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NOISE RADIATION FROM NATURAL-DRAFT COOLING TOWERS FOR NUCLEAR POWER PLANTS

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CONTENTS

ABSTRACT

A procedure for computing the noise levels in the vicinity of natural-draft cooling towers is presented. The noise levels are computed in overall and octave band levels with A-weighting and with no weighting. Attenuation of the noise by wave spreading, atmospheric absorption, barrier screening, vegetation, and wind and temperature gradients are included. The procedure is applied to a nuclear power plant served by four cooling towers and to a nuclear energy center with forty cooling towers.

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INTRODUCTION

Cooling towers, both forced- and natural-draft, generate and radiate noise when in operation. As the tower size and thermal capacity are increased, the accompanying noise radiation increases. As the generated noise is radiated away from the cooling tower, the resulting sound pressure levels at locations in the vicinity of the power plant will be affected by various features of the landscape and prevailing weather conditions. In addition, the presence of other cooling towers or structures will modify the noise pattern. This paper presents a procedure for calculating the sound pressure levels in terms of both octave band levels and overall levels that can be expected at specified points in the vicinity of a nuclear power station that is served by natural-draft cooling towers. Minor adjustments to the procedure would make it applicable to forced-draft tower installations.

BACKGROUND

In 1971, Ellis[1] published a paper in which he developed a method for predicting the level of noise generated by natural-draft cooling towers and the radiation to points in the surrounding area. The acoustic power of the cooling towers was calculated from an empirical equation that he developed. Ellis's calculations included attenuation due to wave spreading, atmospheric absorption, and screening effects of other cooling towers. The characteristic octave band frequency spectrum shape was obtained from octave band data taken from a number of cooling towers.

In an earlier paper by Dyer and Miller,[2] the acoustic power of mechanical-draft cooling towers was found to correlate very well with the rated fan power. In addition, they found the characteristic spectrum was highest at low frequencies and that it decreased monotonically with increasing frequency. Spectrum measurements made by Ellis indicate a much different character for natural-draft towers, being lowest near the 250-Hz octave band and rising with increasing frequency to a maximum near the 4000-Hz octave band.

Ellis applied his prediction method to a 2000-MW power station served by eight natural-draft cooling towers, two of which were not in service. The predicted overall A-weighted* sound pressure levels were consistently within 2% of measured levels. In each case, he assumed complete acoustical screening of a tower if the line of sight between the receiver and source was obstructed by intervening towers.

In September 1975, Capano and Bradley[3] published the results of a series of noise level measurements near large natural-draft cooling towers. They concluded that Ellis's method, when applied to towers appreciably larger than the sizes upon which his method was based, consistently overestimates the noise levels by approximately 5 dB, indicating that the acoustic power of natural-draft cooling towers is not a linear function of thermal capacity over a large range of tower sizes. They indicate that an improved procedure for computing the acoustic power of a tower is in progress.

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*A sound filtering system having a characteristic that roughly matches the frequency response of the human ear for sound levels up to 55 dB. (Frequently used at higher levels.)

NOISE PREDICTION METHODOLOGY

The methodology described in this paper is based on Ellis's method. The empirical estimate of the acoustic power developed by him is used in addition to the octave band frequency spectrum shape recommended in his paper. Additional attenuation mechanisms of wind, temperature gradients, local vegetation, and terrain have been incorporated into the methodology.

Acoustic Power of Natural-Draft Cooling Towers

The equation given by Ellis for computing the acoustic power of a natural-draft cooling tower is

$$Wac = Mh \left[A\left(\frac{T}{h}\right)^{n} + B\left(\frac{D}{h}\right)^{m} \right] , \qquad (1)$$

in which

Wac = acoustic power (watts),

M = mass flow rate of cooling water (kg/sec),

h = distance water falls from culvert to pond (m),

T = depth of packing below the ring beam (m),

D = height from pond to the base of the packing (m),

A, B, m, n = empirical constants.

Ellis attempted, unsuccessfully, to correlate the acoustic power of each cooling tower to the hydraulic power dissipated, which led to the development of the empirical equation given above.

Sound Pressure Level at a Point

The acoustic intensity at a point is the acoustic power transmitted per unit area. The mean square acoustic pressure at a point is proportional to the intensity and inversely proportional to the acoustic impedance of the medium. For a plane wave,

$$\frac{Prms^2}{Z_o} = I = Wac/A \text{ (watt/m}^2) \quad , \qquad (2)$$

in which

$Prms^2$ = mean square acoustic pressure (N/m^2),

Z_o = characteristic impedance (mks rayls),

I = acoustic intensity (watt/m^2),

Wac = total radiated acoustic power (watts),

A = area normal to wave front through which Wac is transmitted (m^2).

For a concentrated source radiating a total acoustic power of Wac, the mean square acoustic pressure at a point r meters away is

$$Prms^2 = \frac{Wac\ Z_o}{2\Pi r^2} \quad (N/m^2)^2 \quad . \qquad (3)$$

This equation assumes that the radiated acoustic energy is contained in a uniformly spreading hemispherical wave. For a cooling tower, if the open height between the pond and the ring is h', then the mean square acoustic pressure at the pond rim will be

$$(Prms^2)_{rim} = \frac{Wac\ Z_o}{2\Pi R\ h'} \quad (N/m^2)^2 \quad , \qquad (4)$$

in which R is the base radius of the cooling tower.

The sound pressure level is defined as

$$SPL = 10 \log \left(\frac{Prms}{Pref}\right)^2 , \qquad (5)$$

in which $Pref = 2 \cdot 10^{-5}\ N/m^2$.

At a distance a from the rim of the pond, the mean square acoustic pressure will be given by

$$(Prms^2) = \frac{Wac \cdot Z_o}{\Pi^2 (a^2+2aR)} \tan^{-1} \sqrt{\frac{a+2R}{a}} . \qquad (6)$$

This equation, again, assumes uniform hemispherical wave spreading. The corresponding sound pressure level can then be calculated relative to the reference acoustic pressure.

Spectrum Shape of Noise Radiated by Natural-Draft Cooling Towers

Ellis made a series of sound pressure level measurements near natural-draft cooling towers and established the characteristics of the frequency spectrum of the radiated noise. The octave band levels are given relative to the overall A-weighted sound pressure level. Because the spectrum is dominated by high frequencies (>1000 Hz), the overall level calculated is considered to be the A-weighted sound pressure level.

