SENSITIVITY STUDY OF IMPACT RISK MODEL RESULTS TO THERMAL RADIATION DAMAGE MODEL FOR LARGE OBJECTS

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ABSTRACT

NASA's Probabilistic Asteroid Impact Risk (PAIR) assessment model assesses the likelihood of potential damage for asteroid impact scenarios. Fast-running models are used to capture the effects of different hazards. This paper looks specifically at local ground damage hazards, including blast overpressure and thermal radiation damage, for large object impact scenarios. A sensitivity study is conducted to determine which parameters, and over what ranges, cause impact risks to become sensitive to thermal damage. Two additional thermal models with different approaches are used for comparison. The study determined the current thermal model is most sensitive to the luminous efficiency parameter that reflects the model's uncertainty in the amount of energy contributing to the thermal radiation damage. This sensitivity was most apparent for the highest severity damage levels. Comparisons of the three models showed that in addition to sensitivities within the models, the impact risks are also sensitive to the choice of thermal model. The study results were applied to the 2023 Planetary Defense Conference hypothetical asteroid impact scenario and parameter ranges of interest determined. At the serious damage level, luminous efficiencies above 0.006 showed a small chance of thermal playing an important role, while luminous efficiencies above 0.0008 led to thermal playing a significant role at the unsurvivable damage severity level. Study results are used to identify key areas where additional model refinement and better knowledge of asteroid properties may be important for improving damage estimates.

Keywords: *Asteroid impact hazards, thermal radiation modeling, ground damage modeling, risk assessment, sensitivity study*

1. INTRODUCTION

Asteroid impacts and airbursts can cause multiple types of hazards, including local ground damage, tsunami inundation, or large-scale global effects. Decision makers and emergency response planners need the best available information on the range and likelihood of different impact consequences to make the best decisions. NASA has developed the Probabilistic Asteroid Impact Risk (PAIR) model to provide this information (Mathias et al. 2017). PAIR uses fast-running models in a Monte Carlo framework to

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*Corresponding author: ashley.m.coates@nasa.gov determine the potential damage from these hazards across a wide range of uncertain asteroid properties and impact factors. Of the three hazard groups, this study focuses on the local ground damage. Local ground damage consists of blast overpressure and thermal radiation damage. At each damage severity level considered, the leading hazard (the larger of blast and thermal damage) is used to define the zone at risk to that level of damage.

Typically, blast overpressure is the leading local ground damage hazard, although, as will be demonstrated in this study, thermal radiation damage can become a factor in larger object scenarios such as the 2023 Planetary Defense Conference (PDC) impact exercise scenario. A comparison of the PAIR outputs for the 2021 PDC (100m) and 2023 PDC (800m) objects highlights the increase in both the potential for thermal damage and for thermal to dominate blast as object size increases. Based on the initial information for 2021 PDC shortly after discovery when the asteroid was still poorly characterized, 16% of Earth-impacting cases showed thermal damage and in only 0.2% of cases did it dominate blast. The final assessment after further observations showed all thermal damage fell within the most severe blast damage radius, making it insignificant. Initial information shortly after discovery for 2023 PDC, however, shows thermal damage occurring in 54% of Earth-impacting cases and dominating in 5% of cases. Final assessments for this scenario suggest that thermal radiation damage even exceeds blast damage at the highest severity levels (CNEOS Hypothetical Impact Scenarios).

We know there are some uncertainties in the asteroid properties and other parameters used in the thermal model, and as we look beyond smaller airburst cases towards assessing larger object cases, we need to better understand where the overall results become sensitive to the thermal radiation damage model. This study performs a sensitivity analysis to evaluate which parameters, and over what ranges, have the most significant influence on leading hazard determination, which ultimately determines the extent of damage and the affected population. Understanding where and how the impact risks are sensitive to the thermal model will highlight where additional model refinement will be necessary.

2. SENSITIVITY STUDY

In this section we introduce the setup of the sensitivity study. The thermal and blast models currently used in PAIR are described, as well as two additional thermal models considered for comparison. The parameters and ranges of interest in the sensitivity study are defined. We also discuss how thermal radiation damage is defined.

2.1 Thermal and Blast Models

PAIR currently uses an empirical thermal radiation damage model adapted from Collins et al. 2005 that is based on energy-scaled nuclear data from Glasstone and Dolan 1977. The Collins et al. model predicts the thermal radiation damage radius on the ground caused by a spherically expanding fireball generated from a ground impact. The thermal exposure ϕ (heating per area) at a distance r from the impact location is calculated as the energy emitted as thermal radiation divided by the area over which the energy is spread, where the luminous efficiency parameter η represents how much of the total energy contributes to thermal radiation damage (Eqn. [1]). To account for the impact-energy dependence of thermal radiation damage, an energy scaling law is used to determine the thermal exposure required to ignite a given material (Eqn. [2]). We will use this equation to determine the thermal exposure levels for four damage level severities of interest. Combining Equations [1] and [2], we get the final expression for damage radius at a given severity level (Eqn. [3]). PAIR uses a slightly modified version of this model to account for airbursts (Mathias et al. 2017). Because we are concerned in this study with large, impacting objects, the presented equations are sufficient for the sensitivity study. The smallest size ranges in the 2023 PDC Epoch 1 data may still airburst but are outside the range of the sensitivity study cases.

$$\phi = \frac{\eta E}{2\pi r^2} \tag{1}$$

$$\phi_i = \phi_i(1\ Mt)E_{Mt}^{\frac{1}{6}} \tag{2}$$

$$r = \sqrt{\frac{\eta E}{2\pi\phi_i}} \tag{3}$$

While the basis of this work is the Collins et al. model implemented in PAIR, other thermal radiation damage models with different approaches do exist. Two additional models are considered for comparison, one developed by the Institute of Geospheres Dynamics of the Russian Academy of Sciences (IDG RAS) (Popova et al. 2021) and the other developed by NASA's Asteroid Threat Assessment Project (ATAP) (Johnston and Stern 2019).

