An Analysis of the Hazards to a Nuclear Reactor from Meteors

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Objectives : Whilst supporting the Design Assessment Submission for a new nuclear power plant, it was found that the most recent analysis into the hazards posed by meteor events to nuclear power plants was written in 1974 by Solomon et al [1]. In the 4 decades since this paper was written, there have been notable changes in the design of nuclear power plants, in particular with regards to missile events such as aircraft and overpressure events from terrorism attacks. In addition, there have been significant advances in the estimation of meteorite event frequencies, in particular for small meteorites with a diameter of less than 250m.Due to these factors, it was deemed appropriate that a new study into the hazards posed to nuclear reactors from random meteor events be conducted.

Methods : The scenarios investigated were for a meteorite land strike, a meteorite water strike, and an airburst event in which a meteor would fracture and disintegrate whilst travelling through the Earth's atmosphere, producing a powerful shockwave.

Results : Of the three scenarios contributing to the risk hazard posed by meteoroid events to a nuclear power plant, the largest contributor is the water impact scenario. Whilst the initial analysis included both seismic shocks and ejecta damage resultant from land impacts, it was found that for both of these cases, the site would already have been within the effective target area of the meteorite strike in order for the magnitude of these scenarios to be sufficiently high as to seriously damage the site. The land impact scenario is the second highest contributor. The smallest contributing scenario is the airburst scenario with a damaging overpressure value of 34kPa, at which potential damage to the human body occurs leading to operators becoming incapacitated.

Conclusions : The risk due to meteor events may not be insignificant to the risk of a new generation NPP. However, due to the rarity of impact events and the difficulty in recreating them, there is a lack of both observational and experimental data, leading to large levels of uncertainties when analysing the risks posed by meteor events.

Introduction

This report summarises an investigation conducted into the hazards posed by random meteoroid events to nuclear power plants. The potential threats from meteorites are listed as follows:

1. Land impact
2. Water impact and subsequent tsunami
3. Air burst with blast wave
4. Seismic activity
5. Ejecta

The scope of this study includes the first three cases above only, as the seismic activity and ejecta scenarios are considered to be bounded by the land impact event. The justification for this is as follows; for an impact to produce sufficient seismic activity to damage the plant, the plant would already be within the land impact damage zone. For the ejecta scenario to result in sufficient ejecta to land upon the plant to cause damage, the plant would either have to already be with the land impact damage zone of the meteorite, or, be struck by a meteorite of sufficient mass to result in an event of regional destruction. As such, this leaves three scenarios to be considered hazardous to a nuclear power plant; land impact, water impact and subsequent tsunami, and an air burst and subsequent blast wave event.

The purpose and objectives of this report are to:

1. Document all assumptions made during the analyses of the hazards of meteoroid events to a nuclear power plant, (See section 1.2).
2. Provide the methodology used in the analyses of the three meteoroid event scenarios investigated, (See section 2).
3. Present the findings and event frequencies for each meteoroid event scenario, (See section 3).
4. Identify the uncertainties within the analysis, (See section 4).

1.1 DEFINITIONS

Event Frequency: The frequency with which a meteoroid event of given size and type will occur. It is presented in the format of number of events per calendar year.

Damage Area: This refers to the area surrounding the impact (or air burst) in which the resultant conditions are of sufficient severity as to potentially inhibit the safe operation and shut down of a nuclear power plant.

Effective Target Area: The effective target area refers to the area in which a meteoroid event could take place and cause damage to at least some of the plant structures, equipment, or on-site personnel.

Land Impact: A land impact refers to a meteorite event in which the nuclear power plant suffers damage as a result of either being within the damage area of a meteorite which strikes the ground or being physically struck by a meteorite.

Key Buildings: The key buildings are those buildings whose function is necessary for the safe running and shut down of a nuclear reactor. They include the reactor building, the control building, the heat exchanger building and the turbine building.

Key Building Perimeter: This refers to the perimeter surrounding the key buildings of the nuclear reactor. All of the key buildings are enclosed by this perimeter; however, other site buildings may not be situated within this perimeter.

Nuclear Power Plant Perimeter: The nuclear power plant perimeter is defined as enclosing the entire nuclear power plant site. No structures related to the operation of the plant are situated outside this perimeter.

Run-up: Run-up refers to the maximum height above the regular water level which the tsunami wave reaches on-shore.

Ground Zero: The point at which a surface detonation takes place. For an air burst, it is the point on the ground directly below the air burst point.

Overpressure: The increase above ambient pressure experienced as a result of a blast wave.

1.2 ASSUMPTIONS

Assumption 1
For the meteoroid event frequency, it has been assumed that the number of events per year for a meteoroid of given mass has an equal likelihood of occurring anywhere on the planet. In reality, there are zones of 'meteor corridors' which exhibit a higher than average meteoroid flux.

Assumption 2
The average impact angle of a meteoroid is 45° [1], and so this has been the assumed impact angle for all impactors. No further changes or alterations were made to account for extremes of impact angle.

Assumption 3
The ratio of stone to metal meteoroids varies with mass, with a greater proportion of meteoroids being metal as the mass increases. For this analysis, a total ratio of 90:10 for stone and metal meteoroids respectively has been selected [2].

Assumption 4

For the land impact scenario, a previous study conducted by Solomon et al [3] determined that a meteorite of mass 1kg would potentially be able to damage a nuclear reactor. In comparison, the lightest meteorite deemed capable of damaging a nuclear power plant in this report is deemed as 100kg. Part of this discrepancy is due to the increased emphasis placed upon increased protection against external hazards such as missiles for modern-day plants [4]. It is also worth noting that recent analyses into the impact velocities of meteorites and the physics behind their trajectories has determined that, in general, lower-mass bodies will impact with a lower velocity [1] [2]. This is due to the way with which mass scales according to volume and aerodynamic drag laws. As such, the aerodynamic drag experienced by a meteoroid whilst traversing Earth's atmosphere is relatively higher for a smaller meteoroid than for a larger meteoroid. This results in a non-linear relationship between mass and velocity; with lower mass meteorites impacting with much lower velocity and therefore energy.

Assumption 5
For the water impact scenario, the depth at the point of impact has been taken as the average depth of the Atlantic Ocean and its adjacent seas at 3926m.

Assumption 6
There are no compression effects at the impact site for a water impact scenario, and so the target density can be taken as that of water at 1000kg/m^3.

