SAND2014-19794C

Available online at www.sciencedirect.com

SciVerse ScienceDirect

Procedia Engineering 00 (2015) 000–000

Procedia Engineering

www.elsevier.com/locate/procedia

ELSEVIER

The 13th Hypervelocity Impact Symposium

FEMA asteroid impact tabletop exercise simulations

Mark Boslough[a], Barbara Jennings[a], Brad Carvey[b], William Fogleman[c]

[a]Sandia National Laboratories, PO Box 5800, Albuquerque, NM 87185, USA
[b]DrumFire, 336 Whiteoak Dr NE, Albuquerque, NM 87122, USA
[c]Geo-Relational Information Technologies (GRIT) Inc., 8817 James Ave NE, Albuquerque, NM 87111, USA

Abstract

We describe the computational simulations and damage assessments that we provided in support of a tabletop exercise (TTX) at the request of NASA's Near-Earth Objects Program Office. The overall purpose of the exercise was to assess leadership reactions, information requirements, and emergency management responses to a hypothetical asteroid impact with Earth. The scripted exercise consisted of discovery, tracking, and characterization of a hypothetical asteroid; inclusive of mission planning, mitigation, response, impact to population, infrastructure and GDP, and explicit quantification of uncertainty. Participants at the meeting included representatives of NASA, Department of Defense, Department of State, Department of Homeland Security/Federal Emergency Management Agency (FEMA), and the White House. The exercise took place at FEMA headquarters. Sandia's role was to assist the Jet Propulsion Laboratory (JPL) in developing the impact scenario, to predict the physical effects of the impact, and to forecast the infrastructure and economic losses. We ran simulations using Sandia's CTH hydrocode to estimate physical effects on the ground, and to produce contour maps indicating damage assessments that could be used as input for the infrastructure and economic models. We used the FASTMap tool to provide estimates of infrastructure damage over the affected area, and the REAcct tool to estimate the potential economic severity expressed as changes to GDP (by nation, region, or sector) due to damage and short-term business interruptions.

Keywords: Asteroid, impact, airburst, near earth object, infrastructure.

1. Introduction

On May 20, 2014, we participated in a tabletop exercise (TTX) at the Headquarters of the Federal Emergency Management Agency (FEMA) in Washington, D.C. Other participants included representatives of the interagency Emergency Support Functional Leadership Group (ESFLG), NASA, Department of Defense (DoD), White House Office of Science and Technology Policy (OSTP), Department of State, the European Space Agency (ESA), and other organizations. For a full list of attendees, see [1]. Our role was to help create a scenario involving an impending asteroid impact in the United States, to run simulations to determine the likely effects over a range of uncertainty, and to give scripted briefings to decision makers and stakeholders.

We attempted to provide realism for our presentation at the exercise, which was designed to familiarize the participants with the near-earth object (NEO) impact threat in order to gauge the ability of emergency management agencies and decision makers to respond to such a disaster. Advance reading material was sent to TTX participants and contained the following script:

> *"The Federal Emergency Management Agency has activated the National Response Coordination Center to prepare for an imminent and certain large scale catastrophic event which will affect Texas, neighboring states, and possibly nations bordering the Gulf of Mexico. The catastrophic event will occur at approximately noon local time on September 5, 2021 and will be caused by impact of an asteroid estimated to be about 50 meters (~160 ft.) in size. Details of what is currently known about the threat and of our past*

efforts to deflect the object are included in this package. This disaster will be unprecedented in recorded times and will seriously affect our nation's oil refining and other major industries, as well as the lives and property of many of our citizens. The President has directed FEMA to lead the response effort and be prepared to execute with state and local officials plans to minimize/mitigate these effects."

2. Impact scenario

We assisted in the design of a scenario that would provide enough advance notice to enable an attempt at mitigation by deflection, with a significant and realistic amount of uncertainty in both asteroid size and impact location. The exercise was conducted with as much realism as possible, but with a compressed time scale. The asteroid was "discovered" on April 29, 2014 and was given the name "2014 TTX." Based on its brightness, it was estimated to be between 140 and 300 meters in diameter, but with unknown density. In our scenario, an attempt at deflection was only a partial success. Most of the target mass was sufficiently deflected, but the attempt broke the asteroid apart (as might be the case for a contact binary). A significant fragment (approximately 40-60 meters in diameter) remained on a collision course with Earth, but because it was given an unknown impulse its orbit was "reset" by the event and its trajectory became highly uncertain. Furthermore, there was no longer enough time to attempt a second deflection. At the time the broken piece was discovered, the uncertainty in impact location encompassed a long, narrow ellipse extending from central Texas into the Gulf of Mexico south of Louisiana.

