DEPARTMENT OF
MINERALS AND ENERGY

BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS

RESTRICTED
Record 1973/42

BROKEN HILL POWER-STATION VIBRATION MEASUREMENTS, NOVEMBER 1972

by

F.J. Taylor

RESTRICTED

[redacted]

Record 1973/42

BROKEN HILL POWER-STATION VIBRATION MEASUREMENTS, NOVEMBER 1972

by

F.J. Taylor

[redacted]

CONTENTS

		Page
	SUMMARY	
1.	INTRODUCTION	1
2.	RESULTS OF TESTS	3
3.	MECHANISM OF VIBRATION	9
4.	CONCLUSIONS	11
5.	ACKNOWLEDGEMENTS	12
6.	REFERENCES	12
	Appendix A - Vibration criteria	13

PLATES

1. Locality map
2. Recording sites at 47 Wright Street
3. Peak particle velocity versus distance
4. Sample record.

SUMMARY

Vibration measurements were made in and around the Galena Street power station at Broken Hill, NSW, at the request of the New South Wales Electricity Commission. The request was made following persistent complaints from a resident at 47 Wright Street, near the power station. The resident claimed that the effect of the vibrations from the power-house was causing windows and glass fittings to vibrate at extremely annoying levels.

The series of measurements of ground vibrations and air noise taken during the survey established that the cause of the complaint was the ground vibrations originating from the generating sets and not the sound waves generated by the exhaust systems. The entire foundation of the complainant's house and indeed the foundations of all houses in the immediate vicinity are subjected to a continuous vibration of frequency 28 Hz, with ground movement confined almost solely to a direction at right angles to the orientation of the generating sets and in the horizontal plane. The amplitude of the vibrations is constant over short periods of time and the peak particle velocity at 47 Wright Street varies from 0.005 cm/sec to 0.05 cm/sec. depending on the location within the property.

It is established conclusively that the vibrations investigated are generated by the V-type engines designated V16 and V12. These sets are capable of generating 2.84 MW and 4.25 MW respectively. They are the largest generators in use at this power station, and the V16 sets produce the largest vibrations. Smaller generating plants designated HF8 have vertical cylinders and do not contribute to the vibrations.

Measurements show that the maximum level of vibration of the ground is only one hundredth of that required to produce structural damage and that it is also below the threshold of perception (see Plate 3). However, when all the larger generating units are operating simultaneously it is possible that the level of vibration could well rise above the threshold of perception in the upper parts of the house, particularly the roof.

An appendix discusses the criteria involved in assessing vibration.

1. INTRODUCTION

General

Vibration measurements were made at the Galena Street power station at Broken Hill (Plate 1) at the request of the NSW Electricity Commission. The request was made following persistent complaints from the resident of 47 Wright Street, near the power station. This resident claimed that vibrations from the power station caused the windows and glass fittings of this house to vibrate at annoying levels and that the house was being damaged. The survey was carried out by the author on 13, 14, and 15 November 1972.

Power station

Fifteen generating units are installed at present, all parallel to one another (Plate 1). The installation of each set is identical - alternators and flywheels to the southeast. As in all power stations, all units are synchronized to keep their outputs in phase. The history of the power station installations and details of generator type are given in Table 1.

TABLE 1 - DETAILS OF GENERATORS

Generator type	Year installed	Brake horsepower	Load capacity and rev/min	Unit numbers
Harland and Wolff HFS8 (straight cylinder block)	1957-58	1650	1.0 MW 333 rev/min	1, 2, 3, 4
Merle HFS8 (straight cylinder block)	1958-60	1188	0.9 MW 375 rev/min	5, 6, 7, 12, 13, 14
KVSS 16 (V-type cylinder block)*	1964-65	4013	2.84 MW 428 rev/min	15, 16, 17
Vulcan 12C (V-type cylinder block)**	1970-71	6160	4.45 MW 428 rev/min	18, 19

* Generating sets number 16 and number 17 were not operational during this survey.

** The foundation for a third set of this type is being laid at the present time.

Complaints

Complaints from the resident were first received and recorded in 1970. The owner stated, however, that the vibrations had occurred for several years before this time. Generally speaking the complaints have been associated with vibrating glass surfaces such as window panes, glass doors, and a bathroom screen. Records from the power station show that inspections following the complaints confirmed that some such surfaces were vibrating. During the author's stay at Broken Hill it was possible to observe a rear window of the house vibrating continuously. When touched with the fingers, the glass stopped vibrating.

The times of complaints and the generators in operation at these times are listed in Table 2.