Assumption 7
For a shore-based nuclear power plant, the distance of open water to which the power plant is exposed has been defined as 8000km in a 180° arc. This is approximately the distance from the UK to the Caribbean and the UK to the equator,

Assumption 8
There is currently no full consensus as to the appropriate energy conversion rate to use for the formation of a tsunami from a water impact event. As such, a conversion rate of 15% has been assumed in accordance with the methodology laid out by Ward and Asphaug [5].

Assumption 9
The air burst model upon which this analysis is based, does not take into account the variation of air density with altitude, nor the effect that the air density at the burst altitude has upon the percentage of burst energy used in producing the blast wave. Therefore, in this analysis, the overpressure has been assumed to directly scale to density as according to Boyle's Law, with the density value used being the average of the burst altitude air density and the ground level air density. No accommodation has been made for the compressibility of air at supersonic velocities and higher, nor for the effect of air density at burst altitude on the initial energy of the blast wave.

Assumption 10
The plant area, key building area and key building ground footprint area have all been based upon the UK ABWR plans. When calculating the target area, the height of the buildings and consequential shadowing effect, has not been taken into account.

2 METHODOLOGY AND INPUTS

2.1 METHODOLOGY

Each of the scenarios associated with a meteoroid event used the same basic methodology to determine an approximate frequency of an event. This methodology requires the global impact frequency data for meteoroids over a range of masses, as well as the approximate radius of damage associated with each meteoroid mass/size for a given scenario. As such, each meteoroid mass will have three damage areas associated with it, one for each of the different scenarios.

It is possible for a meteoroid event to cause significant damage to a nuclear power plant by partially overlapping the plant area with the damage area associated with the meteoroid event. For this reason, an effective target area for each meteoroid mass and scenario must be defined. The most conservative approach for this is to define any meteoroid event in which the damage zone associated with a specific impactor overlaps the plant area as being damaging. This is illustrated in Figure **1**.

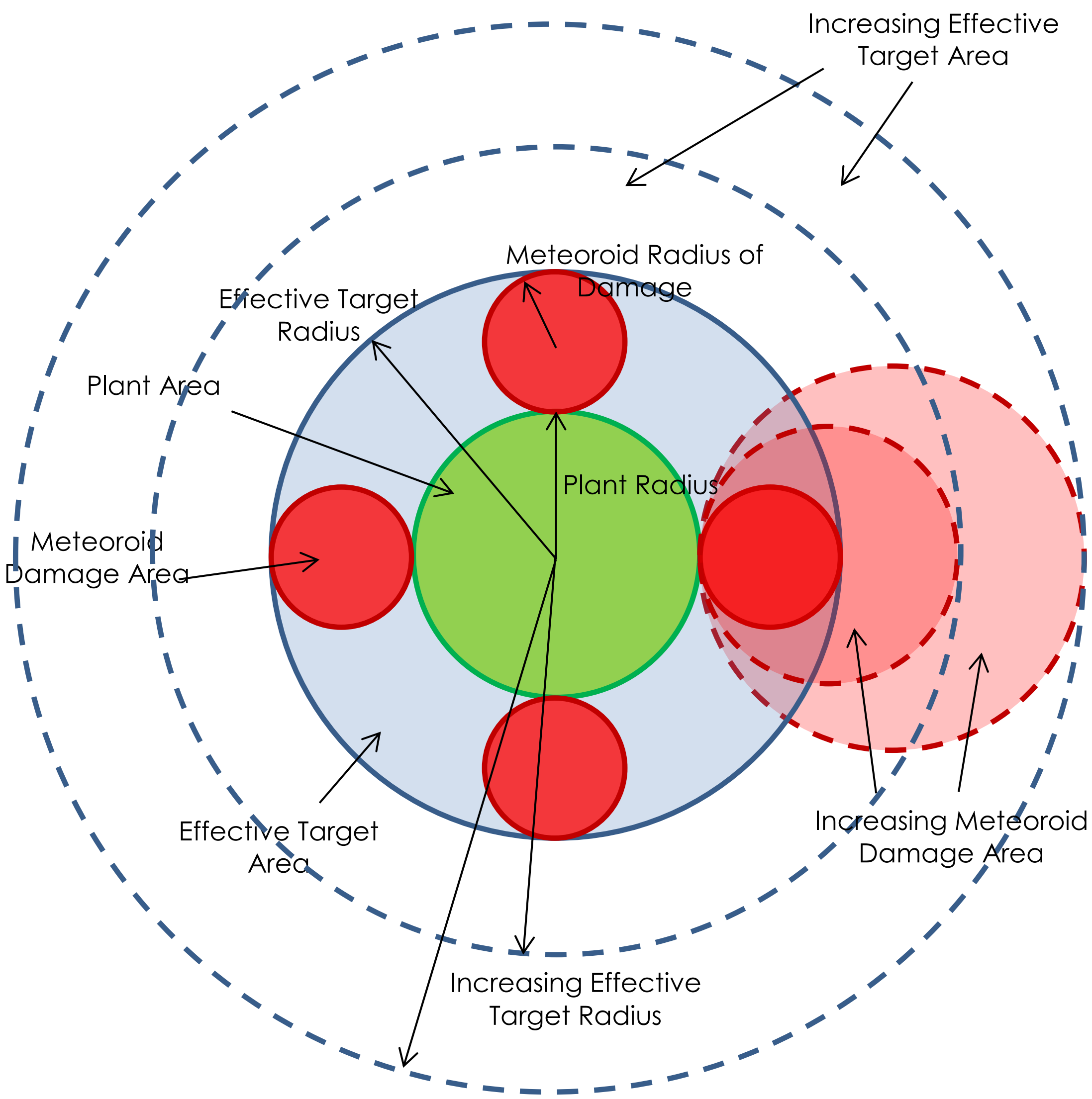

Figure 1: Effective Target Area

A simple relationship between the surface area of the Earth and the effective target area in which an event could take place around a site could then be used to determine an approximate frequency for each event. This is demonstrated by Equation 1.

$$Frequency\ of\ Event\ for\ a\ given\ area = Global\ event\ frequency \times \frac{Effective\ Target\ Area}{Earth's\ Surface\ Area}$$

Equation 1: Event Frequency for an Effective Target Area of Given Size

The methodology used to calculate the damage area and the consequential effective target area differs for each of the three scenarios. This is explained further in the following sections.

