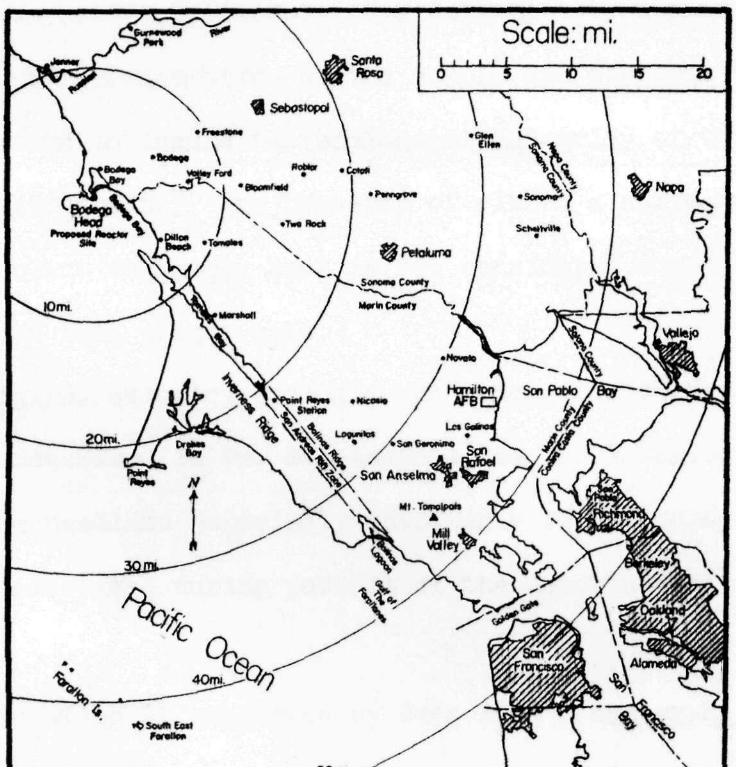
Meteorological Aspects of Nuclear Reactor Hazards at Bodega Bay



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PREFACE

This is the second major publication by the Northern California Association to Preserve Bodega Head and Harbor. The first, Geologic and Seismologic Study of Bodega Head, by consulting seismologist Dr. Pierre St.-Amand, was released in August 1963.

The Northern California Association to Preserve Bodega Head and Harbor is a non-profit California corporation, established in March 1963 "to work for preservation of the scenic and historic headlands of Bodega Bay and to insure the ecological integrity of the surrounding marine environment." The presence of either a nuclear or conventional power plant on Bodega Head is not considered consistent with preservation of this unique site.

The ambiguous seismic, geologic and meteorologic characteristics of the site, described in Dr. St.-Amand's and Dr. McDonald's reports--which make the headland especially unsuitable for a nuclear power plant--were discovered during pursuit of the Association's conservation objectives.

The Association is supported by dues from a membership of about 1800 citizens in the San Francisco Bay and Sonoma County areas and is staffed entirely by volunteers. Consistent with this character, both Dr. St.-Amand and Dr. McDonald contributed their work without fee.

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1. INTRODUCTION

1.1 Objectives. In the following discussion, meteorological factors influencing possible hazards accompanying operation of one or more large power reactors at Bodega Head, on the northern California coast, will be examined. Meteorological conditions set certain limits to the amount of volatile fission products that can safely be permitted to escape during routine operation of any reactor; and meteorological conditions become still more important in event of a major accidental release of reactor fission products. The latter possibility forms the subject of chief concern of this report. No assessment of the safety of a proposed reactor site is complete until both the local meteorological conditions at the site and the general climatological conditions in the surrounding regions have been studied in detail. This report summarizes such a study for the case of the Bodega site.

1.2. Earlier Studies. As one part of the Preliminary Hazards Summary Report filed on December 28, 1962 with the Atomic Energy Commission by the Pacific Gas and Electric Company (designated hereafter as "PG&E", for brevity), Eberly and Robinson (1)*

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* Numbers in parentheses denote references listed near the end of this report.

prepared a "Report on Meteorological Conditions at Bodega Head and Bodega Bay", mentioning briefly previous work by Smalley (2), Humphreys and Wilkins (3), and Edinger (4). Some of the data assembled by Eberly and Robinson will be used here; but it has been necessary to search much further in the literature for other relevant studies, since there are many features of the meteorology and climatology of the Bodega area and of the down-wind San Francisco Bay area of importance in assessing reactor hazards which Eberly and Robinsion (1) did not consider.

Features of sea-breeze circulations and of air currents flowing inland through gaps in the coastal mountains determine whether reactor effluents might be carried to populous areas in event of a major accident on Bodega Head. The work of Schroeder and Fosberg (5-10) on wind patterns and sea-breeze behavior in the Bodega-Petaluma area, carried out in the course of studies of forest-fire meteorology, will be especially pertinent here. Wind data for Dillon Beach, reported by Kadib (11) supplements the Pt. Reyes wind data assembled by Eberly and Robinson (1). A number of Bay area hodograph analyses of July wind data reported by Frenzel (12) contain useful information on the way in which airflow through Golden Gate interacts with air currents flowing from Bodega to the Petaluma valley via a gap in the coast range near the reactor site. Bay area circulation features are illuminated further by Edinger's work on the Oakland winds, and also indirectly by the studies of Schultz, Akesson, and Yates (13) on deep penetrations of marine air into the Central Valley near Sacramento. Work of Neiburger (14), Edinger (4, 15-18), Staley (19), and Lowry (20,21) on sea-breeze systems elsewhere along the West Coast will prove relevant. As will be shown later, their work leads to predictions that are well borne out by the studies of Schroeder and Fosberg on sea breeze circulations near Bodega.

The summer coastal inversion is extremely important as a stable lid capable of confining to a shallow surface layer reactor effluents that might be emitted as a result of a site accident. An extensive report on the summer inversion of the eastern Pacific has been presented recently by Neiburger, Johnson, and Chien (22) and concisely summarized elsewhere by Neiburger (23). Additional reports that will be utilized below for their relation to inversion climatology, include those of Holtzworth, Bell, and De Marrais (24), on California radiosonde data, a study by the Stanford Research Institute (25) on California air pollution climatology, plus others to be cited later. Use of those reports will permit a much more detailed examination of meteorological aspects of Bodega reactor hazards than that contained in the Preliminary Hazards Summary Report (1).

2. RELEVANT SITE CHARACTERISTICS

2.1. Geography and Terrain. The Bodega Bay reactor is proposed for construction at a site on Bodega Head (see aerial photos in Fig. 1). The Head is an offshore promontory about 2 miles SSW of the small town of Bodega Bay and about 50 airline miles NW of the San Francisco Bay area (see map, Fig. 2). The coastline near Bodega Bay trends NW-SE. The westernmost outliers of the Coast Range, running roughly parallel to the coast, have their foothills almost at the shoreline, there being no distinct coastal plain present. The portion of the coast beginning at Bodega Bay and extending southeastward for about 15 miles is unlike that farther north or south in that the Coast Range is interrupted there by a broad gap in which the low rolling hills are generally less than 500 ft above sea level. Farther south along the coast the terrain rises, and summits of the order of 2000 ft are found in the southern end of Marin County, culminating in 2600-ft Mt. Tamalpais. Still higher and rougher portions of the Coast Range lie northward from the reactor site, especially north of the Russian River. The gap in the Coast Range extending from Bodega to Petaluma will be of particular interest below, because it is one of two principal gaps through which westerly winds could readily transport radioactive effluents to inland communities in event of a mishap. For brevity, that important gap in the Coast Range will be referred to below as the Petaluma gap, following the terminology used by Schroeder and associates (5) in their studies of sea-breeze flow through that natural route for inland penetrations of marine air.

