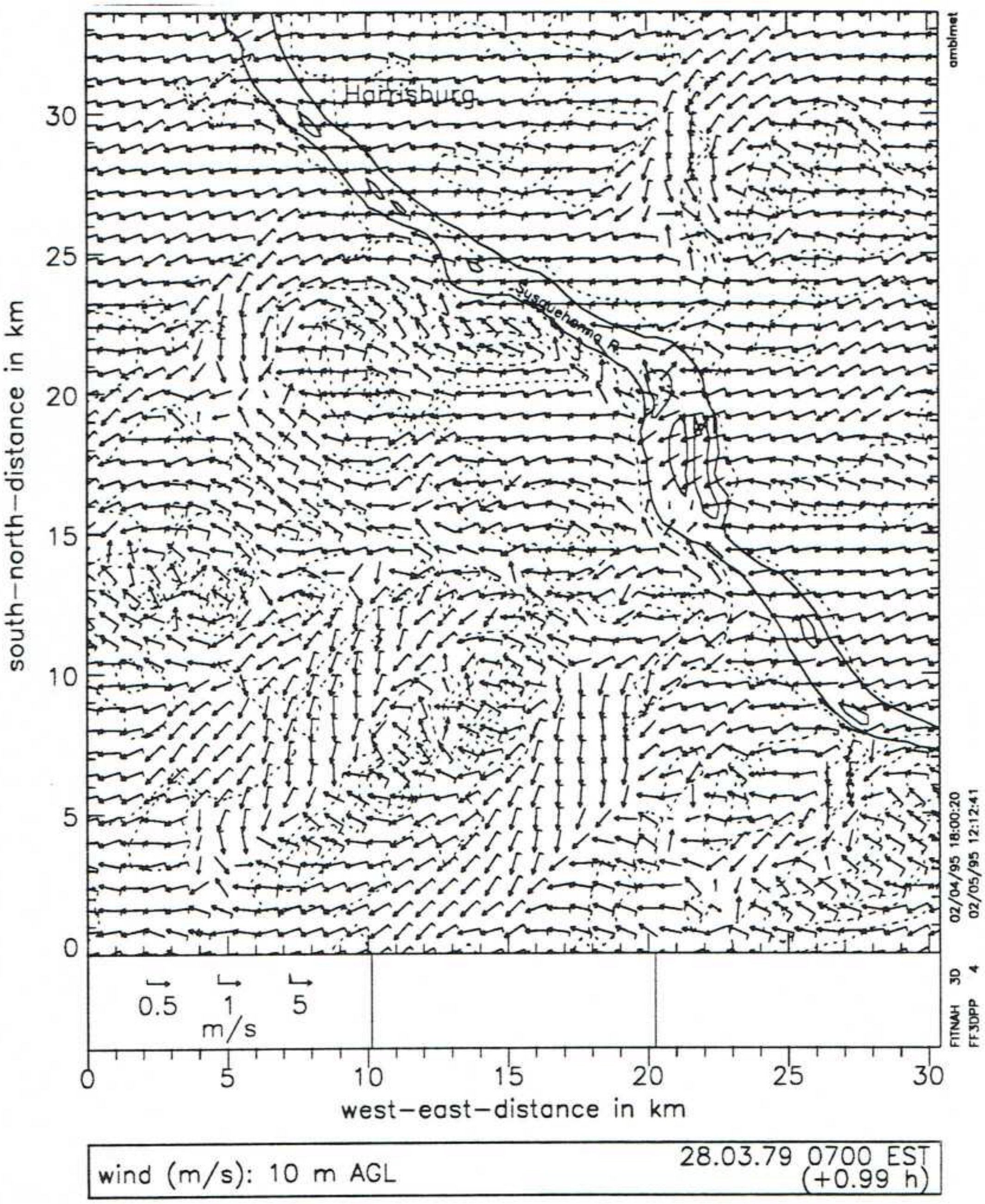


Fig. 6.1: *Wind vectors for flow 10 m a. g. l.*

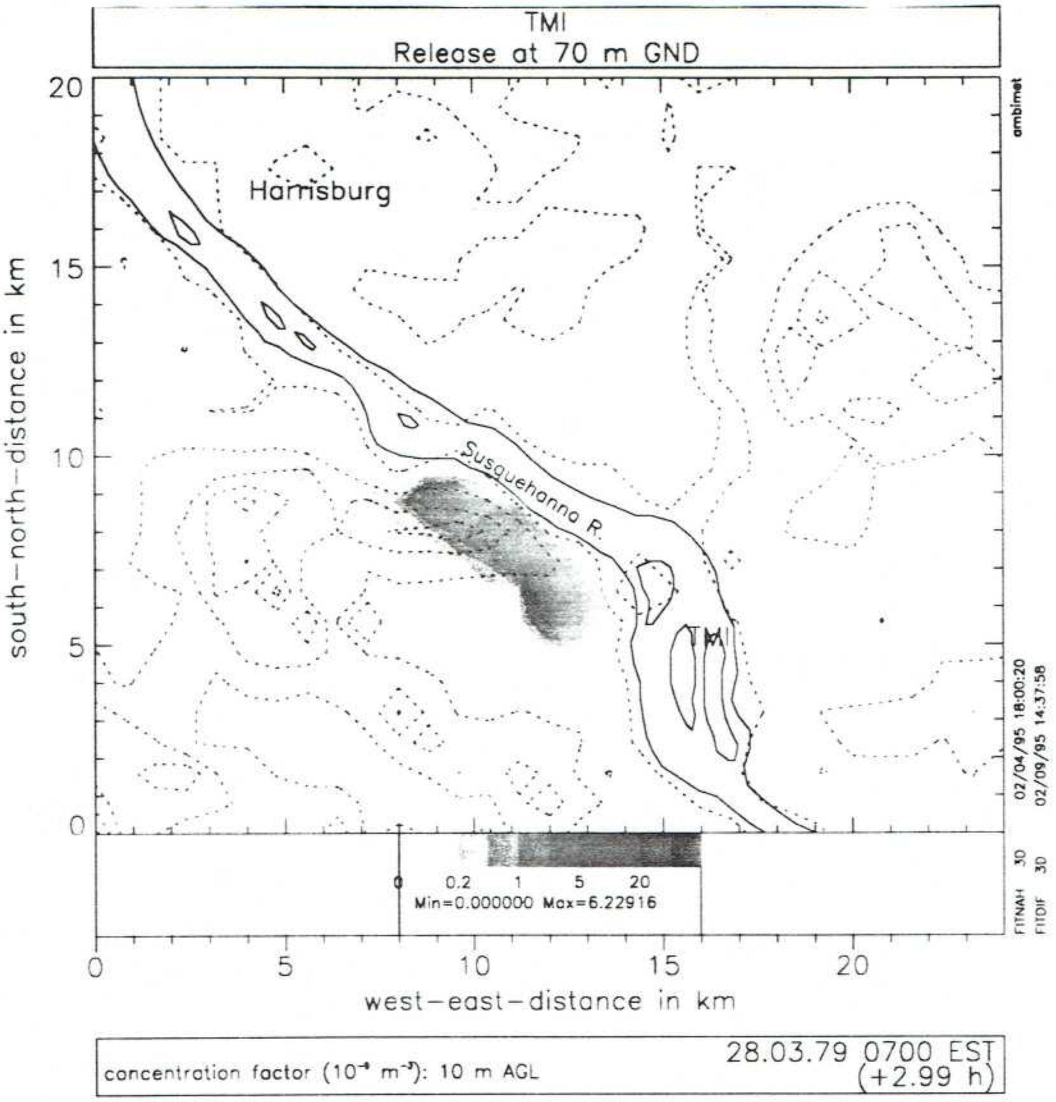


Fig. 6.2: *Particle cloud (puff mode) in the flow field fig. 6.1 after 3 hours.*

7. A laboratory shallow-water model of stratified flows in the TMI environs

With the purpose of understanding possible flow features in the near vicinity of TMI and visualizing transport and dispersion of plumes, a physical model of the Susquehanna river valley and its hilly environs around TMI was built at the University of Karlsruhe, Germany, Institut für Hydrologie und Wasserwirtschaft (Prof. Dr. E. Plate) from 45 x 45 grid points at 800 m grid distance. It can be inserted in a water tank ≈ 4 m wide and 12 m long and flooded to varying depths and with flow speeds as slow as 2 - 3 cm/s.

