Modeling Effects on Materials of Exposure to Cold X-rays in Space

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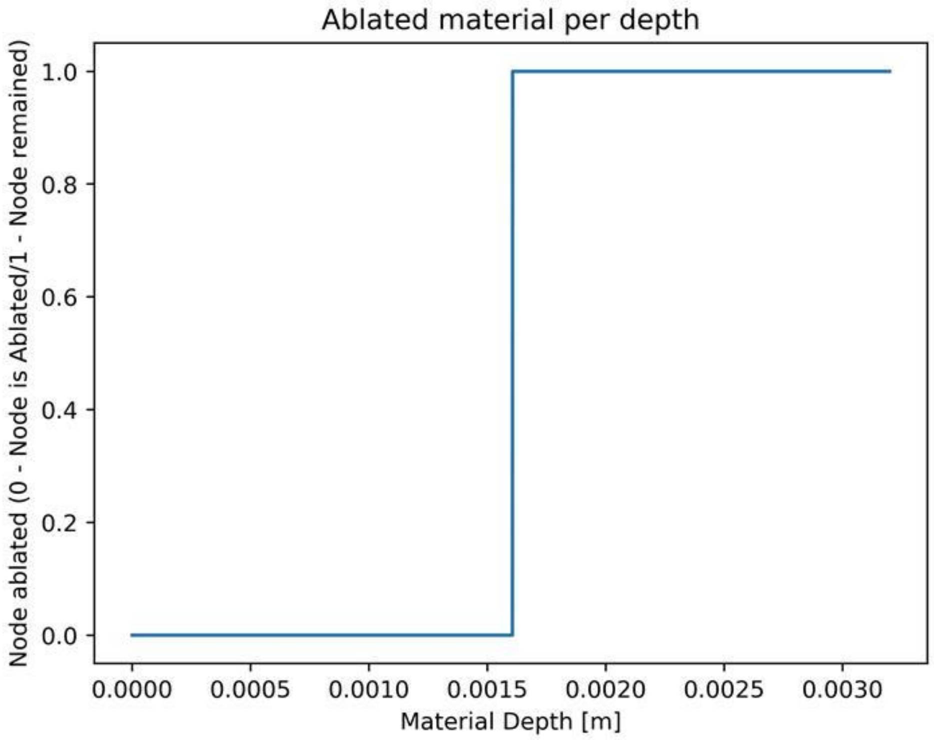
EN.535.610 Project Presentation

Project Summary

For this project, the group developed a library to simulate the effects of a high dosage cold x-ray exposure event and its effect of spacecraft materials. Cold x-ray events deposit significant amounts of energy on outer facing surfaces which can result in material removal via ablation from extreme energies and temperatures. The group performed an example simulation on a space radiator, used to exhaust satellite heat and found the cold x-ray exposure removed the specialized radiator's thermal paint and even some of the radiator's underlying structure.



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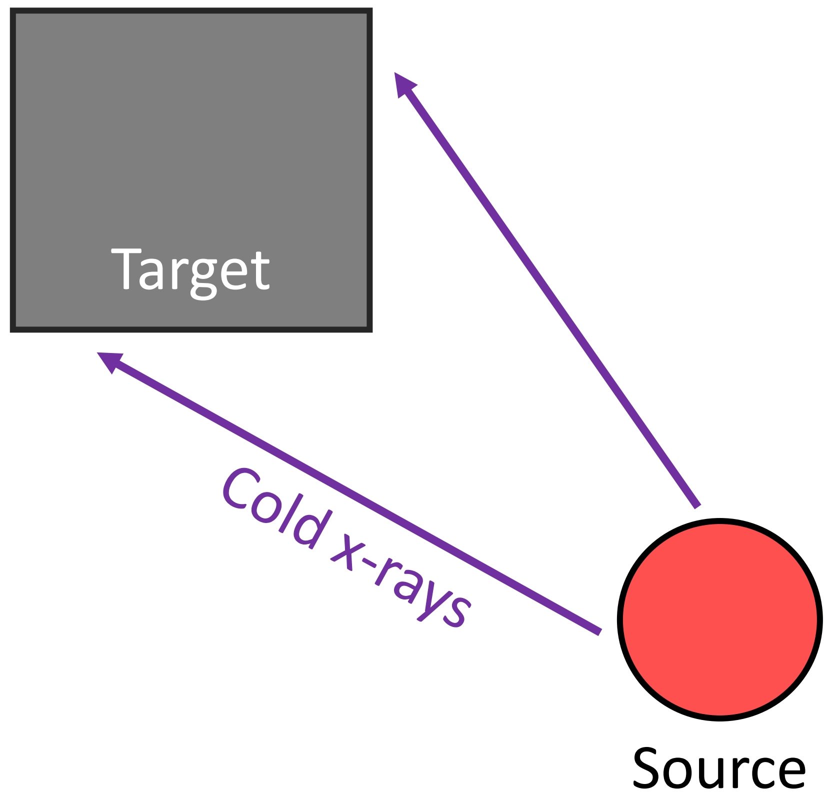
Cold X-rays

- Cold x-rays are photons with energies approximately between 1 keV and 15 keV [6][7].
- A source of concern for these x-rays are when a nuclear weapon is detonated in space. Per Smith et al, approximately 75% of the total energy is released in this form.
- The cold x-rays disperse radially until interacting with some form of matter. For solid surfaces (e.g. satellite radiator or solar panel) most of the energy is absorbed in shallow depths, resulting in high temperatures and even ablation and shock given enough x-ray flux.



Problem Breakdown and Tools Used

- The entire process is broken down into three separate components.

1. X-ray transport/absorption through material.

   Python libraries: xraydb (x-ray related material properties), Matplotlib (data visualization), and numpy (efficient numerical calculations and data structures)

2. Ablation evaluation.

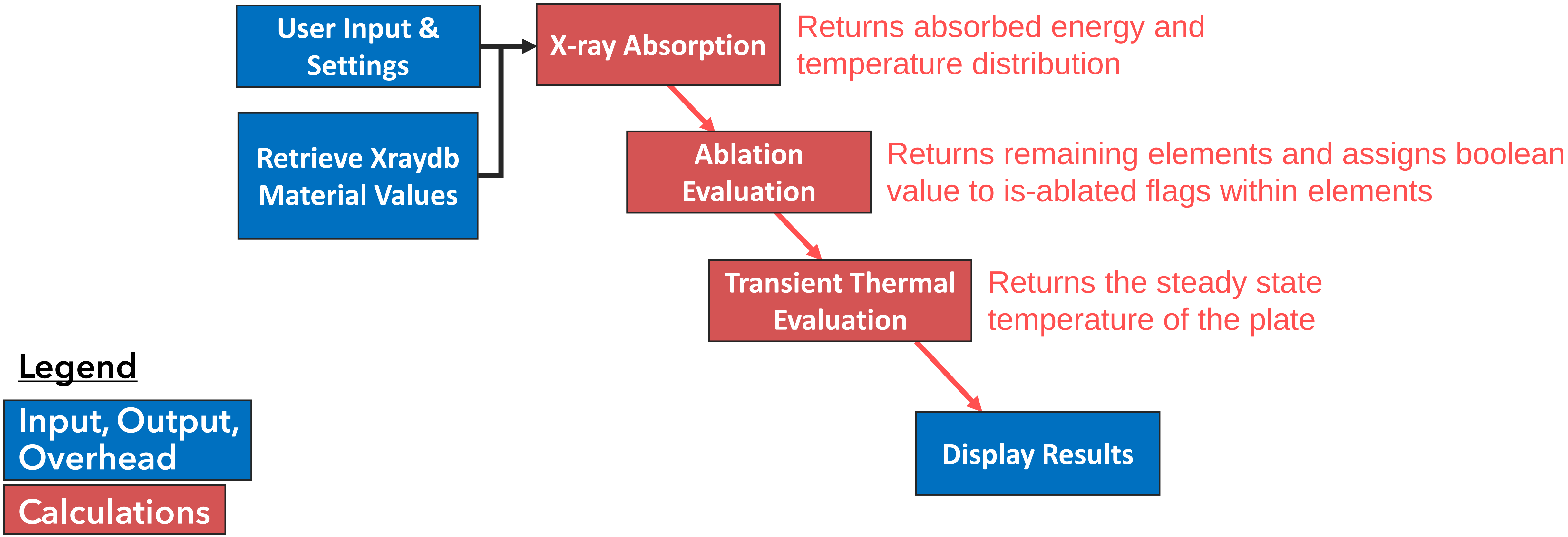
   Python libraries: Matplotlib (data visualization), and numpy (efficient numerical calculations and data structures)

