STEEP321

Version 2.X

Manual

Gaithersburg, MD
2013

[*www.virial.com*](http://www.virial.com)

Content

1. Introduction

The program STEEP321, working under operating systems MS Windows® from 2000 to 7, is intended for numerical modeling of radiation characteristics of blackbody cavities. The program is applicable to design optimization and performance assessment of blackbodies used as standard reference sources in radiation thermometry (pyrometry), radiometry, photometry, and for of optical radiation detector calibrations (e.g., in remote sensing).

STEEP321 is based on the unique algorithm of the Monte Carlo ray tracing method implemented for axially symmetric cavities formed by rotation of polygonal line around the axis. The algorithm performs the modeling of various viewing conditions of cavities with arbitrary axially symmetric temperature distributions. The Uniform Specular-Diffuse (USD) model of reflection is used for optical properties of each surface forming cavity.

The requirements for hardware and software are the following:

- CPU frequency 1 GHz or higher
- Screen Resolution 1280×720 or greater
- Hard disk space 20 MB minimum
- RAM 2 MB minimum
- OS MS Windows® 2000/ME/XP/Vista/7/8 (in compatibility mode)

2. Theoretical basis

2.1. Definitions of Principal Quantities

A source of optical radiation whose radiation characteristics can be calculated on the basis of fundamental physical laws makes possible calibration of radiometers, spectroradiometers, and radiation thermometers. From theoretical point of view, a perfect blackbody is the most suitable object for this purpose. However, a perfect blackbody is a physical abstraction that does not exist in real world. The perfect blackbody conditions are approximately realized inside an isothermal cavity with opaque walls. The radiation escaping cavity through a tiny opening imitates blackbody radiation very closely. In order to employ a blackbody as a standard reference source for radiometry and radiation thermometry, it is necessary to know how large are differences between radiation characteristics of a cavity for a given geometry and wall material and those of a perfect blackbody.

As things stand, there are two different objects referred in literature as “blackbody”:

1. A theoretical object that completely absorbs all radiant energy incident upon it. A blackbody emits maximum amount of radiant energy at given wavelength and given temperature in comparison with all other radiating bodies.
2. An artificial source of radiation designed to simulate characteristics of a perfect blackbody and used as a reference radiation source of calculable radiation characteristics.

In order to differentiate them, we shall use the term “perfect blackbody” for a theoretical object, keeping the term “blackbody” for an artificial source.

Quantitative measure of difference in the radiation characteristics between an artificial blackbody and a perfect one is the effective emissivity. The qualifier *effective* is used due to the effect produced by multiple reflections. Unlike a flat sample, outgoing radiation of an element of a cavity wall consists not only of its own thermal radiation, but also of radiation falling from other surface elements and reflected by the element under consideration. Generally speaking, effective emissivity is the ratio of a radiometric quantity (usually, radiance or spectral radiance) that characterizes a blackbody at a certain temperature to the same quantity of a perfect blackbody with the same temperature. Real-world cavities are always nonisothermal. Temperature nonuniformity might significantly change cavity radiation characteristics. Effective emissivity of a nonisothermal cavity is a function of a reference temperature assigned to a perfect blackbody in the effective emissivity definition and might be less or greater than unity, depending on the reference temperature assigned.

First, the most important quantities that characterize blackbody radiation sources will be defined for the nonrefracting, nonabsorbing, nonscattering, and nonemitting environment (i.e., vacuum at 0 K). It will be also assumed that optical properties of cavity wall do not depend on temperature. Effect of background radiation will be considered later.

The primary characteristic of an artificial blackbody (hereinafter – blackbody, for short) is the spectral local directional effective emissivity, ε_e - defined by the following equation:

$$\varepsilon_e\left(\lambda,\boldsymbol{\xi},\boldsymbol{\omega},T_{ref}\right)=\frac{L_\lambda\left(\lambda,\boldsymbol{\xi},\boldsymbol{\omega}\right)}{L_{\lambda,bb}\left(\lambda,T_{ref}\right)}, \quad (1)$$

where L_λ is spectral radiance (in W·m^{-3}·sr^{-1}) emitted from a point on blackbody wall at a particular wavelength, λ, with coordinates specified by the vector ξ, and the direction in which the radiation is emitted that is given by the vector $\boldsymbol{\omega}$; $L_{\lambda,bb}$ is spectral radiance of a perfect blackbody at a reference temperature T_{ref} and the same wavelength λ.

Denominator in Eq. (1) is expressed by the Planck law:

$$L_{\lambda,bb}\left(\lambda,T_{ref}\right)=\frac{c_1}{\pi\cdot\lambda^5\left[\exp\left(\frac{c_2}{\lambda\cdot T_{ref}}\right)-1\right]}, \quad (2)$$

where c_1 = 3.74177118(19)×10^{-16} W·m^2 and c_2 = 1.4387752(25)×10^{-2} m·K are the 1st and 2nd radiation constants, respectively [1].

Integration over the entire spectrum of radiation reduces the equation to a ratio of radiances. The Stefan-Boltzmann law allows to define total local directional effective emissivity:

$$\varepsilon_e\left(\boldsymbol{\xi},\boldsymbol{\omega},T_{ref}\right)=\frac{\pi L\left(\boldsymbol{\xi},\boldsymbol{\omega}\right)}{\sigma T_{ref}^4}, \quad (3)$$

where L is radiance of the cavity wall and σ = 5.670400(40) ×10^{-8} W·m^{-2}·K^{-4} is the Stefan-Boltzmann constant [1].

Integration over a hemispherical solid angle transforms the term for spectral radiance, L_λ, to spectral radiant exitance, M_λ. The spectral and total hemispherical effective emissivities are defined by the following two equations:

$$\varepsilon_{e,h}\left(\lambda,\xi,T_{ref}\right)=\frac{M_\lambda\left(\lambda,\xi\right)}{M_{\lambda,bb}\left(\lambda,T_{ref}\right)}=\frac{M_\lambda\left(\lambda,\xi\right)}{\pi L_{\lambda,bb}\left(\lambda,T_{ref}\right)}, \tag{4}$$

$$\varepsilon_{e,h}\left(\xi,T_{ref}\right)=\frac{M\left(\xi\right)}{M_{bb}\left(T_{ref}\right)}=\frac{M\left(\xi\right)}{\sigma T_{ref}^4}. \tag{5}$$

Often, it is needed to know *the spectral integrated effective emissivity*. This quantity, $\varepsilon_{e,c}$, is the ratio of spectral radiation flux falling onto the detector from a blackbody, Φ_λ, to spectral radiation flux, $\Phi_{\lambda,bb}$, from a perfectly black surface, that replaces a blackbody aperture and has the temperature T_{ref}:

$$\varepsilon_{e,c}\left(\lambda,T_{ref}\right)=\frac{\Phi_\lambda\left(\lambda\right)}{\Phi_{\lambda,bb}\left(\lambda,T_{ref}\right)}. \tag{6}$$

Integration over complete spectrum results in total integrated effective emissivities:

$$\varepsilon_{e,c}\left(T_{ref}\right)=\frac{\Phi}{\Phi_{bb}\left(T_{ref}\right)}. \tag{7}$$

Depending on particular viewing conditions used for various types of radiation thermometers, pyrometers, radiometers etc., one can define appropriate types of effective emissivities by averaging local directional effective emissivity over a visible part of cavity's internal surface and a suitable solid angle.

All previous definitions have been developed for a non-radiating background environment. However, real environments have temperatures greater than absolute zero. Thermal radiation from surrounding environment falls onto the aperture of a blackbody cavity and can irradiate detector after multiple reflections inside the cavity. The simplest case of isotropic blackbody radiation corresponding to background temperature, T_{bg}, is usually considered. The effect of background radiation on the spectral local directional effective emissivity of a nonisothermal blackbody is taken into account by the second term in the following equation:

$$\varepsilon_e\left(\lambda,\boldsymbol{\xi},\boldsymbol{\omega},T_{ref},T_{bg}\right)=\varepsilon_e\left(\lambda,\boldsymbol{\xi},\boldsymbol{\omega},T_{ref}\right)+\left[1-\varepsilon_e\left(\lambda,\boldsymbol{\xi},\boldsymbol{\omega}\right)\right]\frac{\exp\left(\dfrac{c_2}{\lambda T_{ref}}\right)-1}{\exp\left(\dfrac{c_2}{\lambda T_{bg}}\right)-1}, \qquad (8)$$

where $\varepsilon_e\left(\lambda,\boldsymbol{\xi},\boldsymbol{\omega},T_{ref},T_{bg}\right)$ is spectral effective emissivity of a nonisothermal blackbody taking into account background radiation; $\varepsilon_e\left(\lambda,\boldsymbol{\xi},\boldsymbol{\omega},T_{ref}\right)$ does not include this correction; $\varepsilon_e(\lambda,\boldsymbol{\xi},\boldsymbol{\omega})$ is spectral effective emissivity of an isothermal blackbody.

The total effective emissivity of a nonisothermal blackbody taking into account the background radiation can be defined by the equation:

$$\varepsilon_e\left(\boldsymbol{\xi},\boldsymbol{\omega},T_{ref},T_{bg}\right)=\varepsilon_e\left(\boldsymbol{\xi},\boldsymbol{\omega},T_{ref}\right)+\left[1-\varepsilon_e\left(\boldsymbol{\xi},\boldsymbol{\omega},T_{ref}\right)\right]\left(\frac{T_{bg}}{T_{ref}}\right)^4. \qquad (9)$$

Radiance temperature T_S is defined as temperature of a perfect blackbody, for which the spectral radiance at the given wavelength λ has the same value as for thermal radiator under consideration. For an artificial blackbody having spectral effective emissivity ε_e, the radiance temperature is equal to

$$T_S\left(\lambda,\boldsymbol{\xi},\boldsymbol{\omega}\right)=c_2\left\{\lambda\ln\left[1+\frac{\exp\left(\dfrac{c_2}{\lambda T_{ref}}\right)-1}{\varepsilon_e\left(\lambda,\boldsymbol{\xi},\boldsymbol{\omega},T_{ref}\right)}\right]\right\}^{-1}. \qquad (10)$$

Radiance temperature is sometimes called *brightness temperature* in such areas as remote sensing, astrophysics, etc.

Radiation temperature T_R is defined via Stefan-Boltzmann law:

$$T_R\left(\boldsymbol{\xi},\boldsymbol{\omega}\right)=T_{ref}\sqrt[4]{\varepsilon_e\left(\boldsymbol{\xi},\boldsymbol{\omega},T_{ref}\right)}. \qquad (11)$$

2.2. Viewing Conditions

Effective emissivities as well as radiometric temperatures derived from them depend on *viewing conditions* (i.e., geometrical conditions of collecting the radiation by a measurement device). Effective emissivities can be obtained by averaging primary (local directional) effective emissivities over given spatial and angular domains. Main types of viewing conditions are shown in Fig. 1.

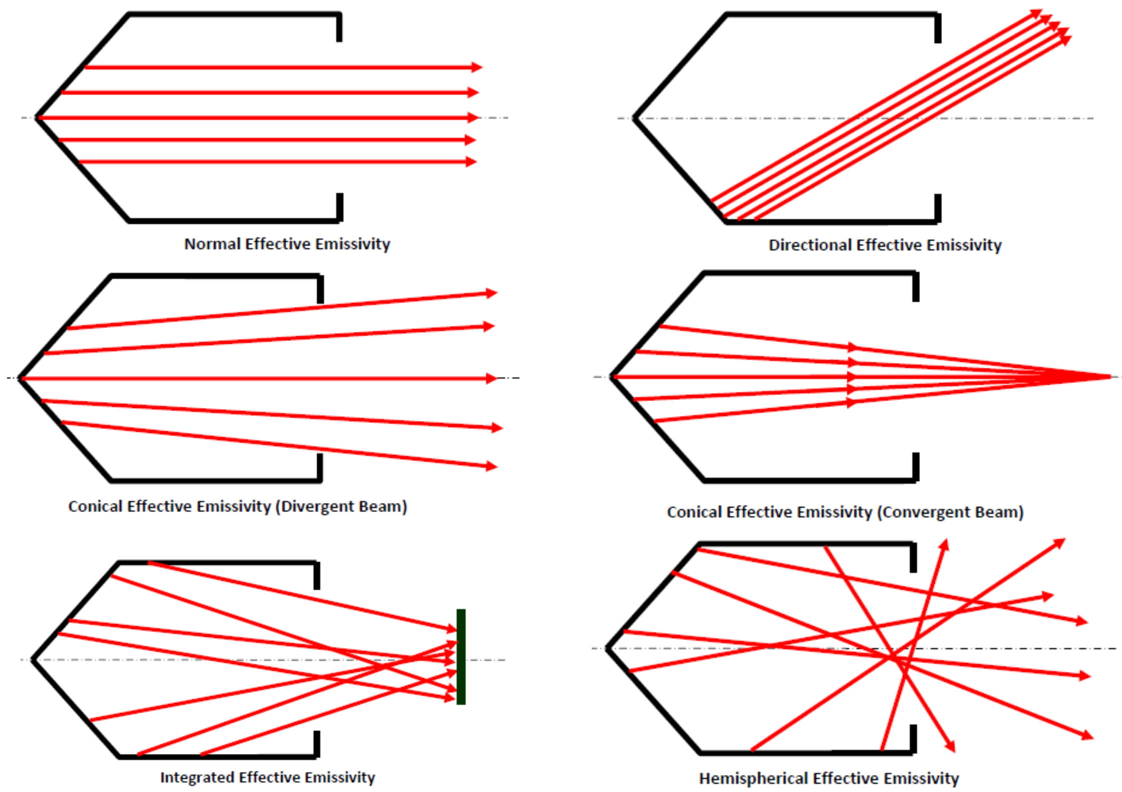


Fig. 1.Main types of viewing conditions.

Normal Effective Emissivity might be considered as a special case of Directional Effective Emissivity. Both these types correspond to the collimated beams. Such viewing conditions are approximately implemented for the radiometric or pyrometric measurement scheme that uses very long focal-length optics. For Conical Effective Emissivities, the beam axis might be not coincided with the cavity axis, so one should distinguish Right (Normal) Conical Effective Emissivity and Oblique (Skew) Conical Effective Emissivity. Hemispherical Effective Emissivity is a special case of Integrated Effective Emissivity when the detector radius is equal to the cavity aperture radius and the distance between cavity aperture and detector is equal to zero.

2.3. Methods for Calculation of Effective Emissivities

Direct measurements of effective emissivity of blackbody radiation sources are often extremely difficult or even impossible. Sometimes, computational methods are the only way to determine effective emissivity. Moreover, calculation of effective emissivities should be done at the design stage. Many computational methods have been developed to this end (see Refs. [2–4]). They are based on the various physical and mathematical assumptions, have different areas of applicability and provide different degrees of accuracy. For diffuse cavities (i.e., cavities whose walls are considered as Lambertian emitters and reflectors) of simple shapes, series of papers by R. E. Bedford and C. K. Ma [5-7] gave *de facto* standard method for calculation of local hemispherical effective emissivity.

At present, the most general and flexible method for calculating radiation characteristics of blackbody radiators is the Monte Carlo Method [8-11]. It is based on the ray tracing algorithm that models radiation heat exchange among cavity walls, propagation of radiation from a blackbody to a radiation detector.

The ray (geometrical) optics approximation is employed, so such phenomena as polarization and diffraction are ignored.

