# Deep Impact:
# Are we prepared to handle an asteroid collision?

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## Write Around the World Competition

**Abstract**

In recent years, hurricanes have made people realize that despite of technical developments we are severely vulnerable to natural hazards. One such natural hazard with tremendous destructive potential is an impact from asteroid or NEO. Scientist and astronomers have estimated that more than a million near earth objects (NEOs) are present in our solar system, some of which are recognized as Potential Hazardous Objects. We can categorize a major asteroid related disaster of regional consequences as "low probability - high consequence" event. Most small to medium asteroids on a collision course with earth may get detected only few days or weeks before actual impact date. Although there are studies being carried out internationally on detection and mitigation of NEO hazards, there is no formal process in place for forwarding notice of a high-priority threat to agencies responsible for civil defense. We should use the time available to develop necessary international protocols with help of all stakeholders and agencies working in this field. This would help in responding to any future NEO threats. This paper deals with the legal, ethical, engineering and policy aspects associated with the problem, and recommends a strategy for preparedness.

## INTRODUCTION

There are estimated to be more than a million near earth objects (NEOs) orbiting in our solar system. [1] These objects (such as asteroids or comets) could range in sizes from a few meters to thousands of kilometers. The Earth's atmosphere acts as a protective shield from most NEOs smaller than 40 m (for solid / iron asteroids) to 140 m (for rubble pile asteroids).[2] From this size up to about 1 km diameter, an impacting NEO can do tremendous damage on a local or regional scale. Larger asteroids of size few kilometers can produce severe environmental damage on a global scale. Still larger impacts (10's of kilometers) can cause mass extinctions. [1] We can categorize a major asteroid related disaster of significant consequences as "low probability - high consequence" event.[18] Table 1 shows the estimate of the chances of an individual dying from selected causes in the USA.[3] The actual risk to each of us from similar or larger impacts is very small. [1]

**Table 1: Comparison of risk of death due to asteroid impact with other common hazards[3]**

| Cause of Death | Chances |
|---|---|
| • Motor vehicle accident | 1 in 100 |
| • Fire | 1 in 800 |
| • Asteroid/comet impact (lower limit) | 1 in 3,000 |
| • Electrocution | 1 in 5,000 |
| • Asteroid/comet impact | 1 in 20,000 |
| • Passenger aircraft crash | 1 in 20,000 |
| • Flood | 1 in 30,000 |
| • Tornado | 1 in 60,000 |
| • Asteroid/comet impact (upper limit) | 1 in 250,000 |

In 1990, based on the recommendations from the American Institute of Aeronautics and Astronautics (AIAA), the United States House of Representatives asked the National Aeronautics and Space Administration (NASA), to set up two workshop studies related to NEOs. [4] At present several teams of astronomers worldwide are surveying the sky. The Spaceguard Survey and most associated search and tracking programs are concentrating on NEOs larger than 1 km in diameter. U.S. House also approved on May 17th, 2005, *Near-Earth Object Survey Act*. to establish a program within NASA to detect, track, catalogue, and characterize the physical properties of near-Earth asteroids and comets equal to or greater than 100 meters in diameter in order to assess the threat of Earth being struck by such NEOs.[5]

1 David Morrison; FAQs about NEO impacts; NASA Ames Research Center @ http://impact.arc.nasa.gov/intro_faq.cfm

2 J. G. Hills et al; Tsunami generated by small asteroid impacts

3 Reprinted from Clark Chapman and David Morrison, Nature, Vol. 367, page 39 (1994).

4 Space Guard UK: Current Situation, http://www.spaceguarduk.com/currentsit.htm

5 NOAA, NASA bills sail through committee, 05-17-2005, http://www.house.gov/science/press/109/109-78.htm

The last known major asteroid impact was in 1908 in Tunguska, Siberia due to a 60 m diameter object exploding in atmosphere.[6] Fig. 1 shows impact location of an earlier meteor crater created in Arizona, USA.

