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The Hampshire epidemic of foot-and-mouth disease, 1967

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SUMMARY

An analysis was made of the spread of foot-and-mouth disease during the epidemic in Hampshire in January and February 1967. To explain the pattern of spread, it had to be postulated that virus was present seven days before the first outbreak was reported. It is suggested that the disease occurred initially in pigs fed on infected meat and that the virus was subsequently disseminated from the local abattoir, where the pigs were killed, to four farms by movement of animals, slaughterhouse waste, people or vehicles, and to fifteen by the airborne route. Subsequent spread from these farms was by movement in two instances and by the airborne route in five. The source and route of infection of the last farm in the outbreak were not determined.

The risk of spread through movement was associated more with carriage of infected slaughterhouse waste, movement of animals, people or vehicles carrying animals than through collection of milk, artificial insemination or movement of other types of vehicles. Outbreaks of disease among pigs gave rise to more secondary spread than outbreaks in cattle. Secondary outbreaks attributed to airborne spread occurred only in ruminants. Most airborne spread was into areas of high livestock density and cattle in the larger herds became infected. Airborne spread could be correlated with wind direction and speed but not with rain. The reduction in the number of outbreaks at the end of the epidemic could be attributed to the elimination of the largest sources of virus, the control of movements and the fact that in all instances except two the wind was blowing virus over towns and out to sea, to areas of low stock density and to areas where animals had been killed.

INTRODUCTION

As a result of the epidemic in Great Britain in 1967–1968 a number of studies of the epidemiology of foot-and-mouth disease in that epidemic and in others has appeared (Henderson, 1969; Smith & Hugh-Jones, 1969; Wright, 1969; Hugh-Jones & Wright, 1970).

A series of foot-and-mouth disease outbreaks due to strain O_1 occurred in Hampshire between 6 January and 3 February 1967. The disease was confirmed on 29 farms and 2774 cattle, 414 sheep, 4708 pigs and six goats were slaughtered. Of these, 170 cattle, 285 pigs and four sheep had developed foot-and-mouth disease (Report on the Animal Health Services in Great Britain, 1967). The same report described the spread of disease (see later). Smith & Hugh-Jones (1969)

examined the epidemic in detail and reported on the weather elements involved. In the light of recent findings on the factors involved in airborne spread of foot-and-mouth disease (Sellers & Parker, 1969; Donaldson, Herniman, Parker & Sellers, 1970; Sellers, Donaldson & Herniman, 1970; Sellers, 1971; Sellers, Herniman & Donaldson, 1971; Barlow, 1972; Donaldson, 1972; Sellers & Herniman, 1972), we decided to re-examine the course of the epidemic.

In the paper we quote first the description given in the Report on Animal Health Services; second, the results of Smith & Hugh-Jones (1969); and, third, our version of the course of spread. The remainder of the paper is devoted to the presentation of the data available, to the arguments for our interpretation and to conclusions that can be drawn on the nature of the spread.

The Hampshire epidemic – the spread of the disease

(Report on Animal Health Services in Great Britain, 1967)

'On 6 January foot-and-mouth disease was confirmed in cattle at Southwick, Hampshire (1).* Lesions were recent in the two affected animals, and at the time of confirmation there was no indication of the source of infection.

On 7 January two further outbreaks (2, 3) were confirmed within 2 miles of the original case. There was no apparent connexion between the three cases, all of which were of recent occurrence, and consequently it seemed probable that an undisclosed source of disease existed in the district.

On 8 January recent disease was confirmed in a large number of pigs in a swill-fed herd (4) some 3 miles distant from the first outbreak. This proved to be the primary case. Infection was considered to have been introduced in waste food which could have contained imported meat scraps.

A further outbreak was confirmed on 9 January in pigs at a local abattoir (9). It was found that pigs from the swill-fed herd (4) had been moved to this abattoir on 3 January. They were slaughtered on the same day but the affected pigs at the abattoir had occupied the same pens between 4 and 9 January, and had presumably contracted disease from the infection left in the pens by the swill-fed pigs. These were undoubtedly shedding virus although showing no clinical signs of foot-and-mouth disease.

Four farms (5, 11, 14, 16) became infected through the movement either of animals, persons or vehicles from the abattoir on the days following the slaughter on 3 January of the pigs from the primary case. Disease also occurred on one farm (13) which had received offal and meat trimmings from the abattoir for boiling before feeding to pigs.

In addition there were 18 cases of disease which occurred in the vicinity of other outbreaks, or were on the route taken by the vehicles which conveyed the pigs from the swill-fed herd to the abattoir on 3 January. Foot-and-mouth disease was also confirmed in the swill feeder's other herd of pigs (6).

Infected area. The usual 10-mile radius infected area restrictions were imposed around the initial outbreak on 6 January.'

* The numbers in brackets refer to the farms listed in Table 1.

The weather factor in foot-and-mouth disease epidemics
(Smith & Hugh-Jones, 1969)

'We have examined four epidemics of foot-and-mouth disease in detail, those in Hampshire (1967), Northumberland (1966), Cheshire (1952) and Oswestry (1961). As will be seen, the feature common to the initial stages of each of them was the apparent relative inability of the disease to spread upwind. In the early stages of the epidemic in Hampshire in 1967 several outbreaks were traced from the movement of vehicles to and from the abattoir at Fareham. The first outbreak (1) was confirmed on 6 January and the two cows affected were slaughtered the same day, but by the morning of January 7 there were probably seven sources of virus (2–8) in existence. The largest of these was one of 141 infected pigs (4) in which the disease probably started on 3 or 4 January (confirmed on 8 January). Between 08.00 hr. on 3 January and 16.00 hr. on 6 January, the surface wind lay between 280° and 360°, that is, in the quarter between west and north. There was no rain during this period and there was no subsequent spread of the disease to the south-east. But on the evening of 6 January it began to snow, later turning to rain, during which the wind backed from 210° to 060° at dawn. These directions determine the rain–wind sector of the figure centred on the outbreak among 141 pigs (4). All the subsequent outbreaks occurring within the next 15 days lay within this sector.'

