## Cratering Phenomenology and Yield Estimation

Estimation of yield from crater diameters relies on several parameters. The most important ones are (1) the depth of emplacement (2) The type of medium and the (3) type of explosive that is chemical high explosives (HE) or nuclear explosives (NE). The relation between these various parameters was carried out by several people principally, M.D. Nordyke [1] and J. Toman [2] at Livermore Radiation Laboratory. These experiments were carried out to evaluate possible use of nuclear explosives for peaceful purposes, or PNE's. Let us summarize some of the conclusions of these authors.

**The Toman Curves**

The mechanism of crater formation in nuclear explosions(NE) and that caused by high explosives(HE) and various scaling laws has been studied in the fundamental papers by Nordyke [1] and Toman [2]. [1] contains an excellent review of the subject, while [2] discusses several technical aspects. Toman [2] introduces normalized parameters(scaled parameters) to study various types of explosions, HE and NE in different media. We introduce these parameters. First we have the scaled radius $R_s$ defined as,

$$R_s = \frac{R}{Y^{1/3.4}} \tag{1}$$

where $R$ is the observed radius of the crater in meters or in feet, and $Y$ the yield in kilotons. Next we have the scaled depth $D_s$,

$$D_s = \frac{D}{Y^{1/3.4}} \tag{2}$$

where $D$ is the depth of emplacement in metres or feet, and again $Y$ the yield in kilotons. Toman plotted for various explosions (see [2] and also Nordyke [1] who reproduces Toman's curves) the value of $D_s$ along the x-axis and $R_s$ along the y-axis. Toman [2] obtained the curves presented in Fig. 1 in our article which is a reproduction of the plots on pg. 368 of [2].

The following observations are immediate from the plots obtained by Toman.

**Effect of Media**

It is seen that the curves for hard, dry rock, are bounded above by the curve for alluvium. This is true for both HE and NE. That is for a given yield and same depth of emplacement, the crater will be smaller for hard rock than for alluvium. In a sense these media are the extreme cases and for any other media the curves have to lie between the two displayed extremes. This is the situation for the medium at Pokharan.

**Chemical or Nuclear**

It is seen from the curves that if the medium is either hard rock or alluvium the plots for nuclear explosions is enveloped by those for high explosives. Thus chemical explosions for a given yield and same depth of emplacement give a **larger** crater than nuclear explosions. That is the coupling is different. This is the result of various gases and other chemical products produced in HE explosions. [2] has a discussion on pg. 354

explaining the fundamental differences between HE and underground nuclear explosions. One may also consult [8] for a further technical discussion on this point elucidating the differences between HE and NE and crater formation.

**Depth of emplacement**

It is seen the curves for NE in hard rock decay sharply and cut the x-axis at the parameter value 60 where the depth of emplacement $D$ is now measured in meters and where the scaled depth of emplacement $D_s$ was plotted along the x-axis. The plots show that for NE when $D_s = 60$ in hard, dry rock there will be no crater but a retarc ( a reversed crater, a mound of rubble). This cut-off point is determined by the event Sulky. The mechanism of crater formation is explained in Toman's paper. For a device buried at a shallow depth, first a small crater is formed since the bulk of the content escapes into the atmosphere or as ejecta. As the device is emplaced at deeper depths, the crater diameter increases to a maximum, then again starts to decrease and then at a certain stage instead of a crater a retarc is formed. Emplacing it deeper produces then no visible disturbance on the surface. Thus from the Sulky event depths of emplacement $D$ given by:

$$D = 60(Y)^{1/3.4} \text{ meters} \tag{3}$$

will produce a retarc in hard, dry rock. $D$ is clearly larger in softer alluvium. Now for the event S-1(Indian thermo-nuclear explosion of May 11, 1998), $Y = 45$. In hard, dry rock using (3) we compute easily that the critical depth for producing a retarc is 194 metres, which is close to the shaft depth for S-1 stated by Chengappa in [3], pg. 427. In fact the medium for S-1 was wet [3], and somewhat softer and since Chengappa says [3] that the S-1 shaft was over 200 metres, the S-1 event did produce a small sand mound, consistent with our equation (3).