Effective emissivity calculations are based on the optical reciprocity theorem, the technique of backward ray tracing, and the method of statistical weights. A ray with statistical weight equal to unity is directed from the point of observation into a cavity. Its history is being traced until it leaves the cavity after reflections from the walls, or until its statistical weight becomes less then the given value (flux threshold). The last point of reflection is considered to be a birth point of a ray propagating in opposite direction. By choosing reference temperature T_{ref} and analyzing the history of a large number *n* of rays one can evaluate spectral and total effective emissivities of a cavity for given observation conditions and reference temperature:

$$\varepsilon_e\left(\lambda, T_{ref}\right) = \frac{1}{n}\left[\exp\left(\frac{c_2}{\lambda T_{ref}}\right) - 1\right]\sum_{i=1}^{n}\sum_{j=1}^{m_i}\varepsilon_j(\lambda)\left[\exp\left(\frac{c_2}{\lambda T_j}\right) - 1\right]^{-1}\prod_{k=1}^{j-1}\rho_k(\lambda),$$

$$\varepsilon_e\left(T_{ref}\right) = \frac{1}{nT_{ref}^4}\sum_{i=1}^{n}\sum_{j=1}^{m_i}\varepsilon_j T_j^4 \prod_{k=1}^{j-1}\rho_k,$$

where m_i is the number of ray reflections in the i^{th} trajectory; λ is the wavelength; c_2 is the second radiation constant in Planck's law; ε_j, ρ_j, and T_j are the emissivity, reflectance and temperature in the j^{th} point of reflection, respectively.

Quality of the Monte Carlo modeling depends to a great extent upon adequacy of stochastic model adopted for optical properties of materials forming a blackbody cavity. The simplest (but often insufficient) model is the diffuse model of reflection. The most powerful models must take into account bi-directional reflectance distribution function (BRDF) [12] that describes angular distributions of reflected radiation for every direction of incident radiation. However, such an approach is complicated and requires significant computational resources; besides, very often, the measurement data required for such a model is incomplete or absent at all. The specular-diffuse model of reflection representing BRDF as a sum of the Lambertian (diffuse) and the perfect specular components is a reasonable trade-off, suitable for the Monte Carlo modeling of radiation characteristics of blackbody cavities. STEEP321 uses the Uniform Specular-Diffuse (USD) model of reflection.

2.4. Uniform Specular-Diffuse Model of Reflection

Uniform Specular-Diffuse (USD) model of reflection represents radiation reflected from a surface as a sum of two components – diffuse and specular – that do not depend on incidence angle, i.e., spectral directional-hemispherical reflectance $\rho(\lambda)$ can be a function only of a wavelength. For all wavelengths, proportion of diffuse $\rho_d(\lambda)$ and specular $\rho_s(\lambda)$ components is the constant value:

$$\rho(\lambda) = \rho_d(\lambda) + \rho_s(\lambda), \tag{12}$$

$$\rho_d(\lambda) = \rho(\lambda) D, \tag{13}$$

$$\rho_s(\lambda) = \rho(\lambda)(1 - D), \tag{14}$$

$$D = Const, \tag{15}$$

where D is the *diffusity* (not to be confused with the *diffusivity*!)

Diffusity D does not depend on wavelength or on incidence angle. It is assumed that Equations (12) – (15) hold true for total reflectances (integrated over the entire spectrum):

$$\rho = \rho_d + \rho_s, \tag{16}$$

$$\rho_d = \rho D, \tag{17}$$

$$\rho_s = \rho(1 - D), \tag{18}$$

According to Kirchhoff's law, for opaque materials, spectral and total emissivities can be expressed as

$$\varepsilon(\lambda) = 1 - \rho(\lambda), \tag{19}$$

$$\varepsilon = 1 - \rho. \tag{20}$$

3. Key Features of STEEP321

- Axially symmetrical cavities can be formed by rotation of polygonal line having up to 1001 vertices
- Calculation of effective emissivity and radiance temperatures for up to 2001 wavelengths and up to 8 temperature distributions simultaneously
- Up to 1001 temperature points in each temperature distribution
- Calculation of total (integrated over the whole spectrum) effective emissivities and radiation temperatures
- Five types of viewing conditions each having up to 5 variable parameters
- Sequential calculations for up to 201 viewing conditions of the same type
- Possibility to take into account the contribution of a non-zero background radiation
- Built-in expandable databases for:
    - Geometrical parameters and temperature distributions
    - Optical properties of materials and coatings (Uniform Specular-Diffuse Model of reflection)
    - Results of numerical modeling (effective emissivities and radiance temperatures)
- Possibility to save tabulated data in text files or as MS Excel spreadsheets
- Automatically generated reports in ASCII format
- Editable, exportable, and printable graphs representing:
    - Cavity section
    - Viewing conditions
    - Dependence of material's reflectance on wavelength
    - Temperature distributions along cavity generatrix
    - Dependences of effective emissivities on the wavelength
    - Dependences of effective emissivities on one variable parameter of viewing conditions

4. Structure of STEEP321

STEEP321 doesn't require installation. The zip-archive with the Evaluation Version can be downloaded free of charge from www.virial.com and STEEP321 folder can be placed at any convenient place of the hard drive. Please do not change the content and mutual arrangement of STEEP321 subfolders and files.

The schematic of the STEEP321 structure is shown in Fig. 2. The DATASETS database (file steep321.dbs in the DB folder) contains initial data on geometry, materials, and temperatures of a blackbody. Data on materials optical properties (total emissivity, diffusity, and spectral reflectances) are saved in the MATERIALS database (steep321usd.dbs file in the DB folder). Preprocessing Unit extracts all necessary initial data from these two databases, checks data self-consistency, and performs preliminary calculations. Then the Monte Carlo Ray Tracing Unit executes stochastic modeling and writes the results to the RESULTS database (steep321res.dbs file in the DB folder). Postprocessing Unit can extract results from the RESULTS database in order to plot graphs and prepare reports.

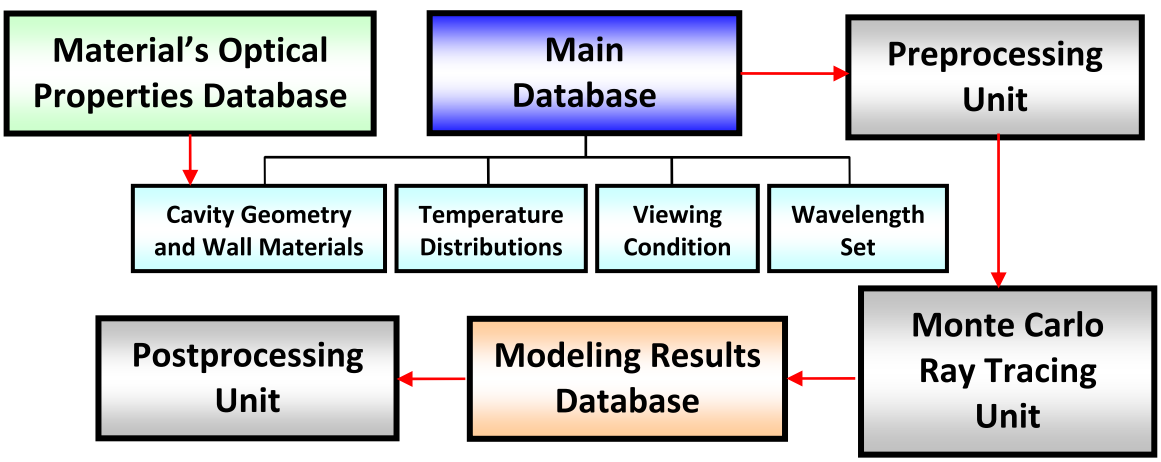


Fig. 2. Schematic of the STEEP321 structure

5. Units of Measurement

STEEP321 uses the International System of Units (SI). Below, you'll find the table with the units of physical quantities that STEEP321 uses.

Quantity	Unit	Comments
Linear dimensions	Arbitrary	All the cavity and viewing conditions linear dimensions must be expressed in the same units
Wavelength	Micrometer	1 µm = 10^{-6} m
Angular dimensions	Degree, °	$1^\circ = \pi/180 \approx$ 0.0174532925 rad
Temperature	Kelvin, K	Conversion formulas: [K] = [°C] + 273.15; [K] = ([°F] + 459.67) × $5/9$

6. Working with STEEP321

6.1. Working with STEEP321 Databases

The common mode of data representation of STEEP321 databases is a spreadsheet or a table. A table may be single, or have a link with other table(s). In the last case, the main table is referred as master table, and its depended tables are called detail tables. For instance, in MATERIALS database, each record of a master table contains fields for material name, date and time of a record creation, diffusity, and total emissivity while a detail table contains fields for wavelength and spectral reflection. Some editable fields can be associated with the stand-alone controls. Non-editable fields have yellow colored background. “Date and Time” field in Main Database is an example of such a field. It fills in automatically when a new record is created. All the fields except “Comments” in the RESULTS Database are non-editable.

To manipulate data in a spreadsheet, use keyboard commands or the special control - Database Navigator (see Fig. 3). To move between cells of the data grid that represents each table, use *Tab* and arrow keys, mouse or other pointer device.

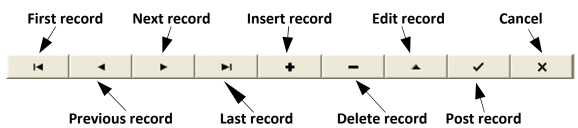


Fig. 3. Database Navigator.

To add a new record to a table, use one of the following methods:

- Click *Insert Record* in Navigator;
- Press *Insert* on the keyboard;
- Press *Down* key if you’d like to append a new record to the end of a table.

To delete a current record:

- Click Delete Record in Navigator or
- Press Delete on the keyboard.

When you delete a record in master table, all records in detail table(s) associated with deleted record in master table are automatically deleted.

To edit a record, click *Edit Record* in Database Navigator or directly enter the value in an input field. Typically, editable fields are edited by entering appropriate values, setting switches or choosing values from pop-up lists. Usually, changes made in an edited or newly added record are saved in database as soon as you exit from the data grid. However, to make sure that changed values are saved, you may click *Post Edit* in Database Navigator. Until changes are saved, one can restore original values in an edited record by pressing *Esc* on keyboard or by clicking *Cancel* in Database Navigator.

Some fields cannot be left empty. If you leave them blank, the STEEP321 may react by a message **Field "…" must have a value.** In this case, press "OK" button below the message then click "Cancel" or "Delete" of an appropriate Database Navigator.

"Comments" fields store arbitrary text information that can be useful for your dataset identification. Three master tables (DATASETS, MATERIALS, and RESULTS databases) allow performing incremental search in the first column by using the input field "*Find"*. Search is performed as long as symbols are entered.

Records in master tables of DATASETS, MATERIALS, and RESULTS databases may be arranged by several fields. To switch sorting mode, use the radio-buttons within the group "Sort by".

It is possible to show/hide some columns of a detail table grid in the RESULTS database using checkboxes within the group "Show Columns".

Three database files (*steep321.dbs, steep321usd.dbs, and steep321res.dbs*) are stored in the STEEP321\DB folder. You can move them to another place (for example, for archiving purposes). If STEEP321 cannot find some database file, a new empty one will be created. Since cavity data, including names of materials are saved in *steep321.dbs* while optical properties for these materials are saved in *steep321usd.dbs*, the user should watch the compatibility of these files. If some material assigned to a cavity wall is absent in MATERIALS database, the message **Material "…" not found** will appear before calculations.

All data contained in the table can be loaded from and saved in text (ASCII) file by clicking "Load" and "Save As..." items in drop-down menus of appropriate buttons marked by the ▼ sign.

6.2. Working with STEEP321 Graphs

Graphs for functions of a single variable are used in STEEP321 for several purposes:

- To show cavity shape, positions of points in which temperatures are defined, and for preliminary targeting which allows to check up viewing conditions
- To display cavity surface temperatures vs. coordinate along cavity generatrix
- To plot spectral reflectance of a material or coating vs. wavelength
- To display results of interpolation/extrapolation of cavity walls spectral reflectances for wavelengths set that is used for spectral effective emissivity calculations
- To plot computed spectral effective emissivities and radiance temperatures vs. wavelength
- To plot computed spectral effective emissivities and radiance temperatures against variable parameter of viewing conditions

STEEP321 allows plotting a magnified fragment of the graph: holding left mouse button depressed, drag the cursor right and downwards to zoom (see Fig. 4) and left and upwards to unzoom.

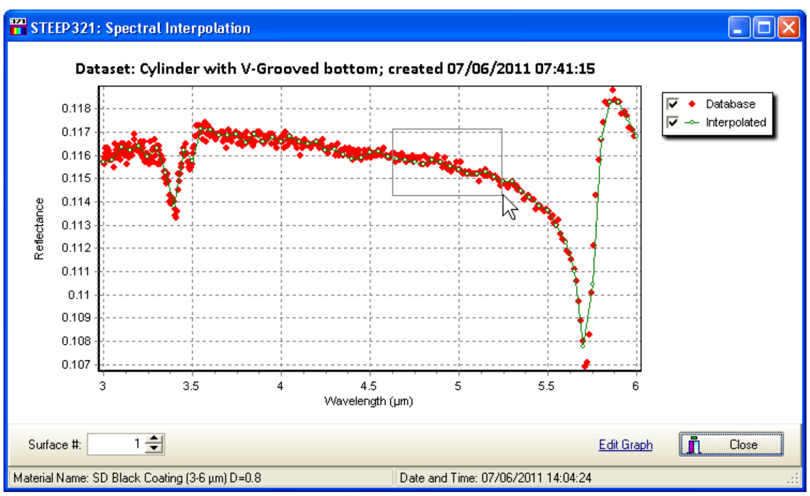
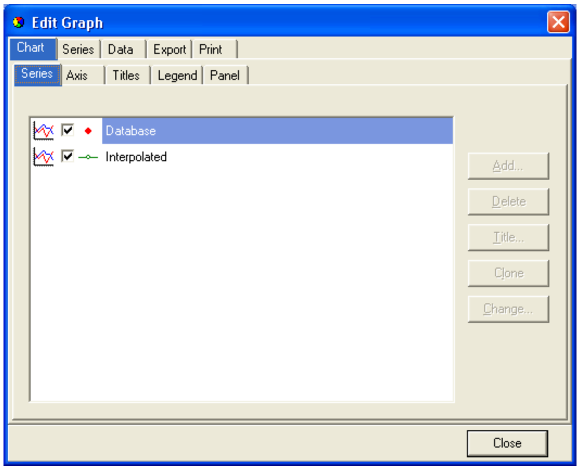


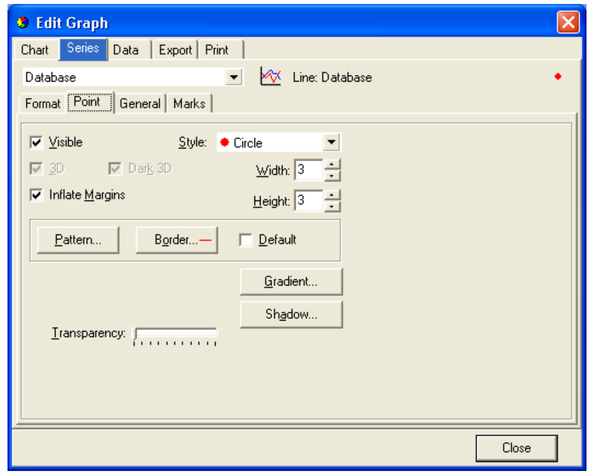
Fig. 4. Use of zoom

To displace curves relative to graph axes, hold the left mouse button depressed and move cursor. To restore graph original position, draw a rectangle of arbitrary size by moving from the bottom right corner to the top left one while left mouse button remains pressed.