Paul Chodas of the Jet Propulsion Laboratory (JPL) calculated an orbit for 2014 TTX that would provide the desired uncertainty and impact characteristics and with properties typical of an Earth-crossing asteroid: significant eccentricity, inclined 3.2° from the ecliptic plane, and having a period of 2.36 years. In the scenario, the asteroid is more than 24 million kilometers from the Earth at the time of its discovery and appears as a single pixel, so the only information about its size comes from its brightness. Asteroids have a wide range of reflective properties (albedos) leading to large uncertainty in reflecting area from which volume is estimated. Likewise, there is a wide range of compositions and porosities, so the mass can be uncertain by an order of magnitude. Even though the point of impact is uncertain, the orbit is determined well enough to precisely know the velocity at impact, so the mass uncertainty translates directly to uncertainty in kinetic energy which, upon impact, is transformed to effective explosive yield.

It is typical for an asteroid to have a very small assessed probability of impact shortly after its discovery, because its orbit is uncertain. When projected into the future, its uncertainty ellipse at the time of its encounter with the Earth is much larger than the size of the Earth itself. As the asteroid's orbit (and its position within it) is refined by follow-up observations the uncertainty ellipse shrinks. If the Earth is still inside the uncertainty ellipse after the refinement, the assessed probability increases in proportion. The changes in probability estimates tend to come in discrete steps because observation is not possible at great distances or small solar elongations (angular distance from the sun). Opportunities arise when the asteroid comes close to the earth and is visible in the night sky. In the vast majority of cases, further observational refinements eliminate the possibility of impact. In rare cases, the reduction of orbital uncertainty will lead to the projection of an impact. There will always be some uncertainty in position of the asteroid within its orbit, and when projected onto the Earth's surface at the time of the encounter it leads to a narrow ellipse containing the "risk corridor." In practice, this is performed using a Monte Carlo method in which an ensemble of asteroids with perturbed orbits is projected to multiple impact points.

Our scenario was designed to provide participants with two opportunities to respond, first for the original asteroid and second for the broken fragment. According to the script, NASA reports on May 1, 2014 the possibility of a future impact occurring on September 5, 2021 with odds of about one in a million. By mid-May, the odds have increased to 1 in 3000, and by the end of May they are 1 in 500 (probability of 0.2%), generating serious concern. The probability continues to increase to 1% in June, 2% in July, and 6% in August as the orbital uncertainty narrows with a risk corridor that crosses from the Pacific over the US, Gulf of Mexico and mid-Atlantic into Africa. This leads to an international meeting to discuss the possibility of a deflection mission. The best estimate of the kinetic yield of the impact at that time is 700 Mt (where a megaton of TNT is a unit of energy defined by $1 \text{ Mt} \equiv 4.184 \times 10^{15}$ J). The worst-case possibility (for a fully-dense 300-meter object) is far worse.

By February of 2015, as the asteroid recedes beyond observational distance, its impact probability has reached 35%, where it remains until the object becomes visible again in late 2015. The impact becomes certain with further observations in January 2016, and the risk corridor begins to shrink. With only five years until impact, the most reliable deflection method for an object of this size would be a nuclear detonation. Decision makers, however, order a kinetic deflection mission in which momentum is transferred from massive hypervelocity impactors. Six missions will be launched independently from different locations, with two different designs by different agencies for redundancy. The intercept will take place on March 1, 2019 (only 2.5 years before the impact date). The choice is made to use all resources for the deflection mission, so no observer spacecraft is launched to provide an immediate assessment. Success will therefore not be known until the object returns to a distance from which it can be observed from the Earth.

By March 2018, the risk corridor is much smaller, crossing from southern New Mexico into the Caribbean between Florida and Cuba, centered on the Gulf of Mexico. The possible consequences of a failed deflection mission range from a water impact that generates a massive basin-wide tsunami that destroys the entire Gulf coast, to a direct hit on Houston that wipes out the whole metropolitan area. All six launches take place in August 2018, but the failure rate is high because the hard deadline requires a vastly accelerated pace of engineering and construction. On the appointed date, only three impactors strike the asteroid.

The asteroid finally becomes observable from Earth again in December 2019, revealing that it was fragmented by the collisions. The brightest part, assumed to contain most of the mass, has been successfully deflected, but a dimmer—and presumably smaller—fragment is still on a possible collision course. Unfortunately, its trajectory is highly uncertain due to lack of post-intercept observational data. An impact from the fragment of unknown size cannot be ruled out. The risk corridor is reset to its maximum extent. The mass is highly uncertain and therefore its kinetic yield is unknown. At this late date, another deflection mission is not an option because there is insufficient time.

