USER GUIDE

RadMap

Radiation physics, on your desktop.



Release v2.0.0

radmap.tech

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RadMap is a desktop application for radiation dose rate calculations. It uses the Geant4 Monte Carlo toolkit as its calculation engine and provides a graphical interface for building geometry models, defining radiation sources, setting up dose maps, and viewing results.

1 Installation

This document guides you through installing and licensing RadMap on Windows.

1.1 System requirements

- **Windows 10 version 1803 (April 2018 Update, Build 17134) or later**, or Windows 11 — 64-bit only. Earlier Windows 10 builds and Windows 7/8/8.1 are not supported.
- Administrator account for installation
- Approximately 1 GB of free disk space
- Graphics supporting **OpenGL 3.3** or later — any graphics card or integrated graphics from the last decade. Some virtual machines and remote desktop sessions do not provide it; RadMap then shows an *OpenGL initialisation failed* message and closes.

> **Note:** RadMap uses Geant4's multi-threaded simulation engine. A multi-core processor reduces simulation time roughly in proportion to the number of cores.

1.2 Install RadMap

1. Download `RadMap_setup.exe` from the RadMap release page.
2. Optionally, verify the download. In PowerShell, in the folder you saved it to, run `Get-FileHash .\RadMap_setup.exe -Algorithm SHA256`. The *Hash* it prints must match the checksum in `RadMap_setup.exe.sha256` on the release page, also shown under the Download button on radmap.tech. A match shows that the installer arrived complete and unaltered.
3. Run the installer. Windows may show a User Account Control prompt — click **Yes** to allow the installer to run with administrator privileges.
4. Read the license agreement and accept it.
5. Choose an installation directory. The default is `C:\Program Files\RadMap`. You may change this to any path you prefer. The installer creates the directory if it does not already exist.
6. Click **Install** and wait for the Geant4 data sets to be extracted. This step takes a minute or two depending on your hardware.
7. When the installer finishes you can optionally launch RadMap immediately by leaving the **Launch RadMap** checkbox checked.

You can now use RadMap under the **free license**. The free license limits each simulation run to **50,000 primary particles** — enough to evaluate

RadMap and build your models. How many particles a precise result needs depends on the case; a full license removes the limit (see *Licensing*).

To look at an example project, choose **File** → **Load project** and open one from the `Samples\Examples` folder of the installation directory; to keep your changes to it, save it to a folder of your own with **File** → **Save project as**.

1.3 Licensing

Free license

No action is required. RadMap starts in free mode automatically. Each simulation run is capped at 50,000 primary particles.

Full license

A full license removes the particle limit. To obtain one:

1. Open RadMap and choose **Help** → **License**. The dialog shows your machine ID; **Copy Machine ID** copies it to the clipboard.
2. Send that machine ID to the RadMap team to request a license file.
3. When you receive the `.lic` file, open **Help** → **License** again and click **Install License File...**.
4. Browse to the `.lic` file and click **Open**. The license takes effect immediately — no restart required.

To renew a license, install the new file the same way. It replaces the license in force. A file RadMap cannot validate is refused, and the license in force stays. RadMap keeps the license in `C:\ProgramData\RadMap\radmap.lic`, for every user of the machine, and **Help** → **License** shows that path.

The license is tied to the machine it was issued for and is not transferable to another machine. A full license may carry an expiry date; **Help** → **License** shows it, or *Perpetual (no expiry)*. When a license expires, RadMap returns to the free license.

1.4 Verifying your installation

RadMap comes with five projects that check whether your installation reproduces the results this version of RadMap gave when it was released. Run them after installing, or whenever you need to show that an installation works as released.

1. Choose **File** → **Load project** and open a project from the `Samples\Verification` folder of the installation directory.
2. Open **Simulation** → **Simulation settings**. Under **Save location**, choose a folder of your own, such as *Documents*: the verification projects are installed read-only, so the results go into a copy and the project itself stays as released. With the free license, set **Number of primary particles** to 50,000. Leave the other settings unchanged.
3. Click **Start simulation** and wait for it to finish.

4. Select each dose map in turn and compare its dose rate in the Property panel with the table below, in the column of the check you ran: it must lie within the limits.
5. Choose **Report** → **Create PDF report** and open the report. Its dose rates must be the same, and so lie within the same limits; it states the number of primary particles. Keep it as the record of the check.

There are two checks:

- **The full check**, at 2,000,000 primary particles, the number the projects are saved with. It shows that your installation reproduces this version's results, to within about ±1 % for most dose maps. It needs a full license.
- **The quick check**, at 50,000 primary particles, the most the free license allows. It finds a broken installation – missing or damaged data or program files – but not differences of a few percent: its limits are wider because 50,000 primary particles give a less precise result.

A run with any other number of primary particles is not a check.

Project and dose map	Expected value	Full check, 2,000,000 primary particles: acceptance limits	Quick check, 50,000 primary particles: acceptance limits
1 Cs-137 in air: Effective_dose_ROT (Sv/h)	4.92e-04	4.87e-04 – 4.96e-04	4.67e-04 – 5.17e-04
1 Cs-137 in air: Ambient_dose_H10 (Sv/h)	7.33e-04	7.26e-04 – 7.39e-04	6.96e-04 – 7.69e-04
1 Cs-137 in air: Air_kerma (Gy/h)	6.10e-04	6.05e-04 – 6.15e-04	5.80e-04 – 6.40e-04
2 Co-60 behind lead: Ambient_dose_H10 (Sv/h)	9.10e-04	9.01e-04 – 9.19e-04	8.58e-04 – 9.62e-04
3 Na-22 positrons: Ambient_dose_H10 (Sv/h)	2.59e-03	2.57e-03 – 2.61e-03	2.51e-03 – 2.67e-03
4 I-125 X-rays: Ambient_dose_H10 (Sv/h)	2.85e-04	2.83e-04 – 2.87e-04	2.73e-04 – 2.97e-04
5 Sr-90 bremsstrahlung: Ambient_dose_H10 (Sv/h)	1.32e-04	1.27e-04 – 1.36e-04	1.09e-04 – 1.54e-04

Acceptance limits: the expected value ± 4 standard deviations of a run with the given number of primary particles, the uncertainty of the expected value

included, rounded outwards to the three digits RadMap shows. The expected values come from long runs of this version, ten times as many primary particles as the full check or more.

