ABSTRACT Experiments were performed in situ with a supersonic aircraft flying at low altitude over two desert valleys in the French Alps in order to see what would be the effect of sonic boom on the stability of the snow cover under critical conditions.

Four flights were made in 1974, one in 1976, and two in 1977 under various snow conditions, with a total of 20 runs at supersonic speed.

Sonic boom overpressure were measured at different places in the valleys, close to the spot of possible avalanches. The highest value recorded was 6 mbar but, by calculation by computer, using the atmospheric conditions data, and flight trajectories, it was found that larger overpressures were reached at some places on the slopes due to focalization.

Snow conditions for each flight were carefully observed by stratigraphic techniques in order to predict critical conditions for snow motion.

Some experiments of weak choc waves (sonic boom and detonation) penetration in the snow thickness were performed in situ.

Out of the twenty runs, only one of them generated few avalanches of loose fresh snow with high overpressure, the others were unsuccessful. It is concluded that sonic boom is a poor means to produce avalanches.

OPERATION "BANGAVALANCHES"
EFFETS DU BANG SONIQUE SUR LES AVALANCHES

RESUME Les essais ont été réalisés in situ avec un avion supersonique volant à basse altitude au-dessus de deux vallons alpins afin d'observer les effets du bang sonique sur la stabilité du manteau neigeux dans des conditions critiques.


Les surpressions dues au bang ont été mesurées à différents points des vallons, à proximité des zones avalancheuses. La surpression maximum mesurée est de 6 mbar
mais, les calculs effectués par ordinateur en utilisant les données météorologiques, la vitesse et la trajectoire de l'avion, ont montré que des surpressions bien plus fortes ont été produites sur des pentes à cause du phénomène de focalisation.

L'état de la neige a été soigneusement mesuré à chaque vol par techniques stratigraphiques, afin de prévoir les conditions critiques pour le déclenchement d'avalanches. Quelques expériences de pénétration du bang et d'ondes de choc faibles dans l'épaisseur du manteau neigeux, ont été effectuées in situ.

Sur les vingt passages supersoniques seulement l'un d'eux a été concomitant avec le départ de quelques avalanches de neige fraîche sans cohésion soumise à des surpressions élevées, les autres ont été infructueux. On en conclut que le bang sonique est un moyen peu efficace pour le déclenchement d'avalanches.

1. INTRODUCTION

The operation "BANGAVALANCHES" conceived in 1971, aimed finding out whether the sonic boom affects the stability of the snow-cover and whether it can cause avalanches.

Because of the impossibility of recreating the conditions in a laboratory, and of making exact calculations in order to find an answer to the questions, it was decided that real tests in the mountains should be done, using a supersonic aircraft flying over sites reputed for their avalanches. Similar work was done in USA (Lillard et al. (1965), Martinelli (1972)). After an exploration by plane, of certain alpine regions, Vallon de La Lavey (Commune of St Christophe-en-Oisans, Isère) was chosen. First because of its geographical position in the heart of an almost uninhabited mountain region, near Grenoble (70 km by road), 185 km as the crow flies from the Istres air-base (Bouches-du-Rhône) and second, snow falls abundantly on the mountains bordering the valley, and the steep slopes are ideal for avalanches. The valley is bowlshaped which allows the boom to be concentrated without over-flowing into other valleys, on the condition that the plane flies at low-altitude, above the talweg. There is only one access route thus making it easy to forbid others from coming into the area. A large refuge belonging to the Club Alpin Français was used to shelter material and personnel.

Another test-site had to be chosen (having the same geographical aspects as the site mentioned above) because of the recent laws forbidding disturbances due to noise in the Parc National des Ecrins and thus in the Vallon de La Lavey. That was l'Arvette Valley (Savoie).

The first site was used early 1974, there were four flights. The second site was used late 1976 : one flight, and early 1977 : two flights. In all, twenty supersonic runs were made in various snow conditions.
2. THE ORGANIZATION OF THE OPERATIONS

The D.R.E.T. (Direction des Recherches Etudes et Techniques) acting on behalf of the D.G.A.C. (Direction Générale à l'Aviation Civile) mandated Laboratoire A.S.P. (Applications Spéciales de la Physique, C.E.A.-CENG) to organize the tests "insitu". This was done in collaboration with the C.E.V. (Centre d'Etudes en Vol d'Istres), which brought into the scene the supersonic aircraft, the I.S.L. (Institut Franco-Allemand de Recherches de St-Louis) for the working out of the plane trajectory and the ONERA (Office National d'Etudes et de Recherches Aérospatiales) for the calculations concerning the sonic boom. ANENA (Association Nationale pour l'Etude de la Neige et des Avalanches) was used for coordination.

