12 6-17-83 JS ①

Dr # 1505-9

I-9833

UCID--19812

DE83 012881

A REVIEW OF GEOMECHANICS DATA FROM FRENCH NUCLEAR EXPLOSIONS IN THE HOGGAR GRANITE, WITH SOME COMPARISONS TO TESTS IN U. S. GRANITE.

Francois E. Heuze

May, 1983

Lawrence
Livermore
Laboratory

Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore Laboratory under Contract W-7405-Eng-48.

ACKNOWLEDGMENTS

The documents analyzed were obtained from Milo Nordyke and Robert Terhune. J. Hannon, D. Springer and R. Terhune provided valuable comments. Lydia Burrow typed the manuscript. Their assistance is gratefully acknowledged.

This work was supported by the U.S. Department of Energy under contract W-7405-ENG-48 with the Lawrence Livermore National Laboratory.

SYMBOLS

A : amplitude
C : cumulative spectrum function
C_s : "structure coefficient" equivalent to shear strength (bars)
d : distance from shot point (m, or km)
H : depth of burial of device (m)
H_c : height of chimney (m)
k : a constant
R_c : cavity radius (m)
R_f : radius of fractured zone (m)
R_p : radius of crushed (pulverized) zone (m)
R_r : radius of disked zones (m)
t : time to collapse of chimney (min.)
u : displacement (cm)
V : velocities of materials or waves (m/s)
W : yield of devices (kt)
WP : working point; location of device
α : coefficient related to coupling (dimensionless)
δ : displacement (cm)
ρ : density of rock (g/cm^3)
σ_t : tensile strength of the rock mass (bars)

CONTENTS

Pg

ABSTRACT

Numerous unclassified reports available at Lawrence Livermore National Laboratory (LLNL), on the French nuclear explosions in the Hoggar (1961-1966) were reviewed from the standpoint of geomechanics. The documents were both in French and English.

The following aspects of the tests are summarized:

- spectral content of the tests compared to U.S. results
- shock front positions with time
- cavity radius as a function of yield, coupling, density of rock, rock shear strength, and overburden
- radial pressure, tangential pressure and peak velocity as a function of distance and yield
- pressure vs. time at various distances
- mechanical properties of granite
- scaling laws for acceleration, velocity and displacement as a function of yield and distance for all Hoggar shots
- extent of tunnel damage as a function of distance and yield
- time to collapse of chimney as a function of yield, or cavity radius
- extent of granite crushing and disking as a function of distance and yield
- cavity height relation to cavity radius
- faulting and jointing on the Taourirt Tan Afella massif
- influence of water content on cavity radius vs. yield.

Whenever possible, these French data are compared to corresponding data obtained in the U.S. granite events Hard Hat, Shoal, and Piledriver. The following results emerge from the comparison:

- agreement is found between the French and U.S. experience for: mechanical properties of the granites, rock damage due to the blast, and yield-scaled peak values of acceleration, velocity and displacement.
- lack of agreement exists for: cavity size, chimney height, and time to cavity collapse. Average spacing of rock joints also was about 5 times greater in the Hoggar.

This review may be useful in current matters related to treaty verification.

1. INTRODUCTION

Numerous unclassified reports available at Lawrence Livermore National Laboratory (LLNL), on the French nuclear explosions in the Hoggar (1961-1966) were reviewed from the standpoint of geomechanics. The documents were both in French and English.

The following aspects of the tests are summarized:

- spectral content of the tests compared to U.S. results
- shock front positions with time
- cavity radius as a function of yield, coupling, density of rock, rock shear strength, and overburden
- radial pressure, tangential pressure and peak velocity as a function of distance and yield
- pressure vs. time at various distances
- Hugoniot for granite
- scaling laws for acceleration, velocity and displacement as a function of yield and distance for all Hoggar shots
- extent of tunnel damage as a function of distance and yield
- time to collapse of chimney as a function of yield, or cavity radius
- extent of granite crushing and disking as a function of distance and yield
- cavity height relation to cavity radius
- faulting and jointing on the Taourirt Tan Afella massif
- influence of water content on cavity radius vs. yield.

The next chapter presents the information which was retained from 15 selected references among the 78 French documents which were reviewed. The other French documents either were not relevant to geomechanics, or contained material which duplicated that in the selected reports. Of the numerous U.S. references on granite events we retained only those which contained information comparable to the French geomechanical data. These U.S. references are also listed at the end of the report. The figures have been regrouped in an Appendix.

2. SUMMARY RESULTS

Reference 1 (in French), Albaret and Duclaux, 1969

- Rock behaves elastically at a distance > $(k/\sigma_t)^{0.84} \cdot W^{1/3}$ where the granite tensile strength, σ_t, is assumed to be 100 bars and k is not specified.
- Examines the amplitude spectrum of P-wave records from French nuclear explosions in the Hoggar.
- Results are presented in the form of a cumulative spectrum C(N): it is the integral of the function A(N) (amplitude as a function of frequency) *within a frequency domain. C(N) is plotted in a normalized fashion* as a cumulative percentage, from 0 to 100, between the two limit frequencies (Fig. 1). The second derivative of C is the slope of the amplitude spectrum in the frequency interval, from which one can find the peak amplitude frequency.
- Some examples are given for C(N) with N = 10 to 60 Hz at a distance d = 15 km from shot point (Fig. 2).
- For N = 10 to 20 Hz and d = 15 and 50 km, an empirical relation is found for Hoggar shots, regarding the slope of C(N):

$$dC/dN = 0.36 \cdot (d \cdot W^{-1/3})^{0.43}$$

d in km, W in kt.

- The French amplitude spectra are said to agree remarkably well with the theory of Peet (1960).
- Although no examples are given for granite, cumulative spectra are displayed for two U.S. shots in tuff, Blanca (19 kt) and Logan (5 kt), at distances from 15 to 287 km, in the domain Nϵ [2 to 20 Hz] (Fig. 3).

Reference 5 (in English), Berger, 1970

- Comprehensive report on the French program; contains 65 references.

- Shock front position vs. time up to 600 μs and 5 m given for Michele/3.6 kt (Fig. 4). Agrees with calculations using the CEA's (Commissariat a l'Energie Atomique) S code. This one-dimensional code is essentially the LLNL SOC code. It is discussed in the French reference 56.

- Cavity radius vs. yield for four French shots in granite (Carmen/16 kt, Georgette/13 kt, Michele/3.6 kt, and Monique/117 kt), and three U.S. Shots (Hardhat/5.5 kt, Piledriver/60 kt, and Shoal/13 kt) are shown in Fig. 5. French radii were determined by postshot drilling.

- Radial pressure, tangential pressure, and peak velocity calculated with the S code, are given as a function of distance, up to a few 100 m's for Michele and Monique. These calculations and some actual data are compared in Figs. 6 and 7.

- Pressure vs. time record at 30 m from WP, from Michele (Fig. 8) pressure vs. time record at 100 m from WP, for Monique (Fig. 9) pressure vs. distance record at 35.5 ms for Monique (Fig. 10).

- Hugoniot of granite: Hoggar and U.S. results are compared in Fig. 11. The U.S. data are from refs. 61 and 62 in the Berger document, which are Bass et al. (1963) and McQueen et al. (1967).

Reference 18, (in English), Delort, 1969

- Scaled accelerations, velocities and displacements for all Hoggar observations shown as Figs. 12-14. However, the corresponding equations are not given in this reference; they are found in Ref. 49.

- Cavity radius (R_c) as a function of yield (W` and depth of burial (H)

$$R_c = a\,W^{1/4} + bH \qquad H\ (m),\ R_c(m),\ W(kt)$$

	Hoggar granite	Alluvium	Tuff
a	9.72	21.25	21.06
b	-0.0023	-0.0289	-0.0173

Reference 21 (in French), Derlich and Supiot, 1969

- Cavity radius $R_c = 52 \dfrac{\alpha W^{1/3}}{(\rho g H + C_s)^{1/3\gamma}}$ (m)

α = 1 for full coupling C_s = 0 to 250 bars
H: depth of burial (m) γ = 1.03 to 1.14 (adiabatic coeff.)

- Note that Boardman (1967) suggests ignoring the effect of overburden pressure in granite because of tectonic stresses. He proposes simply $R_c = CW^{1/3}$. This seems to fit well Shoal, Hard Hat and Piledriver, with C = 11.4 (Fig. 15).

Reference 22 (in French), Derlich, 1970

- Tunnel damage in the Taourit Tan Afella granite:

  total damage (collapse) for $d(m) < 52\ W^{1/3}$
  variable damage for $52\ W^{1/3} < d < 110\ W^{1/3}$ (Fig. 16)
  no damage for $d > 110\ W^{1/3}$

- Based on Figs. 6 and 7 we estimate the radial pressure to be 1 kbar at $d = 52\ W^{1/3}$ and 100 bars at $d = 110\ W^{1/3}$.

Reference 23 (in English), Derlich, 1969

- Time of chimney collapse as a function of yield for the French events: 6 to 46 min. for 3.6 to 117 kt.

- This is empirically given as:

$$t(\text{min}) = 1.25\ W^{1/3} - 0.52$$

- Note that this relation does not hold for U.S. granite shots: the Piledriver cavity collapsed at 14 sec., for 61 kt (Borg, 1970) and Hard Hat (5 kt) collapsed at 11 hrs (Boardman et al., 1964).