A correct installation falls outside the limits only rarely. If a result does, run that project again; if it is outside again, the installation is faulty. Reinstall RadMap, and if that does not help, get in touch (*Getting help*).

The projects exercise the parts of an installation that a fault would show in: the decay data and each table of conversion coefficients (project 1), photon interactions in shielding (2), positrons (3), the X-rays that follow electron capture (4), and electron transport with bremsstrahlung (5, which has *Simulate electrons* on).

> **Note:** The projects are made to give precise results quickly, not as examples of how to model. Their dose maps are large and close to the source, so each map's value is an average over a steep gradient: it means something only compared with this table.

1.5 Uninstall RadMap

Open **Control Panel** → **Programs** → **Uninstall a program**, locate **RadMap**, and click **Uninstall**. The uninstaller removes the application and all installed files. Your own project files (`.rma`) and results are not deleted.

2 User guide

2.1 About RadMap

RadMap calculates dose rates from radioactive sources, and the effect of shielding on them, at the points you choose. You describe an environment in terms of geometrical objects and sources of radiation, and RadMap follows the radiation through it with a full Monte Carlo simulation.

With RadMap you can

- calculate external gamma dose rates, in the dose quantity that suits your question, from a large number of radioactive isotopes in complex geometries
- build geometries from nested solids, and save parts of them as reusable volumes
- use the many predefined materials, or define new materials, elements and isotopes when they do not suit your needs
- save your geometries and sources for later use and sharing, and report the results as a PDF

RadMap is intended for radiation protection calculations; it is not a medical device. It is developed, verified and released under its development plan, and each release comes with a V&V report generated from the tests run on that build. Its results are estimates, within the limits listed under *Known limitations*, and whether they suit your purpose is yours to judge. The *EULA* states its intended use in full.

2.2 Starting RadMap

Starting RadMap brings up a program window divided into five parts: the **Geometry tree**, the **Geometry view**, **Dose maps**, **Sources**, and **Properties**. There is also a menu bar at the top with the menus **File**, **Simulation**, **Dose**, **Materials**, **Report** and **Help**.

Geometry tree — shows the geometrical objects in a tree structure, each inside the one it is placed in.

Geometry view — displays the objects you create in the geometry tree visually.

Dose maps — a list of dose maps. Each dose map is a box-shaped region that registers particle fluence and converts it to a dose rate.

Sources — a list of radiation sources. Each source is associated with a solid in the geometry tree, making that object the source of radiation.

Properties — shows and edits the properties of whatever is selected in the geometry tree, dose maps, or sources.

RadMap always has a project open. When it starts, a new project containing only the world volume is ready for you to work in.

2.3 A simple case — walk-through

The world volume

The first thing you need is a world volume — a box-shaped region in which particles are transported. Particles that leave the world volume are lost and no longer affect the simulation. All other solids and dose maps must be contained within it.

A new project already contains the world volume, shown as *World* in the Geometry tree. To start over from an empty world at any time, choose **File** → **New project**. Select *World* in the Geometry tree to make the Property panel active.

The world volume cannot be deleted.

Set the dimensions

The world volume is not yet visible because it has no size. Open the **Dimensions** tab in the Property panel and set the X, Y and Z side lengths (for example 100 cm each). The outline of the box appears in the geometry view.

Each length and angle field has its own unit list next to it, and the project keeps the unit you choose. Changing the unit keeps the number and reads it in the new unit: 10 cm becomes 10 mm, not 100 mm.

Note that the rotation and position tabs are disabled for the world volume — it cannot be moved or rotated.

Navigate the geometry view

Use the mouse and keyboard to explore the 3-D view:

- **Left-click and drag** — rotate the view around the focus point.
- **Up/Down arrow** — move the camera forwards and backwards.
- **Shift + arrow keys** — pan the view.
- **Ctrl + arrow keys** — turn the camera.

The Geometry tree's right-click menu has three helpers for the view:

- **Set focus** — make the selected solid the point the view rotates around.
- **Focus and fit to view** — centre the solid on screen and zoom so it fills the view. Useful if you have lost an object.
- **Set step size** → **Max dim / Min dim** — set how far each arrow-key press moves the camera, from the largest or smallest dimension of the selected solid. Choose *Min dim* to move precisely around a small object and *Max dim* to cross a large scene quickly.

The same commands are available for dose maps from the Dose maps list.

Whatever is selected — a solid, a dose map or a source's solid — is highlighted in the view.

Set the material

Every solid must have a material. Select the world volume in the Geometry tree, open the **General** tab in the Property panel, and choose *AIR* from the **Material** drop-down. The drop-down lists the materials in the project's material library; to add or change materials, use the **Materials** menu (see *Materials*).

Add a child solid

Right-click an entry in the Geometry tree and choose **New sub solid** → **Tube** to add a tube inside the world. The other choices are **Box** and **Sphere**. The new solid appears in the tree and in the 3-D view. Give it a descriptive name (e.g. *lead_shielding*) and assign a material as before.

The same menu has **Delete solid**, which removes the selected solid together with everything inside it, and **Delete children**, which keeps the solid but removes everything inside it.

> **Note:** Names may contain letters, digits, underscores, hyphens and dots, may not contain spaces, may not start with a digit and are at most 20 characters long. Names must be unique among solids, among sources and among dose maps. A name that breaks these rules is kept as you typed it and the field turns red; the project cannot be saved or simulated until it is corrected.