The IDG RAS model (Popova et al. 2021) is a scaling relation (Eqn. [4]) that calculates thermal exposure $Q\ (J/cm^2)$ on the ground based on a series of entry and impact simulations. This model is broken up into airburst and crater forming equations for the luminous efficiency η, radiation source height H_{rad}, and ellipticity parameter el. The crater forming equations, suited for diameters greater than 300m, are used for all cases in this study. The crater forming equation for the luminous efficiency is presented in Equation [5] and depends on diameter D, velocity V, and energy E. Spatial heterogeneity is not considered in the crater forming equations so the ellipticity parameter el becomes a constant value of 1. The radiation source height H_{rad} in the crater forming equations becomes a scaling factor of sorts. The authors of this paper are unsure how it is calculated for the crater forming equations, so we relied on the online impact effects calculator (www.asteroidhazard.pro) to determine the baseline value. The resulting thermal exposure contours on the ground are circular because the ellipticity is 1. Damage radius is taken as the radius of the circular area defined by a given thermal exposure level.

$$Q = 4.184e12 \cdot \frac{1}{4\pi} \cdot \frac{\eta}{100} \cdot \frac{E_{kt}}{10^{10}(H_{rad}^2 + x^2 + el * y^2)} \tag{4}$$

$$\eta = \frac{0.021D^{1.3}V^{1.5}}{E_{kt}^{0.45}} \qquad [5]$$

NASA's ATAP model (Johnston and Stern 2019) is a correlation (Eqn. [6]) for ground radiative flux q_{ground} (W/cm^2) based on detailed flow field and radiation simulations where $a = 0.69\left(\frac{V}{H}\right)^2$ and $b = 1.3 - 0.015V^{1.12}R^{0.21}$ depend on radius R, velocity V, and altitude H. The view angle $\phi = \cos^{-1}\left(\frac{(x_g - x_m)\cos\theta + H\sin\theta}{L}\right)$ and the distance from the asteroid to the point of interest on the ground $L = \sqrt{\left(x_g - x_m\right)^2 + y_g^2 + H^2}$ depend additionally on the entry angle θ, the meteor location (subscript m), and the point of interest on the ground (subscript g). To account for atmospheric absorption effects, the ground radiative flux is multiplied by the atmospheric absorption ratio G (Eqn. [7]) where the angle from the ground normal $\psi = \cos^{-1}\left(\frac{H}{L}\right)$. Thermal exposure on the ground from the shock-layer and wake of an asteroid entry is then computed by integrating the ground radiative flux through the trajectory. This model was originally developed based on smaller objects, and further study is being done to ensure the validity of the model for larger objects. The equation used in this study (Eqn. [8]) is a revision of the original correlation developed based on new simulations at larger diameters. The resulting thermal exposure contours on the ground are not constrained to be circular and tend to be more elliptical in shape. An effective damage radius is calculated by determining the radius of a circle with area equal to the area defined by a given thermal exposure level.

$$q_{ground} = \left[2.75 + 9.6\left(\frac{\phi}{60}\right)^{a}\right]\left(4.15e^{-0.1423H}\right)^{b}\left(\frac{R}{25}\right)^{1.7}\left(\frac{10}{L}\right)^{2} e^{4.1267-0.0357V-\frac{54.137}{V}} \qquad [6]$$

$$G = \left(-9.56\times10^{-5}\psi^2 + 2.54\times10^{-3}\psi + 0.59\right)\frac{(1.32 + 0.11\phi)}{(2.75 + 0.16\phi)} \qquad [7]$$

$$\boldsymbol{q_{ground} = 133.2\left(\frac{V}{15}\right)^{\left[1.4-\frac{7.5}{(H+5)}\right]}\left[\frac{(5+H)}{15}\right]^{0.3}\left[\frac{(\phi+45)}{135}\right]^{3}\left(\frac{60}{L}\right)^{2}\left(\frac{D}{800}\right)^{2}} \qquad [8]$$

The blast overpressure model implemented in PAIR is based on height-of-burst (HOB) maps, which give ground damage radii as a function of burst altitude and energy (yield). The blast damage radius is calculated from curve fits of a combination of HOB maps. Nuclear-based HOB maps (Glasstone and Dolan 1977) are used for smaller yields (up to 5Mt) and simulation-based HOB maps (Aftosmis et al. 2019) are used for larger yields (above 250Mt). Interpolation is used between the two sets of HOB maps (Wheeler et al. 2021, Stokes et al. 2017).

2.2 Parameter Ranges

Based on Equation [3], the parameters of interest for this sensitivity study are luminous efficiency and energy, where energy depends on density, velocity, and diameter of the object. The blast model in PAIR depends on energy and burst height (Wheeler et al. 2021). In the large object cases of concern, burst height goes to zero (ground impact), so the main parameter of interest in the blast model, energy, is also captured by the sensitivity study parameters defined by the thermal equations.

The parameters of interest for the sensitivity study based on the IDG RAS model are velocity, diameter, and energy, where energy also depends on density. Additionally, a parameter for radiation source height is considered because the authors of this paper are unsure how that parameter is calculated in the crater forming cases based on the available equations, and we currently have to rely on the online impact effects calculator. NASA's ATAP model includes diameter, velocity, density, entry angle and strength on its list of parameters of interest. Entry angle and strength are needed in the pre-impact calculations.

To perform the sensitivity study, we vary each parameter of interest one at a time across a range of values while all other parameters remain at the baseline values. Changes in the results as one parameter is varied are used to assess the influence of that parameter. The baseline case for each model is defined in Table 1, while the variations are listed in Table 2. The range of variations was largely based on the 2023 PDC Epoch 1 asteroid property and entry details (CNEOS Hypothetical Impact Scenarios). Epoch 1 is less than 3 months after initial discovery when the asteroid is still poorly characterized. Luminous efficiency is a parameter known to be uncertain and the variations were selected to span the accepted uncertainty range of 1e-4 to 1e-2 (Ortiz et al. 2000). The baseline value of 0.003 is considered the nominal value. Velocity is well known in this impact exercise, so velocity variations outside the 2023 PDC range are chosen for this parameter.

***Table 1**: Parameters describing the baseline case for each of the three models considered in this study. Some parameters are not used directly in the calculation but are needed for the energy calculation where* $E = \frac{1}{2}mV^2$ *and* $m = \frac{4}{3}\pi\left(\frac{D}{2}\right)^3\rho$.

	Collins et al.	IDG RAS	NASA ATAP
Energy (Gt)	10.29	10.29	-
Diameter (m)	800	800	800
Velocity (km/s)	12.673	12.673	12.673
Density (kg/m^3)	2000	2000	2000
Luminous Efficiency	0.003	-	-
Source Height (km)	-	38	-
Entry Angle (deg)	-	-	54.34
Strength (MPa)	-	-	2

***Table 2**: Variations in each parameter used in the sensitivity study. Ranges are largely based on 2023 PDC Epoch 1 information. Velocity is well known in this scenario, so the variations for that parameter are outside the range.*

	Value 1	Value 2	Value 3	Value 4
Diameter (m)	300	700	1100	1500
Velocity (km/s)	12	13	14	15
Density (kg/m3)	1500	2500	3000	-
Luminous Efficiency	1e-4	1e-3	1e-2	-
Source Height (km)	25	50	75	100
Entry Angle (deg)	30	45	60	75
Strength (MPa)	0.1	1	10	-

2.3 Damage Severity

PAIR results are calculated at four damage severity levels ranging from serious to unsurvivable. This sensitivity study will consider all four levels to determine whether parameter sensitivities in the models are limited to certain damage severities. At each severity level, the blast and thermal models are calculated separately and the bigger of the two is used to define the damage zone. One of the goals of this work is to determine how parameter sensitivities affect which hazard is the dominant local ground hazard.