TABLE 2 - GENERATORS WORKING AT TIMES OF COMPLAINTS

Date	Time	Generators working
16 August 1970	2030	2, 3, 4, 5, 7, 9, 15, 16, 17, 18
16 August 1970	2210	4, 5, 7, 9, 15, 16, 17, 18
2 August 1972	0445	15, 18
20 September 1972	2315	7, 15, 16, 18

(Generator number 9, capacity 1.0 MW, had been removed at the time of the author's visit to Broken Hill)

More complaints have been recorded during the winter months, when power demand is at a maximum and when household noise and suburban noise are at a minimum. In all instances at least two of the larger generating units were operating. The resident has stated that on these occasions the windows vibrate at audible levels and that a glass door and a glass screen rattle continuously. On one occasion it was stated that audible vibration of the roof prevented sleep. Finally, the resident stated that at times it was possible to feel the vibrations on the bathroom floor.

2. RESULTS OF TESTS

GENERAL

The vibration measurements were made using a Sprengnether three-component Seismograph system (Model VS1200) together with a sound sensor. The radial component of the seismometer was oriented towards the source of disturbance being investigated.

Audio noise

The level of sound waves generated by the engines was measured inside the power station, immediately outside the power station, and at the residence in question. The results are summarized in Table 3.

TABLE 3 - AUDIO SOUND MEASUREMENTS

Location	Peak sound level		Remarks
	dB	Pascals	
Inside power station	112	8.5	Mechanically generated noise from the larger engines
Outside power station	90	2.0	Exhaust, engine, and cooling-tower noise
47 Wright Street (rear of house)	-	-	Sound level from the power-house is below the sensitivity of the instrument. Level of sound is below that of normal conversation at 1 metre

From Table 3 the author concludes that the energy of the air waves (sound) at 47 Wright Street due to the generators is too low to cause vibration of window panes etc. and hence cannot be the cause of the complaints.

Ground vibrations

Ground vibration levels were measured at 26 different places ranging from alongside the largest generator to approximately 500 metres from the power station. The measurements taken are placed in the following categories:

(1) Vibration levels adjacent to the foundation of each type of generator.

(2) Vibration levels and modes of vibration in the rear yard of the power station for different combinations of generating sets in operation.

(3) Vibration levels at various distances from the power station.

(4) Vibration levels in and around the house at 47 Wright Street.

In all cases the radial-component seismometer was pointed towards the source of disturbance. At distances away from the power station this component was pointed towards the power station; inside the power-house this component was directed at right angles to the axis of the crankshaft of the generating set in question. Plate 1 shows the locations of the recording sites.

Vibration levels alongside the foundation of the generators

The results of the measurements taken inside the power-house are presented in Table 4. This table gives the peak ground motion for the three components at a distance of one metre from the foundation of the generating set in question. The separation of the generating sets is such that measurements are generally independent of neighbouring sets. Measured levels of vibration show that the two V-type engines - No. 15 (V16) and No. 18 (V12) - generate vibrations of much greater amplitude than the smaller straight engines (No. 5, 6, and 7). Also most of the ground vibration originating from No. 15 (V16) set is confined to the horizontal plane in a direction at right-angles to the axis of the crankshaft of the set. The frequency of vibration is 28.2 Hz. Though the vibration level from the No. 18 (V12) set is lower than that from No. 15 (V16), it is not confined so much to the radial component; this is probably due to contributions from the No. 15 set being recorded during measurements on the No. 18 set (V16). The vibrations from No. 18 (V12) set when measured without interference from No. 15 (V16) set show an amplitude distribution similar to that from No. 15 (V16) (though the frequencies differ). All smaller generators (5, 6, and 7) generate approximately the same level of ground vibrations.

TABLE 4 - PEAK GROUND VELOCITY MEASURED IN THE POWER-HOUSE

(Velocity v in cm/s; Dominant frequency f in Hz)

Engine No.		Transverse		Vertical		Radial	
		v	f ± 2	v	f ± 1	v	f ± 1
5	(HFS 8)	0.15	40	0.15	25	0.35	26
6	(HFS 8)	0.25	44	0.10	26	0.30	26
7	(HFS 8)	0.15	46	0.25	25	0.35	25
15	(V 16)	0.30	28*	0.25	29*	1.30	28*
18	(V12)	0.55	43*	0.20	43*	0.54	43*

* There is an overriding beat of 3.6 ± 0.1 Hz

The peak ground velocity of 1.3 cm/s recorded alongside No. 15 (V16) set is below that which will produce structural damage to the power station building. However, this vibration level represents a peak displacement of 0.0075 cm at 28 Hz at the concrete foundation, and according to one reference (Harris & Crede, 1961) to avoid rapid wear, bearings on machinery should not be subjected to vibration amplitudes greater than 0.005 cm at this frequency.