Set tube dimensions and position

The **Dimensions** tab for a tube exposes inner radius, outer radius, length, **Start phi** and **Delta phi**. Try, for example: inner radius 10 cm, outer radius 20 cm, length 30 cm, delta phi 270°. Varying start phi and delta phi changes how much of the tube wall is present — useful for modelling a shielding container with an opening.

A **sphere** has an inner and an outer radius, and two pairs of angles: start phi and delta phi around the Z axis, and start theta and delta theta measured from it. Like every new solid, a new sphere starts with all dimensions at zero. For a full sphere set delta phi to 360° and delta theta to 180°; an inner radius larger than zero makes it a spherical shell, and smaller angles cut out a segment.

Under the **Position** tab, set the position relative to the parent volume (e.g. X 5 cm, Y 10 cm, Z 15 cm).

> **Note:** No volume may overlap another, and every volume must be fully contained by its parent. RadMap checks for overlaps at the start of a simulation by sampling random points on each surface. Because only a finite number of points are sampled, very small overlaps may occasionally go undetected.

Coordinate systems, rotation and appearance

To understand how a solid is oriented, tick **Coordinate system** in the **Appearance** section of the General tab — three coloured axes appear at the solid's centre. A dose map has the same checkbox in its own General tab.

If the axes, or solids further in, are hidden by a solid's surface, tick **Wireframe** in the same section to draw that solid as an outline. The section also has a **Colour** picker. Appearance is saved with the project but only affects the display, never the simulation. The world volume is always drawn as a wireframe.

Set the rotation of a solid from the **Rotation** tab. The solid turns about its own axes, which turn with it: first about X, then about the new Y, then about the newest Z. Only the three angles count, not the order you type them in: the X turn always comes first, about the solid's original X axis, so setting Y and then X does not turn the solid about its Y-turned X axis. Turns about different axes do not commute, so tick **Coordinate system** to see where the axes end up.

Add a source

Sources are attached to solids. First add a small solid to act as the source: for example a 2 cm box of material *Fe*, a child of *World* at the tube's own position, X 5 cm, Y 10 cm, Z 15 cm, so that it sits at the centre of the tube's hollow.

The decays of a source are spread evenly through the volume of its solid, less the volume of any solids placed inside it. RadMap samples the decay positions in a box enclosing the solid and keeps those that fall in that volume, so the volume must fill a fair part of the box. A curved shell thinner than about 1/5000 of its radius, or a solid almost filled by the solids inside it, cannot hold a source: the simulation is refused, naming the solid.

Right-click the solid in the Geometry tree and choose **Attach source**. An entry *source_1* appears in the Sources panel. In the Property panel, set the element (e.g. *Caesium*) and isotope (e.g. *137*), then enter the activity (e.g. 100 GBq).

The isotope list holds every isotope in Geant4's radioactive decay data whose ground state is radioactive, each shown with its half-life. Isotopes with a half-life under 1 minute are hidden. Under **File** → **Preferences** you can change that limit and add an upper one, for example to hide the practically stable isotopes with half-lives of 10^{15} years and more; leave a field empty for no limit. A limit can be written in scientific notation, such as `1.4e9`. The limits are your own setting, the same for every project; the *Isotope filter* line above the element list shows the ones in force. A source keeps its isotope even when the limits would hide it; the list then marks it with an asterisk, and hovering over the isotope explains why.

Isotope info, next to the isotope, shows its half-life, how it decays and to what, and the photons one decay gives off: energy, photons per 100 decays and origin (a gamma of the daughter, an X-ray or annihilation). They are computed from the same Geant4 data the simulation uses, so the table lists what is simulated. The photons of a radioactive daughter's own decay are

not included; with **Full chain** on, the simulation adds them. Click a column heading to sort by it, and again to reverse the order.

> **Caution:** The decay scheme used is that of the ground state nucleus. You cannot directly specify an excited state. ^{99}Tc therefore does not yield the dose rate of ^{99m}Tc. Selecting ^{137}Cs does give the expected result because the Cs nucleus decays to the metastable ^{137m}Ba.

The **Full chain** checkbox controls whether the entire decay chain is followed. When enabled, unstable decay products are themselves decayed during the simulation — their half-lives are not considered. This is physically meaningful only when the half-lives of the decay products are much shorter than that of the primary isotope. When disabled, the simulation follows one decay to the ground state of the first product. For an isotope whose decay products do not decay further, such as Cs-137 or Co-60, there is no chain to follow, so the setting is off and the checkbox is disabled. The setting is per isotope: sources of the same isotope must all have it on or all off, or the simulation is refused. Sources of different isotopes may differ, even when their chains meet: with Te-132 off and I-132 on, the I-132 born from Te-132 is dropped, while the I-132 source's own decays follow its chain.

Give the activity as a concentration

The **Activity** row offers three mutually exclusive choices: *Absolute*, *Per mass* and *Per volume*. *Absolute* is the total activity of the source, as above. The other two state how much activity there is in each unit of mass, or of volume, of the source material — RadMap then derives the total.

The unit list follows the choice. An absolute activity can be given in any unit from nBq to EBq, or from nCi to ECi. A concentration is given in Bq, kBq, MBq, GBq, µCi, mCi, Ci or kCi per g or kg (*Per mass*), or per cm³ or m³ (*Per volume*).

The **Total** field below shows the derived total and cannot be edited. It is the number the simulation normalises its results to, so it is worth a glance before running: a concentration that looks reasonable can still give a total that does not.

Two things determine it. The volume used is the source solid's own volume **minus the volume of any solids placed inside it**, because RadMap emits decays only in material that belongs to the source itself — a point inside a child volume belongs to that child. For *Per mass*, that volume is then multiplied by the density of the solid's material, taken from the project's material library.

RadMap stores what you entered rather than the derived total. Resizing the solid, placing a child inside it or changing its material therefore changes the total, while the concentration stays as you typed it.