The serious severity level affects 10% of the population and can include shattered windows and some structural damage from blast damage, and/or 2nd degree burns from thermal damage. Severe damage affects 30% of the population and includes widespread structural damage and/or 3rd degree burns. Critical damage affects 60% of the population and can include the collapse of most residential structures and/or clothing ignition. The highest damage severity level is unsurvivable in which 100% of the population is affected by complete devastation and/or incineration.

The severity levels for the blast damage correspond to 1, 2, 4, and 10 psi overpressure (Stokes et al. 2017), while the severity levels for the thermal radiation damage depend on the energy scaled thermal exposure described by Equation [2]. In that equation, the thermal exposure level for a given severity is calculated by scaling the thermal exposure required to ignite a given material during a 1 Mt explosion by the energy. The values of $\phi_i(1\,Mt)$ corresponding to the four damage severity levels are 0.25, 0.42, 0.84, and 1.2 MJ/m^2. The same four thermal exposure levels are used for all three thermal radiation damage models for a direct comparison of damage radii.

3. RESULTS

This section presents the results of the sensitivity study. We discuss both sensitivities within each model as well as sensitivities between model approaches. A focus is placed on sensitivities observed in the current model implemented in PAIR. The damage radius calculated by each model is compared for the baseline case conditions. The study is then extended to a comparison of the total number of people affected by local ground hazards.

3.1 Current Model – Collins et al.

The parameters of interest for the Collins et al. model are energy (diameter, density, and velocity) and luminous efficiency. Blast and thermal damage results were computed for each combination of these parameters and at each severity level to look for sensitivities. Results of the sensitivity study for the serious and unsurvivable severity levels are shown in Figure 1, where blast damage radius for a given case is represented by the x-axis and the thermal damage radius for the case by the y-axis. If blast and thermal produced the same damage radius, then the point would be on the leading hazard line. If a point falls below the leading hazard line, then blast is the leading ground hazard, and if a point falls above the line, thermal is the leading hazard. Note that blast is generally the leading hazard at the serious damage severity level, but thermal leads at the unsurvivable level.

Looking at individual parameters, diameter, velocity, density, and therefore energy variations produced similar trends in both blast and thermal, making the local leading hazard determination not very sensitive to uncertainties in energy for this regime. Diameter variations do approach the hazard line for the smallest diameters considered, although this is where the fully crater forming assumption starts to break down. The luminous efficiency parameter, however, only affects the thermal damage radius calculation and results suggest the potential for this parameter to have a strong influence on the leading hazard determination. In both damage severities shown, luminous efficiency variations can change the leading hazard. This influence does also depend on the likelihood of sampling a given luminous efficiency value. PAIR uses a log-uniform distribution (uniform in log10 space) to get samples across all the orders of magnitude in the accepted uncertainty range. Additional study to reduce the uncertainty range on this parameter and develop better distributions of its likely ranges for airburst and ground impact scenarios would improve damage estimates.

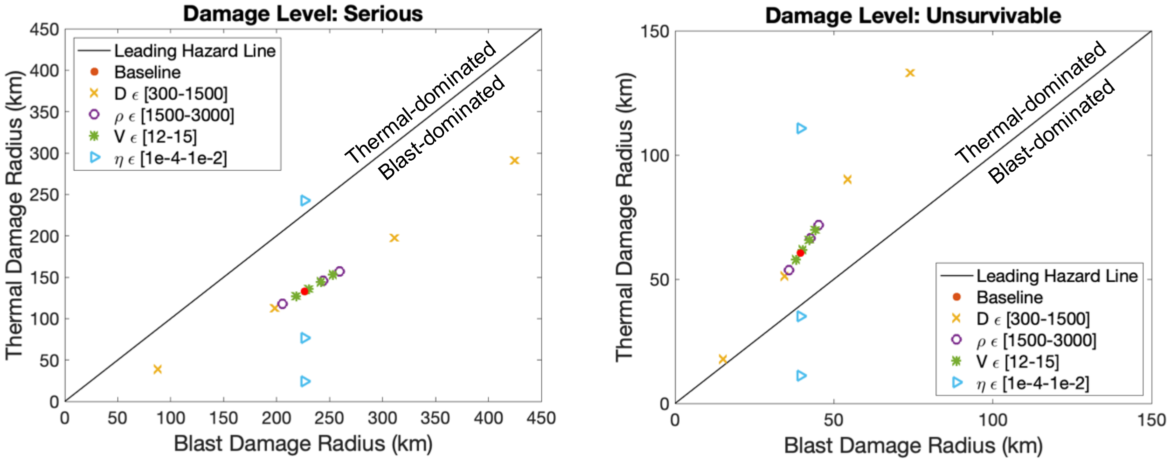

***Figure 1**: Thermal (Collins et al. model) versus blast damage radius results for each case in the sensitivity study at the serious and unsurvivable damage severity levels. Baseline case represents an 800m, 10.29Gt object. Decreasing diameter, density, or velocity decreases the thermal and blast damage radii. Decreasing luminous efficiency decreases the thermal damage radius. Leading hazard determination is sensitive to the luminous efficiency parameter.*

Further investigating the luminous efficiency sensitivity, Figure 2 (left) compares the blast and thermal damage for the baseline case at all four severity levels. The bar is shown for the nominal luminous efficiency value of 0.003, and the uncertainty bars show the spread of potential thermal damage radius values assuming a luminous efficiency range of 0.0001 to 0.01. A consistent sensitivity is observed across all severity levels with the possibility of either blast or thermal being the leading hazard. The crossover luminous efficiencies where blast and thermal damage would equal each other are 0.0087, 0.0045, 0.0030, and 0.0013 for the serious, severe, critical, and unsurvivable damage severity levels, respectively (Figure 2 (right)). Thermal becomes more likely to dominate as luminous efficiency increases and higher luminous efficiency values are needed at lower severity levels for thermal to overcome blast.