2.1.1 Land Impact Methodology

For the land impact scenario, the radius of damage for a meteorite of given mass was defined by Solomon et al [3] based upon the work by Blake in "A Prediction on the Hazards from the Random Impact of Meteorites on the Earth's Surface", shown in Table 3.

Upon defining the effective target area, the event frequency for a meteorite of a given mass striking the power plant could be determined using Equation 1. The total event frequency of a direct land impact is then the sum of the individual event frequencies associated with meteorites of a specific mass.

2.1.2 Water Impact and Subsequent Tsunami Methodology

In the event of a water impact, the displacement of water can result in large tsunamis that may pose a threat to a shore-based nuclear power plant. Currently, there are various methodologies used when modelling tsunamis formed by impactors. Solomon et al draw a comparison between impactor-induced tsunamis and seismically-induced tsunamis, whilst Fliegel and Hulman compare an impactor-induced tsunami to an explosion and subsequent tsunami [5]. In comparison, Ward and Asphaug use classical tsunami theory in conjunction with some basic assumptions about the initial shape of the impact cavity to determine the maximum wave height of a tsunami at a given distance away from the impact point [5].
For this analysis, the methodology used by Ward and Asphaug has been applied, though it is important to note that shoaling effects from run-up and other factors have not been applied, as these are location dependent. In addition, some generic assumptions have been made about the impact location and how much open water surrounds the hypothetical nuclear power-plant.

The first step of this methodology was to determine the impact crater diameter in the water from the impactor properties. This was done by setting Equation 2 and Equation 3 as equal to each other in order to determine the value of the variable q. These values were then substituted back into Equation 3 to calculate the crater diameter.

$$d_c^{S-H} = 2R_I\left[\left(\frac{1}{3.22}\right)\frac{V_I^2}{gR_I}\right]^{\beta}\left(\frac{\rho_I}{\rho_T}\right)^{1/3}\left\{\frac{C_T}{1.24}\right\}$$

Equation 2: Crater diameter as defined by the Schmidt and Holsapple scaling rule

Where d_c^{S-H} = the crater diameter as defined by the Schmidt and Holsapple scaling rule
R_I = the impactor radius
V_I = the impactor velocity
β = dependent on target parameters (set to 0.22 to equate Equation 2 and Equation 3)
ρ_I = the impactor density
ρ_T = the target density
C_T = dependent on target parameters (set to 1.88 to equate Equation 2 and Equation 3)

$$d_c = 2R_I\left[(2\varepsilon)\frac{V_I^2}{gR_I}\right]\times\left(\frac{\rho_I}{\rho_T}\right)^{1/3}\left\{\left(\frac{\rho_T}{\rho_I}\right)^{1/3-\delta}\left(\frac{1}{qR_I^{\alpha-1}}\right)^{2\delta}\right\}$$

Equation 3: Crater diameter with respect to q
Where d_c = the crater diameter
ε = the energy conversion factor
δ = the energy conversion factor
q = dependent on target and impactor properties
α = dependent on target and impactor properties
The crater radius R_c could then be defined as half of d_c.

Equation 4 was then used to determine the crater depth D_c.

$$D_c = qR_I^{\alpha}$$

Equation 4: Crater depth

With the crater parameters now defined by the impactor parameters and assumptions made about the impact point, the tsunami generated could now be calculated. It is important to note that the maximum crater depth for a given impact was defined as the depth of water in which the impact took place. Otherwise, the model could produce tsunamis with wave heights well in excess of the water depth in which the impact took place. Equation 5 calculates the maximum wave height at a given distance away from the impact point.

$$u_z^{max}(\boldsymbol{r},\boldsymbol{r_0},R_I) = D_c^{eff}\sqrt{\frac{\Delta}{\sin\Delta}[1+|\boldsymbol{r}-\boldsymbol{r_0}|/R_c]^{-\psi}}$$

Equation 5: Maximum tsunami wave height

Where u_z^{max} = the maximum tsunami wave height (dependent on r, r_0, and R_I)
r = observation point away from the impact point
r_0 = impact point
R_I = impactor radius
D_c^{eff} = effective impact crater depth
Δ = angular distance between r and r_0
Ψ = power to account for wave amplitude losses associated with geometrical spreading on a plane and additional losses due to dispersion

$$\psi = 1/2 + 0.575e^{-0.035R_c/h(\boldsymbol{r_0})}$$

Equation 6: Power scaling factor for geometrical spreading and dispersion losses

The UK ABWR is designed to withstand a flood height of 13m, and so a tsunami wave height of 12m was deemed a suitable lower limit for this analysis. A wave height slightly lower than the flood height provides some allowance for local topography effects and coastal run-up, as both of these factors can result in an effective wave height greater than what would be expected at a generic coastline.

Using the estimated wave height data for a given impactor mass and distance from the impact site, it is possible to provide an approximate area of effect in which a tsunami height of at least 12m would be generated. This provides the effective target area for a meteorite of given mass, from which it is now possible to produce an event frequency using Equation 1.

2.1.3 Air Burst and Subsequent Blast Wave Methodology

Meteoroids with a lower mass and lower compressive strength are prone to undergoing an air burst event, in which the meteoroid fractures under the pressure of atmospheric entry. In such an event, the fracture takes place with such force that a shockwave is produced in a similar fashion to a high altitude detonation of explosives. Whilst not actually an explosion, a meteoroid air burst event observes sufficiently similar characteristics such that modelling an air burst as a high altitude detonation is currently standard practice [6].

Conflicting information exists as to an appropriate overpressure value required to significantly affect the operations at a nuclear power plant. As such, two overpressure values were investigated; a conservative investigation in which the maximum allowable overpressure is assumed to be 10kPa (100mbar), and a more realistic case with a maximum allowable overpressure of 34kPa. The reason for the second case is that, for an External Explosion, the UK ABWR should be capable of withstanding a maximum overpressure of 10kPa for 300ms, increasing to a maximum of 20kPa due to reflection effects from surrounding buildings and terrain [7]. However, according to Sharp and DeCarli, the shock wave from a meteorite lasts in the tens of milliseconds, significantly shorter than the 300ms quoted previously [8], resulting in a less damaging event if the same overpressure is observed. In addition, tests conducted with nuclear detonations indicate that reinforced concrete structures can survive in excess of 40kPa overpressure [9] [10], whilst the human body will observe incapacitating effects, primarily rupture of the eardrum, at an overpressure of 34kPa (5psi) [10] [11]. It is expected that operators within the buildings will be protected to some extent from the blast wave and resultant injuries and therefore, in order to reduce the conservatism, the higher case was defined as having an overpressure limit of 34kPa, representing the threshold at which damage to the human body is expected to affect all operators on site. It is worth noting that whilst the human body is remarkably resilient to overpressure, the primary source of damage at low overpressures of between 10kPa and 34kPa will be associated with flying debris moved by the shockwave and blunt force trauma associated with the operators being blown off their feet and into a solid object.