As was noted above, southeastward from the Petaluma gap the terrain forms a natural barrier to inland penetration of marine air under the stable meteorological conditions that so often prevail along the California coast. A low natural trough,

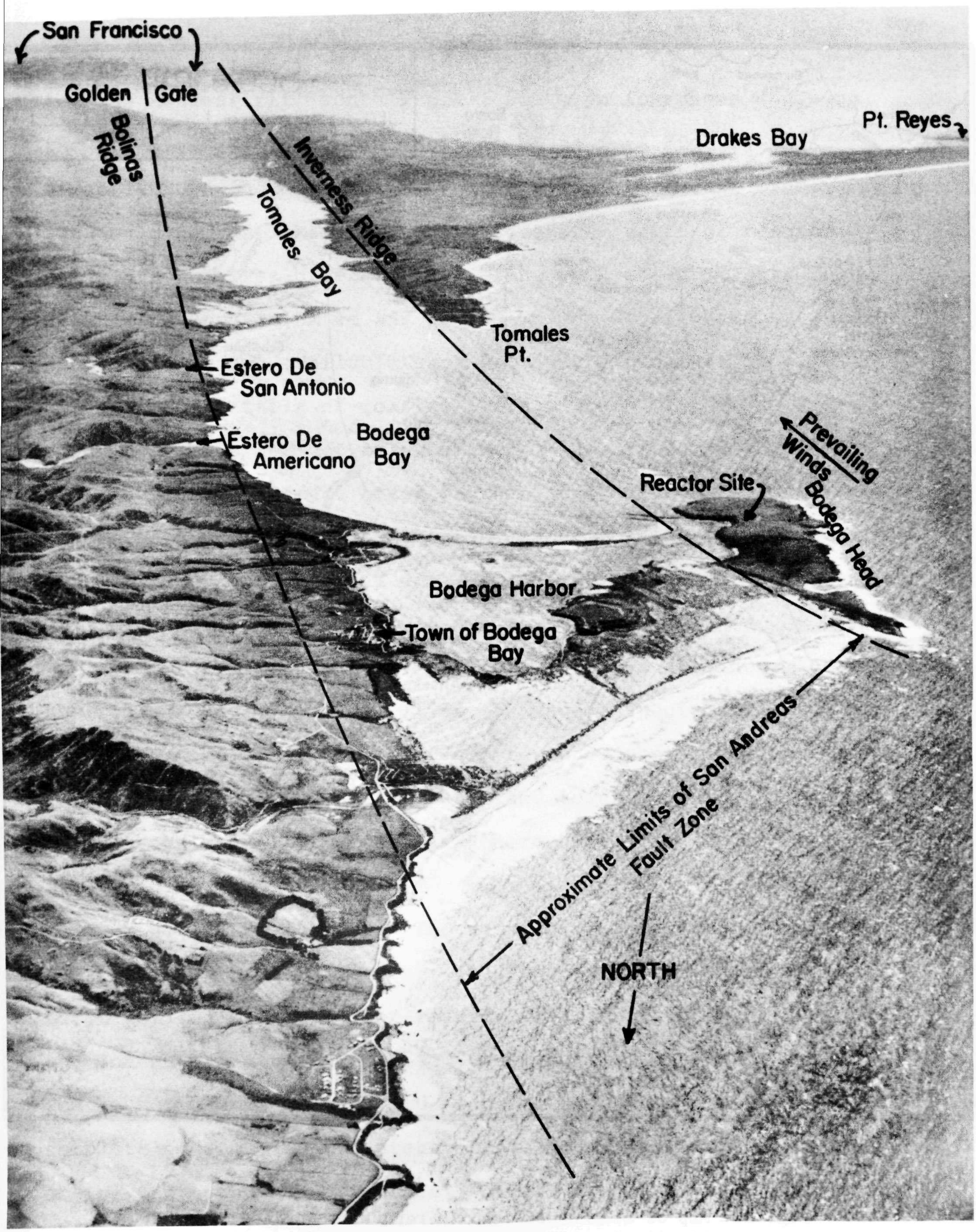

Fig. 1. Aerial photo of Bodega Head and coastal area to southeast.

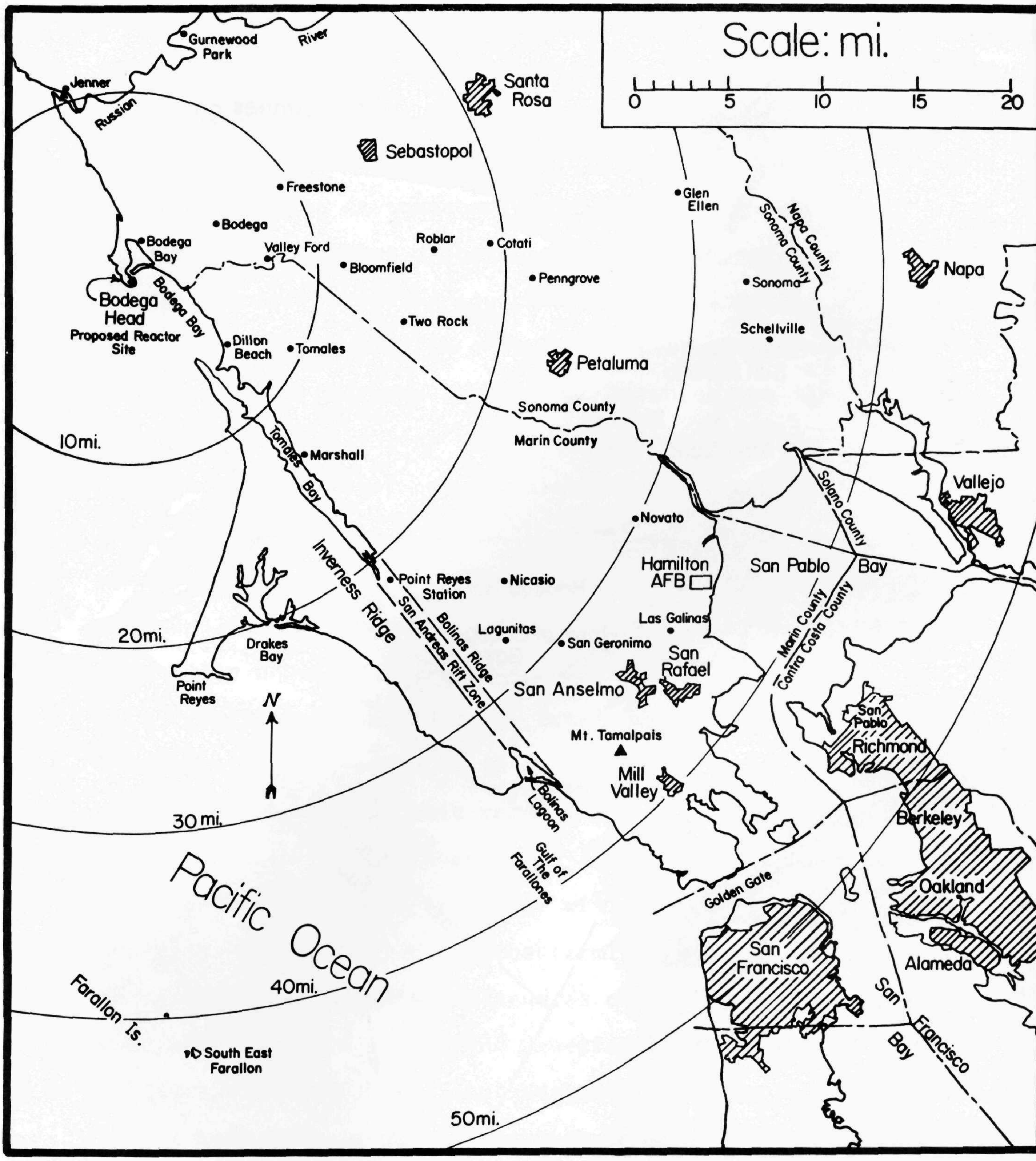

Fig. 2. Map of area considered in report. Range circles at 10-mile intervals.