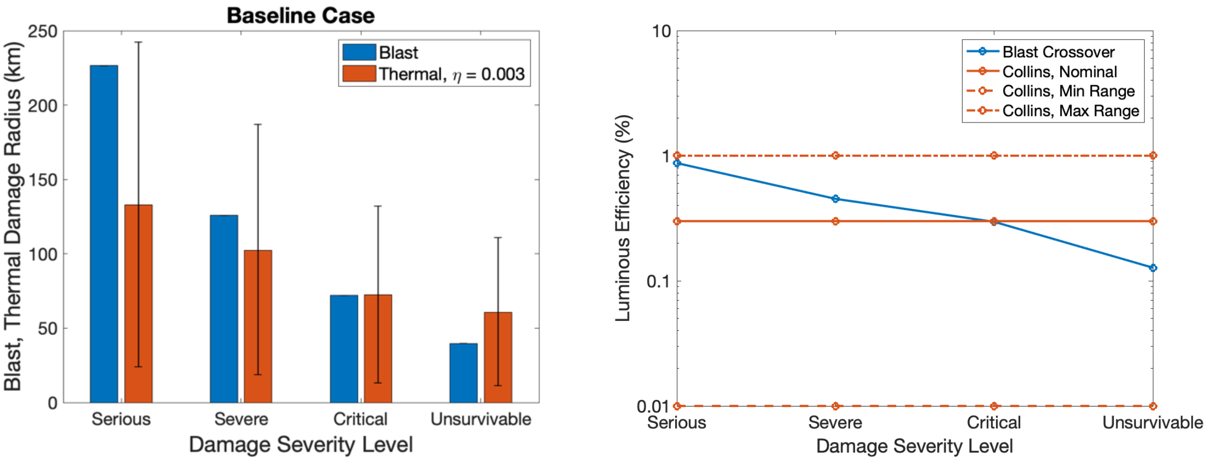

***Figure 2**: (left) Comparison of blast and thermal (Collins et al. model) damage radius results for the baseline case. Uncertainty bars on the thermal results represent the range of potential thermal damage radii given the accepted range of luminous efficiency values. (right) Crossover luminous efficiency values where blast and thermal would equal each other. Leading hazard determination is affected at all damage severity levels.*

Figure 3 presents a comparison of blast and thermal damage radii across a range of object sizes, where the shaded region represents the range of thermal damage as luminous efficiency is varied across the accepted range. At the lowest severity level (serious), the nominal blast radii are all above the nominal thermal radii and shifted towards the top of the shaded region. As damage severity increases to the unsurvivable level, this reverses and the nominal thermal blast radii exceed the nominal blast radii which have been pushed lower within the shaded region. Overall, blast damage is shown to fall within the range of potential thermal damage across the range of energies. These results highlight that the luminous efficiency parameter sensitivity is present across a range of energies in addition to severity levels in this regime.

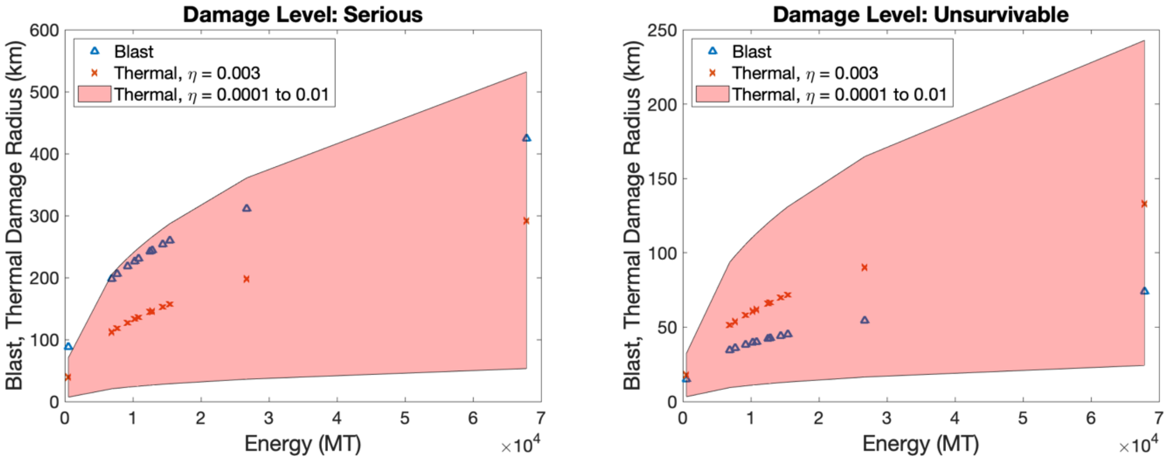

***Figure 3**: Blast and thermal (Collins et al. model) damage radius versus energy for all cases in the sensitivity study. Shaded region highlights the range of potential thermal damage radius values given the range of luminous efficiency values. Lower luminous efficiency values produce smaller thermal damage radii. Leading hazard determination is affected across a wide range of energies, particularly at higher damage severity levels.*

3.2 Additional Models – IDG RAS, NASA ATAP

The current model in PAIR showed one clear sensitivity in the luminous efficiency parameter. Now we expand the study to the other available models. Neither the IDG RAS nor NASA ATAP model have the same luminous efficiency parameter as the Collins et al. model but could have sensitivities of their own.

The parameters of interest for the IDG RAS model are diameter, velocity, density, as part of the energy calculation, and the radiation source height. Results of the sensitivity study for this model are presented in Figure 4. As was observed with the Collins et al. model, the parameters associated with energy do not have a strong influence on the leading hazard determination because variations produce trends generally in the same direction for both blast and thermal. Results for the smallest diameters did approach the line, but again this is where the fully crater impact assumption starts to break down. The radiation height parameter H_{rad} had the potential to influence the results because it is only in the thermal calculation, but results show that uncertainty does not appear to change the calculation significantly for objects of this size. This parameter is not well understood by the authors of this paper for the crater impacting case. Overall, results consistently showed thermal exceeding blast damage (points above the leading hazard line) with the IDG RAS thermal model, and uncertainties in individual model parameters did not lead to any significant influence on leading hazard determination for this regime. This held across all four severity levels.

While luminous efficiency is not a parameter to be directly chosen in the IDG RAS model, and therefore not included in the sensitivity study, it can be calculated. Using Equation [5] (Popova et al. 2021), the luminous efficiency for the baseline case was calculated as 3.94% which is an order of magnitude higher than the nominal luminous efficiency used in the Collins et al. model. Values ranged from 3.28% to 4.48% for the cases considered in the study. The luminous efficiency calculation is also what caused the results from variations in diameter, velocity, and density to not fall along a single line as they did in the Collins et al. model. The luminous efficiency calculation is dependent on these parameters instead of being constant.

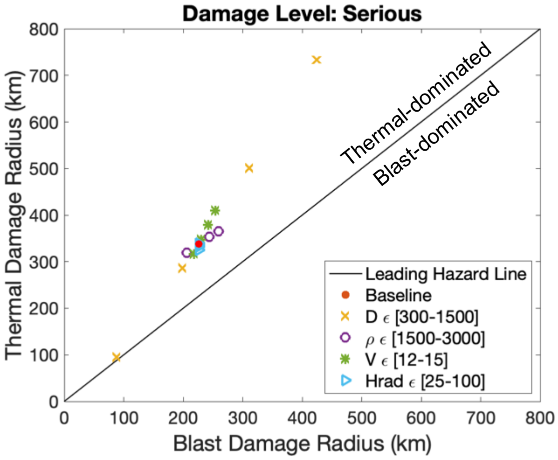

Figure 4: *Thermal (IDG RAS model) versus blast damage radius results for each case in the sensitivity study at the serious damage severity level. Baseline case represents an 800m, 10.29Gt object. Decreasing diameter, density, or velocity decreases the thermal and blast damage radii. Decreasing the radiation source height increases the thermal damage radius. Thermal damage with this model is generally much larger than blast, and leading hazard determination is largely unaffected by variations in individual parameters.*

The NASA ATAP thermal model introduces a few new parameters of interest, namely strength and entry angle. Strength and entry angle are relevant parameters in this model because the model is based on radiation during the pre-impact entry rather than a static burst or fireball approximation. Continuing work is being done to determine how radiation during the entry compares to radiation from the impact fireball to help determine the applicability of this model to this scenario. As with the other models, the results in Figure 5 show that most of the parameters do not have a strong influence on leading hazard determination in this regime. The one parameter that the model does appear to be sensitive to is the entry angle, with shallow entries leading to larger thermal damage radii. Uncertainty in this parameter could change the leading hazard, particularly at the highest severity damage levels, in this regime. Outside of the highest damage severity levels, the thermal damage predicted by this model was generally much lower than the blast damage results, and uncertainties in individual parameters had little influence on the overall leading hazard determination.