Our version of the origin and spread of disease

We suggest that infection was present in the area before 3 January and probably on 29 December. The primary outbreak was one of the following: the swill-fed herd (4) (most likely), the local abattoir (9), or the farm which had received offal and meat trimmings (13). Movement to and from the abattoir accounted for five or at the most eight outbreaks. The abattoir was probably a source of airborne virus from 31 December until 9 January. From 31 December until 6 January the wind was from the west and north-west and there was spread downwind to nine (1, 2, 3, 5, 7, 8, 10, 11 and 12) or at the least six outbreaks. On 6 and 7 January the wind from the south-west gave rise to possibly one outbreak (25). From 7 January to 9 January the wind was from between the north and east and there were five (19, 21, 22, 23, 26) or possibly six outbreaks downwind. The swill-fed herd (4) gave rise to one further outbreak (6) due to movement of people and swill. The farm which had received offal (13) was a source of infection for one farm due to movement of one person (18) and for three farms by the airborne route (17, 25, 27). The remaining outbreaks were due to airborne spread from other infected farms (10 → 20, 16 → 24, 24 → 28) or due to unknown causes (29).

Sources of information

1. The files on each infected premises and the summaries, maps and plans prepared by the Animal Health Division of the Ministry of Agriculture, Fisheries and Food.

2. The weather records of surface wind direction and strength, precipitation and relative humidity from the RAF Station at Thorney Island, Hampshire, from 26

Table 1. *Farms, dates and animals affected during the Hampshire epidemic*

Out-break no.	Date of reporting	Stock				Number affected	Suggested earliest date of disease
		C*	S*	P*	G*		
1	5. i. 67	86	—	21	—	2 c*	5. i. 67
2	6. i. 67	123	—	—	—	5 c	5. i. 67
3	7. i. 67	93	39	—	—	17 c 4 s	6. i. 67
4	8. i. 67	—	—	508	—	141 p	29. xii. 66†
5	8. i. 67	139	—	—	—	2 c	8. i. 67
6	9. i. 67	61	10	106	—	4 p	6. i. 67†
7	9. i. 67	45	—	—	1	4 c	9. i. 67
8	9. i. 67	130	—	—	—	12 c	8. i. 67
9	9. i. 67	60	114	226	—	10 p	31. xii. 66†
10	9. i. 67	106	—	—	—	11 c	9. i. 67
11	9. i. 67	66	—	—	—	4 c	8. i. 67
12	10. i. 67	84	—	100	—	22 c	9. i. 67
13	10. i. 67	125	—	473	—	126 p	6. i. 67†
14	11. i. 67	—	—	617	—	1 p	11. i. 67
15	11. i. 67	69	1	621	—	10 c	10. i. 67
16	11. i. 67	144	39	29	—	5 c	10. i. 67
17	11. i. 67	76	—	99	—	1 c	10. i. 67
18	12. i. 67	—	—	14	—	3 p	10. i. 67†
19	12. i. 67	97	—	—	—	4 c	11. i. 67
20	14. i. 67	128	—	—	—	1 c	13. i. 67
21	14. i. 67	14	—	9	—	2 c	13. i. 67
22	15. i. 67	49	—	—	—	2 c	14. i. 67
23	15. i. 67	49	—	—	—	4 c	14. i. 67
24	16. i. 67	134	—	149	—	8 c	15. i. 67
25	17. i. 67	69	—	—	—	21 c	16. i. 67
26	17. i. 67	94	—	—	—	1 c	16. i. 67
27	20. i. 67	236	—	547	—	10 c	19. i. 67
28	26. i. 67	98	—	56	—	8 c	24. i. 67
29	3. ii. 67	16	—	—	—	10 c	27. i. 67†

* C, c = cattle; S, s = sheep; P, p = pigs; G, g = goats.

† Lesions over 48 hr. old reported.

Note. In addition, 363 cattle, 211 sheep, 1097 pigs and 5 goats were slaughtered as 'direct contacts'.

December 1966, to 4 February 1967. Records of wind direction and strength from Calshot Meteorological Station, South Farnborough Meteorological Station, Hurn Airport and Southampton Weather Centre for 6 and 7 January 1967.

3. Visits to the areas and interviews with Divisional Veterinary Officers, Veterinary Officers and others concerned with the outbreak.

Farms, number of stock, number of outbreaks and date of reporting

Statistical information about the outbreaks is shown in Table 1. The farms are given in chronological order of reporting disease.

Topography of the outbreak

A map of the area and the site of the outbreaks are shown in Fig. 1.

Excluding the outbreak at farm 14, the area covered was 26 km. east–west by 16 km. north–south. Most of the outbreaks occurred in the valley of the Wallington

Fig. 1. Map of the area involved in the epidemic showing rivers, 200 ft. contours, towns and farms involved. Cross-hatching indicates built-up areas. S = Southampton, F = Fareham, G = Gosport, P = Portsmouth, W = Waterlooville, H = Havant. 1–29: Farms with animals infected. No. 14 is not shown but lies north-west of No. 16.

river, which on the west joins with the Meon Valley at Funtley. To the south lie the Portsdown and Fareham ridges and to the north the Hampshire Downs. Southampton lies to the west, Fareham and Portsmouth to the south and Havant to the east of the area.

Movement of animals, vehicles, people or materials between premises

The movements are shown in Table 2. The abattoir (9) was, as to be expected, the centre with which most movement was concerned. In two instances, potentially infected slaughterhouse waste and animals were taken to farm 13 and farm 16 respectively; in the other cases, people visited the abattoir or the animals were brought for slaughter. Thus, if virus were carried back to the farm, it would be on the visitors or in their vehicles.