Reference 24 (in English), Derlich, 1970

- Cavity radius $R_c = 7.3 \cdot W^{1/3} \pm 10\%$, R_c(m), W(kt).
- Radius of crushed zone $R_p = 7.3$ to $10\ W^{1/3}$
- Radius of fractured zone $R_f = 10$ to $26\ W^{1/3}$. In this zone the particle diameter is at least 5 cm.
- Radius of zone with core disking $R_r = 30\ W^{1/3}$. Disking means that the core is recovered as thin chips during coring.
- The above scaled radii can be compared to the results obtained in the Piledriver event (Borg, 1973):
  radius of crushed zone $R_p = 10$ to $13\ W^{1/3}$
  radius of fractured zone $R_f = 13$ to $28\ W^{1/3}$
  These results are quite similar to those for Hoggar events. However, disking was not reported in the Piledriver case.

Reference 25 (in English), Derlich, 1972

- Chimney height depends upon in-situ stress and initial jointing. Different results for U.S. and Hoggar shots:
  $H_c \simeq 3.6\ R_c$ in Hoggar, versus
  $H_c \simeq 6.2\ R_c$ for Piledriver, 4.5 for Shoal, and 4.2 for Hard Hat.

Reference 28 (in English), Duclaux et al., 1967

- Cavity radius related to chimney collapse time for French shots:
  $R_c(\text{m}) = 0.8\ t\ (\text{min}) + 3$
  This would not hold for Hard Hat, or Piledriver.

Reference 40 (in English), Faure, 1972

- Faults and joints in the Tan Afella. The mass joint spacing is of the order of 1 m, as compared to about 20 cm for the Climax granite of Piledriver and Hard Hat (Maldonado, 1977).

Reference 42 (in English), Ferrieux, 1970

- Velocity vs. yield at 52 km (remote zone), shown in Fig. 17.

- Velocity vs. distance: comparison of close-in and remote zones in Fig. 18.

Reference 49 (in French), Guerrini and Garnier, 1969

- Scaling laws for Hoggar events, valid for the close-in zone ($0.06 < dW^{1/3} < 1$):

  peak acceleration $A = 2.2 \cdot (d/W^{1/3})^{-2.44} = 2.2\ W^{0.48}\ d^{-2.44}$

  peak velocity $V(m/s) = 0.1\ (d/W^{1/3})^{-1.73} = 0.1\ W^{0.58}\ d^{-1.73}$

  peak displacement (cm) $u = 0.21(d/W^{1/3})^{-1.4} = 0.2\ W^{0.8}\ d^{-1.4}$

  where W(kt) and d(km).

- The standard deviation on each parameter corresponds to the following error percentages:
  acceleration: + 60%, -40%
  velocity : + 50%, -30%
  displacement: + 40%, -30%

- The above scaled relations are compared to the U.S. granite results presented by Sauer et al. (1964) in Figs. 19 to 21. A more recent comparison by Cooper and Brode (1973) is shown in Figs. 22 and 23.

Reference 50 (in English), Habib, 1972

- Tensile strength, triaxial compression test results, and laboratory wave velocities on two Hoggar granites with different microfracturing. The tensile strength (4.5 MPa), compressive strength, and modulus (75 GPa) are very similar to the values for the Climax granite (Schock et al. 1973). The compressional velocity is reported at 4,700 to 5,400 m/s and the shear velocity 2,500 to 2,600 m/s, depending upon the degree of microfracturing.

Reference 64 (in French), Perrier, 1970.

- Presents another relation between W and time of cavity collapse:

$$t\ (\text{min}) = 6.5\ W^{0.4}$$

- This relation does not fit the Hard Hat and Piledriver data any more than the relation of Reference 23.

Reference 67 (in French), Riffault, 1969

- Convenient summary of physical and mechanical properties for numerous rocks.

Reference 75 (in English), Supiot, 1972

- Results of calculations with the formula of reference 21 for cavity radius: influence of water content on cavity radius vs. yield for hard rock (Fig. 24), and influence of "structure coefficient" (C_s) on cavity radius vs. yield (Fig. 25). The C_s for the Hoggar site is taken as $120 < C_s < 320$ bars whereas it is taken as $10 < C_s < 45$ bar for the granite of U.S. events. No explanation is given for the difference. However, it can be hypothesized that a wider joint spacing will rate a higher C_s.

- Chimney height vs. cavity radius in various media (consistent with results of reference 25):

	Salt	Dolomite	Granite	Sandstone	Tuff
H_c/R_c	1.0	3.2	3.6 to 6.2	4.0	3.8 to 6.8

SUMMARY - CONCLUSIONS

Of the 78 documents reviewed, 15 contained original geomechanical results which have been summarized. It is noteworthy that no in-situ stress measurements were performed at the French sites. More details on the waveforms and other geomechanical test records have been requested by the author during his visit to the CEA's Bruyeres-le-Chatel Center in August 1982. They have not been forthcoming yet.

Whenever possible, the French data are compared to corresponding data obtained in the U.S. granite events Hard Hat, Shoal, and Piledriver. The following results emerge from the comparison:

- agreement is found between the French and U.S. experience for: mechanical properties of the granites, rock damage due to the blast, and yield-scaled peak values of acceleration, velocity and displacement.
- lack of agreement exists for: cavity size, chimney height, and time to cavity collapse. Average spacing of rock joints also was about 5 times greater in the Hoggar.

This review may be of practical use in current matters related to treaty verification.

4. APPENDIX: FIGURES

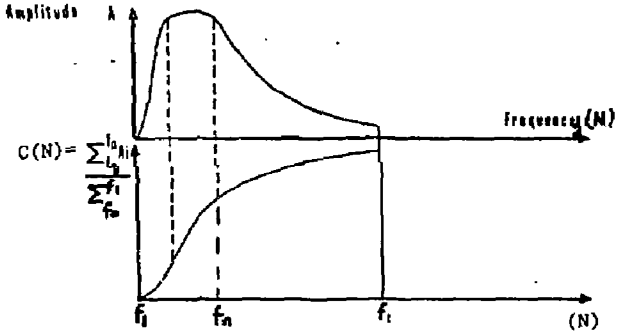


Figure 1: Definition of the Cumulative Spectrum, C(N) (ref. 1). C(N) is expressed as a percentage

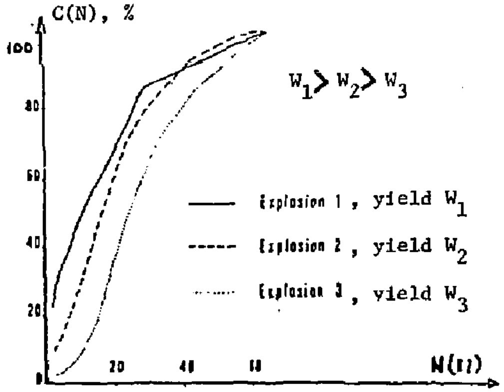


Figure 2: Cumulative Spectra for Three Hoggar Events, (ref. 1)

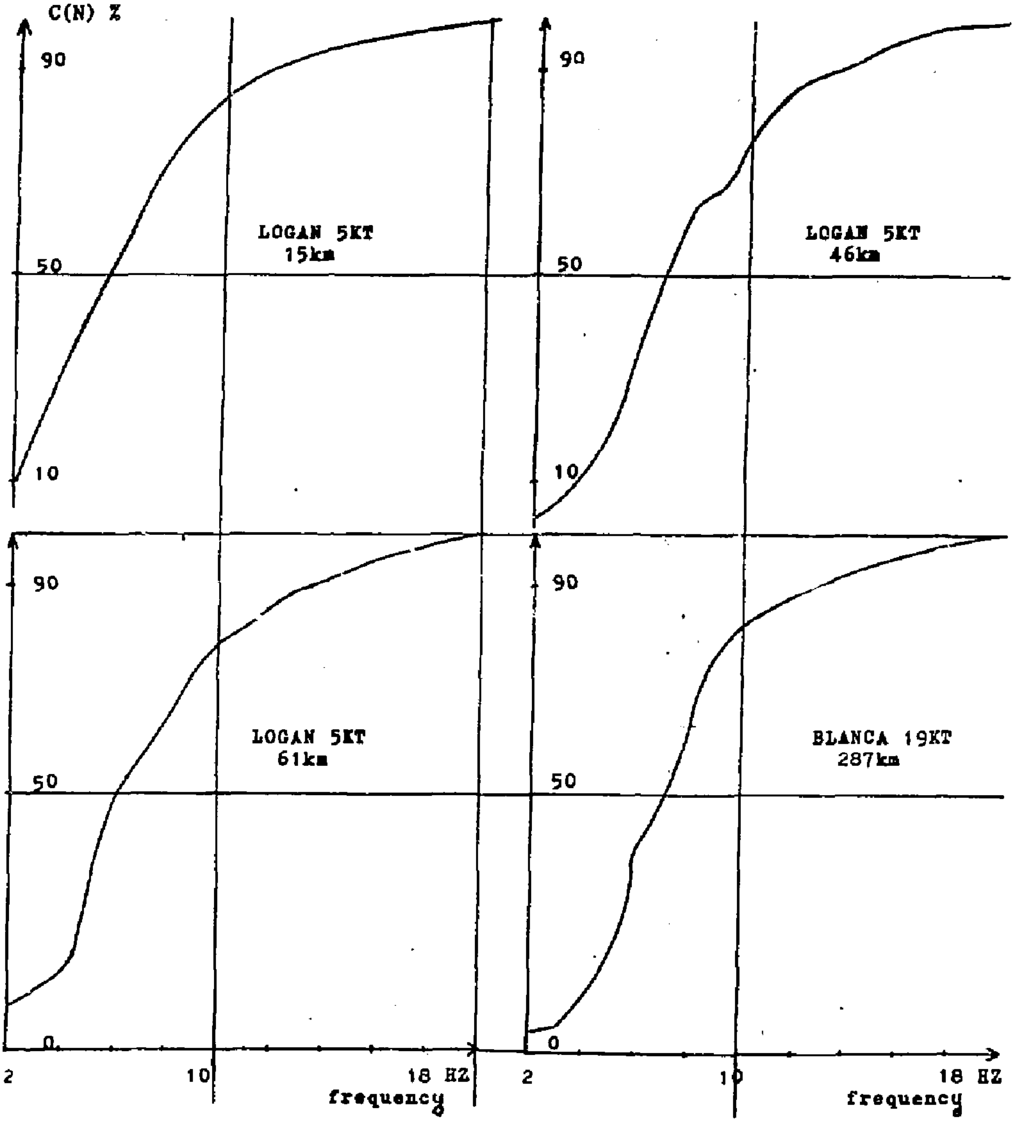


Figure 3: Examples of Calculations of C(N) for Two U. S. Shots in Tuff Monitored at Various Stations (ref. 1). No Comparable Calculations Were Found for U. S. Granite Shots.