Additionally, thermal radiation damage for the baseline case was computed using the original correlation to investigate how the revised correlation based on simulations of larger objects used in this study differed from the original correlation. A comparison of the damage radii showed that the revised correlation produced damage radii approximately twice as large as the original correlation for this 800m diameter case across all four severity levels. Generally, the revised correlation was less sensitive to velocity variation and more sensitive to entry angle than the original correlation.

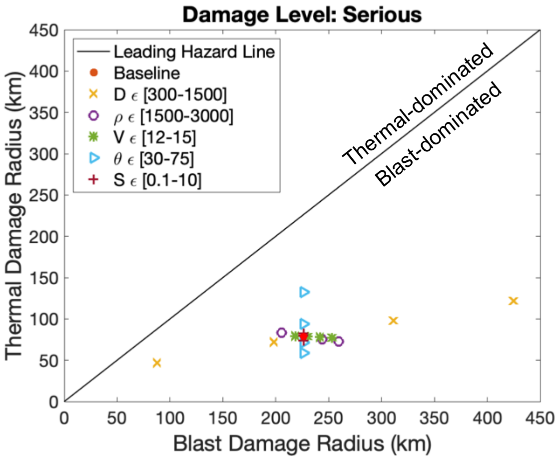

Figure 5: *Thermal (NASA ATAP model) versus blast damage radius results for each case in the sensitivity study at the serious damage severity level. Baseline case represents an 800m, 10.29Gt object. Decreasing diameter decreases the thermal and blast damage radii. Decreasing density or velocity increases the thermal and decreases the blast damage radii. Decreasing entry angle or strength increases the thermal damage radius. Entry angle does not change the leading hazard at the serious damage severity level presented, but leading hazard determination can be sensitive to the entry angle at higher severity levels.*

3.3 Baseline Case Comparison

The results thus far have highlighted the sensitivities within each thermal radiation damage model. Now we will discuss the sensitivity of PAIR results to the model approach. A comparison of the different thermal models to the blast results at the baseline case conditions is presented in Figure 6 for both damage radius (left) and luminous efficiency (right). The three models are compared at thermal exposures of 116.6, 195.9, 391.8, and 559.7 J/cm^2 corresponding to the four damage levels. Assuming nominal conditions (luminous efficiency 0.003) for the baseline case with the Collins et al. model implemented in PAIR, thermal damage dominates blast at higher severity levels, but not at lower severity levels. The IDG RAS model dominates blast damage across all severity levels and is outside the upper bound of the Collins et al. model damage radius range. The results correspond to an effective luminous efficiency value of about 0.02 across the damage severity levels. This is lower than the calculated luminous efficiency by the IDG RAS model, which was about 4%. The NASA ATAP model damage radius is well below blast at lower damage levels but more similar by the highest damage levels. While the NASA ATAP model results are below the nominal Collins et al. model results, they are within the lower bound of the damage radius range. The results of this model correspond to an effective luminous efficiency value ranging from 0.001 at the serious damage severity level down to 0.0007 at the unsurvivable level. Effective luminous efficiency was calculated as the Collins et al. model luminous efficiency required to produce the given thermal damage radius.

Each of the models additionally has some uncertainty introduced in the development of the models which could impact the results. We have discussed at length the uncertainty in luminous efficiency for the Collins et al. model. It is suggested in Popova et al. 2021 that the ratio of thermal exposure from the scaling relation to the simulations is within 4 when using the crater forming equations for this range of thermal exposures. The NASA ATAP model correlation produces radiative flux results within 50% of the simulations (Johnston and Stern 2019). Despite having similar trends, significant differences in magnitude are observed between the thermal models suggesting that the leading hazard determination is sensitive to the thermal modeling approach.

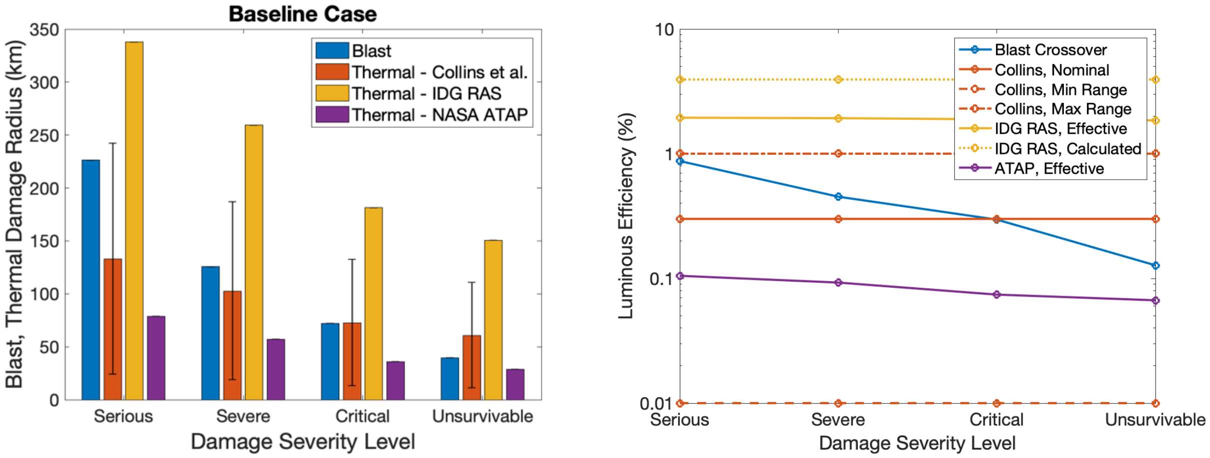

Figure 6*: (left) Comparison of blast damage results with all three thermal models considered. Wide variation in results between thermal models is noted. Leading hazard determination is sensitive to thermal model choice. (right) Comparison of calculated and effective luminous efficiency values. The IDG RAS model values exceed the accepted range used in the Collins et al. model.*

3.4 Extension to Affected Population

The majority of results in this paper are focused on the impacts of model sensitivities on the leading hazard determination because the ultimate results of interest, damage extent and affected population, depend on it. Damage extent has been highlighted throughout the sensitivity results presented so far, and now we extend the results to an affected population calculation. The number of people affected at a given damage severity level is calculated by multiplying the population density by the area affected and then scaling by the 10, 30, 60, and 100% values described in Section 2.3. PAIR uses a gridded population density that varies with location; however, a constant population density will be used for this analysis, making the affected population proportional to the damage area. An average population density of 232.1 people/km^2 is used based on UN Statistics Division Database information for Nigeria (2021), where the 2023 PDC object impacts. Some regions could be affected by blast and thermal at different damage severity levels, but the overall local hazard damage severity of a region is defined by the maximum of the two.