It will not be until May 2021—four months before the September 5 target date—that there is enough observational data to confirm that an impact will take place. Because it is now a short-warning impactor there is no hope of deflection, so civil defense plans must be made. The size and location of impact are still highly uncertain and more observations are required to generate a specific plan. By August 5, 2021, only a month before impact, the risk corridor has been reduced to a narrow band from central Texas to a point in the Gulf of Mexico south of Louisiana. The size estimates range from 40 to 60 meters in diameter. Because the density is still unknown the kinetic yield upon impact could be anywhere between about 4 and 11 Mt (similar to the range of estimates for the 1908 Tunguska airburst).

The tabletop exercise begins at this time, as the 30-day update. The above backstory was provided as read-ahead material for the participants in advance of the TTX. It is described in more detail in the final report [1], which includes orbital diagrams and maps of the risk corridor evolution. The 6-day update is based on new information with reduced uncertainty after radar data becomes available. The impact of a 50-meter diameter stony asteroid of unknown density will take place in the Houston area. The Sandia team gave play-acted briefings for both updates, providing information based on our impact simulations and consequence estimates, which are summarized in the following sections.

3. Impact simulations

For the 30-day update we determined that the impact would probably yield an airburst very similar to the explosion over the Tunguska region of Siberia in 1908. The current best estimate of the equivalent explosive yield of Tunguska is 3 to 5 Mt with an entry angle of 35° above the horizon [2], whereas the simulated best estimate of the TTX impact was 4.15 Mt with an entry angle of 40°. To be realistic, the scenario assumed that the exact diameter of the impacting object would still be somewhat uncertain (40-60 meters) immediately prior to the event. The density (therefore the mass and yield) and the strength (therefore the burst altitude) would also be highly uncertain. Thus, we performed a matrix of simulations using Sandia's CTH Eulerian hydrocode over a wide range of assumptions about yield and burst altitude that included the best estimate as well as the worst case. CTH has been used to simulate terrestrial airbursts since it was first successfully applied to model the impact of comet Shoemaker-Levy 9 on Jupiter [3], which was treated as a "validation experiment."

For purposes of the TTX, we also assumed that damage would be dominated by dynamic pressure associated with the blast wave at the surface beneath the burst. In reality, damage would depend on thermal loading and overpressure as well. Due to limited resources, we used dynamic pressure as a surrogate to keep the exercise as simple as possible. When an asteroid deposits most of its kinetic energy in the lower stratosphere or troposphere, the resulting fireball continues to expand and descend toward the surface, driving a bow shock ahead of it that is reinforced by the explosion that results from the conversion of kinetic energy to heat and pressure. The directed nature of a collisional airburst enhances its destructive power relative to a point-source explosion of the same yield at the same altitude [4]. A tacit simplifying assumption for previous risk assessments was that airbursts could be approximated using nuclear weapons effects data.

We used CTH to simulate exploding asteroids of various sizes, densities, and burst altitudes in a gravitationally stabilized atmosphere, and allowed the blast wave to propagate to a radial distance of 50 km on the surface. We stored particle velocity data (wind speed) at a dense array of surface tracer locations, retaining the maximum value at each. From this we generated contour maps. In all cases we specified an explosion at a prescribed altitude by sourcing sufficient additional energy for complete vaporization. This requires about 10% of the original kinetic energy. We reduced the corresponding impact velocity to compensate, ensuring that the total energy would be correct. This leads to an effective underestimate of the momentum by a few percent. Thus, the coupling to the ground is actually a slight underestimate.

The worst case, given the specified uncertainty, would be that the approaching object is already fractured and weak enough to explode at high altitude. Such an airburst can spread its energy out over a larger area and will be more damaging than a crater-forming impact. The worst-case scenario would be a high altitude airburst releasing about 10.6 Mt of energy. The best estimate would be that the fragment is a slightly less dense 50-meter object. Even a relatively strong object of this size is likely to explode at high altitude; although it is possible some fraction of it could reach the ground and form a crater. This best estimate is almost identical to current understanding of the Tunguska explosion (the object that exploded is thought to have entered the atmosphere at the slightly shallower angle of 35°).

Expected effects on the ground from a 2014 TTX impact can therefore be compared to the effect of the Tunguska event. The center map in Figure 1 shows the 2000 square km area in which the Tunguska explosion damaged forest, with the darker blue indicating complete destruction (the maps are 60 km wide and 80 km high). This is compared to two computational experiments, based on assumptions considered to be realistic for the event, using a 15 Mt impactor (left) and a 5 Mt impactor (right). Wind speeds in the affected area could exceed 30 m/s over more than 2000 km^2, with peak winds exceeding 50 m/s, consistent with the observed forest damage.