The model has a diameter of 2.20 m corresponding to ≈ 35 km (horizontal scale 1 : 16000) and hills up to ≈ 12 cm high corresponding to a relative elevation of ≈ 300 m (vertical scale 1 : 2500). Without exaggeration of the vertical dimension the layer of water would have come out too thin to give meaningful results. Of course, the model can be turned into any flow direction, but it is restricted to reproducing stationary flows, as the adjustment to a proper water level and flow speed takes hours, and the model is too clumsy and has too much buoyancy to be turned without precautions. Some nonstationary flow phenomena of crucial importance can therefore not be modelled directly, but must be pieced together and argued separately.

Faced with the given deadline, I will not be able to include in this treatise the full range of experiments, to be shown and commented on a video. I have, however, spent three days at Karlsruhe (Feb. 1 - 4, 1995) witnessing the experimental setup and the first few runs, and I will try to give as much advance consideration to these and later results here as I possibly can.

Some remarks on basics are in order. It may seem surprising at first glance why the flow of water could be useful for modelling air flow. In fact, the "shallow-water approximation" has a long meteorological tradition in the attempts to understand air flows at all scales from global to small-scale. There are good arguments for this, but I cannot review them here: This would amount to reinventing the wheel.

The shallow-water model is a simplification, like any model. Like the Gaussian model, it has strong points and weak points. Essentially, it models the atmosphere as being homogeneous = well-mixed in a lower layer, with all the static stability being concentrated at the free water surface. There can be no transfer of gravity-wave energy further upward. The model would therefore be quite inappropriate in a situation where this wave flux is dominant. To be sure, an elevated inversion doesn't necessarily "trap" all the wave energy below. Under particular circumstances, the inversion could be excited to "swing" at large amplitude. The FITNAH model (chapter 6) should give us a cue whether such a response could have occurred, but I have not obtained the proper output yet.

This numerical model has to be a better fit to the real atmosphere than a shallow-water model. Only the computing required for many cases and the pertinent visualization would have been prohibitive both timewise and moneywise.

Returning to the shallow-water model, remember that its main purpose is to visualize important flow features. The slower the flow speed and the lower the fluid height, the higher we must imagine the matching atmosperic stability. However, there can be no one to one correspondence between complicated, continuous atmospheric structures and a layer of water. One Froude number (see part I, chapter 4) just doesn't tell the whole story. The real atmosphere is bound to contain essential flow features reproduced by the shallow-water model, e. g. pressure forces building up in front of obstacles and diverting fluid parcels, advection, and the restoring force of gravity. In this sense we can learn a lot from looking at water tank experiments, although we must bear in mind any number of complicating factors acting in the real atmosphere, but not in the model.

The shallow-water situation is one of minimal complications, in a sense, yet by no means trivial. It is instructive to experience one's inability to foresee the combined effect of many hills on the shape of blocking zones, for example. If we are faced with surprises here already, predictability isn't going to improve in the real atmosphere. If flow features are sensitive to rather small changes of parameters, e. g. fluid height or flow direction, it is fair to assume that we can learn a lot about sensitivity in matching atmospheric conditions. The same is true for channelling of flows through valleys and gaps.

Something that can definitely not be modelled realistically here is turbulence and dispersion. A homogeneous layer of water is much too turbulent compared to a continuously stratified atmospheric boundary layer, and the physics and extent of wake formation is bound to be different, too.

Obviously, most flow phenomena come out much better in a video than on a photo: You can't really see stagnation or recirculation on a photo. I show three photos in fig. 7.1.

In the deep layer of water (lower right), the plume climbs and crosses the ridge almost as if it were not there. In the shallow water, simulating strongly stable stratification, the plume changes completely:
In the easterly current (90°), where you would expect it to be caught upstream of the concave hill ensemble, a stagnation region seems to form there, which is apparent only in that it forces the entire plume to deviate the hill towards the right, heading northwestward up the Susquehanna river valley. With only a slight turning of the "general flow" to 80 °, where, from pure geometry, the plume should make for the gap in the hills towards Lewisberry, it now splits along the northern ridge that runs parallel to the Susquehanna river. The major part would appear to travel along the southern flank of that ridge, filling the windward volume. A minor part still makes its way up the Susquehanna river. At 70 ° ("gradient wind" from the ENE), the TMI plume finally indicates easterly flow (90°), filling the concave hill region (no photo shown).

Fig. 7.1 (next page)
TMI-plume originating to the right, fanning out towards the characteristic concave group of hills roughly 10 km WNW of TMI. Arrow pointing north.

Upper left:	*Water depth = half maximum hill height = 6 cm* *Easterly current (90 °, from right to left)*
Upper right:	*Water depth = half maximum hill height = 6 cm* *Current from 80 ° (slightly north of east)*
Lower right:	*Water depth = maximum hill height = 12 cm* *Current from 80 °*
Lower left:	*not available*

In another experiment (no photos available), a "west wind" (270 °) is simulated. With strong stability, a massive recirculation region forms, filling the entire volume between TMI and the abovementioned group of hills. The TMI plume here is drawn westward into that region, contrary to the general eastward flow! It is interesting to speculate whether this result could be connected to the early east winds reported from the TMI Met. Tower at 100 ft a. g. (06 a. m.), when at the same time a bit higher up (at the height of release) the general flow was probably still westerly or westnorthwesterly (see chapter 5 and chapter 8).

For most of the material, the reader must be referred to the video film in preparation.

8. Estimating concentrations
A meteorological tour de force

8.1 Setup of the problem

In part I, chapter 7, I had pursued several specific scenarios for plumes or puffs impacting on a hill slope in a rather general way. Now, I have been asked by the attorneys for the plaintiffs to supply estimates of concentrations of radionuclides and of duration of exposure for specific people ("test cases") at specific places: home, school or work. Based on these estimates, doses incurred will be supplied by Dr. Douglas Crawford-Brown. I will attempt to focus the abundance of meteorological material presented in part I and II into a repeatable method, and, at last, into a few numbers, with some reminders of the uncertainties and bandwidths.

I will consider submersion in a radioactive cloud only (ignoring distant γ-penetration). Release rates and concentrations will for convenience be for Xe-133 only, as "weighted" dose conversion factors will take care of the different mix of nuclides depending on the age of the plume.

Instead of my earlier rounded numbers, I will use R. Webb's release estimates or plausible variations thereof. I will not defend and need not defend my earlier speculative factor ten on the damaging "quality" of the betas, but I do note that my dose conversion factor F_β (part I, page 95) was in a reasonable range. For visualization, I must rely on my earlier scenarios, on illustrations of numerical model results (chapter 6), and of the shallow-water experiments (chapter 7, with a video in preparation).

