LAWRENCE LIVERMORE LABORATORY
University of California/Livermore, California/94550

UCRL-51171

**FRENCH-AMERICAN TECHNICAL EXCHANGE
OF GEOLOGIC INFORMATION RELATED TO
PEACEFUL USES OF NUCLEAR EXPLOSIVES**

D. R. Stephens

MS. date: January 11, 1972

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

Contents

Abstract	1
Introduction	1
Technical Summary	2
Agenda	2
Rock Mechanics	3
Calculations	3
Field Data	4
Geochemistry	8
Conclusions and Future Work	9
Acknowledgments	9
References	10
Appendix A. U. S. Proposed Agenda for the U. S.-French Exchange Meeting	11
Appendix B. Reports Exchanged	12
Appendix C. Samples Exchanged	15
Appendix D. List of Participants	16
Appendix E. Program	18
Appendix F. Statement on A French-U. S. Exchange of Geological Information Related to Peaceful Nuclear Explosions	20

FRENCH-AMERICAN TECHNICAL EXCHANGE OF GEOLOGIC INFORMATION RELATED TO PEACEFUL USES OF NUCLEAR EXPLOSIVES

Abstract

The French-American technical exchange of geologic information related to peaceful uses of nuclear explosives was held in Berkeley, California, from October 26-29, 1971. Topics discussed included rock sample selection and testing, numerical calculations, field data collection and interpretation, and geochemical data and interpretation. The results of the 13 French underground detonations in Hoggar granite were extensively discussed along with the U. S. Pile-

driver, Gasbuggy and proposed Wagon Wheel experiments. Reports and new information were exchanged; the French furnished Hoggar granite samples to the U. S. for study and the U. S. gave Wagon Wheel sandstone samples to the French for examination.

The meeting participants concluded that another meeting would be beneficial to each country's program. At which time the U. S. would discuss the Hoggar granite results and the French their Wagon Wheel studies.

Introduction

The French-American technical exchange of geologic information related to peaceful uses of nuclear explosives was held in Berkeley, California, October 26-29, 1971.

Unlike the USA and USSR, the French have not conducted any PNE experiments; however, during the period 1961-1966 the French detonated 13 underground nuclear explosions in the Taourirt Tan Afella granite intrusive in what was then French Algeria (Fig. 1). These were military experiments, but were also studied from a flowshare point of view as part of the CRA APEX (Applications des explosions) program. The French reported on some of the results of this study at the 1970

American Nuclear Society meeting in Las Vegas, and in the IAEA meetings in Vienna in 1970 and in Geneva in 1971. The results were quite different from the U. S. granite shots.

The French-American technical exchange arose out of a desire to exchange U. S. rock samples and French granite samples for testing, and also a need for a technical meeting whereby some of the unusual features of the French data could be described in greater detail.

Appendix A shows the proposed U. S. agenda of the technical discussions which consisted of four parts: rock sample selection and testing program, calculational interpretation, field data collection

Fig. 1. French test site, Taourirt Tan Afella.

and interpretation, and geochemical data and interpretation. Appendix B presents a list of reports exchanged. The samples which were exchanged are listed in Appendix C. The primary French interest in nuclear applications is in gas storage and hydrocarbon

stimulation^{1,2} and to them the most interesting U.S. experiment is Wagon Wheel, a proposed stimulation experiment; hence their request for these sandstones. The list of French and U.S. attendees to the meeting is given in Appendix D.

Technical Summary

AGENDA

On Tuesday, October 26, the French delegation was welcomed by Roger Batzel,

LLL and Carl Gerber, USAEC. A tentative agenda based on the U. S. proposal was drawn up, starting with rock mechanics, followed by calculations, field data

collection and interpretation and chemistry. An attempt was made to alternate French and U. S. talks. As the meeting proceeded, the subjects were not always given in order nor were talks always alternated. The final program as actually given is shown in Appendix E.

ROCK MECHANICS

Properties of the Taourirt Tan Afella (also called Hoggar) granite are shown in Table 1.^{1,3} Failure envelope data⁴ are given in Table 2. The rock has been described as remarkably homogeneous.¹ Some Hugoniot data have been reported⁵; however, reliable data below 320 kbar are not available at present. Andre Lascar, CEA, presented some preliminary Hugoniot data at low pressures; the Hugoniot elastic limit is reported to be 42 kbar. He will send us his data when his studies are completed.

