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USAARU REPORT NO. 68-3

EFFECTS OF DOWNWASH UPON MAN

By

W. P. Schane, LTC, MC

November 1967

U. S. ARMY AEROMEDICAL RESEARCH UNIT
Fort Rucker, Alabama

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Eight types of threat are explored in some detail, and conclusions are drawn concerning needs for protection.

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APPROVED: ROBERT W. BAILEY
LTC, MSC
Commanding

LIST OF SYMBOLS

A = surface area exposed in square feet

A_c = duct exit area in square feet

a = diameter in inches

C_D = coefficient of drag

C_L = coefficient of lift

D = drag in pounds

d = density in pounds/cubic foot

L = lift in pounds

l = length in feet

μ = coefficient of viscosity in slugs/ft second

P = total pressure in pounds/sq ft; $P = (p + q)$

p = static pressure in pounds/sq ft

q = dynamic pressure in pounds/sq ft

RQ = respiratory quotient

ρ = air density, in slugs/cubic foot

T = thrust in pounds

V_o = forward air speed in ft/sec

V_T = equilibrium velocity of spherical particle or object

v = velocity in ft/sec

W = weight in pounds

CONVERSION FACTORS

FROM	TO	MULTIPLY BY
psi	psf	144
ft/sec	knots	0.5921
ft/min	knots	0.009868
mph	knots	0.8684

FORMULA

$$V_T = \sqrt{\frac{W}{\frac{\rho C_D}{2} \times \frac{\pi}{4} \times \left(\frac{a}{12}\right)^2}}$$

$$q = 1/2\, \rho\, v^2$$

$$v = \sqrt{\frac{2q}{\rho}}$$

$$L = C_L\, q\, A$$

$$D = C_D\, q\, A$$

$$\text{Reynold's number} = \frac{\text{Inertial force}}{\text{Viscous force}} = \frac{\rho\, v\, l}{\mu}$$

$$\text{Disc loading in a hover} = \frac{\text{aircraft gross weight}}{\text{total rotor disc area}}$$

$$\text{Blade loading in a hover} = \frac{\text{aircraft gross weight}}{\text{total rotor blade area}}$$

TABLE 1

	GROSS WEIGHT IN LBS.*	ROTOR DIAMETER IN FEET *	DISC AREA IN SQ FEET	DISC LOADING IN LB/SQ FEET
OH-13S	2,850	37	1,075.2126	2.6506
OH-23G	2,800	35.425	985.6223	2.8408
OH-6A	2,163	26.33	544.6337	3.9714
UH-19D	7,500	53	2,206.1886	3.3995
UH-1B	6,600	44	1,520.5344	4.3405
UH-1D	9,500	48	1,809.5616	5.2498
CH-21	15,200	44 x 2	3,041.0688	4.9982
CH-34	13,000	56	2,463.0144	5.2780
CH-37	31,000	72	4,071.5136	7.6138
CH-47A	33,000	59 x 2	5,467.9548	6.0351
CH-47B	40,000	60 x 2	5,654.8800	7.0735
CH-54A	42,000	72	4,071.5136	10.3155
XC-142A	37,500	15.5 x 4	754.7692	49.6840
AH-1G Cobra	9,500	44.0	1,520.5344	6.2478
AH-56A AAFSS	16,995	50.4	1,995.0416	8.5186

* Reference 3

EFFECTS OF DOWNWASH UPON MAN

The question has arisen, what are the present and anticipated threats to man imposed by helicopter and VTOL downwash?

Very little direct research has been performed in this area. Therefore, it has been necessary to draw heavily upon indirect information.

This paper is a composite of information derived from:

1. Data generated for other reasons, but applicable to helicopter downwash.

2. Mathematical calculations.

3. Data collected by this laboratory to characterize downwash patterns in Army helicopters and experimental aircraft.

4. Personal experience.

The conclusions presented are thoughtful opinions, and should be looked upon as nothing more. It is hoped, however, that the following discussion may provide insight that will assist in answering the question asked, and may indicate where direct research would be most helpful.