Vibration levels at rear of power station

Since the level of vibration from the smaller generators is very much smaller than that from either the V12 (No. 18) or V16 (No. 15) sets, all further measurements were designed to investigate the nature of vibrations from the larger units. (That is to say the operation of smaller units does not appreciably influence the level of vibration at distances from the power-house). A recording station was set up in the rear yard of the power station approximately 40 metres from the larger generators. This is in the general direction of 47 Wright Street and also in the direction of the axis of the crankshaft of the motors. Recordings were taken intermittently over a period of two hours for the following combinations of large generators:

(a) No. 18 (V12) and 15 (V16) with load 7.2 MW

(b) No. 18 (V12), 15 (V16), and 19 (V12) with load 7.2 MW

(c) No. 18 (V12) and 19 (V12) with load 7.2 MW

(d) No. 18 (V12), 19 (V12), and 15 (V16) with load changing abruptly from 7.5 MW to 9.5 MW

The results of these four tests are shown in Table 5. In each case the transverse component is now largest.

TABLE 5 - PEAK GROUND VELOCITY (cm/s) MEASURED AT REAR OF POWER-HOUSE

Engines tested	Transverse	Vertical	Radial	Remarks
(a) 1 x V12 1 x V16	0.062	0.015	0.027	Frequency 42 Hz. Beating occurring owing to presence of 28-Hz signal.
(b) 2 x V12 1 x V16	0.075	0.01	0.025	Frequency 42 Hz. Beating occurring owing to presence of 28-Hz signal.
(c) 2 x V12	0.075	0.01	0.022	Frequency 42 Hz. Almost a pure sine-wave.
(d) 2 x V12 1 x V16	All quantities measured were essentially the same as (c). There was no observable increase in vibration levels during or after the increase in load.			

The measurements taken inside and immediately outside the power station support the following conclusions.

(1) Most of the vibration is confined to one axis. This axis is in the horizontal plane and at right-angles to the axis of the crankshaft of the generating sets.

(2) The major components of vibration are a frequency of 42 Hz from the V12 generating sets together with a frequency of 28 Hz from the V16 generating set.

(3) The amplitude of vibration is independent of the load, under the conditions prevailing at the time of these tests.

(4) The amplitude of vibration increases marginally when similar sets are in operation as opposed to dissimilar sets. This increase is directly related to the vibration frequency because of the constructive addition of two like signals in phase. The relative increase in vibration level is around 20 percent.

(5) For a fixed set of conditions the peak ground velocity of the recorded vibrations at a particular site does not vary by more than ± 5 percent and even with varying load there was little change.

Vibration levels at various distances from the power station

The third group of observations concerned the monitoring of ground vibrations at various distances from the power station while units No. 15 (V16), 18 (V12), and 19 (V12) were in operation. Details of these measurements are presented in Table 6.

TABLE 6 - PEAK GROUND VELOCITY MEASURED AT DIFFERENT DISTANCES FROM THE POWER STATION

Location of test	Approximate distance from power station. (metres)	Peak ground velocity		
		Transverse	Vertical	Radial
Dirt road at rear of 47 Wright Street	140	0.003 cm/s Frequency 28 Hz	Nil	Nil
47 Wright Street (concrete footpath)	220	0.005 cm/s Frequency 28 Hz	Nil	0.001 cm/s Frequency 28 Hz
47 Long Street	360	0.002 cm/s Frequency 28 Hz	Nil	Nil
*77 Williams Street	540	50 Hz electrical interference prevented any measurement of ground vibration.		
Centre of Memorial Oval	540	Vibrations from power-house below level of ambient ground vibrations.		

*When the level of ground vibration is very small and hence the gain of the recording instrument very high the proximity of high-voltage power-lines induces sufficient 50-Hz electrical signal in the instrument to completely mask the electrical signals from the seismometer.

Plate 3 gives the peak ground velocity for the major component at various distances from the power station. Also shown are tolerance levels taken from the literature (Harris & Crede, 1961; US Bureau of Mines, 1971) for perception, degree of unpleasantness, and structural safety. The comments apply to continuous vibration.