The impact of a given quantity of effluent depends on

- The mode of exit from the vent stack
- Possible physical and chemical interactions of the plume with its environment
- Horizontal and vertical dilution during the plume's transport
- The manner in which the plume or puff does or does not get near to the target
- Duration of impact

The above items will be dealt with briefly in the following subchapters. It is important to understand how the results do critically depend on many assumptions.

8.2 Release mode

Nominal flow rate is given by Woodard (1993) as ≈ 95000 ft^3/min (≈ 45 m^3/s), with the vent's inner diameter $\phi = 9.5$ ft and exit velocity 22.6 ft/s. However, in his table 2, other flow rates are noted at certain times, down to 7000 ft^3/min! The exiting jet is a source of turbulence, but not a very efficient one without buoyancy. Consider for contrast the plume of a 1000 MW cooling tower - there is an abundant energy source there to maintain turbulence and initial dilution of a plume!
Building wake influence should only come in at higher wind speeds and selective wind directions, but details are quite uncertain (see part I).

8.3 Interaction of ionizing fission products with their environment

By bombardment from the radioactive decay air molecules are transformed into radicals and ion clusters. These are chemically very aggressive. I merely note here that possible consequences and combined effects, including the role of aerosols, await further study. This is particularly true for the chemistry and biology of trees. It is plausible that "noble" gases are neither filtered out by nor deposited on trees, although their daughters may be. Radiation appears to boost certain chemical transformations in air much like the sun's energy (photochemistry). A bit of rain (early morning March 29) may worsen damages.

8.4 Dispersion and Transport

Consider a puff being released. If there is very little dilution, concentrations in the puff will be very high, but the volume (area) affected will be very small. It's the other way around with large dilution. When that puff gets carried off by the wind, any target (person, tree, animal) will be exposed to the impact of radiation in proportion to

- the concentration (see above)
- the duration of the exposure:
  In light winds, that duration is longer than in a brisk wind, stagnation being an extreme limiting case. Also, a larger puff, although it has the effluent more diluted, will take longer to pass the target.

As a rule, stable stratification (weak dilution) occurs together with very light and changeable winds. The morning hours of March 28, 1979, are a perfect example. If you contrast a plume in a straight wind (quasi infinitely stretched out) with a plume/puff formed by winds drifting about back and forth, it is immediately obvious that in the latter case concentrations and times of exposure will be larger, although the area affected is smaller. The simultaneous occurrence of the two aggravating conditions is an invitation for using a large span of "dispersion factors" between the morning and the noon hours (see chapter 8.5). Around noon, a mixing layer of ≈ 1 km depth has formed, more or less simultaneously with the southerly winds picking up strength. The early evening hours require some discriminating considerations:
The lower atmosphere becomes quite stable again, while the winds continue at speeds of some m/s until they tend to stagnate over Cumberland County.

Extensive material on winds has been collected and presented here in the Sequence of Events (chapter 5), drawing on the wind measurements available, on concepts of slope winds (chapter 3), on numerical flow simulations (chapter 6) and shallow-water laboratory experiments (chapter 7). It will not be repeated here.

It should be obvious from that wind collection, if from no other reasoning (part I, chapter 5), that the Gaussian model is not fit for computing realistic concentrations, as it assumes a wind field uniform in space. In principle, the "segmented plume model" goes in the right direction, but without proper winds it is bound to give very wrong answers. Consider, for example, early morning times like March 28, 06 E.S.T., when there must have been northerly wind components at release height from all indications, when the TMI tower at 100 ft a. g. showed easterly winds all along. I couldn't and wouldn't try to do alternative segmented plume computations, feeling that it would be a futile effort: Such detailed data are not on hand, and even if numerical models were perfect and contained all the necessary physics (which they certainly don't), the many necessary simulations couldn't realistically be done.

8.5 Dispersion factors

In part I, I had argued puff or plume volumes and concentrations directly in terms of boxes, rather than using "dispersion factors". As will be checked easily, my plume impaction scenarios in very stable conditions amount to postulating extreme dispersion factors X/Q of up to 10^{-3} s/m^3 at the site of impaction. This number X/Q is a relative concentration - if multiplied by the plume source strength Q (e. g. Ci/s), the result is local concentration X (Ci/m^3).

A suggestive way to think of X/Q is to write down the continuity of fluxes across any cross section of an imagined straight plume:

$$Q = \overline{u} A \overline{X} \tag{8.1}$$

Here,
Q = rate of release (Ci/s)
$\overline{u}$ = mean wind speed (m/s) along plume
A = effective cross-sectional area across the plume (m^2 or km^2)
$\overline{X}$ = average concentration (Ci/m^3)

From equ. (8.1)

$$\frac{\overline{X}}{Q} = \frac{1}{\overline{u} \cdot A} \qquad \text{(units } s \cdot m^{-3}\text{)}$$

Thus, the "dispersion factor" X/Q may be thought of in plain geometric terms. X/Q and, therefore, concentration X will decrease downwind as A increases. Assuming that each effluent (each nuclide) disperses in the same way, such that the respective concentrations anywhere are proportional to the respective release rates, the meteorological problem is reduced to the one of determining or estimating X/Q.

I start out with X/Q's on the upper end of the range. Further up, I had quoted my scenarios from part I as requiring X/Q's of up to ≈ 10^{-3} sm^{-3}, attempting to verify this order of magnitude by connecting estimated releases with estimated extreme doses incurred at the site of impact. No meandering is included in this estimate: Meandering of a plume effectively lowers the average concentration observed at a fixed site, as the high concentrations occur only rarely. The point of my scenarios was, however, that a real, very narrow plume or puff "got stuck" in a suitable site or cavity, not an average plume!

In the following, I will argue that values of X/Q as high as 10^{-4} to 10^{-3} sm^{-3} are plausible in very stable, light-wind conditions. The main point is that after the initial dilution phase at the vent stack exit, the plume or puff may essentially not meet any turbulence at all on its path until it approaches a hill's surface. So why should it be more diluted? Where is the energy input necessary for maintaining turbulence to come from?

Sure enough, there is wind shear, but speeds are low, and any ensuing turbulence would be restricted to isolated patches (see my part I, chapter 5).

There is abundant visual evidence of very thin plumes stretching for miles and miles without any apparent dilution. Interestingly enough, Woodard himself (1993, table A-3) exhibits values of X/Q of up to 3.5 10^{-4} sm^{-3} on March 28, close to 10^{-3} on March 29 and ≈ 10^{-3} sm^{-3} on March 30 and 31, 1979, albeit for a distance of 600 m only!

The EPA Milestone Reports quote 0.55 x 10^{-3} sm^{-3} as the maximum value observed (Third Milestone Report 1983, p. 151). This is an hourly average, but again at rather close distance. Weng and Carruthers (1994) compute the concentration distribution due to a point source in plane flow around a hill below the "dividing streamline height". Values X/Q of several times 10^{-3} sm^{-3} are shown. Again, the distance is only a few hundred meters, but, on the other hand, the assumed eddy diffusivity of 5 m^2/s seems too large to be representative for stable conditions.