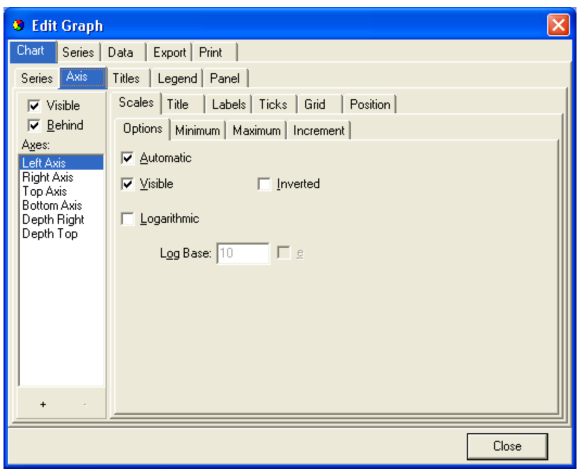
Clicking Edit Graph under the graph calls the Graph Editor that provides comprehensive access to the most of the editable properties of the graph and has intuitive interface.



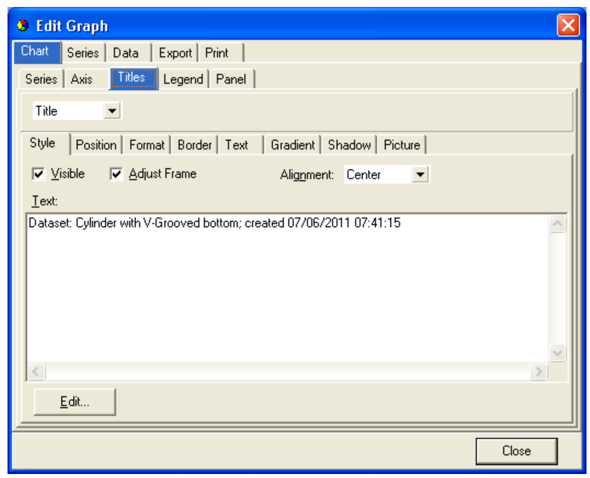
Access to individual series (curves)



Formatting series



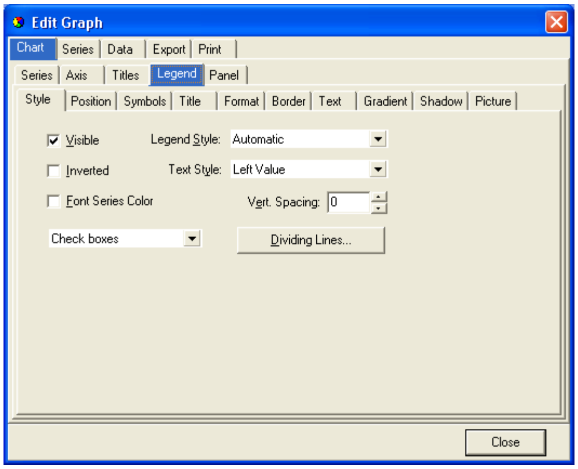
Editing the graph axes



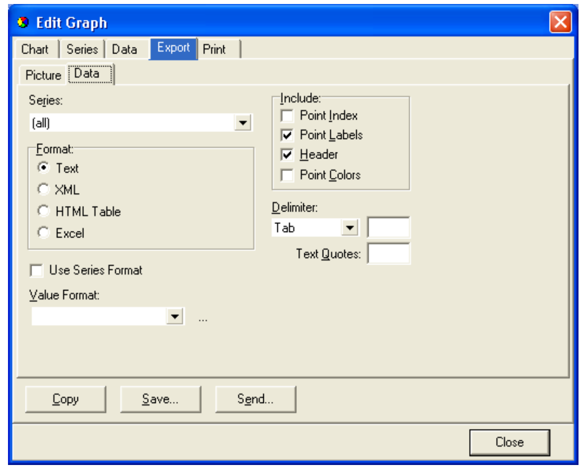
Editing the graph title

Fig. 5A. Screenshots that demonstrate the general possibilities of the Graph Editor

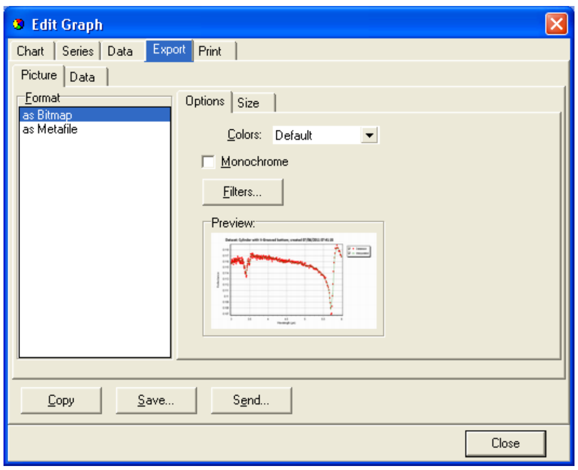
Graph Editor provides access to individual curves (series) and allows editing all elements of the graph (points, axes, legend, title, etc.) and adjusting their properties. The Graph Editor gives the possibility of copying to clipboard, saving in the file, and printing graphs, as well as exporting series values in formats of text (ASCII) file, MS Excel spreadsheet, HTML and XML tables (see screenshots in Figures 5A and 5B).



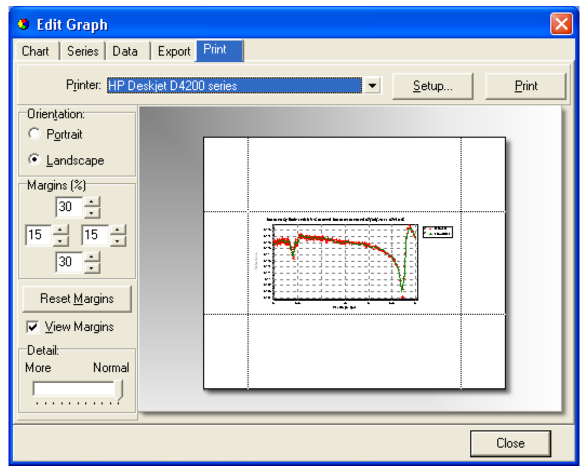
Formatting the graph legend



Data Export



Graph copying and saving



Graph printing

Fig. 5B. Screenshots that demonstrate the general possibilities of the Graph Editor

7. Getting Started

7.1. Activating STEEP321

After downloading Evaluation Version of STEEP321 from www.virial.com and unpacking zip-archive, open the folder STEEP321 and run steep321.exe. STEEP321 main form will appear (see Fig. 6). Working with Evaluation version will be described in the last section of this Manual.

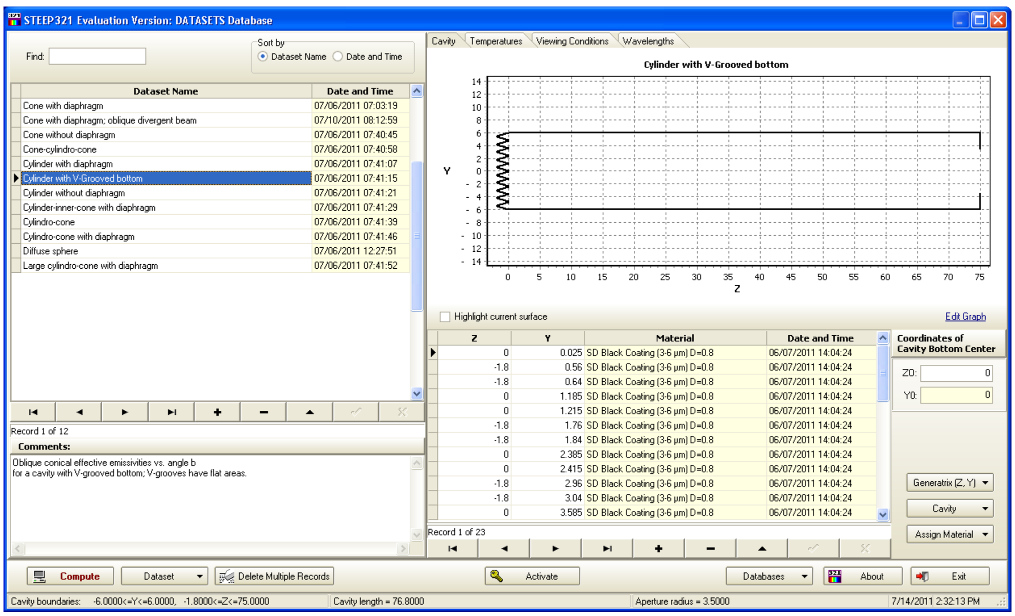


Fig. 6. STEEP321 Main window before activation

If you purchased user's license, you must activate STEEP321. For this, press 

, enter your Activation Code into Activation window (see Fig. 7), and press "OK" button.

Fig. 7. Activation window

The screenshot of activated STEEP321 main window is shown in Fig. 8.

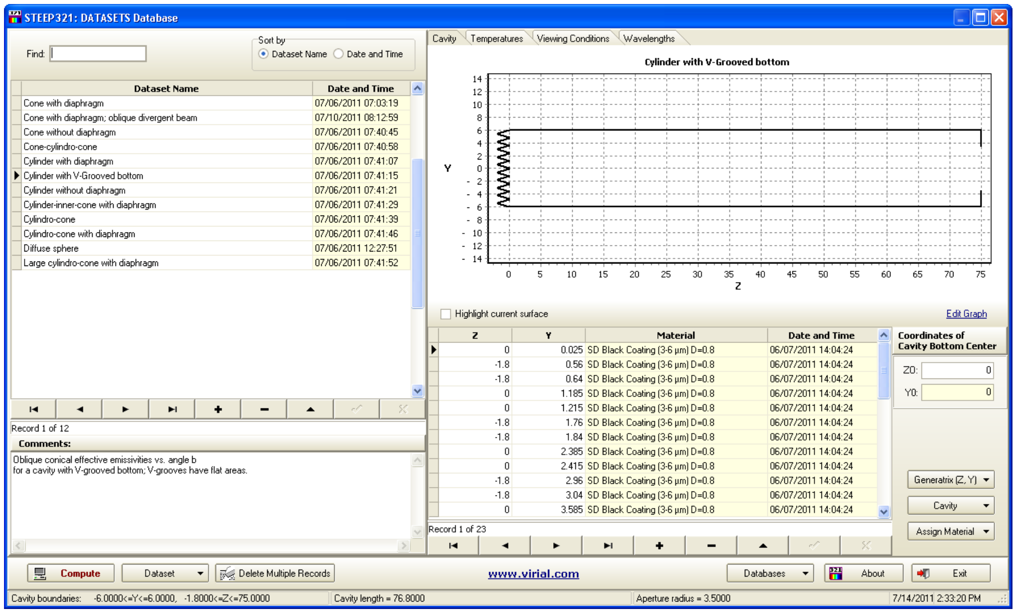


Fig. 8. STEEP321 main window after activation

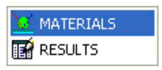
That's all. Now, you can start solving your tasks with STEEP321. We recommend to hold to the following line of actions:

1. Enter all materials used for cavity walls to the MATERIALS database.
2. Enter new dataset name (and optional comments) to the DATASETS database.
3. Enter coordinates of the cavity generatrix nodes.
4. Assign materials to each surface forming the cavity.
5. Specify the number of temperature distributions for which Monte Carlo modeling will be performed.
6. Enter reference and background temperatures for each temperature distribution.
7. Enter positions of temperature points on the cavity generatrix.
8. Assign temperatures for each temperature point of each temperature distribution.
9. Specify the type of viewing conditions for which Monte Carlo modeling will be performed.
10. Enter geometrical parameters of viewing conditions.
11. Perform targeting to check validity of viewing conditions.
12. Enter wavelengths for which Monte Carlo modeling will be performed.
13. Check quality of interpolation for the spectral reflectance of each material used in your dataset; change wavelength set if necessary.
14. Perform Monte Carlo calculations with moderate values of accuracy parameter (e.g., for 10,000 rays traced and flux threshold of 0.0001) to evaluate the necessary values of accuracy parameters.

15. Perform Monte Carlo calculations with the accuracy sufficient for your goals.
16. Browse results of calculations and plot dependences of effective emissivity and radiance temperature on wavelength and, if necessary, variable viewing conditions parameter.
17. Create and, if necessary, save report for the task completed.

7.2. Defining Materials

We recommend first entering data for materials of a blackbody you're going to model. Click [Databases ▾] and select MATERIALS from the drop-down menu:



The MATERIALS database window will be opened (see Fig. 9).

Note that the button [Select] is disabled when you open MATERIALS database window by such a way. This button becomes enabled when you open MATERIALS database window in order to assign a material to one or several surfaces forming the cavity.

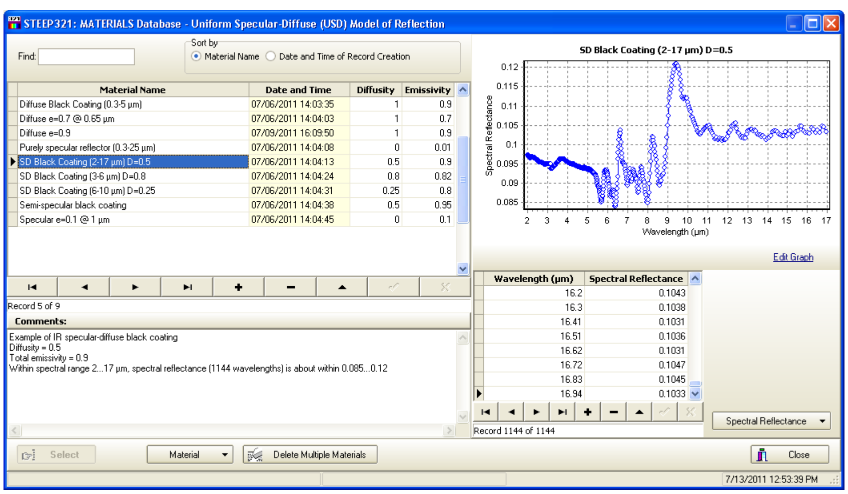


Fig. 9. MATERIALS database window

The left-hand part of this window contains table of Materials consisting of the following fields:

- *Material Name* – a string field of 1 to 100 symbols length; cannot be left empty.
- *Date and Time* – an automatically filled field specifying the date and time of the record creation.
- *Diffusity* – a numerical field for the diffusity $0 \le D \le 1$; cannot be left empty.
- *Emissivity* – a numerical field for the total emissivity $0 \le \varepsilon \le 1$; cannot be left empty.

An additional field *Comments* below the table can contain arbitrary text information serving for better identification of material or user's remarks.

To create a new record, press "Add" (+) button of Database Navigator of <Insert> key of the keyboard. Enter *Material Name*, *Emissivity* (total), and *Diffusity*. If you have no data for total emissivity of your material, enter any reasonable value from 0 to 1. When calculations will be performed, you can ignore computed values of total effective emissivities and radiation temperatures.

Now you can enter spectral reflectance values into the table in the right-hand part of the form. One can do this manually, but if you have a large amount of data, the best way is to load data from a text file previously prepared using some text editor (for example, MS Notepad) or using MS Excel (data must be saved as "Text - Tab Delimited"). The samples of appropriate text files can be found in the folder ***STEEP321/Data/Spectral Reflectance***. Like all tabular data in STEEP3, spectral reflectance data can be also saved in a text file. For both operations, click 

and use the drop-down menu:

To delete several values of the spectral reflectance click Delete Multiple Records item. The window shown in Fig. 10 will appear.

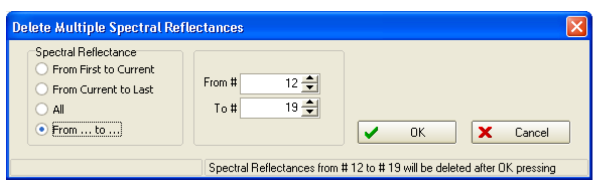


Fig. 10. "Delete Multiple Spectral Reflectances" window

If you'd like to delete spectral reflectance data within or outside certain spectral range, click Clear Spectral Range item; the window shown in Fig. 11 will be opened.