In comparing the French rock mechanics measurements with ours, we find that of our five experiments the French conducted two—the failure envelope and the Hugoniot equation of state. In addition to these, we measure acoustic velocities as a function of pressure, the pressure-volume hydrostat, and three-dimensional stress-strain measurements. However, what we now know about Hoggar granite suggests that it is quite similar to Pile-driver and Hardhat granite; its strength properties are almost exactly the same.

CALCULATIONS

The French have reported two techniques for calculating shock effects in rock: the CADES code, an analytical cal-

Table 1. Properties of the granite of Taourirt Tan Afella.

<u>Mineralogical analyses</u>			
Quartz	35%	Chaye's	index 64
Microcline	37%		
Plagioclase	25%		
Biotite	2.1%		
Muscovite	0.6%		
<u>Chemical analyses</u>			
SiO ₂	75.80%	K ₂ O	4.79%
Al ₂ O ₃	12.49%	TiO ₂	0.08%
Fe ₂ O ₃	1.30%	P ₂ O ₅	0.01%
MnO	0.04%	CO ₂	0.13%
MgO	0.03%	H ₂ O ⁺	0.48%
CaO	0.59%	H ₂ O ⁻	0.06%
Na ₂ O	3.80%		
<u>Physical properties</u>			
Density	2.63		
Young's modulus		710-930 kbar	
Poisson's ratio (calculated from laboratory-determined seismic velocities)		0.30-0.38	
Tensile strength		40-50 bars	
Compressive strength		2.0 kbar	
<u>Acoustic velocities</u>			
Compressional wave			
In situ measurement		5.85 km/sec	
Laboratory measurement		5.50 km/sec	
Shear wave			
In situ measurement		3.23 km/sec	
Laboratory measurement		2.40 km/sec	
Porosity:	0.3%		
Permeability:	Almost zero		
In situ temperature:	30°C		

ulation valid in the shock region, and code S^{5,6} which is the U. S. SOC code. Henri Ferrieux, CEA, presented calculations of time of arrival, particle velocity and peak pressure for the Hoggar shots

Table 2. Summary of triaxial compressive tests, Hoggar granite.

Samples	σ_1 (bars)	σ_3 (bars)	τ (bars)	P_m (bars)
Core	2,000	0	1,000	670
Core	1,970	0	985	655
Core	2,140	0	1,070	715
Core	5,300	245	2,530	1,930
Core	7,540	490	3,480	2,820
Core	9,450	1,000	4,225	3,820
Core	12,500	2,000	5,250	5,500
Core	15,550	3,000	6,275	7,170
Core	18,350	4,000	7,175	8,790
Core	21,100	5,000	8,050	10,370
Block	1,500	0	750	500
Block	4,150	245	1,950	1,545
Block	6,350	490	2,930	2,440
Block	8,650	810	3,920	3,420
Block	12,500	2,000	5,250	5,500

and compared them to the experimental data. Agreement was fair; better than the calculation reported in Ref. 5 which also presents French calculations of the Gasbuggy experiment. The French calculational techniques are very similar to those of the U. S. which is, of course, not surprising since they used a U. S. code. One interesting difference is that the French allowed only tensile failure; not, as in the U. S. versions, shear and tensile failure.

In discussing the calculations, the principal difference between the French and the U. S. granite field data is in the smaller cavity radii in French granite— $R_c = 7.3 W^{1/3}$ m in the Hoggar versus $11.2 W^{1/3}$ m in the U. S. This is all the more surprising since the U. S. and French granite media seem to have very similar mechanical properties. Both the

French^{5,6} and U. S.^{7,8} calculational groups are successful in calculating Hoggar phenomenology, while the U. S. granite shots (Hardhat, Shoal and Piledriver) have not been successfully calculated using the physical properties measured in the laboratory; the strength of the rock must be drastically reduced to fit the observed cavity radii. This very important problem was not resolved at this meeting.