The values that, when subtracted from the A-weighted overall level, give the octave band levels are given by Ellis[1] as:

Octave band center frequency	Level difference relative to A-weighted level
125	19.4
250	19.8
500	13.0
1000	7.8
2000	6.3
4000	4.3
8000	7.2

Attenuation of Radiated Sound due to Atmospheric Absorption

As the sound radiated by the cooling tower travels through the air, acoustic energy is extracted by viscous effects, heat transfer, and molecular absorption. Molecular absorption, which is the predominant mechanism, is strongly dependent on the ambient temperature and relative humidity of the air. In 1964,[4] the results of a number of studies were reported for determining the dependence of this atmospheric absorption of sound energy on temperature and relative humidity. These data are given in terms of attenuation in decibels per 1000 ft of wave travel for each 1/3 octave and 1/1 octave frequency band. The attenuation in each octave band is subtracted from the corresponding spectral value of the radiated sound pressure level at the receiving point.

Attenuation of Radiated Sound due to Screening

The attenuation attributable to barriers is based on wave diffraction theory and depends upon the Fresnel number, which is calculated from the wave length of the sound and the straight line distance and shortest propagation distance between source and receiver. Also, a thin rigid barrier is assumed to be obstructing the sound propagation. Experimental data show substantial departure from this theory for screening by buildings. The data show at least a 10-dB reduction in sound pressure level for complete line-of-sight screening by intervening buildings.

When the noise is being generated by an installation with more than one tower, many receiving points will be screened by one tower from another. If the noise level at the receiving point is reduced by 10 dB for the screened tower, the level due to both towers (assuming equal acoustic power for each tower) will be less than half a decibel higher than the level at that point due to the unshielded tower alone. Consequently, when visual line of sight between a receiving point and a tower occurs, the contribution of that tower to the noise level at that receiving point is taken to be negligible. Correspondingly, the computer code requires the screening data for each receiving point and each cooling tower.

Attenuation of Radiated Sound due to Gradients of Wind and Temperature

The variation of mean temperature and horizontal wind speed with height above the ground causes refraction of propagating sound waves. This is because these gradients cause the mean speed of sound to vary with height. The sound can be refracted upward away from the ground and cause an acoustical shadow zone when there is a strong negative temperature gradient or at points upwind from the source. The effect of a wind gradient is usually the more important of the two and will override the temperature gradient effect resulting in no shadow zone down wind. Wiener and Keast[5] have developed equations with which the location of the shadow zone, if one exists, can be approximated and with which the excess attenuation can be calculated at any distance from the source. The data required for the computer code input are the wind and temperature gradients prevailing in the vicinity of the power plant.

Attenuation of Radiated Sound due to Vegetation

The excess attenuation of a propagating sound wave due to vegetation is considered in two parts: first, the attenuation due to shrubbery and thick grass and, second, the attenuation due to thick stands of trees. Analytical approximations of the corresponding attenuations are given in Beranek.[6] These equations give the excess attenuation for these two cases as a function of distance from the source and the frequency of the sound wave. For broad band noise, the equations are applied to the sound pressure levels in each octave band using the octave band center frequency in the appropriate attenuation equation.

Each of the appropriate attenuations are made for each boundary point and cooling tower to obtain the octave band sound pressure levels at the boundary point at which the total noise level is being calculated. The total attenuated octave band and overall sound pressure level due to all towers is calculated at each boundary point by superimposing the level at that point calculated for each tower.

If the attenuation is such that a negative sound pressure level results (i.e., a sound pressure less than the reference sound pressure), a value of 0 dB is given, which means the sound level attributable to the cooling towers is inaudible.

APPLICATION OF NOISE PREDICTION METHODOLOGY TO THE KENTUCKY LAKE NEC SURROGATE SITE

The noise prediction methodology was coded in FORTRAN IV for numerical computation on the IBM System 360 Model 91 at the Oak Ridge National Laboratory and was used to compute the predicted noise levels at various points at the Kentucky Lake Nuclear Energy Center Surrogate Site. First, the levels were computed at points around an arbitrarily chosen boundary of one of the four-reactor groups as though it were operating as a single dispersed reactor installation. The methodology was then used to predict the noise levels at a series of points in the NEC Surrogate Site with ten of the four-reactor units, making a total of 40 cooling towers. The points chosen were along a line, one end of which was near the center of the site, extending over 11 miles to the north.

In both cases, the elevations of the cooling tower bases and the points at which the noise levels were computed were assumed to be identical. Ecological surveys indicated that the site is covered with heavy stands of deciduous trees. Consequently, noise levels were computed to include both possible cases: when the trees are in full foliage and when they are bare. In the absence of data concerning wind and temperature variations, the gradients of both were assumed to be negligible.

Acoustical screening was assumed whenever the line of sight between a particular cooling tower and computation point was obstructed by another cooling tower or by an adjacent building. The values of the various parameters used to calculate the acoustic power of each of the cooling towers are given below:

Cooling tower base radius, m	61
Distance from water culvert to pond, m	11.8
Packing depth below ring beam, m	0
Pond to packing height, m	8.96
Pond to ring beam height, m	8.96
Elevation of tower base, m	152
Cooling water flow rate, kg/sec	57,500

The corresponding acoustic power of each cooling tower using these data was computed to be 7.06 W. This acoustic power corresponds to an A-weighted sound pressure level of 93.2 dB(A) at the rim of each tower.

Results for a Typical Four-Reactor Site

The noise levels were computed at twenty points along the arbitrarily chosen boundary of the typical four-reactor site. The site chosen was the four-unit group farthest north and west at the Kentucky Lake NEC Surrogate Site, as designated in Fig. 1. The noise levels computed at these points are given in Table 1 for both cases — when the trees are in full foliage and when they are bare.

As can be seen from Table 1, the noise levels vary from a minimum of 51 dB(A) at point number 12 to a maximum of 64 dB(A) at point number 18.

Results for Kentucky Lake NEC Surrogate Site

The noise levels were computed at twenty points along a line starting near the center of the Kentucky Lake Surrogate Site and extending due north 11.4 miles. The points along the line are 3/5 of a mile apart and are shown in Fig. 1. The computed noise levels are given in Table 2 for the cases of full tree foliage and bare trees.