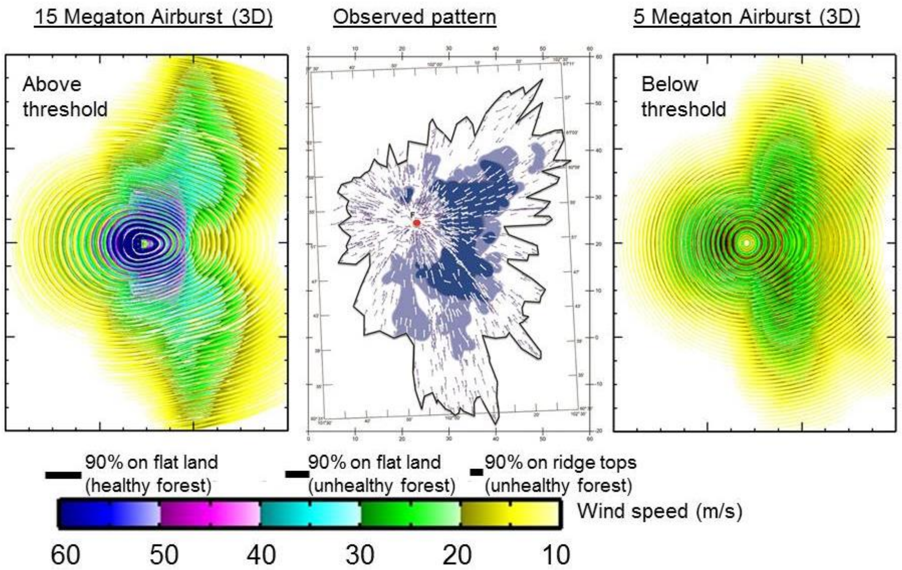


Figure 1. Two CTH airburst simulations (15 Mt on left, and 5 Mt on right) compared with map of observed Tunguska forest damage (center).

In our initial 30-day briefing slide, we announced to the participants “what we have been told” and our expert assessment of what that would mean. On August 5, 2021, what is known about the object is the following.

- Entry speed: 15.4 km/s
- Size: 40-60 meters diameter
- Composition: Stone, density 2.2-3.3 g/cm^3
- Entry angle: 39.5° from horizontal

Given these entry conditions, a 10.6-Mt airburst or impact cannot be ruled out. The density and strength of the object are not known. It could be as strong and dense as granite or as weak and porous as a pile of gravel. Due to these uncertainties, we cannot say with certainty how big the explosion will be, or whether the object will explode in the atmosphere or hit the ground and make a crater. Emergency planners must consider all of the possible outcomes.