Farms 2, 3, 5 and 10 were visited by inseminators. The only possible transfer of virus to initiate disease would have been from farm 2 to farm 10 on 4 January, before the cattle at farm 2 had developed lesions on 5 January. This would give an incubation period of 5 days. For any other implication of inseminators the incubation period would be too short (between farms 2 and 3) or no virus could have been present in the animal (between farms 2 and 5).

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Table 2. *Movement of animals, vehicles, people or materials between infected farms*

Farm no.	Movement
9	From Farm 4: 44 pigs, 29 December; 65 pigs, 3 January
	From Farm 2: Visit, 2 January
	From Farm 5: 1 calf, 2 January; 2 calves, 6 January
	From Farm 11: 6 cows, 5 January
	From Farm 13: 2 pigs, 30 December. Slaughterhouse waste collection daily till 5 January
	From Farm 14: 10 pigs, 29 December. Visit, 2 January, 2 pigs, 4 January
	From Farm 15: 7 pigs, 2 January
	From Farm 16: 8 cattle, 2 January. Visit, 4 January, 1 bullock, 5 January (subsequently taken back to Farm 16 with seven other cattle)
2	A.I. visits on 1, 2, 3, 4 and 5 January
3	A.I. visits on 1 and 5 January
4	Daily visits to Farm 6
5	A.I. visit on 1 January
10	A.I. visits on 1, 2 and 4 January
11	Relief milker from Farm 5, 2 January
14	Father of owner of Farm 13 visited, 7 January
18	Owner worked at Farm 13 till 7 January
29	Cattle broke out on 28/29 January
	Milk collections: (A) Farms 5, 11, 7
	(B) Farms 8, 10, farm, 13
	(C) Farms 15, three farms, 19
	(D) Farms 17, 26, 22
	(E) Farms 24, farm, 28

Although a number of farms were on the same milk collection route, FMD was found on all these farms within one day (A, in Table 2), the same day (B) and one day (3), i.e. too short an incubation period. A possible spread by infected milk within a reasonable incubation period might have occurred from farm 17 to farms 22 and 26 (D) and from farm 24 to farm 28 (E).

Meteorological conditions

The surface wind bearing and strength at Thorney Island from 26 December 1966, to 4 February 1967, are shown in Table 3. From 28 December till 6 January the surface wind came from westerly sectors between south and north (180°–360°) with speeds of up to 26 knots. During the night of 6/7 January the wind veered to 70° and from then until 9 January came from the north-easterly sector. Subsequent sectors were north-westerly, 350°–170°, southerly and westerly.

On the night of 6/7 January the records of surface winds at Calshot were similar to those at Thorney Island, whereas at Southampton and South Farnborough there was a period of calm between winds from the south-east and winds from the north-east.

Rain and wind speed from 29 December until 16 January (except 13 and 14 January) are shown in Table 8.

Table 3. *Wind bearing and strength at Thorney Island before and during the epidemic*

Period		Wind bearing	Wind speed (knots)
26. xii. 66	01.00–06.00	70°–80°	5–7
26–27. xii. 66	07.00–13.00	150°–200°	7–21
27–28. xii. 66	14.00–01.00	280°–300°	5–9
28. xii. 66	02.00–06.00	10°–80°	Nil–1
	07.00–17.00	180°–250°	4–17
28–30. xii. 66	18.00–10.00	220°–280°	1–25
30–31. xii. 66	11.00–01.00	180°–240°	5–18
31. xii. 66	02.00–08.00	230°–250°	20–26
31. xii. 66–1. i. 67	11.00–22.00	250°–290°	6–26
1–2. i. 67	23.00–24.00	290°–330°	2–12
3–6. i. 67	01.00–14.00	290°–360°	0–15
6–7. i. 67	16.00–05.00	190°–320°	1–14
7. i. 67	05.00–06.00	320°–70°	7–14
7–9. i. 67	07.00–04.00	10°–120°	6–15
9–15. i. 67	05.00–12.00	250°–360°	Nil–11
15–16. i. 67	13.00–24.00	350°–170°	1–11
17–20. i. 67	01.00–24.00	150°–220°	7–22
21–24. i. 67	01.00–10.00	150°–300°	Nil–27
24. i. 67	11.00–22.00	230°–360°	Nil–10
25–26. i. 67	02.00–24.00	120°–290°	Nil–24
27. i. 67	01.00–10.00	230°–270°	7–12
27–28. i. 67	11.00–24.00	190°–240°	8–16
29–31. i. 67	01.00–07.00	110°–200°	4–19
31. i. 67–4. ii. 67	08.00–03.00	230°–290°	4–23
4. ii. 67	04.00–23.00	290°–360°	2–9

Virus output

Estimates of the daily amount of airborne virus put out from 5 January to 3 February are shown in Fig. 2. One infected pig was assumed to have produced at least 30 times as much airborne virus as one cattle or one sheep (Sellers & Parker, 1969), although in practice this may have been higher. Cattle or sheep were estimated to produce 10^2 ID50 per minute and this represents one unit in Fig. 2.

Considerations

Incubation period

(*a*) *Direct and indirect contact.* In experiments at Pirbright with the O_1 strain of FMD virus, the range of onset of disease in animals housed in the same box or isolation unit was 2–4 days for pigs and 3–6 days for cattle.

(*b*) *Feeding of pigs with infected material.* One of 30 pigs fed on liver and bone from a steer infected with an O strain of FMD virus showed lesions on the fourth day (Henderson & Brooksby, 1948). Since a small dose was given in this experiment, the incubation period for pigs infected by feeding on swill was taken to be 3–4 days.

(*c*) *Artificial insemination.* One heifer artificially inseminated with $2{\cdot}5 \times 10^6$ mouse ID 50 of virus of an O strain had clinical signs of FMD on the second day (Cottral, Gailiunas & Cox, 1968).