the San Andreas rift zone (Fig. 2), between Inverness Ridge on the Pt. Reyes peninsula and Bolinas Ridge (see Fig. 1) lies directly downwind of Bodega with prevailing northwest winds, and would be the likely route for coastwise drift of reactor effluents when sea-breeze circulations were absent. This route would carry contaminated air to the Golden Gate, where the second of the two available gaps for inland penetration of marine air exists. Details of coastal terrain south of the San Francisco peninsula are not relevant here, for little effluent would be left to affect areas farther south after the flow through Golden Gate had drawn into the San Francisco Bay area the coastwise drifting contaminated air. All of these flow patterns will be examined in detail below.

The writer has made several visits to the area downwind of the reactor site. In June, 1963, he made a special trip to Bodega Head to study local terrain features that might have bearing on dispersion of effluents and to examine the siting of the meteorological tower erected there by PG&E.

2.2. Reactor Parameters. Two details of Bodega reactor design are pertinent to this report: (1) The design rating of the first boiling water nuclear reactor proposed for construction at the Bodega Bay Atomic Park is 1008 megawatts (thermal). (2) The core replenishment period is to be 8 months. Those two data completely determine the steady-state core inventory of radioactive isotopes whose presence in the reactor constitutes its ultimate potential for human hazard.

The radiological hazards considered in this report are those which would arise from release into the atmosphere of some portion of the volatile fission products that will accumulate in the reactor core during steady operation (26,27). The volatiles comprise many isotopes of two noble gases, xenon and krypton, plus many isotopes of two halogens, iodine and bromine. All of the half-lives of those particular nuclides are short enough compared with the 8-month core replenishment period that we may assume that they are always essentially at equilibrium. Hence the usual conversion ratio of 1 curie of fissions per watt of thermal power, combined with standard fission data on percentage chain yields permits calculation of core inventories of all of the many isotopes of the four cited volatile species. (Note that we may ignore here 10-year Kr-85, since about 80 per cent of the activity flowing through the fission chain of mass number 85, goes via the 4.4-hr form of Kr-85.)

Because of present concern over the possibility of intense seismic activity on Bodega Head in event of an earthquake on the nearby San Andreas fault (28-30),it becomes important to examine the radiological consequences of an accident in which direct venting of volatile fission products might result from a major core meltdown (stemming from control malfunctions at time of seismic action) plus rupture of containment structures. Consideration of such a dire event does not constitute further evidence of its liklihood. This report offers no analysis of that likelihood. Prudence merely dictates that the most careful possible evaluation be made of the radiological consequences of such an event. To seismologists, geologists, and engineers must be left the task of assessing the likelhood of such a major seismic accident at the Bodega Bay Atomic Park.

Direct venting would bring into radiological consideration volatile isotopes of short half-life, inasmuch as the usual assumptions of plate-out and engineered holdup (27) could then be largely irrelevant. From the 1008 Mw(t) rating plus requisite nuclear data, the author has computed a total core inventory (at time of accident-triggered shutdown) of approximately 400 megacuries of volatile isotopes having half-lives greater than two hours, or about 300 megacuries of volatiles of half-life in excess of six hours for the Bodega No. 1 reactor core at equilibrium. (To be certain that the basis for calculation of these two figures is quite clear it may be well to emphasize that each value is computed for the instant of accidental shutdown. The difference in the two activities results from considering two different fractions of the total equilibrium fission-product activity. Considering just those volatiles whose characteristic half-lives are equal to or greater than two hours, one finds an equilibrium activity of about 400 megacuries, while the portion having half-lives of six hours or more contribute 300 megacuries to the instantaneous activity that would prevail at and immediately after shut down. For the moment we omit consideration of the ensuing decrease of both of the cited activities.) This curiage is high both because of the large power rating of the Bodega plant and because the unusual possibility for a drastic seismic accident demands that one consider the possibility of very rapid venting with negligible holdup time. It is the latter possibility that requires that one consider the appreciable fraction of total inventory in volatiles having half-lives or order of only a few hours.

The total range of conceivable accident conditions is so great that it is quite out of the question to make radioactivity estimates to match exactly each set of conditions. In practice, the actually effective activity could be increased considerably beyond the above-cited levels by decay of short-lived precursors generating more volatiles during the venting period. Also, some venting of other low-boiling-point nuclides could augment total radioactive loadings of effluents after an accident. On the other hand, it must be recognized that venting might be slight enough to make the above-cited levels far too pessimistic. Indeed, a seismically-induced accident which was very serious from plant-operation viewpoint might lead to no rupture of secondary containment, with the result that off-site contamination might be almost negligible.

Again, the viewpoint taken here needs emphasis: Prudence dictates that the meteorologist examine the worst possible outcome of a major accident, while it must be left to others to weigh the probability that such an accident might occur. We assume, then, that a major portion (50 to 100 per cent) of the volatile fusion products might quickly escape and we then ask whether meteorological and climatological features of the site and the environs are likely to be favorable or adverse from the radiological-safety viewpoint. Eaton (29), in summarizing a U.S. Geological Survey study of the Bodega reactor site states: "The magnitude of possible human damage that would result from destruction of the plant by an earthquake suggests that it should be built only if there is no reasonable doubt that it would survive an earthquake likely to occur on the nearby San Andreas fault. It appears to me that the site does not meet this test and that it is not an adequately safe location for a nuclear power plant." Saint Amand (28), summarizing his study of bedrock-faulting and fracturing states, "A worse foundation situation would be difficult to envision." Such viewpoints expressed by experienced geologists surely justify a careful assessment of the meteorological conditions that would play decisively important roles in event of a major seismic accident at the Bodega reactor site.

3. METEOROLOGICAL FACTORS

3.1. Inversions. An unfortunately adverse meteorological factor having strong bearing on safety considerations at all coastal California sites that might be considered for nuclear reactors is the locally high frequency of low inversion layers. The West Coast subsidence inversion has, since the start of the civilian reactor program, been recognized as a special hazard with respect to diffusion of reactor effluents. Thus, "the persistent West Coast inversion lid" was cited by U.S. Weather Bureau meteorologists in the 1955 AEC manual on "Meteorology and Atomic Energy" (31) as a prime example of a special hazard of meteorological origin that would have to be carefully weighed in assessing local hazards should reactors ever be built in California. Although much is known of the meteorlogy of California coastal inversions, much more needs to be known before prediction of reactor hazards can be made with complete confidence at coastal locations. Only very recently has urgent need for more knowledge about the relation between the coastal inversion and reactor hazards been stressed. Special studies have been initiated (in the Los Angeles Basin) as a result of emphasis placed on this peculiarly California hazard-factor in the April, 1962, JCAE hearings on "Indemnity and Reactor Safety" (32, p. 187). To date only a few such studies, conducted by the U.S. Weather Bureau with A.E.C. support, have been completed. Fortunately, during and after World War II, work done at U.C.L.A. by Neiburger and by Edinger has clarified a number of salient features of coastal inversions. Most of the more detailed U.C.L.A. studies were, of course, conducted in the Los Angeles area; but general conditions are sufficiently uniform along much of the California coast to permit one to extropolate certain of the Los Angeles findings to the northern coastal area, so long as oceanographic and topographic details are properly taken into account.