The number of people affected by blast or thermal damage individually is presented in Figure 7 (left). These calculations used just blast or just thermal damage radii to determine the damage area. Over an order of magnitude more people would be expected to have thermal damage affect them if using the IDG RAS model in comparison to the ATAP model. The Collins et al. model itself has a wide range of affected numbers of people depending on the luminous efficiency value chosen. Combining the blast and thermal into a single local hazard category, Figure 7 (right) captures the number of people affected by a local hazard. These calculations used the bigger of blast and thermal damage radii to determine the damage area, affecting the area calculation particularly for the nominal Collins et al. model where some damage severity levels are dominated by blast and others thermal damage. Because the blast damage radius is larger than the thermal damage radius determined by the ATAP model and the Collins et al. model below about the nominal conditions, blast dominates the affected people calculation in the lower half of this plot. As a result, the choice between using the ATAP thermal model or the Collins et al. model with a luminous efficiency value on the lower end of the range makes little difference in the number of affected people for this case. Influence on the affected number of people at each damage severity level when choosing larger luminous efficiency values or the IDG RAS model is still observed, particularly at the highest severity levels where differences of over an order of magnitude are observed.

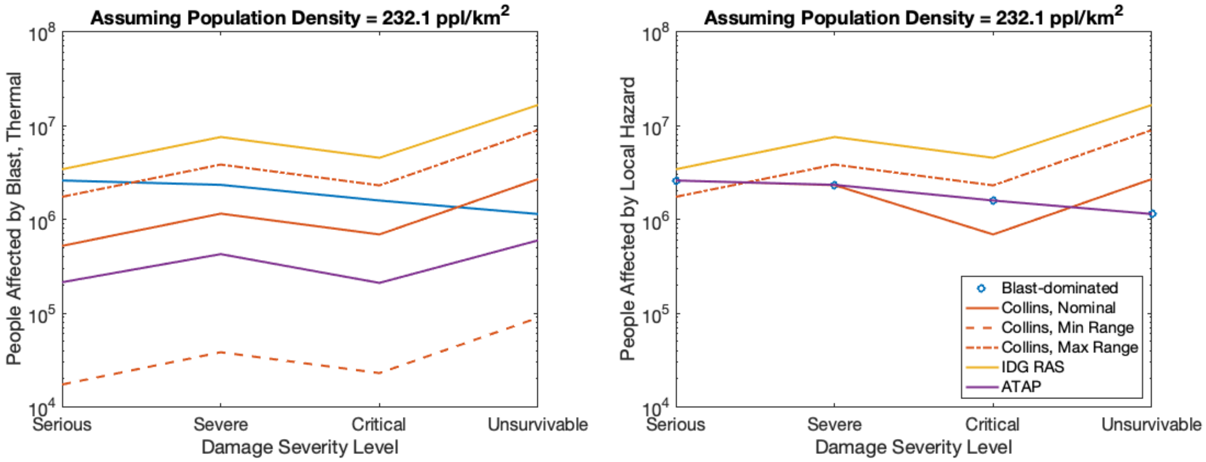

Figure 7*: (left) Comparison of the number of people affected by blast or thermal damage individually at each damage severity level. Order of magnitude or more difference depending on model and parameter choices. (right) Comparison of the number of people affected by a combined local hazard. Some of the model and parameter choices lead to blast-dominated scenarios which limits the influence of model choice on this calculation.*

The total number of people affected by blast, thermal, or a local hazard in general, determined by summing the number of people affected at each damage severity level, is given in Figure 8. The total number of affected people from a local hazard for the 800m diameter object of interest is 8.3 million with the nominal Collins et al. model (range 7.6 to 17 million), 32 million with the IDG RAS model, and 7.6 million with the ATAP model. While the Collins et al. model at approximately the nominal level and below and the ATAP model are close, the IDG RAS model produces numbers about twice the maximum Collins et al. value and four times the nominal value. Overall, the total number of affected people can be influenced by the choice of thermal radiation damage model and the choice of luminous efficiency in this large object regime because of the influence these parameters have on leading hazard determination, although some sensitivities observed in the thermal damage radius comparisons have been eliminated in this calculation when blast dominates the damage.

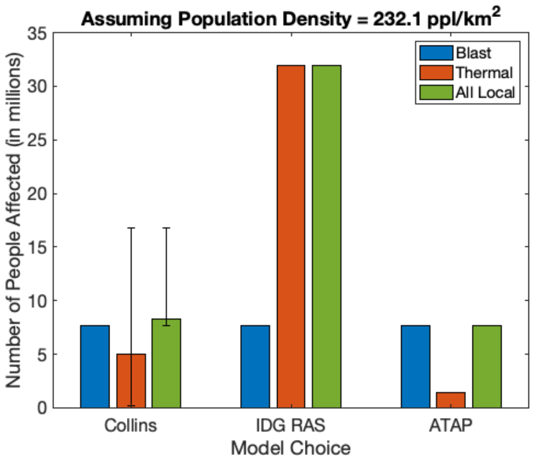

Figure 8: *Comparison of the total number of people affected by blast, thermal, or a local hazard in general. The IDG RAS model leads to about four times as many people affected as the ATAP model or nominal Collins et al. model.*

4. DISCUSSION

In this section we discuss the sensitivity study results in context of the 2023 PDC scenario. The sensitivities observed by varying individual parameters across a range of values are now compared to the actual impact cases the PAIR model used to represent the range of possible asteroid properties and impact locations for the 2023 PDC object at Epoch 1. Twenty-five million cases are considered.