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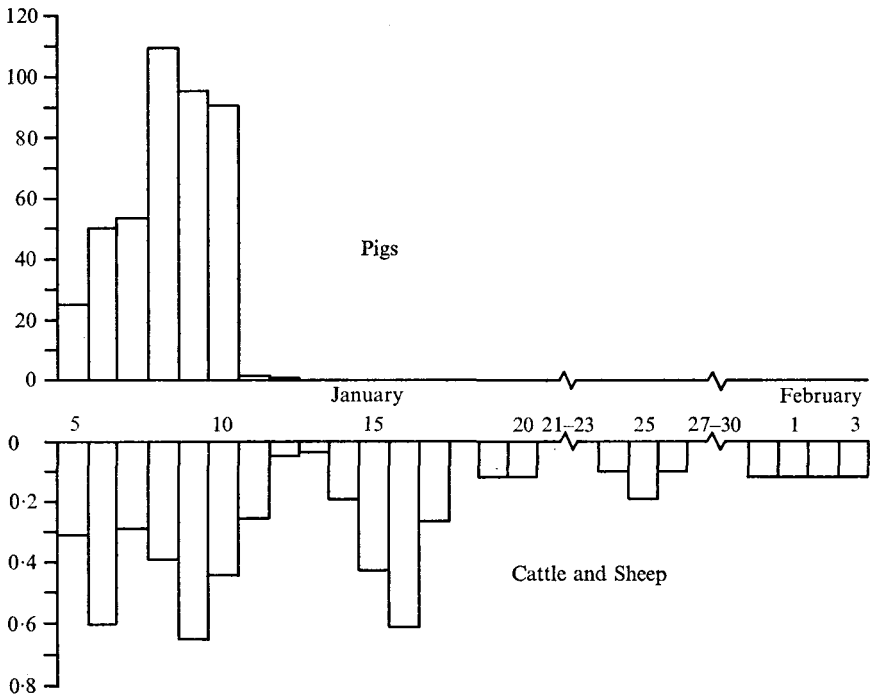

Fig. 2. Estimated relative amounts of airborne FMD virus produced by pigs and by cattle and sheep from 5 January till 3 February 1967. The amounts were calculated from the evidence found at slaughter, so do not include any virus that might have been produced before 5 January. It should be noted that the scale for cattle and sheep is a hundred-fold less than that for pigs. Cattle and sheep were estimated to produce 10^2 ID_{50} per minute.

(*d*) *Intramammary*. Cows given O_1 virus by the intramammary route developed generalized disease on the third day (Burrows *et al.* 1971).

(*e*) *Transfer by man*. Where cattle were infected by being breathed on, sneezed, coughed or talked at by people who had virus in their noses, the incubation period was 13–14 days (Sellers, Herniman & Mann, 1971). The estimated dose the animal received was 100 ID 50.

(*f*) *Airborne between farms*. The shortest incubation period for cattle in the same unit was 3 days; we have therefore assumed that, where cattle subsequently had disease, the incubation period between farms could vary from 4 to 10 days with a possibility of 14 days at the end of the epidemic when the amount of airborne virus emitted was likely to be low.

Route of infection

Cattle are more readily infected through inhalation of material containing virus than by ingestion (see Sellers, 1971) and this is probably also true of sheep. Pigs are difficult to infect intranasally (Graves & Cunliffe, 1960); on the other hand, when they are feeding on infected swill they are likely to take the virus in both by inhalation and by ingestion. Where different species are equally at risk, cattle are likely to receive a larger dose than sheep or pigs and show the disease first (Sellers

& Parker, 1969). Thus, pigs are likely to be infected through feeding on infected swill, through contact with infected pigs, through movement in contaminated vehicles or through contact with people contaminated with virus. Cattle and sheep are likely to be infected by inhalation in the open air or in buildings, in contaminated vehicles or by inquisitive sniffing of people contaminated with virus.

Source of virus

Pigs produce more airborne virus than cattle or sheep (Sellers & Parker, 1969; Donaldson *et al.* 1970). Cattle produce high titres of virus in milk and in faeces (Hedger & Dawson, 1970; Parker, 1971).

THE EPIDEMIC

Table 4 gives the bearings and distance of various farms from the abattoir (9), farm 13 and other farms (1, 10, 16 and 24). The date of earliest lesions was estimated from the description given by the Veterinary Officer examining the animal(s) and from that we determined the period of 4–10 days (i.e. range of incubation period) during which infection of the animals could have occurred.

The primary outbreak and initial spread of virus

Farm 1

Unless airborne virus from the Continent is assumed, which is unlikely (Hurst, 1968), farm 1 could not have been the primary outbreak. The only recorded movement to and from the farm was a meal lorry, which was unlikely to have carried infection. The virus is presumed to have reached the farm by the airborne route. With an incubation period of at least 4 days according to our criteria, a source of airborne virus for farm 1 must have been present in the area on 1 January 1967, if not earlier. Four farms had pigs with lesions described as at least 48 hr. old – 4, 9, 13 and 18 – and one or more of these could be suspected of having produced airborne virus on 1 January 1967.

Farm 4

Farm 1 was not downwind of farm 4 from the early morning of 26 December 1966, until disease was found on 5 January 1967. Farm 4 is therefore unlikely to have been the airborne source of disease at farm 1. On 29 December 1966, and on 3 January 1967, pigs were taken from farm 4 to the abattoir (9) at Fareham.

Fareham abattoir (9)

Farm 1 was downwind of the abattoir (winds 220°–280°) during 29 December. The pigs from farm 4 could have disseminated airborne virus on arrival at the abattoir or could have infected other pigs held at the abattoir which, in turn, could have disseminated virus on 31 December 1966, and 1 January 1967, when farm 1 was still downwind of the abattoir. There was no killing of animals on the afternoon of Saturday, 31 December 1966, and on Sunday, 1 January 1967.