For obvious reasons, there are few dispersion data available in very stable conditions, none of them at larger distances. The main purpose of the EPA field studies was model development. Going for model verification, one doesn't necessarily pick the most extreme cases. Statistics is what counts. And even if the investigators had looked for extreme cases, the practical problems inherent in any field program would make the choice of meteorological conditions covered more a matter of chance than intent. Given a very stable weather situation, it is difficult enough to sample a concentrated plume on a rough hill slope at short distance, but hopeless at distances of several miles. One can cover a small, isolated hill with receptors, and although the plume will often skirt the hill one way or the other, occasionally it will impact. Our situation is entirely different from the EPA's model development background: TMI plumes may impact anywhere on the forested Appalachian hills several miles away. These are not isolated obstacles, but chains of hills and ranges - the plumes have nowhere to go but to approach the hills somewhere. They can't escape. Only it would be futile to try to sample hundreds of square miles in order to locate concentration maxima.

How about the lower end of the range of "dispersion factors" X/Q? Let the early afternoon plume from TMI fan out northward, attaining a well-mixed state below the inversion ≈ 1000 m a. g. after 10 or 15 km, with a width of, say, 5 km. Let the average wind speed be 5 to 10 m/s. Then, at the quoted downstream distance

$$X/Q \approx \frac{1}{7\,m/s \cdot 1\,km \cdot 5\,km} \approx \frac{1}{3} \cdot 10^{-7}\ sm^{-3}.$$

Similar, somewhat larger values are obtained from models of the convective planetary boundary layer. Concentrations are very much lower in this well-mixed case as compared to the stable case, but the areas affected are much larger.

So, altogether, the range of values of X/Q spans roughly four orders of magnitude. So does, in analogy, the daily range of the eddy diffusivity K_z, which is commonly taken to vary between ≈ 0.01 m^2/s in stable nighttime conditions and ≈ 100 m^2/s in unstable daytime conditions.

Dispersion under late afternoon and evening conditions is not easy to handle. The evening transition from mixed layer to stable boundary layer is notoriously little studied and ill-understood (see part I, chapter 5, or Whiteman, 1990). A mixed layer still appears to persist in disintegration for some time, but the upward sensible heat flux, energy source for turbulence, should stop at around 4 p. m. or little later, with shallow cold-air pooling near the ground beginning thereafter. There is still wind shear as a source of turbulence, and winds on the evening of March 28 are stronger than in the morning.

The beginning stagnation to the windward side of the Blue Mountains has repeatedly been mentioned. Downslope flows might push the oncoming plume aside and up in places, the hills will excite wavy vertical motions in the southerly flow, reaching close to 1 m/s up and down according to the FITNAH model (chapter 6). Such vertical motions, disregarded of course in the Gaussian model, are capable of carrying a plume up or down, whether they be dynamically or thermally forced. A plume carrying a lot of liquid water would be brought down along its way by evaporative cooling.

Certainly the vertical extent of the plumes would have to shrink fast in the course of the evening. Their release height is close to the elevation of Rutherford Heights, Colonial Park and neighbouring hills. The low-level flow will increasingly be funnelled between the hills. The plumes will be increasingly streaky, but these streaks will meander and wobble around to some extent. Possibly the topographic funnelling action will lead the plumes into preferred directions, hitting some sites very hard and skirting others to some extent.

Highly concentrated wisps of a plume could get stuck in a fixed place (see the next chapter 8.6). Each of these processes will have a bearing on effective values of X/Q applicable to a particular site at a particular time. All in all, we are left with reasonable order-of-magnitude estimates somewhere between the very stable upper-limit dispersion factors quoted above, and the more or less agreed values for a mixed layer. We may also take cues from the numerical model results (chapter 6).

The range of uncertainty applied to all the later estimates ought to remind the reader of the complexities of the real world.
Interpolation of X/Q's to smaller distances is much less of a problem than extrapolating X/Q's out from small distances with Gaussian mathematics.

8.6 How do contaminated plumes or puffs get near a hill site?

Stationary flow models typically show smaller or larger quasi-stagnating regions (blocked flow) upstream of the obstacle, when the Froude number is small enough (part I, chapter 4). One might think, at first glance, that oncoming fluid parcels would never get into these stagnation zones. This is, of course, not true, if only because real flows are never stationary. Stagnation zones form, get carried off by the changing pressure and flow patterns, and reform much like cavities. It is important to realize that most flow models on small scales are simulating stationary flows only, such that some essential non-stationary features of the real world must be given proper consideration separately. R. Smith (1990) has argued very well that the pressure pattern determines the character of the flow in potential blocking regions, and that pattern depends on the flow in the entire domain, downstream and up to higher levels. In the real atmosphere, there are abundant causes triggering pressure disturbances or simply slight shifts and readjustments of the pressure field, as evidenced by the nonstationary character of observed winds (fig. 5.7). "Chunks of air" will remain trapped for some time in a concave section of a hill, as illustrated in part I, fig. 7.4, page 100, and break away on a sufficient shift of the pressure field to make room for a new chunk of air.

In that scenario, I let the general wind shift its direction. There are other possibilities: A plume or puff could be approaching a hill, on its way to climb over it, then find itself stagnating immediately upwind of the hill, either due to a slackening of the wind or to increased thermal stability.

To be sure, there are scenarios for air parcels approaching hill sites in completely stationary flows: Plumes straddling alongside a hill or ridge (see e. g. part I, fig. 7.2, or chapter 7 here), or plumes engulfed in a recirculating regime upwind of a suitably formed ensemble of hills or ridges (see chapter 7).

Zooming in on a smaller scale yet:
How well or how badly does the wind "get to" or into groups of trees, houses or other obstacles or irregularities of the local terrain? That depends, for one, on thermally or dynamically forced mini-features of the pressure field, including local channeling of the flow through narrowing paths, gaps between hills, or ravines, including also wakes (part I, chapter 4). It also depends on the drag or "porosity" of the obstacles. A good case in point is the problem of constructing a wind machine properly:
If it is too compact, the wind will go around.
If it is too "porous", too "transparent", the wind will blow through it without much resistance.
Only in a range somewhere in between will the windmachine extract maximum power from the airstream.

Trees on top of a hill are exposed to stronger winds ("speedup", see e. g. chapter 6, case 1) and are, therefore, in a preferred location (what a preference!) for filtering aerosols and certain gases out of the airstream, a fact which could be of some relevance in the late afternoon blowout from TMI.

Consider once more a passing contaminated puff or plume embedded in a wind flow. Let a house, school, factory be in its way. The impact can be very, very different on two distinct levels:

a) How well does the flow "get to" the target? See above. If it does,
b) Is the house, school, factory well ventilated or not? Obviously, with closed windows and doors, a passing radioactive cloud, even if it lasted for a couple of hours, might not replace much of the air inside.

So there is room for both the worst case (outdoors exposure), and for comparatively well-sheltered environments.

9. Conclusions

For conclusion, I present my own tentative TMI plume "movie" for the first few hours in fig. 9.1 . Its chief purpose is visualization of possible plume shifts and exposures, and

realization of the kind of information we would need to be reasonably sure about transport and dispersion of TMI-2 effluents. Fig. 9.1 is the beginning of an investigation, not the end. A big warning: The smooth outlines of my plumes are NOT to imply by any means that concentrations in there are uniform! In fact, not even average concentrations would look nearly so smooth. Plume shapes are kind of orderly for lack of more detailed information. The tail of the plumes consists of the earliest releases . The width of the plumes is not to scale. If we had concentration measurements at given locations and times of day, we would be in a vastly better position to pin down some pieces of the puzzle.
For a start, W or WNW winds in the way of an LLJ (see part I, chpt.5) are hypothesized for the earliest, "hottest" releases. Although they are not reflected in the measured TMI wind at 100 ft, their plausibility has been argued in chpt.5. Interestingly, the winds turning from W across N and NE to E (easterly) by 8 a.m. or somewhat earlier suggest another "inertial circle", analogous to the one described in chapter 5, which was related to the unusual late-morning westerlies at TMI.