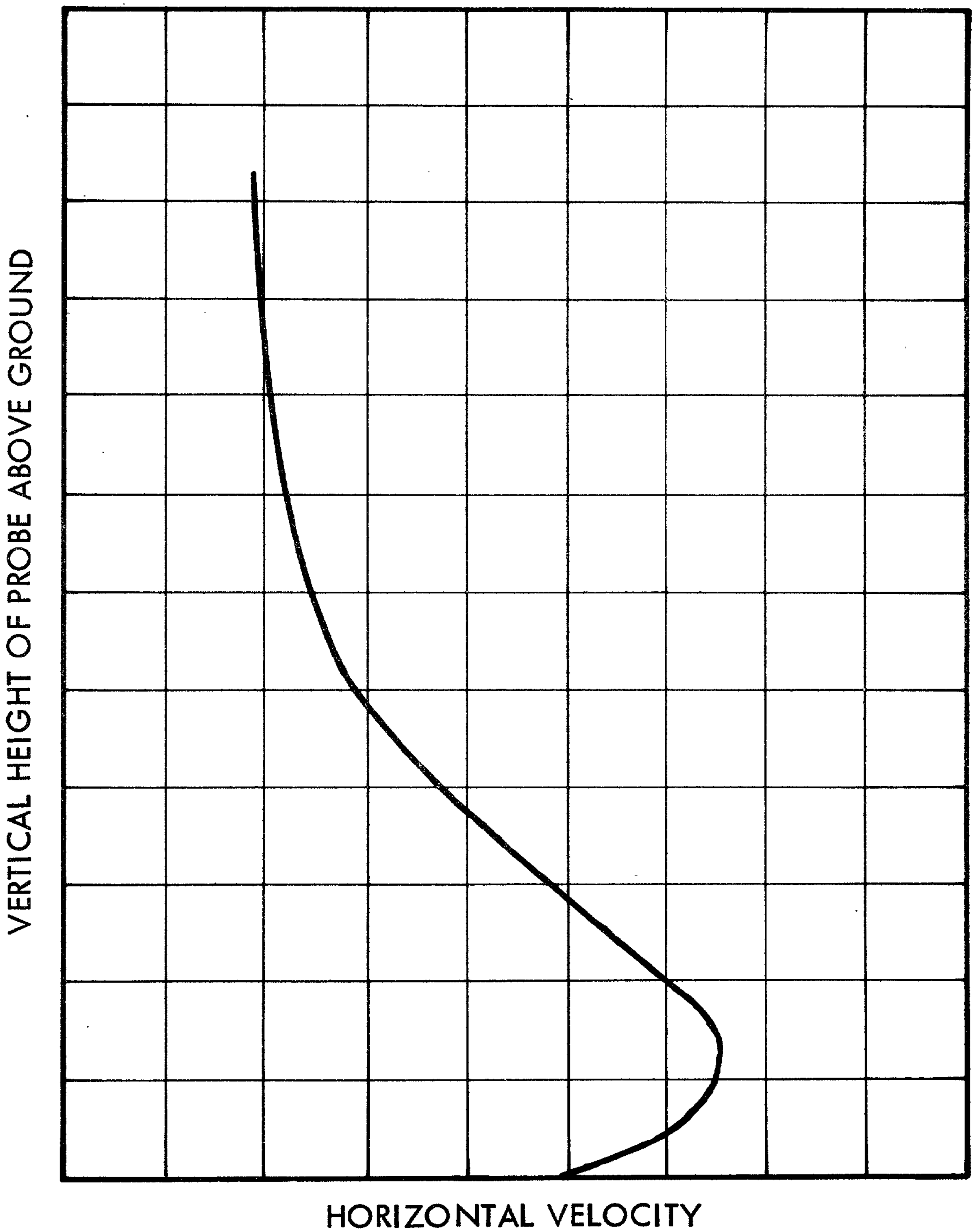
GENERAL CHARACTERISITCS OF HELICOPTER DOWNWASH

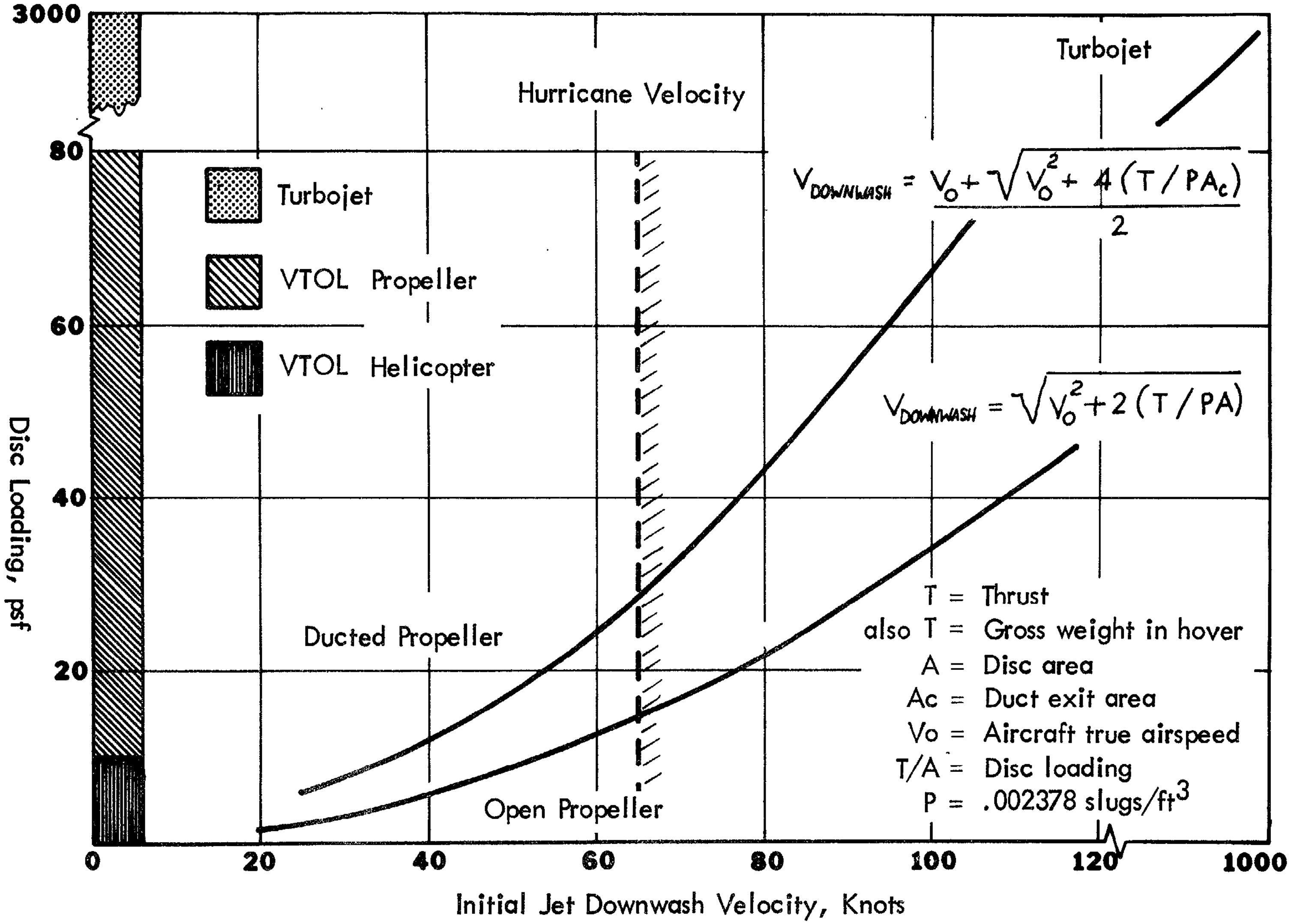
The following comments are generally applicable to downwash when the helicopter is at a hover.

1. "Downwash" does not produce significant vertical components to the resultant wind when a helicopter is within ground effect. The resultant winds are horizontal at all levels to which a standing man is exposed.

2. The magnitude of resultant wind is directly related to the gross weight of the aircraft, and to some extent to disc loading. Initial downwash velocity is directly proportional to the square Root of disc loading. The maximum gross weights and disc loadings at maximum gross weight of many Army helicopters are reviewed in Table 1.

FIGURE 1


VERTICAL HEIGHT OF PROBE ABOVE GROUND
HORIZONTAL VELOCITY



DISC LOADINGS vs AVERAGE DOWNWASH VELOCITY
FOR VARIOUS LIFT DEVICE CONFIGURATIONS

FIGURE 2

3. The magnitude of resultant winds at ground level is inversely proportional to the height above the ground of the thrust generator when the thrust generator is within ground effect.

4. The magnitude of resultant wind is not uniform vertically above a point on the ground. Figure 1 indicates the general shape of the curve which relates wind velocity above any particular point within the downwash pattern with heights above the ground of the measuring probe at that location. In general, maximum winds are estimated to be between 5 and 20 inches above the ground for most operational helicopters and VTOL aircraft.

5. The height above the ground of maximum winds is directly proportional to the effective disc diameter of the thrust generator, and to the height above the ground of the thrust generator.

6. Maximum wind velocities generally are recorded in a circle of radius 1 to 1.5 disc diameters from the center of impingement.

7. In helicopters, operation "within ground effect" occurs when the rotor is at 1.0 disc diameter or less above the deflecting surface. Operation within ground effect is favorable in helicopters, and requires less power than hovering out of ground effect.

8. The downwash characteristics of the various types of VTOL aircraft must be evaluated by type, since the disc loadings, downwash geometry, and decay curves are independently variable with each type of lift generator.

MAGNITUDE OF THE PROBLEM

Figure 2 (Reference 7) indicates the general range of downwash velocities that can be expected with various types of VTOL aircraft at various disc loadings. It is important to note the breaks in scale at the top of the ordinate and right of the abscissa. If turbojet propulsion is considered, the magnitude of downwash will increase by 10 fold.

Table 2 indicates maximum wind velocities in ft/min measured in the downwash of a variety of operational helicopters while in a hover mode within ground effect. (XC-142A was at a hover an estimated 50 feet above the ground).

In 1961, Leese measured downward velocities under the CH-21, CH-34, and CH-37. His findings are noted in Table 3 (Reference 15).

TABLE 2

AIRCRAFT	ROTOR DIAMETER	DISC LOADING	MAXIMUM WIND VELOCITY	
OH-13	37 feet	2.65 lb/ft^2	2500 ft/min	*
UH-1A	44 feet	4.34 lb/ft^2	3000 ft/min	*
CH-21	44 feet x 2	5.00 lb/ft^2	3500 ft/min	*
CH-34	56 feet	5.28 lb/ft^2	3800 ft/min	*
CH-37	72 feet	7.61 lb/ft^2	5200 ft/min	*
CH-47A	59 feet x 2	6.04 lb/ft^2	5500 ft/min	‡
CH-47B	60 feet x 2	7.07 lb/ft^2	>10,000 ft/min	‡
CH-54A	72 feet	10.32 lb/ft^2	>10,000 ft/min	
XC-142A	15.5 feet x 4	49.68 lb/ft^2	Much >10,000 ft/min	

* Reference 15

‡ Reference 17

TABLE 3 **

Distance from Rotor Center Line, ft	Rotor Height ft	Horizontal Velocities, fpm, at Indicated Heights Above Ground 18 in.	26 in.	42 in.	50 in.
	H-21 Helicopter, 44-ft-diam Rotor *				
40	15.4	2700	2100	1900	1200
50		2200	1700	1600	900
60		--	--	400	400
	H-34 Helicopter, 56-ft-diam Rotor				
40	9.2	3400	2600	1300	560
50		3100	2400	2300	2100
60		3200	2600	2200	800
70		3400	2600	2400	2300
80		3100	2900	2000	2300
	H-37 Helicopter, 72-ft-diam Rotor				
40	14.1	3000	4200	3500	3600
50		3800	4900	3900	3900
60		4000	5200	3400	3600
70		3800	4700	3300	3300
80		3700	4600	3100	3400

* Velocities shown for the dual-rotor H-21 were measured below the front rotor.