**Figure 1: Meteor Crater, Arizona, USA.** ***Photo by Rahul Walawalkar © 2005***

## *ASSESSING POTENTIAL THREAT OF AN ASTEROID*

For assessing the potential threat of an asteroid, let's assume a scenario where astronomers detect an asteroid with potential impact location somewhere in South America with in 18 months. To make this threat realistic, let's assume that the NEO is a single solid body with estimated diameter of 300 meters with density of 3.6 g/cm$^3$ and has a rating of 9 on the Torino scale. This rating means that the collision is certain, capable of causing unprecedented regional devastation for a land impact or the threat of a major tsunami for an ocean impact.[7] Fig. 2 shows an illustration of orbits of earth and an asteroid detected in 2002 for ease of understanding.


**Figure 2: Illustrations show positions of Earth and asteroid 1950 DA on April 5, 2002. Source: NASA/JPL[1]**

Before proceeding with the impact and risk assessment for the threat proposed from this asteroid it is important to understand the number of uncertainties we need to consider.

6 Adushkin and Nemchinov; Consequences of impacts of cosmic bodies on the surface of the earth

7 The Torino Impact Hazard Scale @ http://neo.jpl.nasa.gov/torino_scale.html

### Uncertainties with available information about the NEO

- **Information on NEO:** Detecting an NEO is considered as the easiest part of the process. It is very important to make sure we have accurate information on properties of asteroid such as density, structure, class, composition, spin and velocity.
  - Information in the example of probable density of the asteroid (3.6 g/cm$^3$) suggests that the asteroid can belong to either the Chondrites Class or Stony Irons (Pallasites) Class. Chondrites are fragile stones, and thus are likely to break up during entry into earth's atmosphere and result in meteorite showers, where as Stony Iron asteroid would result in major impact.[8]
  - Most of the original density estimates of asteroids have been found to have as much as 50% error after detailed analysis. Most deflection and destruction methods have drastically reduced effectiveness if the asteroid has a weak porous surface. Kinetic impactor may work well for solid asteroids, where as nuclear blast may be required for porous asteroids. [9]

**Figure 3: The Holsinger Meteorite, largest discovered fragment of the meteor that created Meteor Crater in Arizona, USA.** ***Photo by Rahul Walawalkar © 2005***

- **Impact location:** Even if the orbit of the NEO is known for certain, the speed of the NEO and actual location of impact may get affected by exact shape (most asteroids are not spherical), spin state, effect of solar radiation etc.[10] A slight deviation in speed (few cm/s) may result in the impact location either moving towards east (acceleration) or west (deceleration). Similarly a change in inclination (due to spin state, effect of gravitational forces of other planets) may result in the impact location shifting to north or south.

## *ASSESSMENTS OF RISKS*

In the event of the impact, there are 2 possibilities. The NEO may crash in to land or ocean. Based on the general guidelines about size and density of the asteroid, the current impact is expected to have regional consequences. There are large number of factors that make it difficult to predict the exact extent of damage: difference in population density, types and structures of buildings, geology of impact region, configuration & topography of ocean, weather conditions at the time of impact and characteristics of the impactor.[6]

8 John Lewes, Comet and Asteroid impact Hazard on a Populated Earth; chapter 3; 1999

9 Keith Holsapple; Mitigation of Hazards from Asteroids and Comets; 2004

10 Chapman et al, The Comet/Asteroid Impact Hazard: A Systems Approach; 2001

### *Impact Effects*

With some simplified assumptions, the approximate kinetic energy released by the impact can be calculated by following equation: [11]

$KE_{(MegaTons)} = (6.256*10^{-8})* (diameter_{(m)})^3 * (Velocity_{(km/s)})^2 * (Density_{(g/cm^3)}) = 6.7*10^3{}_{MegaTons}$

I calculated the anticipated impact effects based on the estimates for asteroid properties using a software program developed by Arizona University.[12] Table 3 provides the summary of relevant results.

**Table 2: Summary of Impact Effects**[12]

- **Atmospheric Entry:**
  - The projectile begins to breakup at an altitude of **59,600 meters**
  - The impact energy is **$2.59 \times 10^{19}$ Joules = $6.18 \times 10^3$MegaTons**
- **Crater Dimensions:**
  - Final Crater Diameter: 10.3 km & Final Crater Depth: 0.597 km
- **Thermal Radiation:**
  - Time for maximum radiation: 0.176 seconds after impact
  - Visible fireball radius: 5.91 km (The fireball appears 134 times larger than the sun )
  - Thermal Exposure: **$1.23 \times 10^8$ Joules/$m^2$** for 76.9 seconds
- **Seismic Effects:**
  - Richter Scale Magnitude: **7.1**

The impact could also result in Electro Magnetic pulse (EMP) that can damage electronic and computer equipment. Other effects of the blast may include acid rain due to nitrous and nitric acid produced during the impact explosion. [11] The blast may also result in injecting dust and sulfur compounds into stratosphere.

