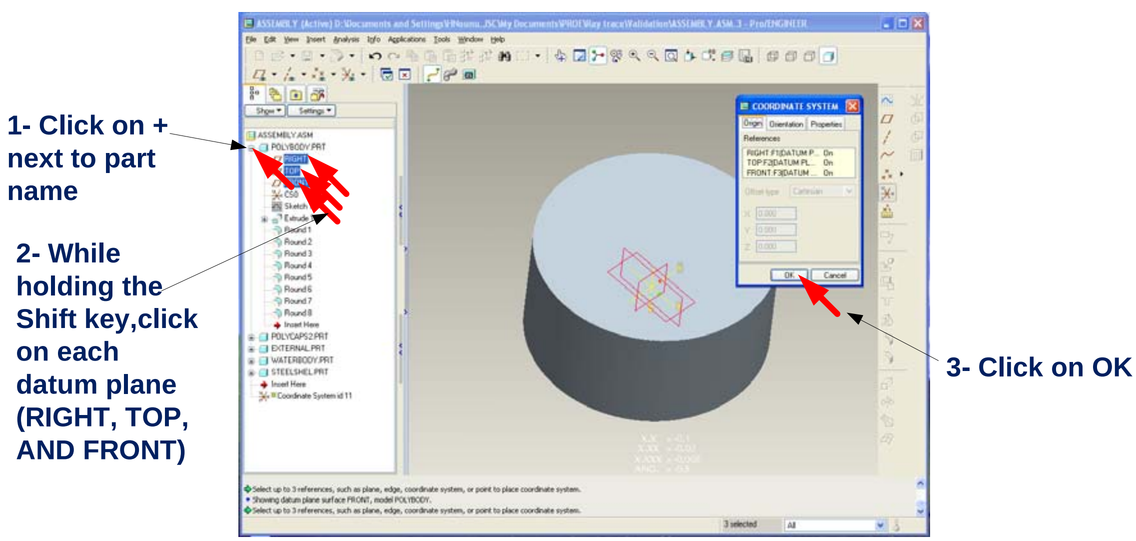


Figure 15. Selecting the desired coordinates in the coordinate system.

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 a ray-tracing can be made.

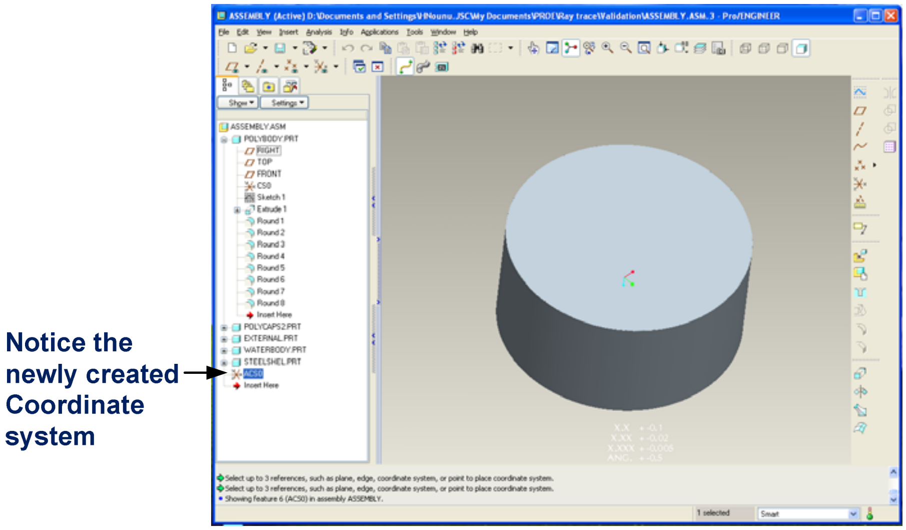


Figure 16. The display of the newly selected coordinate system is shown.

4.2 Ray-tracing features in Fishbowl

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

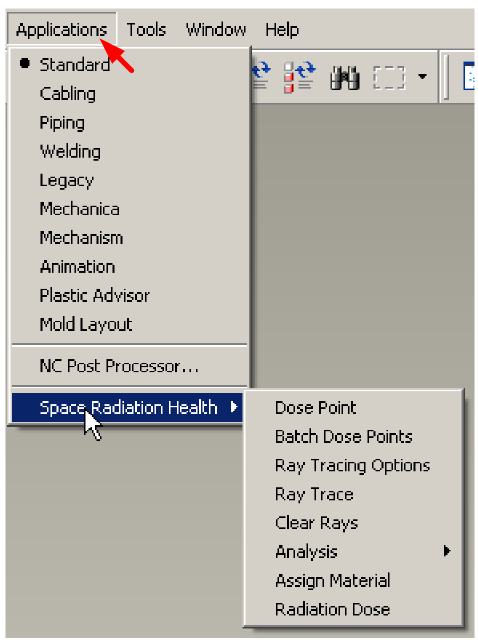


Figure 17. Fishbowl drop-down menu shows all of its control options.

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 that defines 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 as many as 200 dose points of interest for analysis. The coordinate systems for the dose points have to be pre-assigned before their selection by using the coordinate system selection method that was 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 figure 18 below. The selections are "saved" while the Assembly is in session. The options under this item are listed in the following subsections.