Fig. 9.1 (next page and following)
TMI plume locations for indicated date and hour (E,S.T.)
Very schematic and tentative (see text).
Locations given by capital letters, among them:
Harrisburg, Mechanicsburg, Middletown, Hummelstown, Elizabethtown, Goldsboro, Bainbridge, York, Lewisberry, Dillsburg.

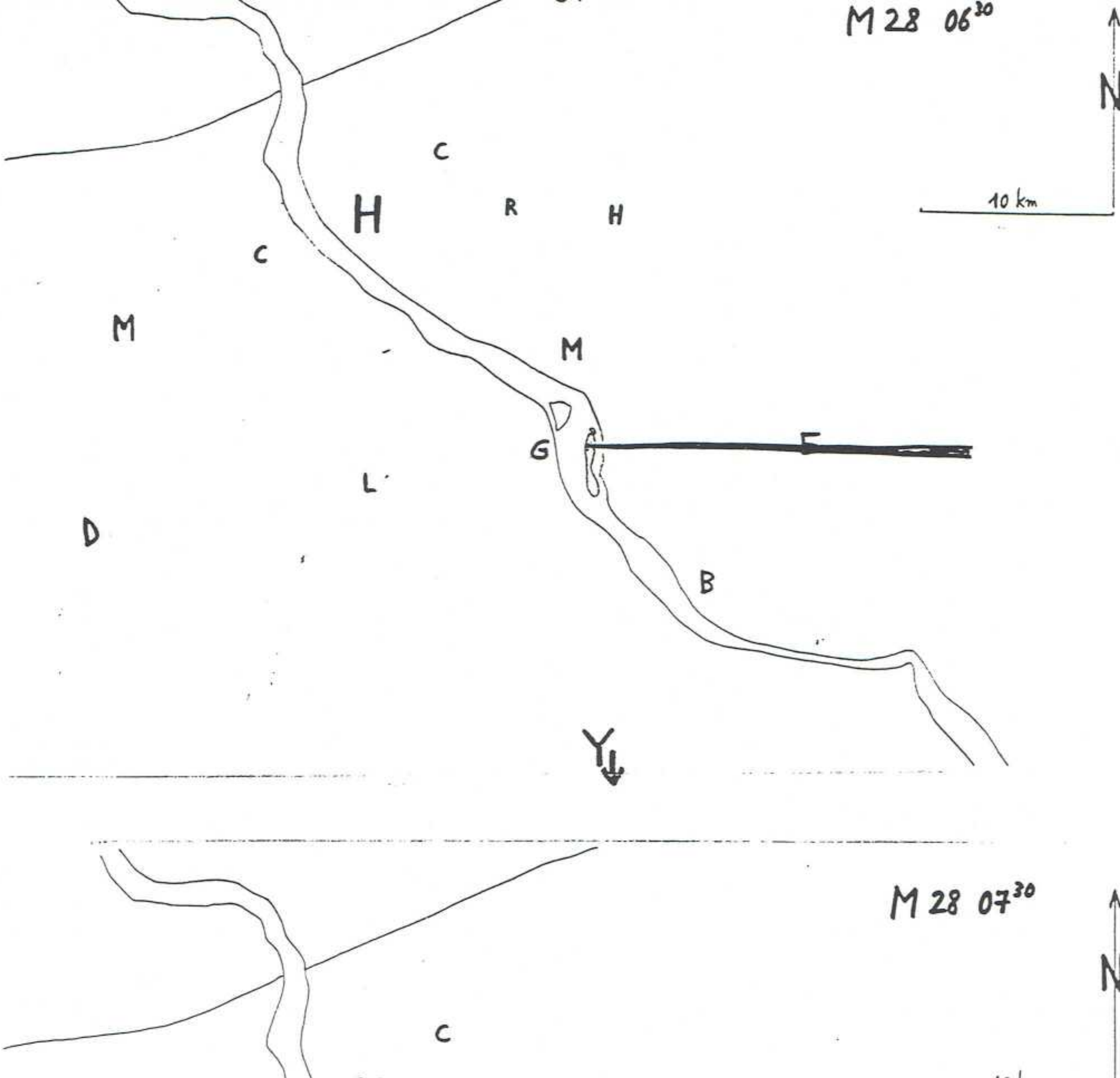
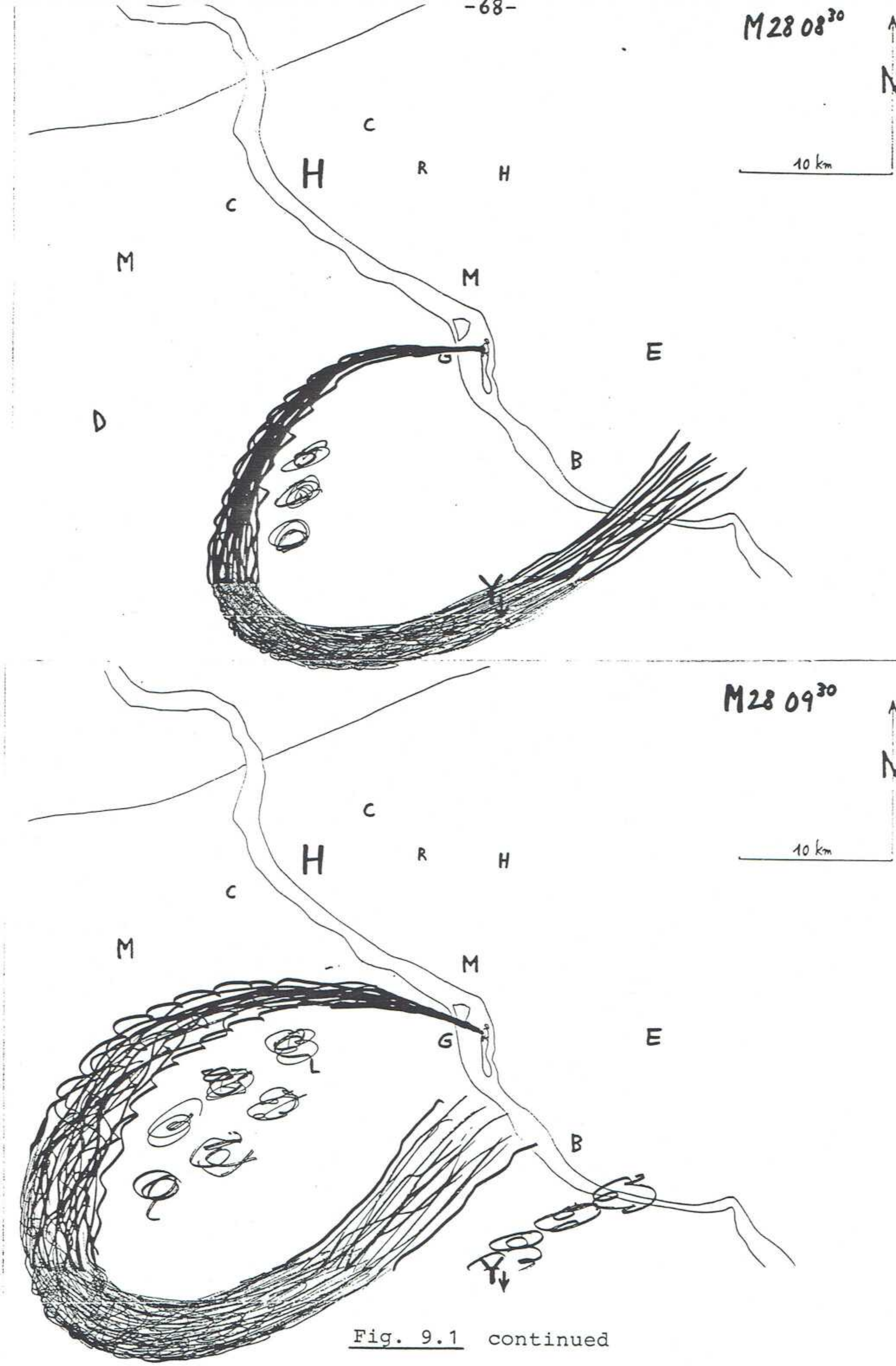


Fig. 9.1.