3. Transient thermal evaluation.

   Python libraries: Matplotlib (data visualization), and numpy (efficient numerical calculations and data structures)

- General Tools: Github was used for version control. PyPI was used to provide access/installation for the finished package. Microsoft Teams was used for collaboration.

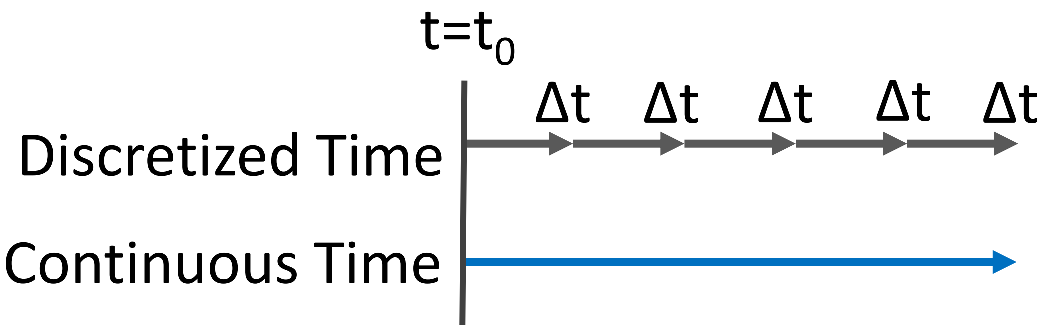
Simulation Flow



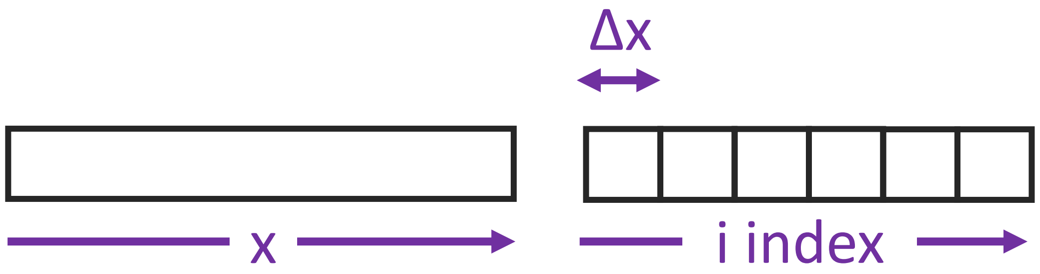
Simulation Discretization

- The simulation uses spatial and temporal discretization to solve the governing equations numerically.

- Continuous time is broken up into individual, small time steps so that differential equations can be solved as difference equations through time.



- Continuous space is broken up into small elements so that differential equations can be solved as difference equations through space. This is helpful when multiple materials are layered together.



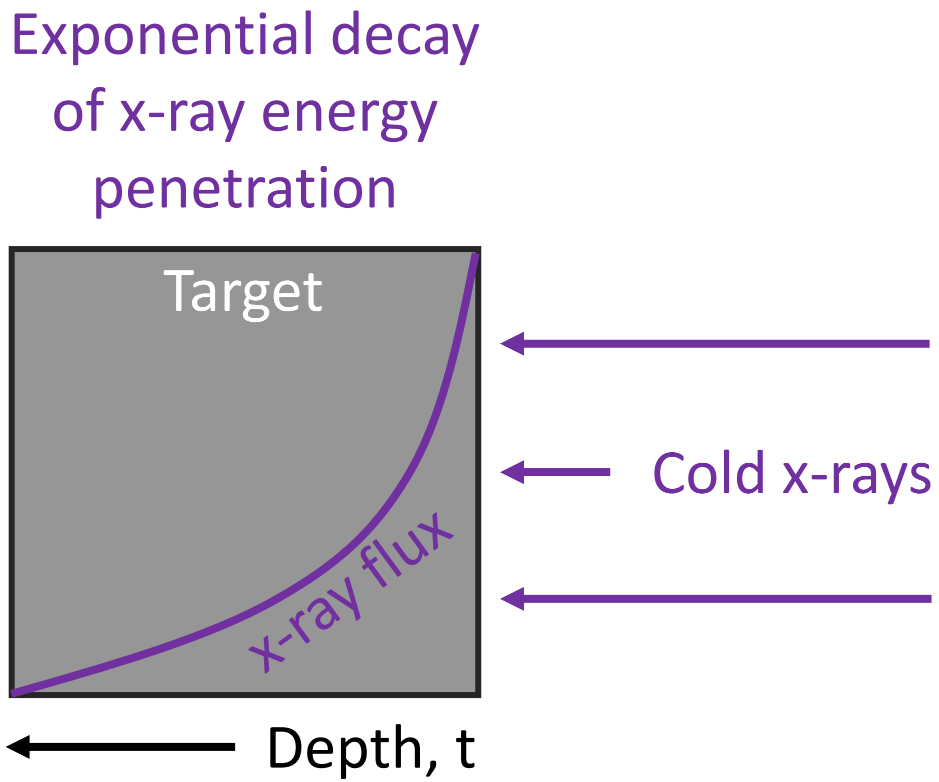
X-ray Energy Absorption

- **Most of the energy from the cold x-rays is absorbed in the outermost depths of a material. The energy transmitted decays exponentially as a function of depth (t), mass attenuation factor (μ/ρ), and starting energy I_0. [6]**

$$I(t) = I_0 e^{\left(-\frac{\mu}{\rho}x\right)}$$

$$x = \rho t$$

Where ρ is density [6].