**Maximum crater size**

The cratering curves in [2] achieve a maximum at $D_s = 40$ and for this value of $D_s$ the corresponding $R_s$ value in hard rock is 45 and 50 for alluvium. This means that for a shaft like S-1 with depth of emplacement $D = 200$ metres or thereabouts, the maximum crater size will be obtained by a device whose yield is

$$(200/40)^{3.4} = 237 \text{ kilotons}$$

and this will produce a crater of **radius** 250 metres. Thus one can conclude that a device with yield 230 kilotons could have been emplaced in the shaft S-1. But this would have produced a gigantic crater, the largest ever if one looks at the table of PNE explosions compiled by M. Nordyke that appears in Toman's article [2]. This is Fig. 2 in this article. The largest crater in a US conducted PNE experiment was the event Sedan (see the table in Fig. 2) which was emplaced in a shaft 194 metres deep in desert alluvium and produced a crater of radius 185 metres. In fact Nordyke [1] recommends using $D_s$ values between 40 and 50 for digging craters and in fact suggests using NE in a fantastic scheme to dig out a secondary Panama Canal. The aim of POK-2( Indian nuclear explosions of May 11, 1998) was not the creation of craters of maximum radii which would be consistent with a PNE type of shot, but the weaponization of devices. Furthermore it would have been ludicrous to test such massive yield devices with the device relatively shallowly emplaced. One could ask the question what $D_s$ value would BARC be comfortable with. To answer this question we recall POK-1(Indian nuclear explosion of May 18, 1974). We will see in an instant that its $D_s$ value is around 52 thus it qualifies as a PNE, but we will use the terminology MCE, maximal cratering experiment. In fact for POK-1, the depth of emplacement was 107 metres[6] and the yield 12 kt. Using (2),

$$D_s = \frac{107}{12^{1/3.4}} = 52.$$

Thus POK-1 is a genuine MCE. Now the shaft for S-1( the thermo-nuclear device at POK-2) was supposedly over 200 metres [3]. Thus let us compute the maximum allowed yield for a device that is to be emplaced in a shaft exactly 200 metres long and with scaled depth of emplacement parameter chosen so that $D_s = 52$. We pick $D_s = 52$ since this is the parameter picked by BARC for a maximal cratering experiment on May 18, 1974. Thus BARC used this parameter confident that there would be no release of radio-active gases and at the same time to produce the largest possible sub-surface effect, a PNE which is consistent with the geology of the Pokharan site. Thus using $D_s = 52$ and depth of emplacement $D = 200$ metres, we compute using (2),

$$52 = \frac{200}{Y^{1/3.4}}.$$

Solving for $Y$ the permissible allowed yield for shaft S-1 we get, $Y = 100$ kilotons. For the $D_s$ value 52 the corresponding value for $R_s$ is $R_s = 30$ where we have taken a point between hard, dry rock and alluvium. This would have produced a crater of radius 138 metres. This is a far more reasonable assumption of what the shaft S-1 could have carried maximally. Thus the shaft S-1 was at most capable of a maximum of 100 kilotons.

**R. Chidambaram's Lecture at IISc(Indian Institute of Sciences)**

In notes taken by Dr. Shiv Sastry [4] at a lecture by R. Chidambaram at IISc, (also see [5]) the following points were made by Dr. Chidambaram.

(a) For a 1 kt. device a burial depth of 150 metres is needed to prevent crater formation. The meaning of this is now clear from the Toman plots. The emplacement depth Chidambaram refers to is clearly in **alluvium**. Thus in alluvium the critical burial depth $D_{\text{critical}}$ satisfies the relation,

$$D_{\text{critical}} = 150(Y)^{1/3.4}. \tag{4}$$

(b) Chidambaram also made the statement that the burial depth at Pokharan is about half. One thus suspects that the strength of the material at the depth at which the S-1 device was emplaced is roughly double that of alluvium. Thus the material has a strength midway between alluvium and hard, dry rock. Thus the critical depth of emplacement where only a retarc will be produced at Pokharan is

$$D_{\text{critical}} = 75(Y)^{1/3.4}. \tag{5}$$

Now using the announced yield of S-1, $Y = 45$ kilotons, we easily compute using (5) that $D_{\text{critical}} = 229$ metres. Thus if S-1 was buried at over 200 metres as per Chengappa[3], pg. 427, S-1 would have produced a small subsidence crater or a retarc. This was indeed the case, pg. 431, [3].

