2021 PDC Hypothetical Impact Exercise: Probabilistic Asteroid Impact Risk

Scenario Day 3

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HYPOTHETICAL EXERCISE

Asteroid Impact Threat Assessment

Probabilistic Asteroid Impact Risk (PAIR) Model

Asteroid Properties & Entry Parameters

Entry & Breakup Modeling

Surface Hazards
- Thermal
- Blast
- Tsunami

Impact Threat Scenario

Asteroid Property Distributions

Orbital Entry Parameters (JPL/CNEOS)

Probabilistic Risk and Damage

PAIR Model

Impact Threat Scenario

Populations
Impact Risk Summary

Characterization Summary & Updates

- Assessment date: 30 June 2021
- Potential impact date: 20 October 2021 (<4 mo.)
- Earth impact probability: 100%
- Diameter: mean 136 m, range ~35–500 m
- Energy: mean 136 Mt, range 0.7–3700 Mt
- Entry: 15.2–15.3 km/s, 50–55° entry angle
- Properties: unknown type or physical properties

Hazard Summary

- Affected Population: 0–6.6M, average 580k, most likely several hundreds of thousands
- Primary hazard is airburst or impact causing blast overpressure and possibly thermal damage
- Damage radii: 0–250 km, average ~80 km
- Damage levels: minor structural damage and burns to potentially unsurvivable levels

Damage Swath
Full range of regions potentially at risk to ground damage, given all potential impact locations and largest damage.

Sample average damage sizes over largest cities

Affected Population Risk

Asteroid Properties & Entry

- **Entry parameters are well known**: 15.2–15.3 km/s, 50–55° entry angle
- **Asteroid sizes and properties remain highly uncertain**: Observational data reduced max sizes, but range is still large and likely sizes remain similar.
  - Diameter constraint from NEOWISE weak detection eliminated largest, low-probability sizes
  - Reduced maximums from ~700m to ~500m
  - Main size distribution remains similar
  - Type and properties are unknown, ranging from more common stony types to rare iron-types
  - Maximum sizes are very large, but also unlikely

<table>
<thead>
<tr>
<th></th>
<th>Diameter (m)</th>
<th>Energy (Mt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full range</td>
<td>~35–500</td>
<td>~1–3700</td>
</tr>
<tr>
<td>Average</td>
<td>136</td>
<td>136</td>
</tr>
<tr>
<td>Median</td>
<td>114</td>
<td>47</td>
</tr>
<tr>
<td>Most likely</td>
<td>~65–120</td>
<td>~20–50</td>
</tr>
<tr>
<td>5th–95th %</td>
<td>65–270</td>
<td>~8–570</td>
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</table>

[Property inference model: J. Dotson PDC 2021] [NEOWISE: J. Masiero PDC 2021]
• Damage is likely to affect several hundred thousand to a million people
• Average of ~580k people affected
• Maximum worst case: 6.6 million people (among modeled cases)
• 97% chance of affecting at least 10k people, 74% chance of >100k, 21% chance of >1M
• <1% chance of affecting fewer than 1k people. 0.4% chance of no damage.
Affected Populations Across Swath

Affected population ranges vary significantly across swath, depending on local population densities

- Average affected population range: ~200k–1.3M across entry points (~580k overall avg)
- Max affected population range: 2M-6.6M across entry points (4M avg max among all points)

Maps of average and maximum affected population for each sampled impact entry point, given the potential range in asteroid properties and resulting damage
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Ground Damage Severity Levels

- Blast and thermal damage are assessed at four severity levels, with each level affecting different fractions of the population within that region.
- For each damage level, the larger of the equivalent blast or thermal radius is used to determine the area and affected population for that level.
- Blast is the predominant hazard for most cases in this scenario.

<table>
<thead>
<tr>
<th>Damage Level</th>
<th>Population fraction</th>
<th>Blast Overpressure Threshold (psi)</th>
<th>Thermal Exposure Threshold</th>
</tr>
</thead>
<tbody>
<tr>
<td>Serious</td>
<td>10%</td>
<td>1 psi – window breakage and some structural damage</td>
<td>2nd degree burns</td>
</tr>
<tr>
<td>Severe</td>
<td>30%</td>
<td>2 psi – doors and windows blown out, widespread structural damage</td>
<td>3rd degree burns</td>
</tr>
<tr>
<td>Critical</td>
<td>60%</td>
<td>4 psi – most residential structures collapse</td>
<td>clothing ignition</td>
</tr>
<tr>
<td>Unsurvivable</td>
<td>100%</td>
<td>10 psi – complete devastation</td>
<td>incineration</td>
</tr>
</tbody>
</table>
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Damage Risk Swath
(full extent of regions potentially at risk)