Bland and Artemieva provide data showing the approximate burst altitude for a meteoroid of a given mass [2]. This data was used to provide a maximum meteoroid mass for which an airburst may occur, as well as a minimum blast radius required for a given meteoroid to cause damage at ground level. Should the blast radius produced by the airburst be smaller than the approximate burst altitude, the resultant overpressure would be deemed insufficient as to cause enough damage to the nuclear power plant such that safe operation and shutdown are not possible. The approximate burst altitude for a range of meteoroid masses are presented below in Table 1.

Table 1: Approximate Burst Altitude for Meteoroids of Varying Masses

Meteoroid Mass (kg)	Approximate Burst Altitude (km)
10^4	34
10^6	26
10^8	14
10^{10}	0 (ground impact)

As stated previously, when modelling the effects of an airburst event, the current standard practice is to draw comparisons to high altitude detonations. In particular, nuclear detonations provide the closest approximation in terms of equivalent yield. Conventional explosives generally have a much lower TNT equivalent yield than nuclear weapons and meteoroids. Whilst high altitude (greater than 30km) nuclear detonations have taken place, the results from these experiments are extremely sensitive and not currently available to the public. As such, it is only possible to draw comparisons to low altitude and ground-level nuclear detonations, where the variation in air density is negligible. The result of this is that overpressure calculations for high altitude detonations are over-estimated, as recognised in the Earth Impacts Effects Program from where the basic model used in this analysis was sourced [12].

As with the land and water impact scenarios, it was important to define the area damaged by the blast wave associated with a meteoroid of a given mass. This was done by solving for the 10kPa and 34kPa of pressure using Equation 7 from the Earth Impacts Effects Program in which the equation was derived through comparison to experimental data from the detonation of a 1 kiloton surface blast.

$$p = \frac{p_x r_x}{4 r_1}\left(1 + 3\left(\frac{r_x}{r_1}\right)^{1.3}\right)$$

Equation 7: Overpressure for a 1 kiloton surface blast at a distance r_1 from ground zero

Where p = overpressure at a distance r_1 from ground zero measured in Pa,

p_x = the pressure at the crossover point measured in Pa,

r_x = the crossover distance measured in m,

r_1 = equivalent distance from ground zero measured in m.

The crossover point of a blast wave defines the point at which the dominant part of the overpressure equation (Equation 7) changes.

This equation requires the air burst detonation parameters to be converted into equivalent parameters, such as an equivalent burst altitude and an equivalent distance from ground zero. These parameters follow an inverse cube law as shown in Equation 8 below.

$$r_1 = \frac{r}{E_{kT}^{1/3}}$$

Equation 8: Equivalent distance from ground zero with respect to energy yield in kilotons of TNT

Where r = distance from ground zero measured in m,

E_{kT} = equivalent yield measured in kT TNT.

All other equivalence values follow this standard relation but with the distance to ground zero variables switched for the variable to be altered.

Equation 7 does not take into account the variation of air density and how this may affect the generation of a blast wave. In order to address this, an assumption was made that the overpressure generated by the blast wave is directly proportional to the fluid medium in which it moves through. The density used to adjust the overpressure is defined as being the average of the burst altitude density and the ground level density. This is in accordance with Boyle's Law which states that density and pressure are directly proportional in a gas under normal conditions. This assumption does not take into account the compressibility of the gas under supersonic conditions, nor does it take into account how the percentage of the detonation energy used to produce the blast wave varies with density.

With the blast radii for the different meteoroid masses calculated, it is possible to screen out those which exhibit a blast radius at least 20% smaller than the approximate burst altitude. The 20% margin gives some allowance for the variations expected with the burst altitude.

At this point, the event frequency of those meteoroids exhibiting a blast radius equal to or greater than the estimated burst altitude can be determined. Equation 7 determines the pressure at a distance away from ground zero, and so this distance can be used to determine the damage area of a given air burst event. From here, Equation 1 can then be used to determine the overall frequency of such an event for a given target area.

2.1.4 Total Event Frequency

The total event frequency for a given meteoroid scenario is the sum of the individual frequencies for each meteoroid mass band.

The total event frequency for all meteoroid scenarios is calculated based upon a generic plant location. This generic plant location is based upon the assumption that the nuclear power plant is situated upon a straight shoreline, such that a meteoroid has a 50% chance of striking either land or water, and that the plant has an unobstructed view through the 180° arc of water such that there are no intervening bodies of land or structures for at least 3200km. Based upon these assumptions, the total event frequency can be calculated using Equation 9 below.

$$f_{total} = \frac{f_{land\ (m>1000\ tons)}}{2} + f_{land\ (0.1<m<1000\ tons)} + \frac{f_{water\ (m>10{,}000\ tons)}}{2} + f_{airburst}$$

Equation 9: Total Event Frequency for all Meteoroid Events

2.2 FREQUENCY OF EVENTS AND METEORITE STRIKES

In order to determine the threat posed by random meteoroid activity, it is important to select the most reliable source for meteoroid event frequency. This analysis compares four sources of event frequency, introduced below.

Frequency Source 1: "Estimate of the Hazards to a Nuclear Reactor from the Random Impact of Meteorites"; Solomon, Erdmann, and Okrent, 1975 [3]

This paper was published in January 1975 in the Nuclear Technology journal and presented an estimated frequency of meteorite impacts on a generic nuclear reactor site location as well as the threat posed by meteorite-induced tsunamis. It should be noted that this source does not comment on the threat posed by an air burst. The meteorite impact frequency estimate was derived using the historical data model, which considers the number and size of meteorite impact craters globally and then estimates the size of the meteorite upon impact based upon an assumed final velocity. This method assumes that;

1. Meteorites fall randomly throughout the surface of the Earth.
2. The number of meteorites that fall per year is constant.
3. The distribution in sizes of meteorites that fall to the Earth remains invariant during subsequent years.
4. The potential damage area from a meteorite impact is directly proportional to the kinetic energy on impact.