**Pokharan-1, The Indian PNE of May 18, 1974**

As seen above the $D_s$ value for POK-1 was 52. The curves of Toman show that for a medium that has the strength midway between hard, dry rock and alluvium the corresponding $R_s$ value is approximately, 30. Since the yield of POK-1 was 12 kilotons we see that POK-1 would have produced a crater of radius, $(12)^{1/3.4}30 = 62$ metres. This agrees very well with the crater radius stated in [6], [7].

**C. Sublette's analysis of the Pokharan-1 event**

Sublette[6] has made an analysis of the crater data for the Pokharan explosion of May 1974. However, there are serious errors in his analysis. We now point out these flaws.

(a) In arriving at the plot, Fig. 1 in [6] Sublette has completely ignored the effect of the medium and essentially assumed that cratering effects are the same in all media, thus the plot in [6] consists of a single curve as opposed to the plots in [2] where multiple curves are obtained for different media.

(b) More seriously the plot in [6] has been obtained by combining data from both NE and HE. Thus Sublette assumes that the coupling for NE and HE is the same. This is false as is clearly seen from Fig. 1 in this article which is taken from [2]. Both [1], [2] emphasize that one cannot combine data from HE and NE to arrive at cratering curves. Furthermore, computer simulations by Burton et al[8] clearly show that coupling is markedly different for Nuclear and High explosives and one cannot estimate yields by combining data from both types of explosions.

(c) To arrive at his plot [6], Sublette uses the Sulky event which produced no crater but a retarc, (see Nordyke's table, Fig. 2 in our article). In fact [2] contains a photograph of the retarc formed by Sulky,on pg. 361. Furthermore the Sulky event defines the point where the cratering curve for NE in hard, dry rock crosses the $x$- axis in Fig. 1, that is produces no crater. Thus one is baffled as to how Sublette assigns a crater radius to Sulky in his plot.

(d) To arrive at his plot Sublette uses another event, Palanquin. As is seen from Nordyke's table Fig. 2 in our article, Palanquin, was emplaced at 24 metres, and had a yield of 4.3 kilotons. It was supposed to produce a retarc. However, a failure of the stemming mechanism occured and thus a crater of radius 36.4 metres formed. This failure of the experiment has been explained on pg. 375, [2]. Thus Palanquin was a flawed experiment. However, Sublette has used data from this event to construct his plot. It also clear that in the all important steep part of the graph from where yield estimates for the POK-1 event are deduced, Sublette uses only two data points from nuclear explosions, one the flawed experiment Palanquin and another event Sulky which did not produce a crater but to which Sublette nevertheless assigns a crater radius.

The effect of failure to be careful and address the issues pointed out in (a)-(d) above is that Sublette produces a plot that is markedly shifted to the right in comparison with the plots in [1] and [2]. Thus the conclusion one would obtain using Sublette's plot is a clear underestimation of yields due to the rightward shift of the plot. This is the origin of Sublette's lower estimate of the yield of Pokharan-1.

**Further Comments**

(a) The surface features of the S-1 shaft after the explosion coupled with information of its burial depth indicate that the yield of S-1 is in agreement with crater and emplacement data.

(b) The data of $7,000$ sq. metres of steel sheets to line shafts as claimed by Chengappa [3], pg. 40 is now seen as the amount needed to line **both** shafts S-1 and S-2.