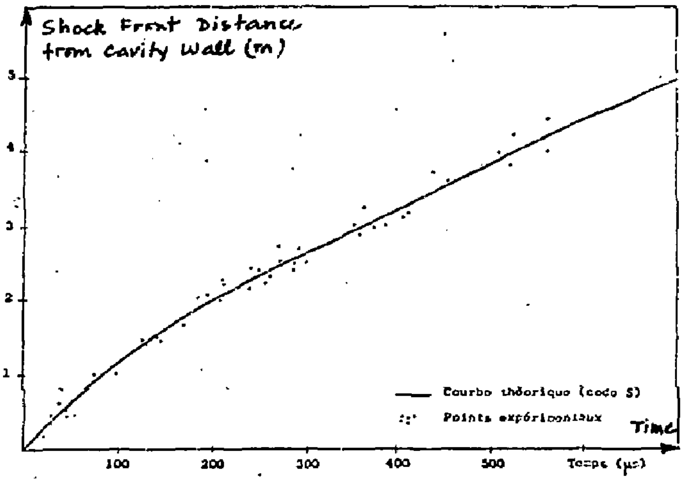


Figure 4: Position of Shock Front vs. Time for Michele (ref. 5)

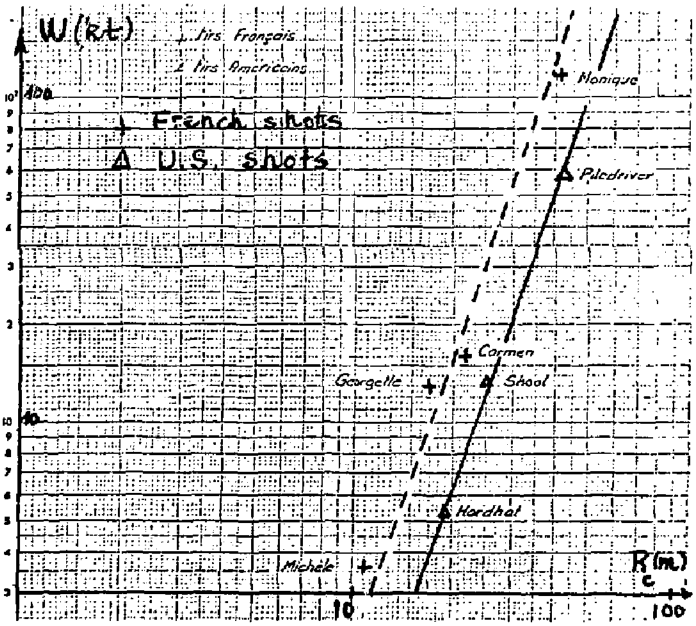


Figure 5: Cavity Radius vs. Yield for French and U.S. Tests (ref. 5) The dashed line is from the original document. The line through the U.S. data was added by this author.

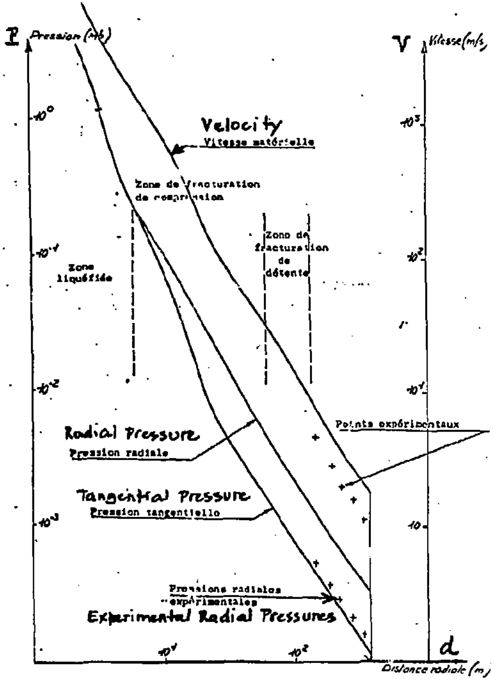


Figure 6 : Pressures and Velocity vs. Distance for Michele (ref. 5)

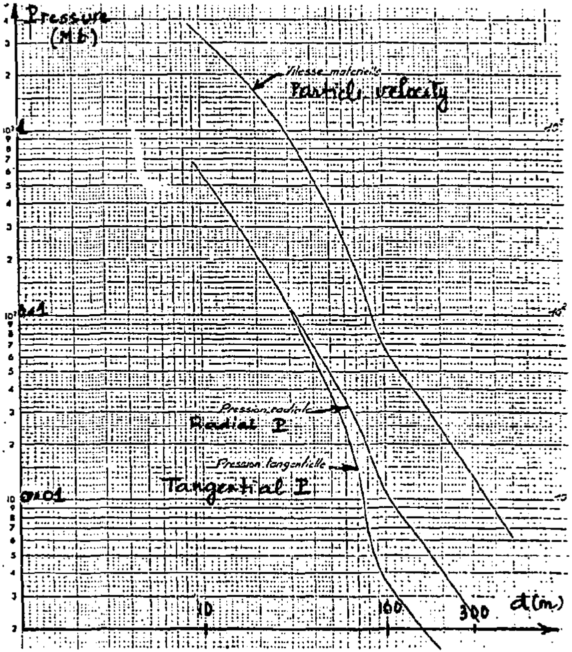


Figure 7 : Pressures and Velocity vs. Distance for Monique (ref. 5)

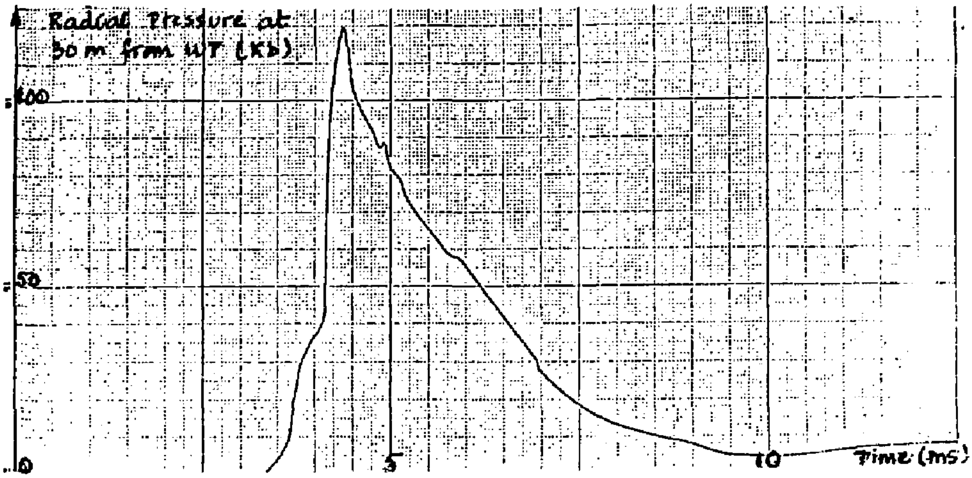


Figure 8 : Radial Pressure at 30m vs. Time for Monique (ref. 5)

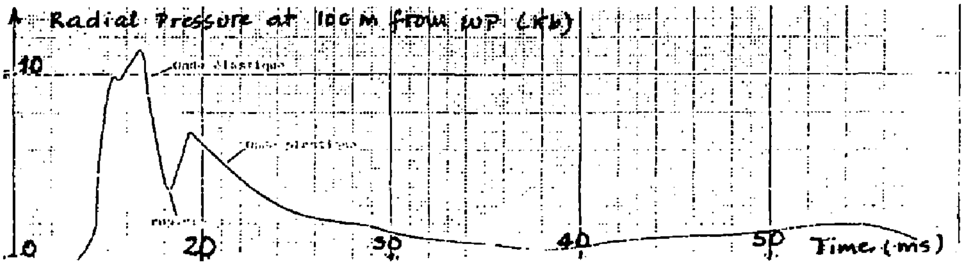


Figure 9: Radial Pressure at '00m vs. Time for Monique (ref. 5)