Due to the action of erosion and other processes at ground level, this method for determining the impact frequency of meteorites is far more suited to larger impactors; smaller impactors produce smaller craters which are far more vulnerable to erosion and infilling and being obscured by changes in the terrain or vegetation. These factors are likely to contribute to an under-representation of small impact craters meaning that data collected using the historic approach is likely to either under estimate the frequency of small meteoroid events, or, to have some kind of estimation as to number of small meteoroid events which would inherently have some error associated with it.

Frequency Source 2: "Study to Determine the Feasibility of Extending the Search for Near-Earth Objects to Smaller Limiting Diameters"; Near-Earth Object Science Definition Team, NASA, 2003 [13]

Published in mid-2003, this report presents a far more up-to-date frequency of events in comparison to Solomon et al and uses the known population of Near-Earth Objects at the time to determine the impact frequency for a given size of meteoroid. This introduces a second method for modelling the impact frequency upon the Earth, called the astronomical approach. As with the crater analysis method used by Solomon et al, is more suitable to larger meteoroids due to the difficulties associated with spotting small objects in space. This method defines an impact as being a body that passes within 0.05 AU from the Earth's orbit and as such, provides a higher than expected impact frequency.

Frequency Source 3: "The Rate of Small Impacts on Earth"; Bland and Artemieva, Imperial College London, 2006 [2]

This paper's primary interest is in addressing the lack of data for Earth impactors producing craters of less than approximately 10km diameter. As stated previously, small craters are affected to a much larger degree by erosion, tectonism and other natural processes in comparison to larger craters. As such, a different method using the flux data for upper atmosphere impacts is used to approximate the frequency of Earth impacts on the surface for small meteoroids. Many different sources of data exist for meteor impacts, with many of them expressing the impactor flux in relation to either mass, impact energy, impactor diameter, or crater size. In order to combat this variation in how data is presented across different sources, Bland et al scaled all of the data used in their analysis to impactor mass, as this allows for all of the upper atmosphere data as well as non-crater-forming data to be included. It should be noted that, whilst this method allows for a greater number of sources to be included, conversion of the data to a single parameter generates additional errors to those that are specific to each source of data.

Frequency Source 4: "Estimates of the Impact Frequency of Cosmic Bodies on the Earth"; Amelin, Gusiakov, and Lyapidevskaya, Bull. Novosibirsk Computing Center 1, 2013 [1]

This report provides the most recent impact frequency data currently available and also makes reference to the reports written by both the Near-Earth Object Science Definition Team and Bland and Artemieva. Amelin et al detail the four major methodologies for estimating the impact frequencies for meteoroids of different sizes and masses, stating the advantages and disadvantages of each as well as the range of meteoroids for which they are particularly well suited to analysing. These methodologies are:

1. The astronomical approach, which analyses the population of near-Earth objects and estimates the frequency of impacts from this data.
2. The planetological approach, in which the age and size of meteorite craters on the terrestrial planets (Earth, Mars, and Venus) and the Moon are analysed and the differences in gravity of the different celestial bodies is taken into account.
3. Space observations of the Earth's atmosphere, where meteor impacts upon the upper atmosphere are analysed. This method currently allows the most precise estimations for the impact frequencies of small asteroids and meteoroids with a diameter of less than 10m.
4. The historical approach, which is based upon the geological-geophysical data of the Earth's impact structures. For small impactors with a diameter of less than 10-20m, the data from meteoritic catalogues are used.

Being the most recent estimation for impact frequency as well as making the most comprehensive effort to minimise the uncertainties associated with the different frequency methodologies, this report was selected as the basis for the impact frequencies of meteoroids used in this analysis. In addition, Amelin et al make use of all four methodologies, minimising the risk of significant error for those meteoroid masses in which multiple sets of data are available.

A comparison of the different datasets is presented in Table 2 below.

Table 2: Comparison of the Frequency Datasets Reviewed

Diameter approx (m)	Mass (kg)	Source 4 Frequency (E/yr)	Source 3 Frequency (E/yr)	Source 2 Frequency (E/yr)	Source 1 Frequency (E/yr)
3.1	$5x10^{4}$	-	$2.01x10^{-2}$	-	$2.59x10^{-1}$
4.0	$1x10^{5}$	$9.50x10^{-2}$	$1.01x10^{-2}$	-	-
6.8	$5x10^{5}$	-	$2.03x10^{-3}$	-	$7.76x10^{-2}$
8.6	$1x10^{6}$	$2.70x10^{-2}$	$1.02x10^{-3}$	-	-
14.7	$5x10^{6}$	$7.90x10^{-3}$	$2.61x10^{-4}$	-	$1.68x10^{-2}$
18.5	$1x10^{7}$	$3.00x10^{-3}$	$1.86x10^{-4}$	-	-
32	$5x10^{7}$	-	$8.53x10^{-5}$	$3.17x10^{-3}$	$2.72x10^{-3}$
40	$1x10^{8}$	$8.10x10^{-4}$	$6.09x10^{-5}$	$1.84x10^{-3}$	-
50	$2x10^{8}$	-	-	$1.07x10^{-3}$	-
68	$5x10^{8}$	-	$2.95x10^{-5}$	$6.19x10^{-4}$	$7.63x10^{-4}$
85	$1x10^{9}$	$3.00x10^{-4}$	$2.47x10^{-5}$	$3.60x10^{-4}$	-
100	$1.5x10^{9}$	-	-	$2.09x10^{-4}$	-
125	$3x10^{9}$	-	-	$1.21x10^{-4}$	-
150	$5x10^{9}$	-	$1.65x10^{-5}$	$7.03x10^{-5}$	$1.55x10^{-4}$
185	$1x10^{10}$	$1.20x10^{-4}$	$1.38x10^{-5}$	$4.08x10^{-5}$	-
250	$2.5x10^{10}$	$3.50x10^{-5}$	-	$2.37x10^{-5}$	-
320	$5x10^{10}$	-	$9.18x10^{-6}$	$1.38x10^{-5}$	$3.36x10^{-5}$
400	$1x10^{11}$	$9.40x10^{-6}$	$7.70x10^{-6}$	$7.99x10^{-6}$	-
500	$2x10^{11}$	-	-	$4.64x10^{-6}$	-
685	$5x10^{11}$	-	$5.12x10^{-6}$	$2.69x10^{-6}$	$5.95x10^{-6}$
800	$8x10^{11}$	-	-	$1.56x10^{-6}$	-
860	$1x10^{12}$	$1.70x10^{-6}$	$3.98x10^{-6}$	-	-
1000	$1.5x10^{12}$	-	-	$9.07x10^{-7}$	-
1260	$3x10^{12}$	-	-	$5.26x10^{-7}$	-
1470	$5x10^{12}$	-	$2.12x10^{-6}$	$3.06x10^{-7}$	-