<u>Fig. 9.1</u> continued

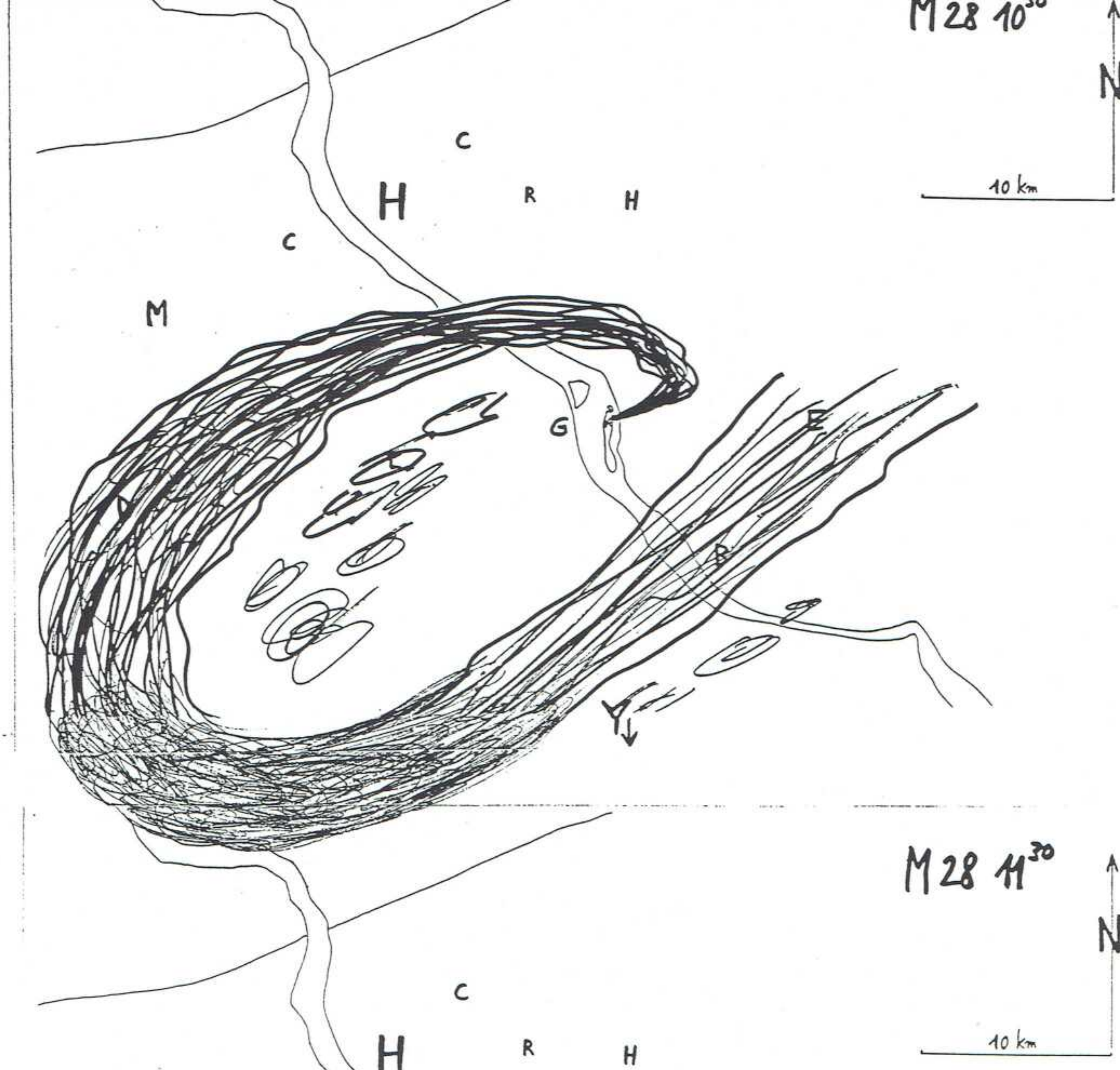


Fig. 9.1 continued

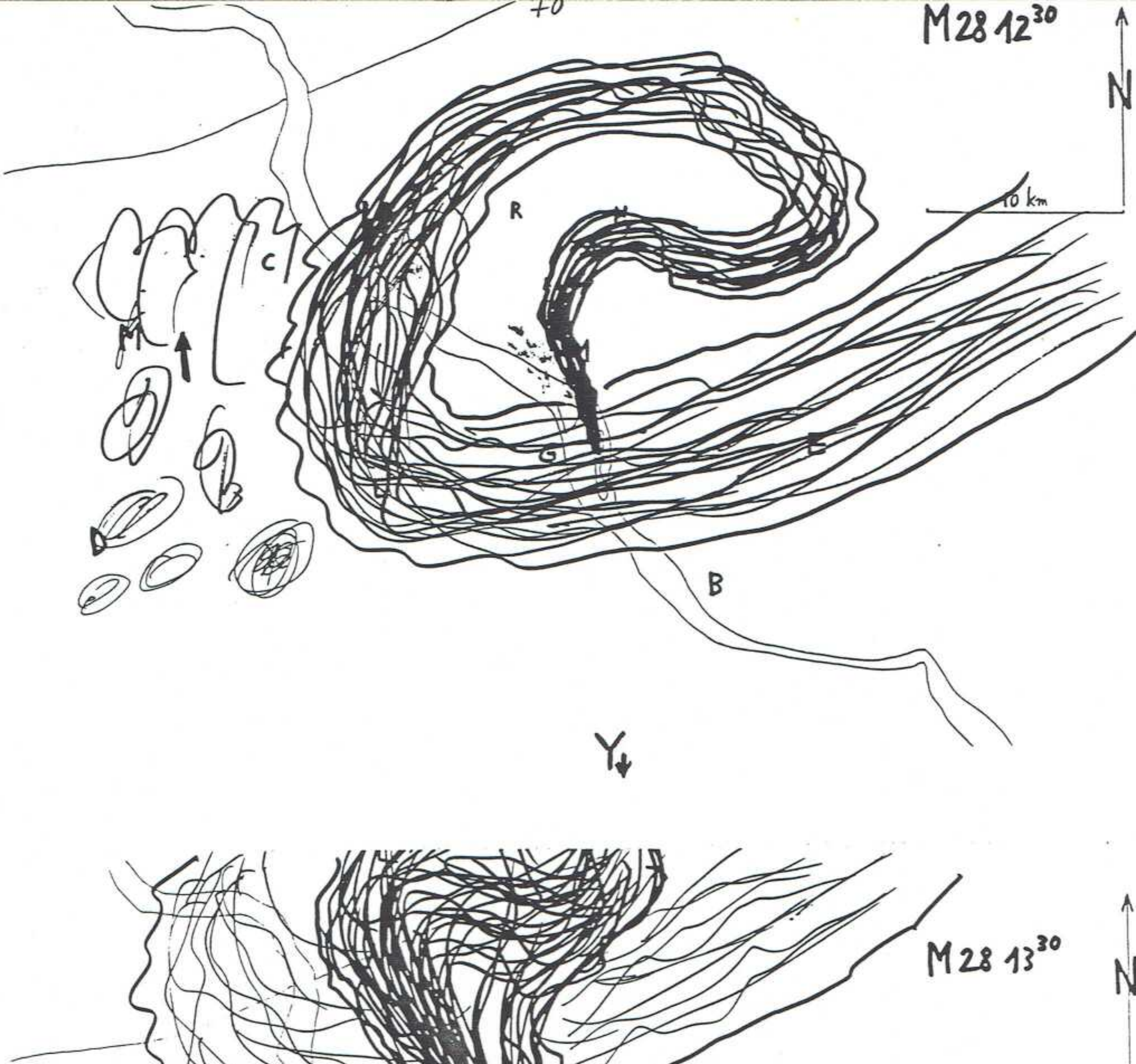


Fig. 9.1 continued

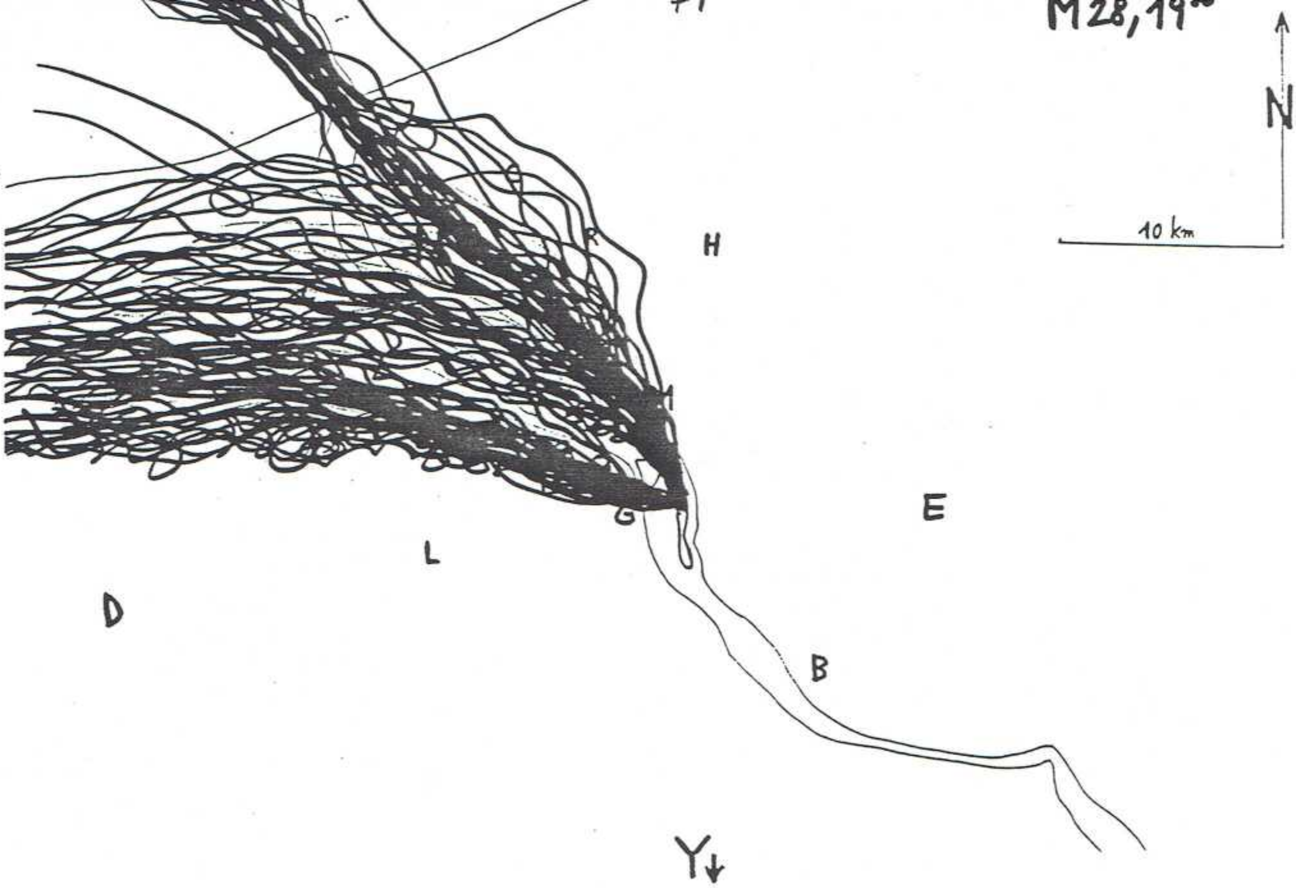


Fig. 9.1 continued

Later in the morning, I assume that the measured TMI winds become more representative of the winds at the height of releases, but watch my discussion of some queer wind observations! Note that the longer the travel time of a plume segment, the more uncertain becomes its position and, of course, its state of dispersion . The uncertainties add up, in a way. As soon as a plume attains some vertical extent by mixing (after 8 or 9 a.m.), the different winds at different elevations add to the dispersion. In some figures, indication has been made of plume segments or puffs remaining trapped by features of the hilly or mountain relief (sheltered corners) and "staying behind", while the plume as a whole moves on. At noontime, I expect that these contaminated stagnating patches (mostly, but not exclusively, across the western areas) will be dragged off northward by the prefrontal southerly winds, some sooner, some later.

As an example for concentrations, let's take the western region. At inflow time, the flow is still highly stable, despite slope circulations and a growing shallow mixing layer. The plumes will preferentially flow through gaps in the terrain, unless they impact directly or straddle