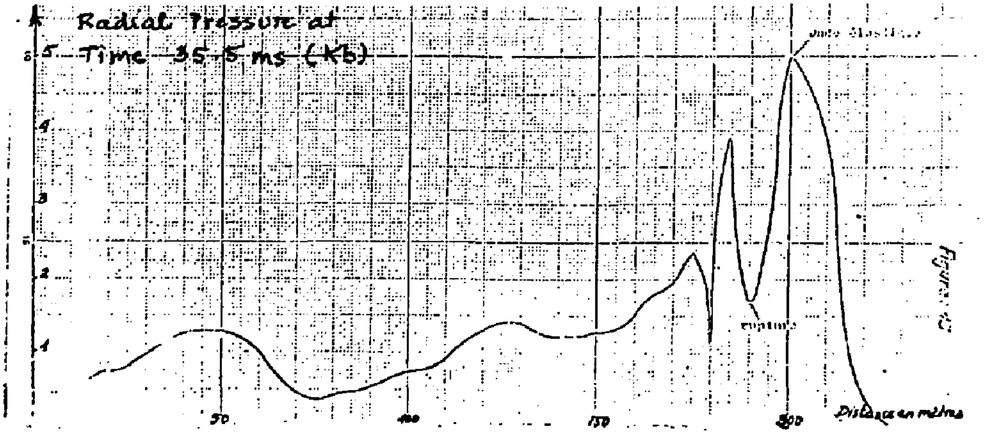


Figure 10: Radial Pressure at 35.5ms vs. Distance for Monique (ref. 5)

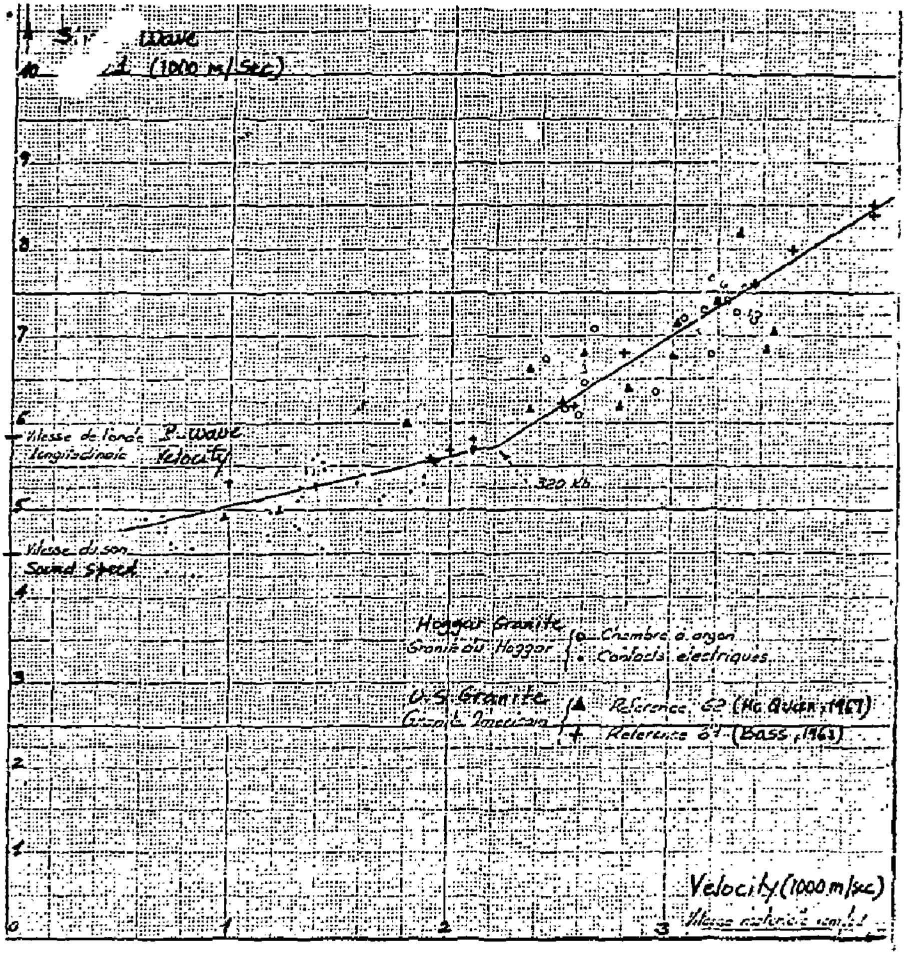


Figure 11: Comparison of Hugoniot for French and U. S. Granites (ref. 5)

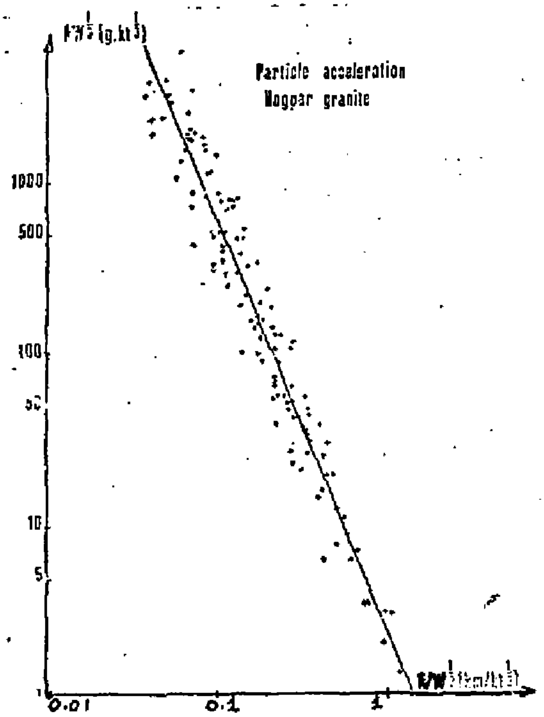


Figure 12: Scaled Acceleration vs. Scaled Distance for Hoggar Shots (ref.18)

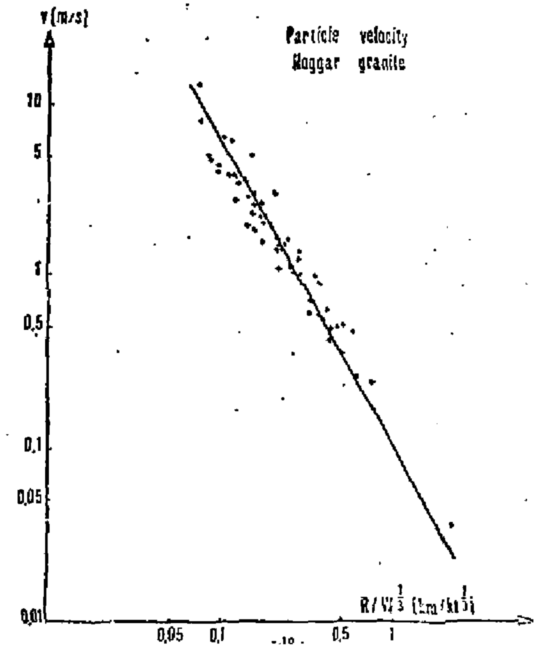


Figure 13: Velocity vs. Scaled Distance for Hoggar Shots (ref. 18)

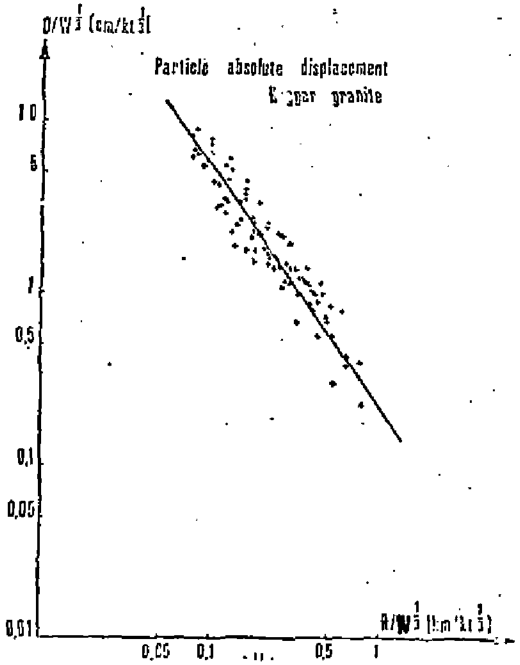
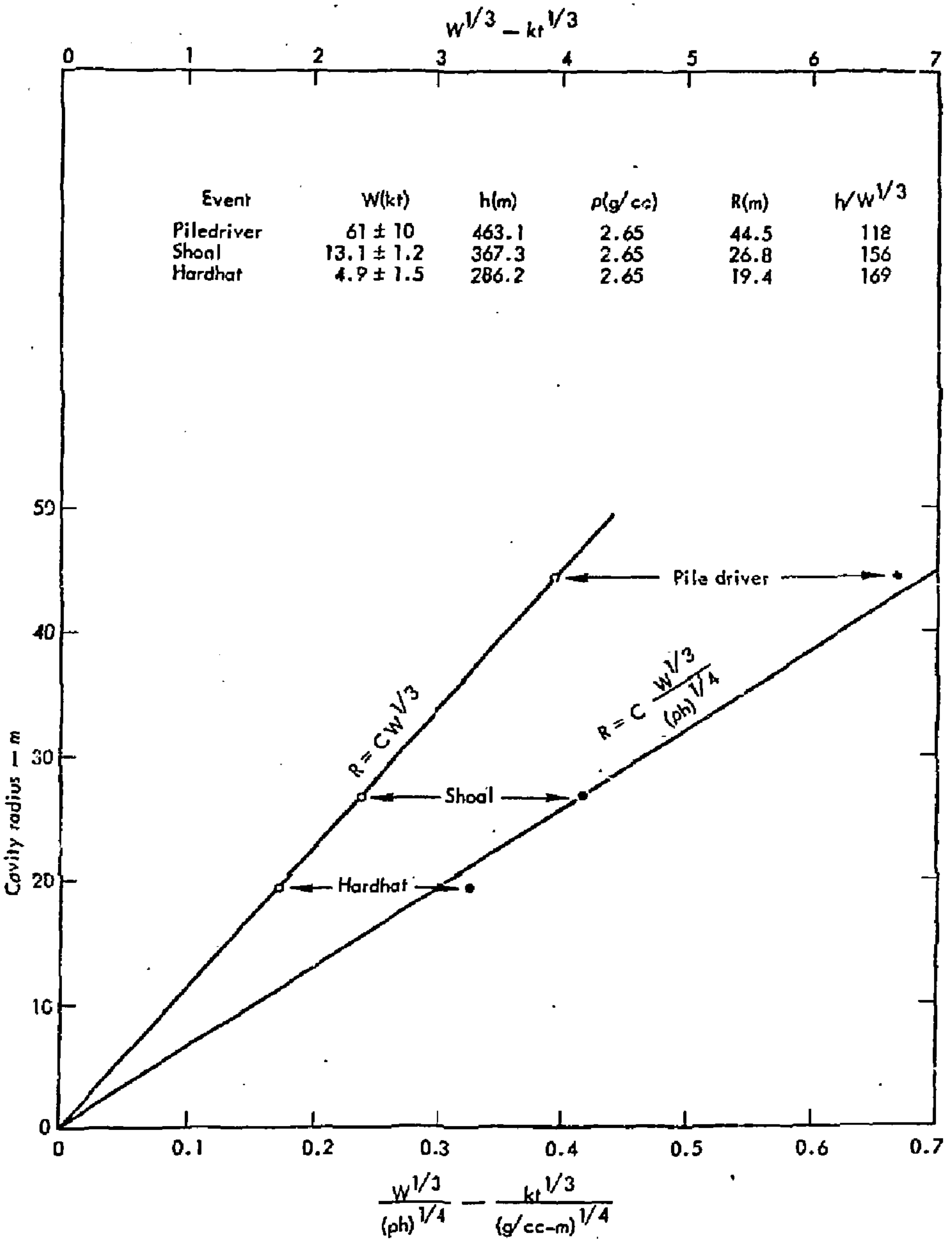