2.1. The operation

The weather forecast announces several days in advance the coming of favorable conditions for avalanches: periods of considerable snow falls or lengthy period of mild weather on old snow. Any development in the state of the snow cover is noted by the meteorologists-nivologists observers who work around the clock at fixed posts in the region. The work-party assembles the measuring equipment which has been modified so as to operate quickly on snowy ground at temperatures reaching -15°C.

The operation is launched on day J-1 or -2; all the organizations involved are alerted. The main team, 6 or 7 people go to the LaLavey refuge where they get the equipment ready: microphones, tape recorders; cameras and other photographic equipment, radio UHF for communication with the plane.

At the Clos-d’en-Haut (1 505 m), a smaller team of 3 or 4 people armed with cameras and photographic equipment make sure that radio and telephone contact is kept between the participants.

An "Alouette III" helicopter, belonging to the Sécurité Civile plays an important role in the transport of material and general surveys of the site.

Early in the morning, if the meteorological conditions are favourable, the C.E.V. at Istres sends up the plane. When the plane arrives at the site it makes contact with La Lavey to find out the latest weather conditions and the ground atmospheric pressure; the plane then follows the planned trajectory and sends out time signal which will be recorded on the ground and be used for synchronizing the measurements. One run lasts for less than 10 seconds. On average, the plane carries out 3 to 4 runs at supersonic speed to take place with 3 to 4 minutes interval. The flight occurs at the warmest part of the day when avalanches are most likely to occur.

Likewise, the same scenario took place in vallon de l'Arvette but here the whole operation was conducted with an helicopter on the same day as the flight, due to lack of a refuge.

3. MEASURING TECHNIQUES ON THE GROUND

The theoretical trajectory that the plane was to follow involves a subsonic approach from the North at an altitude of 3 500 m, a slight accelerated dive brings the plane to an altitude of 2 700 m at Mach>1,
then a climbout in order to leave the valley. The acceleration phase is programmed so that the focus line is placed upstream of the microphones in order that the latter are not too disturbed. The horizontal projection of the trajectory follows a straight line which passes along the valley axis.

FIG. 1 Sketch of field operation.

3.1. Working-out the trajectory and speed of the plane

On the ground measurements are taken at two points: at Clos-d'en-Haut where, with the aid of a photographic camera (9 X 12 cm) and a movie camera both pointed vertically upwards, one locates at least one point (x, y, z). At La Lavey, where one can use the stereophotogrammetrical method two "HASSELBLADS", synchronized (f 50 mm, 6 X 6 cm), about 200 m apart were used recorded on tape. Thus one measures 3 to 4 points on the trajectory (x, y, z and t) and can then work out the speed (frame speed = 1/sec).

An analogous procedure was used in l'Arvette valley; the cameras were placed at Chamossière, and at the Col, 2 150 m apart.

These measurements will be compared with those made aboard the plane, where pressure and Mach number are recorded as a function of time.

3.2. Acoustical measurements

The theoretical acoustic signal has a classic "N" shape: i.e. a pressure peak $\Delta p^+$ followed by a depression $\Delta p^-$ the total length being in the order of 100 ms, $\Delta p^+$ was supposed to attain a value of 1 to 5 mbar.

Three types of microphones were used: ceramic piezoelectric, strain gauge and capacitance. The range of measurements reaches several tens of mb, the band width from 0.1 to 20 kHz, and the sensitivity 100 to 400 mV/mbar. They were calibrated. The signals were recorded on portable tape recorders, which were also used to record other information: moment of filming, time signals form the plane and commentaries.
In the La Lavey valley, 12 microphones spread over an area of 17.5 ha around the refuge were used. In l'Arvette valley, the microphones were installed in 3 stations, 2 to 3 km apart: at Chamossière (2070 m), le Col Jétolet (2621 m). Furthermore, several automatic 'CANIBALS' (Contrôleur Automatique de Niveau de Bang Local) were put at 3 or 4 points on the left valley side. They measure the peak $\Delta P^+$ and the specific impulse.

3.3. Meteorology and nivology

Local meteorological observations allowed us to ensure that the flights took place in good conditions. In addition, measurements of air temperature and wind at different altitudes were used in the calculations for sonic boom distribution in the valley.

The snow measurements in situ: tests with ransonde in order to evaluate the resistance of the layers and stratigraphical profile (temperature, texture, hardness, humidity, shear stress) gave information on the stability of the snow cover. Tests with explosives were also performed.

4. RESULTS OF THE CAMPAIGNS

4.1. Results of measurements

The numerous results were grouped into three categories of each flights:

- meteorological and snow conditions,
- trajectory ($x, y, z$) and plane's speed,
- intensity of the sonic boom, at numerous points on the color film, 16 mm, 15 min, retraces the various phases of the operation "BANGAVALANCHES".

4.2. Sonic boom effects on snow

Twenty runs were made during 7 flights in all, and therefore under 7 different snow conditions, since for every flight the runs were only several minutes apart. A large variety of snow conditions were tested. However, early pre-winter snow could not be tested because of the lack of authorization.