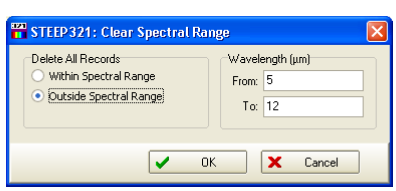
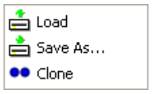


Fig. 11. "Clear Spectral Range" window

The button  with its drop-down menu



allows to load, save and clone (i.e., make a copy under new name) entire record. An example of a text file contained all information on the current material is provided below:

```
// Material Name:
SD Black Coating (3-6 µm) D=0.8
 // Record creation date and time:
07/06/2011 14:04:24
 8.20000000000000E-0001 // Total emissivity;
 8.00000000000000E-0001 // Diffusity;
432 // Number of wavelengths;
 // SPECTRAL HEMISPHERICAL REFLECTANCE:
   3.0003 0.1157
   3.0038 0.1159
   3.0073 0.1156
……………………………………………………
   5.9320 0.1179
   5.9456 0.1177
   5.9592 0.1172
   5.9730 0.1171
   5.9868 0.1168
 // COMMENTS:
Example of IR specular-diffuse black coating
Diffusity = 0.8
Total emissivity = 0.82
Within spectral range 3...6 µm, spectral reflectance (432 wavelengths) is about within 0.11...0.12
```

You can find examples of such files in ***STEEP321\Data\Materials*** folder.

To delete multiple materials click  . The window shown in Fig. 12 will appear.

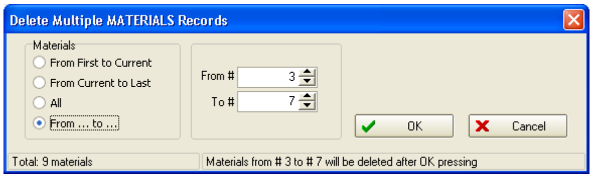


Fig. 12. Window for deleting multiple materials

When you finished entering all materials into database, you may close the Material's Database form and return to main form of STEEP321 (Fig. 8). Now you can enter cavity data.

7.3. Defining Cavity Shape

First, you have to specify geometrical dimensions of a cavity. Cavity shape is defined by coordinates of generatrix nodes as it is shown in Fig. 13. Here, red numbered points represent the generatrix nodes, and linear segments between neighbor points represent generatrix of surfaces of revolution numbered with blue figures.

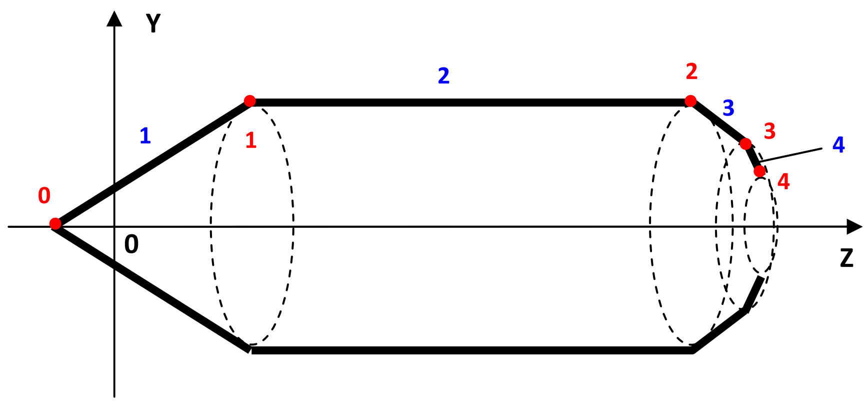


Fig. 13. Defining the cavity shape by the generatrix nodes

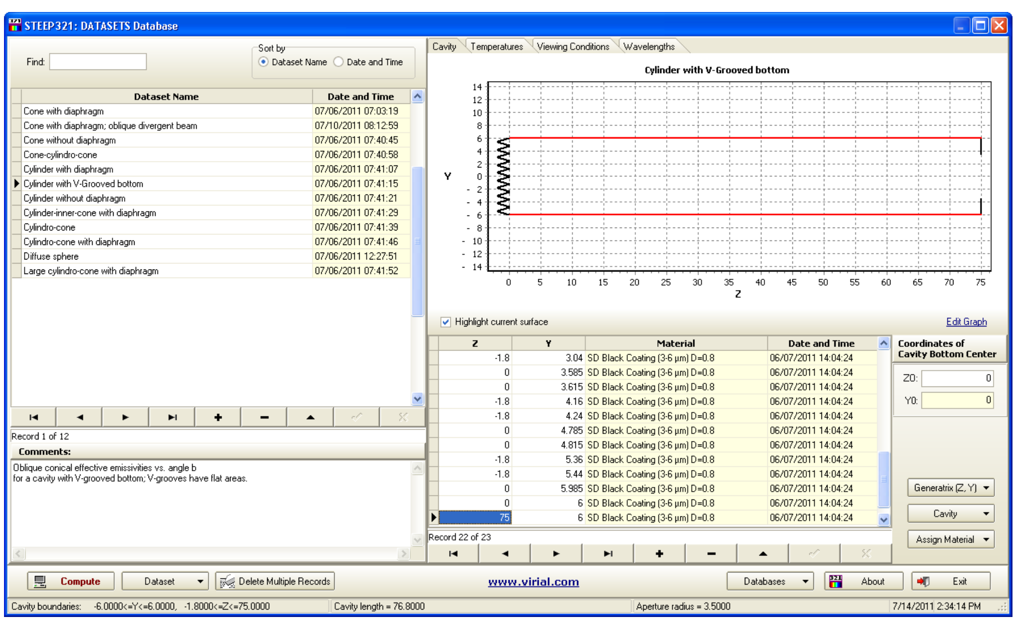
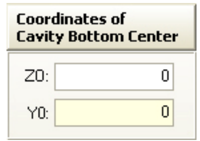


Fig. 14. Tabbed page "Cavity"; the current (cylindrical) surface is highlighted

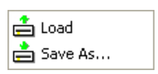
The 0th node (the center of the cavity bottom) may have any value of Z-coordinate, but Y-coordinate must be equal to zero. The 0th node Z-coordinate has separate input field in the tabbed page “Cavity” of the main STEEP321 window (see Fig. 14):



Z- and Y-coordinates of all other nodes have to be entered into appropriate columns of a table in the tabbed page “Cavity”. All nodes are numbered and linked in the order of their position in this table; thus *n*th and *(n-1)*th generatrix nodes form the *n*th surface. A circle formed by rotation of the last node around Z-axis is considered as cavity aperture.

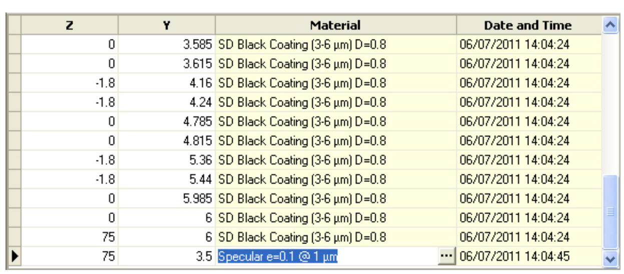
Coordinates of a cavity generatrix nodes can be entered into two first columns manually, point-by-point. In order to insert a node after the current record, use the <Insert> key or the button “+” of Database Navigator. Use <↓> keys to append a node to the end of the table. As soon as Z- and Y-coordinates of a node are posted to the database, the scaled section of the cavity above the table will be re-drawn. Check the checkbox ☐ Highlight current surface to highlight in red the current (selected in the table) surface as it is shown in Fig. 14.

You can also save in and load from text file entire generatrix by clicking [Generatrix (Z, Y) ▾] and choose Load or Save As... in the drop-down menu:



Examples of such files can be found in the folder ***STEEP3\Data\Generatrices***.

To assign material to one surface double-click on the appropriate row of the table. You may also use two separate clicks. In this case, the small button with ellipsis (...) will appear (see Fig. 15) and you’ll have to click it again.

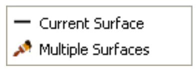


Z	Y	Material	Date and Time
0	3.585	SD Black Coating (3-6 µm) D=0.8	06/07/2011 14:04:24
0	3.615	SD Black Coating (3-6 µm) D=0.8	06/07/2011 14:04:24
-1.8	4.16	SD Black Coating (3-6 µm) D=0.8	06/07/2011 14:04:24
-1.8	4.24	SD Black Coating (3-6 µm) D=0.8	06/07/2011 14:04:24
0	4.785	SD Black Coating (3-6 µm) D=0.8	06/07/2011 14:04:24
0	4.815	SD Black Coating (3-6 µm) D=0.8	06/07/2011 14:04:24
-1.8	5.36	SD Black Coating (3-6 µm) D=0.8	06/07/2011 14:04:24
-1.8	5.44	SD Black Coating (3-6 µm) D=0.8	06/07/2011 14:04:24
0	5.985	SD Black Coating (3-6 µm) D=0.8	06/07/2011 14:04:24
0	6	SD Black Coating (3-6 µm) D=0.8	06/07/2011 14:04:24
75	6	SD Black Coating (3-6 µm) D=0.8	06/07/2011 14:04:24
75	3.5	Specular e=0.1 @ 1 µm ...	06/07/2011 14:04:45

Fig. 15. The “Cavity” table

The MATERIALS database window will be opened (Fig. 9). Choose the material then click Select. The material chosen will be entered into the current row of the "Cavity" table together with the date and time of material's record creation (Fig. 15). A material specified in certain row is assigned to the segment of the generatrix starting at the point defined by previous row and ending at the point defined by current row. One can assign materials to the surfaces in arbitrary order.

It is possible to assign material to one or multiple surfaces by clicking Assign Material and using associated drop-down menu:



If you chosen Multiple Surfaces item in the drop-down menu, the window shown in the left part of Fig. 16 will appear. Clicking Select leads to MATERIALS database. Choose material and click Select. You'll obtain a window like that shown in the right part of Fig. 16. Clicking Assign completes the assignment of material.

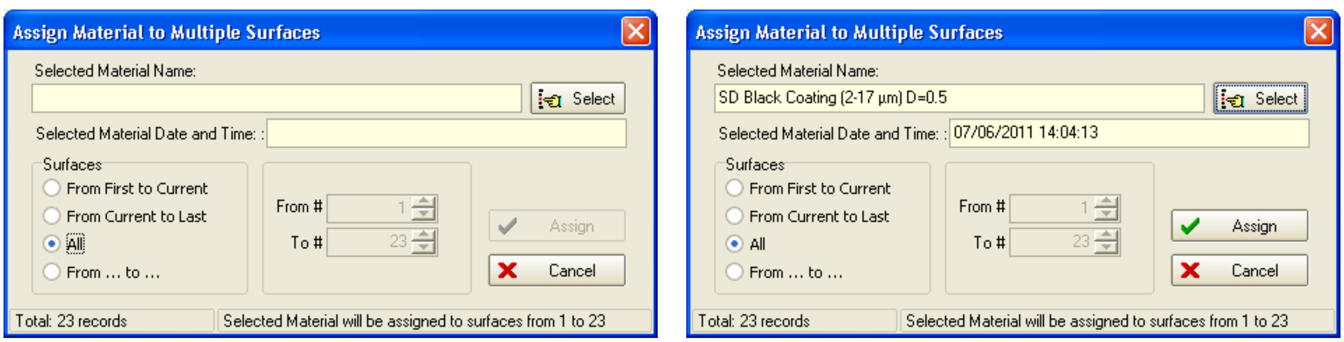
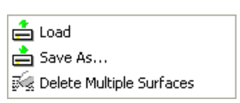


Fig. 16. Assigning material to multiple surfaces

The button Cavity with the associated drop-down menu



allows to load from and save in text file entire contents of the "Cavity" table. The fragment of such a text file is shown below. The third column represents the date and time of material's record creation in internal format (analogous with the Julian Date but having another starting point).

```
 0.00000000000000E+0000  0.00000000000000E+0000
 0.00000000000000E+0000  2.50000000000000E-0002  4.07305863921412E+0004 SD Black Coating (3-6 µm) D=0.8
-1.80000000000000E+0000  5.60000000000000E-0001  4.07305863921412E+0004 SD Black Coating (3-6 µm) D=0.8
.........................................................................................................
 0.00000000000000E+0000  6.00000000000000E+0000  4.07305863921412E+0004 SD Black Coating (3-6 µm) D=0.8
 7.50000000000000E+0001  6.00000000000000E+0000  4.07305863921412E+0004 SD Black Coating (3-6 µm) D=0.8
 7.50000000000000E+0001  3.50000000000000E+0000  4.07305866321181E+0004 Specular e=0.1 @ 1 µm
```

Other examples can be found in the folder ***STEEP321\Data\Cavities***. Clicking Delete Multiple Surfaces menu item calls the window shown in Fig. 17 and allows erasing several surfaces (generatrix nodes + materials assigned to appropriate surfaces) at once.

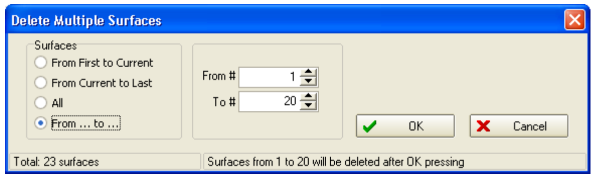


Fig. 17. Deleting multiple surfaces

7.4. Entering Temperature Distributions

STEEP321 allows computing effective emissivities for 0 to 8 temperature distributions at one run. This facilitates investigating dependence of effective emissivities upon uniformity of cavity's temperature. The Number of Temperature Distributions can be defined by the group of radio buttons at the left top edge of the tabbed page "Temperatures" on STEEP321 main form (see Fig. 18). Zero Number of Temperature Distributions corresponds to the case of an isothermal cavity. Note that this case will be processed also for any Number of Temperature Distributions.

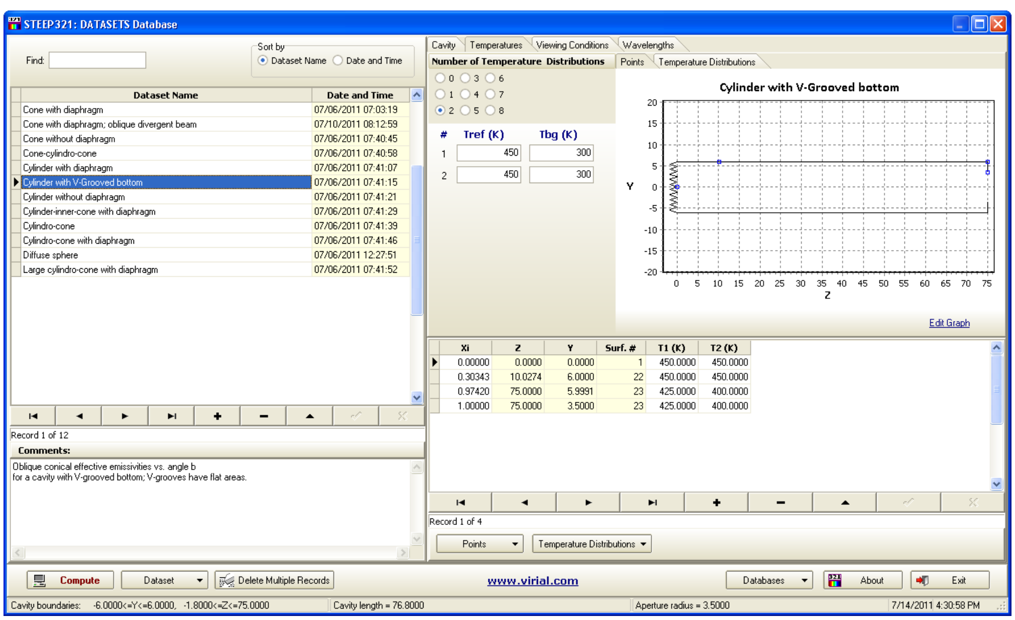
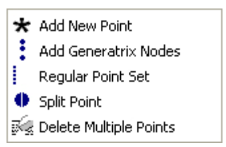


Fig. 18. Tabbed Page "Temperatures"

For non-zero Number of Temperature Distributions, you have to enter reference and background temperatures (T_{ref} and T_{bg}) for each temperature distribution.