Vibration levels at 47 Wright Street

The fourth series of vibration measurements was taken in and around the house at 47 Wright Street - the house concerned in the complaints. Some measurements were taken on the afternoon of 13 November and others were taken on the afternoon of 14 November. The peak particle velocity for the major component (transverse) of vibration is given for each recording site. The level of vibration of the other components is insignificant. Plate 2 shows a plan of the house and the location of the recording sites. Directions left and right as used in describing these sites refer to an observer standing at the front of the house facing Wright Street. The reader is referred to Plate 2 to clarify these descriptions:

TABLE 7 - HOUSE SITE - PEAK PARTICLE VELOCITIES OF TRANSVERSE COMPONENT

Record No.	Location	Units 15, 18 & 19 operating	Units 15 & 18 operating
22	Centre, front - concrete path	0.005 cm/s	-
23	Window sill above front porch	0.021	-
*25	Right, front corner - concrete path	0.045 0.003	-
26	Right side, middle - " "	0.01	-
27	Right, rear corner - " "	0.015	-
28	Window sill at right near corner	0.05	0.018
29	Centre, rear - concrete path	0.005	0.004
30	Left, rear corner - concrete path	0.006	-
31	Left side, middle - " "	0.007	-
32	Left, front corner - " "	0.005	-
34	Concrete floor of bathroom	0.005	-

*These two readings were taken about 20 minutes apart and both are considered to be correct, i.e. both are a true record of the movement of the concrete path at the time of recording. The difference must be attributed to some secondary effect probably resulting from the proximity of the house and change in response of the house.

Measurements were made on the afternoon of 14 November while generators 15, 18, and 19 were operating, and on 13 November when generators 15 and 18 were operating. The dominant frequency (28 Hz) and direction of vibration are the same for all observations. The results of all measurements taken around the house are shown in Plate 3 as '+'.

Several observations can be made from these measurements. The vibration level is amplified 4 times in going from ground level to the window sill. Records 25, 26, 27, and 28 show much higher vibration levels than records from similar locations around the house. During each recording, which in general lasted for about 10 seconds, there were no measurable changes in peak amplitude or the general appearance of the record. The variations in level at these positions are regarded by the author as transients, lasting much more than 10 seconds and less than 20 minutes. It is not considered possible that the increase in vibration level at these positions could be attributed to an increase in the energy of the transmitted wave arriving from the power station. During the time of the measurements, conditions at the power station remained unchanged. It would seem more probable that the explanation lies in a change in response of the house to the ground vibrations.

The vibrations were confined almost solely to the transverse component, as with all other measurements except those inside the power-house. Small fluctuations in the level of vibration caused by an over-riding frequency of around 3 Hz are obvious on the recordings taken both at the power-house and at 47 Wright Street.

3. MECHANISM OF VIBRATION

All the generators within the power-house generate continuous vibrations. However, it is the vibrations from the V-type engines which are recorded at distance. This is caused not only by the relatively large size of the engines but also by the fact that most of the energy of vibration from these engines is confined to one axis. If this energy were distributed equally over all three axes, then the amplitude of vibration of any one component would be much lower. A second cause of the persistence of this vibration is that synchronization of like generators ensures that ground vibrations are in phase. Thirdly it happens that the transverse wave is the least rapidly attenuated of the seismic waves with increasing distance, and fourthly the 28-Hz vibrations from the V16 sets is less rapidly attenuated than the higher-frequency vibrations from the other sets (US Bureau of Mines, 1971).

The horizontal vibration originating from the V16 engine can be explained as follows. The engine has 16 cylinders, 8 on either side of the centre line, and has a speed of 428 rev/min. The firing order is such that cylinders from either side of the centre line are fired consecutively and this action has a push-pull effect on the foundations. The frequency generated is worked out as follows.

16 cylinders, 4-stroke action, V-type block, 428 rev/min or 7.1 rev/s.

Firing rate, 8 per 360 degrees or one per one-eighth of a revolution.

Therefore, the firing rate per second is

$$7.1 \times 8 = 56.8 \text{ per sec}$$

Two consecutive firings will produce a knock in opposite directions which will constitute one cycle of ground vibration. Hence the frequency of ground vibration will be

$$\frac{\text{Firing rate per second}}{2} = \frac{56.8}{2} = 28.4 \text{ Hz}$$

This agrees with the frequency monitored at the base of the V16 engine. Also since the speed of the engine is 7.1 rev/s and since it takes 2 revolutions to complete a firing sequence for all 16 cylinders we can expect that if there is any imbalance in the construction of the engine then a periodic vibration of 3.55 Hz will result. This frequency is also obvious on the records.

The V12 engines also produce a large horizontal vibration but in this case the frequency is 42.9 Hz with an over-riding beat of 3.6 Hz. The operational characteristics of this engine are as follows.