** Reference 15

In 1967, measurements were made by this laboratory under the CH-47A, CH-47B, CH-54A and XC-142A.

Tables 4, 5 and 6 indicate our findings under the CH-47A, CH-47B, and CH-54A.

Studies performed under the XC-142A were not as academically precise as the studies under the CH-47 and CH-54, but were no less revealing.

XC-142A

Ground winds 4-6 knots. Hovered over hard surface runway at height above terrain of 50 to 150 feet as estimated by radar altimeter.

Hovered over trees at 75 feet above tree-top.

Measuring height 4 feet.

Measuring instruments, Anemometer, wind vane ML-446A/PMQ-3; Velometer, Alnor, Type 3002 No. 22644 and No. 29906.

Fixed reference was to the ground. The aircraft drifted considerably.

Density altitude + 1200 feet.

Rotor diameter 15.5 feet x 4.

Our measurements were taken around a flight profile to satisfy Air Force and contractor desires.

It is our impression that our observations are only gross approximations because:

1. The aircraft drifted in all 3 axes during measurement. Our reference point was to a point on the ground over which the aircraft was attempting to hold. We had no communication whatever with the aircraft and could only estimate height of the aircraft above terrain.

2. In many instances the downwash velocities encountered exceeded 10,000 feet/min which was the limit of our recording capability.

3. Winds were very gusty with much variation in both magnitude and direction.

Understanding these conditions we noted the following:

1. With the aircraft at a hover 100 feet above terrain, winds directly under the aircraft were erratic and gusty to 20 knots.

TABLE 4 *

CH-47A

Ground winds 6-10 knots
Hover, wheel height 5 feet
Measuring height 4 feet
Measuring instrument Anemometer wind vane ML-446A/PMQ-3 Belfort Inst. Co.
Fixed reference was to the aircraft.
Density altitude at 1000 hr local + 100 feet.
Rotor diameter 59 feet 1 inch x 2.
Nominal gross weight = 33,000 pounds.
Nominal disc loading = 6.0351 lb/ft^2.

	10	20	30	40	50	60	70	80	90	100	110	120	130
Front	1.5	3.5	4.0	3.5	3.0	3.0	3.0	1.5	.8	.5	GUSTS ±.5		
Rt Front	1.2	1.2	4.0	5.5	4.5	5.0	4.0	4.5	4.5	5.0	3.5	3.5	±.5
Lt Front	1.5	1.5	4.0	5.0	5.5	5.0	4.0	4.0	4.5	4.5	4.0	3.5	±.5
Rear	2.0	3.0	5.0	5.5	4.5	4.0	4.0	3.5	3.0	3.0	2.5	2.5	±.5
Rt Rear	1.5	2.5	4.5	5.5	4.0	3.5	3.0	3.5	3.0	3.5	3.0	3.5	±.5
Lt Rear	1.5	2.5	4.0	5.5	4.5	4.0	3.5	3.0	3.0	3.5	3.5	3.0	±.5

* Reference 17

Numbers are wind velocities in fpm x 10^3

TABLE 5 **

CH-47B

Ground winds 5-8 knots
Hovered wheel height 3 feet
Measuring height 4 feet
Measuring instrument Velometer Type 3002 No. 29906
Fixed reference was to the aircraft.
Density altitude at 0900 + 380 feet.
Rotor diameter 60 feet 1 inch x 2.

Nominal gross weight 40,000 pounds.
Nominal disc loading 7.0735 lb/ft^2
Actual gross weight during test varied from 39,300 pounds to 37,600 pounds.

	FEET FROM CENTER OF ROTOR SHAFT																		
	20	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180	190	200
Front	3	5*	5	3*	4*	2	2*	1	1	.5									
Front Rt	5*	7*	8	8	8*	6	4	4*	4*	3*	2	2	2	2	1	1	1	.5	.5
Front Lt	3*	3	6	6*	7*	3*	3*	3*	2*	2*	2	2	1	1	1	1	.5	.5	.5
Rear Lt	2	5*	8*	8*	8*	8*	8*	8*	6*	6*	6*	6*	6*	8*	6*	4*	2*	2*	2*
Rear Rt	4*	10*	10*	10*	9	9	6	6	6	4	4	3	4*	2	2*	2*	1	1	.5
Rear	4	6	6	8*	10*	10*	6*	6*	4*	4*	4*	4*	4*	2	2	2	2	2	3*

Nominal gross weight 33,000 pounds.
Nominal disc loading 5.8356 lb/ft^2
Actual gross weight during test varied from 33,000 pounds to 31,500 pounds.

	FEET FROM CENTER OF ROTOR SHAFT																		
	20	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180	190	200
Front	3	6	6*	4*	6*	6*	3*	2*	1*	1*	.5								
Front Rt	8*	8*	8*	4*	4*	2*	3*	2*	2*	3*	2*	2*	1*	1*	2*	1*	1*	1*	1*
Front Lt	6*	6*	6	4*	7*	8*	6*	6*	4*	5*	2*	2*	2*	2*	1*	2*	2*	1	1
Rear Lt	3*	4	6	7*	7	7*	7*	4	4*	4*	3*	4*	3*	2	3*	2*	2*	1*	1*
Rear Rt	3	8	6	6*	4*	6*	4*	4*	4*	3*	3*	2*	2*	2	1*	2*	2*	1	1
Rear	4	6	7	6	4*	6*	3*	4*	3*	3*	2*	2*	2*	2*	1*	3*	3*	1	1

** Reference 17

Number are wind velocities in fpm x 10^3

* = gusting $\pm$ 1.0 x 10^3 fpm

TABLE 6

22 September 1967 Gross weight 42,000 lbs.

CH-54-A

Ground winds 0-4 knots.
Hovered, load height 4 feet, wheel height 20 feet.
Measuring height 4 feet.
Measuring instrument Velometer Type 3002 No. 29906.
Fixed reference was to the load.
Density altitude at 1200 hours $\pm$ 1500 feet.
Rotor diameter 72 feet.

	FEET FROM CENTER OF LOAD																	
	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180	190	200
Front	6	5	4	4	3	2	1	.5	.5									
Lt Side	2	4	10	4.5	6	2.5	2.5	2	3	2	2	2	2	.5	.5			
Rt Side	4	6	6	4	5	3	2	1	1	1	.5	1	.5	.5				
Rear	3	4	6	7	8	9	6	4	3	3	4	3	2	2	1	1	.5	.5

Numbers are wind velocity in fpm x 10^3

Some gusting was present $\pm$ .5 x 10^3 fpm

2. With the aircraft at a hover 100 feet above terrain, winds of 60 knots were recorded along the circumference of a circle with radius 75 feet from the reference point.

3. With the aircraft at a hover 100 feet above terrain, winds between these two references were gusty and exceeded 100 knots.