FIELD DATA

The French report the following radii as deduced from field tests^{1,5}:

Cavity radius	$R_c = 7.3 W^{1/3}$, m
Pulverized zone	$R_p = 10 W^{1/3}$, m
Fractured zone	$R_f = 26 W^{1/3}$, m
Residual stress	$R_r = 36 W^{1/3}$, m

They report chimney heights of about $3.5 R_c$ with the geometry shown in Fig. 2.

Fig. 2. Drill hole exploration of a chimney.

The drill holes and geometry inferred from them in Fig. 2 are a composite of several shots scaled to the same yield. On the average, the French drilled just one or two postshot holes per event.

The French "pulverized" zone corresponds to the U. S. "crushed" zone, while the "fractured" zones appear to be identical. When scaled to cavity radius, these French zones appear to be similar to the U. S. results.⁹

The French equation for cavity radius is¹⁰

$$R_c = 52 \frac{W^{1/3}}{(\rho g h + C_s)^{1/37}},$$

C_s = tensile strength of medium in bars, and

γ = adiabatic gas expansion coefficient.

Since this equation was fit to the French experiments, it of course predicts smaller cavity radii than U. S. equations.

The French have developed a relationship between cavity radius and cavity collapse time which worked quite well for the Hoggar shots¹¹; it is $R = 0.8t + 3$, where R is cavity radius in meters and t is collapse time in minutes.

Scaled free-field data, including shock-wave time of arrival, particle velocity, acceleration and displacement have been reported by Delort¹⁰ and Michaud.¹² The reported velocity data in Refs. 10 and 12 included data from a nontypical classified experiment which resulted in data far different from the rest of the detonations.

Elimination of these data from the least-squares-fit analysis resulted in

$V_p = 0.132 R^{-1.596}$, where V_p is particle velocity in m/sec and R is scaled range, $0.1 < R < 1$ in km/ $W^{1/3}$. These data are

in much closer agreement with the calculations made by Terhune⁸; all are scaled to 1 kt. In addition, Michaud⁶ presented actual (unscaled) free-field data for four French shots: Georgette, Michele, Monique and Carmen.⁵ Table 3 gives pertinent data on the yield of these events, and Figs. 3-6 show the free-field data.

Pierre Cohen, CEA, described their method for determination of cavity radius; they used temperature logs and the ratio of volatile radioactivities of refractories in recovered cores, for example $^{131}I/^{95}Zr$, to define the boundary (Fig. 7).

Gross γ and core examination were less

Table 3. General characteristics of the underground nuclear explosions, Georgette, Michele, Monique, and Carmen.

	Georgette	Michele	Monique	Carmen
Energy (kt)	13	3.6	117	15.4
Volume of detonation chamber (m^3)	58.5	125	66.7	52
Equivalent radius of detonation chamber (m)	2.4	3.1	2.5	2.3
Vertical depth (m)	403	353	785	635
Distance to nearest point on the surface of the massif "normal" (m)	320	305	645	585
Displacement from the "normal" (m)	>2.4	1.5	4.5	0.54
Initial velocity of displacement from the "normal" (m/sec)	8	6.5	9.5	2.8
Cavity collapse time				
Initial (min)	H + 16	H + 6	H + 46	H + 17
Duration (min)	4	3	1	1
Cavity radius (m)	17	10.2	39	20
Radii of zone				
Pulverized (m)	23	14	45.6	—
Fractured (m)	62	39	—	—
Residual stress (m)	79	63	—	—

greater than the U.S. range of 700-1000 tons/kt.

The French have also presented temperature models to fit their Hoggar data.⁵ The COTHERM code was used, for example, to calculate the temperature history of a nuclear explosion in granite; a sphere of $1.3 R_c$ was assumed to be initially at 600°C . They could not fit the Shoal data to this model; they had to assume a hemisphere of $1.0 R_c$ at 600°C . Again, the differences in the French and

Fig. 3. Radial acceleration versus range.

Fig. 4. Particle velocity versus range.

Fig. 5. Radial deformation versus range.

Fig. 6. Displacement versus range.

U.S. data are very real. Certainly the model they assumed for Shoal was not realistic.

Fig. 7. Determination of cavity boundary.