Figure 14: Scaled Displacements vs. Scaled Distance for Hoggar Shots (ref. 18)



Event	W(kt)	h(m)	ρ(g/cc)	R(m)	$h/W^{1/3}$
Piledriver	61 ± 10	463.1	2.65	44.5	118
Shoal	13.1 ± 1.2	367.3	2.65	26.8	156
Hardhat	4.9 ± 1.5	286.2	2.65	19.4	169

Figure 15: Cavity Radius as a Function of $W^{1/3}$ and as a Function of $W^{1/3} / (\rho h)^{1/4}$, after Boardman (1967)

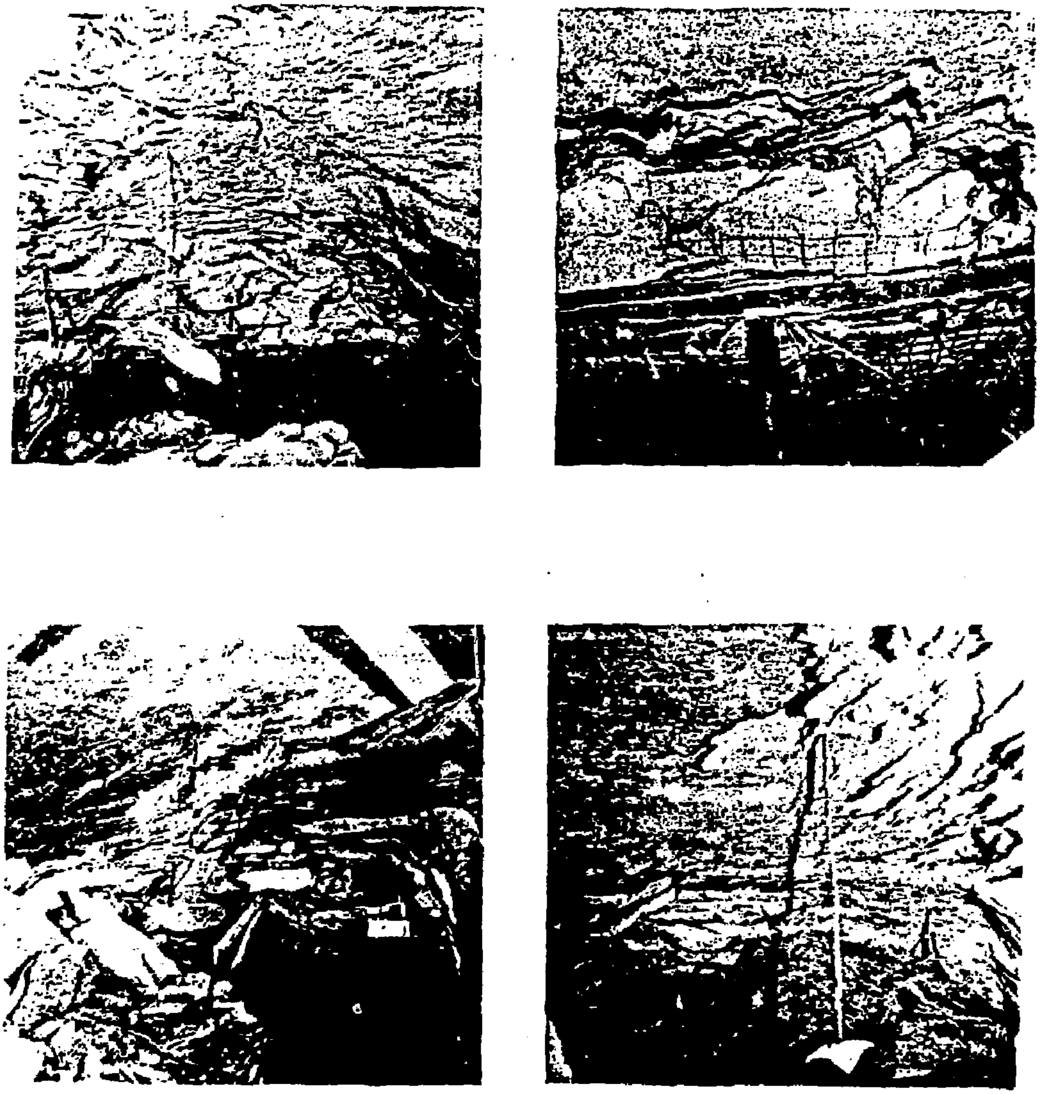


Figure 16: Examples of Damage Sustained by Tunnels at Distances 52 $W^{1/3}$ to 110 $W^{1/3}$ (ref. 22). We Estimate Radial Pressure to Range From 100 Bars (10 MPa) to 1 KBar (100 Mpa).

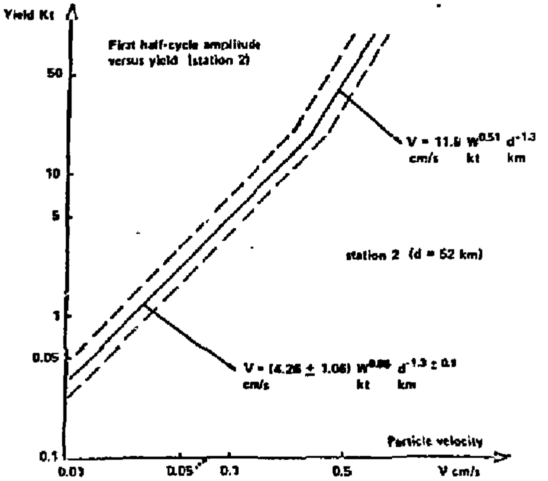


Figure 17: First Half-Cycle Amplitude vs. Yield for Velocity Records at 52km from Hoggar Shots (ref. 42)

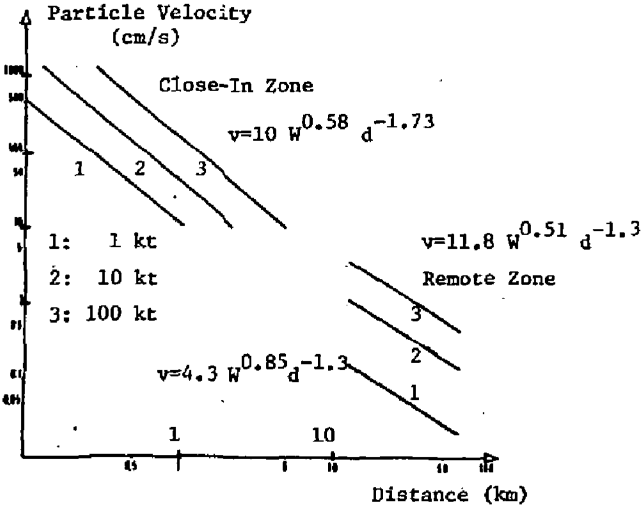


Figure 18: First Half-Cycle Amplitude vs. Distance for Velocity Records from Hoggar Shots (ref. 42)