X-ray Energy Absorption Simulation

- The analytical solution for x-ray energy penetration is a solution to a first order ordinary differential equation (ODE).

$$I(t) = I_0 e^{\left(-\frac{\mu}{\rho}x\right)} \qquad x = \rho t$$

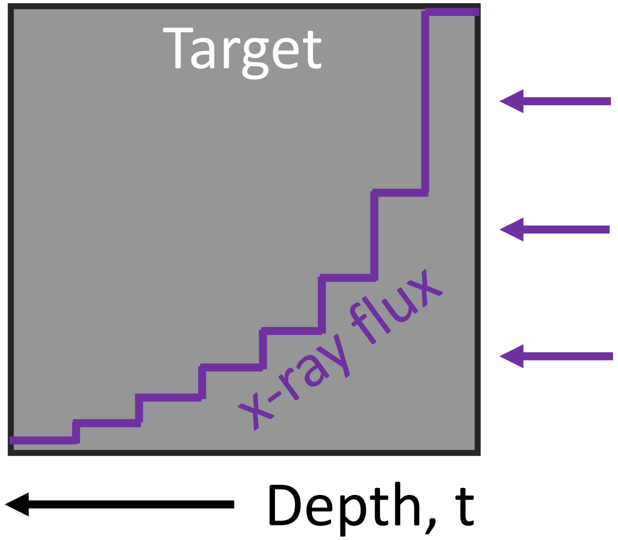
- The original ODE is then of the following form.

$$\frac{dI}{dx} = I\left(-\frac{\mu}{\rho}\right)$$

- The ODE can then be discretized spatially and solved as a difference equation of the following form where we're interested in the change in x-ray energy per element.

$$\Delta I = I\left(-\frac{\mu}{\rho}\right)\Delta x = -I\mu\Delta t$$

Simulation of x-ray energy penetration

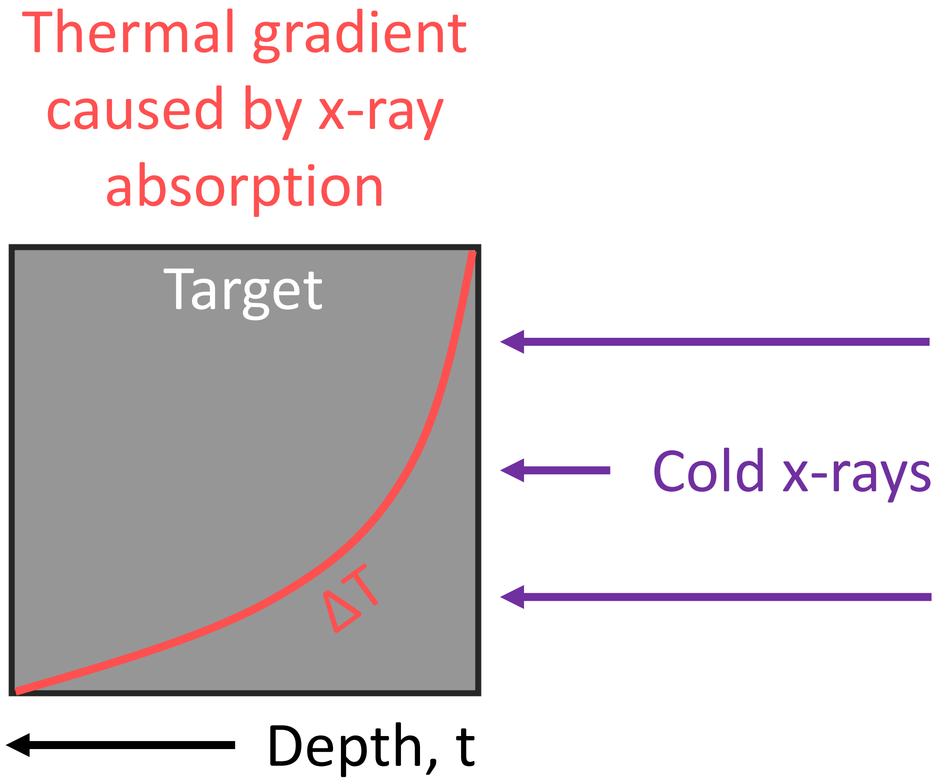


Thermal Effects from X-ray Absorption

- The energy absorbed is converted into heat, resulting in dramatic temperature increases and thermal gradients.
- The change in temperature is described by the following equation.

$$Q = c_p m \Delta T$$

Where Q is the thermal energy from x-ray absorption, c_p is the material's specific heat, m is mass, and ΔT is the change in temperature.



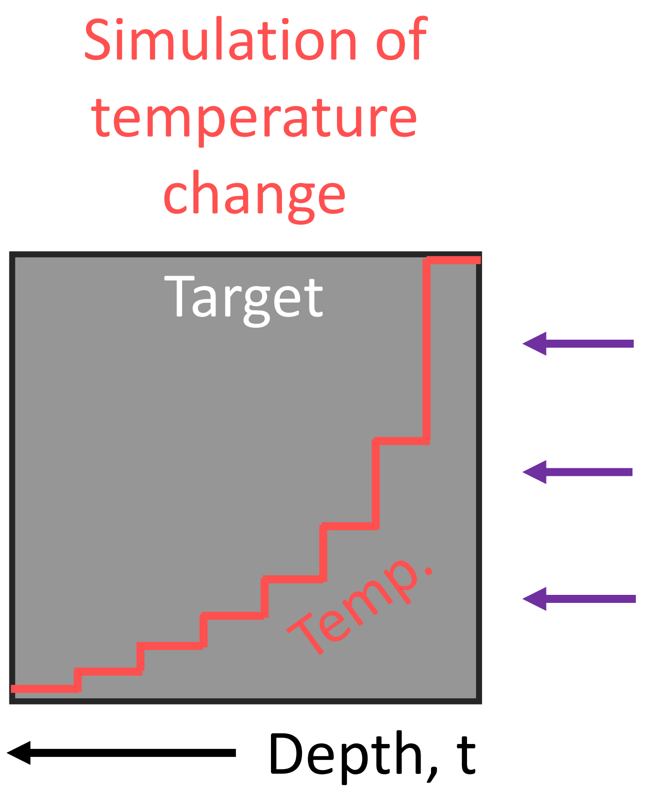
Thermal Effects from X-ray Absorption Simulation

- To simulate the change in temperature of each element as a function of absorbed x-ray energy, the same analytical equation was used, just evaluated for each element treated as an independent volume.

$$Q = c_p m \Delta T$$

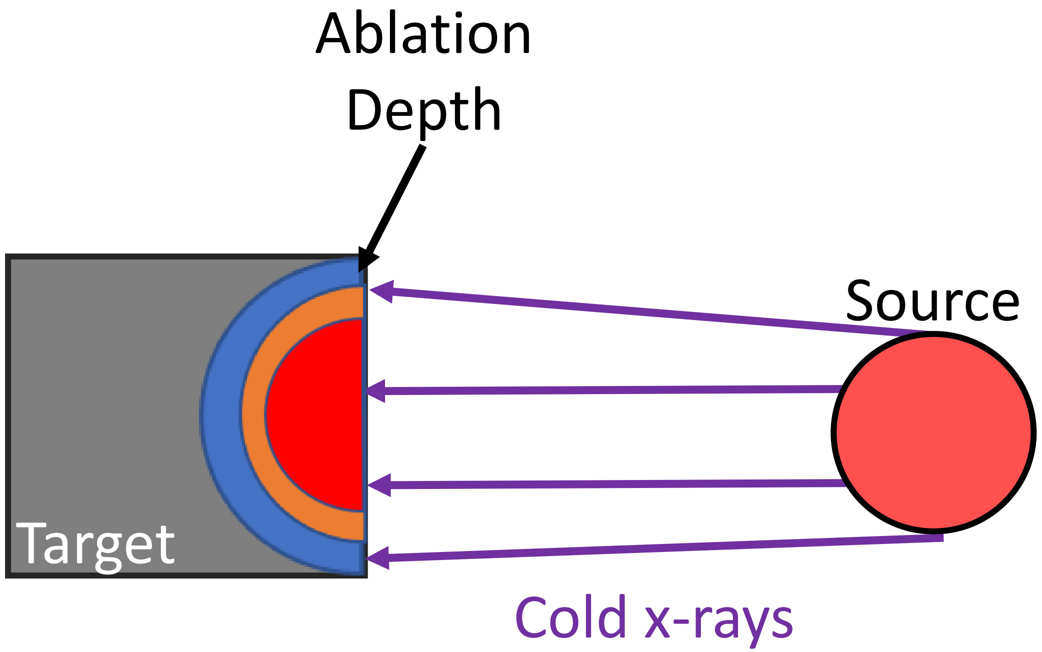
- Which takes the following form in the simulation.