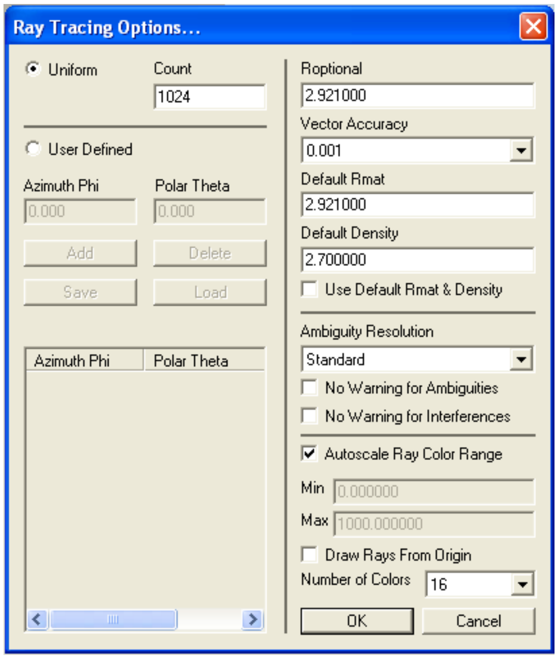


Figure 18. Ray Tracing Options window shows all available options of ray-tracing.

4.2.3.1 Uniform

The user has the option of using predefined, uniformly distributed rays (from 512 to 100,000 rays), or can 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 that is on the order of 1,000 is sufficient for many applications; however, a larger number should be used for higher-fidelity applications, including when a larger number of small parts are considered in the ProE model.

4.2.3.2 User defined

You also can specify certain rays, i.e., as many as 100,000 rays, by entering their **Azimuth Phi** and their **Polar Theta** angles in radians. After entering the angles for each ray, click **Add**. When you are done adding all of the rays, click on **Save** to save all of the added angles in an ***.ray** file that you can access later. To delete an angle, highlight the angle and click on **Delete.** If the list of rays is large, that 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 e.g., polyethylene), you need to change the value of **Roptional** to the range of 50 MeV protons in polyethylene.

4.2.3.4 Vector accuracy

Vector accuracy, which is the allowable movement in the origin of the ray, is in the current model units. The origin is allowed to "wiggle" within this amount to try to resolve ambiguous intersections. The default value of this option is set to 0.001, which is the maximum ray accuracy. Note that this value will increase computer running time. This value can be changed to any one of the values (0.001, 0.010, 0.100, 1.000, 10.000) that is 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 and 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 in the XY, then in the XZ, etc., up to the value that is specified for vector accuracy. Higher resolutions iterate through more attempts and longer run times. This option has four choices: **Disabled**, **Minimal**, **Standard**, and **Aggressive**.

No Warning for Ambiguities and **No Warning for Interferences** can be selected for the cases in which 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. Color-coding is coloring each ray with a color that represents the aluminum equivalent thickness. The purpose of this option is to produce a 3D 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 that are found during the *Tmat* analysis will be used. If unchecked, the user may define the minimum and maximum and choose the number of colors that are 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 the number of colors is four (remember, the available numbers of colors are 2,4,8,16,32, and 64), the colors would be 60, 160, 260, and 360, or yellow, green, blue, and red, according to the color chart that is shown in figure 19.

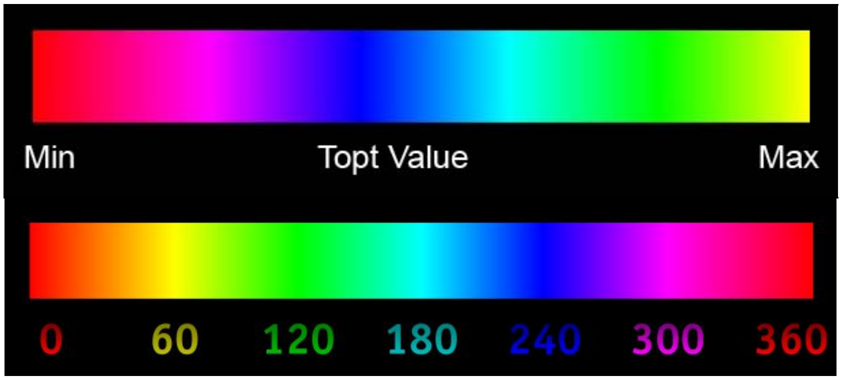


Figure 19. This color code chart shows the range of colors that will be linearly distributed over the selected range of *Topt* values. If no range is selected, the default range is from the minimum value to the maximum value.

4.2.3.10 Draw rays from origin

When checked, the color rays that are generated using **Analysis - Display Topt Values - Draw Rays** will be displayed from the dose point origin. By default, the rays are two inch long and appear to start from the point where they exit the outer surface of the part.

4.2.3.11 Number of Colors

This specifies the number of colors that are to be used for the color rays that are 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

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

4.2.6 Analysis

The analysis menu has four selections, as shown in figure 20.