4. With the aircraft at a hover 100 feet above terrain, winds of 60 knots extended from 75 feet to 125 feet from ground reference, then gradually diminished such that winds of 30 knots with 10 knot gusts were recorded at 250 feet from ground reference.

5. At 150 feet above terrain, the aircraft transitioned from hover to forward flight. At 75 feet behind the aircraft, the winds abruptly increased from gusty winds at 60 knots to steady winds above 100 knots.

6. During test, large metal meterorological anemometers were used by the Air Force. The aircraft never hovered below 50 feet above terrain. Nonetheless, three of these anemometers were destroyed by the downwash. (See Figure 3).

7. When the aircraft hovered an estimated 75 feet over tree tops and 125 feet above terrain, long leaf pine trees 8 inches in diameter were markedly deformed by the downwash (See Figure 4), 4 inch hardwood limbs were broken off (See Figure 5) and small trees were uprooted (See Figure 6).

ADVERSE EFFECTS OF DOWNWASH

The following adverse effects of aircraft downwash upon man have been suggested (Reference 14 and 18).

1. Tissue damage due to downwash per se.

2. Tissue damage due to secondary effects of downwash.

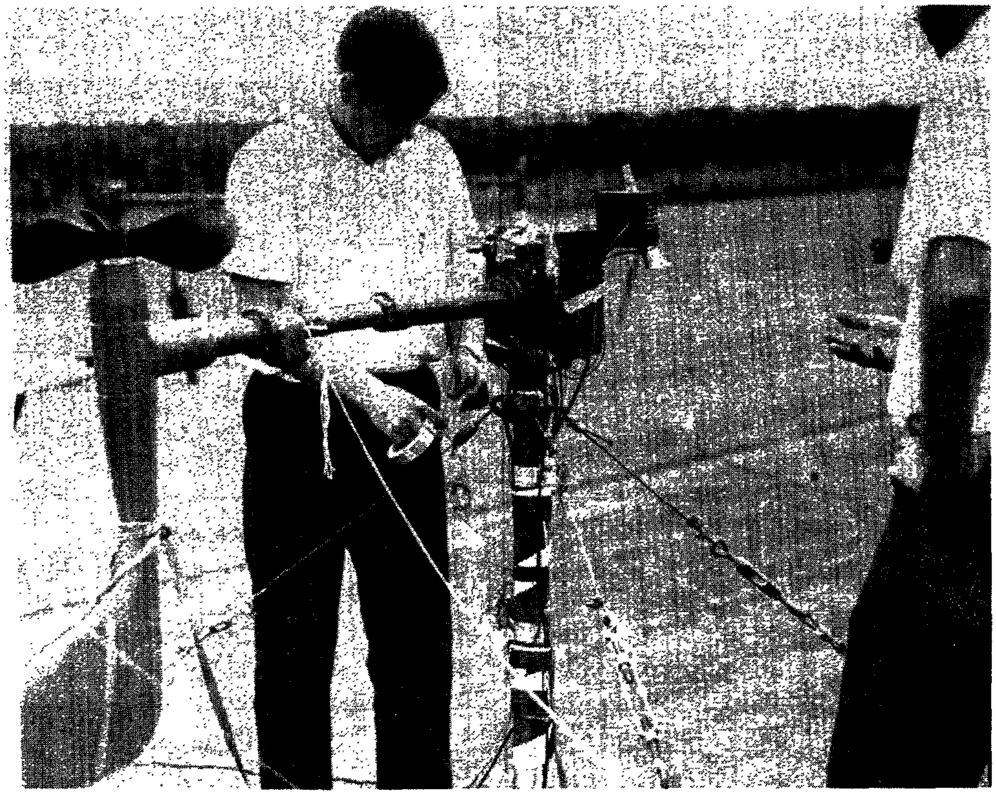
3. Energy costs imposed by working in a high wind environment.

4. Massive convective heat loss with consequent hypothermia caused by exposure to downwash.

5. Impaired work capabilities due to disruption of equilibrium due to the high and gusty winds.

FIGURE 3

BEFORE



AFTER

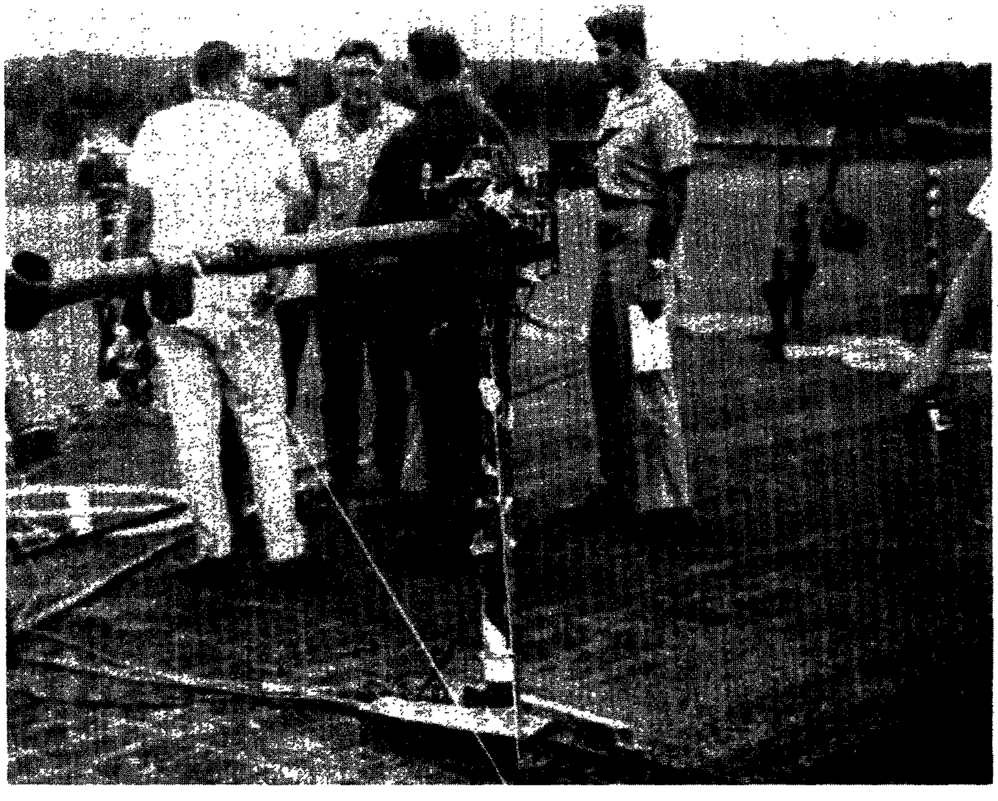


FIGURE 4

FIGURE 5

FIGURE 6

6. Detrimental effects of physically, chemically, and microbially active dust.

7. Detrimental effects of the high sound pressure levels which usually are associated with aircraft downwash.

8. Threats imposed by the interaction of downwash and the impedimenta of man.

Each will be covered, in order.

Tissue damage due to downwash per se - There is considerable information in aviation literature about the tolerances of man to high q loading. These works were performed to provide information relative to emergency egress from aircraft in flight, but the data is equally applicable to downwash.

German investigators in the early years of World War II noted that with winds above 100 knots, some sort of face protection was necessary to prevent discomfort and to prevent damage to loose areolar tissues, especially about the eyes. Therefore, in all subsequent studies, eye protection, and often full face and head protection, was provided for subjects when wind velocities exceeded this limit.

With full face protection, Fryer (Reference 10) noted the first evidence of structural damage to human subjects exposed to high q loading at $q = 518$ psf, equivalent to 375 knots IAS. At this level, petechia were noted over the chest and shoulders of his subjects. At $q = 806$ psf, equivalent to 460 knots IAS, subjects complained of severe hip and chest pain. When q loading reached 1037 psf, equivalent to 515 knots IAS, subjects developed severe confluent subconjunctional hemorrhages and the study was terminated.