The **Total** field reads *Undefined* when no total can be worked out: the solid's material has no usable density, its dimensions describe no volume, or the solids inside it are too large to fit. A source whose total is undefined — or works out as zero — cannot be simulated, and RadMap says so when the run

is started. The project still saves, since the concentration you entered is not what is at fault.

> **Note:** The derived total assumes child volumes are fully contained, which is required of any geometry in any case (see the note under *Set tube dimensions and position*). Where a child protrudes, too much volume is subtracted and the total comes out too low — but such geometry is rejected when a simulation is started, so a wrong total cannot reach a result or a report.

Adding dose maps

A dose map registers the photon fluence in a box-shaped region and converts it to a dose rate using published conversion coefficients. The result is the mean over the box's **volume**: see *What a dose map measures*. Dose maps do not interfere with radiation transport and may overlap solids or other dose maps. A simulation can score at most 15 dose maps; a project with more is refused when you start the run.

Right-click a solid in the Geometry tree and choose **Attach dose map**. The dose map's coordinate system is defined relative to that parent solid, but otherwise the two are independent.

Set the dose map dimensions, position and rotation as you would for a solid.

For this example, create two dose maps attached to the tube, one on each side. Place one at X 15 cm, Y −15 cm (facing the open side of the tube) and a second at X −15 cm, Y 15 cm (shielded by the tube wall).

What a dose map measures

A dose map reports the dose rate **averaged over the volume of its box**. That is neither the dose rate at the box's centre nor the dose rate on its surface. Where the radiation is the same throughout the box, all three are equal, and the size and orientation of the box make no difference.

Near a source, or at the edge of a shield's shadow, the radiation changes across the box, and the box reads its mean over the volume. A large box close to a source covers points both near the source and far from it, and its reading lies between the two. Turning a box changes its reading only as far as it changes the region the box covers.

Choose the box for the question you are asking:

- **The dose rate at a point**, such as where a person stands or where a survey meter would be read: make the box small compared with its distance from the source and from the edges of shields, so that the radiation hardly changes across it. A plate a few millimetres thick, facing the source, reads the mean over its face. A cube of side s at a distance d from a small source reads about $s^2/12d^2$ more than the value at its centre: 0.75 % for a 30 cm cube at 1 m. The difference grows with the square of the box's size over its distance.
- **The mean over a region**, such as a work area or a room: make the box that region.

A smaller box is crossed by fewer photons, so its result carries a larger statistical uncertainty: make it no smaller than the question needs. A dose map that encloses a source, or part of one, also counts the photons emitted inside it, so its mean includes the high dose rate close to the source.

RadMap versions before 2.0 counted the photons entering the box through its faces instead. For a thin box the result is the same. A deep box near a source, however, read nearer the dose rate at the faces the radiation entered by, and its reading changed when it was turned: see the errata page, defect D-0005, and *Methods*.

Choosing what the dose map scores

The **Dose** section of the General tab decides what the map reports.

Radiation selects the particle type. It stays fixed on *Photons* while that is the only type RadMap has coefficients for.

Dose Quantity selects the quantity. The available quantities answer different questions.

Effective dose is the whole-body, risk-weighted quantity that radiation protection limits are expressed in, reported in sieverts. It is not a measurable quantity: it is calculated for a reference human body, so you must also say how that body is oriented in the radiation field. The six orientations appear as separate entries in the dropdown:

- **Effective dose (AP)** / **(PA)** — parallel beam incident on the front or back of the body.
- **Effective dose (ROT)** — body rotating in a broad beam; generally the most meaningful choice for a single-source scenario.
- **Effective dose (ISO)** — isotropic radiation field, independent of direction.
- **Effective dose (LLAT)** / **(RLAT)** — beam from the left or right side.

H*(10), the ambient dose equivalent, is the operational quantity used for area monitoring, reported in sieverts. It is defined in a reference sphere that is always aligned with the radiation field, so it has no orientation and appears as a single entry. Area survey meters are normally calibrated in H*(10), which makes it the quantity to use when comparing with such a meter's reading.

Air kerma is a property of the radiation field itself, reported in grays. It describes the energy released in air at that point with no body present, which makes it the quantity to use when comparing against an instrument or a figure quoted in air kerma. Having no body, it has no orientation, so it appears as a single entry.

> **Caution:** The concept of effective dose assumes whole-body exposure. Using AP or PA with multiple sources at different angles is not physically meaningful; prefer ROT or ISO in such cases.

> **Note:** The unit follows from the quantity and is not a separate choice: effective dose and H*(10) are reported in Sv/h, air kerma in Gy/h. The **Dose rate** row always shows the unit next to the value.

For this example, set the Dose Quantity to *Effective dose (ROT)* for both dose maps.

Origin of conversion data

RadMap does not simulate dose directly. The Monte Carlo calculation transports particles through the geometry and scores the photon **fluence** in each dose map: the total length of the photons' paths inside it per unit volume — at each point the same as the photons crossing a unit area there. That fluence is then multiplied by a published *conversion coefficient* for the selected quantity, which is what turns a count of particles into a dose rate.

This holds for every dose quantity RadMap reports. The division of labour is worth knowing, because it is what stands behind the number you get: the transport is physics RadMap calculates, while the step from fluence to a dose quantity is fixed by internationally agreed tables published by bodies such as the ICRP and ICRU. RadMap applies those coefficients; it does not derive them. *Methods* describes the whole calculation.

No single publication covers every quantity, so different quantities may draw on different publications. The **Data source** row shows which publication the selected quantity uses. At present they are:

Quantity	Publication	Photon energies covered
Effective dose	ICRP 116 (2010, corrected 2015)	10 keV – 10 GeV
H*(10)	ICRP 74 (1996)	10 keV – 10 MeV
Air kerma	ICRP 74 (1996)	10 keV – 10 MeV

> **Note:** Photons outside these ranges are not refused. Below 10 keV, effective dose and H*(10) count them as zero, which is the physics: they do not get past the skin. Air kerma counts them at its 10 keV value, which is too low for them. This matters only within tens of centimetres of an unshielded source of X-rays below 10 keV, such as bare Am-241; a source in a capsule does not emit them.