### *Affected population*

I have conducted preliminary assessment so that we can get a better idea about extent of potential damage for impact location somewhere in South America.

### Case 1) Land Impact

For land impact, primary cause of damage and loss of life will be the atmospheric blast wave in case of land impact.[17] The criteria for determining the evacuation area can be based on the amount of pressure that will be experienced in the surrounding area. Blast wave pressure can be used as preliminary indicator for the extent of damage. e,g, 20 psi pressure would level reinforced concrete structures and can cause severe internal injuries to humans, where as 1 psi pressure would cause light damage to structure and cause injuries due to flying glass / debris.[11] Using the peak overpressure estimates, Fig 4 shows the estimated distances from point of impact which will get affected in case of a land impact. [11,13]

11 James Marusek; Comet and Asteroid Threat Impact Analysis; 2001

12 The program can be accessed at http://www.lpl.arizona.edu/impacteffects/ .

13 Civil Defense Shelters: A State of the Art Assessment – 1986, Oak Ridge National Lab

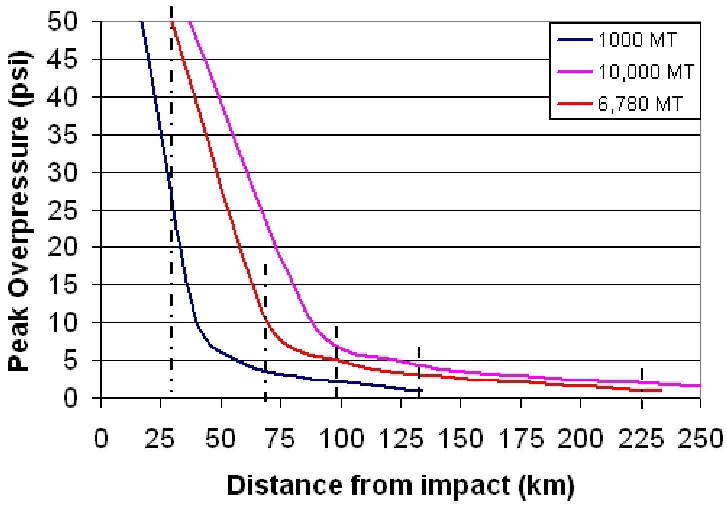


**Figure 4: Evacuation area based on Impact's Kinetic Energy and Overpressure**

Figure 5 shows the estimated affected area on a sample population density map of South America.[15] The outermost circle represents area experiencing 1 psi overpressure (233 km radius), where as inner most circle shows area experiencing 50 psi pressure (30 km radius). According to CIA fact-sheets, the population density of the various countries in South America ranges from 8.6 people / km$^2$ for Bolivia to 21.9 people / km$^2$ for Brazil and Chile. The average population density in Argentina is 14.5 people / km$^2$.[14]