Stapp indicates (Reference 21 and 22) that at $q = 630$ psf, equivalent to 431 knots IAS, head and extremity flailing becomes evident and that by $q = 650$ psf, equivalent to 438 knots IAS, this flailing is beyond muscular control. In contrast, Sperry and Nielson report arm fractures and dislocations of two subjects caused by flailing during downward ejection from an altitude of 10,000 ft MSL at an indicated airspeed of 389 knots (Reference 20). If, however, the extremities and head are adequately restrained, and the head is enclosed in a windproof helmet, q loading of 1108 psf, equivalent to 580 knots, causes no ill effect to man (Reference 21). In fact, a North American test pilot survived the combined stress of emergency ejection at an altitude of 6500 feet and an airspeed of Mach 1.05. q loading at 1240 psf was estimated (Reference 11).

It has been suggested that q loading could cause respiratory difficulties, and experimental evidence does indicate that high static and dynamic pressures could threaten man's ability to breath normally.

1. Fryer's subjects (Reference 10) were able to breath without difficulty up to q loadings of 288 psf. Thereafter, noticeable effort was necessary to expand the chest against the dynamic pressure.

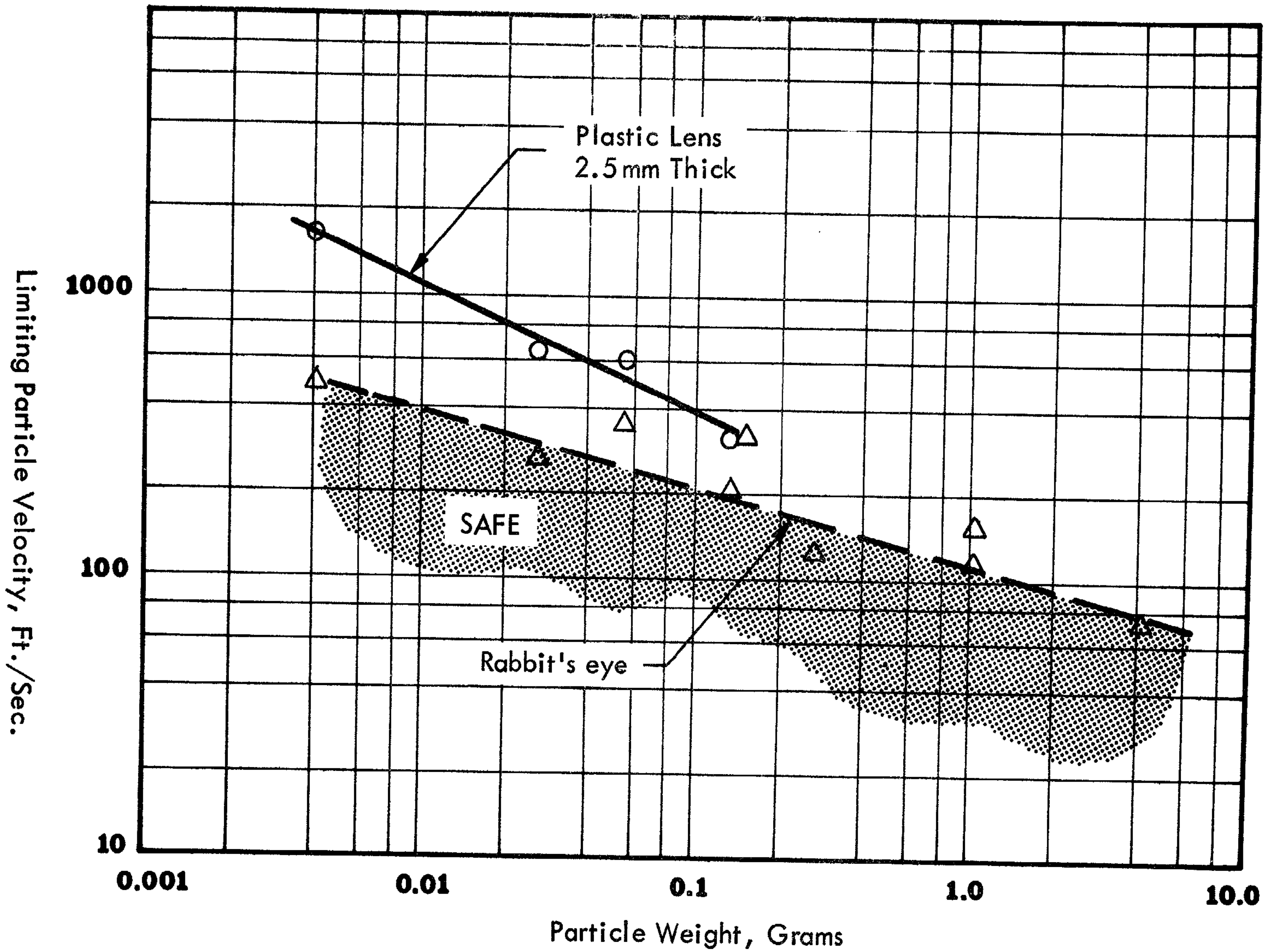
2. It is conceivable that dynamic pressure could cause lung rupture. It is known that winds of 600 knots cause unpreventable entrance of air into the stomach if the mouth and/or nose are not protected; and that sustained static overpressure of 278 lb/ft^2 is the top safe level to avoid lung rupture.

It appears, therefore, that q loading alone will pose no serious threat to man with our present family of aircraft since the very high velocities necessary to cause direct damage are not produced. If, however, it is decided to use turbojet thrusters to power future aircraft, a review of Figure 2 will show that q loading of 3000 psf and velocities of 1000 knots can be expected at the jet nozzle. Should this occur, this area of threat will have to be re-evaluated, as will the threat of burns induced by the hot jet exhaust.

Secondary effects of downwash -

1. Dust and particles - Engineering data indicates that a q loading of 50 lb/ft^2 over sandy terrain causes superficial airframe damage such as pitting and abrasion (Reference 7). It is known, therefore, that considerable energy can be imparted to sand particles by downwash. In general, however, all parts of the body except the eyes will absorb small particle impacts without serious injury if ordinary battle dress is worn (Reference 7). Work by German authors at the turn of the century suggest that man can tolerate impact by small fragments with energies up to 58 foot pounds without incapacitation.

Eyes, on the other hand, are extremely susceptible to small particle damage (Reference 16). Figure 7 summarizes the work of Stewart et al, indicating the relationship between particle weight, and the limiting velocity of rabbit cornea. Since all our present family of helicopters generate winds above that required to make sand airborne, eye protection is absolutely essential in downwash. Table 7 (Reference 15) indicates the velocities necessary to propel various type of soil particles.



MAXIMUM PARTICLE VELOCITY AND WEIGHT LIMITS FOR EYE PENETRATION

FIGURE 7

TABLE 7 *

VELOCITY	PARTICLE CHARACTERISTICS	TYPE MOVEMENT
1200 fpm	Fine sand dry (#50 sieve)	On ground
1500 fpm	Fine sand dry (#50 sieve)	Becomes airborne
1800 fpm	Clay	On ground
2800 fpm	Coarse sand (#4 sieve)	On ground
3800 fpm	Wet sand	On ground

* Reference 15

If goggles are worn, they prevent:

a. Corneal penetration which can occur with winds above 59 knots.

b. Deposition of conjunctival foreign bodies which can occur with winds above 15 knots.

c. Conjunctional dehydration due to extreme convection drying.