12 cylinders, 4-stroke action, V-type block, 428 rev/min or 7.1 rev/s.

Firing rate, 6 per 360 degrees or one per one-sixth of a revolution.

Firing rate per second,

$$7.1 \times 6 = 42.6/\text{second}$$

If two firings produce one cycle of ground vibration then we would expect a vibration frequency of 21.3 Hz. However, in this particular case the resultant frequency is 42.6 Hz. The author has no adequate explanation for this. It could be related to the natural resonant frequency of the engine mounting block, but more measurements would be required to determine the precise reason. The origin of the 3.6-Hz signal is the same as with the V16 engines.

Since all these generators are synchronized then similar engines will give in-phase addition of similar frequencies. For this reason one would expect the vibration levels from three V16 engines to be greater than that from one V16 engine. As previously stated the effect of adding one engine increases the ground vibration amplitude by about 20 percent. Hence, the effect of three V16 engines can be expected to be around 1.5 times as great as the effect from one engine. The effect of bringing the two V12 engines into operation while the three V16 engines are operating is not expected to increase the level of vibration greatly. However, the resultant beat effects may produce larger fluctuations in amplitude.

4. CONCLUSIONS

There is no doubt that ground vibrations give rise to the complaints and that the cause of these vibrations is the relatively large horizontal component of ground vibrations originating from the power station. These vibrations originate from the larger V-type engines - the smaller vertical-cylinder engines make no significant contribution. The level of vibration measured at the house at 47 Wright Street cannot cause any damage to the structure. Further, this measured level of vibration of the ground is below the threshold of perception as determined by various researchers. The peak particle velocity recorded at this house was 0.05 cm/s (on a window sill) with a frequency of 28 Hz. This can be expected to increase to 0.075 cm/s (within the threshold of perception) when all the large engines are in operation. Similarly the peak velocity of vibration on the bathroom floor can be expected to increase from the measured value of 0.005 cm/s to 0.007 cm/s.

Since the vibrations were magnified (presumably by resonance) by a factor of 4 between ground level and the window sill one may expect a similar magnification between the window sill and the roof. If such is the case then the level of vibration at the roof could reach 0.3 cm/s, which is well above the threshold of perception and is approaching the level of vibration which could be annoying if a person were in physical contact with the roof.

The level at which the glassware, roof, and other parts of house vibrate cannot produce audible sounds at a frequency of 28 Hz. It is the secondary effects which produce audible sounds, e.g. when one object, while vibrating, strikes another. The effect is greatest where loose fittings are attached to large suspended surfaces such as hanging doors, screens, and windows. Thus, the roof might rattle if there were any loose sheets of iron. Similarly a loose catch on a door will rattle if the door is vibrated. Finally it is the author's conclusion that the vibrating windows could not produce an audible sound unless the glass were loose enough to permit rattling in the window frames.

5. ACKNOWLEDGMENTS

The author acknowledges the assistance and co-operation given by the staff of the Electricity Commission of New South Wales at the Broken Hill power station.

6. REFERENCES

GETLINE, G.L., 1955 - Shock and Vibration Bulletin No. 22, Supplement. Washington, D.C., Dept of Defence.

HARRIS, G.M., & CREDE, C.E., 1961 - Shock and Vibration Handbook, Vol. 3 - Engineering Design and Environmental Conditions. New York. McGraw - Hill.

U.S. BUREAU OF MINES, 1971 - Blasting vibrations and their effects on structures. US Bur. Min. Bull. 656.