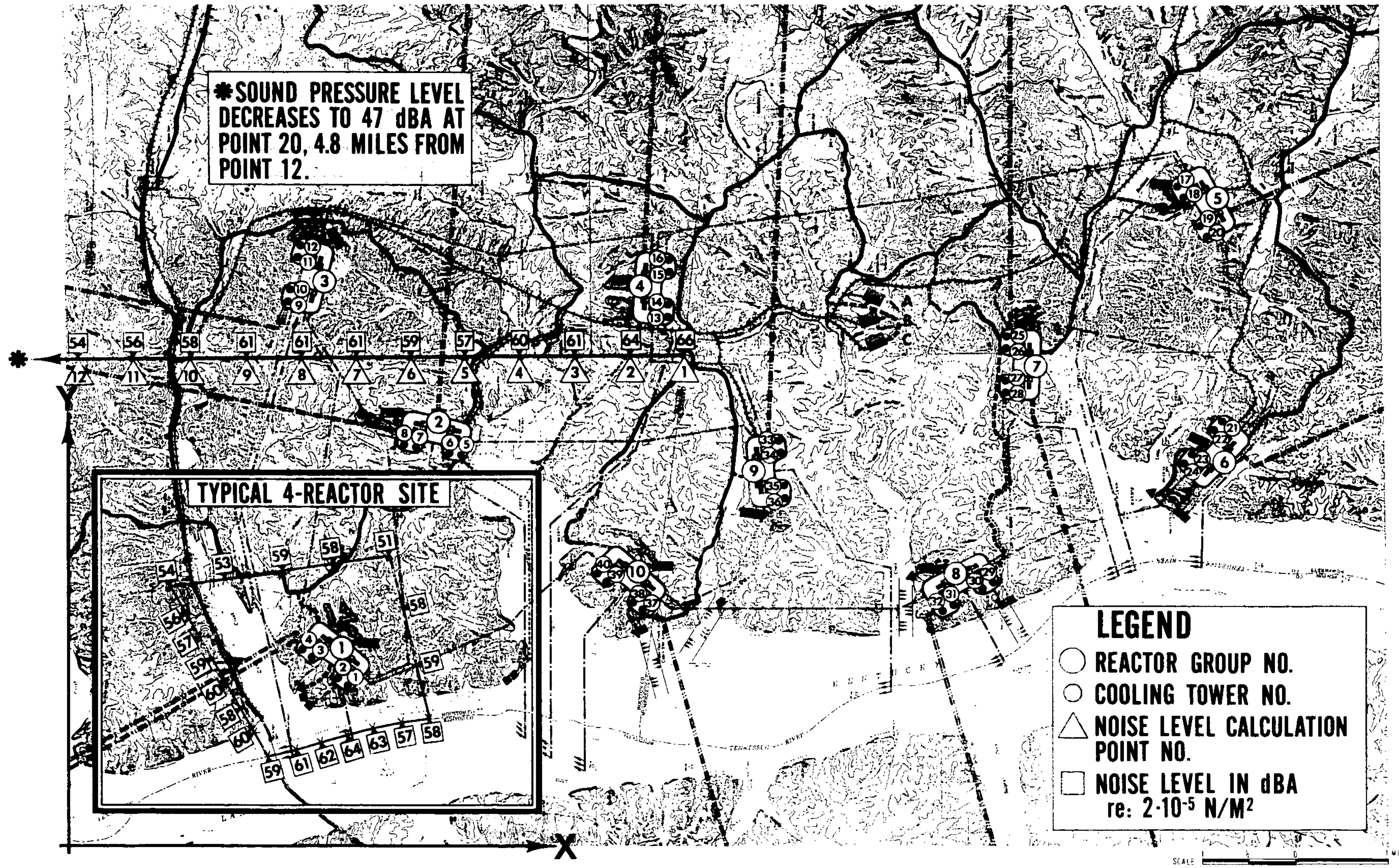

Fig. 1. Kentucky Lake NEC Surrogate Site.

Table 1. Computed sound pressure levels around a typical four-reactor site

Boundary point number	Sound pressure level[a] [dB(A)]	
	Trees in full foliage	Trees bare
1	59	59
2	60	60
3	58	58
4	60	60
5	59	59
6	57	57
7	56	56
8	54	54
9	53	53
10	59	59
11	57	58
12	0	51
13	52	58
14	5	59
15	58	58
16	57	57
17	63	63
18	64	64
19	62	62
20	61	61

[a]Re: 2×10^{-5} N/m^2.

Table 2. Computed sound pressure levels for Kentucky Lake NEC Surrogate Site

	Sound pressure level[a] [dB(A)]	
Noise computation point number	Trees in full foliage	Trees bare
1	8	66
2	7	64
3	0	61
4	0	60
5	0	57
6	0	59
7	0	61
8	6	61
9	5	61
10	0	58
11	0	56
12	0	54
13	0	52
14	0	51
15	0	50
16	0	49
17	0	49
18	0	49
19	0	48
20	0	47

[a]Re: 2×10^{-5} N/m^2.

The levels vary along this line from a minimum of 47 dB(A) at point 20 to a maximum of 66 dB(A) at point 1. The attenuation effect of a thick stand of trees over appreciable distances is evident in that the levels at sixteen of the measurement points are inaudible and very nearly so at the remaining points.

REFERENCES

1. R. M. Ellis, *J. Sound Vib.* 14: 171-182 (1971).

2. I. Dyer and L. N. Miller, *Noise Control*, pp. 180-183 (May 1959).

3. G. A. Capano and W. E. Bradley, *Radiation of Noise from Large Natural Draft and Mechanical Draft Cooling Towers*, ASME Paper 74-WA/HT-55, 1975.

4. Society of Automotive Engineers, *Standard Values of Atmospheric Absorption as a Function of Temperature and Humidity for Use in Evaluating Aircraft Flyover Noise*, A.R.P. 866, New York, 1964.

5. F. M. Wiener and D. N. Keast, *J. Acoust. Soc. Am.* 31: 724-733 (1959).

6. U. Kurze and L. L. Beranek, Chapter 6 in *Noise and Vibration Control*, L. L. Beranek, ed., McGraw-Hill, 1971.

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6	0	59
7	0	61
8	6	61
9	5	61
10	0	58
11	0	56
12	0	54
13	0	52
14	0	51
15	0	50
16	0	49
17	0	49
18	0	49
19	0	48
20	0	47

[a]Re: 2×10^{-5} N/m^2.

The levels vary along this line from a minimum of 47 dB(A) at point 20 to a maximum of 66 dB(A) at point 1. The attenuation effect of a thick stand of trees over appreciable distances is evident in that the levels at sixteen of the measurement points are inaudible and very nearly so at the remaining points.

REFERENCES

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5. F. M. Wiener and D. N. Keast, *J. Acoust. Soc. Am.* 31: 724-733 (1959).