Seismic studies have been made by the French^{5,13,14} and, like the Russians but unlike the U. S., their damage criteria appear to be based only on particle velocity.

A reentry plan was described for the Carmen Event.⁵ The emplacement drift

Table 4. Gas evolution from the Carmen event (steam and air removed).

	Experimental	Calculated
Gas composition (%)		
H ₂	52.6	49.2
CO	10.3	7.9
CO ₂	36	42.8
CH ₄	0.9	0.018
Vol/kt (m ³)	2600	2250

ended in a spiral for shock closure and "airtight" blast doors were installed in the drifts, yet radioactivity and combustible gases were detected outside the doors, within the drifts, and on the surface of the massif. Air was blown into the top of the drifts and pulled out at the bottom to remove the explosive and radioactive gases. Gases in the drifts were sampled by rubber tubing leading out to the entry portal where manual valves were operated to collect the samples. Their experience was similar to ours in that radioactive gases were sometimes collected, sometimes only inert gases were obtained, and sometimes no sample was obtained. The chemical composition of Carmen gas (free of air and steam) is given in Table 4.

In summary, their field data program was very thorough. They have obtained and interpreted much more data than the U. S. has on granite, and these data should be of considerable benefit to the U. S. Flowshare Program.

GEOCHEMISTRY

The French reported very detailed studies of their explosion-produced glasses^{5,15}; e.g., using autoradiography

they found a homogeneous distribution of α emitters and a heterogeneous distribution of β and γ . The last two emitters tend to accumulate at the surface of bubbles.

Pierre Cohen reported fission product volatilities in the following order, which is also consistent with U. S. experience: $^{131}\text{I} > ^{137}\text{Cs} > ^{129-132}\text{Te} > ^{90}\text{Sr} = ^{127}\text{Te} > ^{103,106}\text{Ru} > ^{99}\text{Mo} > ^{91}\text{Y} > ^{141}\text{Ce} > ^{95}\text{Zr} > ^{143}\text{Pr} > ^{147}\text{Nd} = ^{144}\text{Ce}$.

Activation (^{37}Ar , ^{45}Ca) products were calculated using a method reported by Batzel,¹⁶ and agreement was found within a factor of two.

New minerals have been found in the shocked rock. These include sanidine, one of the high-temperature polymorphs of potassium feldspar, and low cristobalite, one of the high-temperature forms of SiO_2 .³

Gas compositions were calculated based on the escape of the volatile components of the melted rock and compared to the gas concentrations obtained postshot (Table 4) from Carmen.^{5,17} Agreement between observation and calculation was good if equilibrium was assumed to be frozen at 1300°C and 200-bar pressure. Gas evolution with time has also been reported.⁵ By radioactive puddle integration and gas analytical techniques, they have reported that 30-70% of residual tritium was retained in the melt, while ^{85}Kr was retained much less.⁵ Picq¹⁵ has also performed laboratory experiments on gas evolution from preshot and melt samples, and these data compare well to calculations and postshot gas evolution from nuclear explosives. They want to make estimates of the chimney gas composition for nuclear applications in hydrocarbon-bearing rock.

In summary, their radiochemistry studies appear similar to ours, though somewhat simpler in interpretation. The French puddle glass and gas evolution

studies appear to be very thorough. Their number for tritium retention in the melt seems to be the only direct measurement of this very important parameter.

Conclusions and Future Work

The participants of the meeting, both French and American, concluded that another meeting would be highly beneficial to each country's program. The U. S. will be prepared to discuss their experimental rock mechanics data on the Hoggar granite samples furnished by the French, and could also discuss calculation of the nuclear explosion phenomenology of the French shots using these data. The French proposed to discuss their rock mechanics measurements on the Wagon Wheel samples furnished by the U. S. and their calculations of Wagon Wheel phenom-

enology. The French also expressed an interest in making some chemical equilibria and seismic effects calculations and predictions of radioactivity for Wagon Wheel. Leo Rogers stated on behalf of El Paso Natural Gas Co. that he welcomed such an interaction with the CEA APEX group.