APPENDIX A - VIBRATION CRITERIA

Use of peak particle velocity

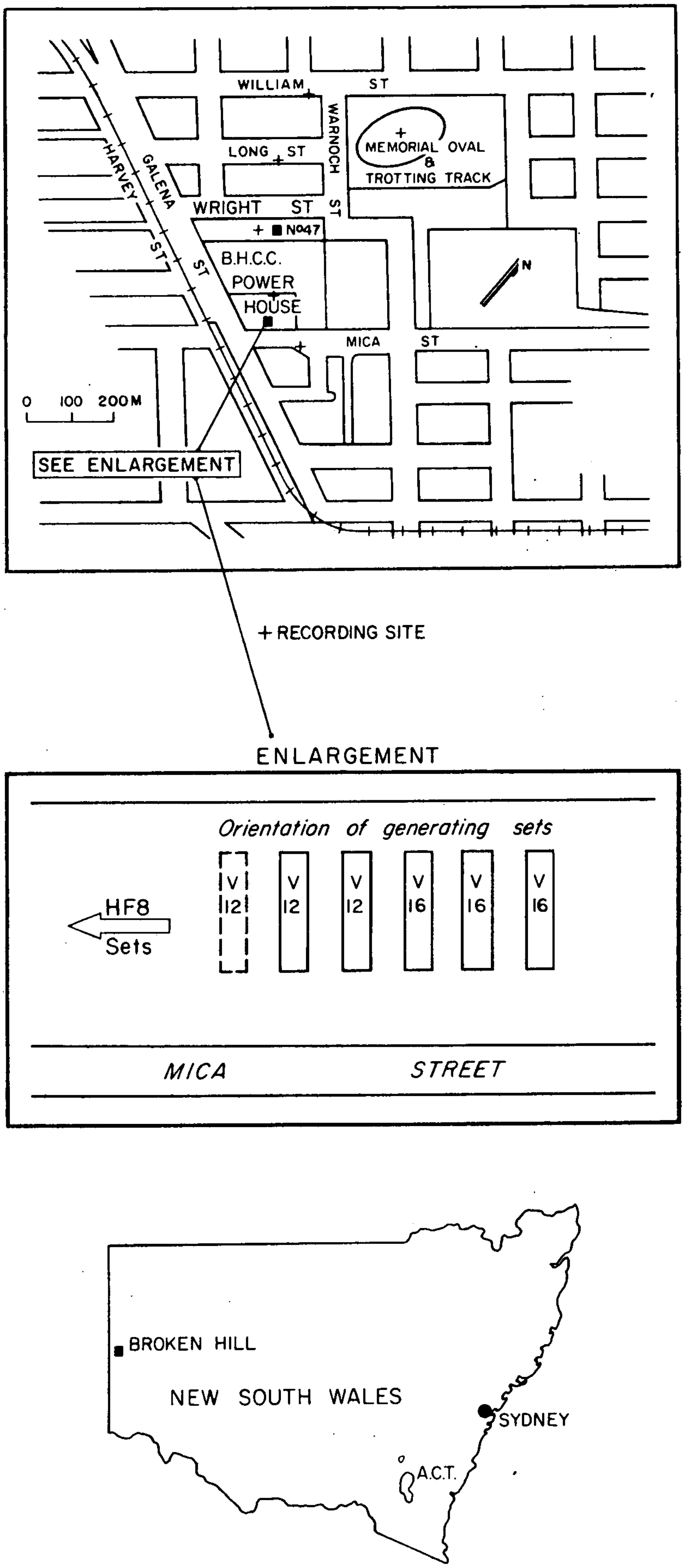
Vibration level is now most commonly measured as peak particle velocity since this is the factor most closely related to observed levels of damage due to vibrations (US Bureau of Mines, 1971).

For blasting, a peak particle velocity of 5 cm/s has been adopted as a safe limit below which structural damage is extremely unlikely to occur. This figure was reached as a result of numerous experiments and includes a safety factor of about 2.

Continuous vibrations and human response

In cases of continuous vibration, even when there is no possibility of structural damage to houses it is necessary to consider the subjective response of the human body to vibratory motion. Various researchers have conducted experiments on volunteers by exposing them to vibrations of various amplitudes and frequencies. Generally there are three accepted levels for subjective responses to shock and vibration: the thresholds of perception, of unpleasantness, and of tolerance. The threshold of perception is defined as that level of vibration which the subject can just perceive through the sense of touch. A compilation of the results of some experiments for tests lasting 5 to 20 minutes is given in the literature (Harris & Crede, 1961). The levels for a frequency of 28 Hz are shown in Plate 3. The threshold of perception varies somewhat with the individual but is considered to be fairly well defined, whereas the thresholds of unpleasantness and tolerance are more subjective and difficult to identify and reproduce.

Experimental data on long exposures to vibratory motion are limited. Some information on comfort and tolerance levels for aircraft pilots has been documented (Getline, 1955) and the general opinion is that prolonged exposure to vibration much above the level of perception can be irritating and fatiguing.