(c) Finally, we address the question as to why BARC did not test a 100 kt device in shaft S-1. The aim was to test a Agni configured device with the sole opportunity provided to the weapons design team. Thus to fit a package into the requisite dimensions probably called for a device design with yield of about 45 kt. If there were no constraints, most likely a test of 100 kilotons would have been likely with the attendant large crater.

(d) Lastly a perusal of Fig. 2 shows PNE experiments for craters were either sub kiloton, sub-sub kiloton or within 2 kilotons. Only two experiments were large. These were Sedan already mentioned above and Schooner at 35 kilotons at 135 metres emplacement. This produced a crater of, 130 metres radius.

(e) The reader who is more mathematically minded perhaps will gain a better understanding of this topic in the context of the Pokharan events by studying the articles [9], [10].

## REFERENCES

[1] Nordyke, M.D., Peaceful Uses of Nuclear Explosions, IAEA-PL-388/12, 49-107, Peaceful Nuclear Explosions, Phenomenology and Status Report, Proceedings of a Panel, International Atomic Energy Agency(IAEA), Vienna, 2-6 March 1970.

[2] Toman, J., Results of Cratering Experiments, IAEA-PL-388/16, *ibid*, 345-375.

[3] Chengappa, R., Weapons of Peace, Harper Collins, India, 2000.

[4] Sastry, S., Notes taken at R. Chidambaram's lecture at IISc, Strategic Affairs Archives at http://www.bharat-rakshak.com

[5] Chidambaram, R., The May 1998 Pokharan Tests: *Scientific Aspects*, http://www.saag.org/papers5/paper451.html

[6] Sublette, C., What are The Real Yields of India's Tests? http://nuketesting.enviroweb.org/hew/India/IndiaRealYields.html

[7] First Nuclear Test In Pokaran in 1974, http://www.fas.org/nuke/guide/india/nuke/first-pix.htm

[8] Burton at al, Computer Design of High Explosive Experiments to simulate subsurface Nuclear detonations, Nuc. Tech., **26**, 1975, p.65

[9] Ranga Rao, M.P., Cavity Radius Estimation for Contained Peaceful Nuclear Explosions, An analytic approach, Proc. Indian Acad. of Sciences, Section A, **87A**, 1978, 13-21.

[10] Chidambaram, R., et al, Phenomenology of the Pokharan Peaceful Nuclear Experiment, Pramana, **24**, 1985, 245-258.

TABLE I. SUMMARY OF PROJECTS OR EVENTS CONTRIBUTING DATA FOR NUCLEAR CRATERING TECHNOLOGY (FROM NORDYKE [2])