Pigs brought from farm 4 on 3 January could also have had disease but they or pigs housed in the same pens after them were unlikely to have given out airborne

Table 4. *Bearings and distances from infected farms and dates of lesions and incubation periods*

Suggested origin	Infected farm	Bearing to suggested origin	Distance (km.)	Estimated earliest date of lesions	Period of 4- to 10-day incubation period
9	1	267	9	5 January	26 December– 1 January
	2	264	6	5 January	26 December– 1 January
	3	270	1·5	6 January	27 December– 2 January
	5	280	2·5	8 January	29 December– 4 January
	7	303	2	9 January	30 December– 5 January
	8	270	4·5	8 January	29 December– 4 January
	10	268	6	9 January	30 December– 5 January
	11	278	3	8 January	29 December– 4 January
	12	276	10	9 January	30 December– 5 January
	15	079	1·5	10 January	31 December– 6 January
	19	025	3·5	11 January	1 January – 7 January
	21	091	1·5	13 January	3 January – 9 January
	22	084	1	14 January	4 January –10 January
	23	340	0·5	14 January	4 January –10 January
	26	090	1	16 January	6 January –12 January
	25	218	4	16 January	6 January –12 January
13	17	225	0·5	10 January	31 December– 6 January
	25	355	7	16 January	6 January –12 January
	27	297	6	19 January	9 January –15 January
1	12	325	1·5	9 January	30 December– 5 January
10	20	245	1	13 January	3 January – 9 January
16	24	308	2	15 January	5 January –11 January
24	28	090	3	24 January	14 January –20 January

virus to farm 1 because the incubation period was too short (i.e. 2 days). Other outbreaks on farms downwind of the abattoir during the period from 29 December 1966, were at farms 2, 3, 5, 7, 8, 10, 11 and 12 and in Table 4 the bearings, distance, estimated earliest date of lesions and dates covered by a 4–10 day incubation period are shown. Farms 2 and 3 must have been infected on or before 1 and 2 January respectively; the other farms (5, 7, 8, 10, 11 and 12) by 4 or 5 January 1967, though probably not before 29 and 30 December 1966. During the period the abattoir was closed (from 13.00 hr. on 31 December until 05.00 hr. on 2 January), disease could have developed in the pigs held there; this time could have been the optimum for dissemination of airborne virus to all the farms mentioned, as the pigs would be giving out virus at this time and the wind was blowing from 250°–290°. Alternative possible sources of infection by movement of people or vehicles exist for 2, 5, 10 and 11 (Table 2) and the disease at farm 12 could have been airborne either from the abattoir (9) or from farm 1. The abattoir was a potential source of infection until disease was found on Monday, 9 January 1967, i.e. after the weekend (7 and 8 January) during which pigs may well have been disseminating disease (see later).

That infection and disease were present at the abattoir (9) on 2 January 1967, is suggested by the records of visits listed in Table 2:

(i) The owner of farm 5 took calves to the abattoir on 2 and 6 January 1967.

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If he took infection back to his premises on 2 January, the incubation period was 6 days. (However, the source of infection is more likely to have been airborne – see before.)

(ii) The owner of farm 15 visited the abattoir on 2 January 1967, and on his return fed his cattle, which showed lesions on 10 January, i.e. an 8-day interval. Farm 15 was downwind of the abattoir on 7 January 1967; this would give a 3-day incubation period, which according to our criteria is too short.

(iii) Although it is possible that the owner of farm 16 took infection back to his premises after his visit on 2 January 1967, there were two other opportunities – on 4 January when he went among pigs at the abattoir (9) and on 5 January when he delivered and brought back a bullock which subsequently developed lesions. (He also brought back another seven cattle on the same day but they did not have lesions at the time of slaughter.)

(iv) The owner of farm 13 took two pigs to the abattoir on 30 December 1966. He had been collecting slaughterhouse waste daily from the abattoir for pig feed until movement restrictions were imposed after the outbreak at farm 1. Lesions developed in the pigs nearest to where the waste was dumped. At farm 17 the one affected animal probably had lesions on 10 January 1967. Assuming a 4-day incubation period, the infection must have reached the animal on 6 January, i.e. pigs at farm 13 were excreting virus on 6 January, if not earlier. The owner of the pigs at farm 18 probably transferred infection from farm 13 where he worked. The lesions were described as at least 48 hr. old, so that disease was probably apparent on 10 January, suggesting the presence of disease at farm 13 on 6 January. With a 3- or 4-day minimum incubation period for pigs fed on slaughterhouse waste, 2 or 3 January was the latest time that pigs could have received infection from the abattoir waste.

(v) The owner of farm 14 visited the abattoir (9) on 29 December 1966, and on 2 January and 4 January 1967. Disease in one pig developed on 10 January 1967, indicating an 8- or 6-day incubation period.

In summary, (iv) and (v) point to the presence of FMD at the abattoir on 3 and 4 January 1967, and possibly a day earlier. It could also be argued that the abattoir was the primary case and had infection in pigs on 29 December 1966. On that day infection would have been carried to farm 4; carriage on 3 January 1967 would give too short an incubation period, unless the lesions in pigs at farm 4 were not more than 48 hr. old. Infection would also have been carried in the slaughterhouse waste to the pigs at farm 13.

Farm 13

The pigs at farm 13 could also have been the primary source of infection. Slaughterhouse waste was collected from the abattoir daily and two pigs were delivered to the abattoir on 30 December 1966. The infection would have had to be transferred to the abattoir (9) before 29 December in order to infect the pigs at farm 4.

Of the three possible primary sources of infection, farm 4 appears to have been the most likely.

Subsequent spread of infection

From farm 4

As well as being a source from which the abattoir apparently became infected, farm 4 was the most likely source of disease for farm 6 which belonged to the same owner. No other spread can be assigned to farm 4, since a possible airborne spread to farm 12 on 7 January 1967 would demand too short an incubation period (2 days).