Neiburger, Johnson, and Chien (22) have assembled the most extensive analyses of the characteristics of the coastal inversion published to date. A useful synopsis of that analysis has been reported elsewhere (23) by Neiburger. The Stanford Research Institute has published a compilation (25) of California meteorological data bearing on air pollution problems, and that compilation contains useful quantitative data on inversion climatology. Edinger (15, 16, 17, 18) has also discussed a number of important features of the inversion problem. One of his analyses includes data on inversion features at Oakland (4); and further useful tabluations of Oakland radiosonde data have been assembled by Holzworth, Bell and DeMarrais (24). The cited references, and particularly the work of Neiburger, Johnson and Chien, will be used here to discuss inversion implications for Bodega reactor hazards; but I would emphasize again that there are features of inversion meteorology having important bearing on the reactor hazards problem which are not yet adequately known. A particularly important class of missing information concerns quantitative details on how and under what conditions sub-inversion air sweeping in off the Pacific is diverted by coastal barriers under varying conditions of inversion strength, of wind speed and direction, and of inland heating.

Useful indication of the average frequency of occurrence of inversions in the vicinity of San Francisco can be obtained from tabulations (24) of Weather Bureau radiosonde data for Oakland. It will be conservative to consider only the 1600 P.S.T. soundings, for this will exclude morning radiation inversions. From the four-year sample of inversion data for the Oakland area tabulated by Holzworth, et al., one finds the following percentage frequency of days having inversion bases at or below 1500 ft at 1600 P.S.T.:

Month	J	F	M	A	M	J	J	A	S	O	N	D	Y
Per cent	26	5	9	37	31	61	82	81	56	34	22	36	[illegible]

A year-round average frequency of low inversions as high as 40 per cent, even in the late afternoon, implies extremely high hazard-potential for this area, and the frequency will undoubtedly be somewhat higher at Bodega Bay itself, since at least some over-land passage of marine air weakens inversions upwind of Oakland, but not at Bodega. The worst inversion months are those of the summer half-year, as can be seen from the above tabulation, although frequency of diurnally persistent inversions is appreciable for all months but February and March.

It is first necessary to assign a best estimate of the average depth of the subinversion layer near Bodega, i.e., to secure a best estimate of the height of the base of the inversion. That height has a controlling influence on the volume of air into which any released fission products would be diluted after a reactor accident occurring in the summer half-year. There is slight disagreement among the above-cited references as to mean base-heights. The U.C.L.A. study (22), indicates a mean summer inversion base-height for the Bodega Bay area of about 1500 ft, that height being indicated as decreasing northward to a local minimum of about 1200 ft near Eureka. The S.R.I. analysis (25) indicates average summer inversion bases closer to 1200 ft near Bodega, but has them increasing northwards to more than 1500 ft near Eureka. In the Final Hazards Summary Report on the Humboldt Bay reactor, Appendix I, prepared by the PG&E Meteorological Office (33) inversion statistics based on about a year and a half of Navy soundings at Arcata indicate a median inversion-base height of about 2000 ft there, which seems to support the S.R.I. conclusion that the inversion bases should be lower at Bodega than near Eureka.

Edinger's study of conditions at Oakland (4) showed inversion bases at Oakland at about 800 ft, but his sample was taken from only about half of all days in July and August data for just two years (1957-8), the selection being made on the basis of existence of strong inversions at the time of the 1600 P.S.T. sounding. Thus it might be expected that his mean base height would be selectively lower than the overall summer mean. From the tabulation of Holzworth, et al., (24) one can obtain data on the distribution of heights of inversion bases at Oakland. For the four summer months June,July, August, September, and for the four years 1957-61, I find that, at the time of the 1600 P.S.T. radiosonde ascent, 32 per cent of all days exhibit an inversion base at or below 500 ft, 55 per cent at or below 1000 ft, and about 70 per cent at or below 1500 ft. Since air arriving at Oakland on summer afternoons comes predominantly from a westerly direction with some modification (on the average) by passage over heated land surfaces (San Francisco peninsula, Marin peninsula), these data would suggest that inversion bases may run somewhat lower off the coast than the average of 1500 ft indicated by Neiburger, et al., (22), and even lower than the S.R.I. indicated average of 1200 ft. Some of the cited differences in various references may reflect different sample-years, and some undoubtedly reflect diurnal variations of the sort now well documented for the Los Angeles area (14, 15). Thus 0400 P.S.T. data for Oakland for the June-September period, 1957-8 shows only 38 per cent of inversion bases at or below 1000 ft and 55 per cent at or below 1500 ft. However, in summary, we may conclude that for the day as a whole, summer inversions probably have bases that average 1000-1200 ft above sea level, with diurnal departures from that average that are a few hundred feet, just as in the case of Los Angeles.

The thickness of the inversion layer itself (difference in height from cool base to warm top) is relevant to certain aspects of the Bodega reactor hazards. The U.C.L.A. study (22,23) indicates mean thickness of at least 1500 ft throughout the entire length of the California coast, with two local maxima, one near Pt. Mendocino and one in the Big Sur region. The notorious thickness of the California coastal inversion layer during the summer half-year implies that the inversion will not be easily destroyed when sea-breezes draw the marine layer inland. This has adverse radiological implications for the Petaluma area and for the San Francisco Bay area.

Not only is the thickness of interest, but also the actual magnitude of the inversion (temperature-increase from base to top) is of importance in the diffusion climatology of the Bodega area. The U.C.L.A. study indicates that nowhere along the entire coast is the inversion stronger than just off the coastal strip running from Bodega Bay northward towards Mendocino, with a local center of 12°C-magnitude lying just offshore there. At the Bodega site itself, their data suggest about a 10°C-magnitude for the mean inversion in summer, representing an extremely effective lid on vertical dispersion of reactor effluents in the area of the proposed reactor. This lid will tend to resist quick burn-off or convective destruction (18) during marine-air penetrations onto the adjacent land areas, which will in turn permit deeper inland penetrations of effluents, a point to be considered further below.