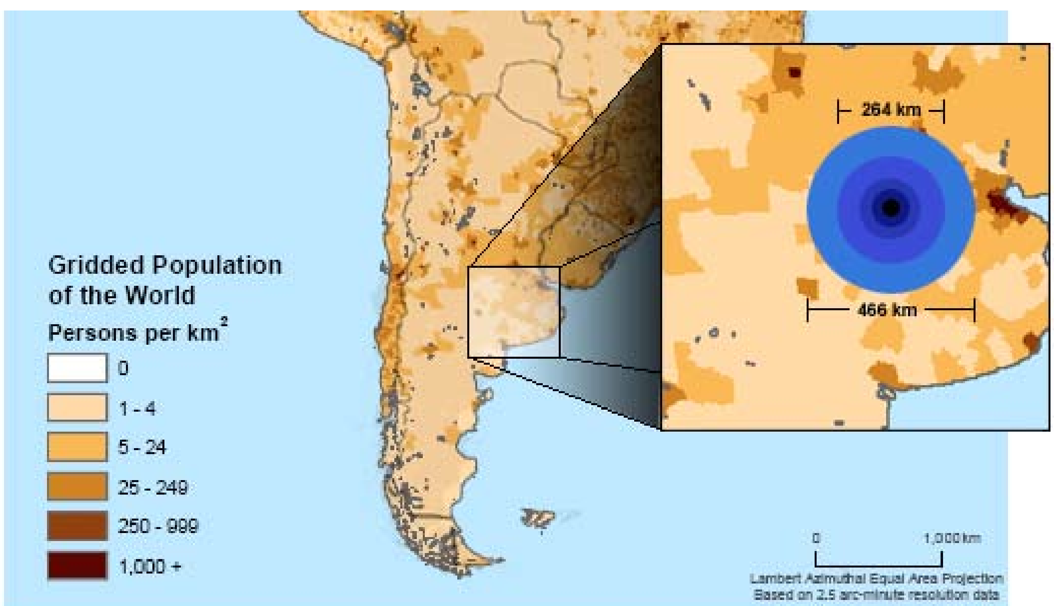


**Figure 5: Sample area of impact and size of area and population affected (modified from the original population density map of South America from Center for International Earth Science Information network (CIESIN), Columbia University)[15]**

14 CIA World Fact Book @ http://www.cia.gov/cia/publications/factbook/index.html

15 South America Population Density Map 2000 http://sedac.ciesin.columbia.edu/gpw/country.jsp?iso=ZAF

### *Case 2) Ocean Impact*

An NEO impact into ocean can produce intense compressive pulse in the water which produces a surge and subsequent waves. An ocean surface blast in either Pacific or Atlantic Ocean would result in Tsunami, that may affect not only South American coastlines, but coastlines of west coast of Africa, western US, Hawaii, Australia and Japan as well. The shores of sea and ocean usually are the regions of high density population and industry, thus increasing the hazard of Tsunami. [6] Tsunamis can account for the most devastating damage caused by asteroid impact with diameter between 200 m to 1 km. The magnitude 9 earthquake that triggered the deadly Tsunami in Indian Ocean on 26$^{th}$ Dec 2004, was centered off the west coast Indonesia[16] and traveled over 5,000 kms to Africa. Preliminary calculations using equations provided by Shuvalov[17], I estimate that the wave height generated by a deepwater impact at 1000 kms from the impact location would be 9.81 m in the Pacific Ocean and 7.65 m in the Atlantic Ocean.

## Estimated cost of impact

Some previous studies have shown that several common cost analysis methods, such as benefit-cost analysis, cost efficiency analysis or human capital approach is not appropriate for analyzing impact from asteroids. A more appropriate approach is cost prevention method.[18] If we have sufficient time to take precautionary measures, we will need to evacuate people from large areas to avoid significant loss of life in the case where we are not able to avoid the impact. If we do not take such measures, the death toll could be in thousands as shown from recent examples of Indian Ocean Tsunami of 2004 and Kashmir Earthquake of 2005. Even with a well designed and executed evacuation plan, we may experience few 100 casualties in case of impact, due to difficulties in identifying all the people in remote areas or ensuring that everyone knows the procedure. Based on the experience from Hurricane Katrina, we will definitely need state sponsored or internationally funded evacuation program for maximum success.

Apart from the evacuation costs and direct damages, such impact could also have other economic consequences for rest of the world. e.g. Argentina exported approximately 108 Million bbl oil in 2004 to Brazil and Chile.[19] Any major disruptions in the supply due to NEO impact may cause world oil prices to increase.

16 Tsunami Region Ripe for Another Big Quake, National Geographic News, March 2005
http://news.nationalgeographic.com/news/2005/03/0316_050316_sumatra.html

17 V. V. Shuvalov, "Numerical Modeling Of The Eltanin Impact," Lunar and Planetary Science, XXXIV, 2003.

18 Gritzner and Kahle, “Mitigation technologies and their requirements” in Mitigation of Hazardous Comets and Asteroids, 2004

19 Energy Information Administration’s Country Analysis Brief @ http://www.eia.doe.gov/emeu/cabs/argentna.html

### ***MITIGATION OPTIONS:***

Before discussing the mitigation options, I would like to clear a misconception that we can use Inter-Continental Ballistic Missiles (ICBMs) for destroying the asteroid close to earth's atmosphere. All the literature and expert presentations[20] indicate that only option to mitigate the asteroid impact threat is while the NEO is far away from earth (preferably years away, but at least weeks away). ICBMs and other similar missiles are not capable of achieving 11.2 km/s speed[21] required to escape from earth's gravitational field. Hence use of such weapons is limited to cases when asteroid is approaching earth's atmosphere, which would be less than 40 seconds before the actual impact (considering 35 km/s speed of asteroid). Even a successful intercept at such distance would result in only fragmentation of the asteroid, which would result in multiple impacts causing more damage.