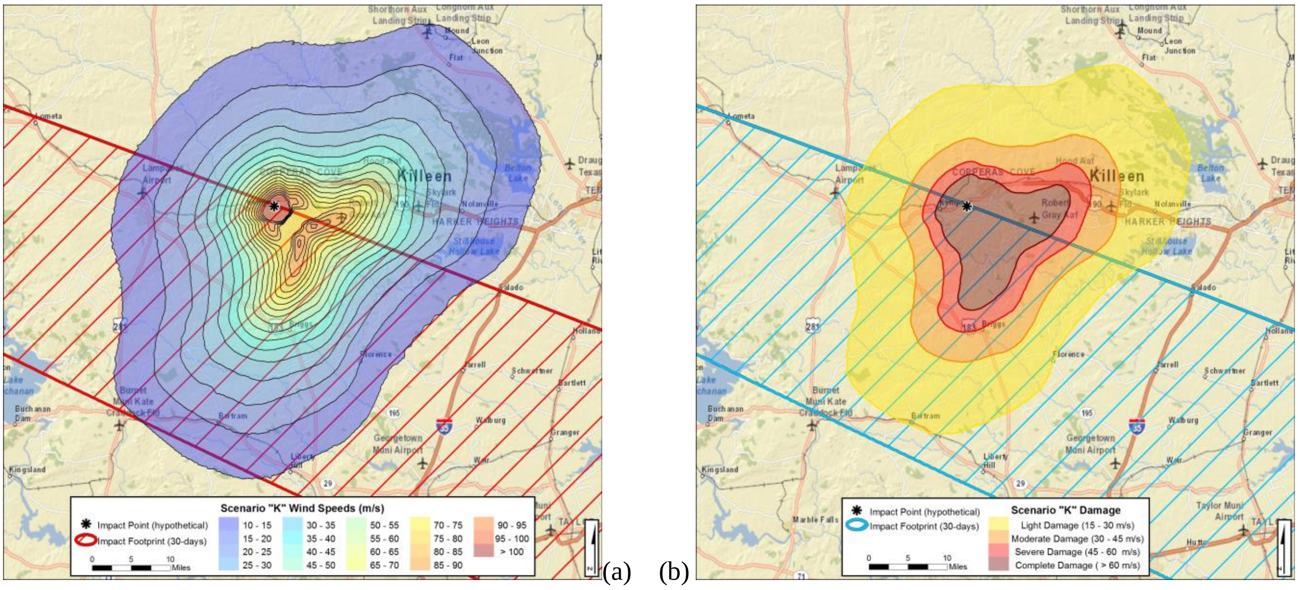


Figure 2. (a) CTH-generated worst-case wind speed contours from a 10.6 Mt surface burst from a 60-m asteroid at Fort Hood, Texas. (b) Damage contours used for the FASTMap application (b). Asterisk denotes projected point of impact. Hatched area to the south is uncertainty ellipse.

In Figure 2, the results of our worst-case element of the matrix is shown, as wind speed (a) and damage (b) assuming an airburst over Fort Hood, near the northern edge of the inland portion of the impact ellipse (hatched area). We used the nuclear weapons effects literature [5] as a rough guide for damage assignment, but if this were an actual event we would include overpressure and thermal loading in a much more detailed and quantitative analysis. We repeated this process for all six elements of a test matrix assuming three different heights of burst (0, 6, and 12 km above the surface) for two different yields. The highest possible yield (10.6 Mt) assumed a full-density (3.3 g/cm3) 60-m diameter asteroid. The best-estimate yield (4.15 Mt) assumed a porous (2.2 g/cm3) 50-diameter asteroid. The three heights of burst corresponded to strong, moderate, and weak asteroids. The most damaging of all cases was the highest altitude burst of the most massive asteroid.

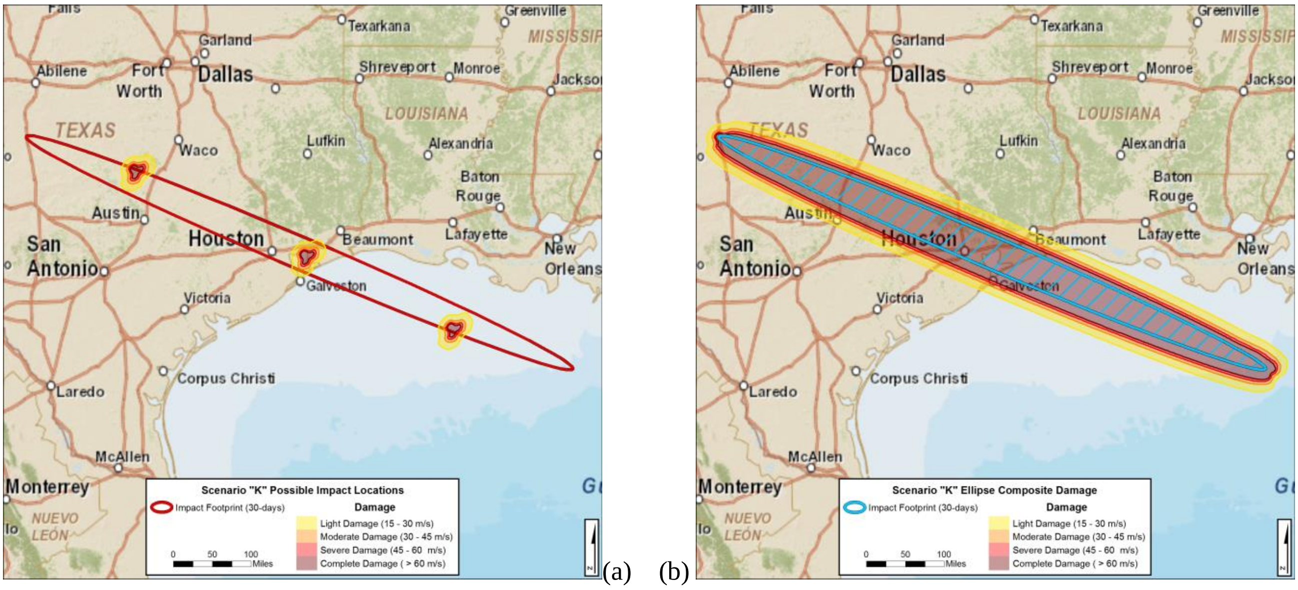


Figure 3. (a) Damage contours for three possible locations within the impact ellipse. (b) Composite damage contours for ensemble of all possible impact locations.