2. Objects - Meterological information (Reference 8) indicates that chimney and roof damage with falling bricks, chimney pots, and slates occurs when winds reach 48 knots, and that winds above 75 knots cause usually stable objects to become airborne.

It is possible to calculate the velocity required to make a solid object free-flying if certain assumptions are accepted. The formula

$$V_T = \sqrt{\frac{W}{\frac{\rho C_D}{2} \times \frac{\pi}{4} \times \left(\frac{a}{12}\right)^2}} \qquad \text{(Formula 1)}$$

calculates the velocity (V_T) in ft/sec necessary to sustain flight of a spherical object of W weight in pounds and a diameter in inches.

ρ = air density in slugs/ft^3 and at sea level under standard conditions is 0.002378 slug/ft^3. C_D = coefficient of drag, which for a sphere is approximately 0.5 for most situations.

Therefore, it is possible to generate a table with W and a as the independent variables and V_T as the dependent variable, since the other factors remain constant.

Table 8 shows:

W = weight in pounds
a = diameter in inches
v = velocity, in both ft/sec and knots
d = density of the spherical object in pounds/cubic foot

TABLE 8

WT	a	v FT/SEC	v KNOTS	d LB/FT^3	WT	a	v FT/SEC	v KNOTS	d LB/FT^3
1	1	555.56	328.9	3,333.33	3	7	137.41	81.4	28.87
	2	277.78	164.5	416.66		8	120.24	71.2	19.34
	3	185.12	109.6	123.57		9	106.88	63.1	13.59
	4	138.85	82.2	51.81		10	96.19	57.0	9.90
	5	111.07	65.8	26.46		11	87.44	51.8	7.44
	6	92.56	54.8	15.29		12	80.16	47.5	5.73
	7	79.34	47.0	9.62	4	1	1111.11	657.9	13,333.33
	8	69.42	41.1	6.45		2	555.56	328.9	1,666.66
	9	61.70	36.5	4.53		3	370.24	219.2	493.83
	10	55.53	32.9	3.30		4	277.70	164.4	207.25
	11	50.48	29.9	2.80		5	222.14	131.5	105.82
	12	46.28	27.4	1.91		6	185.11	109.6	61.16
2	1	785.67	465.2	6,666.66		7	158.67	93.9	38.50
	2	392.84	232.6	833.33		8	138.84	82.2	25.79
	3	261.80	155.0	246.91		9	123.41	73.1	18.12
	4	196.36	116.3	103.63		10	111.07	65.8	13.20
	5	157.08	93.0	52.91		11	100.97	59.8	9.92
	6	130.90	77.5	30.58		12	92.56	54.8	7.64
	7	112.20	66.4	19.25	5	1	1242.26	735.5	16,666.66
	8	98.17	58.1	12.95		2	621.13	367.8	2,083.33
	9	87.26	51.7	9.06		3	413.94	245.1	617.28
	10	78.54	46.5	6.60		4	310.48	183.8	259.07
	11	71.40	42.2	4.96		5	248.36	147.0	132.28
	12	65.45	38.8	3.20		6	206.96	122.5	76.45
3	1	962.25	569.7	10,000.00		7	177.40	105.0	48.12
	2	481.12	284.9	1,250.00		8	155.23	91.9	32.24
	3	320.64	189.8	370.37		9	137.98	81.7	22.64
	4	240.49	142.4	155.44		10	124.18	73.5	16.51
	5	192.38	113.9	79.36		11	112.89	66.8	12.40
	6	160.31	94.9	45.87		12	103.48	61.3	9.55

As a frame of reference, the density of the following elements is supplied:

Osmium	1404.6 lb/ft^3	(The heaviest element known).
Platinum	1334.1	
Gold	1204.8	
Lead	708.0	
Iron	493.2	
Aluminum	168.5	
Water	62.43	
Liquid hydrogen	4.4	(The lightest element known).

It is apparent that the table exceeds the densities of earth elements on both extremes. The graph in Figure 8 plots a family of curves from the table. The inset is plotted using a linear scales. The graph itself is plotted on log-log scale. The family of curves derived are all straight lines with a slope of -1. By knowing the weight and diameter of a sphere, it is possible from this graph to extract the velocity of wind in knots necessary to keep the sphere airborne.

To relate this formula to the real world, Table 9 indicates the wind velocity necessary to keep some familiar objects airborne.

3. Dislocation of vital gear - Works by Schütze and by Peacock, (See Reference 14) done during World War II on opposite sides of the English Channel, indicate that goggles and oxygen masks are blown from the face with winds at about 174 knots, and that the flight helmet is torn off at winds of about 217 knots.

It seems reasonable to suspect that the face protective mask would be blown off by winds of this same magnitude.

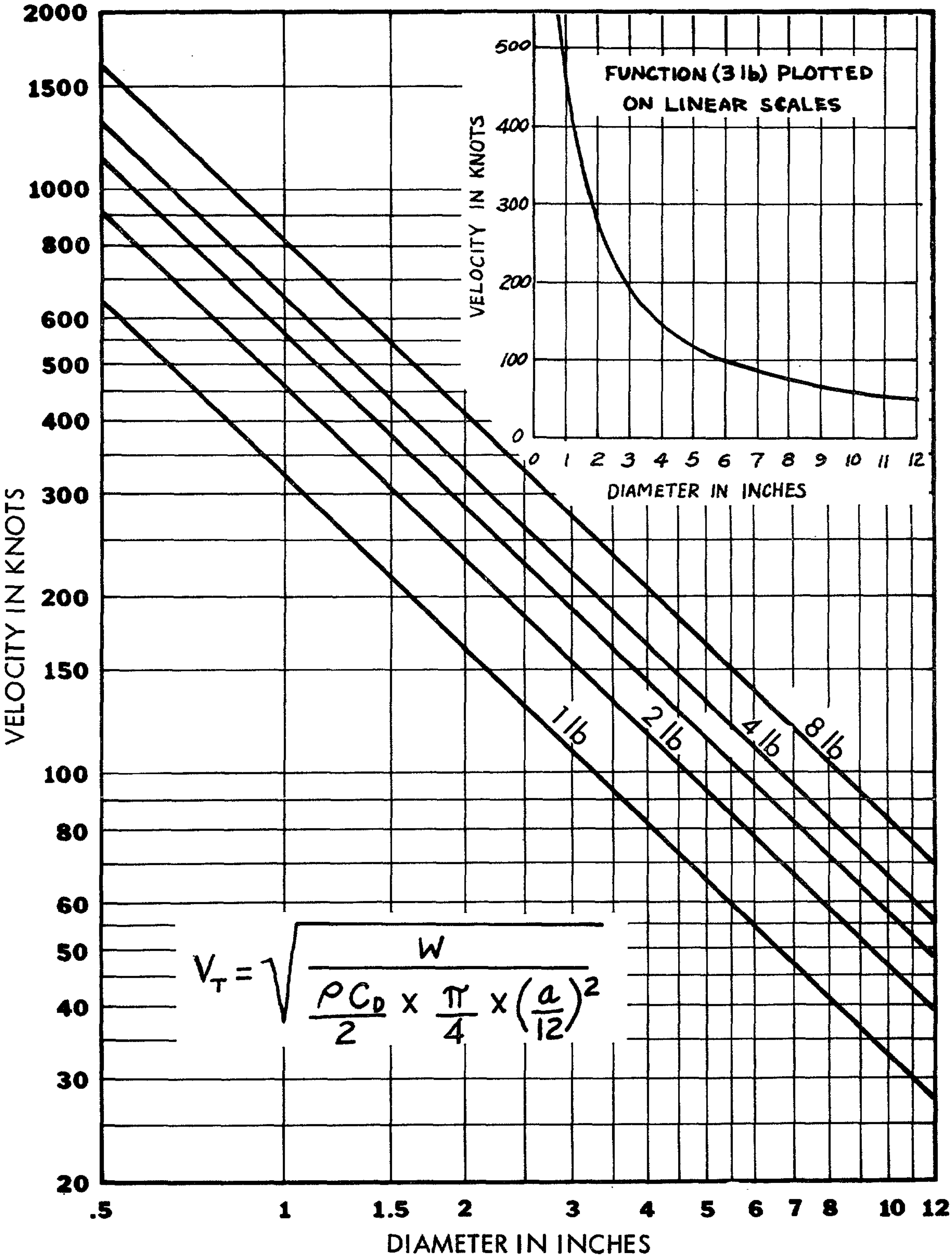
Energy costs imposed by work in a high wind environment. - A trained man walking at 2.7 mph on level ground carrying a 58 pound load consumes 2.9 kcal (Reference 9). He would expend 64.44 kcal in walking one mile.