Generally we can mitigate the NEO impact by either deflecting the NEO (by speeding, decelerating or moving the NEO by few cm/s by perpendicular deflection) or by destroying the object. For avoiding a certain collision, we need to deflect the NEO by at least 10,000 km away from earth. Most potential technologies can provide 1cm/s deflection, which results in 1000 km/year, thus minimum duration required for such mission is 10 years.[22] Where as with short warning time (as is our case), we can achieve the desired result by perpendicular force using single or multiple impacts of either nuclear or kinetic nature.[18] In either intentional or unintentional (by applying excess force during deflection attempt) destruction of the NEO, we need to consider the damage that may be caused by fragments that stay on collision course. Resulting fragments could be large enough to cause even more damage than a single object due to larger area affected. Thus diversion may be the only practicable option to prevent impact of an object larger than a few hundred meters. Below is a summary of some technologies that could be used for this purpose.[20] So far none of these technologies have been tested to deflect a NEO in a controlled way.

**Table 3: Options for mitigating NEO threat**

| | |
|---|---|
| • Nuclear Weapons<br>  o Standoff mode<br>  o Surface / Buried Explosion<br>• Chemical Explosives<br>  o Surface / Buried Explosion<br>• Kinetic Impacts | • Beamed Energy:<br>  o Solar Collector<br>  o Lasers<br>  o Microwaves<br>• Mass Drivers<br>• Propulsion / Solar Sails |

Due to requirement of higher energy levels for short term deflection missions, nuclear explosives and kinetic impactor are the only possible options in near future, but the effectiveness of both methods is unknown. [18] Current international agreements forbid testing or use of nuclear explosives in space, even for peaceful

20 Various presentations from the 2004 Planetary Defense Conference: Protecting Earth from Asteroids available at http://www.aero.org/conferences/planetdef/

21 Wikipedia encyclopedia http://en.wikipedia.org/wiki/ICBM

22 Smith et al, "Deflecting a Near Earth Object with today's Space Technology", Planetary Defense Conference 2004

purposes.[23] Use of nuclear devices would face significant political hurdles that could delay or derail a deflection effort. The possibilities of launch failure, sensor failure, and off-nominal performance by deflection systems, as well as uncertainties in the properties of the NEO, must be recognized and factored into the overall design of the mission. Any failed or partially successful mission (that may change the location of impact, but not avoid the impact) may result in severe liabilities unless due care was taken in planning and execution of the mission.

### *Sensitivity Analysis for Mitigation Option*

Final decision on mitigation option should be made based on detailed technical analysis and study of simulations of various options available. Selection criteria would involve: Certainty of result, flexibility to adapt to new information that may become available after launch and Low Energy use to avoid any unintentional damages. Success of a mitigation plan greatly depends on following factors:

- **Warning time:** If we detect the NEO earlier, we will have more time to plan the mission and implement proper deflection
- **Speed of interceptor / rocket:** A faster rocket will take less time to reach the NEO, thus giving more time for deflection.
- **Distance for the interceptor to reach the NEO:** As the NEO and earth are moving in 2 different orbits as shown in Figure 2, we need to carefully plan the launch date, so that the interceptor needs to travel minimum distance.
- **Launch date:** Once we identify the suitable launch date, it is advisable to meet the target, as any deviation would mean that interceptor needs to travel more distance, at the same time the asteroid has less distance to impact point. Such delay would mean larger $\Delta V$ (change of velocity required to deflect the NEO from its orbit) requirements for achieving result.