$$T = \frac{Q}{c_p m} + T_0$$



Effects on Materials

- Due to the extreme heat and energy absorbed by the cold x-rays, the material ablates.
- Ablation is a mixture of vaporization and pressure which causes the material to essentially be blown away.
- Unfortunately, ablation is a complex process and was beyond the scope of our project. Instead, we approximated the ablated material by comparing vaporization temperatures of material to the temperature rise due to the x-ray event.

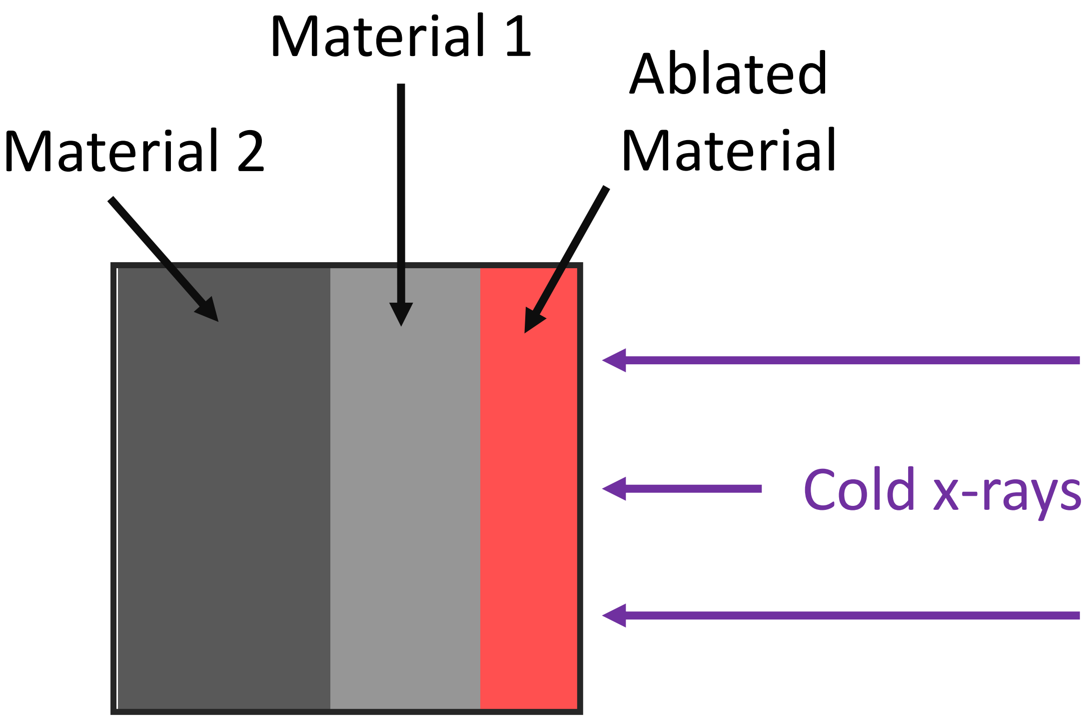


Effects on Materials Simulation

- The simulation was done at the nodal level with a simple comparison

$$T_{node} > T_{mat\_vaporization}$$

- After that comparison, the simulation updates the material section to show which nodes have been ablated.
- The ablation status is stored within each element as a Boolean (i.e., True/False variable)

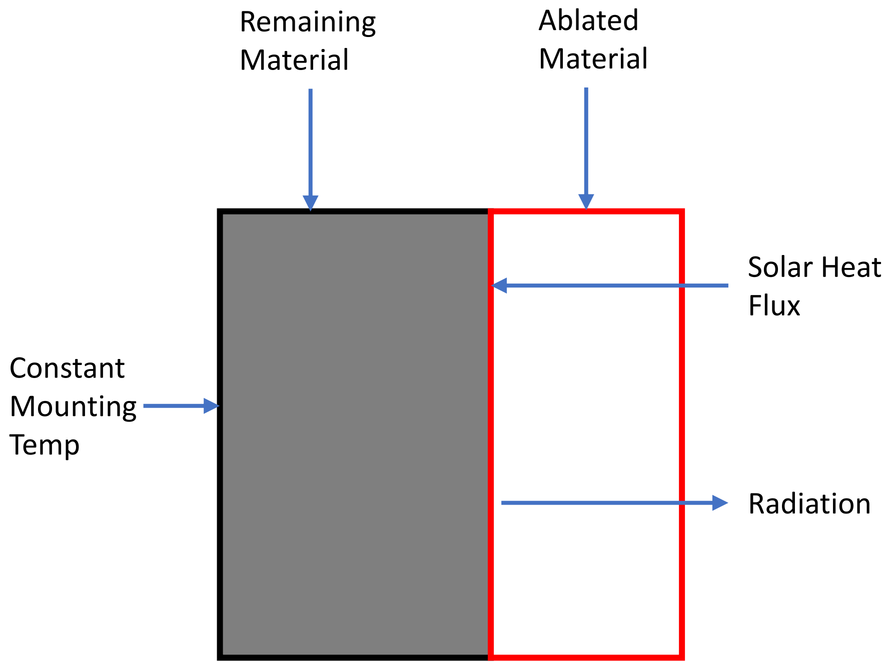


Effects on Transient Thermal Analysis

- After ablation the model will iterate over spatial and time steps solving the 1-D partial differential equation using the Stefan-Boltzmann law to model the radiative heat transfer on the remaining material of the plate

$$\frac{\partial Q}{\partial t} = \sigma \cdot e \cdot A \cdot (T_1^4 - T_2^4)$$

- Where σ is the Stefan-Boltzmann constant, e is the emissivity of the material, A is the surface area of the radiator, and T is the temperate difference between the radiator and black body space.



Check Your Understanding

Question 1

- The x-ray energy penetration curve through a material with a constant absorption coefficient has the following shape.