Diameter approx (m)	Mass (kg)	Source 4 Frequency (E/yr)	Source 3 Frequency (E/yr)	Source 2 Frequency (E/yr)	Source 1 Frequency (E/yr)
1850	$1x10^{13}$	-	$1.54x10^{-6}$	-	-
2000	$1.25x10^{13}$	$2.60x10^{-7}$	-	$1.77x10^{-7}$	-
2520	$2.5x10^{13}$	-	-	$1.03x10^{-7}$	-
3170	$5x10^{13}$	-	$7.44x10^{-7}$	$5.98x10^{-8}$	$2.85x10^{-7}$
4000	$1x10^{14}$	$5.00x10^{-8}$	$5.43x10^{-7}$	$3.47x10^{-8}$	-
5040	$2x10^{14}$	-	-	$2.01x10^{-8}$	-
6830	$5x10^{14}$	-	$2.62x10^{-7}$	$1.17x10^{-8}$	$5.69x10^{-8}$
8600	$1x10^{15}$	-	$1.84x10^{-7}$	$6.79x10^{-9}$	-
12000	-	$7.00x10^{-9}$	-	-	
14700	$5x10^{15}$	-	$6.24x10^{-8}$	-	$1.29x10^{-8}$
18500	$1x10^{16}$	-	$3.91x10^{-8}$	-	-
31700	$5x10^{16}$	-	$1.33x10^{-8}$	-	-
40000	$1x10^{17}$	-	$8.32x10^{-9}$	-	-
68300	$5x10^{17}$	-	$2.82x10^{-9}$	-	-

Table 2 shows the frequencies for different meteoroid sizes for the 4 sources. For meteoroids between 8m and 2000m, there is broad agreement between sources 3 and 4, whilst sources 1 and 2 exhibit broad agreement between approximately 30m to 800m. Across all four of the sources, the least agreement for impact frequency is exhibited for meteoroids at the extremes of the diameters investigated; below approximately 250m and above approximately 3000m. Across Sources 2, 3 and 4 only, the average spread around the mean frequency for a meteoroid mass is ±66.7%. For those meteoroids whose masses are within the 250m to 3000m range stated above, the chosen source, source 4, provides the highest frequency in most cases.

Those meteoroids with diameters greater than 12000m have a frequency sufficiently low as to be screened out of this analysis.

It has been assumed that there is an average meteoroid impact flux at the plant location, based upon the global impact flux and scaled for target area. In reality, there are “meteor corridors” that see increased meteor and meteorite activity that will be more at risk of a meteor-initiated event.

3 RESULTS

3.1 LAND IMPACT RESULTS

For the land impact scenario, all of the impactors have an associated damage area, as defined in section 1.1. For the meteorites exhibiting a damage area less than the area footprint of the key buildings (Reactor Building, Control Building, Turbine Building, and Heat Exchanger Building), it would be possible for the meteorite to ‘hit’ the plant but impact an area in which no equipment or buildings are present. As such, the plant area for these smaller meteorites was defined as being equal to the total area footprint of these key buildings. For meteorites with damage areas of sufficient size as to at least partially cover any of the key buildings in the event of an impact within the key building perimeter, the target area was defined as being the area enclosed by the key building perimeter. Finally, for meteorites with a damage area in excess of the area enclosed by the nuclear power plant site perimeter, the target area was defined as being the entire site area.

Table 3 shows the effective target area associated with each stone meteoroid mass grade investigated in this report. These values were determined using the method described in section 2.1.1.

Table 3: Stone Meteorite Scale, Approximate Damage Area, Plant Area and Effective Target Area

Meteorite Diameter (m)	Meteorite Mass (t)	Approximate Damage Area of Effect (m^2)	Plant Area (m^2)	Effective Target Area (m^2)
0.4	$1x10^{-1}$	$1.02x10^{1}$	$1.40x10^{4}$	$8.93x10^{4}$
0.7	$5x10^{-1}$	$1.02x10^{1}$	$1.40x10^{4}$	$8.93x10^{4}$
0.9	$1x10^{0}$	$9.10x10^{1}$	$1.78x10^{4}$	$1.03x10^{5}$
1.9	$1x10^{1}$	$1.77x10^{3}$	$1.05x10^{5}$	$1.67x10^{5}$
4.0	$1x10^{2}$	$1.49x10^{4}$	$1.05x10^{5}$	$3.23x10^{5}$
5.0	$1.96x10^{2}$	$1.49x10^{4}$	$1.05x10^{5}$	$3.23x10^{5}$
8.0	$8.04x10^{2}$	$1.49x10^{4}$	$1.05x10^{5}$	$3.23x10^{5}$
13	$3.45x10^{3}$	$1.02x10^{5}$	$1.00x10^{6}$	$2.33x10^{6}$
23	$1.91x10^{4}$	$5.48x10^{5}$	$1.00x10^{6}$	$5.60x10^{6}$
43	$1.25x10^{5}$	$5.48x10^{6}$	$1.00x10^{6}$	$3.10x10^{7}$
84	$9.31x10^{5}$	$1.30x10^{7}$	$1.00x10^{6}$	$6.56x10^{7}$
170	$7.78x10^{6}$	$1.30x10^{7}$	$1.00x10^{6}$	$6.56x10^{7}$
250	$2.46x10^{7}$	$6.22x10^{7}$	$1.00x10^{6}$	$2.78x10^{8}$
500	$1.96x10^{8}$	$2.79x10^{8}$	$1.00x10^{6}$	$1.17x10^{9}$
1100	$2.09x10^{9}$	$3.00x10^{9}$	$1.00x10^{6}$	$1.22x10^{10}$
2400	$2.17x10^{10}$	$6.22x10^{9}$	$1.00x10^{6}$	$2.52x10^{10}$
5300	$2.34x10^{11}$	$2.79x10^{10}$	$1.00x10^{6}$	$1.12x10^{11}$
12000	$2.72x10^{12}$	$1.30x10^{11}$	$1.00x10^{6}$	$5.22x10^{11}$

With the effective target area defined for each impactor mass, Equation 1 can be used to determine the event frequency for each given target area. Table 4 present the results of this determination for stone meteorites.