| Project or event name | Date | No. of shots | Configu-ration | Explosive [a] | Approx. equiv. yields [b] | Depth of burst (ft) (m) | Apparent crater radius (ft) (m) | Apparent crater depth (ft) (m) | Medium [c] | Ref. |
|---|---|---|---|---|---|---|---|---|---|---|
| Jangle S | 1951 | 1 | Single | NE | 1.2 kt | 3.5(1.07) | 45(13.7) | 21(6.4) | Alluvium-10 | 3 |
| Jangle U | 1951 | 1 | Single | NE | 1.2 kt | 17.0(5.18) | 130(39.6) | 53(16.2) | Alluvium-10 | 3 |
| Jangle HE | 1951 | 10 | Single | TNT | 1.2-20 ton | ← | Series | → | Alluvium-10 | 3 |
| Teapot ESS | 1955 | 1 | Single | NE | 1.2 kt | 67.0(20.4) | 146(44.5) | 90(27.4) | Alluvium-10 | 3 |
| Mole, ERDL, SO | 51/60 | 30 | Single | TNT | 0.13 ton | ← | Series | → | Alluvium-10 | 3 |
| Toboggan | 59/60 | 92 | Linear | TNT | – [d] | ← | Series | → | Playa | 4 |
| Stagecoach | 1960 | 3 | Single | TNT | 20 ton | ← | Series | → | Alluvium-10 | 3, 5 |
| Scooter | 1960 | 1 | Single | TNT | 500 ton | 125(38.1) | 154(46.9) | 75(22.9) | Alluvium-10 | 3, 6 |
| Buckboard | 1960 | 13 | Single | TNT | 0.5-20 ton | ← | Series | → | Basalt | 7 |
| Sandia, Alb. [e] | 60/65 | | Row | TNT | – [e] | ← | Series | → | Alluvium-Alb. | 8 |
| Rowboat | 1961 | 8 | Row | TNT | 0.14 ton | ← | Series | → | Alluvium-10 | 9 |
| Danny Boy | 1962 | 1 | Single | NE | 0.42 kt | 110(33.5) | 107(32.6) | 62(18.9) | Basalt | 10 |
| Sedan | 1962 | 1 | Single | NE | 100 kt | 635(194) | 608(185) | 323(98.4) | Alluvium-10 | 11 |
| Pre-Buggy I | 1962 | 18 | Row | NM | 0.5 ton | ← | Series | → | Alluvium-5 | 12 |
| Pre-Buggy II | 1963 | 10 | Row | NM | 0.5 ton | ← | Series | → | Alluvium-5 | 13 |
| Pre-Schooner I | 1964 | 4 | Single | NM | 20 ton | ← | Series | → | Basalt | 14 |
| Dugout | 1964 | 1 | Row | NM | 20 ton | 59(18.0) (spacing: 45(13.7)) | width: 136(41.5) | 35(10.7) | Basalt | 15 |
| Sulky | 1964 | 1 | Single | NE | 87 ton | 90(27.4) | – | – | Basalt | 16 |
| Palanquin | 1965 | 1 | Single | NE | 4.3 kt | 280(85.4) | 119(36.3) | 78.8(24.0) | Rhyolite | 17 |
| Pre-Schooner III | 1965 | 1 | Single | NM | 85 ton | 71(21.6) | 95(29.0) | 61(18.6) | Rhyolite | 18 |
| Pre-Gondola I | 1966 | 4 | Single | NM | 20 ton | ← | Series | → | Saturated shale | 19 |
| Pre-Gondola II | 1967 | 1 | Row | NM | 20-40 ton | 50-60(15.2-18.3) (spacing: 80(24.4)) | – | – | Saturated shale | 20 |
| Cabriolet | 1968 | 1 | Single | NE | 2.6 kt | 170.75(52.0) | 178(54.3) | 120(36.6) | Rhyolite | 21 |
| Buggy | 1968 | 5 | Row | NE | 1.1 kt | 135.0(41.2) (spacing: 150(45.7)) | width: 254(77.5) | 69.8(21.3) | Basalt | 1 |
| Pre-Gondola III | 1968 | 7 | Row | NM | 30 ton | (spacing: 50-56(15.2-17.1)) | width: 187-214(57.0-65.2) | 50-53(15.2-16.2) | Saturated shale | 20 |
| Schooner | 1968 | 1 | Single | NE | 35 kt | 355(108) | 426(130) | 208(63.4) | Tuff | 2 |

[a] NE, nuclear explosives; TNT, conventional high explosives; NM liquid nitromethane.

[b] For 1 kt, equivalent yield = $10^{12}$ g-cal.

[c] Alluvium-10: Desert alluvium, Area 10, Nevada Testing Site (NTS).
Alluvium-5: Desert alluvium, Area 5, NTS.
Alluvium-Alb.: Desert alluvium, Albuquerque, New Mexico.
Playa: Yucca Lake, NTS.
Basalt: Buckboard Mesa, NTS.
Rhyolite: Schooner Site, Bruneau River Plateau, Idaho.
Saturated shale: Fort Peck, Montana.

[d] Toboggan line charges ranged from 0.23 to 42.7 lb/ft. (0.065-13.0 lb/m).

[e] Since 1960, Sandia Corporation has conducted a continuing small-scale cratering program at Albuquerque, to investigate various problems related to rows and arrays of charges.