6. U. Kurze and L. L. Beranek, Chapter 6 in *Noise and Vibration Control*, L. L. Beranek, ed., McGraw-Hill, 1971.

APPENDIX

INPUT DATA FORMAT

CARD 1 FORMAT (7I5, 2 F10. 3)

COLUMNS	VARIABLE NAME	MEANING
1-5	M	Number of grid points in X-direction
6-10	N	Number of grid points in Y-direction
11-15	NBP	Number of site boundary points
16-20	NOT	Number of cooling towers
21-25	NOP	Number of points at which noise levels are to be computed
26-30	IWIND	0 — No wind or temperature effects 1 — Wind and temperature effects considered
31-35	IBOUN	0 — Coordinates of all boundary points not input 1 — Coordinates of all boundary points input
36-45	GS	Grid size in meters
46-55	AI	Acoustic impedance of air

CARD 2 FORMAT (I 3) (SKIP IF IBOUN = 0)

COLUMNS	VARIABLE NAME	MEANING
1-3	NUM	Number of boundary point in ROW

CARD 3 FORMAT (20I3) (SKIP IF IBOUN = 0)

COLUMNS	VARIABLE NAME	MEANING
1-NUM	IVECT	X-coordinates of boundary points in row

(CARDS 2 AND 3 ARE REPEATED N TIMES)

CARD 4 FORMAT (20I4)

COLUMNS	VARIABLE NAME	MEANING
1-80	ICX, ICY	X and Y grid coordinates of cooling towers

(REPEATED IF MORE THAN 10 COOLING TOWERS)

CARD 5 FORMAT (20I4)

COLUMNS	VARIABLE NAME	MEANING
1-30	IBX, IBY	X and Y are grid coordinates of points at which noise levels are to be computed

(REPEATED IF MORE THAN 10 POINTS)

CARD 6 FORMAT (10F8.2)

COLUMNS	VARIABLE NAME	MEANING
1-80	BDYEL	Base elevation of cooling towers

(REPEATED IF MORE THAN 10 TOWERS)

CARD 7 FORMAT (I4)

COLUMNS	VARIABLE NAME	MEANING
1-4	NOSP (I)	Number of computation points which are screened from cooling tower I

CARD 8 FORMAT (10I5)

COLUMNS	VARIABLE NAME	MEANING
1-50	NVECT (I, J)	Grid coordinates of points J screened from cooling tower I

CARD 9 FORMAT (F5.1, 7F5.2)

COLUMNS	VARIABLE NAME	MEANING
1-5	TEMP	Ambient temperature — °Celsius
6-40	ATMOS	Octave band atmospheric absorption values — dB/100 meter

CARD 10 FORMAT (7F6.2)

COLUMNS	VARIABLE NAME	MEANING
1-42	ARIM	Octave band spectrum shape values to be subtracted from A-weighted level at cooling tower rim

CARD 11 FORMAT (6F10.2, E15.3)

COLUMNS	VARIABLE NAME	MEANING
1-10	R	Cooling tower base radius (m)
11-20	H	Cooling tower hydraulic height (m)
21-30	T	Depth of packing below ring beam (m)
31-40	D	Distance from pond to packing (m)
41-50	HP	Open height at tower base (m)
51-60	BEL	Elevation of tower base (m)
61-75	RM	Water mass flow rate (kg/sec)

(REPEAT NOT TIMES)

CARD 12 FORMAT (3F10.4)

COLUMNS	VARIABLE NAME	MEANING
1-10	VANE	Wind direction relative to X-axis (rad.)
11-20	BETA	Wind speed gradient (m/sec/m)
21-30	GAMMA	Temperature gradient (°C/m)

CARD 13 FORMAT (20I4)

COLUMNS	VARIABLE NAME	MEANING
1-80	IVEG (I, J)	Code for vegetation attenuation 0 — No vegetation attenuation 1 — Shrubbery and grass — no forest 2 — Forest — no shrubbery or grass