Next step is the input of points on the cavity generatrix in which temperatures will be defined. This set of points is the same for all temperature distributions. In order to provide self-consistent representation of temperature distributions for cavities of various shapes, uniform coordinate ξ (Xi) is used. It passes from cavity bottom center, where $\xi = 0$, along the generatrix, to the aperture edge, where $\xi = 1$. STEEP321 offers several tools to simplify entering points where you have to specify temperatures by using:
You may enter temperature points manually or using several tools available in the drop-down menu of the button Points:



When you need to insert a temperature point on the cavity generatrix, you may use slide bar on the form (see Fig. 19) that will be opened after clicking Add New Point menu item, or enter the numerical value of Xi manually. This value is synchronized with the movement of red marker in the cavity drawing. After choosing suitable place of temperature point, press Append. New point will be entered into table and will appear as a small blue square on the drawing.

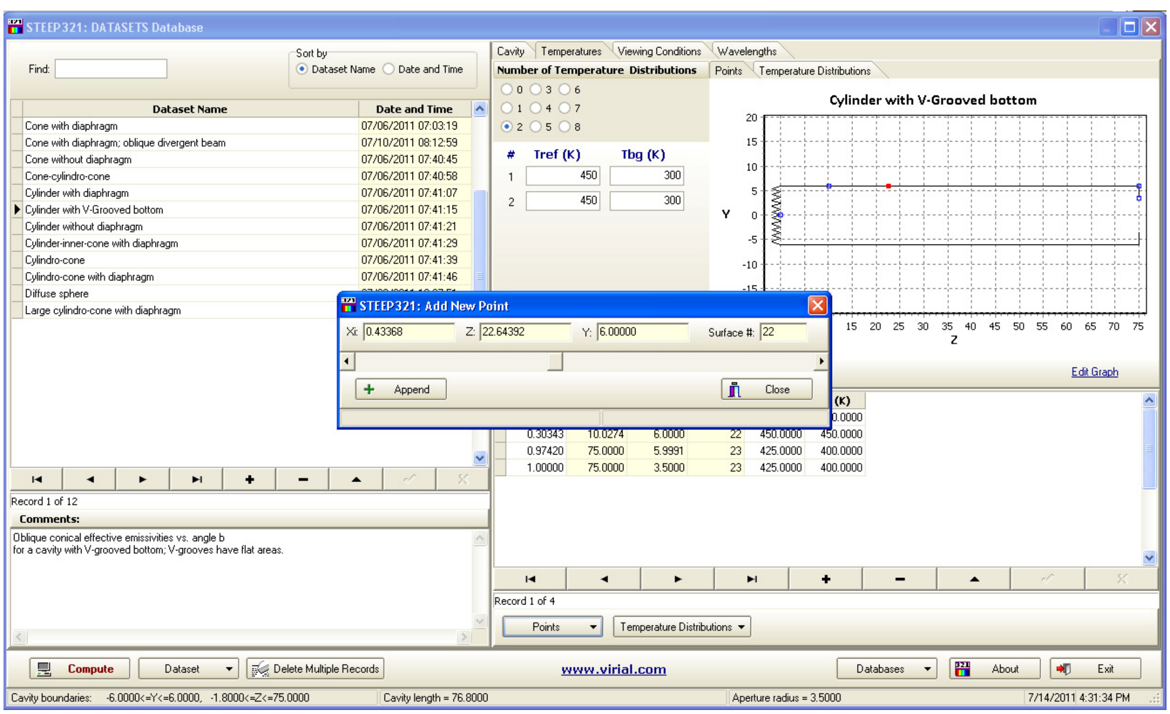


Fig. 19. Interactive input of a new temperature point

Add Generatrix Nodes menu item allows to employ all generatrix nodes as points where temperatures will be defined (see Fig. 20).

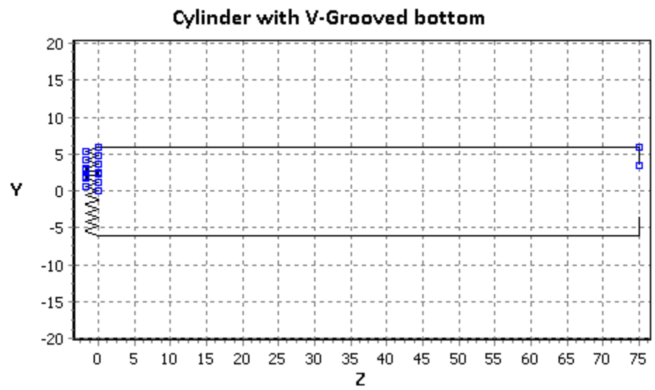


Fig. 20. Use of generatrix nodes as temperature points

Regular Point Set item allows to create temperature point set uniformly distributed along entire generatrix or its part (see Fig. 21). An example of regular point set is shown in Fig. 22.

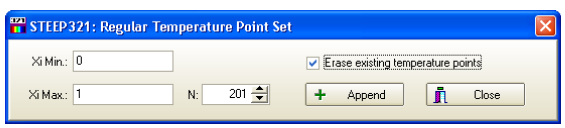


Fig. 21. Creating regular temperature point set

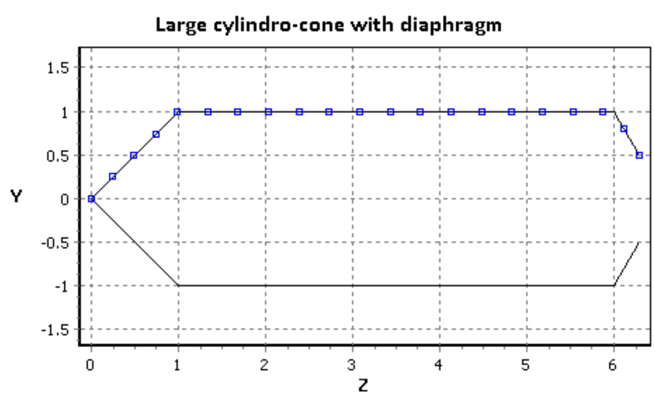


Fig. 22. Example of regular temperature point set

Sometimes, it is necessary to model the contact of two surfaces having different temperatures at their junction. The natural way to do this is to place two temperature points on both surfaces as close one to another as possible. For the current record, this can be doing by clicking Split Point menu item. Fig. 23 shows zoomed drawings of the edge of cylindrical cavity bottom before and after splitting.

In all cases, coordinates Y and Z, as well as surface number are calculated automatically.

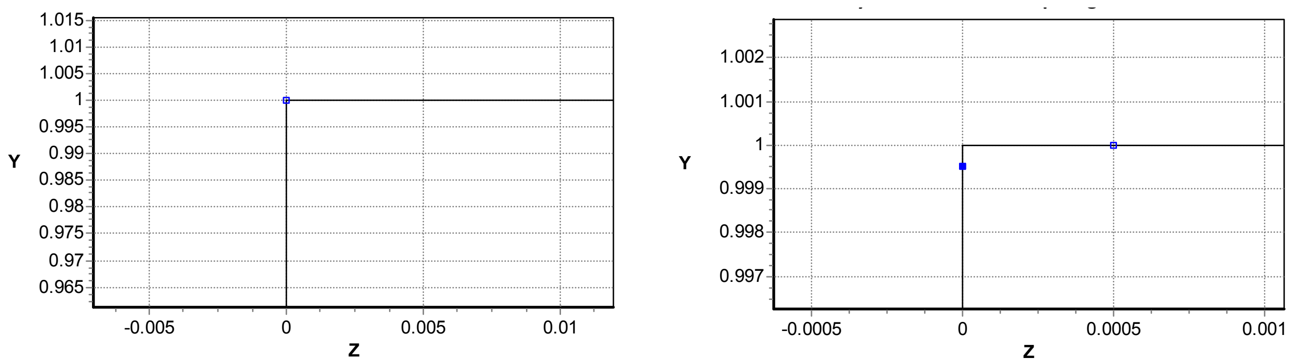


Fig. 23. Temperature point at the edge of two surfaces before and after splitting

Delete Multiple Points menu item calls the window shown in Fig. 24 and allows deleting several temperature points at once.

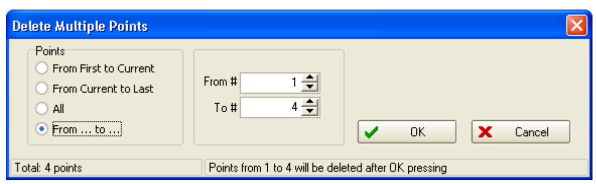
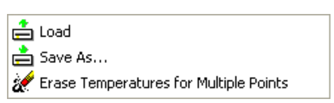


Fig. 24. Deleting multiple temperature points

It is possible to load from and save in text file all temperature distributions as well as erase temperatures for more multiple points by clicking 

and choosing action from the drop-down menu:



Example of a text file for temperature distributions is presented below:

```
0.00000000000000E+0000  4.50000000000000E+0002  4.50000000000000E+0002
3.03430000000000E-0001  4.50000000000000E+0002  4.50000000000000E+0002
9.74200000000000E-0001  4.25000000000000E+0002  4.00000000000000E+0002
1.00000000000000E+0000  4.25000000000000E+0002  4.00000000000000E+0002
```

Here the first column represents Xi values, two other columns correspond to two temperature distributions. Other examples can be found in the folder ***STEEP321\Data\Temperature Distributions***.

Please note that the usage of temperature distributions composed from one cavity can be applied to another one, but may provoke displacement of temperature points.

To erase only temperatures for several temperature points click Erase Temperatures for Multiple Points menu item. The window shown in Fig. 25 will be opened.

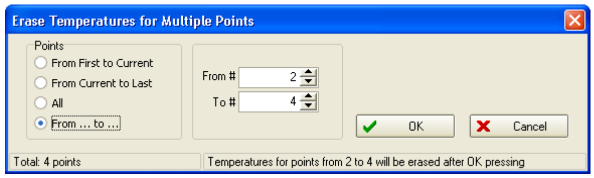


Fig. 25. Erasing temperatures for multiple points

The dependence $T(\xi)$ is re-plotted in the graph on the tabbed sub-page "Temperature Distributions" as soon as temperature of a temperature point is posted (Fig. 26).

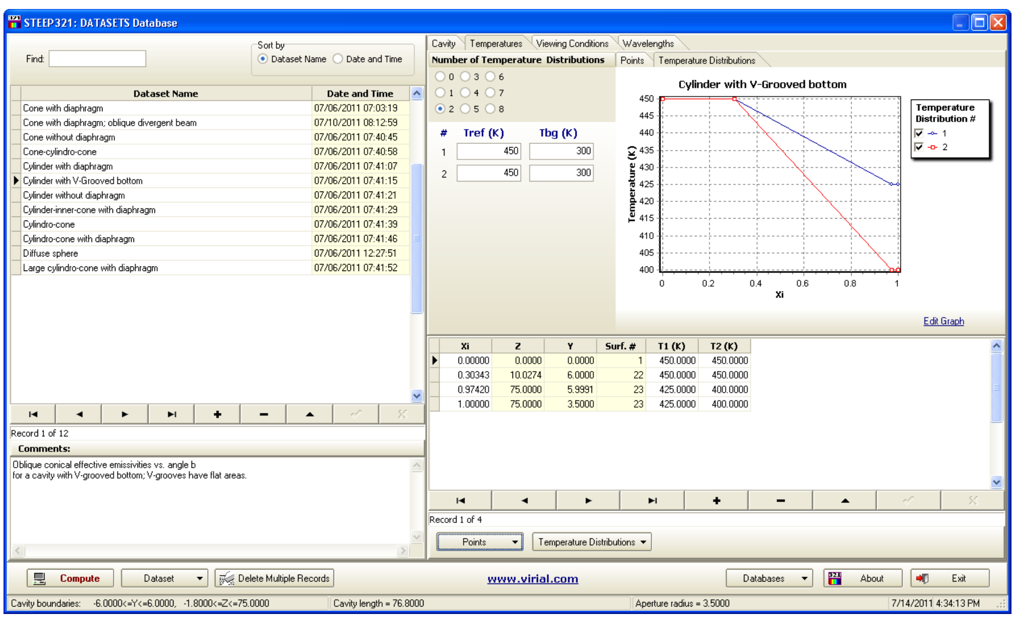


Fig. 26. Tabbed sub-page "Temperature Distributions"

7.5. Entering Viewing Conditions

STEEP321 provides 5 types of viewing conditions, but only one certain type can be used in one run of a modeling code. However, one can use up to 201 combinations of geometrical parameters that define the given type of viewing conditions (see Fig. 27).

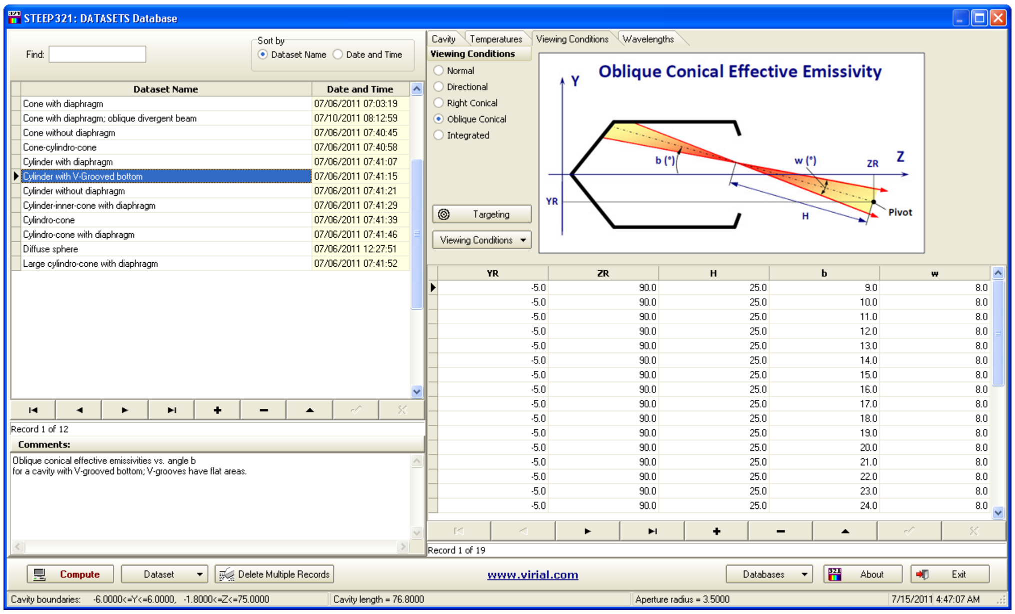
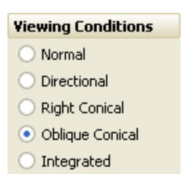


Fig. 27 Tabbed page “Viewing Conditions”

Type of Viewing Conditions (Normal, Directional, Right Conical, Oblique Conical, and Integrated) can be chosen by clicking radio-buttons of the group in the upper left part of the tabbed page “Viewing Conditions”:



Simultaneously with the switching between radio-buttons, the table at the bottom of tabbed page changes columns corresponding to geometrical parameters of selected Viewing Condition type. These parameters are shown in the pictures (see Fig. 28) displayed in the top right part of the tabbed page.