Although the ultimate meteorological origins of the California coastal inversion are not of direct concern in the present reactor hazards discussion, it is pertinent to note briefly that the inversion results from flow conditions prevailing over a vast area of the eastern Pacific Ocean. Early views held that it was a local effect of cooling from below, due to the cold California current augmented by upwelling of cold bottom water. But as Neiburger (23) has emphasized, this explanation does not fit the facts. Rather, the inversion is maintained by widespread subsidence due to low-level divergence. The latter is due partly to frictionally induced outflow in the Pacific anticyclone and partly to Coriolis divergence in equatorward flow on the east side of the anticyclone, probably enchanced along the California coast by land-sea difference in surface frictional deflection of the winds. The above commentary on the dynamic origins of the inversion underscores the point that the inversion is associated with large-scale circulation patterns of a semi-permanent nature that tend to be present over much of the year, broken intermttently and weakened in mid-winter when extratropical cyclones pass eastward across the coast. Finer details of how turbulence and ocean-surface heating and cooling effects interact with the widespread subsidence to determine inversion topography are inadequately understood at present, a situation having unfortunate relevance to the present problem, for it prevents one from giving a truly definitive estimate of how conditions at Bodega Head, where direct observations are comparatively scarce, will differ in detail from those in more extensively studied areas such as the Los Angeles coastal area. Perhaps the greatest value of the present discussion will be to emphasize strongly that if nuclear power is to be safely used along the California coast, far more meteorological reasearch on the coastal inversion is urgently needed. Only with much more detailed knowledge of inversion climatology, inversion dynamics, and sea-breeze meteorology than now available can reliable reactor hazard predictions be made for future reactor sites along the West Coast.

3.2 Surface-layer Stability. Prediction of the way in which atmospheric processes will transport and disperse reactor fission-product gases requires information not only on overlying inversions, but also on typical lapse-rates in the layer from the surface up to the base of the inversion. Unfortunately here again direct observational data for the Bodega area are not available, nor will the meteorological tower-data, reportedly now being gathered on Bodega Head (1), answer this important question in full, since the top of that tower is only about a fourth to a third of the way from sea level to mean inversion base. An extended program of balloon soundings at the site would be needed to establish quantitatively the nature of year-round stability conditions in the layer that will transport plant effluents under routine emission conditions and in event of an accident.

Fortunately, some data are at hand to give rough indications of what may be expected. Neiburger (14) found that the summer marine layer farther south along the coast generally has lapse rates nearly equal to or a bit less than the dry adiabatic rate. Since there is a generally warming tendency accompanying coastwise movement of the marine layer as it sweeps southward from the latitude of Bodega towards the Los Angeles area, one must expect a tendency for more stable subinversion air near Bodega than at Los Angeles under summer conditions. Particularly significant is the fact that the coldest sea-surface temperatures along the entire California coast in summer are found at and just northward from Bodega Head (22, Fig. 36), which implies a marked stabilizing tendency at and just upwind of Bodega. This tendency may be somewhat counteracted by prevailingly stronger winds in the Bodega area (stronger mixing), but it seems reasonable to predict that superadiabatic lapse rates in air arriving at Bodega from the Pacific will be rare, and that mean subinversion lapse rates stabler than the dry adiabatic value will usually be found in summer at Bodega. This conclusion, if correct has adverse implications.

Eberly and Robinson (1) citing the analysis of Edinger (4) of 50 summer soundings at 1600 P.S.T. when inversions lay over Oakland, note indications of superadiabatic lapse rates below the inversion base in Edinger's data. Since air reaching Oakland from the west (prevailing surface wind direction at Oakland in summer) has had to pass over land, afternoon surface-heating on such an overland route makes 1600 P.S.T. Oakland surface lapse rates unrepresentative of conditions at Bodega Head. Only about 2^{o}C heating of the surface air would suffice to change subadiabatic lapse rates to superadiabatic lapse rates in these Oakland soundings. One finds that just that magnitude of heating for overland drift of 6-8 miles (width of San Francisco peninsula) would be expected on the basis of studies (18) of modification of marine air as it moves in off the ocean. The effect of Bay surface-temperatures on westerly air currents reaching Oakland is a further factor that would have to be taken into account before one would have confidence in extrapolating Oakland low-level lapse rates to Bodega. What Edinger's Oakland data do show unequivocally is that at least by the time that marine air has penetrated 10 or 20 miles inland on summer afternoons, the subinversion layer has become superadiabatic. It seems important that further information on this point be secured, because if the subinversion layer is moderately stable as it first comes onshore near Bodega, and only becomes superadiabatic at some distance inland, fumigation (see for example 34) could be almost a characteristic process on pasture lands 10 or 15 miles inland from Bodega under routine operating conditions, increasing local deposition rates of radioiodine at that point in summer. On the other hand, if the subinversion layer is already superadiabatic on arrival at Bodega much better mixing will occur immediately downwind of the plant (though probably at the expense of increased cumulative hazards to boat operators in Bodega Bay, since that Bay would then be intermittently bathed in looping plumes). In all, the question of the degree of stability of subinversion air arriving at Bodega from the Pacific in summer must be regarded as one more important feature on local diffusion climatology that is rather inadequately understood at present. Since the present report is, however, concerned more with major accidental releases than with routine emission hazards, these points will not be elaborated further.

In mid-winter, average lapse rates at Bodega will be distinctly steeper due to frequent synoptic regimes involving arrival of air from higher latitudes subjected to sea-surface warming from below. At such times, the subsidence inversion will be weak or absent, and these will be times of optimum diffusion conditions, yielding rapid dilution of plant effluent gases. Unfortunately, many of such situtations will be accompanied by widespread precipitation, as will be noted below.

3.3 <u>Winds</u>. The wind analysis in the PG&E Preliminary Hazards Summary Report (1) was limited to a discussion of speed and direction data for four years at Pt. Reyes, about 20 miles down the coast from Bodega Head (Figs 1 and 2). The exact location at which those wind observations were taken seems to be in doubt. Eberly and Robinson state (1, Appendix III, p. 3) that they were taken "4 miles east of Point Reyes Lighthouse"; but that point lies in the middle of Drakes Bay since the easternmost land on the Point lies only 3 miles east of the Light. Inquiries made with U.S. Coast Guard authorities revealed that no anemometer has ever been located on that end of the Coast Guard Reservation. Further inquiries as to present anemometer location disclosed that there is no anemometer at the Light now, wind speeds being merely estimated. Inquiries at the U.S. Weather Bureau National Weather Records center, Asheville, N.C., shed no further light on this question. Exact anemometer-location can be of crucial importance for wind data taken on bold promontories such as Pt. Reyes (or Bodega Head), and if the original data were not made with an anemometer, but estimated (as is now done), there is even stronger doubt as to validity of the wind data used in the Preliminary Hazards Summary Report (1).

For reference purposes, some of the wind data presented for Pt. Reyes in (1) are reproduced in Table 1, despite this uncertainty as to their reliability. The prevailingly northwesterly winds characteristic of the California coast stand out. In Fig. 3 is reproduced a wind rose, prepared recently by the U.S. Army Corps of Engineers (35), also stated to be for Pt. Reyes; but again inquiry failed to disclose the exact source of data and failed to reveal whether the same four years of observations are involved as in Table 1. Hence, both Fig. 3 and Table 1 must be viewed with some reservation.