By calculation, if certain assumptions are accepted, it is possible to determine the number of kcal expended walking one mile against a 50 knot wind.

Assumptions:

1. Trained man.
2. Body surface area exposed to the wind = 6.59 ft^2 (Reference 25).

FIGURE 8



FUNCTION (3 lb) PLOTTED ON LINEAR SCALES
VELOCITY IN KNOTS
DIAMETER IN INCHES
1 lb
2 lb
4 lb
8 lb
$V_T = \sqrt{\dfrac{W}{\dfrac{\rho C_D}{2} \times \dfrac{\pi}{4} \times \left(\dfrac{a}{12}\right)^2}}$
VELOCITY IN KNOTS
DIAMETER IN INCHES

TABLE 9

	WEIGHT POUND	DIAMETER INCHES	DENSITY LB/FT^3	VELOCITY	
				FT/SEC	KNOTS
Shot	16	5	422.45	444.28	263.06
Bowling Ball	16	8.59	83.31	258.60	153.12
Soccer Ball	1.0000	8.91	4.66	62.33	36.90
Soft Ball	0.4218	3.86	24.06	93.44	55.33
Baseball	0.3281	2.94	42.61	108.21	64.07
Tennis Ball	0.1250	2.5	26.40	78.55	46.51
Golf Ball (American)	0.1012	1.68	70.44	105.17	62.27
Golf Ball (British)	0.1012	1.62	78.57	109.11	64.61
Ping Pong Ball	0.0058	1.51	5.56	28.02	16.59

3. 20% work efficiency (Reference 9). *
4. RQ = 0.82

With these assumptions, walking one mile against a 50 knot wind would expend 475 kcal, more than 7 x the energy required for our trained man to walk one mile with a 58 pound load.

At 1 mph, expenditure would be 7.9 kcal/min.
At 2 mph, expenditure would be 15.8 kcal/min.
At 2.7 mph, expenditure would be 21.4 kcal/min.
At 3 mph, expenditure would be 23.8 kcal/min.

To place these in proper perspective, "Unduly heavy work" if defined as work at $>$ 12.5 kcal/min. (Reference 9).

These calculations are admittedly approximations. Nonetheless, they indicate that walking against a wind velocity commonly encountered under helicopters can be extremely energy consuming, and could produce considerable fatigue. This mathematical exercise agrees with personal observations of investigators in this laboratory who have had to work for extended periods under hovering helicopters to collect the data previously presented. Although regular participants in physical training, we were fatigued after an hour's work within the downwash pattern.

Massive heat loss due to extreme convection - It has been suggested (Reference 14) that exposure to high winds might cause marked body cooling and consequent hypothermia. TB Med 81, dated 20 October 1964, (Reference 27) provides guidelines upon this topic. Wind chill is severe at winds of 40 mph, and could cause hypothermia if prolonged exposure were required. However, the TB Med 81 also tells us that wind speeds greater than 40 mph have little more effect than winds of 40 mph, so that the extreme downwash velocities experienced under the XC-142A, for example, should prove no extra problem over the usual ones experienced under the more pedestrian conditions of simply a 40 mph wind.

In addition, if in fact the man working within the downwash pattern is generating 10 to 20 kcal/min in heat as a by-product of muscular effort, he would be protected to some extent.

* In fact, this is a generous estimate, since walking and especially walking rapidly or against resistance is very inefficient. 5-10% efficiency would be more likely.

It appears, therefore, that although massive convective heat loss is possible, ordinary clothing precautions are sufficient to protect against it.

Impaired work capabilities due to disruption of equilibrium - No specific work has been undertaken to evaluate the ability of man to maintain postural stability in high winds. To my knowledge, for example, the Navy, with its vast experience of high winds at sea, does not provide its ships' captains with guidelines of when it is unsafe for sailors to venture onto deck without a life line to avoid being blown or washed overboard. Mathematical extension of a study done in 1963 by Swearingen and McFadden for a completely different purpose (Reference 25), however, may assist toward a reasonable solution of this problem.

They were concerned with man's well-being if a pressurized aircraft at altitude were to experience skin failure and sudden loss of pressurization. They placed man in various positions 24 inches in front of a 75 x 37 inch membrane - covered opening with a 6.5 lb/in^2 pressure differential across the membrane. They ruptured the membrane separating the chambers, and measured the force in pounds applied to the man. Total pressure change required about 400 m sec. The first three columns of Table 10 are from Tables I and II of their work. The last three columns are appropriate mathematical derivations from their data. The upper half of the table shows forces necessary to unbalance the body. * The lower half of the table shows forces necessary to disorient the body. **

The last two columns indicate the wind velocity calculated from the q loading that would "unbalance" and "disorient" man in various postures. In general, winds of 50 knots unbalance, and winds of 75 knots disorient beyond recovery, the standing or walking man.

As Swearingen points out in this same paper, considerable judgement is necessary to successfully extend experimental data beyond the limits for which it was intended. Nonetheless, the derived values correspond well with our practical experience in the field. When wind velocities under a helicopter or VTOL reached 70-80 knots, it was necessary to send two men to collect data, one to hold and read the anemometer or velometer, and the other to physically support the observer.

* Unbalance in this case is defined as a disturbance of body stability, within the range of recovery.

** Disorient in this case is defined as a disturbance of body stability beyond the point of recovery of equilibrium.

TABLE 10

$$A/B = q \qquad v = \sqrt{\frac{2q}{\rho}}$$

To Unbalance	A LB	B FT^2	q LB/FT^2	VELOCITY FT/SEC	VELOCITY KNOTS
Standing face to blast	59	6.59	8.9530	86.7746	51.18
Standing backto blast	69	6.59	10.4704	93.8406	55.56
Standing side to blast	57	4.18	6.9378	76.3871	45.23
Sitting face to blast	63	4.46	14.1256	108.9963	64.54
Sitting back to blast	71	4.46	15.9193	115.7100	68.51
Sitting side to blast	63	4.17	15.1079	112.7227	66.74
Walking face to blast	59	6.59	8.9530	86.7746	51.38
To Disorient					
Standing face to blast	125	6.59	18.9681	305.126	74.78
Standing back to blast	170	6.59	25.7967	147.296	87.21
Standing side to blast	85	4.18	20.3349	130.776	77.43
Sitting face to blast	91	4.46	20.4036	130.997	77.56
Sitting back to blast	92	4.46	20.6278	131.715	77.99
Sitting side to blast	72	4.17	17.2662	120.506	71.35
Walking face to blast	140	6.59	21.2443	133.669	79.14
Walking side to blast	75	4.18	17.9426	122.843	72.74
Standing back Calculated	367	6.59	55.6904	216.421	128.14

Detrimental effect of physically, chemically, and microbially active dust - In geographic areas where dusts are (1) physically active (silicon, asbestos, radioactive dust or diatomaceous earth, (2) chemically active (bagasse, byssus, manganese, zinc and all allergens), or (3) microbially active (Mycobacterium, Histoplasma, Coccidioides, Blastomyces, Cryptococcus,or Aspergilla), protection would be essential to eyes, skin and especially the respiratory tract in all environments in which dust might become airborne. Since every aircraft in our present inventory has a significant dust signature, it is essential that the soil composition be known and adequate defense measures be taken when necessary.