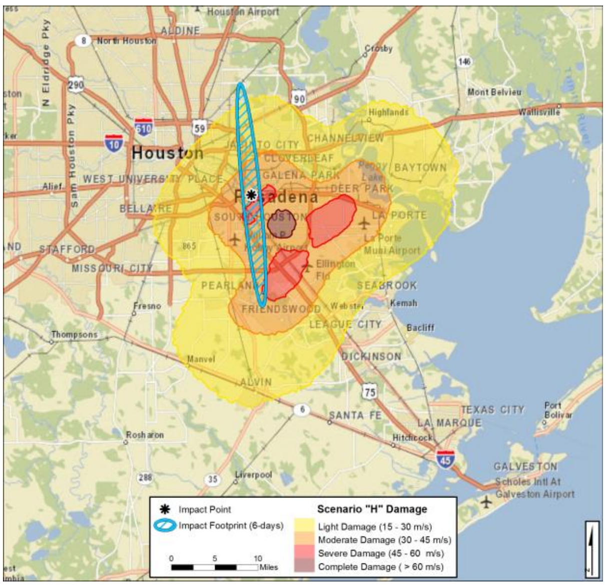
Since the uncertainty in impact location is extensive, we also provided a map showing the damage footprint at several locations within the ellipse, which we then we convolved with the footprint (Figure 3). We advised participants that preliminary evacuation plans for an airburst over land should be in a lateral direction into area known already to be at no risk, but that detailed plans should wait until radar data becomes available (about 6 days before impact) when the uncertainty ellipse will have collapsed to an area similar in size to the damage footprint. In the event of a radar failure, preliminary plans for lateral evacuation could be retained.

Much of the uncertainty ellipse spans parts of the Gulf of Mexico. An impact within that part of the ellipse would produce a tsunami, and would affect the whole of the coastline from Texas to Florida. According to calculations by Souheil Ezzedine of Lawrence Livermore National Laboratory (LLNL) a tsunami generated by an impact in the easternmost part of the ellipse would have wave heights of 3 to 10 m and would arrive at the coast over a time spanning from 1 to 4.25 hours after the impact. The tsunami would first reach the Louisiana coastline, causing near total destruction to the barrier islands, The wave run-up would extend inland as far as 16 km.

For the six-day briefing, the asteroid was within range of the Arecibo radio telescope, providing very precise range and image data that eliminated the possibility of a water impact and resulting tsunami. Because the radar provides high precision along the beam direction but a less accurate lateral position, the axis of the uncertainty changes as well as the size. This reduces the impact risk corridor to a north-south strip centered on Pasadena, Texas (in the Houston metropolitan area, shown in Figure 4, radar imaging of the object determines that it is very close to 50 meters in size and that the stony asteroid is somewhat porous, with a density of about 2.2 g/cm^3. Therefore, there is little uncertainty in the kinetic yield, and best estimate of 4.15 Mt prevails. The spatial uncertainty ellipse continues to shrink on the map as more radar observations are made in subsequent days until the precise impact point is located just prior to atmospheric entry. The greatest uncertainty, by far, is the height of burst.

In our initial 6-day briefing slide, we again announced to the participants “what we have been told” and our expert assessment of what that would mean. On August 29, 2021, what is known about the object is the following.

- Entry speed: 15.4 km/s
- Size: 50 meters diameter
- Composition: Stone, density 2.2 g/cm3
- US population zones at risk: Houston, TX area
- Entry angle: 39.5° from horizontal
- ~4.1 Mt airburst or impact cannot be ruled out



(a) (b)

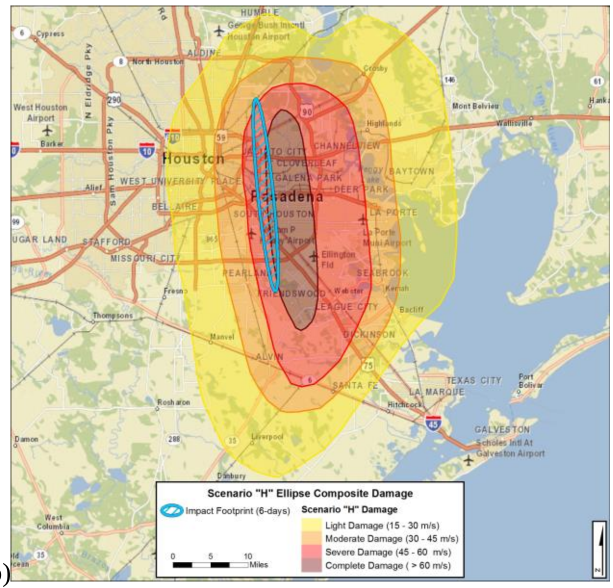


Figure 4. (a) Damage contours for the worst-case scenario at the center of the uncertainty ellipse. (b) Composite worst-case damage contours for ensemble of all possible impact locations.