From Fareham abattoir (9)

From 7 to 9 January the winds were from the north-east quadrant and it is likely that farms 19, 21, 22 and 23 became infected in this period (Table 4). No killing took place from 13.00 hr. on 7 January until 05.00 hr. on 9 January and during this period lesions were probably present or developing. If the cattle at farm 15 were infected by airborne virus, it must have been a 3-day incubation period or at a period of calm or light winds. The cattle at farm 26 could have received infection from the abattoir (9) or from farm 15.

On the night of 6/7 January the wind at Thorney Island backed to the south-west and then veered to the north-east. During this period the cattle at farm 25 could have become infected, giving a 9- or 10-day incubation period (Table 4, see next paragraph).

From farm 13

The infection of the cattle at farm 17 has already been described. The owner of the pigs at farm 18 probably transferred infection from farm 13. The pigs at farm 13 and 18 could have been the source of airborne virus for farm 25, as suitable winds occurred on 9 January, giving an incubation period of 7 days. They could also have been a source of airborne virus for farm 27 on 9–12 January, with an incubation period of 7 to 10 days (Table 4).

From farm 16

Winds on 10 and 11 January could have taken virus to farm 24 (Table 4).

From farm 24

On 15 and 16 January winds could have carried virus to farm 28. Alternatively, the virus came at the time of milk collection (Table 4).

From farm 1

Farm 1 or the abattoir (9) could have been the source of virus for farm 12 (Table 4).

From farm 10

Disease at farm 20 could have come from farm 10 either on 8 or 9 January, giving a 4- or 5-day incubation period (Table 4).

The source of infection for farm 29 is uncertain. The animals may have received infection from farm 23 on 14 and 15 January. There may have been several cycles of disease.

Table 5. *Risks of spread through movement*

	Animals and vehicles	Slaughter-house waste	Milk (farms)	Other vehicles	A.I.	People
Approximate number of movements	72	2	52	54	73	20
Probable movements associated with disease	4 (5·6%)	2 (100%)	0	0	0	1 (5%)
Possible movements associated with disease	2 (2·8%)	0	3 (5·8%)	0	1 (1·4%)	2 (10%)
Probable + possible	6 (8·4%)	2 (100%)	3 (5·8%)	0	1 (1·4%)	3 (15%)

Risks of spread through movement

In Table 5 is shown the number of movements to and from the farms in the area recorded by the Veterinary Officers investigating the outbreak. An estimate of the risk involved has been made by ascribing 'probable' or 'possible' to those movements that were involved in subsequent disease on the farms. Of the movements probably associated with disease, movement of slaughterhouse waste, movements of animals in vehicles and movements of people were the most likely.

Airborne spread of disease

We have ascribed thirteen outbreaks (with the possible addition of another three) to airborne spread from Fareham abattoir (9), three to airborne spread from farm 13 and none to airborne spread from farm 4. According to the records, ten pigs with lesions were found at Fareham abattoir, 126 at farm 13 and 141 at farm 4. If the number of pigs emitting virus was the only factor, a greater number of outbreaks would have been expected around farms 13 and 4. In a previous paragraph we gave reasons for considering that pigs at the abattoir were emitting virus from 29 December until 9 January but we cannot estimate the number of pigs or the amount of virus. During the same period until 8 January, pigs at farm 4 were also infected and probably emitting virus.

At farm 4 the pigs were housed in sheds situated on the north-eastern side of a hill and screened on the south by trees. Most of the area around farm 4 is town and the number of cattle within a 3-mile radius was less than half of that around the abattoir (Table 6). The winds during the period were from 250° to 360° and the virus would have been blown over built-up areas or out to sea. The turbulence over the built-up area would tend to disperse the virus and reduce the concentration. When the winds were from 360° to 120° on 7 January or after, the dispersal of virus would again have been over built-up areas.

Of the area around the Fareham abattoir (9), the sector to which winds from bearings 250°–290° blew had the greatest number of farms with infected cattle and the furthest spread. In addition, the number of cattle per 10° was the highest (Table 6). The abattoir is in the valley and winds from 290° to 360° (3 to 6 January) would have blown the virus over Fareham.

Table 6. *Numbers of cattle per* 10° *arc within a* 3 *mile radius*

		Farm		
		4	9	13
Total number of cattle within a 3 mile radius		1580	3727	3321
Number of cattle per 10° arc of wind bearings	360°–120°	39	110	124
	120°–180°	55	40	64
	180°–250°	15	104	45
	250°–290°	125	179	77
	290°–360°	25	32	119

The remaining infected farms around Fareham lie to the south-west of the abattoir and from 7 January to 9 January winds blew from 10° to 70°. To the north-west of the abattoir (winds 120°–180°) is a wood but north-east the number of cattle per 10° is similar to that to the south-west and the finding of only one outbreak in this area could be attributed to the fact that winds from the south-west were infrequent during the period when pigs were infected.

The number of cattle within a 3-mile radius of farm 13 was similar to those within three miles of Fareham abattoir (Table 6) but only three outbreaks can be attributed to airborne spread. This probably is because emission of virus from the pigs did not start until 5 January and lasted to 10 January, i.e. a shorter period of emission. In addition, the piggery was protected from the action of the wind by being situated in a court-yard on the southern slope of a hill and being screened by trees.

In summary, therefore, the differences in extent of airborne spread between the three premises can be attributed to period of virus emission (abattoir 9 and farm 13), number of cattle and extent of built-up areas downwind (abattoir 9 and farm 4) and situation of the infected farms (9, 4 and 13).

In laboratory experiments, cattle have been shown to give rise to less airborne virus than pigs (Sellers & Parker, 1969) and, in the field, outbreaks in cattle would not be expected to give rise to as many subsequent outbreaks by the airborne route. In our analysis three secondary outbreaks were attributed to spread from cattle (i.e. outbreaks at farms 20, 24 and 28), with the possibility of another three (at farms 12, 22 and 26). In the probable outbreaks, spread was to one farm only; of the possibles, both outbreaks at farms 22 and 26 could have come from farm 15.