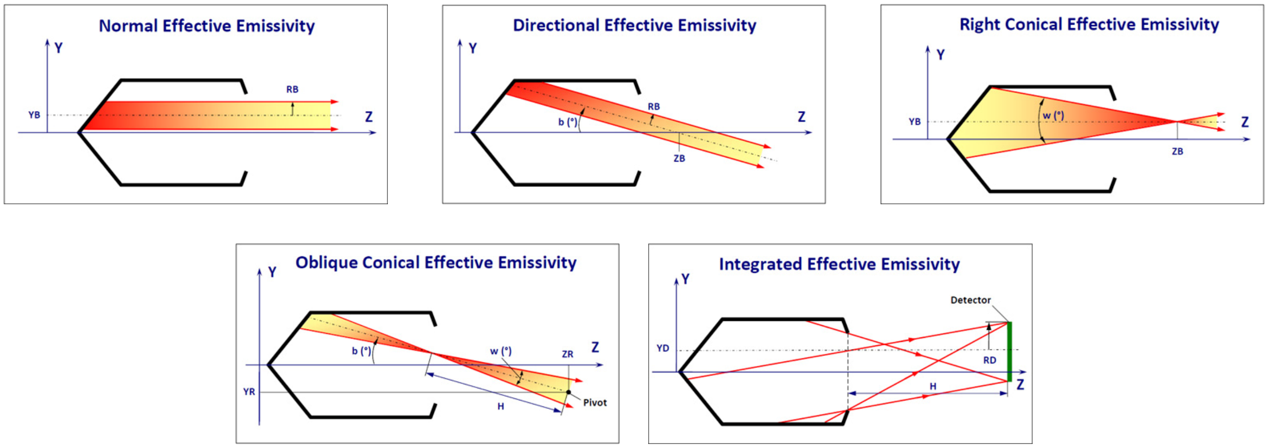


Fig. 28. Five types of Viewing Conditions used in STEEP321

For the Normal Effective Emissivity, rays inside a collimated beam of circular section with the radius RB achieve the detector. The beam axis is parallel to the cavity axis and YB is the distance between them. This case is defined by two parameters, RB and YB and can be applied to modeling, for example, of a blackbody with external aperture and distant detector, or to a case of long focal-length optics. If RB = 0, dependence of the effective emissivity on YB allows to estimate radiance nonuniformity across the cavity aperture.

The Directional Effective Emissivity is similar with the Normal Effective Emissivity but the beam axis forms the angle b (°) with cavity axis and crosses it at a point with the coordinate ZB.

The Right Conical Effective Emissivity is the case of observing a cavity by radiometer or radiation thermometer with the optical system whose optical axis is parallel to the cavity axis. YB and ZB are the coordinate of cone vertex (focal point of optical system); w measured in degrees is the cone vertex angle (angular FOV – field-of-view). Situation shown in Fig. 28 is for the convergent radiation beam; the divergent beam can be modeled if the focal point is placed behind the cavity.

The Oblique Conical Effective Emissivity reproduces the case of oblique observation with an optical system and can be applied to the modeling of the angular scanning with the pivot at the point having coordinates ZR and YR. H > 0 is the distance from the pivot to the focal point of the radiation beam. Divergent beam can be modeled if the focal point is outside the cavity.

The Integrated Effective Emissivity corresponds to the case of registration of the cavity radiation by a circular detector placed on the plane perpendicular to cavity axis at the finite distance to the cavity aperture. If the detector radius RD is equal to the radius of a cavity aperture, YD = 0 and H = 0, the hemispherical effective emissivity will be modeled.

Viewing Conditions parameters might be entered manually into the table at the bottom of the tabbed page, or you can use Viewing Conditions button with its drop-down menu:

The common format of text files with the Viewing Conditions is shown in the fragment of file below. The first row contains the index of the Viewing Conditions type (0 is for Normal, 1 is for Directional, 2 is for Right Conical, 3 is for Oblique Conical, and 4 is for Integrated). Text after the double slash (//) is the comment serving for convenience at the data identification and is inserted automatically at the file saving. Throughout this Manual, the double slash and succeeding text at the end of row of text file samples are considered as comments. Three columns below the first row correspond to three geometrical parameters of the Right Conical Viewing Conditions: YB, ZB, and w (°), respectively. The order of parameters in columns is the same as their order in the table.

```
2 //Right Conical Effective Emissivity
0 0.995 0
0 0.995 5
0 0.995 10
0 0.995 15
0 0.995 20
0 0.995 25
0 0.995 30
0 0.995 35
0 0.995 40
0 0.995 45
................................
0 0.995 155
0 0.995 160
0 0.995 165
0 0.995 170
0 0.995 175
0 0.995 180
```

Regular viewing conditions correspond to a case when one of the geometrical parameters defining viewing conditions, changes incrementally, i.e., with constant step. After clicking Regular item of the drop-down menu, the window shown in Fig. 29 will appear.

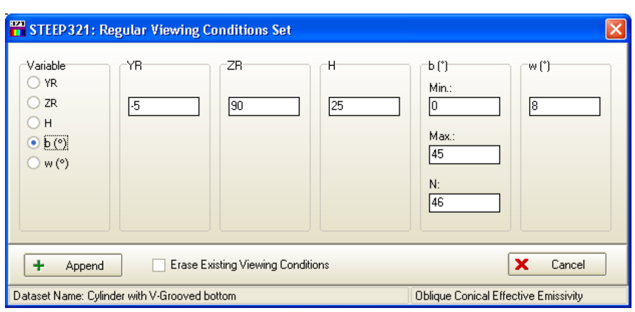


Fig. 29. Defining Regular Viewing Conditions set

You can choose a parameter that will change incrementally using the group “Variable” of radio buttons, and then enter the value for unchangeable parameters. Finally you have to enter minimal and maximal values for the variable parameter, as well as the number *N* of its values, then click Append. Check the checkbox Erase Existing Viewing Conditions if you’d like to delete all Viewing Conditions parameters previously entered into the table. Otherwise, new parameters will be added to the end of the table.

To erase some Viewing Conditions written in the table, click Delete Multiple Viewing Conditions menu item and use controls of the window shown in Fig. 30.

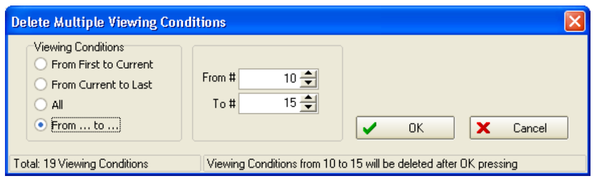


Fig. 30. Deleting multiple Viewing Conditions

Manual entering is an alternative for regular viewing conditions and allows changing more than one geometrical parameter in the table. However, because the resulting graphs show dependence only upon one variable, they become in most cases useless.

7.6. Targeting

Pressing 

in tabbed page “Viewing Conditions” (Fig. 27) calls the window shown in Fig. 31that allows performing initial (until first reflection) ray tracing in order to check the correctness of viewing conditions parameters. The results of preliminary ray tracing are presented in two orthogonal planes YZ and XZ (it is supposed that the coordinate system XYZ has the right-handed orientation, i.e., in the top graph in Fig. 31, X-axis is directed behind the plane of the graph).

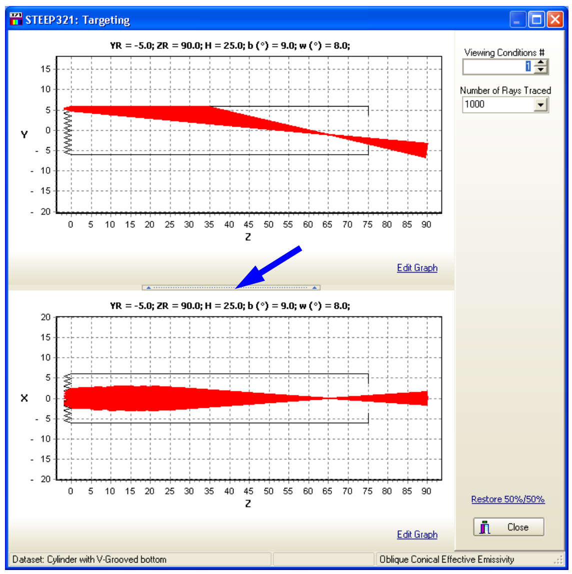


Fig. 31. Targeting (initial ray tracing).
Blue arrow shows the movable border between upper and lower graphs.

As soon as “Targeting” form is open, ray tracing for the first set of parameters starts and plots. By default, number of rays traced is 1000. You can set this value in 100, 1,000, or 10,000. Ray tracing and plotting will start automatically. You can also change viewing conditions number (number of a set for viewing conditions parameters) using “Up” and “Down” arrows on the right hand of the “Viewing Conditions #” input field, and ray tracing results will be redrawn automatically. If a traced ray will be directed out of a cavity aperture, the tracing will be stopped, and message “OUT OF APERTURE” will appear in the graph caption.

The blue arrow in Fig. 31 indicates the movable bar changing relative dimensions of upper and lower graphs. Initial proportions can be recovered by clicking Restore 50%/50%.

7.7. Entering Wavelengths

Since spectral reflectance of different materials assigned to different surfaces forming a cavity may be defined over different sets of wavelengths, STEEP321 employs interpolation and extrapolation of all spectral data for prescribed wavelengths (i.e., wavelengths for which spectral effective emissivities and radiance temperatures will be computed). These wavelengths have to be entered in the table on the tabbed page “Wavelengths” (Fig. 32).

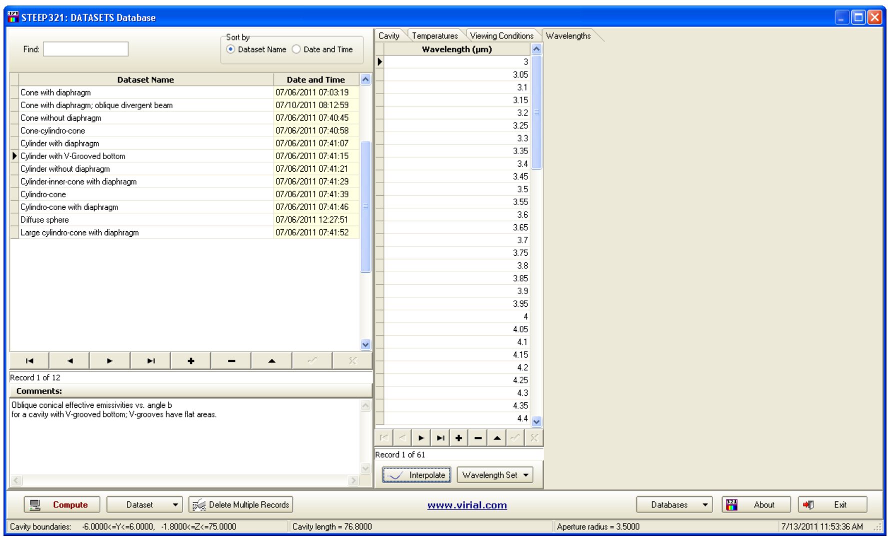
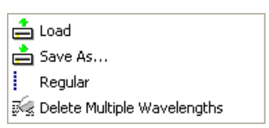


Fig. 32. Tabbed Page “Wavelengths”

Wavelength can be entered manually, value-by-value, or you can use 

with its drop-down menu



to load them from a text file (see examples of such files in ***STEEP321\Data\Wavelengths*** folder) or to define a regular wavelength set by clicking Regular menu item to define equidistant wavelength set. In the last case, the window shown in Fig. 33 will be opened. To erase multiple wavelengths click Delete Multiple Wavelengths menu item. The window shown in Fig. 34 will appear.

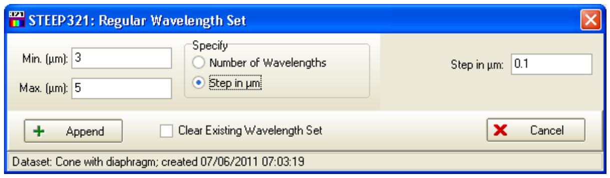


Fig. 33. “Regular Wavelength Set” window

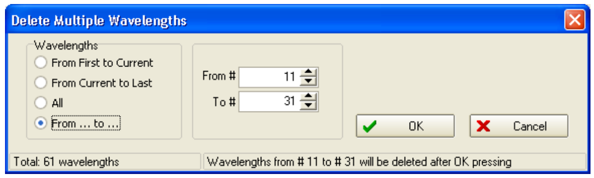


Fig. 34. Deleting multiple wavelengths

7.8. Spectral Interpolation

Finally, the button  can be used for visual evaluation of interpolation/extrapolation quality. Fig. 29 illustrates linear interpolation and extrapolation rules used in STEEP321.

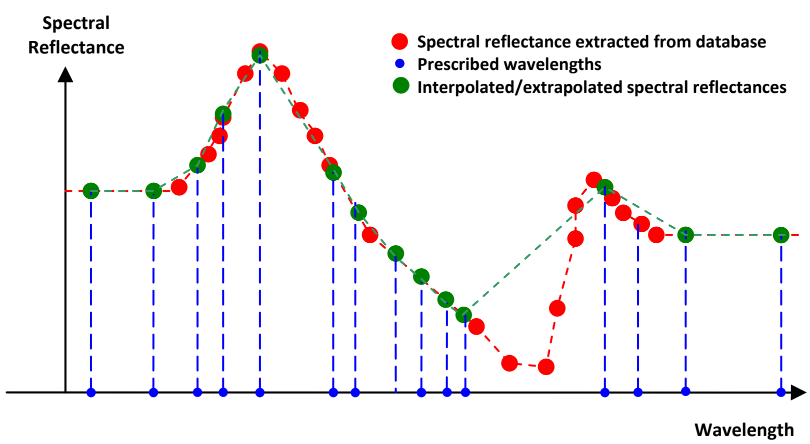


Fig. 35. Linear interpolation and extrapolation for spectral reflectances

After clicking , both spectral reflectances extracted from MATERIALS database and interpolated/extrapolated values will be plotted in the graph for each cavity surface (see Fig. 36). Surface number can be changed by pressing “Up” and “Down” arrows on the right-hand side of the input field “Surface #’.

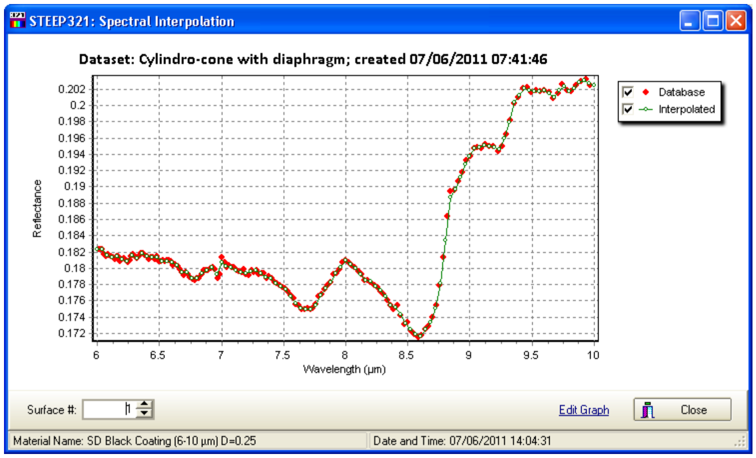


Fig. 36. "Spectral Interpolation" window

It is strongly recommended to check the quality of spectral interpolation/extrapolation before Monte Carlo modeling. The left top graph in Fig. 37 shows examples of the insufficient spectral interpolation (25 wavelengths); the right top graph demonstrates the better spectral interpolation (200 wavelengths). Besides, you can ensure that spectral ranges are matched; lower graph in Fig. 37 shows the case of unmatched spectral ranges. The extrapolation applied may lead to unsatisfactory results of calculations.