Table 4: Event Frequency for Stone Meteorite Land Impacts

Meteorite Diameter (m)	Meteorite Mass (t)	Effective Target Area (m^2)	Event Frequency (E/yr)
0.4	$1x10^{-1}$	$8.93x10^{4}$	$2.47x10^{-8}$
0.7	$5x10^{-1}$	$8.93x10^{4}$	$3.27x10^{-9}$
0.9	$1x10^{0}$	$1.03x10^{5}$	$1.50x10^{-9}$
1.9	$1x10^{1}$	$1.67x10^{5}$	$2.82x10^{-9}$
4.0	$1x10^{2}$	$3.23x10^{5}$	$1.41x10^{-10}$
5.0	$1.96x10^{2}$	$3.23x10^{5}$	$1.34x10^{-10}$
8.0	$8.04x10^{2}$	$3.23x10^{5}$	$3.80x10^{-11}$
13	$3.45x10^{3}$	$2.33x10^{6}$	$8.11x10^{-11}$
23	$1.91x10^{4}$	$5.60x10^{6}$	$5.60x10^{-11}$
43	$1.25x10^{5}$	$3.10x10^{7}$	$5.95x10^{-11}$
84	$9.31x10^{5}$	$6.56x10^{7}$	$4.27x10^{-11}$
170	$7.78x10^{6}$	$6.56x10^{7}$	$1.71x10^{-11}$
250	$2.46x10^{7}$	$2.78x10^{8}$	$1.90x10^{-11}$
500	$1.96x10^{8}$	$1.17x10^{9}$	$2.05x10^{-11}$
1100	$2.09x10^{9}$	$1.22x10^{10}$	$3.72x10^{-11}$
2400	$2.17x10^{10}$	$2.52x10^{10}$	$1.17x10^{-11}$
5300	$2.34x10^{11}$	$1.12x10^{11}$	$9.94x10^{-12}$
12000	$2.72x10^{12}$	$5.22x10^{11}$	$6.46x10^{-12}$
Total			$3.13x10^{-8}$

The combined event frequency from both stone and metal meteorites that could damage a nuclear power plant is then the sum of these data sets, for stone and metal meteorites is a total of 3.48×10^{-8} Events per year. The frequency values for stone to metal meteorites are based upon the assumed ratio of 90:10.

3.2 WATER IMPACT AND SUBSEQUENT TSUNAMI RESULTS

Using the methodology described in section 2.1.2, the following set of data was determined for stone meteorites.

Table 5: Event Frequency for Stone Meteorite Impact-Induced Tsunamis

Meteorite Diameter (m)	Meteorite Mass (t)	Damage Radius (km)	Event Frequency (E/yr)
8	8.04×10^{2}	3.2	7.66×10^{-10}
13	3.45×10^{3}	6.6	9.54×10^{-10}
23	1.91×10^{4}	15.4	1.97×10^{-09}
43	1.25×10^{5}	38.9	3.40×10^{-09}
84	9.31×10^{5}	105	9.17×10^{-09}
170	7.72×10^{6}	302	3.03×10^{-08}
250	2.45×10^{7}	542	2.85×10^{-08}
500	1.96×10^{8}	1560	6.34×10^{-08}
1100	2.09×10^{9}	3270	5.04×10^{-08}
2400	2.17×10^{10}	7630	4.19×10^{-08}
5300	2.34×10^{11}	8000	8.87×10^{-09}
12000	2.71×10^{12}	8000	1.24×10^{-09}
Total			2.41×10^{-07}

The results for stone and metal meteorites give a total frequency of 2.8×10^{-07} Events per year which are capable of damaging the nuclear power plant.

3.3 AIR BURST BLAST WAVE RESULTS

Using the previously described methodology in 2.1.3, the following damage radii for a meteoroid of given mass were determined.

Table 6: Meteoroid Mass, Burst Altitude, and Blast Radius

Meteoroid Mass (t)	Actual Burst Altitude (km)	10kPa Blast Radius (km)	34kPa Blast Radius (km)
1.96×10^{2}	32.5	1.22	0.62
8.04×10^{2}	27.6	1.54	0.79
3.45×10^{3}	25.7	3.17	1.63
1.91×10^{4}	23.8	5.68	2.89
1.25×10^{5}	14.0	11.49	5.80
9.31×10^{5}	12.8	22.79	11.50
7.72×10^{6}	3.2	57.38	28.00

As described previously, a 20% difference between burst altitude and blast radius was allowed in order to accommodate fluctuations in burst altitude. At this point, it is then possible to screen out air bursts associated with meteoroids with masses of below 125000t for the 10kPa analysis and masses of below 931000t for the 34kPa analysis.

With the upper and lower limits determined for this analysis, as well as the damage radius, it is now possible to determine an event frequency for a given meteoroid mass for a given target area followed by a total frequency for an air burst event at the same target area.

Table 7: Event Frequency for a Damaging Meteoroid Airburst Event

Meteoroid Mass (t)	10kPa Event Frequency (E/yr)	34kPa Event Frequency (E/yr)
$1.25\text{x}10^{5}$	$6.96\text{x}10^{-9}$	0
$9.31\text{x}10^{5}$	$3.23\text{x}10^{-9}$	$8.18\text{x}10^{-10}$
$7.72\text{x}10^{6}$	$2.43\text{x}10^{-9}$	$5.79\text{x}10^{-10}$
Total	$1.26\text{x}10^{-8}$	$1.40\text{x}10^{-9}$

The total frequency for a damaging meteoroid airburst event can be found in Table 7, at $1.62\text{x}10^{-8}$ Events per year for a 10kPa maximum overpressure and $3.29\text{x}10^{-9}$ Events per year for a 34kPa maximum overpressure.

3.4 TOTAL EVENT FREQUENCY FOR A DAMAGING METEOROID EVENT

Table 8 shows the total event frequencies for each scenario followed by the total event frequency associated for a generic site with an overpressure rating of 10kPa and 34kPa.