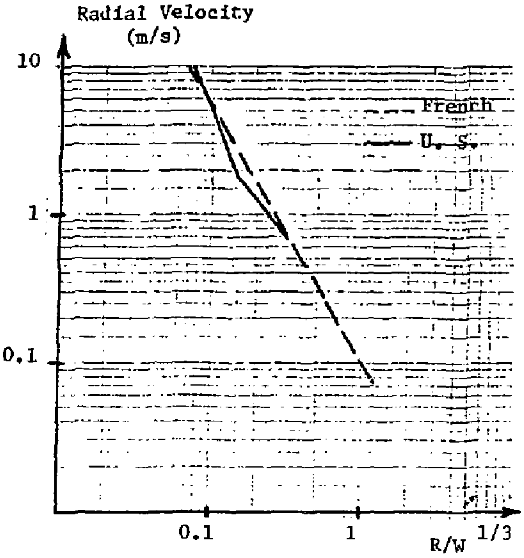


Figure 19: Velocity vs. Scaled Distance. Comparison of French and U.S. Results (ref. 49)

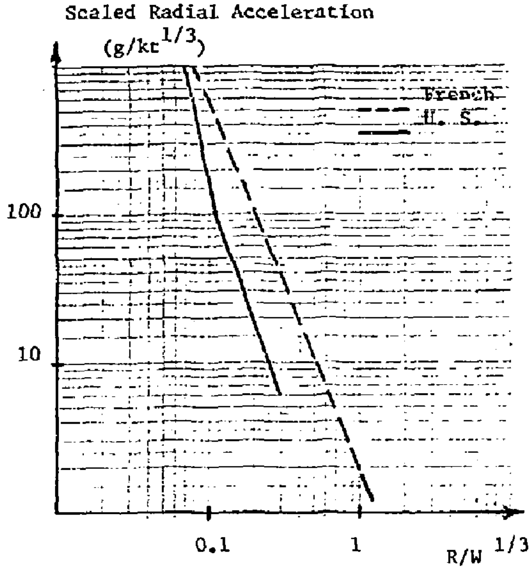


Figure 20. Scaled Acceleration vs. Scaled Distance. Comparison of French and U.S. Results (ref. 49)

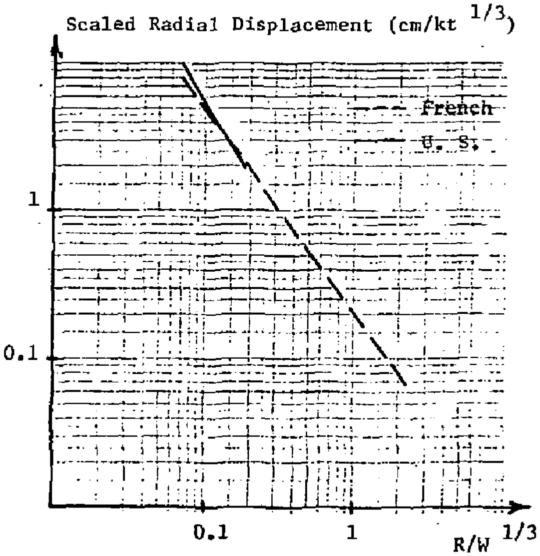


Figure 21: Scaled Displacement vs. Scaled Distance. Comparison of French and U.S. Results (ref. 49)

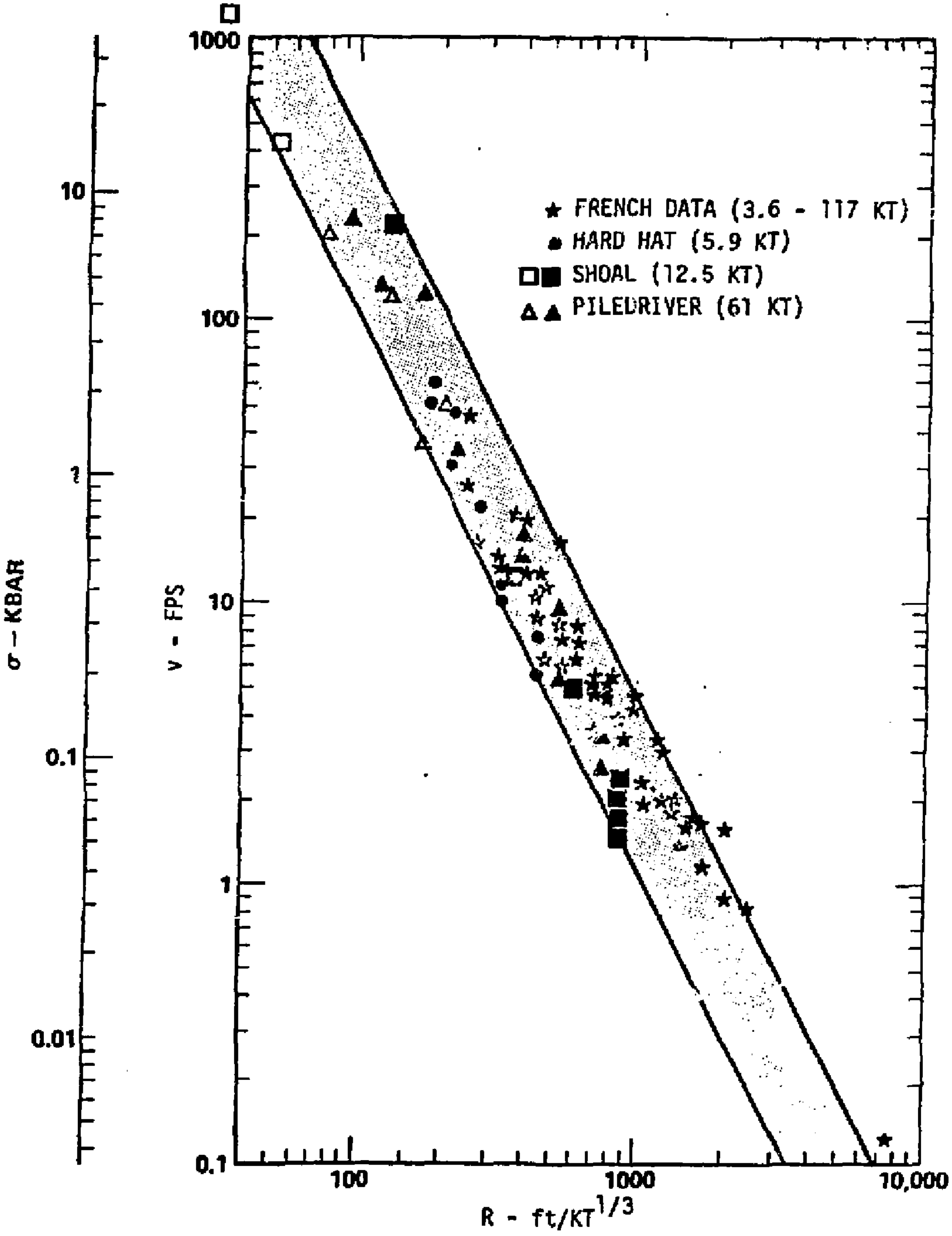


Figure 22: Scaled Peak Particle Velocity and Stress. Comparison of U.S. and French Tests in Granite (Cooper and Brode, 1973)

UNCLASSIFIED

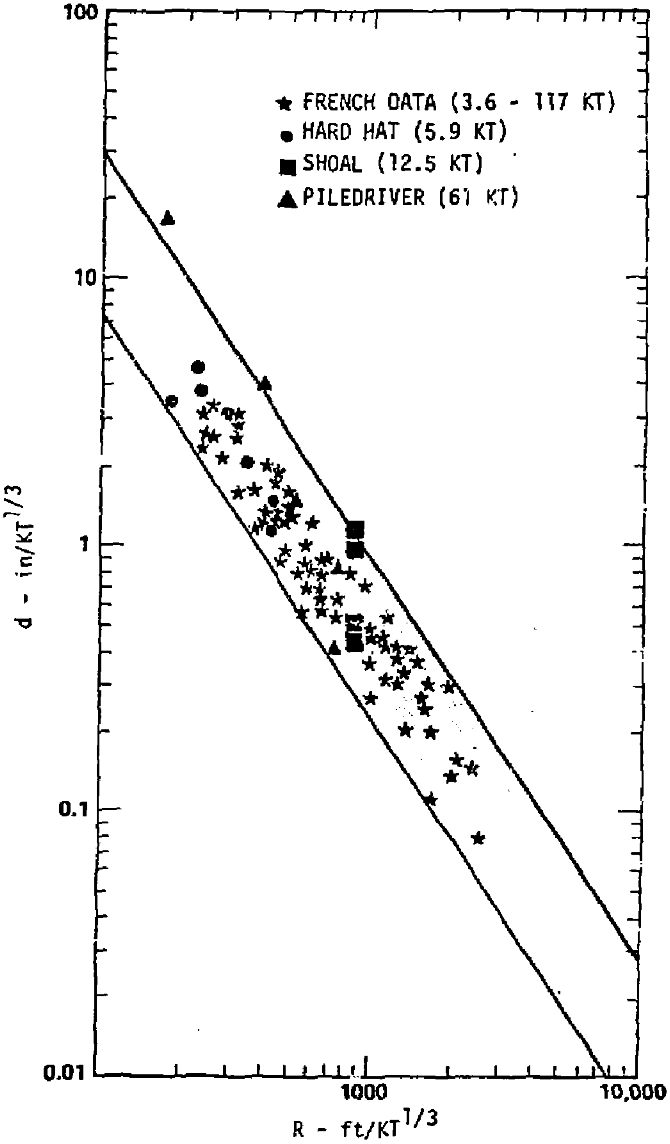


Figure 23: Scaled Peak Displacement. Comparison of U. S. and French Tests in Granite (Cooper and Brode, 1973)