Where spread could be attributed to the airborne route, the mean size of the herd of cattle affected was in all instances higher than the size of those not affected. Where a single herd in a sector was affected, in three instances it was the largest herd and in the other two among the largest (Table 7).

In Table 8 the rainfall and wind speed during the days when airborne spread of virus occurred are given. Relative humidity was above 60 % during the period and airborne virus would not have been inactivated (Barlow, 1972; Donaldson, 1972). From the table, spread could have occurred during periods with or without rain. During the two periods when spread was most likely from Fareham abattoir (9), on 31 December and 1 January, 40 hr. of the 48 were without rain and, out of

Table 7. *Number of farms and of cattle on farms downwind*

Source	Bearing of wind	Distance downwind	Number of farms not affected	Cattle	Number of farms affected	Cattle
Abattoir (9)	250°–290°	0–3 miles	4	34, 48, 52, 79 Mean = 53·25	5	45, 66, 93, 130, 139 Mean = 94·6
		3–6 miles	22	2, 14, 16, 27, 28, 29, 31, 38, 38, 41, 48, 60, 61, 65, 65, 81, 86, 92, 95, 104, 116, 118 Mean = 55·36	5	84, 86, 106, 123, 128 Mean = 104·8
	360°–120°	0–1·5 miles	5	1, 4, 19, 33, 65 Mean = 24·40	4	14, 49, 69, 94 Mean = 56·60
		1·5–3·0 miles	24	1, 1, 2, 3, 4, 4, 5, 6, 7, 8, 10, 11, 13, 14, 14, 16, 23, 26, 53, 78, 81, 97, 193, 209 Mean = 32·46	1	97
	180°–250°	0–3 miles	12	1, 1, 4, 5, 10, 12, 24, 77, 104, 116, 118, 178 Mean = 54·17	1	69
Farm 13	180°–250°	0–3 miles	14	2, 3, 3, 7, 8, 8, 11, 13, 17, 22, 24, 26, 37, 47 Mean = 16·29	1	76
	290°–360°	0–3 miles	21	2, 4, 4, 8, 8, 8, 10, 15, 16, 18, 28, 28, 29, 34, 39, 39, 41, 41, 58, 76, 85 Mean = 26·24	2	69, 236 Mean = 152·5
Farm 16	250°–360°	0–2 miles	13	3, 5, 6, 6, 11, 25, 27, 38, 44, 64, 65, 74, 95 Mean = 35·6	1	134
Farm 24	70°–170°	0–2 miles	19	3, 5, 6, 7, 8, 12, 15, 19, 19, 21, 22, 25, 26, 36, 36, 42, 67, 69, 95 Mean = 28·05	1	98

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Table 8. *Rain and wind speed during possible days of spread during the epidemic*

Date	Possible sources and farms downwind	Duration (hr.) and amount of rain (mm.)	Time	Hours of wind ≥5 knots	Hours of wind ≥10 knots
29 Dec.	9 → 1, 2, 3, 5, 8, 11	10 (10·95)	01.00–11.00	24	23
30 Dec.	9 → 1, 2, 3, 5, 8, 10, 11, 12				
	(10 hr.)	—	—	6	4
	(14 hr.)	4 (0·75)	21.00	13	6
31 Dec.	9 → 1, 2, 3, 5, 8, 10, 11, 12	8 (3·0)	to 10.00	24	22
1 Jan.	9 → 1, 2, 3, 5, 8, 10, 11, 12	—	—	24	14
2 Jan.	9 → 5, 7	—	—	20	3
3 Jan.	9 → 5, 7	—	—	22	2
4 Jan.	9 → 5, 7	—	—	23	0
5 Jan.	9 → 7				
	1 → 12	—	—	18	11
6 Jan.	1 → 12 (16 hr.)	—	—	13	3
	9 → 25 (8 hr.) 13 → 17 (8 hr.)	8 (0·15 snow) (2·8 rain)	17.00 to midnight	8	2
7 Jan.	9 → 25 (6 hr.) 13 → 17 (6 hr.)	5 (2·3)	01.00–05.00	6	3
	9 → 19, 21, 22, 23, 26 (18 hr.)	5 (0·5)	07.00–09.00 14.00–15.00	18	16
8 Jan.	9 → 21, 22, 23, 26 10 → 20	7 (trace) (traces)	10.00 17.00–23.00	24	19
9 Jan.	9 → 21, 22, 23, 26 13 → 25, 27 10 → 20 16 → 24	—	—	17	8
10 Jan.	13 → 27 16 → 24	3 (trace)	14.00–15.00 19.00	12	0
11 Jan.	18 → 27 16 → 24	—	—	14	0
12 Jan.	18 → 27	—	—	21	0
15 Jan.	24 → 28	—	—	6	0
16 Jan.	24 → 28	—	—	16	3

50 hr. on 7, 8 and 9 January, 12 had light rain only. A notable feature during these periods was the number of hours when the wind speed was 10 knots or greater.

In Table 9 we have listed the outbreaks apart from farms 4, 9, 13, 18, 1, 10, 15, 16 and 24 together, where appropriate, with reasons to explain subsequent lack of spread apart from insufficient output. In the majority of cases the virus would have been blown over built-up areas, woods or land where the density of livestock was low. We can offer no explanation for three of the outbreaks (farms 17, 27 and 28), although at farm 17 only one cow had disease.