Since the yield is now precisely known, we only used three simulations at the three different burst heights. Figure 4 shows the damage footprint again for the highest altitude (12 km burst height) which is the most extensive, as expected. This becomes the new 6-day worst-case scenario. We again convolved the footprint with the impact uncertainty ellipse to get a composite risk map on which the evacuation plan must be based because it must commence immediately. This map is also the one that is provided to officials who are responsible for shutting down utilities and dealing with infrastructure and economic losses, which are discussed in the next section.

4. Infrastructure and economic losses

The threat of an asteroid impact to human population and infrastructure is of high importance to FEMA in order to plan for and conduct preparation for disaster response. For this exercise we also provided analysis of population and infrastructure damage. The effects from an asteroid airburst are similar to those from a hurricane or a nuclear explosion. Effects from an impact-produced tsunami are the same as those from a tsunami generated by an earthquake or volcanic eruption. This section provides a general overview.

For the 30-day briefing, the overall worst-case scenario was a tsunami-producing impact in the central Gulf of Mexico. The possible consequences, according to the tsunami calculation by LLNL, include maximum wave heights of 1 to 3 meters that arrive at the coast 1 to 4.25 hours after the impact. Damages from a tsunami are somewhat analogous to storm surge damage resulting from a hurricane. We therefore used the NOAA Coastal Risk Analysis as a measure of the tsunami run up. A wave height of 3 meters would lead to inland flooding up to 10 miles. The major distinctions that exist between a tsunami and storm surge are the force of the wave and the surge effects. There are differences in speed and momentum of a tsunami compared to a slower rise of water and a longer period of inundation for storm surge leading to different consequences for infrastructure. The force with which a tsunami wave arrives is greater than a hurricane and causes more destruction. Secondary damage occurs to infrastructure due to sustained periods of time in standing water.

We also analyzed the potential damage from an airburst to infrastructure and presented estimates in our briefings. The damage would be similar to that which occurs from the blast wave that accompanies a nuclear explosion. The combination of high peak overpressure, high wind pressure, and compression from the blast wave results in mass distortion of buildings similar to that from earthquakes or hurricanes. Structural resistance to the blast is dependent on the general building components and size. Infrastructure constructed of heavily framed steel, reinforced concrete, or with earthquake resistant design, would be best able to withstand the blast.

Commercial structures are generally better able to withstand damage than residential buildings. The severity of damage is reduced as the distance from the impact grows. Previous studies of damage and distance by wind velocity measures have been classified in three categories: severe, moderate and light, according to Glasstone and Dolan [5]. Severe damage means that the structure is not usable as intended and generally collapsed. Moderate damage indicates that the structure is operable with major repairs. Light damage is associated with broken windows or slight damage to roofs and siding.

According to Glasstone and Dolan [5], a 10 kt point-source (nuclear) airburst causes severe damage up to 1,400 feet. For rail transport, railcars are blown from tracks and damaged; however the track generally remains in place. In above-ground facilities such as oil tanks, the damage takes place when those structures are moved from their foundations. Up to 1,600 feet from the blast, moderate damage is possible. In the case of railcars and construction equipment, this involves overturning of cars and possible distortion in the frames. A distance of over 1,600 feet is considered at risk for light damage—broken glass and damage to parts, but equipment is generally usable. Glasstone and Dolan [5] provide scaling laws to enable estimates of damage from explosions with higher yields and larger distances.

Nuclear weapons effects on coniferous forests are primarily due to dynamic pressure from high winds and provide another means to classify damage using the resulting percentage of fallen trees, density of forest debris, and vehicle passability on roads as indicators. Winds with a velocity of 130-140 miles per hour result in severe damage with up to 90% of trees blown down and the area impassable to vehicles. At wind speeds of 90-100, approximately 30% of the trees are blown down and the area must be cleared to allow vehicles to pass. At 60-80 miles per hour trees are generally left standing and the area is passable to vehicles [5].