This discussion ended with the agreement that the CEA would communicate with the USAEC stating their position on the possibility of such a future meeting and its proposed agenda. The communiqué issued at the close of the meeting is given in Appendix F.

Acknowledgments

I have benefitted from discussions with many of the LLL attendees to this French exchange. In particular I wish to thank Milo Nordyke, Robert Taylor, Robert

Terhune, Iris Borg, Hugh Heard, Larry Schwartz, Charles Smith, and Robert Schock for valuable suggestions that were incorporated into this report.

References

1. S. Derlich, "Underground Nuclear Explosion Effects in Granite Rock Fracturing," Proc. Engineering with Nuclear Explosives (Am. Nucl. Soc., 1970), vol. 1, p. 505.
2. J. Berger, private communication.
3. J. Fauré, "Study of the Mineralogical Transformations of Granite by Underground Nuclear Explosions," Proc. Engineering with Nuclear Explosives (Am. Nucl. Soc., 1970), vol. 2, p. 1406.
4. P. Habib, Etude de Deux Granites (1965).
5. J. Berger, Contribution Francoise a L'Etude des Explosions Nucleaires Pacifiques (August 25, 1970).
6. L. Michaud and J. Maury, "Effets Mecaniques en Zone Proche D'Une Explosion Nucleaire Souterraine Dans Le Granite," Proc. Peaceful Nuclear Explosions (IAEA, 1970) p. 139.
7. J. T. Cherry, quoted in H. C. Rodean, An Energy Approach to Seismic Coupling Analysis, Lawrence Livermore Laboratory, Rept. UCRL-72633 (1971).
8. R. W. Terhune, Prediction of Underground Nuclear Explosion Effects in Wagon Wheel Sandstone, Lawrence Livermore Laboratory, Rept. UCRL-50993 (1971).
9. L. Y. Borg, Some Shock Effects in Granodiorite to 270 kbar at the Piledriver Site, Lawrence Livermore Laboratory, Rept. UCRL-73377 (1971).
10. F. Delort, "Dimensional Analysis for the Mechanical Effects of Some Underground Explosions," Proc. Engineering with Nuclear Explosives (Am. Nucl. Soc., 1970), vol. 2, p. 1386.
11. F. Duclaux, S. Derlich, J. Fauré, H. Ferrieux, and M. Perrier, "Liaison entre le Rayon et al'Durre d'Existence des Cavities Creees par les tirs Nucleaires Souterrains," Comp. Rend. Acad. Sci. Paris B264, 496 (1967).
12. L. Michaud, "Effets Mechaniques au-Dela de la Zone Proche d'Une Explosion Nucleaire Souterraine dans le Granite," Proc. Peaceful Nuclear Explosions (IAEA, 1970), p. 151.
13. H. Ferrieux, "Compressional Seismic Waves Recorded During Underground Nuclear Explosion Tests in Hoggar," Proc. Engineering with Nuclear Explosives (Am. Nucl. Soc., 1970), vol. 2, p. 1136.
14. F. Delort and C. Guerrini, Degats dus Aux Explosions Nucleaires Souterraines sur les Habitations et les Equipements, Rapport CEAR-3749 (1969).
15. J. M. Picq, "Study of Chemical Reactions in the Nuclear Underground Explosion-Incidence on Radioactivity," Proc. Engineering with Nuclear Explosives (Am. Nucl. Soc., 1970), vol. 1, p. 850.
16. R. E. Batzel, "Radioactivity Associated with Underground Nuclear Explosions," J. Geophys. Res. **65**, 2897 (1960).
17. P. Cohen, M. Dupuis, and J. M. Picq, "L'Explosif Nucleaire, Atout Potentiel pour l'Industrie Chimique," Energy Nucleaire **10**, 224 (1968).

Appendix A

U.S. Proposed Agenda for the U.S.-French Exchange Meeting

Rock Sample Selection and Testing Program

A discussion of the samples being exchanged, including their size; the reason they were selected; the types of tests that are planned; and the interpretation of such tests that are required.

Calculational Interpretation

A discussion of the types of codes available which requires the use of such rock testing data; the methodology and physics assumptions used in these codes; the results of calculating several key explosions; comparison of theoretical results with experimentally measured shock to be obtained.