DISCUSSION

Any analysis of this epidemic must be speculative because the evidence is circumstantial. Our analysis differs from that of others (Report on the Animal Health Services in Great Britain, 1967; Smith & Hugh-Jones, 1969) in assuming that infectious virus was present in the area on 1 January 1967, if not before then. We cannot otherwise account for the first reported outbreak (farm 1) or for the

Table 9. *Possible reasons for failure of airborne virus to spread*

Farm	No. of animals affected	Bearing of winds at time of disease	Reasons for lack of subsequent outbreaks
2	5	290°–360°	Wind to Portsdown
3	21	190°–120°	Surrounded by infected farms
5	2	10°–80°	Wind to Portsdown
7, 8, 11	4, 12, 4	330°–80°	Wind to Portsdown
12	22	270°–20°	Wind to Portsmouth and Havant
19	4	250°–330°	Wind to Gosport and Fareham
20	4	270°–330°	Wind to Portsmouth
21, 22, 23	2, 2, 4	250°–360°	Wind to Fareham
25	21	80°–210°	Wind to woods and town
26	1	80°–210°	Wind to woods
29	10	230°–290°	Surrounded by built-up areas or previously infected farms
6	4	330°–50°	Wind to Hayling Island, Portsmouth and sea
14	1	250°–330°	Surrounded by woods
17	1	250°–330°	Unknown
27	10	150°–210°	Unknown
28	8	200°–290°	Unknown

next one or two outbreaks. As mentioned in the paragraph on criteria, we postulate a minimum dissemination period between farms of 3 days for pigs and 4 days for cattle. Applying these criteria to the recorded infections, we have worked backwards and forwards in time to fill in details of a pattern of spread that might have taken place.

All evidence points to the dissemination of FMD from the abattoir. We suggest that infection was present at the abattoir from 29 December and one may wonder why disease was not reported until 9 January, when lesions described as at least 2 days old were discovered. Lesions of foot-and-mouth disease in pigs due to the O_1 strain are difficult for the inexperienced to detect. Four of the other five outbreaks where the lesions reported were over 48 hr. old were in pigs and, in the outbreaks at Stratford-on-Avon and Oswestry in 1967, lesions in pigs were reported to be 7 to 10 days and 4 days old, respectively (Report on the Animal Health Services in Great Britain, 1967). Until 7 January 1967, pigs were probably being killed at the abattoir in the early stages of disease when output of airborne virus was maximal (Sellers & Parker, 1969; Donaldson *et al.* 1970); after processing, the lesions would be difficult to detect and the carcase would show no sign of fever. During the period from 29 December to 9 January, there were two weekends when animals were held alive and this break in slaughtering was probably important in allowing spread of disease among the pigs at the abattoir and to the surrounding countryside.

In this epidemic two main methods of virus spread are apparent – one by

movement of animals, slaughterhouse waste (swill), vehicles and people, and the other airborne. Analysis of the movements leading to probable infection showed that movement and feeding of slaughterhouse waste, movement of animals and vehicles and movement of people were the most important. How this occurs has been discussed elsewhere (Sellers, 1971). Where airborne spread and spread by movement were both possibilities (farms 2, 5, 11 and 15), we have considered airborne spread more likely in three instances (farms 2, 5, 11), since winds were available, and less likely in the fourth (farm 15), since the incubation period would have been too short. Spread by artificial insemination, milk lorries or wild animals or birds was also considered less likely because the amounts of virus available would have been less than from infected pigs (Sellers, 1971).

Where spread was attributed to the airborne route, virus coming from pigs gave rise to a greater number of outbreaks than virus from cattle. When calculations were made with Pasquill's (1961) formula, the amount given out by pigs ($10^{4\cdot8}$ ID 50 per pig per minute – Sellers, 1971) was sufficient to account for the cattle downwind breathing in an infective dose (10 ID 50) within a reasonable period. However, the calculated downwind concentration of virus based on the amount emitted by cattle was insufficient to account for infection from farm 10 to farm 20, farm 16 to farm 24 and farm 24 to farm 28. Possibly in these cases spread was not airborne or was from faeces (Parker, 1971) or the virus was not diluted to the extent predicted by the formula.

The greatest extent of airborne spread was in the areas of high cattle density but dispersion of virus was also affected by the situation of the infective farms and the duration of virus emission. The largest herds were the ones most likely to be infected downwind and, if this is confirmed from studies of other outbreaks, it would be advisable to look for disease in such animals when attempting to trace spread of disease.

In our analysis, most airborne spread occurred during the period when wind speeds of 10 knots or over were recorded. If the larger particles ($> 6\ \mu$m) are the more important in initiating infection (Sellers & Herniman, 1972), strong winds would blow them upwards, keep them airborne and prevent deposition under sedimentation. When rain occurred during the period when spread was likely, on 31 December and 7 January, it was light (trace to 0·9 mm. per hr.) and thus would be unlikely to cause deposition of the virus (Sellers & Herniman, 1972).

The decline in the number of outbreaks may be attributed to a number of factors but mainly to the elimination of the pigs as a source of virus. After 12 January only cattle were a source and, as previously mentioned, they emitted less virus. In addition to the restrictions which were in force, the winds were blowing the virus into built-up areas, into woods or to farms where the herds had been eliminated. However, in three instances no explanation is offered for failure to spread, apart from insufficient amounts of virus.

Our analysis therefore falls between that of the Report (1967) and that of Smith & Hugh-Jones (1969), the one attributing most spread to movement and contiguity, the other to wind spread during rain. Our analysis and experimental work (Sellers & Herniman, 1972) indicate that rain may not be such an important factor

as originally thought, although wind speed may play a part (Tinline, 1969; Hugh-Jones & Wright, 1970). However, the meteorological evidence for the wind-rain sector of 160° on the night of 6/7 January is not clear (Smith & Hugh-Jones, 1969). It snowed and rained but the surface winds at Calshot and Thorney Island veered from south-west to north-east, whereas at Southampton and South Farnborough there was a period of calm between winds from the south-east and winds from the north-east.

The fact that the first reported outbreak was not the primary and that the primary would not have been apparent until 8 or 9 January would have made it difficult in the Hampshire epidemic to predict at the time which way spread would occur. Movement of animals, swill, people and vehicles was still continuing until 5 January and it was not until after 12 January, 7 days later (an average incubation period), that outbreaks could be attributed to spread by the airborne route alone. Thus, in any prognosis of the outcome of an epidemic, the main factors involved in spread such as movement (controllable) and airborne (uncontrollable) must be taken into account during the first incubation period.

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