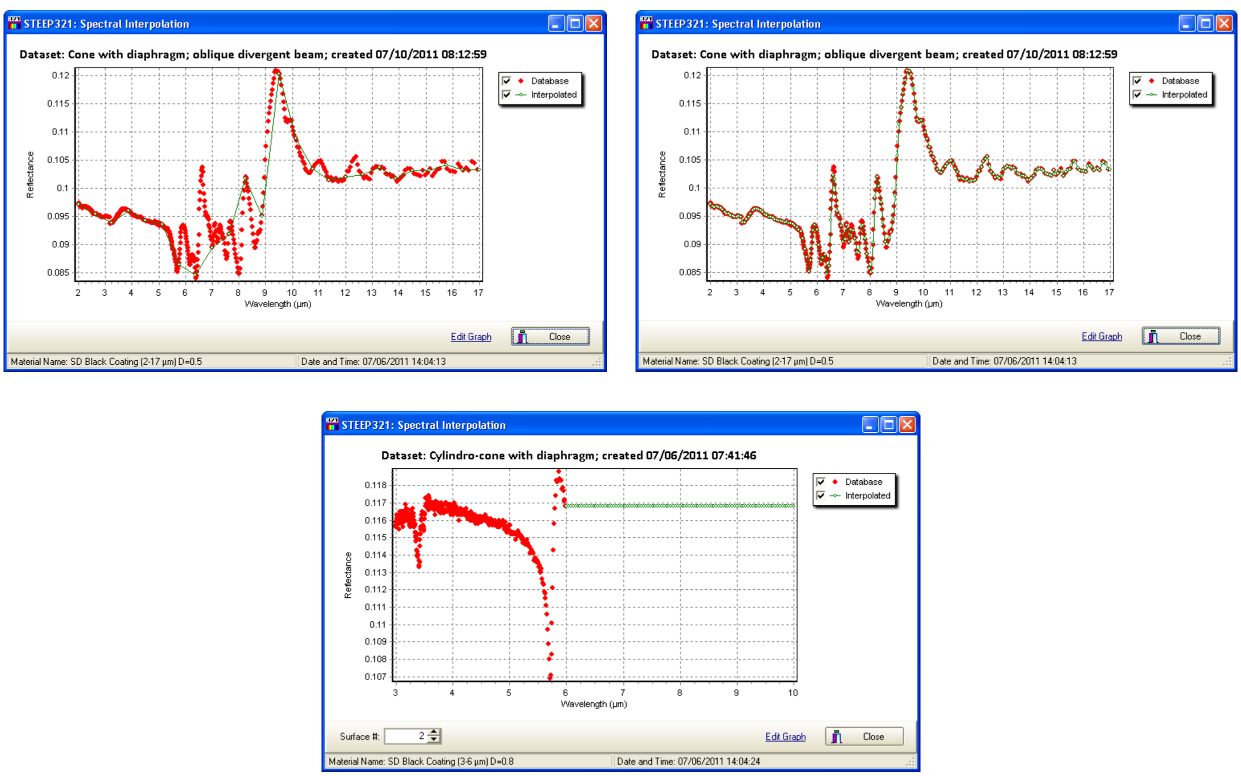
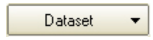
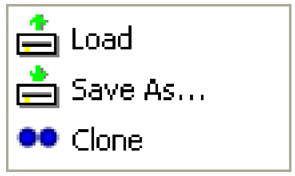


Fig. 37. Examples of spectral interpolation/extrapolation

7.9. Operations with Entire Dataset

To load from or save in text file entire dataset click 

button in the main STEEP321 window (Fig. 8) and use the drop-down menu:



Below, we provide a fragment of a text file containing all information about your task:

```
// DatasetName:
Cone-cylindro-cone
// Dataset Creation Date and Time:
07/06/2011 07:40:58
3   // Number of surfaces
3   // Number of temperature distributions
4   // Number of points in each distribution
41   // Number of wavelengths
2   // ViewIndex
46   // Number of viewing conditions
// Cavity (z, y, Material Creation Date and Time in Internal Format, Material Name):
 0.00000000000000E+0000  0.00000000000000E+0000
 3.75000000000000E+0000  2.37500000000000E+0000  4.07305864794907E+0004 SD Black Coating (6-10 µm) D=0.25
 6.75000000000000E+0000  2.37500000000000E+0000  4.07305864794907E+0004 SD Black Coating (6-10 µm) D=0.25
 8.25000000000000E+0000  1.35000000000000E+0000  4.07305864794907E+0004 SD Black Coating (6-10 µm) D=0.25
// Wavelengths in µm:
 7.00000000000000E+0000
 7.05000000000000E+0000
 7.10000000000000E+0000
 7.15000000000000E+0000
……………………………………………………………
8.95000000000000E+0000
 9.00000000000000E+0000
// Reference and background temperatures (K):
 1.00000000000000E+0003  0.00000000000000E+0000   // for temperature distribution # 1
 1.00000000000000E+0003  0.00000000000000E+0000   // for temperature distribution # 2
 1.00000000000000E+0003  0.00000000000000E+0000   // for temperature distribution # 3
// Temperature distributions:
//       Xi                  Z              Y              Surface #    T1 (K)    T2 (K)    T3 (K)
 0.00000000000000E+0000  0.00000000000000E+0000  0.00000000000000E+0000 1       1000.0000  1000.0000  1000.0000
 4.79844773138187E-0001  3.75242263774085E+0000  2.37500000000000E+0000 2       999.5000   999.0000   998.0000
 8.03810459237053E-0001  6.75075443969161E+0000  2.37448446621073E+0000 3       999.5000   999.0000   998.0000
 1.00000000000000E+0000  8.25000000000000E+0000  1.35000000000000E+0000 3        995.0000   995.0000   995.0000
// Viewing conditions: Right Conical Effective Emissivity
// #               YB                   ZB                   w
   1  0.00000000000000E+0000  8.25000000000000E+0000  0.00000000000000E+0000
   2  0.00000000000000E+0000  8.25000000000000E+0000  2.00000000000000E+0000
   3  0.00000000000000E+0000  8.25000000000000E+0000  4.00000000000000E+0000
   4  0.00000000000000E+0000  8.25000000000000E+0000  6.00000000000000E+0000
…………………………………………………………………………………………………………………………………………………………………………………
   43  0.00000000000000E+0000  8.25000000000000E+0000  8.40000000000000E+0001
   44  0.00000000000000E+0000  8.25000000000000E+0000  8.60000000000000E+0001
   45  0.00000000000000E+0000  8.25000000000000E+0000  8.80000000000000E+0001
   46  0.00000000000000E+0000  8.25000000000000E+0000  9.00000000000000E+0001
// Comments:
Right Conical Effective Emissivity: Dependence on FOV angle
```

Multiple examples of such text files can be found in the folder ***STEEP321\Data\Datesets***. If you loaded the dataset from a text file that contains materials which are absent in the MATERIALS database, STEEP321 before calculations displays the notification like in Fig. 38 and cancels the Monte Carlo modeling. You will have to assign another material instead of absent one.

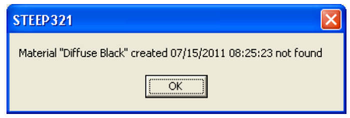


Fig. 38. Notification about absence of the material in the MATERIALS database

To delete multiple datasets click  . The window shown in Fig. 39 will appear.

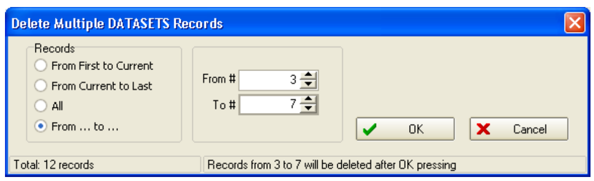


Fig. 39. Deleting multiple datasets.

One can make a copy of the current dataset by clicking Clone menu item. The request for the dataset new name will appear (see Fig. 40). You may change old name or remain it with no changes. In the last case, two datasets will differ in the date and time of creation.

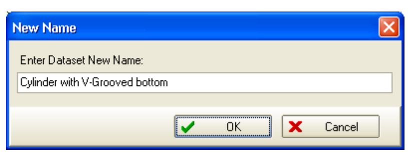


Fig. 40. Request for new name of cloned dataset

8. Monte Carlo Calculations

Now, when all the initial data are ready, you can start Monte Carlo calculations by pressing . The window "Compute" will appear (Fig. 41). You have to enter two parameters that determine the modeling accuracy: the number *N* of rays and the radiation flux threshold γ. The first parameter defines the random component of uncertainty for effective emissivity calculations. Due to stochastic character of the algorithm used in STEEP321, the random uncertainty of calculations varies in inverse proportion of $\sqrt{N}$. The choice of *N* to a great extent depends on cavity blackness, i.e. deviation of effective emissivity from the unity. Probably, the best way is to evaluate the required values of *N* from numerical experiments. We recommend to begin with *N* = 10,000. This also allows to evaluate the total time needed for final modeling. Usually, for modeling a cavity with effective emissivity from 0.99 than 0.9999 for isothermal condition, *N* = 1,000,000 is enough for any realistic temperature distribution.

The second parameter, affecting the accuracy of calculations, - radiance threshold, γ , defines possibility to terminate tracing of rays that transport too small amount of energy. For example, if you need to compute effective emissivity with relative uncertainty of 0.0001, there is no need to trace rays that carry 10^{-8} of their initial energy. Setting $\gamma = 0$ completely eliminates this question, but the total time of calculations may be unacceptably long in some cases. General recommendation is to set γ less than one third of the precision desired.

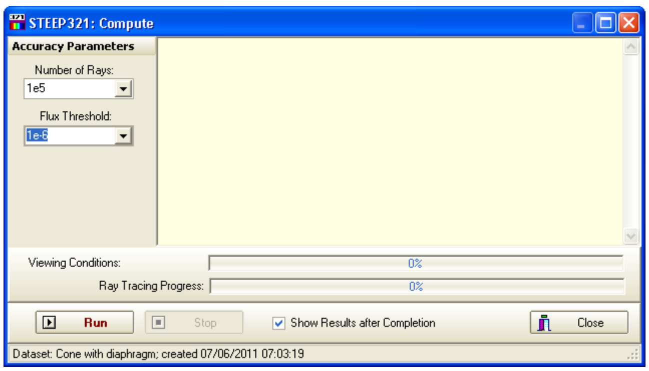


Fig. 41. Window "Compute" before ray tracing

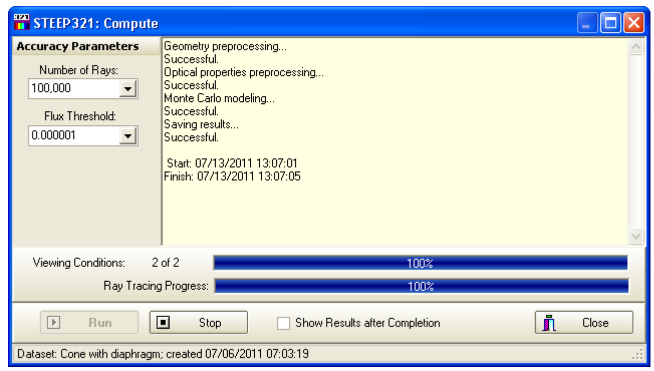
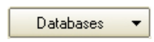


Fig. 42. Window "Compute" after ray tracing

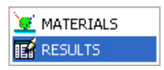
Click [Run] to start the Monte Carlo modeling. It can be interrupted by clicking [Stop] at any time. If the checkbox [✓ Show Results after Completion] is checked, then the window "Compute" will be closed automatically after successful modeling and the RESULTS database will appear. Otherwise (see Fig. 42) you have to close the "Compute" window by pressing [Close] then click [Databases ▾] button on the STEEP321 main window and click RESULTS item of the drop-down menu.

9. Postprocessing

9.1. Viewing Results

To browse results of calculation you have to click 

and select RESULTS in the drop-down menu:



The screenshot of the RESULTS database window is shown in Fig. 43.

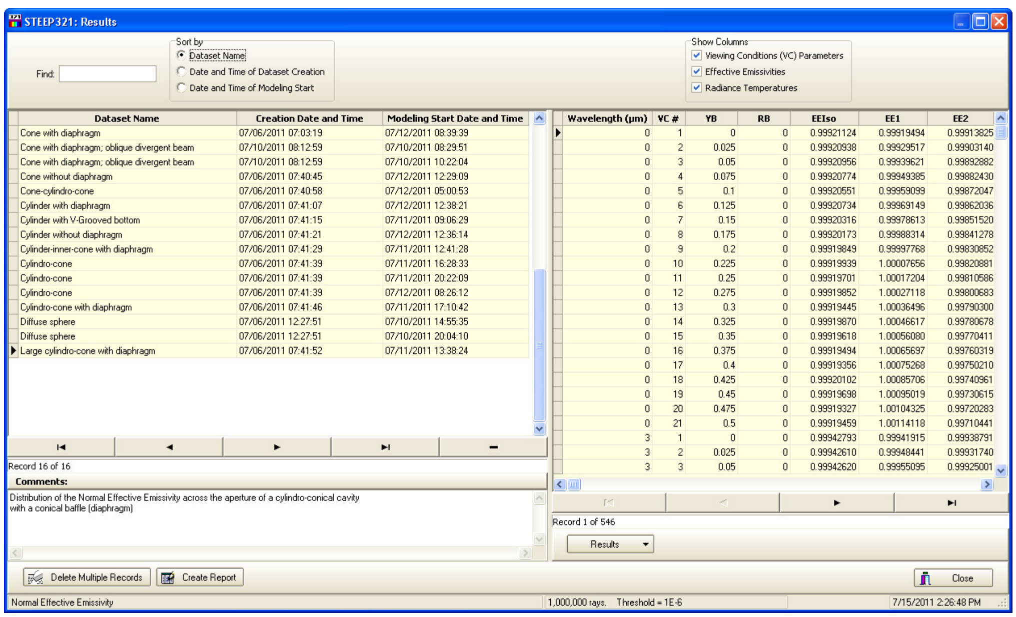


Fig. 43. RESULTS database window

The group of radio-buttons “Sort by” allows sorting results by:

- Dataset Name (in ascending order)
- Date and Time of Dataset Creation (in descending order)
- Date and Time of Modeling Start (in descending order)

Initially, the last way of sorting is applied, so the latest results will correspond to the first record in the left-hand table.

Right-hand table shows: the wavelength in the first column (wavelength equal to zero corresponds to total effective emissivities and radiation temperatures); viewing conditions number (VC #) in the second column; viewing conditions parameters in the next columns; then – the effective emissivities and radiance or radiation (corresponds to zero wavelengths) temperatures for every temperature distribution.

One can show or hide some columns by checking/unchecking the checkboxes in the group “Show Columns”. To delete multiple records click Delete Multiple Records. The window shown in Fig. 44 will appear.

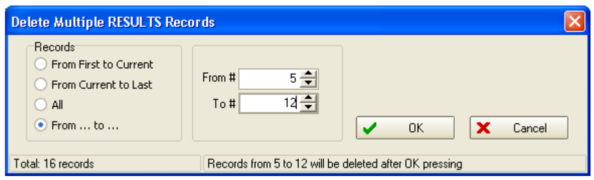
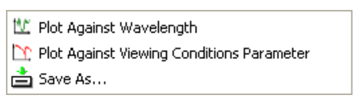


Fig. 44. Deleting multiple records in RESULTS database

9.2. Plotting Graphs

Using Results button with its drop-down menu



You can plot the dependences of the effective emissivities and radiometric temperatures on wavelength (Fig. 45) by clicking Plot Against Wavelength menu item. To plot these dependences for different viewing conditions, change viewing conditions number in the input field “Viewing Conditions #’.