  A) Exponential growth
  B) Linear
  C) Exponential decay
  D) Second-order polynomial

Question 2

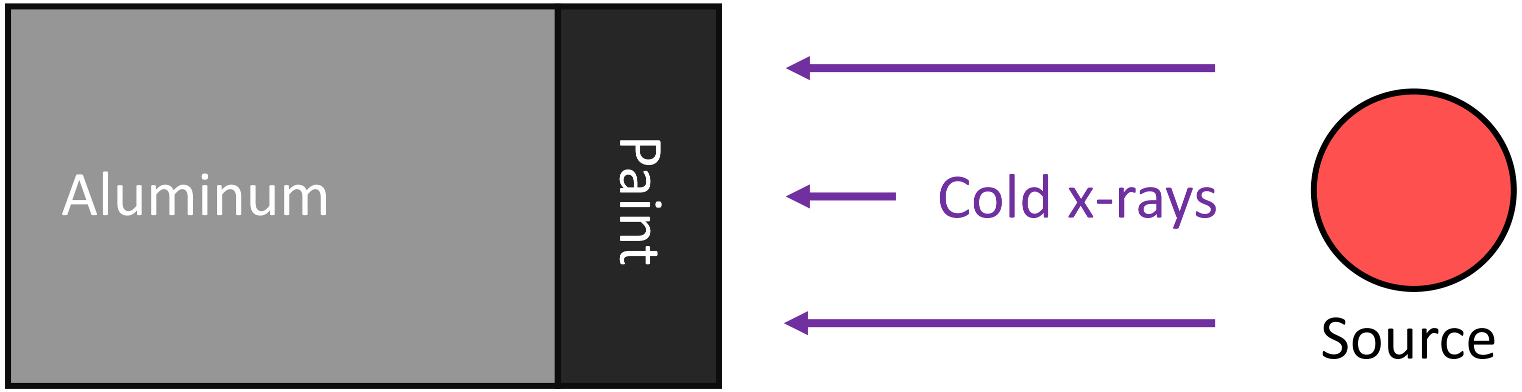
- True or false: The x-ray energy is absorbed uniformly throughout the thickness of the material.

  A) True
  B) False

Answers on last slide

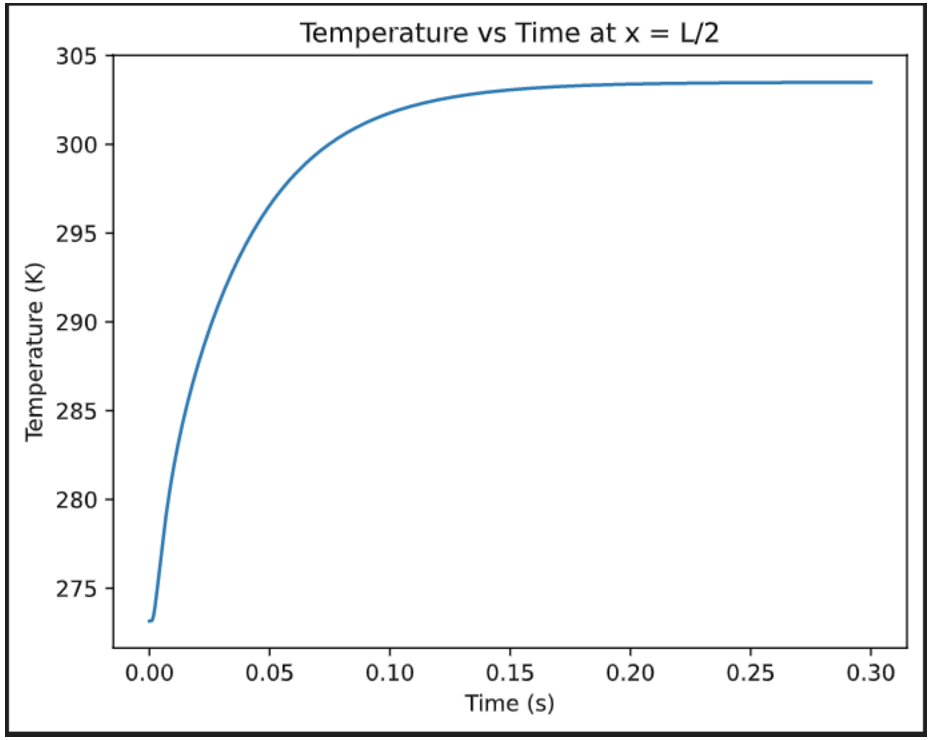
Example Simulation: Cold X-ray Exposure of Satellite Thermal Radiator

- One of the main concerns and application areas for cold x-ray exposure is the effect on satellites when a nuclear detonation occurs in space.
- The x-rays are absorbed near the surface of materials and cause intense heat and temperature gradients. It can even be enough to remove material via ablation.
- This problem evaluates a satellite radiator painted with high emissivity paint. The simulation will be used to determine if enough material remains for the radiator to function after exposure.



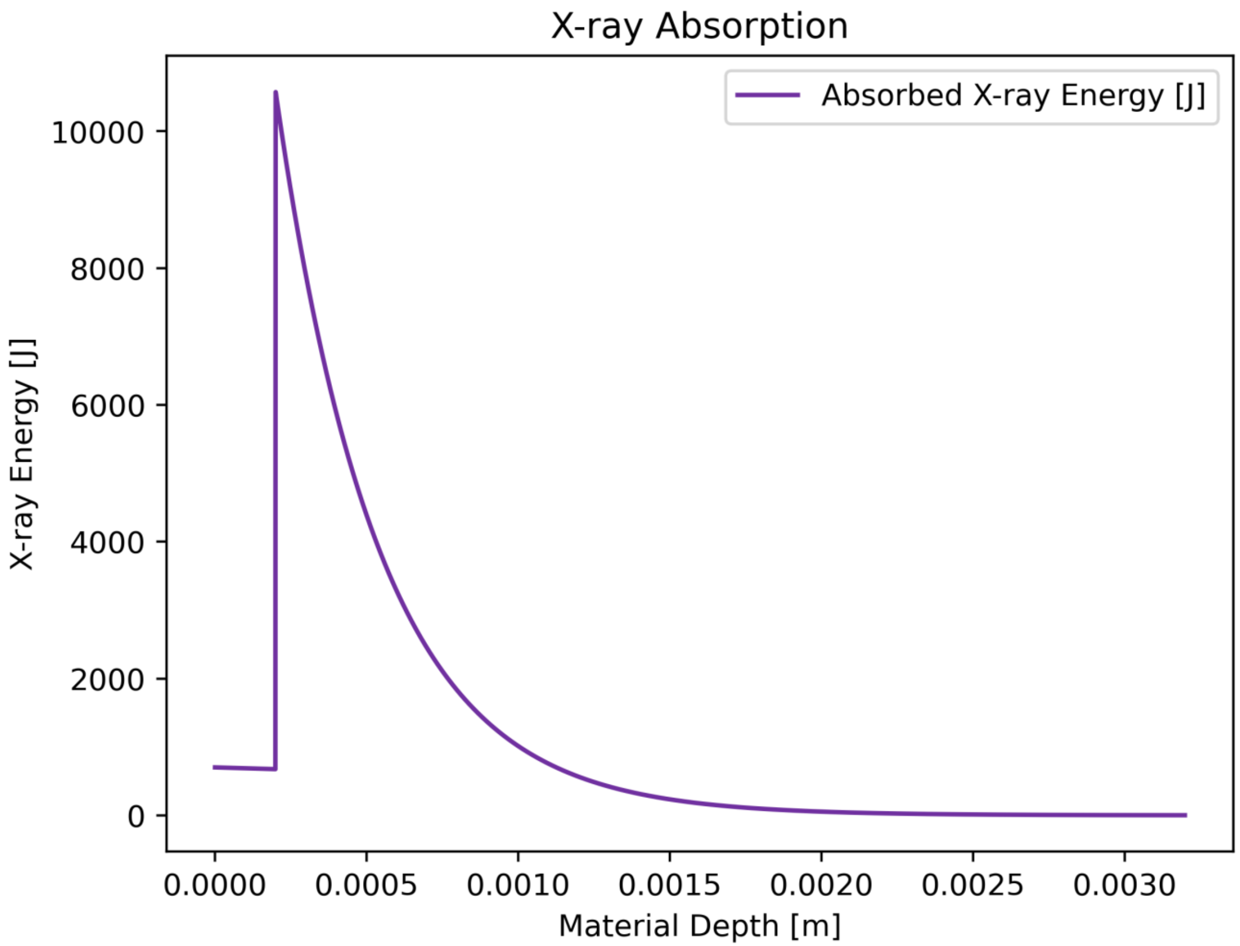
Pre-Cold-Xray Thermal Equilibrium

- Pre-ablation, the radiator starts at 273.15 K and absorbs heat from the spacecraft until it reaches thermal equilibrium near the constant temperature input of 303.15 K from the space craft.