Damage risk swath:
• Shows full range of regions potentially at risk to local ground damage from all modeled cases
• Includes unlikely worst-case objects and all sampled impact locations

Extent of swath region:
• ~1400 km long, ~700 km wide
• ~42–55° N Lat, 6–21° E Lon
Damage Risk Swath
(sample damage footprint variations)

Actual potential damage areas and locations vary widely, including:

- Small areas with only lower damage severities, located over lower-population areas
- Larger regions with greater severity, typical of the average impactor size estimates
- Very large and unlikely worst-case ranges
- …and everything in between
Sample average damage footprints over cities:

- **Average blast radii:**
  - Serious: ~80 km
  - Severe: ~40 km
  - Critical: ~20 km
  - Unsurvivable: ~10 km

- Range/likelihood of potential damage sizes is similar across swath locations
  - Entry parameters don’t vary much over small region
  - Damage area variation driven by asteroid property and breakup/airburst uncertainties
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Damage Risk Swath (maximum affected population among all modeled cases)

Worst case affecting greatest number of people
- Blast from 400m, 1.3 Gt asteroid extending over northern Germany
- Affected population: 6.6M
- Damage area: ~190,000 km²

Worst-case damage extremes are very unlikely
- Point at very edge of potential risk swath (least likely)
- Unlikely large asteroid size (<0.1% are over 400m, <1% are over 1 Gt)
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Maximum Affected Population Case  
(maximum affected population among all modeled cases)

 ![Map of Damage Region Extent and Severity Levels](image)

**Damage region extent and severity levels**

- **Blast damage radii:**
  - Serious (1 psi): 250 km
  - Severe (2 psi): 100 km
  - Critical (4 psi): 56 km
  - Unsurvivable (10 psi): 28 km

- **Thermal damage radii**
  - Much smaller and fall within unsurvivable blast area
  - Serious (2nd deg. burns): 11 km
  - Severe (3rd deg. burns): 7 km
  - No more severe levels

**Total Area:** 190,000 km²
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Maximum Affected Population Case
(maximum affected population among all modeled cases)

Affected population is driven by larger, less-severe damage levels

- Affected population: 6.6 million
  - Serious: 3.9M (10% of 39M)
  - Severe: ~1.2M (30% of 4M)
  - Critical: ~1.1M (60% of 1.9M)
  - Unsurvivable: ~0.4M (100%)
- Most severe damage level is not centered over highest-population city
- Outer damage levels span multiple cities and generally populated area

Affected Population: 6.6M
Total population in area: 45M
Sample Damage Footprint Sizes
(over same sample region near Vienna)

Disaster response plans must consider both the likelihood and severity of the potential range of outcomes

- Worst-case areas can be too large to evacuate, and are very unlikely
- Probabilities of different damage ranges and severities can be used to prioritize effective response
- Radius percentile indicates the chance that the damage will be smaller than that size

Maps of probabilistic damage footprint sizes for emergency response and evacuation planning

- Median: 76 km (bigger than 50% of damage areas)
- Average: 84 km (bigger than 75% of damage areas)
- Max: 250 km (bigger than 95% of damage areas)
- 25th %: ~40 km (bigger than 25% of damage areas)
- 75th %: ~120 km (bigger than 75% of damage areas)
- 95th %: ~170 km (bigger than 95% of damage areas)
Damage Radius Probabilities
(outer serious damage level)

**Damage Radius Histogram**
Probabilities of damage radii within each range

**Damage Radius Exceedance**
Probability of at least the given damage radius or larger

**Serious Damage Radius Stats (km)**

<table>
<thead>
<tr>
<th>Damage Level</th>
<th>Mean</th>
<th>Min</th>
<th>Max</th>
<th>5&lt;sup&gt;th&lt;/sup&gt; %</th>
<th>25&lt;sup&gt;th&lt;/sup&gt; %</th>
<th>Median</th>
<th>75&lt;sup&gt;th&lt;/sup&gt; %</th>
<th>95&lt;sup&gt;th&lt;/sup&gt; %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Serious</td>
<td>84</td>
<td>0</td>
<td>255</td>
<td>26</td>
<td>42</td>
<td>76</td>
<td>121</td>
<td>172</td>
</tr>
</tbody>
</table>

*Percentiles give the probability of the outcome being smaller than the given value (e.g., a 75<sup>th</sup>% damage radius of 100 km means a 75% chance of being smaller than 100 km and a 25% chance of exceeding 100 km).*
HYPOTHETICAL EXERCISE

Damage Radius Probabilities
(all severity levels)

Local Ground Damage Radius Stats (km)