Dose → **Dose settings** lists each radiation type and quantity RadMap can score, with the publication used for each. Where more than one publication is available for a quantity, you choose between them there. The choice applies to the whole project, so two dose maps scoring the same quantity can never disagree about their coefficients. A quantity with only one publication shows it without offering a choice.

> **Note:** The publication decides what the stored numbers mean, so it is part of what a simulation result depends on. On a locked project the dialog still opens but its controls are disabled; choose **File** → **Delete results** first if you need to change it.

Every PDF report contains a **Data sources** table listing the quantities the project actually used and the publication behind each, so a report records the basis of its own numbers.

Run the simulation

Open **Simulation** → **Simulation settings**. Set the **Number of primary particles** to simulate: each is one decay of a source nucleus, followed with all it emits. More particles give better precision, but computation time scales linearly while precision improves only with the square root of particle count — ten times more particles takes ten times longer but reduces the standard deviation by a factor of roughly three.

How many particles you need depends on the case. Shielding between the source and a dose map, the distance between them and the size of the dose map all decide how many particles actually reach it, so a heavily shielded or distant dose map may need many times more than one in direct view of the source. Check the uncertainty reported with each dose rate, and increase the number of particles until it is small enough for your purpose.

The free license caps each run at 50,000 primary particles.

The settings dialog also contains a **Physics options** section with a *Simulate electrons* checkbox. By default this is off: electrons, from decay and from photon interactions, are discarded where they are created, keeping simulations fast. This is the correct choice for the vast majority of sources, where gamma photons carry all the dose of interest.

Switch it on when your source is a **high-energy beta emitter** (such as Sr-90/Y-90 or P-32) placed in or near **high-Z shielding material** (lead, tungsten). In that geometry the beta electrons are stopped quickly in the shielding, and a significant fraction of their kinetic energy is radiated as bremsstrahlung — secondary photons that can contribute substantially to the dose outside the shield. With electron transport enabled RadMap tracks these electrons and scores the resulting bremsstrahlung photons. Note that tracking electrons increases simulation time noticeably, so only enable this option when bremsstrahlung is physically relevant.

Under **Save location**, choose where the project file is saved. The project is saved there before the simulation starts, and the results are stored in the same file when it finishes. **Start simulation** is available once a save location is set.

Click **Start simulation**. The dialog then lists each stage as it runs — parsing the geometry, building the physics tables, checking for volume overlaps, running the simulation and saving the results — with a progress bar during the run. You can cancel at any time. If a stage fails, the error is shown in the dialog, with the full details available under **Show details**. When finished, the

dose rate and its uncertainty appear in the Property panel for each dose map. The uncertainty, after the ±, is one standard deviation: the statistical uncertainty of the Monte Carlo estimate.

After a simulation the project is **locked** — most properties of solids, sources and dose maps cannot be changed while results are attached. The title bar shows *[LOCKED]* as a reminder. Colour and wireframe can still be changed, since they do not affect the results. To make further edits, choose **File** → **Delete results** to discard the current results and unlock the project. Like any other edit, this reaches the file only when you save the project.

Create a report file

Choose **Report** → **Create PDF report** to export the simulation results to a PDF file. The command is available once the project has results. You will be prompted for a save location; the file is then opened by your default PDF viewer.

The report states how many primary particles the results come from and that each ± is one standard deviation. It then gives:

- a **Dose maps** table: the quantity, geometry, radiation type and dose rate of each dose map;
- a **Sources** table;
- the **Data sources** table described above;
- a picture of the geometry view as it looks when the report is created, so set up the view you want in the report first.

The report prints Western European letters only. Other characters in a project, dose map or source name, such as Greek, Cyrillic or Korean, come out as question marks; RadMap lists the affected text when it creates the report.

Under the title, the report names the run its results come from: the RadMap version that ran it, the time it started (in UTC) and its run ID. The same ID is stored with the results in the project file, so a report can always be matched to the file holding its results — keep that file with the report. **Report** → **Run information** shows the same details for the open project without making a report, with the ID ready to copy. After **File** → **Delete results**, the next simulation gets a new ID, even if nothing in the project changed. Results saved by an earlier version of RadMap have no run ID; their reports show the date the report was made and the RadMap version that made it instead.

The report's **Sources** table always gives the total activity of each source. If any source was given as a concentration, the table carries a further column holding the value as entered — headed *Specific activity* when only per-mass sources appear, *Activity concentration* when only per-volume ones do, and *Specific activity / concentration* when the report contains both. A *Full chain* column says how each source was run: *On*, *Off*, or *No chain* for an isotope the setting cannot change. It is left out when no source in the report has a chain.

2.4 The Dose maps and Sources lists

A solid can carry several sources and several dose maps: each **Attach source** or **Attach dose map** adds one more. A tick next to the command in the Geometry tree's right-click menu shows that the solid already has one.

The Dose maps and Sources lists show every dose map and source in the project. Selecting an entry shows its properties in the Property panel and highlights it in the view — for a source, its solid. Right-click an entry for **Delete dose map** or **Delete source**; a dose map's menu also has the view commands of the Geometry tree (see *Navigate the geometry view*).

2.5 Saving and loading projects

A project — geometry, sources, dose maps, the project's material library and any results — is saved as a single `.rma` file. Use **File** → **Save project**, **File** → **Save project as** and **File** → **Load project**. **File** → **New project** discards the current project and starts a new one with an empty world.

While the project has changes that are not saved, the title bar starts with `*`. **File** → **New project**, **File** → **Load project** and closing RadMap then ask before discarding them.

Example projects to open are in the `Samples\Examples` folder of the installation directory.