Detrimental effects of high sound pressure levels - From a practical standpoint downwash is always associated with high sound pressure levels, in the range of 110-115 db. Military standards indicate that ear protection is necessary when sound pressure levels exceed 92 db in the 150-300 Hz octave band and 85 db in the octave bands between 300-9600 Hz (Reference 28). Ear protection, therefore, is essential in areas of downwash to prevent both temporary and permanent hearing loss.

Threats imposed by interaction of downwash and the impedimenta of man - AR 705-15, dated 4 October 1962, and Change 1 of that regulation, dated 14 October 1963, clearly define what can be expected of military shelters under extreme conditions of wind.

Fixed structures are expected to withstand 55 knots with gusts to 85 knots inland and 70 knots with gusts to 105 knots in mountains or on the seashore.

Non rigid structures should withstand 45 knots for 5 minutes and gusts to 65 knots, and with auxiliary guying should withstand 55 knots for 5 minutes with gusts to 85 knots.

Tents are unlikely to be exposed to winds of these magnitudes under utility helicopters of our present inventory. However, with the XC-142A and to some extent with the CH-47B and CH-54A, winds of this magnitude may be expected, and if these aircraft operate near tentage we can expect to see tents fall, and perhaps aircraft along with them. *

* In the period January 1966 to August 1967, 8 hovering helicopters crashed when loose objects from the ground (poncho, parachute canopy, cargo net, etc.) were propelled by the rotor downwash into the rotor system of the helicopter (Reference 29).

The MUST, somewhat more sturdy, is expected to withstand winds of up to 70 knots if properly anchored (Reference 1). Wind tunnel studies have shown that in that environment MUST structures can withstand winds to 105 knots (Reference 6).

SUMMARY

1. Tissue damage due to q loading per se is extremely remote with our present family of operational and experimental aircraft.

a. The first evidence of structural tissue damage occurs at $q = 518.4$ psf, equivalent to 375 knots IAS.

b. The first evidence of compromise of rib cage excursion caused by dynamic pressure is at $q = 288$ psf, equivalent to 291 knots IAS.

c. At $q = 650$ psf, equivalent to 438 knots head and extremity flailing is beyond the control of voluntary muscles.

d. Lung rupture due to static over-pressure may occur with sustained pressure of 278 lb/ft^2 and above.

2. Secondary effect of q loading, however, can threaten man's well-being.

a. Although ordinary battle dress will protect covered areas against serious injury from sand and dust abrasion,

b. Eye protection with goggles is essential in winds above 15 knots to prevent:

1. Deposition of foreign bodies.

2. Corneal perforation.

3. Conjunctional dehydration.

c. With winds above 48 knots, ordinarily stable objects (tree limbs, roofing, bricks)may become detached and fall, causing injury.

d. With winds above 75 knots such objects on the ground may become airborne and free flying, causing injury.

3. It has been demonstrated that high winds can cause dislocation of vital gear.

a. Goggles and oxygen masks are torn off at winds of 174 knots.

b. The flight helmet is torn off at 217 knots.

It can reasonably be expected that the face protective mask would be blown off by winds of this same magnitude.

4. Working in downwash can be very fatiguing. Calculations indicate that energy expenditures in the range classified as "unduly heavy work" (>12.5 kcal/min) may be required merely to walk into winds of 50 knots.

5. Laboratory studies suggest that gusty winds of 50 knots will keep a standing man unbalanced, but able to recover equilibrium with effort. On the other hand, gusty winds of 75 knots is sufficient to disturb equilibrium beyond the point of recovery.

6. In areas where dust, per se, may be physically, chemically, or microbially damaging, protection is essential for the skin, eyes, and especially the respiratory tract.

7. In close proximity to helicopter and VTOL aircraft, sound pressure levels of 110-115 db can be expected. Ear defense is essential to prevent both temporary and permanent hearing loss.

8. The impedimenta with which man vests himself in a field situation are especially sensitive to high winds. Under the best of circumstances, the standard canvas tent can not be expected to withstand winds above 55 knots. MUST, somewhat more sturdy, can tolerate winds of 70 knots if properly anchored.

9. A summary of known effects of winds upon man and his personal equipment is contained in Table 12.

TABLE 11

SUMMARY OF DYNAMIC PRESSURE UNDER STANDARD CONDITIONS WITH CORRESPONDING AIR SPEEDS

$v = \sqrt{\frac{2q}{\rho}}$ * $q = 1/2 \, \rho v^2$ *

q	VELOCITY		VELOCITY		q
LB/FT²	FT/SEC	KNOTS	FT/SEC	KNOTS	LB/FT²
1.0	29.00	17.17	10.00	5.92	0.12
2.0	41.01	24.28	20.00	11.84	0.48
3.0	50.23	29.74	30.00	17.76	1.07
4.0	58.00	34.34	40.00	23.84	1.90
6.0	71.04	42.06	50.00	29.60	2.97
8.0	82.02	48.56	60.00	35.53	4.28
10.0	91.71	54.30	70.00	41.45	5.83
15.0	112.32	66.50	80.00	47.37	7.61
20.0	129.70	76.80	90.00	53.29	9.63
25.0	145.00	85.85	100.00	59.21	11.89
30.0	158.84	94.05	120.00	71.05	17.12
35.0	171.57	101.59	140.00	82.89	23.30
40.0	183.42	108.60	160.00	94.74	30.44
45.0	194.54	115.19	180.00	106.58	38.52
50.0	205.07	121.42	200.00	118.42	47.56
55.0	215.75	127.74	220.00	130.26	57.58
60.0	224.64	133.01	240.00	142.10	68.49
65.0	233.81	138.44	260.00	153.95	80.38
70.0	242.64	143.67	280.00	165.79	93.22
80.0	259.39	153.85	300.00	177.63	107.01

* $\rho = 0.002378$

TABLE 12

SUMMARY OF KNOWN EFFECTS OF WINDS UPON MAN AND HIS PERSONAL EQUIPMENT

KNOTS	q	KNOWN EFFECTS	REFERENCE
15-30	0.7-3.0	Dust and sand become airborne	15
45	6.8	Canvas tents blow down.	2
48	7.8	Falling objects expected.	8
50 (gusty)	8.5	Recoverable loss of equilibrium.	25
59	11.8	Eye damage possible.	16
75	19	Solid objects become free flying.	8
75 (gusty)	19	Unrecoverable loss of equilibrium.	25
174	103	Goggles and O_2 mask blown off.	14
217	160	Helmet torn off.	14
291 *	288	First evidence of respiratory embarrassment.	10
375 *	518	Structural damage to skin and blood vessels.	10
389	379 **	Arm fractures and dislocations from uncontrollable flailing.	20
431	630	Extremity flailing evident but controllable	21
438	651	Extremity flailing beyond control.	21
460 *	806	Severe hip and chest pain.	10
515 *	1037	Severe confluent subconjunctional hemorrage.	10
600	1221	Air forced into stomach	22
676 *	1240	Known survivable.	11

* Value used for ρ determined by the original author.

** $\rho = 0.001756$ In all other cases $\rho = 0.002378$

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