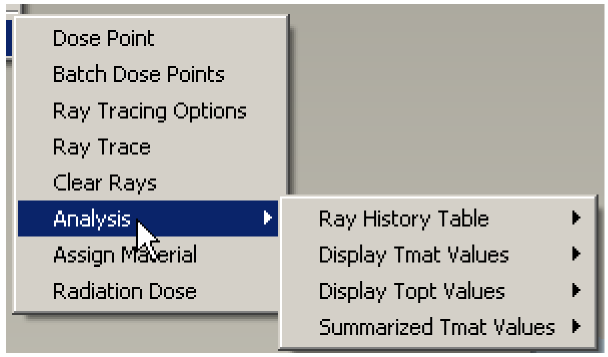


Figure 20. The Analysis options.

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

4.2.6.1 Ray history table

This analysis will record every location that 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 that is similar to the example that is shown in figure 21.

```
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 21. An example of the Ray History Table output.

4.2.6.1.3 Batch analysis

See Item **3. Batch Analysis**, which is under **Summarized T_{mat} Values**.

4.2.6.2 Display Tmat values

This analysis will record the number of areal densities (T_{Mat}) values, which 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 that is similar to the example that is shown in figure 22.

```
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 22. An example of the Display Tmat Values Table output.

4.2.6.2.3 Batch analysis

See Item **3. Batch Analysis**, which is under **Summarized T_{mat} Values**.

4.2.6.3 Display Topt values

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

For every ray,

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

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 that is similar to that shown in the following sample.

4.2.6.3.3 Batch analysis

See Item **3. Batch Analysis**, which is under **Summarized T_{mat} Values**.

4.2.6.3.4 Show rays

When this option is selected and the analysis is completed, the application will show a color-rendered display of the T_{mat} values. The number of colors and T_{mat} range that are used 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 show the results on the screen.

4.2.6.4.2 To File

This option will save the results to an output file for which the user can choose the name and location.

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 by defining the dose points. Once the dose points are assigned, the user starts 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. This means that, for example, if the coordinate system dose_point_1 from the assembly module_1 is 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_MATERIAL_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

Should you get an **Ambiguous intersection found** error message, you can eliminate this problem by going back to the **Ray Tracing Options** and setting 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 for any parts that have no thicknesses, such as surface type parts.

4.3.2 Rmat value is not set

If the **Rmat value is not set for part <part name>** error shows up, this means that the part that was named in the error message was not assigned a material name and characteristics. You will then need to open the part in question, 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 that were mentioned earlier by 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 of the surface that it faces. Number 1 means the first entry or exit that the ray 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 ray projection in the x-y plane and the x axis
8. **Parts**: the part name
9. **Xmat**: cm, which is the distance in centimeter that the ray travels in this part
10. **Density**: g/cm^3, which is the density of the material of the part in g/cm^3
11. **Tmat**: areal density of the material of the part in g/cm^2, which is Xmat * Density
12. **Ral**": the range of 50 MeV proton in aluminum
13. **Rmat**: the range of 50 MeV proton in the material of the part
14. **Ral/Rmat**: conversion factor that converts the material of the part 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

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 to16.

The **Summarized *Tmat* Values Table** includes the items 1, 6, and 7, and as many of item 17 as the number of materials that were used in the design.

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APPENDIX: Physical Constants and Conversion Formulas

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

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

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

2. Basic materials

Material	**R_{Mat}(50 MeV), g/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
^{7}Li	2.696	0.534
^{9}Be	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 MeV), 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 (*m*-phenylene isophthalamide) (Nomex), Poly (*p*-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 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 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 (Al_2O_3/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 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 MeV), g/cm^2**	**Bulk Density (ρ_{Mat}), g/cm^3**
Boron/Epoxy	2.382	1.43
B_4C/Epoxy	2.369	1.44
Epoxy/ Lunar Regolith	2.675	1.46

(90/10 weight fraction)

Composites	**R_{Mat}(50 MeV), g/cm^2**	**Bulk Density (ρ_{Mat}), 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 MeV), g/cm^2**	**Bulk Density (ρ_{Mat}), g/cm^3**	
Al-Li alloy	2.937	2.67	1 % Li 4 % Cu 95 % Al by weight
Ti lightweight alloy	3.258	4.46	4 % Al 6 % V 90 % Ti by weight

9. Planetary regoliths

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

Composite	**Wt fraction**	**R_{Mat}(50 MeV), g/cm^2**	**Bulk Density (ρ_{Mat}), 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

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13. ABSTRACT *(Maximum 200 words)*

This document provides a manual for users who wish to operate the Pro/ENGINEER (ProE) Wildfire 3.0 with the NASA Space Radiation Program custom-designed toolkit, “Fishbowl,” for ray-tracing of complex spacecraft geometries that are 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 3D vehicle geometry can be represented as the input for the space radiation transport code and subsequent risk calculations. This manual will first list, for the user, the contact information for help in installing ProE and Fishbowl in addition to notes on platform support and system requirements information. The document will then show the user how to use the software to ray-trace a ProE-designed 3D assembly, and will serve later as a reference for troubleshooting. The user is assumed to have previous knowledge of ProE and CAD modeling.

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