lateral hill slopes or ridges. Closed slope circulations will help to concentrate pollution in certain places and remove it from others (see chpt. 3). The distribution of nuclides will be highly inhomogeneous. Only the human and tree evidence could tell us details - these are the only data out there we have!

Take $\approx$ 5 x 10^6 Ci inflow into 500 km^2 over a period of 2 hour or some more. If uniformly mixed across 100 m vertically, we ge a mean concentration of $\approx 10^{-4}$ Ci/m^3 (Xe-133 only). But the plumes are not going to be uniformly mixed by far. Accumulation by only a factor of ten in some places would yield 10^{-3} Ci/m^3, a hundredfold would produce spots with 10^{-2} Ci/m^3 .

The rather odd westerlies between 9.40 and 11.40 a.m. could be accompanied by a disturbed thermal structure.

The onset of the prefrontal S or SSE by noon acts to carry the old plumes up north, right across the TMI area. Multiple exposures will thus be experienced in most locations, as would be typical of variable, weak-wind conditions.

Noon and early afternoon is the time of most vigorous mixing. Even so, Gaussian-shaped or other smooth concentration profiles are attained only on the average. There are large thermal plume in a convective boundary layer, which may transport concentrate puffs, and there will be organized thermal circulations in this hilly terrain, whose effects on concentrations are uncertain.