4.1 2023 PDC Scenario

The sensitivity study suggested that the leading hazard determination with the current thermal model in PAIR was fairly insensitive to uncertainties in energy, but sensitive to the choice of luminous efficiency value. Velocity is well known in the 2023 PDC scenario, so sources of uncertainty in energy are from diameter and density. Figure 9 shows how many cases had thermal leading versus how many had blast leading out of all the cases for different density and diameter values at two different severity levels. Agreeing with the sensitivity study, blast dominates at the serious level while thermal is much more a factor at the unsurvivable level. This shift is a result of the thermal model being simpler and having a more linear change with energy and altitude than the blast model. At the serious level we see thermal leading in only a few cases when diameter is above 500m, but at the unsurvivable level we see the potential for thermal to lead starting by 150m, and becoming as likely or even more likely to lead than blast by 700m. Density results showed very similar trends with only a few thermal cases leading (about 1.5%) at the serious level, and many more (about 37.5%) at the unsurvivable level. Bringing diameter, density, and velocity together in energy, thermal dominates in a few cases above 5000Mt at the serious level, and more at the unsurvivable level above 150Mt. The distribution shapes in the plots are similar between thermal and blast suggesting that, while one or the other might lead, the results are not very sensitive to uncertainty in the parameter. While the leading hazard determination may not be impacted, the amount of damage is still highly driven by energy.

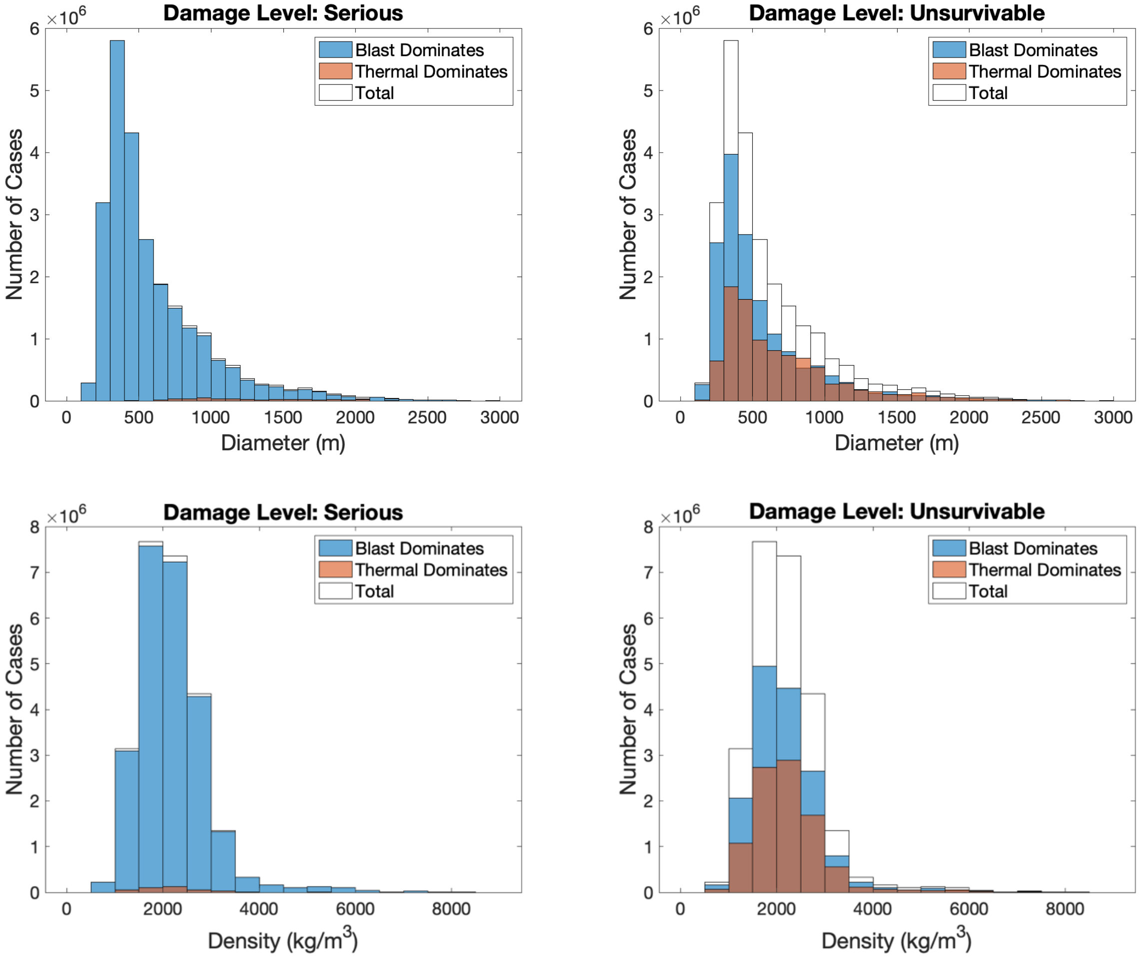

***Figure 9**: Number of cases where either blast or thermal dominates in the 25 million 2023 PDC cases versus diameter or density at two damage severity levels. Thermal is more likely to dominate blast at higher severity levels. Little sensitivity in leading hazard determination is observed across these ranges.*

Figure 10 presents the same information for luminous efficiency. Blast dominates for most cases across all luminous efficiency values at the serious level with thermal leading in just a few cases when luminous efficiency is above 0.006. At the unsurvivable level, blast dominates at the very lowest values of luminous efficiency, but above about 0.0015 thermal is the leading hazard in the majority of cases. The difference in distribution shapes, where blast-dominated cases are shifted to lower luminous efficiency values and thermal-dominated cases are shifted to higher values, shows that the overall leading hazard determination is very sensitive to the choice of luminous efficiency, as previously shown by the sensitivity results in Figure 2.

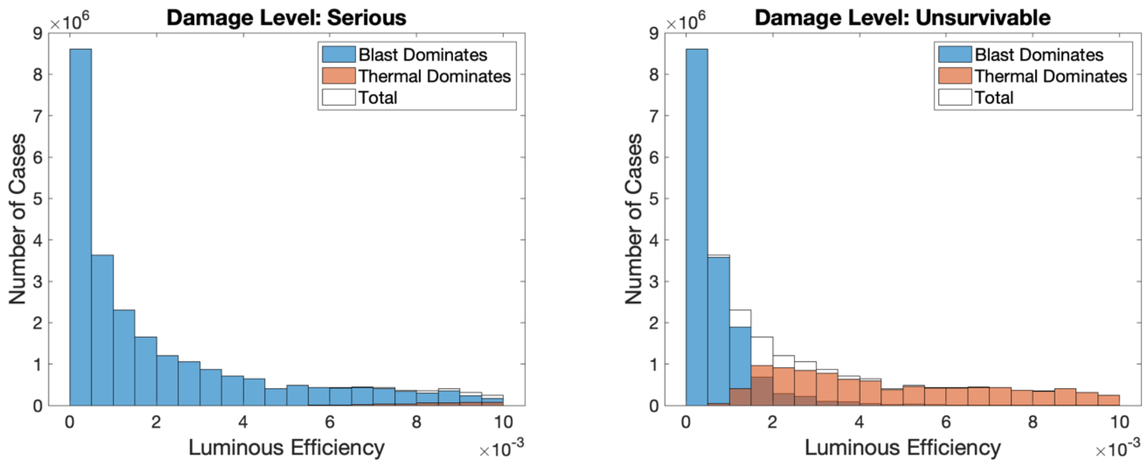

***Figure 10**: Number of cases where either blast or thermal dominates in the 25 million 2023 PDC cases versus luminous efficiency at two damage severity levels. Thermal is more likely to dominate blast at higher severity levels. Leading hazard determination is sensitive to uncertainty in this parameter with larger luminous efficiency values increasing the likelihood that thermal dominates.*

Looking further at the effect of luminous efficiency on the 2023 PDC cases, Figure 11 plots the blast and thermal damage radii versus impact energy for all twenty-five million cases. The blast results generally follow a single curve outside of the lowest energies, while the thermal damage radius results have a large spread. This spread highlights the influence of the luminous efficiency parameter on the thermal results and matches closely with the sensitivity study results in Figure 3.