All these runs were made under conditions ideal for avalanches and numerous occasions snow-flows were produced shortly before or after the plane passed. However avalanches coincided with only two of the runs during the flight on the 15th March 1974 in La Lavey valley. The boom caused 3 avalanches to be released. The recently fallen layer of superficial snow was particularly unstable. Two snow flows were recorded during the first supersonic run, on the steep slopes of Aiguille d'Olan (3371 m), and at Pointe de l'Etret (3559 m). The third was observed at the time of the second supersonic run at again Aiguille d'Olan. At these places sonic boom intensity were higher than 5 mbar.

As for the other flights, no effect accompanying the sonic boom was observed. One may conclude that the boom is not greatly instrumental in the release of avalanches. It does not appear to be a good means of inducing unstable snow-cover to flow as a preventative measure. Under certain conditions it may be the instigator of snow flows which occur shortly after.
5. CALCULATIONS

To locate the snow zones reached by the sonic boom, calculations were undertaken by ONERA which aimed at placing, for every supersonic run, the focus curve on the ground. Besides this, we obtained an estimate of the theoretical overpressure created by the boom at a certain number of points in the valley, giving us an idea of the intensity distribution and its progression according to the relief. Finally, the overpressures which had been calculated were compared with those measured by the CENG.

For the calculations, the following information was used:

- Mach number, and pressure-altitude recorded aboard the plane,
- Photographic data obtained by the CENG providing plane position \((x, y, z, t)\) at several points on its course,
- Meteorological surveys providing the temperature and the wind (force, direction) as a function of altitude above the valley.

Using these elements it is possible to reconstruct the plane's trajectory \((x, y, z, t)\) from its subsonic approach to the climbout at its exit from the valley. Next, one can calculate the characteristic sound rays which propagates the sonic boom, taking into account temperature and wind profiles between plane and ground.

The complexity of the relief gives rise to a certain difficulty when trying to establish the point of impact of a sound ray with the ground. We proceeded in numerizing all the contours level covering the altitudes in between 1400 m and 3200 m indicated on the 1/20000 map. Next, we fed a program into the computer which allowed us to choose the appropriate sound ray (instant of emission on the trajectory and angle of emission on the cone of characteristic ray) and to determine its intersection with the ground.

This program only calculates the sound ray trajectory and not the intensity of the sonic boom on impact. This last result was provided by a second program (HAYES et al. 1969) which was applied only to the previously selected rays.

Fig. 3 shows an example of results obtained, including:

- Relief represented by a certain number of contours levels (100 m intervals),
The horizontal projection of the plane's trajectory,

The focus line which marks the northern limit of the sonic boom (upper part of the figure),

Points at which the CENG had installed its measuring equipment.

The domain of overpressures, these being assessed in Pascals (example: m 320 to 400 indicates that several different measuring instruments have provided various intensities ranging from 320 to 400 Pa, depending on the instrument).

Fig. 3 also shows the highest recorded values in millibars (1 millibar = 100 Pascal) insofar as these were able to be established by the CENG taking into account calibration.

According to calculations, some of the measuring-points can be attained by sound rays. One may then compare the intensity calculated with the intensity measured (example: c 487 signifies that calculations gave the result as 487 Pascal peak overpressure). But, in many cases the ground measurements cannot be checked by calculation for either they lie north of the focal curve, or they are only reached by rising rays (calculation of the intensity for such rays using the HayesProgram (1969) is not possible), or they lie outside the direct boom zone but were relatively large overpressure produced by rays reflected by the terrain.

In general, calculation produced results which compare well qualitatively with the measured results. In particular the position of the focal curve compares well with the measurements: within a hundred meters. As for the intensity, in certain cases the difference are noticeable, but one must bear in mind that when microphones are placed in practically the same spot their measurement of the overpressure do not always coincide.

FIG. 3 Example of sonic boom calculation. L'Arvette Valley 25th March 1977: (c) calculated, (m) measured.

FIG. 4 Attenuation of sonic boom into snow:
A Snow mantle surface
B Depth 0.40 m
C Depth 0.80 m.
MEASUREMENTS OF SONIC BOOM INTO THE SNOW

In addition to the main test, the attenuation of sonic boom intensity with snow depth was investigated.

In order to do this microphones were carefully placed at different depths. Tests were made both with the sonic boom and chemical explosions (dynamite).

As an example, Fig. 4 shows the attenuation of sonic boom intensity during the flight on May 15th 1974, at La Lavey in old snow at 0°C with large grains. Its specific gravity is between 490 and 520 kg/m³.

One can note that after that a part of the energy of the incident wave has been reflected by snow surface, the sonic boom can be felt quite strongly deep down in the snow thickness.

Note: A theoretical analysis of sonic boom effects in the snow cover has been worked out and comparison with experimental results was shown in Montmollin (1976).

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