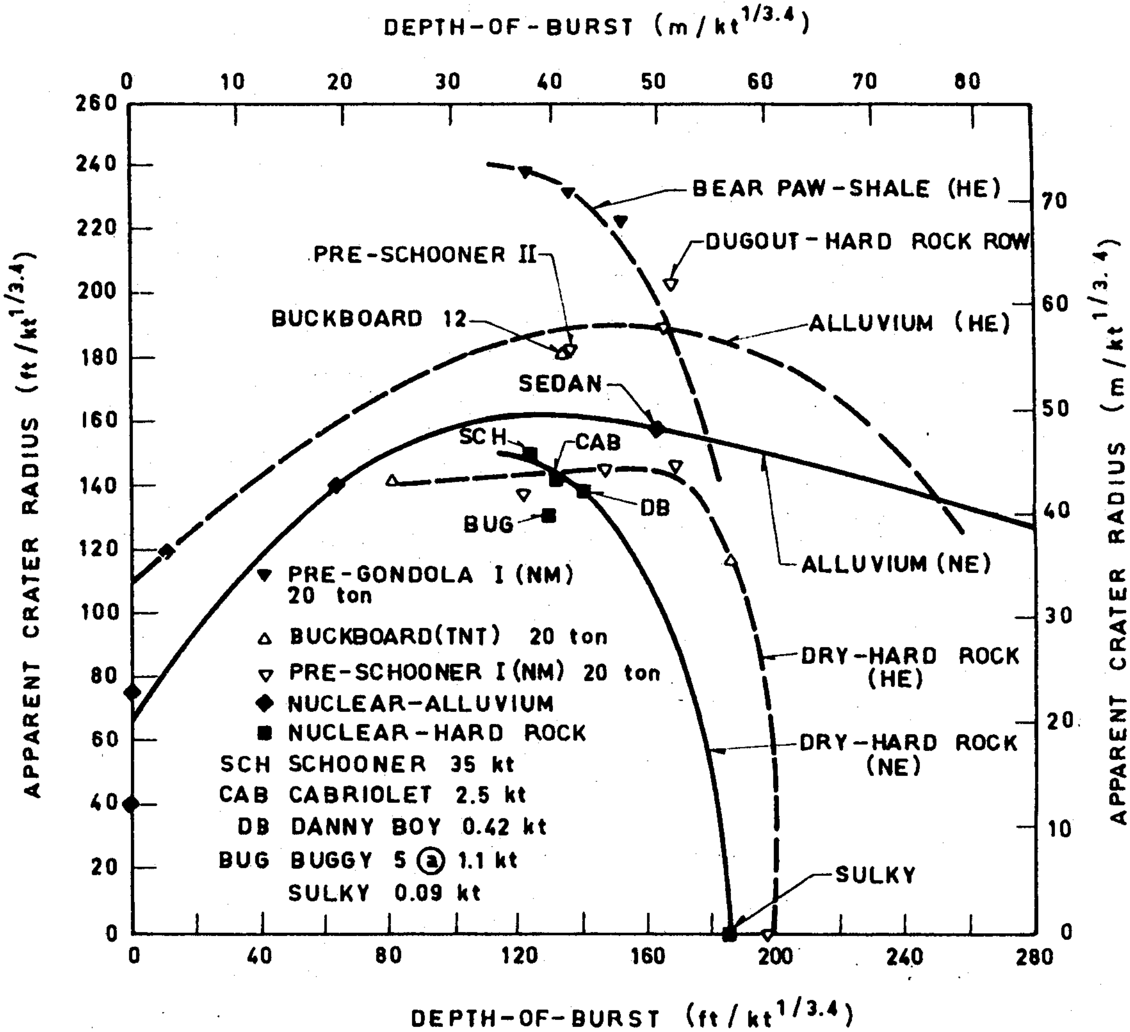


FIG. 13. Effect of depth-of-burst on apparent crater radius.

## Dugout

In June 1964, the Dugout experiment was conducted in basalt on the Buckboard Mesa, NTS[1]. Five spheres each containing 20 tons of the high explosive nitromethane (NM) were detonated simultaneously. The depth of burst was 19.4 m (59 ft) and the spacing 14.8 m (45 ft) between charges.