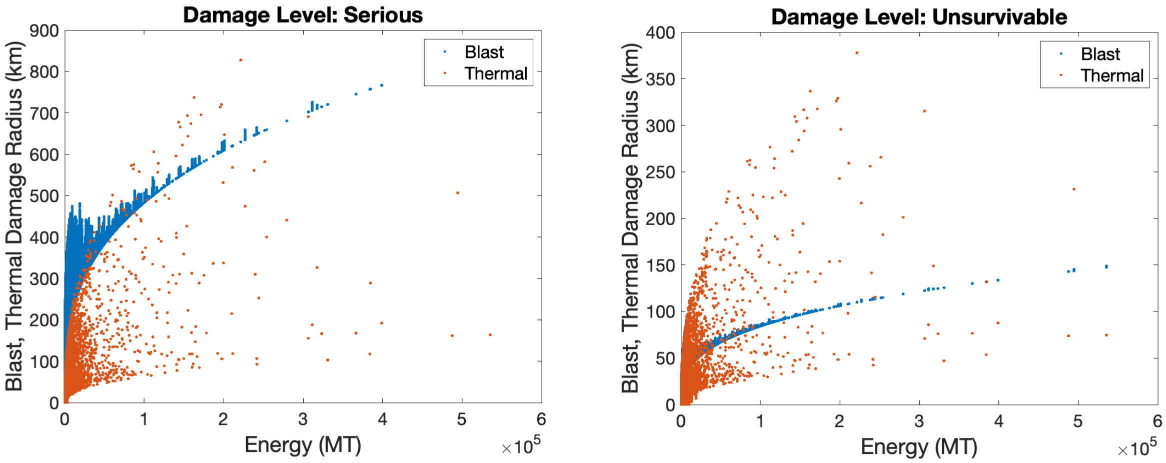

***Figure 11**: Comparison of blast and thermal damage radius versus energy for the 25 million PDC 2023 cases at two damage severity levels. Effect of the luminous efficiency parameter is observed in the spread of the thermal damage results.*

5. CONCLUSIONS

This section provides a summary of the work presented in this paper and highlights where future work is needed to improve our modeling capabilities.

5.1 Summary

A sensitivity study of the PAIR model results to the current thermal radiation damage model was conducted. Sensitivities within the model were investigated as well as sensitivities to the model itself with comparisons to two other available models. Results provide insight into parameter regimes where impact risks become sensitive to thermal radiation damage as well as where further model improvement is necessary.

In this study, a baseline case based on the 2023 PDC impact scenario was varied one parameter at a time over ranges corresponding to the range of potential 2023 PDC Epoch 1 (shortly after discovery) cases to determine parameter sensitivities when applied to large objects. The sensitivity study showed that the leading hazard determination with the current thermal model is not very sensitive to uncertainties in energy, however it is sensitive to the luminous efficiency parameter, particularly at higher damage severity levels. Applying this to the actual 2023 PDC impact cases at the serious damage level, luminous efficiencies above 0.006 showed a small chance of thermal playing an important role. At the unsurvivable level, luminous efficiencies above 0.0008 led to thermal playing a significant role in impact risk calculations. Essentially all potential asteroid cases in this scenario could have thermal radiation dominate blast damage if the luminous efficiency was large enough.

The two additional thermal radiation damage models considered had their own sensitivities with the potential to impact the leading hazard determination. The three models produced noticeably different estimations of the thermal damage areas for the baseline case, with the IDG RAS model being well above the blast results, Collins et al. depending on the damage severity level, and the NASA ATAP model being below the blast damage. In the extension to affected people, differences were limited to the model combinations that were not blast dominated.

5.2 Future Work

Impact risks are sensitive to the thermal model chosen and additional study to understand variations in the results produced by different model approaches would improve confidence in the models for this regime. PAIR is currently only set up to run with the Collins et al. thermal radiation damage model. The Collins et al. model is an empirical fit to nuclear weapons testing data, specifically ground point source explosions. The resulting fireball initially expands spherically and then lifts off the ground as it cools due to buoyancy. This may be fairly representative of ground impacting asteroids but could have extrapolation issues above the sub-megaton explosions it was based on. The 2023 PDC scenario is 10Gt. Additional work would be needed to implement the other models considered in this study into PAIR. The IDG RAS model is a fit to high fidelity simulations of ground impacts. This is good current data, but the velocity of this scenario is outside the range of the velocities considered in the set of simulations. It also suggests the luminous efficiency is outside the range of what is currently used in the PAIR model. The NASA ATAP model, originally developed for airbursts, is appealing because of its basis in high-fidelity fluid dynamics simulation, including line-radiation modeling, which accurately determines the luminous efficiency. This is likely the most accurate model, but further work is still being completed to apply the model to larger and ground impacting objects. Comparing ground impacts using the NASA ATAP model with the Collins et al. and IDG RAS models would help determine if we are underpredicting the luminous efficiency value for ground impacts.

While PAIR takes a Monte Carlo approach to account for parameter uncertainties, further study to better understand the range of luminous efficiency values that produce the most realistic damage estimates would improve the current model in this large object regime. Prior to the NASA ATAP model and IDG RAS model simulations of the last few years, the luminous efficiency value has been poorly constrained. A log-uniform distribution has been being used as a no-knowledge way of covering the multiple orders of magnitude in the accepted luminous efficiency range (1e-4 to 1e-2). Thermal radiation damage has been almost negligible in comparison to blast damage in the airburst sized asteroids that have been the focus of much of the previous work, so the lack of knowledge on luminous efficiency was less important. The work presented in this paper, however, has clearly shown that the predicted damage is highly sensitive to the value chosen for large impacts. Currently the Collins model has a wide range of accepted values, the IDG RAS model is predicting luminous efficiencies larger than expected, and the NASA ATAP suggests values on the lower end of the range. Considering the variation in values between models, improving the distribution of luminous efficiency values for large ground impacting asteroids is very important. Overall, the current uncertainty is largely in the modeling. In the future, ideally the majority of the uncertainty is shifted to the physical parameters. Future work should be focused on running high-fidelity simulations with a line radiation model, like the NASA ATAP model, on a wide variety of ground impacting cases to better understand the luminous efficiency distribution in this regime.

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