(NOT X NOP VALUES)

```
LEVEL  21.6  (DEC 72)                                    OS/360  FORTRAN H

            COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,
                               SOURCE,EBCDIC,NOLIST,NODECK,LOAD,MAP,NOEDIT,NOID,NOXREF
                  C                                *************************
                  C                                *                       *
                  C                                *                       *
                  C                                *  PROGRAM COOLNOISE    *
                  C                                *                       *
                  C                                *   PROGRAM AUTHOR      *
                  C                                *   T.G.CARLEY          *
                  C                                *                       *
                  C                                *************************
                  C
                  C
                  C                         THIS PROGRAM COMPUTES THE OCTAVE BAND AND
                  C                         OVERALL NOISE LEVELS AT SPECIFIED POINTS
                  C                         IN THE VICINITY OF A GROUP OF POWER PLANTS
                  C                         WHICH ARE SERVED BY NATURAL DRAFT COOLING
                  C                         TOWERS.
                  C
                  C
                  C
                  C
  ISN 0002              DIMENSION POW(40),IB(72,120),BOUNBD(20,7),BOUNDA(20,7),
                       >ICX(40),ICY(40),IBX(20),IBY(20),ARIM(7),ATMOS(7),R(40),H(40),
                       >T(40),D(40),HP(40),BEL(40),RM(40),W(40),BAND(7),BDYBND(7),
                       >RIMUW(7),RIMBND(7),BDYUW(7),SLVL(7),NPTSCR(40,20),PR(7),
                       >ARAY1(7),ARAY2(7)
  ISN 0003              DIMENSION IVECT(120),BDYEL(20),NVECT(40,20),NOSP(40),IVEG(40,20)
  ISN 0004              EQUIVALENCE (POW(1),W(1))
  ISN 0005              PI=3.14159
  ISN 0006              READ(5,1000) M,N,NBP,NOT,NOP,IWIND,IBOUND,GS,AI
  ISN 0007         1000 FORMAT(7I5,2E10.3)
                  C
  ISN 0008              IF(IBOUND.EQ.0) GO TO 6
                  C
  ISN 0010              I=1
  ISN 0011            1 READ(5,1001) NUM
  ISN 0012              READ(5,1002) (IVECT(K),K=1,NUM)
  ISN 0013              I2=1
  ISN 0014              J=1
  ISN 0015            2 IF(J.LT.IVECT(I2)) GO TO 3
  ISN 0017              IB(I,J) = 1
  ISN 0018              I2=I2+1
  ISN 0019              GO TO  15
  ISN 0020            3 IB(I,J)=0
  ISN 0021           15 J=J+1
  ISN 0022              IF(J.GT.M) GO TO 4
  ISN 0024              GO TO 2
  ISN 0025            4 I=I+1
  ISN 0026              IF(I.GT.N) GO TO 6
  ISN 0028              GO TO 1
  ISN 0029            6 CONTINUE
  ISN 0030         1001 FORMAT(I3)
  ISN 0031         1002 FORMAT(20I3)
  ISN 0032              READ(5,1020) (ICX(I),ICY(I),I=1,NOT)
  ISN 0033         1020 FORMAT(20I4)
  ISN 0034              READ(5,1030) (IBX(I),IBY(I),I=1,NOP)
  ISN 0035         1030 FORMAT(20I4)
```

```
ISN 0036          READ(5,1015) (BJYEL(K),K=1,NOP)
ISN 0037     1015 FORMAT(10F8.2)
            C
ISN 0038          DO  7 I=1,NOT
ISN 0039          READ(5,1028) NOSP(I)
ISN 0040          IF((NOSP(I)).EQ.0) GO TO 7
ISN 0042          JN=NOSP(I)
ISN 0043          READ(5,1029) (NVECT(I,J),J=1,JN)
ISN 0044        7 CONTINUE
ISN 0045     1028 FORMAT(I4)
ISN 0046     1029 FORMAT(10I5)
ISN 0047          READ(5,1045) TEMP,(ATMOS(I),I=1,7)
ISN 0048     1045 FORMAT( F5.1,7F5.2)
ISN 0049          READ(5,1040) (ARIM(I),I=1,7)
ISN 0050     1040 FORMAT(7F6.2)
ISN 0051          DO 10 I=1,NOT
ISN 0052       10 READ(5,1025)  R(I),H(I),T(I),D(I),HP(I),BEL(I),RM(I)
ISN 0053     1025 FORMAT(6F10.2,E15.3)
ISN 0054          READ(5,1190) VASE,BETA,GAMMA
ISN 0055     1190 FORMAT(3F10.4)
            C  *****READ SCREENING DATA VALUES OF IVEG  *****
ISN 0056          READ(5,1030) ((IVEG(I,J),J=1,NOP),I=1,NOT)
ISN 0057          WRITE(6,6000)
ISN 0058          WRITE(6,6010)  (R(I),H(I),T(I),D(I),HP(I),BEL(I),RM(I),I=1,NOT)
ISN 0059     6000 FORMAT('1',50X,'COOLING TOWER DATA',//6X,'COOLING TOWER',4X,'HYDRA
                 >ULIC',3X,'PACKING DEPTH',5X,'POND TO',6X,'POND TO RING',6X,'BASE',
                 >7X,'COOLING WATER',/' ',6X,'BASE RADIUS',6X,'HEIGHT',5X,'BELOW RIN
                 >G BEAM',1X,'PACKING HEIGHT',2X,'BEAM HEIGHT',5X,'ELEVATION',6X,'FL
                 >OW RATE',/' ',7X,'(METERS)',7X,'(METERS)',7X,'(METERS)',8X,'(METER
                 >S)',6X,'(METERS)',7X,'(METERS)',8X,'(KG/SEC)')
ISN 0060     6010 FORMAT('0',1X,7E15.3)
ISN 0061          CALL POWER(R,H,T,D,RM,POW,NOT)
ISN 0062          WRITE(6,6045) NOT
ISN 0063     6045 FORMAT('0',2X,////40X,'THE ACOUSTIC POWER OF THE COOLING TOWERS IN
                 > WATTS',/55X,I4,' COOLING TOWERS')
ISN 0064          WRITE(6,6050) (POW(I),I=1,NOT)
ISN 0065     6050 FORMAT(10E10.3)
ISN 0066          WRITE(6,6055)
ISN 0067     6055 FORMAT('0',2X,////53X,'NEC SITE DATA')
ISN 0068          WRITE(6,1070) M,N,NBP,NOT,NOP,GS,AI
ISN 0069     1070 FORMAT(5X,'NUMBER OF GRID POINTS IN THE X AND Y DIRECTIONS',/5X,'X
                 > = ',I5,2X,'Y = ',I5,//5X,'NUMBER OF POINTS DEFINING SITE BOUNDARY
                 >  -',I5,//5X,'NUMBER OF COOLING TOWERS - ',I5,//5X,'NUMBER OF POIN