<table>
<thead>
<tr>
<th>Damage Level</th>
<th>Mean</th>
<th>Min</th>
<th>Max</th>
<th>5th %</th>
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<td>121</td>
<td>172</td>
</tr>
<tr>
<td>Severe</td>
<td>43</td>
<td>0</td>
<td>127</td>
<td>8</td>
<td>26</td>
<td>44</td>
<td>60</td>
<td>79</td>
</tr>
<tr>
<td>Critical</td>
<td>23</td>
<td>0</td>
<td>83</td>
<td>0</td>
<td>11</td>
<td>24</td>
<td>35</td>
<td>48</td>
</tr>
<tr>
<td>Unsurvivable</td>
<td>9</td>
<td>0</td>
<td>47</td>
<td>0</td>
<td>0</td>
<td>8</td>
<td>16</td>
<td>22</td>
</tr>
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Impact Risk Summary

- Imminent impact over central Europe in ~ 4 months, with large range of potential damage
  - Object size and properties remain very uncertain, leading to large uncertainties in potential damage region size and severity
  - No in-space mitigation options are possible—civil emergency response is critical
- Large airburst or impact is likely to cause extensive blast damage over areas extending from tens to hundreds of kilometers in radius
  - Potential damage severities range from minor structural damage to unsurvivable building collapse and thermal exposure
  - Potential for subsequent regional environmental effects beyond damage area remains unknown
- Damage is likely to affect hundreds of thousands of people, potentially up to several million in rare worst-cases
  - Population risk is driven most by lower-severity damage levels that cover larger areas (rather than smaller, more severe damage levels)
  - Worst-case locations tend to span multiple urban areas rather than center directly over a single city.

<table>
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<tr>
<th></th>
<th>Asteroid Diameter (m)</th>
<th>Impact Energy (Mt)</th>
<th>Damage Radius (km)</th>
<th>Affected Population</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full range</td>
<td>~35–500</td>
<td>~1–3700</td>
<td>0–250</td>
<td>0–6.6M</td>
</tr>
<tr>
<td>Average</td>
<td>136</td>
<td>136</td>
<td>84</td>
<td>580k</td>
</tr>
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<td>Most likely</td>
<td>~65–120</td>
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<td>20–60</td>
<td>100k–1M</td>
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<td>65–270</td>
<td>~8–570</td>
<td>26–172</td>
<td>16k–1.8M</td>
</tr>
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Risk-Informed Disaster Response Support

- Risk and damage assessments will continue with increasing fidelity as more information is gained about the incoming object
  - High-fidelity simulations can provide more accurate modeling of impact effects and resulting ground damage footprints for specific cases
  - Risk models can identify critical cases for simulations, given remaining unknowns
- Risk modeling will provide information on evolving damage ranges and probabilities to support emergency response planning
  - Damage region maps and ranges can be provided to local emergency response agencies for specific local infrastructure or evacuation planning
  - Probabilities of damage region sizes and severities can help inform most effective achievable civil response efforts, given large potential range of outcomes
REFERENCES
Related PDC 2021 Presentations

Asteroid Property Inference

- **Dotson** et al., “Bayesian Inference of Asteroid Physical Properties: Application to Impact Scenarios” (Impact Effects Session 9b)
- **Kelley** et al., “IAWN Planetary Defense Exercise: Apophis Observing Campaign 2020-2021” (Apophis Session 13)

Impact Effects – Hazard Modeling & Simulation

- **Aftosmis** et al., “High-Fidelity Blast Modeling of Impact from Hypothetical Asteroid 2021 PDC,” (Impact Effects e-lighting)
- **Wheeler** et al., “Probabilistic Blast Damage Modeling Uncertainties and Sensitivities” (Impact Effects e-lighting)
- **Mathias** et al., “Interaction of Meteoroid Fragments During Atmospheric Entry” (Impact Effects e-lighting)
- **Coates** et al., “Comparison of Thermal Radiation Damage Models and Parameters for Impact Risk Assessment” (Impact Effects e-lighting)
- **Berger** and LeVeque, “Towards Adaptive Simulation of Dispersive Tsunami Propagation from an Asteroid Impact” (Impact Effects Session 9b)
- **Titus** et al., “Asteroid Impacts – Downwind and Downstream Effects” (Impact Effects Session 9b)
- **Boslough**, “Airburst Consequence Modeling Using Artificial Ablation” (Impact Effects e-lighting)

Mitigation & Mission Design

- **Barbee** et al., “Risk-Informed Spacecraft Mission Design for the 2021 PDC Hypothetical Asteroid Impact Scenario” (Mission & Campaign Design Session 8b)
Probabilistic Asteroid Impact Risk (PAIR) Model


Entry & Breakup Energy Deposition Modeling


Blast Simulations and Modeling


Tsunami Simulations


Thermal Radiation Modeling and Simulation