Table 8: Scenario and Total Event Frequency Associated with Random Meteoroid Events

Event	**Event Frequency for a Generic Nuclear Power Plant**
Water Impact and subsequent Tsunami	$2.82\text{x}10^{-07}$ Events/year
Land Impact	$3.4\text{x}10^{-8}$ Events/year
Generic Site Land Impact	$3.4\text{x}10^{-8}$ Events/year
Air Burst and subsequent Blast Wave 34kPa	$1.4\text{x}10^{-9}$ Events/year
Air Burst and subsequent Blast Wave 10kPa	$1.3\text{x}10^{-8}$ Events/year
Total (Blast Wave 34kPa)	$2.93\text{x}10^{-07}$ Events/year
Total (Blast Wave 10kPa)	$2.91\text{x}10^{-07}$ Events/year

The major contributors to this frequency are the mid-to-large-sized water impacting meteorites.

4 UNCERTAINTIES

It is believed that the results presented in this report represent a conservative evaluation of the threat posed by meteoroid events to a nuclear power plant, given the data available for meteoroid event frequency.

The primary source of uncertainty associated with this analysis is in the frequency of meteoroid impacts at the Earth's surface. Whilst this has been somewhat mitigated by reviewing data from multiple sources and selecting the most appropriate dataset for event frequency, it should still be noted that the uncertainty for a given frequency value is approximately ±66.7% as detailed in section 2.2.

The water impact scenario has a great deal of uncertainty associated with the impact energy conversion to tsunami energy. Currently, there is no experimental data available for impacts approaching the magnitudes exhibited by meteorite impacts, and in addition there is very little agreement between experts as to an appropriate system comparison. Some experts, such as Solomon et al, compare meteorite-induced tsunamis to seismically-induced tsunamis, whilst others, such as Fliegal and Hulman, make a comparison to explosively-induced tsunamis. As the methodology used in this analysis was based upon the work by Ward and Asphaug, the same energy convergence of 15% was used as found in their analysis.

Another source of uncertainty for the water impact scenario is the estimated wave height required to damage a nuclear reactor after penetrating a seawall. The assumptions presented by Solomon et al in 1975 state that a 6m high tsunami would be required to damage a nuclear reactor situated 160m from the shore and with a sea wall present. However, given the increased focused on external hazards and the stringent design requirements associated with modern nuclear power plants, these assumptions do not accurately represent a more modern plant such as the UK ABWR. As such, a wave height of 12m, 1m below the UK ABWR flood limit, was chosen as a conservative estimation.

It has been assumed for the water impact scenario that there is no funnelling or dissipation effect apparent on the tsunami as it approaches the plant due to the local geography. Whilst for the analysis of a generic plant this is the most sensible assumption, for specific shore-based power plants there may be considerable increases or decreases to the apparent tsunami wave height as a result of the local terrain.

Finally for the water impact scenario, in calculating to the frequency of a water impact event, it is assumed that the nuclear power plant is exposed to at least 8000km of open water through a 180° arc. This increases the target area in which a meteorite could impact the water and damage the plant significantly, providing a more conservative analysis.

For the land impacts, the damage area for a meteorite of given size is related to its equivalent energy in kt TNT. Whilst this is an adequate comparison to draw for this sort of analysis, it should be noted that the explosive properties of TNT are of notable difference to the impact properties of a kinetic collision. As such, the damage area for the meteorites is merely an approximation; the actual damage area for a given meteorite may be either greater or smaller, though this difference is unlikely to be significant.

For the air burst scenario, significant uncertainty is associated with both the TNT equivalence model as well as with the comparison to nuclear detonation data. As noted previously, the detonation of TNT and the explosive fracture of a meteoroid exhibit noticeable differences. In addition, the majority of nuclear detonation data available is for low-yield (1kt – 100kt TNT) and low altitude (<2km) detonations, whereas the detonation altitude of meteoroids very rarely happens below 8.5km (the lowest on record is 8.5km, though more massive meteoroids will detonate lower as explained previously). As such, the density of the air in which the detonation takes place can have a significant impact on both the calculated overpressure and the blast area of effect. The scaling of the overpressure to the ground and detonation altitude ratio is a source of significant uncertainty, though, currently, no models exist for calculating detonations at such a high altitude and their propagation through a medium of varying density.

5 SUMMARY

In conclusion, the findings of this report suggest that the frequency of a damaging meteoroid event to be between approximately $2.93x10^{-07}$ to $2.91x10^{-07}$ events per year, depending on the plant vulnerability to overpressure. These results are based upon the most up-to-date meteoroid event data and current industry standard modelling techniques for the scenarios investigated.

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7 APPENDIX

Table 9: Fliegel and Hulman Wave Height Variation with Meteorite Mass

Meteorite Mass (tons)	Wave Height at 100 miles	Wave Height Ratio at 100 miles (feet)	Wave Height at 500 miles	Wave Height Ratio at 500 miles (feet)	Wave Height at 1000 miles	Wave Height Ratio at 1000 miles (feet)	Wave Height at 2000 miles	Wave Height Ratio at 2000 miles (feet)
10^{12}	7710		1540		771		385	
		3.160		3.143		3.160		3.156
10^{11}	2440		490		244		122	
		3.165		3.182		3.165		3.169
10^{10}	771		154		77.1		38.5	
		3.160		3.143		3.160		3.156
10^{9}	244		49.0		24.4		12.2	
		3.165		3.182		3.165		3.169
10^{8}	77.1		15.4		7.71		3.85	
		3.160		3.143		3.160		3.156
10^{7}	24.4		4.90		2.44		1.22	
		3.165		3.182		3.165		3.169
10^{6}	7.71		1.54		0.77		0.38	
Average		3.16		3.16		3.16		3.16

Table 10: Fliegel and Hulman Wave Height Variation with Distance from Impact Site

Meteorite Mass (tons)	Wave Height at 100 miles (feet)	Wave Height Ratio for varying distance	Wave Height at 500 miles (feet)	Wave Height Ratio for varying distance	Wave Height at 1000 miles (feet)	Wave Height Ratio for varying distance	Wave Height at 2000 miles (feet)
10^{12}	7710	5.01	1540	2.00	771	2.00	385
10^{11}	2440	4.98	490	2.01	244	2.00	122
10^{10}	771	5.01	154	2.00	77.1	2.00	38.5
10^{9}	244	4.98	49.0	2.01	24.4	2.00	12.2
10^{8}	77.1	5.01	15.4	2.00	7.71	2.00	3.85
10^{7}	24.4	4.98	4.90	2.01	2.44	2.00	1.22
10^{6}	7.71	5.01	1.54	2.00	0.77	2.00	0.38
Average		5.00		2.01		2.00	