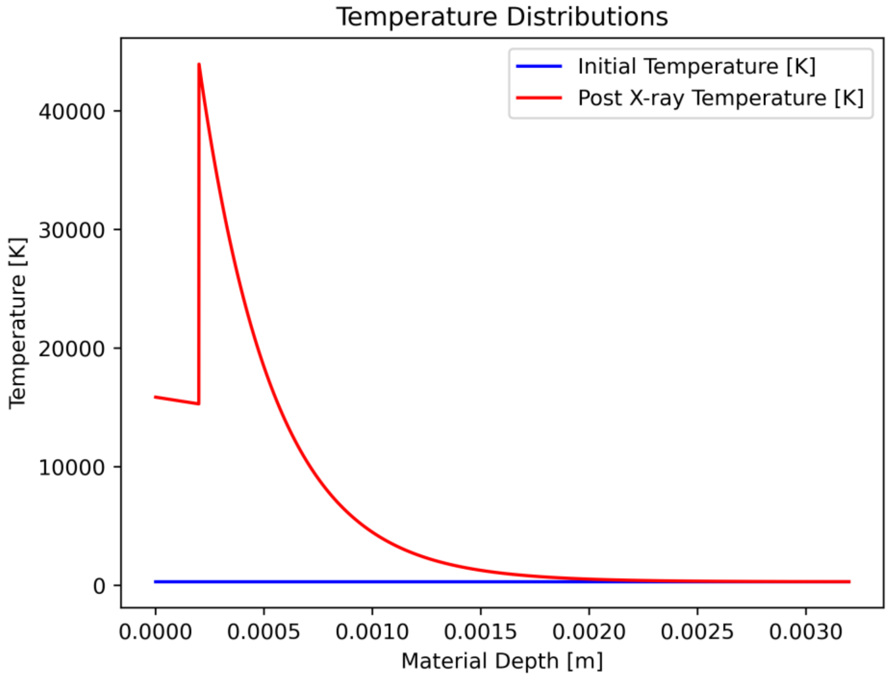
Satellite Radiator Simulation

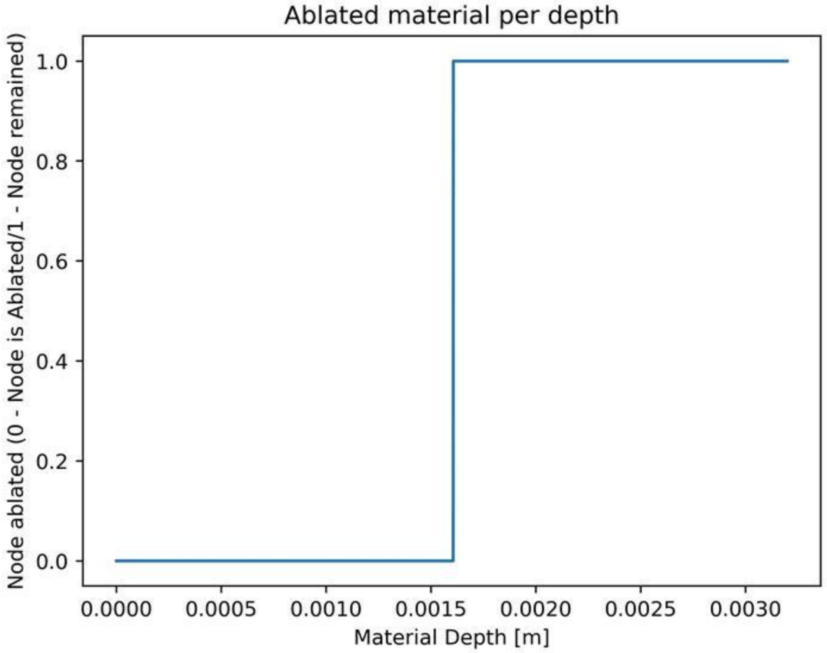
- The incoming x-ray energy profile is as follows per M.S. Smith et al [2].
  - Flux: 1.7882e21 [Total X-rays]
  - Energy: 13.5e3 [eV]
- The mass attenuation factors (from xraydb) and densities are as follows.
  - Aluminum
    - Mass attenuation factor: 1.08 [m^2/kg]
    - Density: 2700.0 [kg/m^3]
  - Paint (approximated as epoxy)
    - Mass attenuation factor: 0.12 [m^2/kg]
    - Density: 1500.0 [kg/m^3]
- The paint is much more transparent than the aluminum and absorbs much less energy.



Satellite Radiator Simulation, Temperature

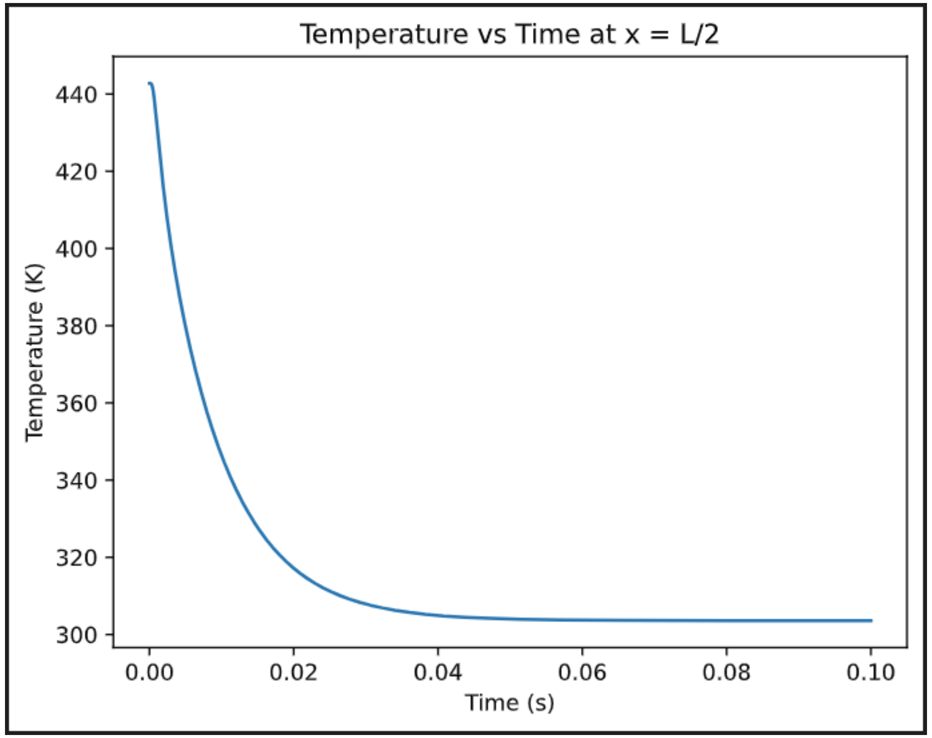
- Post x-ray event, the material gets up to as high as 40,000K.
- These extreme temperatures lead to 53% of the material stack to being removed.