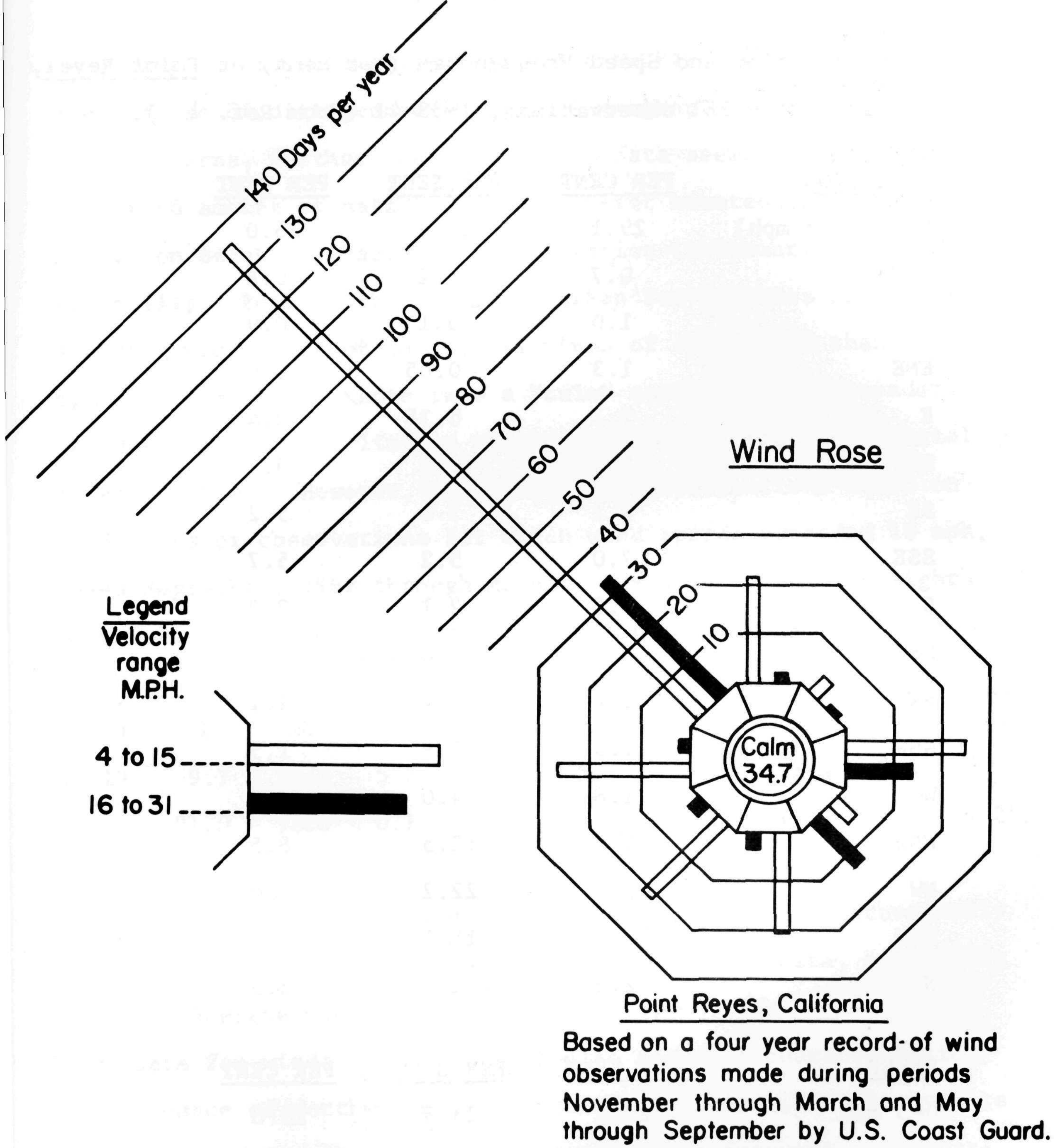

Fig. 3. Wind rose for Pt. Reyes (see Ref. 35).

TABLE I

Wind Direction and Speed Frequencies (per cent) at Point Reyes, based on 9,181 observations, 1938-41 (From Ref. 1).

DIRECTION	PER CENT	PER CENT	PER CENT
CALM (0-3 mph)	29.1	25.6	26.0
NNE	0.7	0.2	0.8
NE	1.0	0.1	0.9
ENE	1.3	0.05	0.6
E	5.2	0.35	2.4
ESE	6.4	0.9	3.3
SE	7.1	3.6	5.2
SSE	7.0	5.2	5.7
S	2.8	2.1	2.2
SSW	3.0	1.4	2.0
SW	2.4	2.4	2.1
WSW	1.3	1.9	1.5
W	1.8	4.0	2.7
WNW	5.2	12.5	8.5
NW	12.9	22.2	18.0
NNW	10.7	15.1	14.6
N	2.3	2.5	3.5

SPEED	PER CENT	PER CENT	PER CENT
0-3 mph	29.1	25.6	26.0
4-15 mph	54.4	66.4	59.0
16-31 mph	15.7	8.0	14.0
32-47 mph	0.8	-	1.0

Because of the 20-mile separation of Pt. Reyes and Bodega, and because of differences in coastal geography that could influence wind patterns, further search for wind data seemed necessary. A limited amount of data for an anemometer mounted near the beach at Dillon Beach the Pacific Marine Station is summarized by Kadib (11). Because the data were taken for purposes of studying wind drift of sands, all winds of speed less than 10 mph were lumped by Kadib into a "calm" category, which renders the data of somewhat limited use in examining diffusion climatology at Bodega Head. However, the percentage distributions based on 1138 hours of observations for which wind speeds exceeded 10 mph, taken September, 1962 through August, 1963, and listed to eight points of the compass, are given here for reference:

Speed (mph)	N	NW	W	SW	S	SE	W	NW	No. Hours
10-19	9.7	55.5	5.2	4.8	5.3	4.9	13.1	1.4	923
20	21.0	32.6	0.1	5.1	6.0	19.1	14.4	0.5	215

As for the cited Pt. Reyes data, the predominance of northwesterly flow is noteworthy also in the above Dillon Beach data, especially for the moderate wind speeds (cf. Fig. 3).

Data for winds at Eureka (33) also show the characteristic predominance of northwesterly directions in summer, but imply more variable winds in the wet winter season, when frequent storm passages occur. Because the Eureka area has local sea-breeze systems governed by its own terrain and coastal geography (33), and because

Eureka is several hundred miles north, the chief value of the Eureka winds for present purposes is that they further emphasize how strong is the control of the Pacific anticyclone in producing chiefly northwesterly flow in summer along the entire coast.

If the northwesterly flow indicated by the preceding data were truly characteristic of conditions governing Bodega reactor hazards, a reactor accident during the summer half-year and a substantial portion of the winter season too would be expected to result in drift of the effluents down the coast to the Tomales Bay area, through the rift zone trough into the Gulf of the Farallones, then to be drawn partly or wholly through the Golden Gate gap into the San Francisco Bay area. Inversions would preclude marked vertical dispersion of the plume, but horizontal dispersion would increase plume width to the order of 10 to 20 miles (36, pp. 165 ff). This would imply that San Francisco would be the populous area most likely to be influenced by effluents in event of accident under such conditions.

Although that possibility is both real and important, another drift pattern is even more likely, although it would not be inferred from the wind data for Pt. Reyes (1). That second possibility is drift of effluents under sea-breeze control through the Petaluma gap and into the Petaluma Valley. This possibility of direct inland penetration of effluents could not be inferred from the Pt. Reyes data for the simple reason that no significant sea-breeze circulations develop there; and it is chiefly for this reason that it is so unsatisfactory to base estimates of Bodega hazards on the

Pt. Reyes wind data. Eberly and Robinson (1) say nothing about the hazard role of sea breeze circulations at Bodega; but we must now examine that question in some detail.