Impact to industrial buildings and infrastructure systems are also largely dependent on structural stability. Electrical utilities would potentially suffer damage from sustained high wind situations from loss of power due to damage to overhead lines. The destructive effects are largely associated with damage to suspension towers. As evident, underground electrical lines would have far less, if any, damage. Damage to gas, water and sewage systems is highly dependent on the surface structure, damage to structural foundations, and equipment used to run the systems. Figure 5 illustrates the chemical industry at risk in the area of the impact.

Using the FASTMap application developed at Sandia, at-risk infrastructure for various sectors was mapped for each impact scenario using Homeland Security Infrastructure Program data and our contour maps. We also estimated direct economic loss in the form of reduction to total gross domestic product (GDP) due business interruptions. The REAcct model uses county-level data covering employment by industry and GDP contribution per employee by industry. Many simplifying assumptions were made within the limited scope of the TTX, but our work demonstrated that shock physics, infrastructure, and economic modeling tools can be integrated to plan for an impact disaster, given sufficient warning.

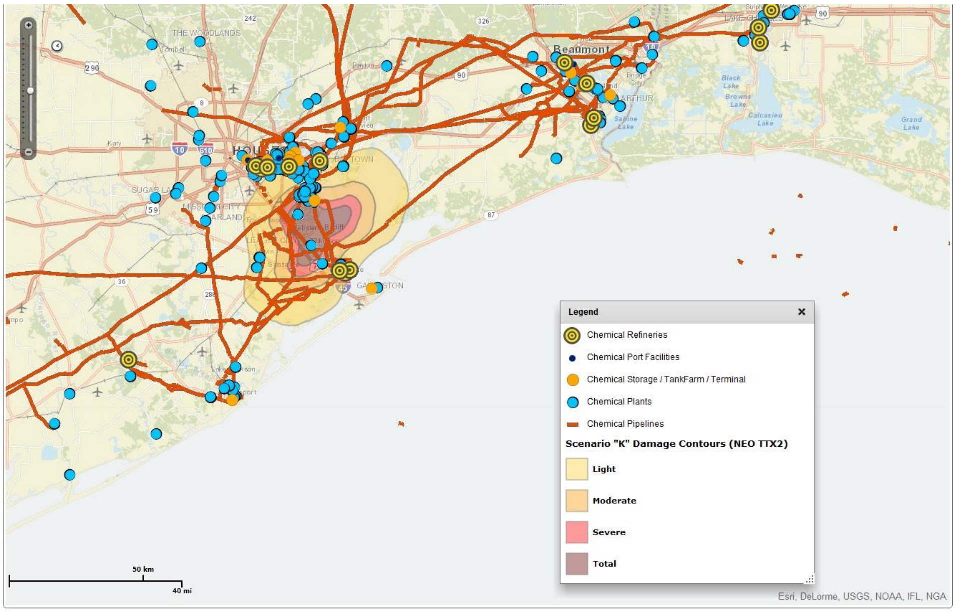


Figure 5. Chemical industry at risk from airburst in the Houston area, with CTH contours superimposed on infrastructure map.

Conclusions

Responding to an asteroid impact is a complex, high-consequence activity involving large numbers of people with different areas of expertise, and multiple agencies with different charters, stakeholders, and constituencies. Advance training is paramount, and tabletop exercises provide the opportunity to exchange information and learn from mistakes in advance—when the stakes are low. Our involvement in the 2014 TTX has led to an improvement in our ability to quickly run physical simulations of a projected impact, generate damage maps, assess the consequences to people, infrastructure, and the economy, and to provide timely information to decision makers. Future tabletop exercises will provide more opportunities to integrate and improve our tools.

Acknowledgements

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under Contract DE-AC04-94AL85000. Funding for this activity was provided by NASA.

References

[1] Summary Report on TTX#2: Tabletop Exercise for Asteroid Impact Event. Report prepared for NASA HQ Science Mission Directorate, Planetary Science Division, NEO Observations Program, Sept. 2014.
[2] Boslough, M., Crawford, D., 1997. Shoemaker-Levy 9 and plume-forming collisions on Earth. Ann. NY Acad. Sci. 822, pp. 236–282.
[3] Crawford, D., Boslough, M., Trucano, T., Robinson, A., 1995. The impact of periodic comet Shoemaker-Levy 9 on Jupiter. Int. J. Impact Eng. 17, pp. 253–262.
[4] Boslough, M., Crawford, D., 2008. Low-altitude airbursts and the impact threat. Int. J. Impact Eng. 35, pp. 1441–1448.
[5] Glasstone, S., Dolan, P. 1977. The Effects of Nuclear Weapons, Third Edition, U.S. Department of Defense, Washington DC, USA.