Field Data Collection and Interpretation

A discussion of the preshot site documentation typical of PNE-type events and the postshot exploration program including the methods of drilling, logging, and testing holes; laboratory studies of samples; and methods of geological interpretation of such items as cavity radius, chimney configuration, and fracture zones.

Geochemical Data and Interpretation

A discussion of the chemistry and radiochemistry data generally obtained as it is related to the geological properties of the explosion sites; the observed distributions of radionuclides; and the high-temperature chemistry and thermodynamic interpretation models used to explain the observed phenomena.

Appendix B

Reports Exchanged

U. S. REPORTS SENT TO FRENCH

Rock Sample Selection and Testing Program

- D. Stephens et al., Pressure-Volume Equation of State of Consolidated and Fractured Rocks to 40 kbar, Lawrence Livermore Laboratory, Rept. UCRL-71238 (1969).
- A. Duba and R. Schock, Static Determination of the Deformational Properties of Solid Materials with Pressure, Lawrence Livermore Laboratory, Rept. UCRL-50852 (1970).
- R. Schock et al., High-Pressure Mechanical Properties of Rocks from Wagon Wheel No. 1, Pinedale, Wyoming, Lawrence Livermore Laboratory, Rept. UCRL-50863 (1970).

Calculational Interpretation

- J. Cherry et al., Numerical Simulation of Stress Wave Propagation from Underground Nuclear Explosions, Lawrence Livermore Laboratory, Rept. UCRL-72216 (1970).
- J. Cherry et al., Two Dimensional Stress-Induced Adiabatic Flow, Lawrence Livermore Laboratory, Rept. UCRL-50987 (1970).
- C. Sisemore and R. Stefani, Rock Fracture Measurements: A New Use for Time Domain Reflectometry, Lawrence Livermore Laboratory, Rept. UCRL-72632 (1970).
- D. Larson and C. Sisemore, A Peak-Stress Gauge for Determining the Yield of Underground Nuclear Detonations, Lawrence Livermore Laboratory, Rept. UCRL-71115 (1968).
- R. Terhune, Prediction of Underground Nuclear Explosion Effects in Wagon Wheel Sandstone, Lawrence Livermore Laboratory, Rept. UCRL-50983 (1971).

Field Data Collection and Interpretation

- L. Borg, Survey of Piledriver Results and Preliminary Interpretation of Three Postshot Cores In and Near the Cavity, Lawrence Livermore Laboratory, Rept. UCRL-50865 (1970).
- D. Rawson et al., Postshot Geologic Investigations—Project Gasbuggy, Lawrence Livermore Laboratory, Rept. UCRL-71354 (1968).
- I. Borg, Microfracturing in Postshot Gasbuggy Core GB-3, Lawrence Livermore Laboratory, Rept. UCRL-50893 (1970).
- T. Butkovich and A. Lewis, Aids for Estimating Effects of Underground Nuclear Explosions, Lawrence Livermore Laboratory, Rept. UCRL-50929 (1970).

Geochemical Data and Interpretation

- R. Taylor et al., Interpreting the Chemical Results of the Gasbuggy Experiment, Lawrence Livermore Laboratory, Rept. UCRL-72112 (1969).
- C. Smith, The Behavior of Radionuclides in Nuclear Gas Stimulation Techniques, Lawrence Livermore Laboratory, Rept. UCRL-72152 (1969).
- E. Catalano, Comments on Some of the Physical Chemical Questions Associated with the Analysis of Water in Earth Materials, Lawrence Livermore Laboratory, Rept. UCRL-50630 (1969).
- G. Werth et al., The Handcar Nuclear Explosion in Dolomite, Lawrence Livermore Laboratory, Rept. UCRL-50951 (1970).
- A. Edwards and R. Holzman, Thermal Effects of Nuclear Explosion in Salt—The Salmon Experiment, Lawrence Livermore Laboratory, Rept. UCRL-70436 (1969).

FRENCH REPORTS SENT TO U. S.