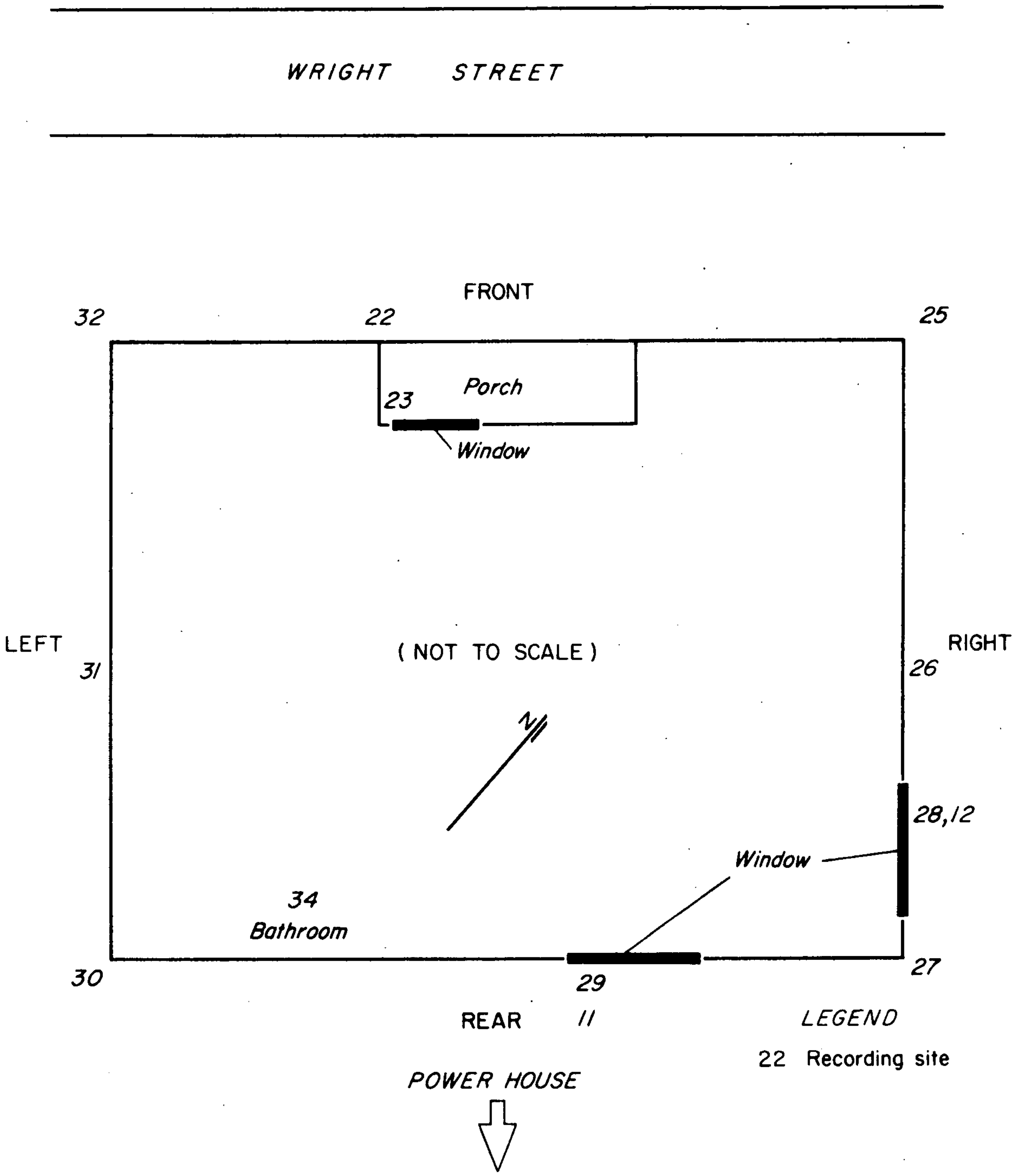


BROKEN HILL LOCALITY MAPS

To accompany Record No. 1973/42

H54/B5-1A

PLATE 2

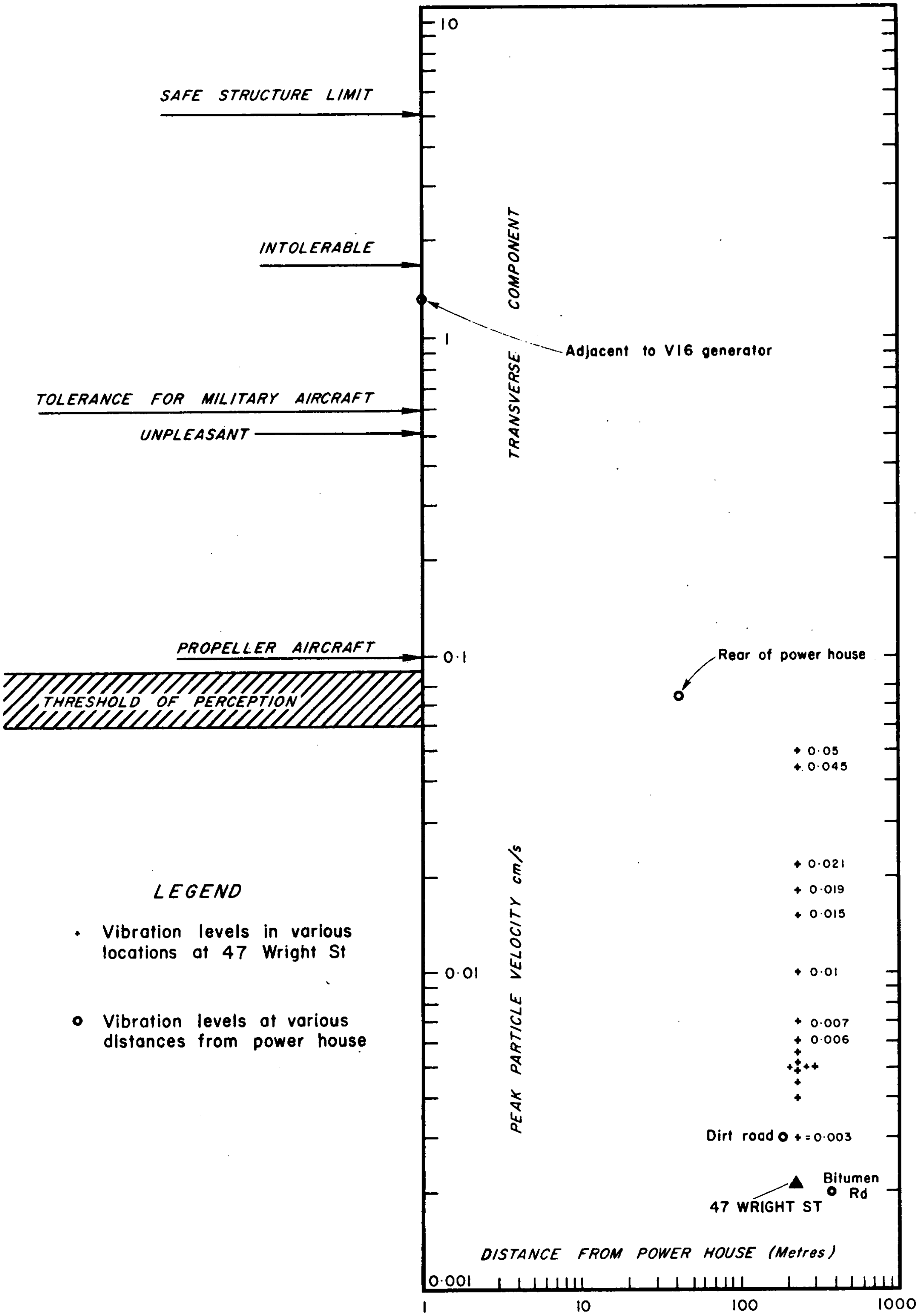


RECORDING SITES AT 47 WRIGHT ST

To accompany Record No. 1973/42