The strong liklihood that sea-breezes blow inland through the Petaluma gap was inferred early in the present study from a peculiarity of the Hamilton AFB July wind hodograph reported by Frenzel (12). Characteristically at about 1600 P.S.T., the local bay-breeze blowing off San Pablo Bay from the southeast gives rise to northwesterly winds at Hamilton AFB. This appeared to be explainable only on the basis of a flow of marine air through the Petaluma gap and down the Petaluma Valley. To check this hypothesis, inquiries were made in the Petaluma area, and it was learned that westerly winds set in near Petaluma shortly after noon almost every day in summer, fog often reaching the area by 1700.

This constituted very strong evidence of diurnal sea-breeze penetrations through the Petaluma gap. That the low, hilly country in the gap could scarcely stop sea-breeze incursions might also have been inferred from information on similar circulations near Los Angeles. Edinger's work on the San Fernando convergence zone (17) makes clear that marine air frequently moves in over Oxnard and drifts eastward over hilly country with mean terrain heights of well over 500 ft, while a recurving sea-breeze from the Los Angeles coastal plain readily passes over the eastern end of the Santa Monica Mountains where elevations also average more than 500 ft. Lowry's studies (20, 21) of sea breezes on the Oregon coast offer further evidence of possibility of such incursions over terrain of such elevations.

The above inferences were found to be rather directly confirmed by Smalley's generalized flow patterns displayed by Root (37) as representative of both average summer conditions (Fig. 4a) and conditions of especially strong northwesterly flow (Fig. 4b). Both charts show marine air penetrating the Petaluma gap, and it should be noted that both charts also show penetration of marine air through Golden Gate.

But the most conclusive evidence for sea breezes in the Petaluma gap came when the writer's attention was called to the work of Schroeder and Fosberg (5-10) on forest-fire meteorology in the area north of San Francisco. In studies extending over two summers Schroeder and Fosberg did field studies that not only establish beyond doubt the typical occurrence of summer sea breezes in the gap, but also reveal a number of important features of the structure and kinematics of that sea breeze flow. Fig. 5 is taken from their work and shows streamline patterns representative of the area. Marine air passes over the Bodega area, moves inland, and then divides into a northward and southward fork. The southward-drifting fork encounters the San Pablo Bay breeze somewhat north of Hamilton AFB in just the manner deduced from Frenzel's Hamilton AFB hodograph. An important new feature, revealed in the study of Schroeder and Fosberg, is the other fork, which carries part of the marine air northward towards Santa Rosa and the mountainous area beyond. Actually, this latter feature

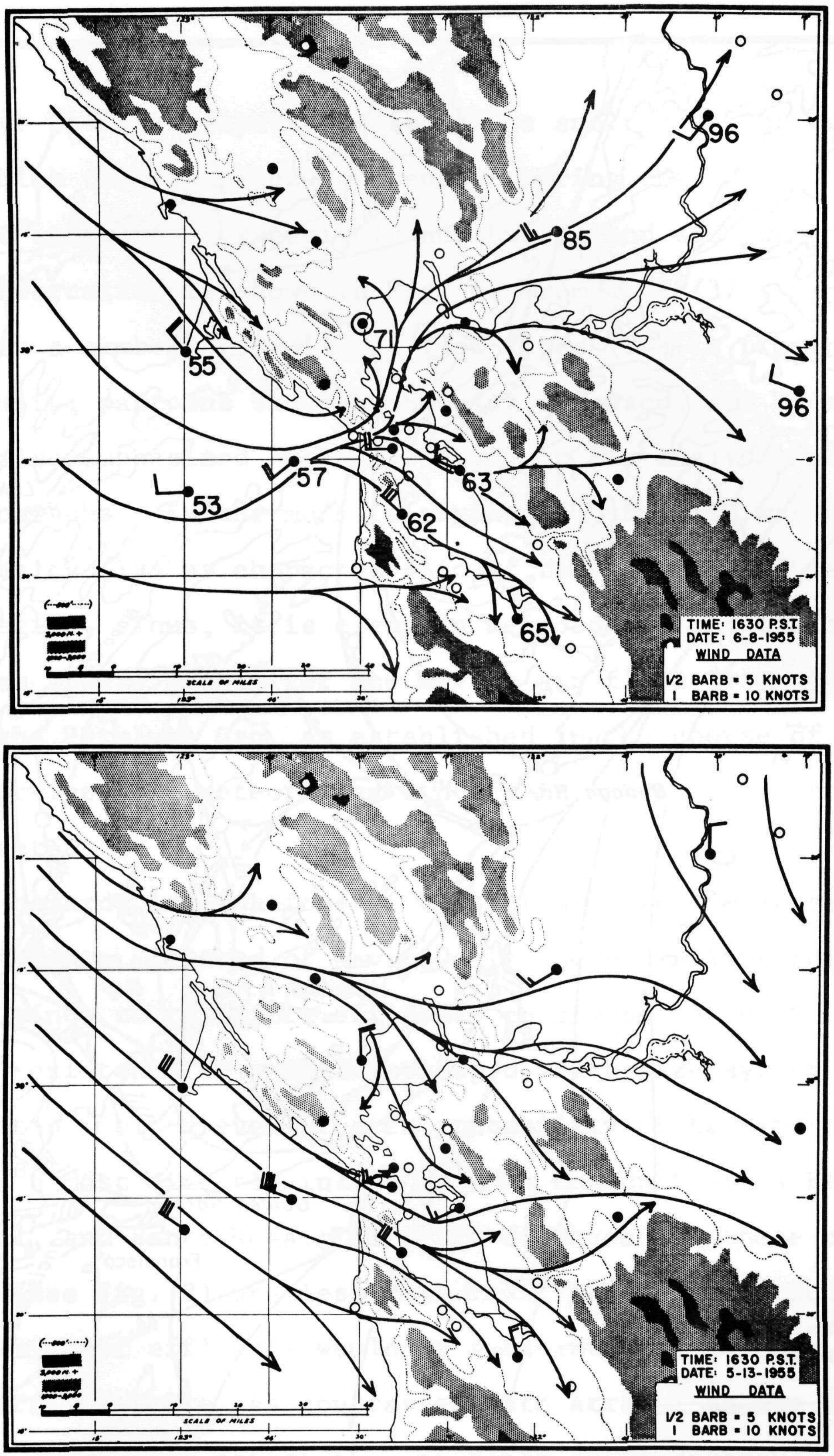

Fig. 4. (a) Generalized afternoon flow pattern of marine air in the San Francisco Bay area under typical summer conditions. Plotted figures are 1630 PST temperatures, indicating sea-breeze cooling effects.
(b) Generalized afternoon flow pattern in summer for conditions of strong northwesterly flow. (From Root, Ref. 37)