- S. Derlich and F. Suptot, Phénoménologie générale des explosions nucléaires souterraines, Rapport CEA R.3750 (1969).
- F. Duclaux and L. Michaud, "Conditions expérimentales des tirs nucléaires souterrains français au Sahara 1961-1966," Comp.-Rend. Acad. Sci. 270, 189 (1970).
- F. Suptot, "Effets mécaniques des explosions nucléaires souterraines contemues. Applications scientifiques et industrielles des explosifs nucléaires," Bull. Infor. Sci. Tech. (Paris) 149, 17 (1970).
- L. Michaud, Explosions nucléaires souterraines Etudes des rayon de cavité, Rapport CEA R. 3594 (1968).
- F. Suptot and J. Brugies, Calcul de l'onde de choc en zone proche d'une explosion nucléaire souterraine (méthode CADES), Rapport CEA R. 3736 (1969).
- J. Maury and C. Levret, Physique des phénomènes en zone proche des explosion nucléaires souterraines, Rapport CEA R. 3850 (1969).
- J. Maury, Code S. Calcul des effets des explosions souterraines contemues. Première partie: méthode de calcul, Rapport CEA R. 3957 (1970).
- S. Derlich, "Métamorphisme de choc dans les cristaux de quartz d'un granite soumis à une explosion nucléaire souterraine," Comp.-Rend. Acad. Sci. 267, 681 (1968).
- S. Derlich, Méthodes d'étude des forages réalisés autour des explosions nucléaires souterraines au SAHARA. Première partie: Etude des échantillons de roche, Rapport CEA R. 3762 (1969).
- J. Faure, Méthodes d'études des forages réalisés autour des explosions nucléaires souterraines au SAHARA. Deuxième partie: techniques d'étude de la paroi des forages, Rapport CEA R. 3762 (1969).
- J. Faure, Explosions nucléaires souterraines. Etude géologique des cavités, Rapport CEA R. 3779 (1969).
- S. Derlich, Etude de la cheminée créée par une explosion nucléaire souterraine, Rapport CEA R. 3851 (1969).

- J. Fauré and B. Ginglinger, "Déterminations minéralogiques aux rayons X sur des échantillons de granite soumis à une explosion nucléaire souterraine," Comp.-Rend. Acad. Sci. 270, 749 (1970).
- J. Fauré and B. Ginglinger, "Analyses chimiques et études à la microsonde électronique d'échantillons de granite soumis à une explosion nucléaire souterraine," Comp.-Rend. Acad. Sci. 270, 901 (1970).
- J. Fauré, "Etude des transformations minéralogiques de granite soumis à des explosions nucléaires souterraines, Bull. Infor. Sci. Tech. (Paris) 150, p. 37 (1970).
- S. Derlich, Explosions nucléaires souterraines: études des zones fracturées, Rapport CEA R. 3841 (1970).
- J. Fauré, Explosions nucléaires souterraines. Etude des transformations minéralogiques. Résultats du champ de tir saharien, Rapport CEA R. 3980 (1970).
- S. Derlich, Explosions nucléaires souterraines. Effets sur des ouvrages dans le granite, Rapport CEA R. 4014 (1970).
- J. Fauré, Recherches sur les effets géologiques d'explosions nucléaires souterraines dans un massif de granite saharien, These de Doctorat es Sciences Naturelles, Université de Nancy (1970).

Appendix C

Samples Exchanged

Samples sent to the French:

Sandstones from hole Wagon Wheel No. 1; depths 10,178 ft and 10,228 ft.

Samples sent to the U. S.:

Granite from hole P71, Taourirt Tan Afella, at depths, 20, 50, 70, 100, 120, 150, 170, 200, 220, 250, 270, 300, 320, 350, 370, 400, 420, 450, 480, 500, 520, 550, 570, 600, 620, 650, 670, 700, 720, 750 m.

Appendix D

List of Participants

Tuesday, October 26

U. S.

Albert Abey, LLL
Roger Batzel, Associate Director for
Chemistry and Biomedical
Research, LLL
Iris Borg, LLL
Carl Gerber, AEC, Washington, D. C.
Willard Hannon, LLL
Hugh Heard, LLL

Joseph Hearst, LLL
Joseph Landauer, LLL
Leo Rogers, El Paso Natural Gas Co.
Robert Schock, LLL
Larry Schwartz, LLL
Douglas Stephens, LLL
Robert Taylor, LLL
Robert Terhune, LLL

French

Jean Berger, CEA, Paris
Pierre Cohen, CEA, Paris
Serge Derlich, CEA, Paris
Henri Ferrieux, CEA, Paris

Andre Lascar, CEA, Paris
Lucien Michaud, CEA, Paris
Pierre Villeaux, French Embassy,
Washington, D. C.