Post Cold-Xray Thermal Equilibrium

- Post ablation, the radiator can dissipate the heat absorbed and equilibrate near the constant temperature input of 303.15 K from the space craft.

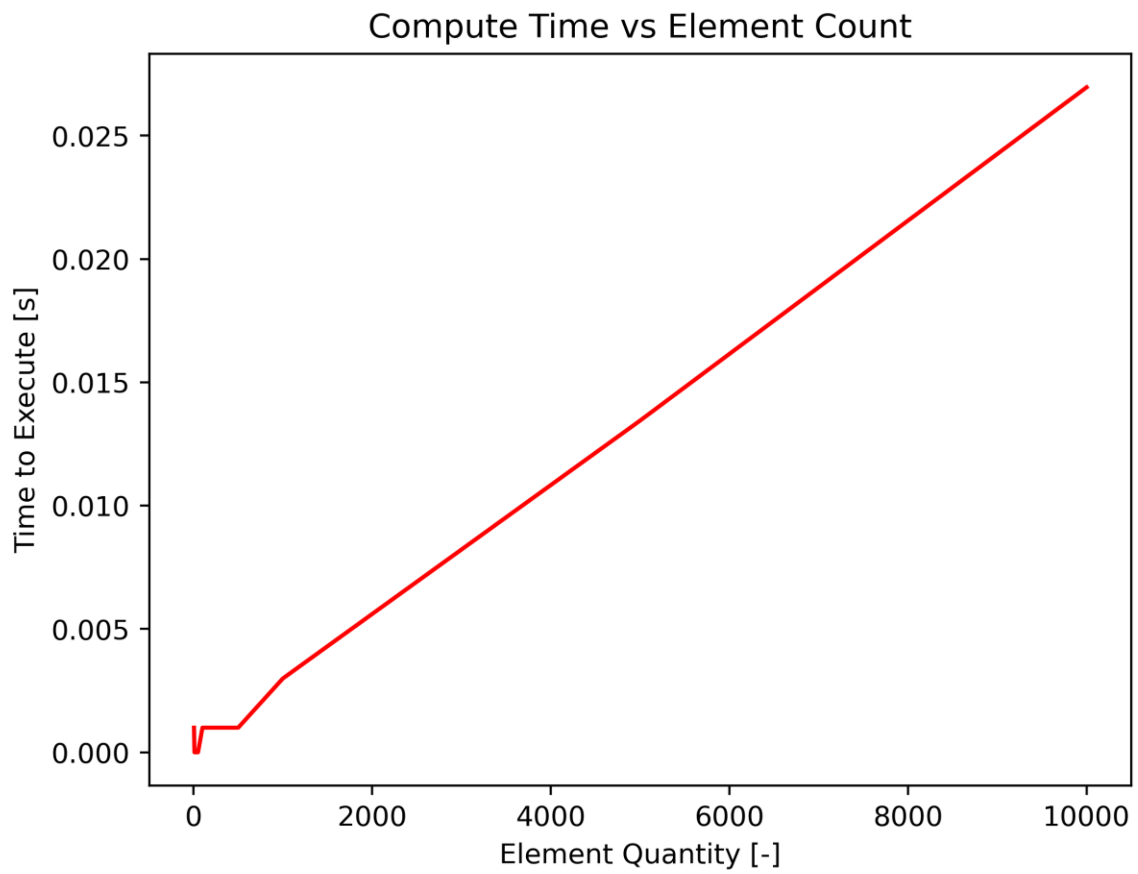


Satellite Radiator Simulation, Conclusions

- The radiator absorbs a significant amount of energy from the cold x-rays, particularly toward the front surface.
- The energy is so significant that all radiator paint and almost half of the Aluminum is lost to ablation.
- From these results, it's evident that the radiator won't be able to dissipate as much heat (compared to the as-designed condition) because the emissivity of Aluminum is much worse than black paint.

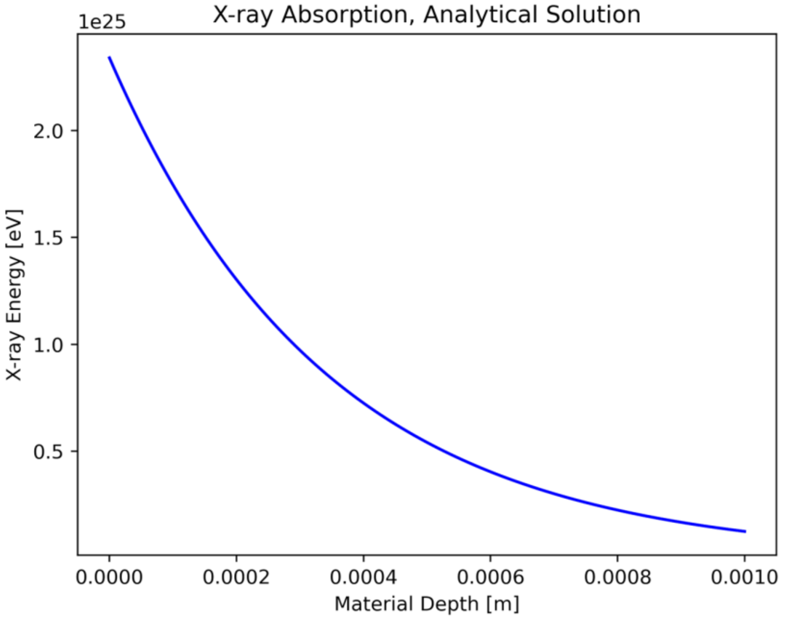
Problem Complexity and Hardware Requirements

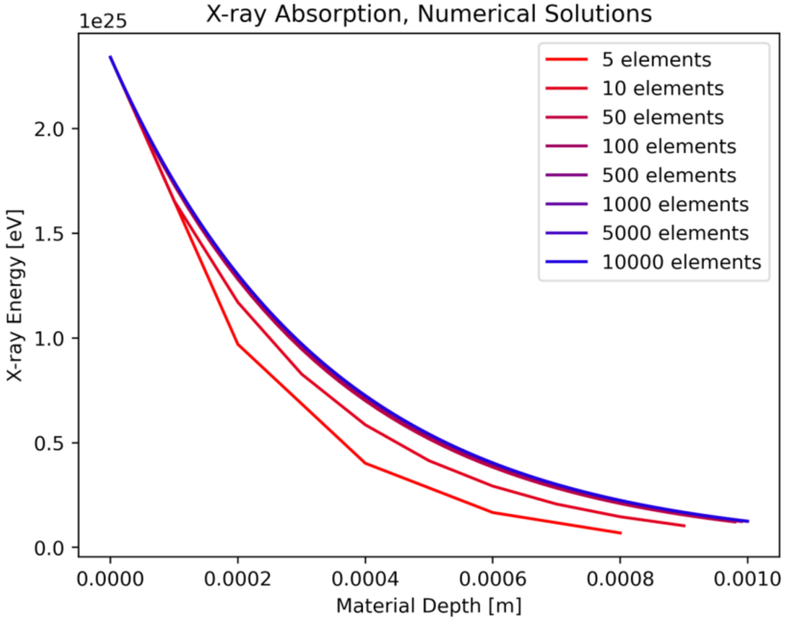
- Each component of the simulation scales linearly, O(n), with both spatial and temporal fidelity and is deterministic.
- This was verified by running the radiation transport model with increasing number of elements and plotting the run time.
- For anything except the most extreme cases, computation power available in most personal computers should be more than adequate.