UNCLASSIFIED

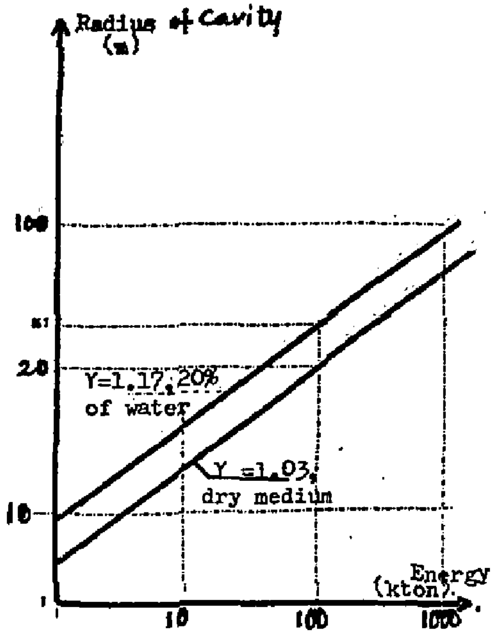


Figure 24: Code S Calculation of Cavity Radius vs. Yield, as Influenced by Water Content. The Event is 1500 m Deep. The C_s is 30 (ref. 75)

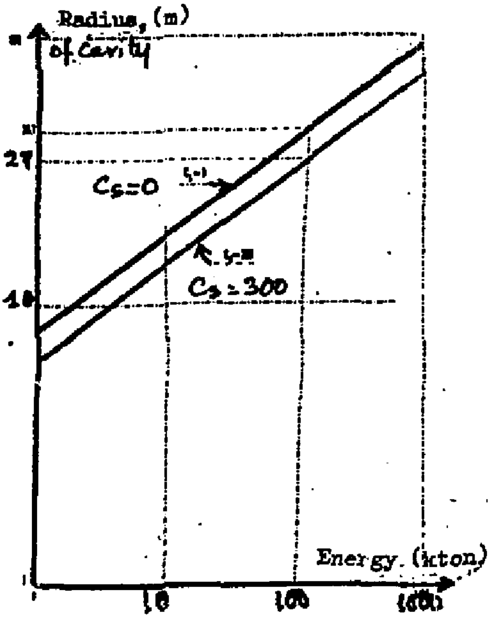


Figure 25: Code S Calculation of Cavity Radius vs. Yield, as Influenced by the Structure Coefficient C_s, for an Event 1500 m Deep in Dry Rock (ref. 75)

5. FRENCH REFERENCES

1. Albaret, A., and Duclaux, F., "Contenu Spectral des Mouvements Séismiques Dus Aux Explosions Nucléaires Souterraines", CEA-R-3767. 1969.

2. Audidière, P., Balard, F., Dupouy, J.O.,, and Van Kote, F., "The Distribution of Radioactivity in Lava from the Cavity of a Nuclear Explosion", UCRL-Trans-10574, 1971.

3. Barthoux, A., Fauré, J., Michaud, L., Nelson, P., and Roux, C., "Underground Storage Cavities Produced by Nuclear Explosions", UCRL-Trans (no number), 1972.

4. Barthoux, A., Cluchet, J., Gérard, R., and Hubert, M., "Scientific and Industrial Applications of Nuclear Explosions, Safety Problems", UCRL-Trans-10617-1, 1972.

5. Berger, J., "French Contribution to the Study of Peaceful Nuclear Explosions", 1970. Lawrence Livermore National Laboratory, Trans (no number), 1970

6. Boulon, M., and Gautier, J., "Etude de Synthèse sur les Dimensions des Cratères d'Explosion", CEA, CENG/ASP-69-18. 1969.

7. Biarez, J., Boulon, M., Gautier, J. and Perroud, P., "Etude de Synthèse sur les Dimensions Optimales des Cratères d'Explosions", CEA, CENG/ASP-70-20, 1970.

8. Boulon, M., and Gautier, J., "Integrated Study of Blast-Crater Dimensions, UCRL-Trans-10459, 1970.

9. Cohen, P., "Gases Formed in an Underground Nuclear Explosion - Chemical Equilibria and Potential Applications", UCRL-Trans-10616-1, 1972.

10. Cohen, P.,"The Radioactivity and Its Fractionation During Underground Nuclear Explosions in a Granite Medium", UCRL-Trans-10616-3, 1972.

11. Cohen, P., Dupuis, M., and Picq, S., "The Nuclear Explosive, A Potential Asset to the Chemical Industry", Energie Nucleaire. v. 10, n. 3, pp 224-230, UCRL-Trans-10372. 1968.

12. Combet, M., and Gerard, R., "Radiological Risks Relative to the Distribution of Contaminated Gas", UCRL-Trans-10617-2, 1972.

13. Commissariat à l'Energie Atomique, "Bulletin d'Informations Scientifiques et Techniques", v. 149, June, 1970. Contains six articles in French, on Peaceful Nuclear Explosions. Three of those are available separately in these files.

14. Commissariat à l'Energie Atomique, "Bulletin d'Informations Scientifiques et Techniques", v. 150, July-August, 1970. Contains eight articles in French, on Scientific and Industrial Applications of Nuclear Explosives. Two of these are available separately in these files.

15. d'Albissin, M., "Essai de Synthèse sur la Réaction des Cristaux et de leurs Agrégats aux Contraintes Mecaniques, *Revue de Géographie Physique et de Géologie Dynamique*, v. xl, n. 5, pp 533-558, 1969.

16. Delort, F., and Guerrini, C., "Dégâts Dus Aux Explosions Nucléaires Souterraines Sur les Habitations et les Equipements", *CEA-R-3749*, 1969.

17. Delort, F., and Supiot, F., "Nuclear Stimulation of Oil Reservoirs", ANS Symposium, January, Las Vegas, Nevada, *CONF-700101*, v. 1, pp 649-661, 1970.

18. Delort, F., "Dimensional Analysis for the Mechanical Effects of Some Underground Explosions", ANS Symposium, January, Las Vegas, Nevada, *CONF-700101*, v. 2, pp 1386-1405, 1970.

19. Derlich, S., "Métamorphisme de Choc dans les Cristaux de Quartz d'un Granite Soumis à une Explosion Nucléaire Souterraine", *C. R. Acad. Sci.*, Paris, v. 267, n. 7, Serie D, pp 681-683, 1968.

20. Derlich, S., "Methode D'Etude des Forages Réalisés Autour des Explosions Nucléaires Souterraines au Sahara", *CEA-R-3762* (1), 1969.

21. Derlich, S., and Supiot, F., "Phénomenologie Génerale des Explosions Nucléaires Souterraines", *CEA-R-3750*, 1969.

22. Derlich, S., "Explosions Nucléaires Souterraines, Effets sur des Ouvrages Dans le Granite", *CEA-R-4014*, 1970.

23. Derlich, S., "Study of a Chimney Created by an Underground Nuclear Explosion", *UCRL-Trans-10449*, 1969.

24. Derlich, S., "Underground Nuclear Explosion Effects in Granite: Rock Fracturing", ANS Symposium, January, Las Vegas, Nevada, *CONF-700101*, v. 1, pp 505-518, 1970.

25. Derlich, S., "Effects of an Underground Nuclear Explosion on the Surrounding Rock", *UCRL-Trans-10616-4*, 1972.

26. Derlich, S., "Underground Nuclear Explosions - A Study of the Zones of Fracturing", *UCRL-Trans-10617-3*, 1972.

27. Dessenne, J.L., Comes, G., Duffaut, P., and Gerard, P., "La Craie au Laboratoire et Dans un Tunnel Profond", *7th Int. Congress, Soil Mech. and Found. Eng.*, Mexico City, Preprint, 1969.

28. Duclaux, F., Derlich, S., Faure, J., Ferrieux, H., and Perrier, M., "Connection Between the Radius and the Duration of Existence of the Cavities Caused by Underground Nuclear Explosions", *UCRL-Trans-10145*, 1967.

29. Duclaux, F., Albaret, A., Ferrieux, H., and Perrier, M., "Etudes Séismiques Effectuées à l'Occasion des Tirs Nucleaires Souterrains Francais", *Ann. Geophys.*, v. 25, n. 3, pp 681-692, 1969.

30. Duclaux, F., and Michaud, L., "Experimental Conditions of French Underground Explosions in the Sahara, 1961-1966", *UCRL-Trans-10617-4*, 1972.

31. Dupuis, M., "Distribution and Evolution of Radioelements After a Nuclear Explosion", *UCRL-Trans-10617-5*, 1972.

32. Dupuis, M., and Humbert-Droz, C., "Forecasting the Radioactivity Levels Likely to Result from a Contained Explosion", *UCRL-Trans*, (no number), 1973.

33. Facca, G., and Pantanetti, F., "Esplosivi Nucleari ed Industria Mineraria", Italian National Committee for Nuclear Energy, 1963.

34. Faure, J., "Méthodes d'Etudes des Forages Realisés Autour des Experiences Nucléaires Souterraines au Sahara", *CEA-R-3762*, 1969.

35. Faure, J., "Explosions Nucleaires Souterraines, Etude Géologique des Cavités", *CEA-R-3779*, 1969.

36. Faure, J., and Ginglinger, B., "Determination Minéralogique aux Rayons X Sur des Echantillons de Granite Soumis à Une Explosion Nucléaire Souterraine", *C. R. Acad. Sci.*, Paris, v. 270, n. 6, Series D, pp 749-751, 1970.