Regarding the late afternoon and early evening plumes, the line of reasoning has been given before: Turbulence dies down fast, although a nearly mixed layer may continue to exist for some time, until the cooling from below gets slowly mixed upwar Plumes will become streaky. Assume, for example, the plume's cross section to be roughly 200 m (horizontal) x50m (vertical) at some distance from TMI. The respective "dispersion factor" according to equ. (1) would then be

$$X/Q \approx 1.4 \times 10^{-5}\ \mathrm{sm}^{-3} \quad \text{(at wind speed 7 m/s).}$$

On top of that, any number of local flow features (katabatic winds, horseshoe vortices) and eddies must be imagined to occasionally bring down puffs in the lee of a hill, in the space between an ensemble of trees and so on (chpt. 8.6). The likely big blowouts later on March 28 would make such scenarios most relevant, particularly in connection with beginning blocking and stagnation across Cumberland County, upstream of the Blue Mountain.

Finally, I have been asked to give estimates of nuclide concentrations and times of exposure at various locations and times, the times being implicit in the estimated plume shifts (fig. 9.1). For convenience, concentrations refer only to Xe-133. They are based on the following release rates Q :

March 28, 1979	06 - 08 a.m.	1300 Ci/s
	08 a.m. - 04.15 pm.	440
	04.15 - 05.30 p.m.	3400
	05.30 - 07 p.m.	830
	07 - 07.30 p.m.	3400
	07.30 - 09.30 p.m.	560
	09.30 - 10.30 p.m.	280 Ci/s

It goes without saying that the possible contributions of all later releases, like ventings, are not being addressed her

"Dispersion factors" X/Q (chapter 8.5) may be used as a rough guide. As shown further up, most locations will have suffered multiple exposures. In most cases, only one or two judged to b the most serious have been entered.

Bandwidths will not be quantified . They are quite substantia however, as is evident from the body of my work. In each of t cities, there will be sites with considerably less exposure than quoted here.

		Estimated mean concentration in mCi Xe-133/m^3	Estimated duration of exposure
York Haven	morning	60	5 min
		1	1.5 hours
York	morning	10	1 hr
Bainbridge	mid-morning	10	1 hr
		1	2 hrs
Lewisberry, Dillsburg, Fishing Creek Rd. ...		5	2 hrs
Elizabethtown	early morning elev.sites	200	5 min
	late morning	5	2 hrs
Afternoon plume:			
Harrisburg area		0.03	3 hrs
Harrisburg - E		0.05	3 hrs
Kunkel school		0.10	3 hours
Middletown		0.15	3 hrs
Mid-afternoon:			
HAR		0.20	1 hr
HAR-E		0.30	1 hr
Kunkel school		0.50	1 hr
Middletown		0.70	1 hr
Late afternoon blowout			
4.15 - 5.30 p.m.			
Mechanicsburg		7	0.5 hrs
HAR		10	1 hr
HAR-E		15	1 hr
Hummelstown		5	1 hr
Kunkel school		20	1 hr
Middletown		25	1 hr
Evening blowout, Shuey Rd. 7 - 7.30 p.m.		50	0.5 hrs

I estimate that the added contribution (mean concentration times duration of exposure) of the releases 05.30 to 10.30 p.m. at all the above sites in the N-W-sector from TMI (except for Hummelstown) will exceed that from the late afternoon blowout, and more so at Mechanicsburg than further east.
Similarly, at Shuey Road, the contributions of all releases beyond the evening blowout could equal or exceed that from the evening blowout.

It is my professional opinion that the pattern of the location of damaged trees is not inconsistent with my analysis. Deposition of particles or reactive gases would, obviously, worsen the impact of exposure. This is true for people, and still more for trees with their well-known filtering capability.

REFERENCES

Bellamy, J. C.; 1945: The use of pressure altitude and altimeter corrections in meteorology. Journal of Meteorology, Vol. 2, pp. 1 - 79.

Blumen, W., 1990: (ed.): Atmospheric Processes over Complex Terrain. Meteorological Monographs, vol. 23, American Meteorological Society, 323 pp.

Egger, J., 1990: Thermally Forced Flows: Theory. Chpt. 3 in: Atmosperic Processes over Complex Terrain, (W. Blumen ed.), pp. 43 - 58.

E. P. A. (United States Environmental Protection Agency),1982 - 1986:
EPA Complex Terrain Model Development
First Milestone Report 1981, Lavery et al.
Second Milestone Report 1982, Strimaitis et al.
Third Milestone Report 1983, Lavery et al.
Fourth Milestone Report 1984, Strimaitis et al.
Fifth Milestone Report 1985, DiCristofaro et al.

Lavery et al., 1986: The full scale plume study: A summary of data collected and phenomena observed. Fifth Joint Conference on Applications of Air Pollution Meteorology, Chapel Hill, North Carolina.

Lu, R. and R. P. Turco, 1994: Air Pollutant Transport in a Coastal Environment. Part I: Two-Dimensional Simulations of Sea-Breeze and Mountain Effects. J. A. S., Vol. 51 (15), pp. 2285 - 2308.

Smith, R. B., 1990: Why Can't Stably Stratified Air Rise over High Ground? Appendix to Chpt. 5 in: Atmospheric Processes over Complex Terrain, (W. Blumen ed.), pp. 105 - 107.

Steinacker, R., 1984: Area - Height Distribution of a Valley and its Relation to the Valley Wind. Beitr. Phys. Atmosph. Vol. 57 (1), pp. 64 - 71.

Steinacker, R., W. Klötzer and A. Lanzinger, 1987: The Quality of ALPEX Level - II b SYNOP and RAWIN Data. A Documentation of Errors, Part I. Dept. of Meteorology and Geophysics, University of Innsbruck, Austria.

Vergeiner, I., 1982: Eine energetische Theorie der Hangwinde. ITAM Berchtesgaden, Proceedings, Deutscher Wetterdienst, pp. 189 - 191.

Vergeiner, I. and E. Dreiseitl, 1987: Valley winds and Slope Winds - Observations and Elementary Thoughts. Meteorol. Atmosph. Physics, 36, pp. 264 - 286.

Vergeiner, I., E. Dreiseitl and C. D. Whiteman, 1987: Dynamics of katabatic winds in Colorado's Brush Creek Valley. J. A. S., Vol. 44, pp. 148 - 157.

Vergeiner, I., 1994: Treatise on the TMI-2 Accident of March 28, 1979, particularly its meteorological aspects including transport and dispersion of the radionuclides released. June 1994.

Webb, R. E., 1993: Analysis of the Three Mile Island Nuclear Accident with respect to the Release of Noble Gas Fission Product Radioactivity into the Atmosphere.

Weng, W. S. and D. J. Carruthers, 1994: Modelling turbulent diffusion from a point source in strongly stratified flow around a three dimensional arbitrarily-shaped hill. In: Stably Stratified Flows (Flow and Dispersion over Topography). ed. by I. P. Castro and N. J. Rockliff. Clarendon Press, Oxford, pp. 263 - 274.

Whiteman, C. D., 1990: Observations of Thermally Developed Wind Systems in Mountainous Terrain. Chpt. 2 in: Atmospheric Processes over Complex Terrain (W. Blumen ed.), pp. 5 - 42.

Woodard, K., 1993: Assessment of Offsite Radiation Doses from the TMI Unit 2 Accident (TDR - TMI - 116, July 31, 1979 = "Revision O"), latest revision dated Jan. 15, 1993 = "exhibit C".

Innsbruck, Feb. 23, 1995

I. Vergeiner, Ph. D.
University of Innsbruck
Department of Meteorology and Geophysics