Characteristics of the asteroid impose a limit on $\Delta V$ for avoiding destruction of NEO. This upper limit can be calculated as [24]: $\Delta V = 0.6$ (m/s) * (Diameter of Asteroid in km) = 0.6 * 0.29 = 0.17 m/s

The $\Delta V$ required for successful deflection can be calculated by formula **Error! Bookmark not defined.**, [25]

$\Delta V = 0.07 / t$  (where t is time available in years from successful intercept to impact)

23 Extended Abstracts from the NASA Workshop on Scientific Requirements for Mitigation of Hazardous Comets and Asteroids, 2002

24 Harris, Deflection Techniques: What Makes Sense?, Planetary Defense Conference 2004

25 t, depends on the speed of rocket, launch date, and the distance needed to be covered by the interceptor

For calculating ΔV, I assumed that a suitable launch date, that would permit sufficient planning and preparation would be 120 days from discovery of asteroid. The average rocket speed was assumed as 15 km/s. ΔV was calculated using these assumptions and a base value for distance required to be traveled by the interceptor as 750 million km. This resulted in a required ΔV of 0.12 m/s, which is within the permissible limit of ΔV to avoid disruption of the asteroid.

I then conducted a sensitivity analysis, to assess impact of variation of the input parameters on the desired ΔV. I assumed that the minimum speed for rocket would be 11.2 km/s (to exceed the escape velocity) and maximum speed available was 25 km/s. Similarly it was assumed that the earliest launch date could be in 30 days and latest launch date considered was after 9 months. It was also assumed that we may be able to find an optimum path to the asteroid or may have to travel a longer distance by varying the base estimate from 25% to 200%.

Figure 6 shows the sensitivity analysis of various decision parameters on the ΔV requirement. Results show that faster rocket speeds can reduce the necessary ΔV, but even by doubling the speed, we can reduce the ΔV only to 0.1 m/s. On the other hand, launching the interceptor earlier or finding an optimum path (lower than assumed base value) can result in required ΔV coming down to as low as 0.075 m/s. For a deflection mission the maximum days we can take for launch (assuming current speed and distance requirements) is ~150 days, as beyond this, the required ΔV goes beyond threshold. Thus if for some reason we can not launch mission in the allocated time, we will have to resort to a destruction mission.

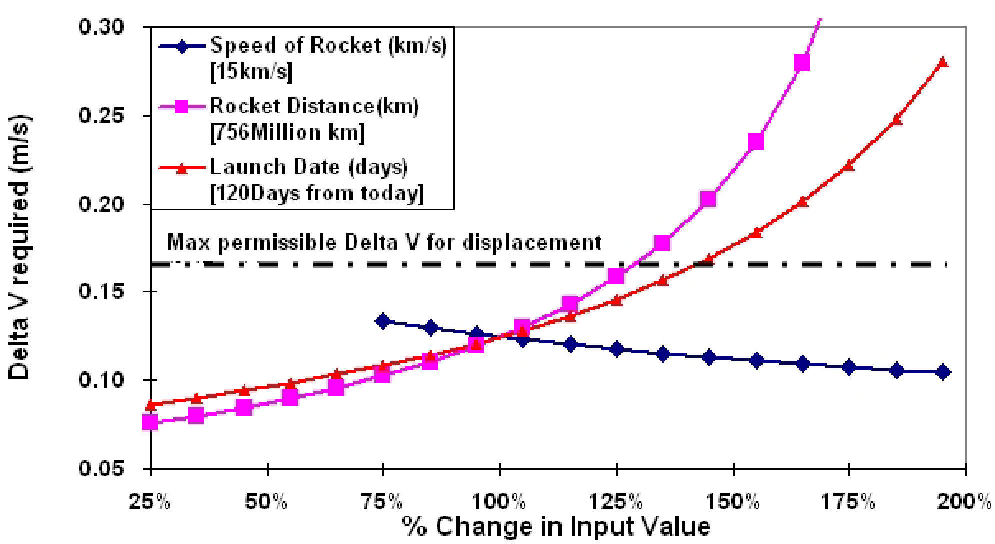


**Figure 6: Sensitivity analysis of various decision parameters on ΔV required for deflecting the asteroid from earth impact orbit**

## RISK COMMUNICATION PLAN

As with any major natural hazard, we need to develop a proper risk communication plan to disseminate the information about the potential hazard of the asteroid impact and reaction plan. Following factors need to be considered carefully in determining the risk communication strategy that will minimize the panic and misinformation to public and stake holders:[23]