H54/B5-2A

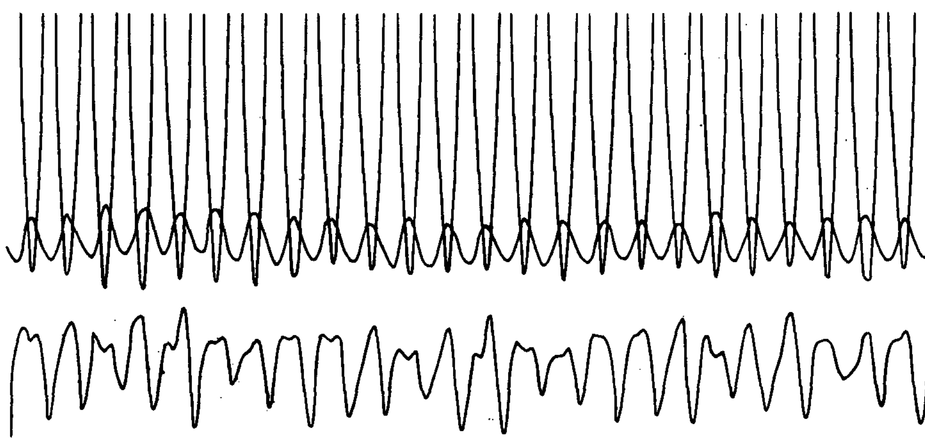
PLATE 3



PEAK VELOCITY VERSUS DISTANCE

To accompany Record No. 1973/42 H54/B5-3A

RECORD No. 23



Window sill on front porch

Vertical Scale 1cm = 0·01cm/s

PART OF RECORD No. 23