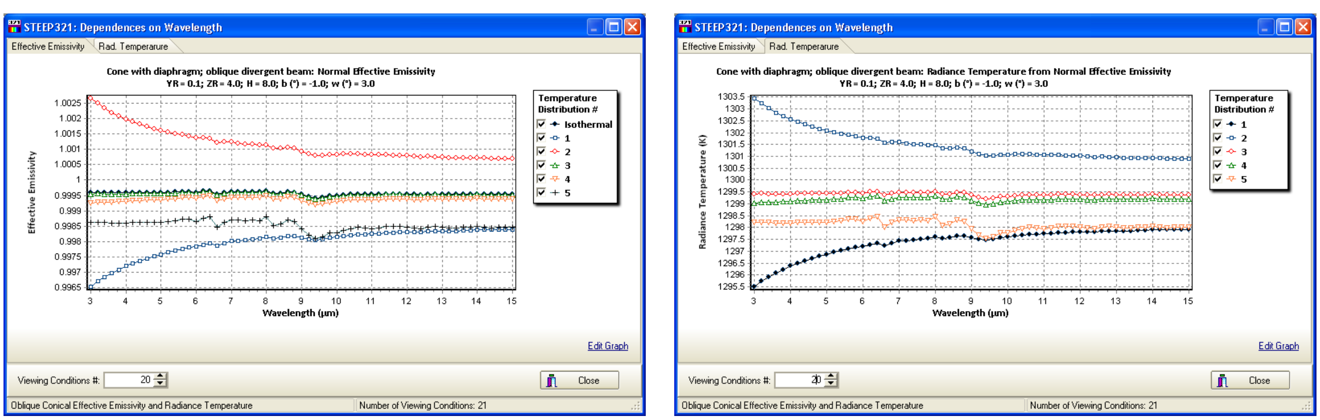


Fig. 45. Plots of effective emissivities and radiance temperatures vs. wavelength

You can also plot dependences of effective emissivities and radiometric temperatures on the viewing condition parameter (Figs. 46 and 47) using Plot Against Viewing Conditions Parameter menu item. The variable parameter can be chosen from radio-buttons "Parameter". To plot these dependences for different wavelength, change wavelength number in the field "Wavelength #'. Wavelength #0 corresponds to total effective emissivities and radiation temperatures.

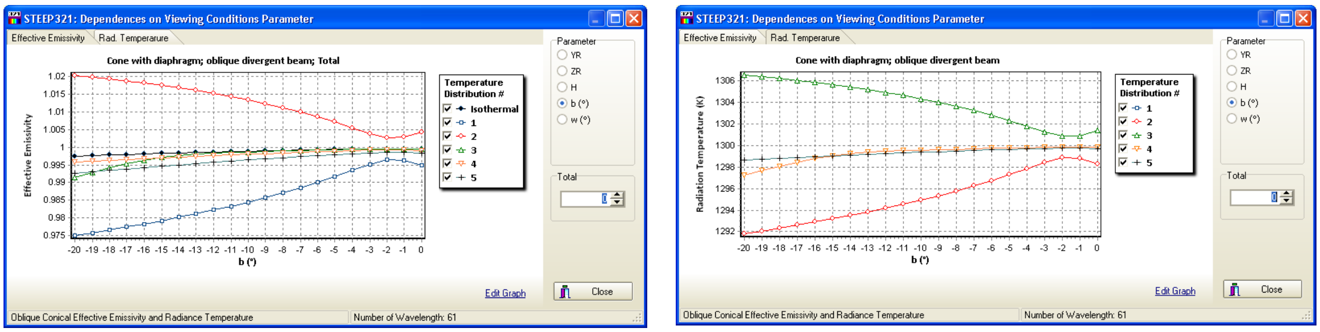


Fig. 46. Plots of total effective emissivities and radiation temperatures vs. the variable viewing conditions parameter.

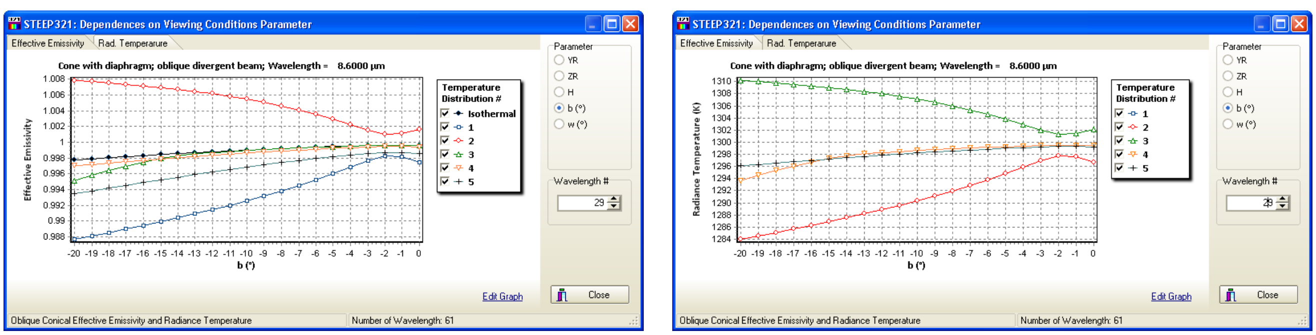


Fig. 47. Plots of spectral effective emissivities and radiance temperatures vs. the variable viewing conditions parameter.

The last menu item (Save As…) allows to save results of calculations in text file (for instance, to import them into MS Excel or some other software for further processing). Multiple examples of such text files can be found in the folder ***STEEP321\Data\Results***.

9.3. Generating Report

To generate report in text (ASCII) format click Create Report. The window for the report generated is shown in Fig. 48. Report can be saved as a text file. If you need to add comments to your report, uncheck the checkbox Read Only to add you text or make some corrections, then save the report in a text file. Without saving, you'll lose all the changes since the report is not saved in the database and re-generated every time when you click .

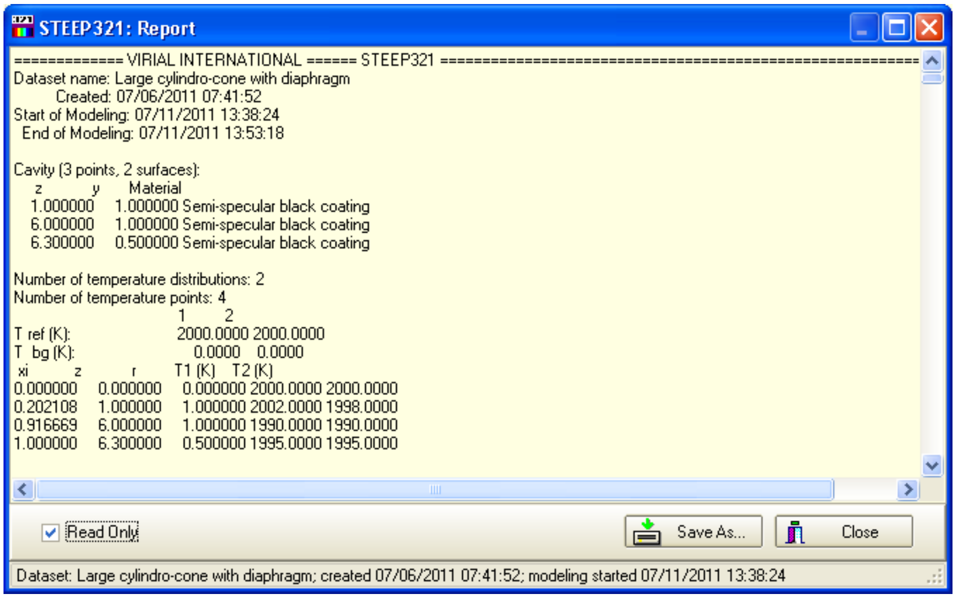
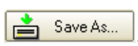


Fig. 48. Window "Report"

To save report in a text file click . Multiple examples of such files can be fond in the folder ***STEEP321\Data\Reports***.

10. Evaluation vs. Full-functioned Version

The Evaluation Version of STEEP321 can be downloaded for free from www.virial.com. You can study the principles of working with STEEP321; investigate examples included in databases and text files, plot graphs, etc.

The only difference between Evaluation Version and full-functioned program is the fact that Evaluation version does not allow to perform precise Monte Carlo calculations. After clicking 

in the main window (see Fig. 8), the "Warning" window shown in Fig. 49 will appear. It displays all restrictions differing Evaluation Version from full-functioned STEEP321.

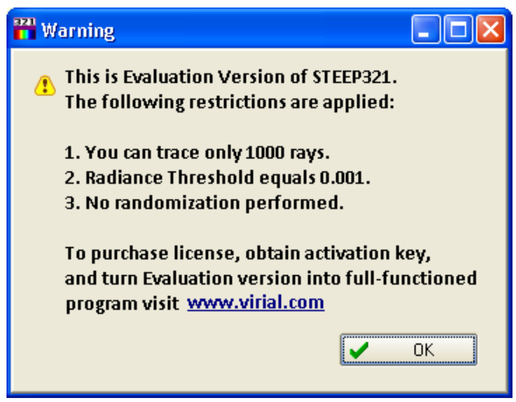


Fig. 49. The "Warning" window (Evaluation Version only)

Purchasing of the license and activating (see Section 7.1) transforms Evaluation Version into full-functioned program.

11. References

1. P. J. Mohr, B. N. Taylor, and D. B. Newell, "The Fundamental Physical Constants," Phys. Today **60**, p. 55 (2007).
2. A. V. Prokhorov, L. M. Hanssen, and S. N. Mekhontsev, "Calculation of Radiation Characteristics of Blackbody Radiation Sources," in Radiometric Temperature Measurements, Volume 42: I. Fundamentals (Experimental Methods in the Physical Sciences), edited by Z. Zhang, B. Tsai, and G. Machin, Academic Press, New York, pp. 181-240 (2009).
3. R.E. Bedford. "Calculation of Effective Emissivities of Cavity Sources of Thermal Radiation," in *Theory and Practice of Radiation Thermometry*, edited by D. P. DeWitt and G. D. Nutter, Wiley, New York, pp. 653-772 (1988).
4. R. E. Bedford. "Effective Emissivities of Blackbody Cavities – A Review," in *Temperature, Its Measurement and Control in Science and Industry*, edited by H.H. Plumb, Vol. 4, Part 1, pp. 425-434, Instrument Society of America, Pittsburg (1972).
5. R. E. Bedford and C. K. Ma, Emissivities of diffuse cavities: Isothermal and nonisothermal cones and cylinders, J. Opt. Soc. America **64**, pp. 339 –349 (1974).
6. R. E. Bedford and C. K. Ma, Emissivities of diffuse cavities, II: Isothermal and nonisothermal cylindrocones, J. Opt. Soc. America **65**, pp. 565 –572 (1975).
7. R. E. Bedford and C. K. Ma, Emissivities of diffuse cavities, III: Isothermal and nonisothermal double cones, J. Opt. Soc. America **66**, pp. 724 –730 (1976).
8. A. V. Prokhorov, "Monte Carlo method in optical radiometry," Metrologia **35**, pp. 465-471 (1998).
9. J. R. Mahan, *Radiation Heat Transfer: A Statistical Approach,* Wiley, New York (2002).
10. V. I. Sapritsky and A. V. Prokhorov, "Calculation of the Effective Emissivities of Specular-Diffuse Cavities by the Monte Carlo Method", Metrologia **29**, pp. 9-14 (1992).
11. V. I. Sapritsky and A. V. Prokhorov, "Spectral Effective Emissivities of Nonisothermal Cavities Calculated by the Monte Carlo Method," App. Opt. **34**, pp. 5645-5652 (1995).
12. F. E. Nicodemus *et al*. *Geometrical considerations and nomenclature for reflectance*, NBS Monograph 160 (US Dept. of Commerce, NBS, 1977).

12. End-User License Agreement

License

1. Under this Software License Agreement (the "Agreement"), Virial International, LLC (the "Vendor") grants to the user (the "Licensee") a non-exclusive and non-transferable license (the "License") to use STEEP321 (the "Software").

2. "Software" includes the executable computer programs, related electronic documentation and any other files that accompany the product.

3. Title, copyright, intellectual property rights and distribution rights of the Software remain exclusively with the Vendor. Intellectual property rights include the look and feel of the Software. This Agreement constitutes a license for use only and is not in any way a transfer of ownership rights to the Software.

4. The Software may be loaded onto no more than three computers. A single copy may be made for backup purposes only.

5. The rights and obligations of this Agreement are personal rights granted to the Licensee only. The Licensee may not transfer or assign any of the rights or obligations granted under this Agreement to any other person or legal entity. The Licensee may not make available the Software for use by one or more third parties.

6. The Software may not be modified, reverse-engineered, or de-compiled in any manner through current or future available technologies.

7. Failure to comply with any of the terms under the License section will be considered a material breach of this Agreement.

License Fee

8. The original purchase price paid by the Licensee will constitute the entire license fee and is the full consideration for this Agreement.

Limitation of Liability

9. The Software is provided by the Vendor and accepted by the Licensee "as is". Liability of the Vendor will be limited to a maximum of the original purchase price of the Software. The Vendor will not be liable for any general, special, incidental or consequential damages including, but not limited to, loss of production, loss of profits, loss of revenue, loss of data, or any other business or economic disadvantage suffered by the Licensee arising out of the use or failure to use the Software.

10. The Vendor makes no warranty expressed or implied regarding the fitness of the Software for a particular purpose or that the Software will be suitable or appropriate for the specific requirements of the Licensee.

11. The Vendor does not warrant that use of the Software will be uninterrupted or error-free. The Licensee accepts that software in general is prone to bugs and flaws within an acceptable level as determined in the industry.

Warrants and Representations

12. The Vendor warrants and represents that it is the copyright holder of the Software. The Vendor warrants and represents that granting the license to use this Software is not in violation of any other agreement, copyright or applicable statute.

Acceptance

13. All terms, conditions and obligations of this Agreement will be deemed to be accepted by the Licensee ("Acceptance") on installation of the Software.

Term

14. The term of this Agreement will begin on Acceptance and is perpetual.

Termination

15. This Agreement will be terminated and the License forfeited where the Licensee has failed to comply with any of the terms of this Agreement or is in breach of this Agreement. On termination of this Agreement for any reason, the Licensee will promptly destroy the Software or return the Software to the Vendor.

Force Majeure

16. The Vendor will be free of liability to the Licensee where the Vendor is prevented from executing its obligations under this Agreement in whole or in part due to Force Majeure, such as earthquake, typhoon, flood, fire, and war or any other unforeseen and uncontrollable event where the Vendor has taken any and all appropriate action to mitigate such an event.

Governing Law

17. The Parties to this Agreement submit to the jurisdiction of the courts of the State of Maryland for the enforcement of this Agreement or any arbitration award or decision arising from this Agreement. This Agreement will be enforced or construed according to the laws of the State of Maryland.

Miscellaneous

18. This Agreement can only be modified in writing signed by both the Vendor and the Licensee.

19. This Agreement does not create or imply any relationship in agency or partnership between the Vendor and the Licensee.

20. Headings are inserted for the convenience of the parties only and are not to be considered when interpreting this Agreement. Words in the singular mean and include the plural and vice versa. Words in the masculine gender include the feminine gender and vice versa. Words in the neuter gender include the masculine gender and the feminine gender and vice versa.

21. If any term, covenant, condition or provision of this Agreement is held by a court of competent jurisdiction to be invalid, void or unenforceable, it is the parties' intent that such provision be reduced in scope by the court only to the extent deemed necessary by that court to render the provision reasonable and enforceable and the remainder of the provisions of this Agreement will in no way be affected, impaired or invalidated as a result.

22. This Agreement contains the entire agreement between the parties. All understandings have been included in this Agreement. Representations which may have been made by any party to this Agreement may in some way be inconsistent with this final written Agreement. All such statements are declared to be of no value in this Agreement. Only the written terms of this Agreement will bind the parties.

23. This Agreement and the terms and conditions contained in this Agreement apply to and are binding upon the Vendor's successors and assigns.

Notices

24. All notices to the Vendor under this Agreement are to be provided at the following address:

Virial International, LLC
538 Palmspring Dr.,
Gaithersburg, MD 20878-2972
USA