- Identifying appropriate Stakeholders / Civic organizations / Governments
- Warning time required for proper planning and implementation of evacuation
- Post warning information management to avoid panic and misinformation
- Post Impact Mitigation requirements such as trauma and psychological issues

Research has indicated that people often remain calm and perform rationally when confronted with an immediate threat or disaster, and are reasonably tolerant of false alarms as long as they are kept informed.[29] People may seek multiple sources of reliable information. Social science research indicates that a top-down, command-and-control approach to communications is not always best. [29] The risk communication plan should involve educating people about the potential hazards, and this may be done by making available scientifically accurate presentations, including visuals and explanations. [29]

It may not be effective to define the threat in probabilistic terms. The information released should be concise, relevant and supported by international experts, so that people can view the sources of information as objective and trustworthy. Social scientists can assist in the development of these protocols. [26] The risk communication plan should not be centrally directed and controlled. It should be flexible, adaptive and focused on handling problems locally as they arise.[27] The communication should include clear information on evacuation protocols, responsible agency details, and information on rescue shelters. Considering the possibility of release of dust, sulfur, NOx and other pollutant in atmosphere, we should warn public to take precautionary measures to avoid respiratory diseases.

To ensure that people take the threat seriously, evidence of previous NEO impacts should be publicized to increase awareness that impacts do happen and that the possibility of future impacts should not be ignored. At the same time, it is important to demonstrate to the public that steps are being taken to mitigate the hazard and such missions are technically feasible. [29] We should also educate public about any existing insurance provisions that may be applicable in this case to cover potential financial losses. [28]

26 Baruch Fischhoff, Risk perception and risk communication, Handbook of Terrorism, 2004

27 Kathleen Tierney, Disaster beliefs and institutional interests

28 Most of the homeowner / business insurance policies provide coverage against asteroid impact, but may not cover Tsunami related damages.

## ***CONCLUSIONS AND POLICY RECOMMENDATION***

Although there are various studies being carried out internationally on detection and mitigation of NEO hazards, there is no formal process in place for forwarding notice of a high-priority threat to agencies responsible for civil defense. Most of the civil defense agencies do not have any plans for responding to such threat. In addition, no national or international organizations or agencies are responsible for taking steps to mitigate the problem. Most organizations likely to be involved if a threat is detected are not even aware of this natural hazard. [29] Thus there is a need to initiate efforts to develop an international collaboration to study the possibility of impact and potential mitigation plan. Based on the detailed study of the literature and presentations from experts at the Planetary Defense Conference[20], I have come up with following policy recommendations.

- **Assemble high level expert committee:** If there is a real and imminent threat of asteroid impact, time is of essence in finding a potential solution, thus we should assemble an international high level expert committee that can evaluate potential threats in detail. Such committee should be given necessary resources, and authorization to access necessary imaging and space data without delays.[29]
- **Develop mitigation plan:** The mission design should involve data collection about the asteroid, and possibly positioning a transponder on the object, so that we can track the object after impact and take necessary follow up steps. The mission design should be flexible enough to attempt either multiple impacts or adapt the impact strategy based on latest information available. Back up missions should also have controls that can adapt to situation that may arise after original attempt.
- **Initiate disaster management planning and risk communication efforts:** Currently the threat of NEO impact is on low priority for most of the governments. International community currently has detected less than 60% of the NEOs which are larger than 1 km, and has just recently started looking for smaller objects. In most of the cases, we may get only a few days or weeks warning for a similar impact.[29] As discussed earlier, such scenario may not provide us enough time to launch mitigation effort, and thus any established procedures for disaster management will be very valuable. Thus we should develop international co-operation required to meet potential regional disaster.
- **Involvement of universities and planning agencies:** Begin a dialog among national and international institutions to study the challenges involved in worldwide planning and execution of any deflection missions. Understanding and solving engineering and public policy issues before they need to be invoked would greatly enhance our ability to mount a successful deflection mission.[30]

**Acknowledgement:**

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29 Findings and Recommendations from the 2004 Planetary Defense Conference:
http://www.aero.org/support/planetarydefense/resources/pdf/conference_white_paper.pdf

30 2004 Planetary Defense Conference: Protecting Earth from Asteroids