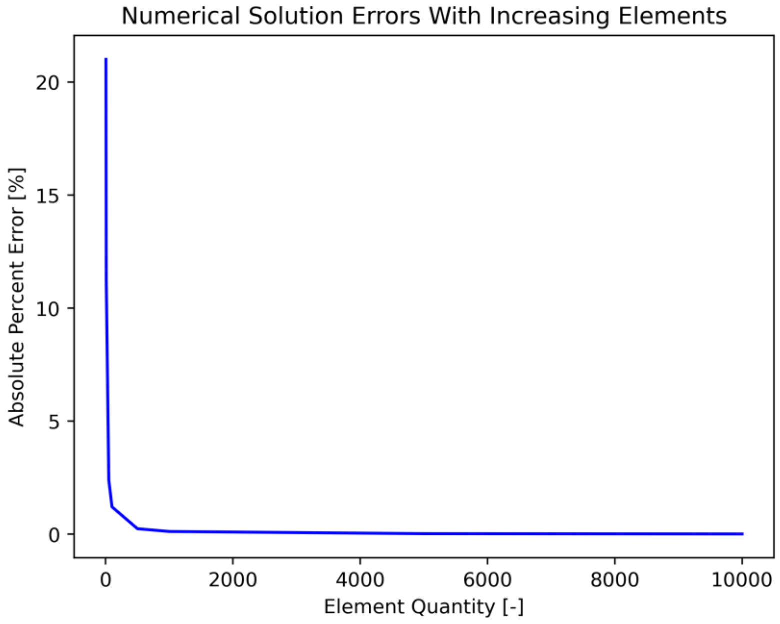


Error and Solution Convergence

- The components of the simulation quickly converge on accepted analytical solutions (where possible given complexity of material composition).
- This is shown for the x-ray transport component where the numerical energy penetration curve quickly approaches the analytical solution. After about 500 elements, the improvement to solution accuracy is negligible.

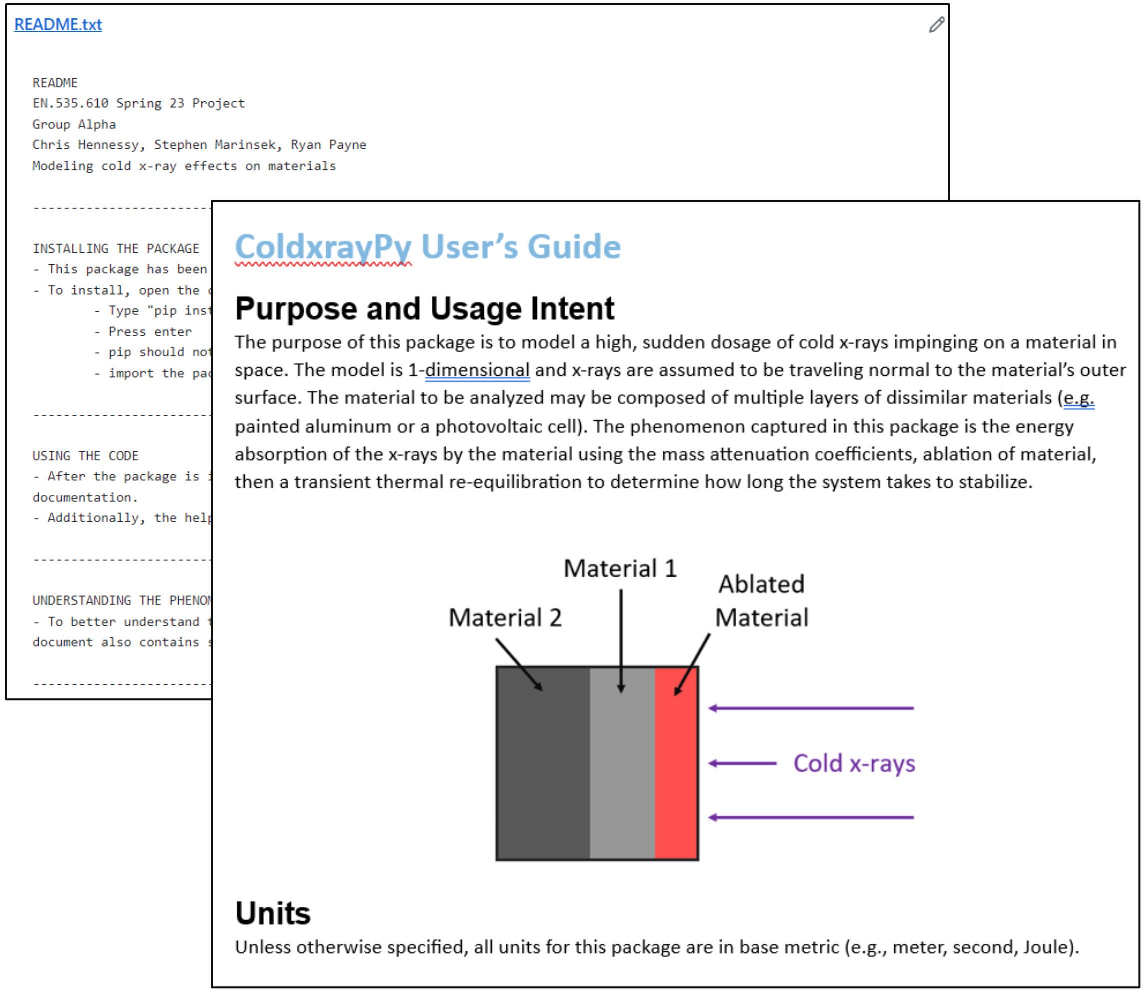






Documentation and Availability

- The Python code generated for this project was exported as a library and uploaded to PyPI as "coldxrayPy". This means the package can easily be installed and used by anyone by running "pip install coldxrayPy".
- Thorough user documentation on the code is provided in the associated Github repository and is publicly available here: https://github.com/smarinsek/EN.535.610.81.SP23-Project
- Additionally, each class and method has descriptive text available via the help() method.



Next Steps and Capability Expansion

- Ray tracing could be added to capture the x-ray's path from the source to the target. This could model things like scattering from small amounts of atmosphere.
- The x-ray absorption and ablation models could be expanded to two and three dimensions.
- Material effects from being exposed to elevated temperatures (but not enough to ablate) could be evaluated. For example, changing the heat treatment of alloys from being taken to elevated temperatures.
- 2D and 3D heat transfer equations would be needed to better represent the boundary condition for the solar flux and radiation because boundary condition surface areas significantly impact results.
- The simulation could be further streamlined with more efficient data containers and algorithms (e.g., all lists switched to numpy arrays after initialization).

References

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Check Your Understanding Answers

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