2.6 Reusing volumes

Part of a geometry can be saved and reused in other projects. Right-click a solid in the Geometry tree and choose **Save Volume** to save that solid and everything inside it as a `.sol` file. If the volume contains sources or dose maps, you choose whether to include them. The file also carries the materials the volume uses. What you save must be complete, as for saving a project: each solid needs a material and valid dimensions, and names must not repeat.

To insert a saved volume, right-click the solid that should contain it and choose **Load Volume**. Materials the project does not have yet are added to its material library. If a material in the file has the same name as one in the project but a different definition, the project's own definition is kept, and a **Material library differences** dialog shows what differed so you can check the result.

2.7 Materials

Each project carries its own **material library**. A new project starts with the default library: the elements, plus common compounds, mixtures and tissues such as *AIR*, *CONCRETE*, *WATER* and lead glass.

Use the **Materials** menu to work with libraries:

- **Edit project material library** — change the materials of the current project.
- **Edit external material library** — open and edit a material library file (`.mlb`) without changing the project.

- **Reset to default library** — replace the project's library with the default library RadMap ships.
- **Export material library** — save the project's library to a file, for example to reuse it in other projects.
- **Import material library** — replace the project's library with one from a file.

Before an edit to an entry that other entries or solids use is applied, or saved to a library file, RadMap lists what the edit changes and asks you to confirm: the elements and materials that hold the entry, the solids made of them, and any source whose total activity changes. A total changes only when you edit the density of the material a source's solid is made of, and the source is given per mass. An edit can still change a source's dose rates, through the solid around it.

Reset and Import replace the whole library. A solid whose material is not in the new library loses its material assignment; RadMap lists those solids afterwards. The project file is changed only when you save.

To share materials between projects — a library of your organisation's own materials, say — keep them in a library file: **Export material library** from a project that has them, add to the file with **Edit external material library**, and bring it into another project with **Import material library**. Since Import replaces the project's library, the file should hold every material the project needs.

The material editor

The material editor has three sections side by side: **Material**, **Element** and **Isotope**. A material is built from elements or from other materials, and an element from isotopes. In each section, choose **Edit** and pick an entry from the list to change it, or **New** to create one; a new entry cannot take the name of an existing one.

When you edit the project's library the button is **Apply**: the change goes into the project, and reaches the project file when you save the project. When you edit an external library it is **Save**, which writes the change to the library file at once. **Delete** removes the entry shown.

Before anything is applied or saved, RadMap checks the entry. A value that is not accepted turns its field red, the **Log** at the bottom of the editor says why, and nothing is changed until it is corrected.

Defining a material

Give the material a name and a density, with its unit, and choose how it is composed:

- **Simple** — one element, given by its atomic number **Z** and its atomic mass in u (**Mass (u)**), as in the default library's *Fe*.
- **Element mix** — choose elements from **Add Element**; each becomes a row. In the **Fraction** column, give each element's share of the mass; the shares must add up to 1. A steel of 98 % iron and 2 % carbon by mass

is *Fe* 0.98 and *C* 0.02. For a compound it is often easier to count atoms: click the column heading to switch it to **Composite** and give the number of atoms of each element in one molecule — water is *H* 2 and *O* 1. Switching clears the column.

- **Material mix** — choose materials from **Add Material** and give each one's share of the mass, adding up to 1. A heavy concrete with iron ore could be *CONCRETE* 0.7 and *FERRIC_OXIDE* 0.3. The density is the mix's own, which you give; it is not worked out from the parts.

Remove item removes the selected rows. Atomic numbers run from 1 to 98 (californium), the range Geant4's data covers.

Defining an element or an isotope

The default library holds the natural elements, so new ones are needed mainly for an isotopic composition of your own, such as enriched boron.

An **element** is either *Simple*, given by Z and its atomic mass in u, or an *Isotope mix*. For an isotope mix, choose isotopes from **Add Isotope** and give each one's share of the atoms, adding up to 1: boron enriched to 96 % in boron-10 is *B10* 0.96 and *B11* 0.04. All isotopes of an element have the same Z, so once one is added the list offers only isotopes with its Z.

An **isotope** is given by its atomic number **Z**, its mass number **A**, which must be at least Z, and its atomic mass in u.

Material, element and isotope names must start with a letter or digit and may contain letters, digits, underscores, dots, commas and hyphens. These rules differ from those for solids, sources and dose maps (see *Add a child solid*): a material's name may start with a digit and may contain a comma.

An entry that another entry is built from cannot be deleted — a material used in a material mix, an element used in a material, or an isotope used in an element. Deleting a material that solids use clears it from those solids, and the editor's log lists them. Importing a library that lacks a material in use does the same. Those solids need a new material before the project can be saved or simulated.

2.8 Known limitations

What RadMap does not calculate, or calculates only approximately. Each point is explained where it applies; this section collects them, so you can check a case against all of them at once.

- **Photon dose only.** Dose maps score photons. The dose from beta, alpha and neutron radiation is not reported. Neutrons, such as those from the spontaneous fission of ^{252}Cf, leave the source but pass through matter without interacting, so the photons they would produce there (capture gammas, for example) are missing too. See *Choosing what the dose map scores*.
- **Bremsstrahlung only on request.** Electrons from decay are discarded unless *Simulate electrons* is on, so the bremsstrahlung of beta emitters in shielding is missing by default. See *Run the simulation*.