Thursday, October 28

U. S.

Albert Abey
Ray Bedford, LLL
Iris Borg
Richard Carlson, LLL
Carl Gerber
Hugh Heard
Joseph Landauer
Art Lewis, LLL

Leo Rogers
Robert Schock
Larry Schwartz
Charles Smith, LLL
Douglas Stephens
Robert Taylor
Robert Terhune
Mark Wilkins, LLL

French

Jean Berger
Pierre Cohen
Serge Derlich

Henri Ferrieux
Andre Lascar
Lucien Michaud

Friday, October 29

U.S.

Albert Abey
Ray Bedford
Iris Borg
Edward Fleming, LLL
Carl Gerber
Hugh Heard
Joseph Hearst
Fred Holzer, LLL
Richard Lessler, LLL

Milo Nordyke, LLL
Leo Rogers
Robert Schock
Larry Schwartz
Charles Smith
Douglas Stephens
Robert Taylor
Robert Terhune

French

Jean Berger
Pierre Cohen
Serge Derlich

Henri Ferrieux
Andre Lascar
Lucien Michaud

Appendix E

Program

FRENCH-U. S. EXCHANGE ON PEACEFUL USES OF NUCLEAR EXPLOSIVES UNIVERSITY HALL, BERKELEY, CALIFORNIA

October 26-29, 1971

Tuesday, October 26

Welcoming Addresses

Roger Batzel

Carl Gerber

Presentations

A. Rock Mechanics

D. Stephens P-V Equation of State

S. Derlich Hoggar Granite Mechanical Properties

H. Heard Rock Failure at Extreme Conditions

R. Schock Stress-Strain Equation of State of Rock

L. Michaud Fracturing in the Hoggar Events

B. Field Data Collection and Interpretation

P. Cohen Cavity Radius and Amount of Rock Melted per Kiloton

Wednesday, October 27

Tour

The six CEA delegates, A. Abey, H. Heard, R. Schock, and D. Stephens toured the National Center for Earthquake Research as the guests of C. B. Raleigh.

Thursday, October 28

A. Field Data Collection and Interpretation

Discussion of Cohen's Tuesday Presentation

Presentations

L. Borg The Piledriver Event

L. Borg Piledriver Shock Effects

A. Lascar Hugoniot Measurements of Hoggar Granite

Thursday, October 28 (continued)

B. Calculations

R. Terhune Calculations of Wagon Wheel, Rullison and Hoggar Explosions

L. Michaud Particle Velocity Data

H. Ferrieux SOC Calculations of Explosion Effects in the Hoggar

C. Geochemistry

P. Cohen Radiochemistry

Friday, October 29

Presentations

A. Chemistry

P. Cohen Chemical Equilibria

R. Lessler Neutron Codes

R. Taylor Chemical Considerations

Discussion

General discussion primarily between Dr. Berger, Dr. Cohen, Carl Gerber, Milo Nordyke and Douglas Stephens concerning conclusions and recommendations for another meeting.

L. Rogers The Wagon Wheel Experiment

Appendix F

Statement on a French-U.S. Exchange of Geological Information Related to Peaceful Nuclear Explosions

To further the understanding of the effects of peaceful nuclear explosions, the French Atomic Energy Commission (CEA) and the U. S. Atomic Energy Commission (USAEC) are exchanging samples of rock. Reports on these samples and the effects of nuclear explosions on such samples are also being exchanged. In addition, scientists from the CEA and the Lawrence Livermore Laboratory have met to discuss the samples and related data and measurements. This meeting, which took place October 26-29 at the University of California at Berkeley, provided the opportunity for very useful detailed, technical discussions on work in this area. The discussions will assist in the studies and measurements which the scientists will be making on the exchanged samples.

Released 29 October 1971