37. Faure, J., and Ginglinger, B., "Analyse Chimique et Etude à la Microsonde Electronique d'Echantillons de Granite Soumis à Une Explosion Nucléaire Souterraine", *C. R. Acad. Sci.*, Paris, v. 270, n. 7, Series D., pp 901-903, 1970.

38. Faure, J., "Study of the Mineralogical Transformations of Granite by Underground Nuclear Explosions", ANS Symposium, Las Vegas, Nevada, *CONF-700101*, v. 2, pp 1406-1427, 1970.

39. Faure, J., "Underground Nuclear Explosions - A Study of the Mineralogical Transformations - Results from the Sahara Explosion Site", *UCRL-Trans-10617-6*, 1972.

40. Faure, J., "Research on Geologic Effects of Underground Nuclear Explosions in a Sahara Granite Massif", *UCRL-Trans-10615*, 3 volumes, 1972.

41. Ferrieux, H., "Effets Géomagnétiques d'Explosions Nucléaires dans la Basse Atmosphère", *C. R. Acad. Sc.*, Paris, v. 269, pp 659-660, Series B, 1969.

42. Ferrieux, H., "Compressional Seismic Waves Recorded During Underground Nuclear Explosion Tests in Hoggar", ANS Symposium, Las Vegas, Nevada, *CONF-700101*, v. 2, pp 1136-1149, 1970.

43. Ferrieux, H., "Ondes Séismiques de Compression Liées aux Explosions Nucléaires Souterraines du Sahara", *CEA-R-4105*, 1970.

44. Ferrieux, H., and Guerrini, C., "Mechanical Effects of a Contained Nuclear Explosion", in UCRL-Trans-10543, pp. 4-35, 1971.

45. Gaussens, J., "Economic Aspects of the Use of Nuclear Explosives for Civil Purposes". Comments on paper P/291 presented at Geneva by G.W. Johnson and G.H. Higgins. Energie-Chroniques, 1965.

46. Gautier, J., "Etudes Expérimentales et de Synthèse de l'Influence des Propriétés des Explosifs et des Caractéristiques Mecaniques des sols et des Roches Sur les Dimensions des Cratères", CEA-R-4242, 1971.

47. Gauvenet, A., "The French Experimentation at the Underground Nuclear Testing Site in the Sahara Desert", ANS Symposium, Las Vegas, Nevada, CONF-700101, v. 1, pp 240-244, 1970.

48. Gauvenet, A., "Etudes Réalisées en France sur les Applications Pacifiques des Explosions Nucléaires", IAEA Panel on Peaceful Uses of Nuclear Explosions, Vienna, 1970.

49. Guerrini, C., and Garnier, J., "Mouvement Materiel du Milieu Environnant une Explosion Nucléaire Souterraine", CEA-R-3885, 1969.

50. Habib, P., "A Study of Two Granites", UCRL-Trans-10617-7, 1972.

51. Lascar, A., and Valo, J., "Hugoniot of Sandstone", UCRL-Trans-10669, 1972.

52. Lascar, A., and Valo, J., "Hugoniot of Granite", UCRL-Trans-10670. 1970.

53. Lepitit, J.P., and Hariguillie, M., "Dépouillement Automatique des Relevés de Fonds sur Modèle Réduit Hydraulique", EDF Bulletin, n. 3, Serie A, pp 133-148, 1966.

54. Louis, C., "Etude des Ecoulements d'Eau dans les Roches Fissurées, et de leur Influences sur la Stabilité des Massifs Rocheux", EDF Bulletin, n. 3, serie A, pp 1-131, 1968.

55. Maury, J., and Levret, C., "Physics of the Phenomena in the Close-In Zone Around Underground Nuclear Explosions", UCRL-Trans-10617-8, 1972.

56. Maury, J., "Code S Calculation of the Effects of Contained Underground Explosions", UCRL-Trans-10617-9, 1972.

57. Maury, V., "Mecanique des Milieux Stratifiés", Dunod, Paris, 1970.

58. Michaud, L., "Explosions Nucleaires Souterraines, Etudes des Rayons de Cavité", CEA-R-3594, 1968.

59. Michaud, L., "Mechanical Effects in the Close-In Zone of an Underground Nuclear Explosion in Granite", UCRL Trans-10616-5, 1972.

60. Michaud, L., "Mechanical Effects Beyond the Close-In Zone of an Underground Nuclear Explosion in Granite", UCRL-Trans-10616-2, 1972.

61. Moreau, E., "Methodes Numériques et Usage Industriel de L'Explosif Nucléaire", IAEA Panel on Peaceful Uses of Nuclear Explosions, Vienna, IAEA-PL-388/6, 1970.

62. Panet, M., "Quelques Problèmes de Mecanique des Roches Posés par le Tunnel du Mont-Blanc", Bull. Liaison Labo. Routiers P. et Ch., n. 42, 1969.

63. Panet, M., and Caracilli, J., "Les Vibrations Produites par les Tirs d'Explosifs", Bull. Liaison Labo. Routiers P. et Ch., n. 38, 1969.

64. Perrier, M., "Activité Mecanique au Sein d'un Massif Granitique Ebranlé par une Explosion Nucléaire", CEA-R-4059, 1970.

65. Perroud, P., et al., "Etude Expérimentale des Effects d'Explosifs Chimiques dans des Sols: Cratères, Tranchées et Phenomènes Associés", CENG/ASP No. 69-12, 1969.

66. Picq, J., "Study of Chemical Reactions in the Nuclear Underground Explosion - Incidence on Radioactivity", ANS Symposium, Las Vegas, Nevada, CONF-700101. v. 1, pp 850-858, 1970.

67. Riffault, "Catalogue des Caracteristiques Géologiques et Mecaniques de Quelques Roches Françaises", Laboratoire Central des Ponts et Chaussées, 1969.

68. Rollin, F., and Delort, F., "Volume de Stockage Créé Par Une Explosion Nucléaire Souterraine Contenue", CEA-R-4096, 1971.

69. Rougeron, C., "L'Explosion Thermonucléaire et les Travaux Souterrains", Attachment to a letter addressed to Edward Teller, Science et Vie, October, 1958.

70. Rougeron, C., "L'Elimination des Residus Radioactifs des Explosions Nucléaires Souterraines", unlabeled article, 1958.

71. Rougeron, C., "Underground Nuclear Explosion in an Empty Chamber", Unlabeled article, 1958.

72. Rougeron, C., "Une Pile Atomique Géante à 600 m Sous le Hoggar", Science et Vie, December, 1960.

73. Rougeron, C., "Underground Explosions - Plutonium and Nuclear Arms", UCRL-Trans-663 (L).

74. Roy, J.R., "The Thermonuclear Bulldozer Will Soon Be in Use", Le Jeune Scientifique, pp 36-41, November 1966, R. Adis Translation, 1967.

75. Supiot, F., "Mechanical Effects of Contained Underground Nuclear Explosions", UCRL Trans-10617-10, 1972.

76. Supiot, F., and Brugies, J., "Calculation of the Shock Wave in the Close-In Zone of an Underground Nuclear Explosion (Cades Method), UCRL-Trans-10617-11, 1972.

77. Therene, J., "Evolution du Programme Français sur les Explosions Nucleaires à des Fins Pacifiques", IAEA-PL-429/12, 1971.

78. Tourenq, C., and Denis, A., "La Resistance à la Traction des Roches", Lab. Central P. et Ch., Rapport de Recherches, No. 4, Feb., 1970.

6. U.S. REFERENCES

Bass, R.C., Hawk, H.L. and Chabai, A.J. (1963) "Hugoniot Data for Some Geologic Materials", SC-4903.

Boardman, C.R. (1967) "Results of an Exploration Into the Top of the Piledriver Chimney", Lawrence Livermore National Laboratory, UCRL-50385.

Boardman, C.R., Rabb, D.D., and McArthur, R.D. (1964) "Responses of Four Rock Mediums to Contained Nuclear Explosions", J. Geophys. Res., v. 69, n. 16, pp 3457-3469.

Borg, I.Y. (1970) "Survey of Piledriver Results, and Preliminary Interpretation of Three Postshot Cores in and Near the Cavity", Lawrence Livermore National Laboratory, UCRL-50865.

Borg, I.Y. (1973) "Comparison of Shock Effects in Granitic Rock Recovered from the Monique Event, Algeria, and the Piledriver Event, Nevada Test Site", Lawrence Livermore National Laboratory, UCRL-51349.

Cooper, H.F. Jr., and Brode, H.L. (1973) "Ground Motion and the Survivability of Deep Underground Superhard Facilities (U)", R and D Associates, Marina del Rey, CA., RDA-TR-128-DNA, (Secret-RD).

Maldonado, F. (1977) "Summary of the Geology and Physical Properties of the Climax Stock, Nevada Test Site", U.S. Geological Survey, Open File Report 77-356.

McQueen, R.G., Marsh, S.P. and Fritz, J.N. (1967) "Hugoniot Equation of State of Twelve Rocks", J. Geophys. Research, v. 72, p 4999, October.

Peet, W.E. (1960) "A Shock Wave Theory for the Generation of the Signal Around a Spherical Shot Hole", Geophysical Prospecting, v. 8, pp 509-532.

Sauer, F.M., Clark, G.B., and Anderson, O.D. (1964), "Empirical Analysis of Ground Motion and Cratering", DASA 1285.

Schock, R.N., Abey, A.E., Heard, H.C., and Louis, H. (1973) "Mechanical Properties of Granite Samples from the Taourirt Tan Afella Massif, Algeria", Lawrence Livermore National Laboratory, UCRL-51296.