                 >TS AT WHICH NOISE LEVELS ARE TO BE CALCULATED - ',I5,//5X,'GRID SI
                 >ZE - ',E10.3,'METERS PER GRID UNIT',//5X,'ACOUSTIC IMPEDANCE OF TH
                 >E AMBIENT AIR - ',E10.3,2X,'  MKS-RAYLS',///)
ISN 0070          WRITE (6,1100)
ISN 0071     1100 FORMAT(5X,'GRID LOCATIONS OF THE COOLING TOWERS',/10X,'X',11X,'Y')
ISN 0072          WRITE (6,1110)  (ICX(I),ICY(I),I=1,NOT)
ISN 0073     1110 FORMAT((8X,I4,8X,I4))
ISN 0074          WRITE(6,1120)
ISN 0075     1120 FORMAT(5X,'GRID LOCATIONS ON THE BOUNDARY AT WHICH NOISE LEVELS AR
                 >E TO BE CALCULATED'/10X,'X',11X,'Y')
ISN 0076          WRITE(6,1130)  (IBX(I),IBY(I),I=1,NOP)
ISN 0077     1130 FORMAT((8X,I4,8X,I4))
ISN 0078          WRITE(6,1140)
ISN 0079     1140 FORMAT(5X,'OCTAVE BAND ATTENUATIONS THAT GIVE SPECTRUM SHAPE RELAT
                 >IVE TO THE OVERALL A-WEIGHTED LEVEL AT THE COOLING TOWER RIM'//12X
```

```
                    >,'OCTAVE BAND CENTER FREQUENCY  ',/6X,'125',5X,'250',5X,'500',6X,'
                    >1000',4X,'2000',4X,'4000',4X,'8000')
ISN 0080             WRITE(6,1150)   (ARIM(I),I=1,7)
ISN 0081        1150 FORMAT(5X,F6.2,6(2X,F6.2))
ISN 0082             WRITE(6,1160) TEMP
ISN 0083        1160 FORMAT('0',//5X,'TEMPERATURE = ',F5.1,' DEGREES CELSIUS',///)
ISN 0084             WRITE(6,1162)
ISN 0085        1162 FORMAT('0','***** OCTAVE BAND ATMOSPHERIC ABSORPTION ATTENUATION C
                    >OFFICIENTS *****',/)
ISN 0086             WRITE(6,1170)    (ATMOS(I),I=1,7)
ISN 0087        1170 FORMAT(5X,'ATTENUATION COEFFICIENTS - DB PER 100 METERS',//12X,'OC
                    >TAVE BAND CENTER FREQUENCIES',/6X,'125',5X,'250',5X,'500',6X,'1000
                    >',4X,'2000',4X,'4000',4X,'8000',//5X,F6.2,6(2X,F6.2))
ISN 0088             WRITE(6,1191) VANE,BETA,GAMMA
ISN 0089        1191 FORMAT(5X,'WIND DIERCTION RELATIVE TO THE X AXIS=',F10.4,'RADIANS'
                    >,//5X,'THE WIND SPEED GRADIENT=',F10.4,'METERS PER SECOND PER METE
                    >R',//5X,'THE TEMPERATURE GRADIENT=',F10.4,'DEGREES CELSIUS PER MET
                    >ER')
                C ** INITIALIZE ACCUMULATED BAND LEVELS **
ISN 0090             DO 8  I=1,NOP
ISN 0091             DO 8  J=1,7
ISN 0092             BOUNBD(I,J) = 0.
ISN 0093           8 BOUNDA(I,J) = 0.
                C    *********BOUNDARY POINT CALCULATIONS********
ISN 0094             DO 35 I=1,NOT
ISN 0095             DO 35 J=1,NOP
ISN 0096          35 NPTSCR(I,J)=1
ISN 0097             DO 37 I=1,NOT
ISN 0098             IF(NOSP(I).EQ.0) GO TO 37
ISN 0100             LIM=NOSP(I)
ISN 0101             DO 36 J=1,LIM
ISN 0102             JT=NVECT(I,J)
ISN 0103          36 NPTSCR(I,JT)=0
ISN 0104          37 CONTINUE
                C
ISN 0105             I=1
ISN 0106          20 WRITE(6,1220)     I,IBX(I),IBY(I)
ISN 0107        1220 FORMAT('1',10X,'BOUNDARY POINT NUMBER',I4,2X,'LOCATED AT GRID LOCA
                    >TION X = ',I4,2X,'AND Y = ',I4,///)
ISN 0108          30 RLBPX = (IBX(I)-1)*GS
ISN 0109             RLBPY = (IBY(I)-1)*GS
                C
ISN 0110          40 IT=1
                C ***** EXCESS ATTENUATION FOR SCREENING *****
ISN 0111          41 CONTINUE
ISN 0112             IF(NPTSCR(IT,I).NE.0) GO TO 50
ISN 0114             IT=IT+1
ISN 0115             IF(IT.GT.NOT) GO TO 140
ISN 0117             GO TO 41
                C
ISN 0118          50 PSQR = (W(IT)*AL)/(2.*PI*R(IT)*HP(IT))
ISN 0119             C1=4.E-10
ISN 0120             RIMA = 10.*ALOG10(PSQR/C1)
ISN 0121             RLCTX = (ICX(IT)-1)*GS
ISN 0122             RLCTY = (ICY(IT)-1)*GS
ISN 0123             DELTX = RLBPX - RLCTX
ISN 0124             DELTY = RLBPY - RLCTY
ISN 0125             DELTZ = BDYEL(I) - BEL(IT)
```

```
ISN 0126          DISTH=SQRT(DELTX**2+DELTY**2) - R(IT)
ISN 0127          DIST=SQRT(DISTH**2+DELTZ**2)
ISN 0128          IF(DELTX.EQ.0.) GO TO 52
ISN 0130          ANG = ATAN(DELTY/DELTX)
ISN 0131          GO TO 54
ISN 0132       52 ANG=PI/2.
ISN 0133       54 CONTINUE
ISN 0134          ACTN = ATAN(SQRT((DIST+2.*R(IT))/DIST))
ISN 0135          PSQB = (W(IT)*AL/((PI**2 )*(DIST**2 +2.*DIST*R(IT))))*ACTN
ISN 0136       60 BOUNA = 10.*ALOG10(PSQB/C1)
             C
ISN 0137          CALL AOCT(RIMBND,ABIM,RIMA)
             C
ISN 0138          CALL AOCT(BDYBND,ABIM,BOUNA)
             C
ISN 0139          DO 70 I1=1,7
ISN 0140       70 RIMUW(I1)=RIMBND(I1)
ISN 0141          CALL  AWEGHT(RIMUW,1.0)
             C
             C
ISN 0142          DO 80 I1=1,7
ISN 0143       80 BDYUW(I1)=BDYBND(I1)
ISN 0144          CALL AWEGHT(BDYUW,1.0)
             C
             C    ***** WRITE UNATTENUATED LEVELS *****
ISN 0145          WRITE(6,1230)  IT,ICX(IT),ICY(IT)
ISN 0146     1230 FORMAT(2X,'>>>> COOLING TOWER NO. ',I2,'  LOCATED AT GRID LOCATION
                 > X = ',I4,2X,'AND Y = ',I4,///)
ISN 0147          WRITE(6,1240)
ISN 0148     1240 FORMAT(5X,'OVERALL AND OCTAVE BAND NOISE LEVELS - RE:2.E-05 NEWTON
                 >S PER METER**2---ATTENUATION DUE ONLY TO WAVE SPREADING')
ISN 0149          WRITE(6,1242)
ISN 0150     1242 FORMAT('0',5X,'***** OCTAVE BAND AND OVERALL SOUND PRESSURE LEVEL
                 >AT THE COOLING TOWER RIM *****',//)
ISN 0151          WRITE(6,1250)  RIMA,(RIMBND(I1),I1=1,7)