- **Conversion coefficients have an energy range.** Below 10 keV, effective dose and H*(10) count photons as zero, which is the physics, while air kerma counts them at its 10 keV value and so reads too low close to an unshielded source of soft X-rays. Above 10 MeV, air kerma and H*(10) use their 10 MeV values; photons from radioactive decay rarely reach that. See *Origin of conversion data*.
- **Ground states only.** A source decays from the ground state of its isotope; an excited or metastable state cannot be chosen. See *Add a source*.
- **Full chain ignores half-lives.** With *Full chain* on, every radioactive daughter decays once for each decay of the source, as in secular equilibrium. That overstates the daughters' share when one lives long compared with the source, or when the source is freshly prepared and its daughters have not yet grown in. See *Add a source*.
- **A dose rate at one moment.** The activity is the one you enter; RadMap does not decay it over time or integrate a dose over a period.
- **Sources are spread evenly** through the volume of their solid, less the solids placed inside it, and that volume must not be too thin: a very thin curved shell cannot hold a source. See *Add a source*.
- **A dose map is a mean over its box, free in air.** It averages the fluence over the box's volume, without a body present; effective dose then assumes whole-body exposure in the chosen irradiation geometry. See *What a dose map measures* and *Choosing what the dose map scores*.
- **Results are Monte Carlo estimates.** Each dose rate carries a statistical uncertainty that shrinks only with the square root of the number of particles. See *Run the simulation*.

2.9 Licensing

RadMap runs under the free license, which caps each simulation run at 50,000 primary particles, or under a full license, which removes the cap. How to obtain, install and renew a full license is described under *Licensing* in the installation chapter.

2.10 Getting help

Which channel to use depends on what you need:

- **Questions about using RadMap** — how to model something, which dose quantity fits your case — ask in the Q&A discussions on GitHub. Search there first: questions and their answers stay public, so yours may already be answered.
- **Bugs and feature requests** — open an issue on GitHub. A short form asks for what is needed to reproduce the problem: the RadMap version (shown under **Help** → **About**), the Windows version and the steps that lead to it.
- **Licensing, anything confidential, or if you do not use GitHub** — email info@radmap.tech.

Caution: Discussions and issues are public. Never post confidential project data there — facility geometry, source inventories or activities. Describe the problem in general terms, or email us instead.

3 Methods

How RadMap calculates a dose rate: what it hands the simulation, what the simulation does with it, and how a dose rate is made of the result. The user guide says how to set up a calculation; this part says what happens to it. What RadMap does not calculate, or calculates only approximately, is collected in the user guide under *Known limitations*.

3.1 Overview

A calculation runs in two programs. RadMap holds the project: the geometry, the materials, the sources and the dose maps. When a simulation starts, it checks the project, writes it out as a geometry description and a list of commands, and starts the simulation program, which comes with RadMap. That program uses Geant4, the Monte Carlo radiation transport toolkit developed by an international collaboration led from CERN, to simulate radioactive decays one at a time and follow the radiation they emit through the geometry. It scores the photons inside each dose map and returns, for each map, the mean score per decay and its statistical uncertainty. RadMap multiplies these by the activity of the sources and reports a dose rate.

RadMap uses Geant4 11.4, built from source with patches of RadMap's own to how decay positions are sampled (see *Sources*), and the Geant4 data sets of that release:

Data set	Version	Holds
G4EMLOW	8.8	Photon and electron interaction data
RadioactiveDecay	6.1.2	Decay modes, branching ratios and beta spectra
PhotonEvaporation	6.1.2	Nuclear levels and gamma transitions
G4ENSDFSTATE	3.0	Nuclear ground states and half-lives

3.2 Geometry and materials

Each solid – a box, a tube or a sphere, including shells and segments – is passed to Geant4 with its dimensions, its position and rotation in its parent, and its material. A solid placed inside another displaces the parent's material where it sits, so the tree of solids describes the geometry exactly as it is drawn. Before any decay is simulated, Geant4 checks every solid against its siblings and its parent, and the run is refused if any overlap or stick out: a point may belong to one solid only.

A material is passed as its density and composition: elements by mass fraction or by number of atoms, or other materials by mass fraction. An element is either one of natural isotopic composition or one defined by its

isotopes, as the material library holds it. Geant4 computes all interaction cross sections from the composition and density; RadMap passes no cross sections of its own.

3.3 Sources

A source is a radionuclide with an activity, spread through the volume of a solid.

Activity. An activity given per volume or per mass is multiplied by the volume of the source's solid, less the solids placed inside it, and for per mass by its material's density. The activities of all sources add up to the total activity of the project.

Choosing a decay. Each history of the simulation is one decay: one primary particle, as the simulation settings count them. The source it belongs to is drawn at random, each source with a probability equal to its share of the total activity.

Where it decays. The position is drawn uniformly in a box around the source's solid and kept only if it lies in the solid and not in a solid placed inside it; otherwise it is drawn again. The positions are thus uniform through the source's volume, right up to its surfaces. A volume too thin to sample this way stops the run with a message naming the solid. Sampling right up to the surfaces, and stopping on a volume too thin to sample, are RadMap's patches to Geant4's source sampling.

The decay. The nucleus decays at rest, by Geant4's radioactive decay module, from the data sets above: its decay mode and branch, the beta spectrum, and the gamma transitions, conversion electrons and X-rays of the daughter's de-excitation, all emitted isotropically. A daughter left in an excited or metastable state de-excites in the same history, however long the state lives; so Cs-137 gives the 662 keV photons of Ba-137m. A daughter in its ground state is dropped, unless *Full chain* is on for the source: it then decays too, and so on down the chain, each member once per decay of the source. Time plays no part, so a chain is counted as in secular equilibrium. Whether a history follows the chain is decided by the isotope it starts from, never by a daughter's, so sources of different isotopes whose chains meet keep their own settings.

What the decay emits is followed as described in *Transport*: photons and positrons always, electrons only when asked for. Alpha particles and neutrinos are dropped at once.

3.4 Transport

Particles are followed through the geometry with Geant4's standard electromagnetic physics, option 3 (`G4EmStandardPhysics_option3`), which is meant for accurate low-energy work. For photons it simulates:

- the photoelectric effect, with Livermore cross sections and the fluorescence X-rays of the atom left behind;
- Compton scattering, with the Klein–Nishina model and the effects of the atomic shells the electron is bound in;

- Rayleigh (coherent) scattering, with Livermore data;
- pair production, above 1.022 MeV.