ISN 0152     1250 FORMAT(5X,'A-WEIGHTED OVERALL LEVEL =',F6.2,//5X,'A-WEIGHTED OCTAV
                 >E BAND LEVELS',//12X,'OCTAVE BAND CENTER FREQUENCY-HZ',/6X,'125',5
                 >X,'250',5X,'500',6X,'1000',4X,'2000',4X,'4000',4X,'8000',//5X,F6.2
                 >,6(2X,F6.2))
ISN 0153          WRITE(6,1252)
ISN 0154     1252 FORMAT('0',5X,'***** UNATTENUATED OCTAVE BAND AND OVERALL SOUND PR
                 >ESSURE LEVEL AT THE BOUNDARY POINT *****',//)
ISN 0155          WRITE(6,1260)  BOUNA,(BDYBND(I1),I1=1,7)
ISN 0156     1260 FORMAT(5X,'UNWEIGHTED OVERALL LEVEL =',F6.2,//5X,'UNWEIGHTED OCTAV
                 >E BAND LEVELS',//12X,'OCTAVE BAND CENTER FREQUENCY-HZ',/6X,'125',5
                 >X,'250',5X,'500',6X,'1000',4X,'2000',4X,'4000',4X,'8000',//5X,F6.2
                 >,6(2X,F6.2))
             C    ***** EXCESS ATTENUATION FOR ATMOSPHERIC ABSORPTION *****
ISN 0157          DO 90 I1=1,7
ISN 0158       90 SLVL(I1)=BDYUW(I1)
ISN 0159          CALL ASORB(ATMOS,SLVL,DIST)
             C
             C ***** EXCESS ATTENUATION DUE TO WIND *****
ISN 0160          IF(IWIND.EQ.0) GO TO 100
ISN 0162          CALL WIND(DIST,TEMP,ANG,BDYBND,VANE,BETA,GAMMA)
ISN 0163      100 CONTINUE
             C ***** EXCESS ATTENUATION FOR GRASS AND SHRUBBERY *****
ISN 0164          IV=IVEG(IT,I)
```

```
ISN 0165          CALL VEG(BDYBND,DIST,IV)
ISN 0166          WRITE(6,1270)
ISN 0167     1270 FORMAT('0',5X,'***** ATTENUATED OCTAVE BAND LEVELS AT THE BOUNDARY
                 > POINT *****',//)
ISN 0168          WRITE(6,2050)  (BDYBND(J),J=1,7)
ISN 0169     2050 FORMAT(5X,'UNWEIGHTED LEVELS WITH EXCESS ATTENUATION',/5X,F6.1,6(2
                 >X,F6.1))
            C
ISN 0170          DO 120 J=1,7
ISN 0171          RK1=(BOUNBD(I,J))/10.
ISN 0172          IF(ABS(RK1).GT.20.) RK1=-20.
ISN 0174          RK2=10.**(RK1)
ISN 0175          RK3=(BDYBND(J))/10.
ISN 0176          IF(ABS(RK3).GT.20.) RK3=-20.
ISN 0178          RK4=10.**(RK3)
ISN 0179          SUM1=RK2+RK4
ISN 0180      120 BOUNBD(I,J)=10.*ALOG10(SUM1)
            C
ISN 0181          CALL AWEGHT(BDYBND,-1.)
            C
ISN 0182          DO 130 J=1,7
ISN 0183          RK5=(BOUNDA(I,J))/10.
ISN 0184          IF(ABS(RK5).GT.20.) RK5=-20.
ISN 0186          RK6=10.**(RK5)
ISN 0187          RK7 = (BDYBND(J))/10.
ISN 0188          IF(ABS(RK7).GT.20.) RK7=-20.
ISN 0190          RK8=10.**(RK7)
ISN 0191          SUM2=RK6+RK8
ISN 0192      130 BOUNDA(I,J)=10.*ALOG10(SUM2)
            C
ISN 0193          WRITE(6,2060) (BDYBND(J),J=1,7)
ISN 0194     2060 FORMAT(5X,'A-WEIGHTED LEVELS WITH EXCESS ATTENUATION',/5X,F6.1,6(2
                 >X,F6.),/////)
            C ** INCREMENT 'IT' FOR NEXT COOLING TOWER **
ISN 0195          IT = IT+1
ISN 0196          IF(IT.GT.NOT) GO TO 140
ISN 0198          GO TO 41
ISN 0199      140 CONTINUE
            C ** WRITE TOTAL ATTENUATED LEVELS FOR BOUNDARY POINT **
ISN 0200          WRITE(6,2070) I
ISN 0201     2070 FORMAT(23X,'TOTAL OCTAVE BAND LEVELS WITH EXCESS ATTENUATION FOR B
                 >OUNDARY POINT-',I4,//45X,'OCTAVE BAND CENTER FREQUENCY-HZ',/45X,'1
                 >25',5X,'250',5X,'500',6X,'1000',4X,'2000',4X,'4000',4X,'8000')
ISN 0202          WRITE(6,2080) (BOUNBD(I,J),J=1,7)
ISN 0203     2080 FORMAT(25X,'UNWEIGHTED',9X,F6.2,6(2X,F6.2))
ISN 0204          WRITE(6,2090) (BOUNDA(I,J),J=1,7)
ISN 0205     2090 FORMAT(25X,'A-WEIGHTED',9X,F6.2,6(2X,F6.2))
            C
ISN 0206          DO 145 J=1,7
ISN 0207          ARAY1(J)=BOUNBD(I,J)
ISN 0208      145 ARAY2(J)=BOUNDA(I,J)
ISN 0209          CALL OVER(ARAY1,UWOA)
ISN 0210          WRITE(6,2100) UWOA
ISN 0211     2100 FORMAT('0',45X,'UNWEIGHTED OVERALL LEVEL = ',F10.2,' DB - RE 2*10*
                 >*(-5) NEWTONS PER SQUARE METER',//)
ISN 0212          CALL OVER(ARAY2,AWOA)
ISN 0213          WRITE(6,2110) AWOA
ISN 0214     2110 FORMAT(46X,'A-WEIGHTED OVERALL LEVEL = ',F10.2,' DB - RE 2*10**(-5
```

```
                              >) NEWTONS PER SQUARE METER')
                            C
                            C ** INCREMENT 'I' FOR NEXT BOUNDARY POINT **
          ISN 0215                I=I+1
          ISN 0216                IF(I.GT.NOP) GO TO 150
          ISN 0218                GO TO 20
          ISN 0219            150 CONTINUE
          ISN 0220                WRITE (6,2120)
          ISN 0221           2120 FORMAT(5X,'***** LE BRUIT EST FINIS *****')
                            C
          ISN 0222                STOP
          ISN 0223                END


LEVEL  21.6  (DEC 72)                          OS/360  FORTRAN H

          COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,
                             SOURCE,EBCDIC,NOLIST,NODECK,LOAD,MAP,NOEDIT,NOID,NOXREF
                  C
                  C
   ISN 0002               SUBROUTINE AOCT(BAND,ARIM,ALEVEL)
   ISN 0003               DIMENSION BAND(7),ARIM(7)
   ISN 0004               DO 10 I=1,7
   ISN 0005            10 BAND(I)=ALEVEL-ARIM(I)
   ISN 0006               RETURN
   ISN 0007               END


LEVEL  21.6  (DEC 72)                          OS/360  FORTRAN H

          COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,
                             SOURCE,EBCDIC,NOLIST,NODECK,LOAD,MAP,NOEDIT,NOID,NOXREF
                  C
                  C
   ISN 0002               SUBROUTINE ASORB(ATMOS,SLVL,DIST)
                  C ***** SUBROUTINE TO ATTENUATE OCTAVE
                  C         BAND LEVELS FOR ATMOSPHERIC ABSORPTION *****
   ISN 0003               DIMENSION ATMOS(7),SLVL(7)
   ISN 0004               DO 10 I1=1,7
   ISN 0005            10 SLVL(I1) = SLVL(I1) - (ATMOS(I1))*(DIST/100.)
   ISN 0006               RETURN
   ISN 0007               END
```

```
LEVEL  21.6  (DEC 72)                              OS/360  FORTRAN H

        COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,
                           SOURCE,EBCDIC,NOLIST,NODECK,LOAD,MAP,NOEDIT,NOID,NOXREF
              C
              C
  ISN 0002          SUBROUTINE AWEGHT(BNDWGT,A)
              C ***** TO A-WEIGHT A=-1 *** TO UNWEIGHT A=+1  *****
  ISN 0003          DIMENSION BNDWGT(7)
  ISN 0004          BNDWGT(1)=BNDWGT(1) + (16.1*A)
  ISN 0005          BNDWGT(2)=BNDWGT(2) + (8.6*A)
  ISN 0006          BNDWGT(3)=BNDWGT(3) + (3.2*A)
  ISN 0007          BNDWGT(5)=BNDWGT(5) - (1.2*A)
  ISN 0008          BNDWGT(6)=BNDWGT(6) - (1.0*A)
  ISN 0009          BNDWGT(7)=BNDWGT(7) + (1.1*A)
  ISN 0010          RETURN
  ISN 0011          END
```

```
LEVEL  21.6  (DEC 72)                              OS/360  FORTRAN H

        COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,
                           SOURCE,EBCDIC,NOLIST,NODECK,LOAD,MAP,NOEDIT,NOID,NOXREF
              C
              C
  ISN 0002          SUBROUTINE OVER(BNDL,OVRAL)
  ISN 0003          DIMENSION BNDL(7)
  ISN 0004          SUM=0.
  ISN 0005          DO 10 J=1,7
  ISN 0006          IF(BNDL(J) .LE. 0.) GO TO 5
  ISN 0008        8 PSQ=10.**((BNDL(J))/10.)
  ISN 0009          GO TO 10
  ISN 0010        5 PSQ=4.E-10
  ISN 0011       10 SUM=SUM+PSQ
  ISN 0012          IF(SUM.GT. 1.1) GO TO 15
  ISN 0014          OVRAL=0.
  ISN 0015          GO TO 20
  ISN 0016       15 OVRAL=10.*ALOG10(SUM)
  ISN 0017       20 RETURN
  ISN 0018          END
```

```
LEVEL  21.6  (DEC 72)                              OS/360  FORTRAN H

        COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,
                           SOURCE,EBCDIC,NOLIST,NODECK,LOAD,MAP,NOEDIT,NOID,NOXREF
              C
              C
  ISN 0002          SUBROUTINE POWER(R,H,T,D,RM,POW,NOT)
  ISN 0003          DIMENSION R(40),H(40),T(40),D(40),RM(40),POW(40)
  ISN 0004          A=0.95E-5
  ISN 0005          B=1.8E-5
  ISN 0006          DO 10 IT=1,NOT
  ISN 0007       10 POW(IT)=RM(IT)*R(IT)*(A*((T(IT)/H(IT))**2.)+B*((D(IT)/H(IT))**2.))
  ISN 0008          RETURN
  ISN 0009          END
```

```
LEVEL  21.6  (DEC 72)                              OS/360  FORTRAN H

         COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,
                            SOURCE,EBCDIC,NOLIST,NODECK,LOAD,MAP,NOEDIT,NOID,NOXREF
                   C
                   C
  ISN 0002              SUBROUTINE VEG (BDYBND,DIST,IV)
  ISN 0003              DIMENSION BDYBND(7),FR(7)
  ISN 0004              IF(IV.EQ.0) GO TO 50
  ISN 0006              IF(IV.EQ.2) GO TO 20
  ISN 0008              DO 10 I=1,7
  ISN 0009              FR(I)=125.
  ISN 0010              IF(I.EQ.1) GO TO 10
  ISN 0012              FR(I)=125.*(2.**(I-1))
  ISN 0013           10 BDYBND(I)=BDYBND(I)-(.18*ALOG10(FR(I))-.31)*DIST
  ISN 0014              GO TO 50
  ISN 0015           20 DO 30 I=1,7
  ISN 0016              FR(I)=125.
  ISN 0017              IF(I.EQ.1) GO TO 30
  ISN 0019              FR(I)=125.*(2.**(I-1))
  ISN 0020           30 BDYBND(I)=BDYBND(I)-0.01*((FR(I))**0.3333)*DIST
  ISN 0021           50 RETURN
  ISN 0022              END
```

```
LEVEL  21.6  (DEC 72)                              OS/360  FORTRAN H

         COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,
                            SOURCE,EBCDIC,NOLIST,NODECK,LOAD,MAP,NOEDIT,NOID,NOXREF
                   C
                   C
  ISN 0002              SUBROUTINE WIND(DIST,TEMP,ANG,BDYBND,VANE,BETA,GAMMA)
  ISN 0003              DIMENSION FR(7),BDYBND(7)
  ISN 0004              IF(GAMMA.EQ.0..AND.BETA.EQ.0.) GO TO 50
  ISN 0006              ATEM = TEMP + 273.2
  ISN 0007              SPEED = 20.05*SQRT(ATEM)
  ISN 0008              PHICR=ARCOS((SPEED/(2.*ATEM))*(GAMMA/BETA))
  ISN 0009              COF1 = 3.22
  ISN 0010              PHI = ANG-VANE
  ISN 0011              IF(ABS(PHI)-PHICR) 25,30,30
  ISN 0012           25 ALPHA=(SPEED*GAMMA)/(2.*ATEM)
  ISN 0013              DENOM=(BETA*COS(PHI))-ALPHA
  ISN 0014              IF(ABS(ALPHA)-BETA) 10,5,5
  ISN 0015            5 IF(ALPHA.GT.0.) GO TO 30
  ISN 0017           10 XSHDW = (SQRT((2.*SPEED)/(DENOM)))*COF1
  ISN 0018              RAT = DIST/XSHDW
  ISN 0019              ATT=27.
  ISN 0020              IF(RAT.GE.3) GO TO 28
  ISN 0022              ATT=9.*(RAT-1.)
  ISN 0023           28 DO 29 I=1,7
  ISN 0024           29 BDYBND(I)=BDYBND(I)-ATT
  ISN 0025              GO TO 50
  ISN 0026           30 DO 46 I=1,7
  ISN 0027              FR(I)=125.
  ISN 0028              IF(I.EQ.1) GO TO 40
  ISN 0030              FR(I)=125.*(2.**(I-1))
  ISN 0031           40 FTR=FR(I)*DIST
  ISN 0032              IF(FTR.LT.1.21945) GO TO 46
  ISN 0034           45 BDYBND(I)=BDYBND(I)-10.*(ALOG(FTR)-5.086)
  ISN 0035           46 CONTINUE
  ISN 0036           50 RETURN
  ISN 0037              END
```

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