Electrons, from decay and from photon interactions, are dropped where they are created unless *Simulate electrons* is on. The dose RadMap reports is photon dose, so this costs only the photons electrons would produce: their bremsstrahlung, which matters for energetic beta emitters in dense shielding, and the X-rays of the atoms they ionise. With *Simulate electrons* on they are followed until they stop, with multiple scattering, ionisation and bremsstrahlung.

Positrons are always followed, and annihilate, in flight or at rest, into photons that are followed in turn. Neutrons, such as those of spontaneous fission, are not given any interactions: they leave the geometry without effect.

Secondary particles are produced only above Geant4's production thresholds, set by a range of 1 mm in each material; below it their energy is deposited locally. Photons are followed down to the lowest energies Geant4 tracks them, well below the 10 keV where the conversion coefficients begin.

3.5 Scoring

A dose map is a box placed in a parallel geometry: it shares positions with the solids but not their materials, so it does not affect the transport, and it may overlap solids and other dose maps. Each map takes one of Geant4's parallel geometries, of which a run can have 15 besides the geometry itself.

Fluence. Each step a photon takes inside the box adds

$$h(E)\,\frac{\ell}{V},$$

where $h(E)$ is the conversion coefficient at the photon's energy, ℓ the length of the step and V the volume of the box. The fluence at a point is the number of photons crossing a small sphere there, divided by the sphere's cross-section; averaged over a volume, it equals the total length of the photons' paths in that volume divided by the volume. So ℓ/V is the step's share of the fluence, which does not depend on the photon's energy; $h(E)$, the dose per unit fluence at that energy, converts the share to dose. The sum is therefore the dose from the fluence averaged over the box's volume, whatever the field and however the box is turned. Every photon in the box counts: those that pass through it, those scattered in it and those emitted inside it.

A mean over a volume, not over a surface. Where the fluence is the same throughout the box, its mean is the fluence at any point in it. Where it changes across the box – near a source, at the edge of a shield's shadow – the mean is not the value at the box's centre, nor the value at the faces the photons enter by. In the field of a point source, a cube of side s whose centre is at a distance d reads about $1 + s^2/12d^2$ times the fluence at its centre, in any orientation: 0.75 % more for a 30 cm cube at 1 m. A thin plate facing the source reads the mean over its face, slightly less than at its centre. RadMap's versions before 2.0 scored the photons entering the box instead, divided by the area of the box seen from their direction. For a thin plate that is the same thing, but a deep box read nearer the fluence at the faces the photons

entered by, and its reading changed when it was turned (defect D-0005 on the errata page).

Conversion coefficients. $h(E)$ comes from the publication the project uses for the map's quantity (*Dose* → *Dose settings*; the user guide's *Origin of conversion data* lists them). Between the tabulated energies it is interpolated with a natural cubic spline. Below the lowest tabulated energy, 10 keV, effective dose and H∗(10) take zero and air kerma takes its 10 keV value; above the highest, all three keep their last tabulated value.

Dose rate. The scores of all histories are summed and divided by the number of primary particles simulated, N, which gives the dose per decay. Multiplied by the total activity, in decays per second, and by 3600 seconds per hour, it gives the dose rate: in Sv/h for effective dose and H∗(10), in Gy/h for air kerma.

3.6 Statistics and reproducibility

The scores of one history are independent of those of another. The uncertainty RadMap reports is therefore the standard deviation of the mean over histories,

$$\sigma = \sqrt{\frac{1}{N(N-1)}\left(\sum_i x_i^2 - \frac{1}{N}\Big(\sum_i x_i\Big)^2\right)},$$

with x_i the score of history i and N the number of primary particles, scaled to a dose rate as the mean is. It is the statistical uncertainty of the Monte Carlo estimate only; the uncertainty of the data and of the model the user built is not in it. It falls as $1/\sqrt{N}$.

Each run draws its random numbers from a new seed and uses all the processor's cores. Two runs of the same project therefore differ within their uncertainties. With a fixed seed on one thread, a run is repeated exactly; RadMap's tests run so. On several threads the result can differ in its last digits from run to run, because the threads' sums are added in the order the threads finish.

3.7 Verification

The V&V report published with each version checks these methods against published data and measurements: the dose from point sources against the published coefficients and decay data, attenuation and buildup in shielding, the sampling of sources, interpolation, and air kerma against measured experiments. It is generated from the tests run on that version's build.

4 End-User License Agreement (EULA) of RadMap

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4.8 Export Control

The Software incorporates radiation transport simulation technology. You agree to comply with all applicable export control laws and regulations, including those of Sweden, the European Union, and the United States, and not to export or re-export the Software to any country, entity, or individual in violation of such laws.

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5 Third-party software

RadMap includes software and data made by others. The copyright notice and the full licence text of every component RadMap or its installer ships are in `ThirdPartyNotices.txt`, in the `Doc` folder of the installation directory, and in **Help** → **About**. This section gives the notices whose licences ask for them in the user documentation.

5.1 Geant4

DoseAlgorithm, which runs RadMap's simulations, uses the Geant4 toolkit for the radiation transport.

This product includes software developed by Members of the Geant4 Collaboration (http://cern.ch/geant4).

RadMap ships a modified version of Geant4, built from RadMap's fork of it, https://github.com/RadMap/geant4; it is not the Geant4 Collaboration's release, and RadMap is not endorsed by the Geant4 Collaboration.

The Geant4 data sets RadMap installs (G4EMLOW, G4ENSDFSTATE, PhotonEvaporation and RadioactiveDecay) are distributed by the Geant4 Collaboration with the toolkit. They are derived from evaluated nuclear and atomic data, among them ENSDF and the Livermore libraries (EPDL97, EEDL, EADL, EPICS2014).

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5.2 g4tools

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5.3 Xerces-C++

This product includes the Xerces-C++ XML parser, which DoseAlgorithm uses to read geometry.

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