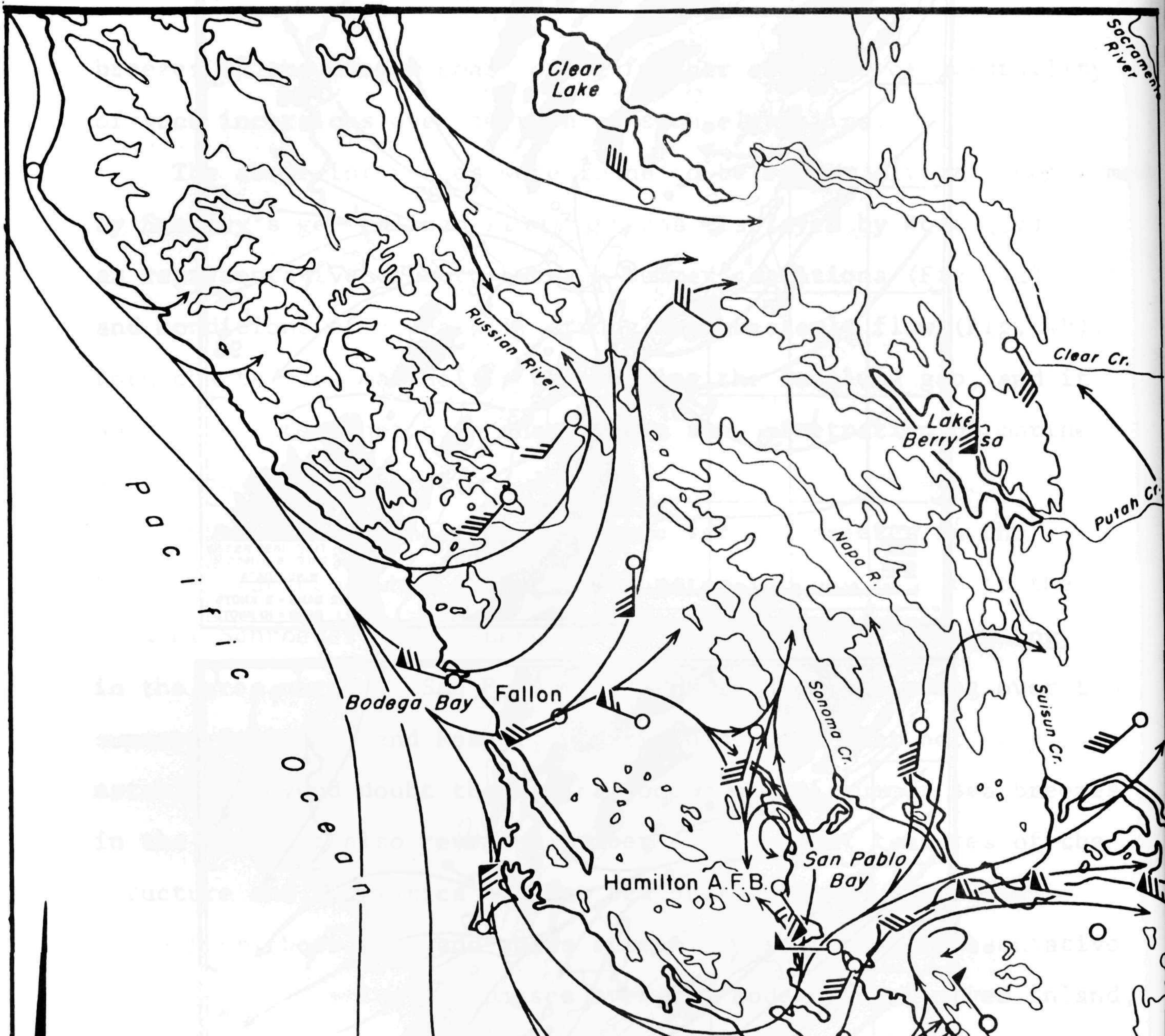

Fig. 5. Sea-breeze flow patterns through the Petaluma gap and Golden Gate. (From Fosberg, Ref. 7)

could have been anticipated by its close analogy to the well-known way in which the sea-breeze currents entering the Golden Gate bifurcate and move, respectively northwards and southward. The latter bifurcation is shown in Fig. 4a from Root (37), is clearly evident in a number of Smalley's flow types (2), is prominent in streamline patterns shown by Schultz, Akesson, and Yates (13), and was also emphasized by Frenzel (12) in his analysis of Bay area hodographs. Furthermore, a similar bifurcation was pointed out by Staley (19) as characteristic of the Puget Sound sea breeze regime. Thus, it is clear in retrospect that the splitting of the sea breeze flow after the marine air flows from Bodega through the Petaluma Gap, as established in the course of the Forest Service fire-meteorology studies is exactly what one should have expected.

The hazards implications of this bifurcating sea-breeze flow are clear: Instead of having only the prevailing northwesterly winds to transport effluents coastwise to the Golden Gate gap, existence of a well-developed sea-breeze system in the Petaluma gap implies even greater probability of transport of effluents almost directly inland to such communities as Petaluma, Sebastopol, and Santa Rosa. The drift distances to these communities (see Fig. 2) are less than half that to San Francisco; so dispersion of effluents would be substantially less by the time of arrival there, as contrasted with arrival at San Francisco.

That one cannot expect the inversion to be destroyed by the time contaminated sea breeze air reached the Petaluma Valley is indicated in some of the U.C.L.A. studies. For example, Edinger's work on the sea breeze penetrations in the Santa Clara Valley (18) shows that even fifty miles of inland penetrations may not lead to complete convective dissolution of the inversion. Similar penetrations are common in the Los Angeles coastal plain (15). Schroeder and Fosberg found evidence that the wind-shift front of the sea breeze entering via the Petaluma Gap persists well east of Petaluma, providing further indication that contaminated marine air would typically still be held under the inversion lid by the time it reached Petaluma or Santa Rosa. The same conclusion is corroborated by the frequent late-afternoon arrival of fog-laden westerly winds near Petaluma in summer. It would be helpful if a wind-rose for Santa Rosa in summer were available to check on the frequency of southwesterly winds there in afternoon, but unfortunately no wind data from the vicinity were located for use in the present study. However, it now seems extremely probable that marine air does reach that area on typical summer days.

The attention that has been given above to summer sea breeze circulations concerns the meteorology of only about half the entire year, of course. In the winter half-year, wind directions are more variable on the California Coast, due to storm and frontal passages. Winds blowing out to sea are then rather more frequent, which is favorable from the viewpoint of accident hazards. However, even in winter the prevailing winds are northwesterly. It seems considerably less likely that the Petaluma Valley would receive effluents in event of a winter accident, and rather more likely that effluents would drift down towards Golden Gate in that season. Stability conditions in winter, as previously noted, favor better vertical mixing, so this decreases likelihood that a plume of high concentration could reach the Bay area in the winter half-year, although this cannot be ruled out as a hazard possibility.

One other matter falling under the general heading of "Winds" demands brief consideration, namely the matter of local aerodynamic effects in the immediate vicinity of the reactor site that may have importance in governing routine-emission activities at sea-surface level over Bodega Bay within the first few miles downwind of the reactor and could have significant residual effects at distances out to as far as Dillon Beach or Fallon. Much attention has been given in recent years to "aerodynamic downwash" effects caused by buildings and other flow-disturbances near the sources of atmospheric contaminants. Bierly and Hewson (34) have presented a recent summary of the process, though the relevant literature includes the work of many others. A rather good photographic illustration of Strom's wind-tunnel studies of aerodynamic downwash will be found in Eisenbud's Environmental Radioactivity (26, p. 81). Although the stack-height for the proposed Bodega reactor has not yet been disclosed, it is likely to be no more than a few hundred feet high judging from present practices. With judicious placement realtive to nearby plant structures, a stack of this height can usually be given the benefit of aerodynamic effects accompanying flow from at least the prevailing direction, thereby minimizing aerodynamic downwash of effluents onto nearby surface areas. In the case of the site on Bodega Head, however, it will not be plant structures, but rather the <u>relief of the entire Head itself</u> which will pose some difficult problems of aerodyanmic downwash. The question could scarcely be settled in advance by anything short of extensive wind-tunnel studies of a model simulating the Head or by on-site smoke tests with elevated smoke-sources; but the question must be pointedly raised here, inasmuch as it appears to have been overlooked to date. The prevailing northwesterly flow across the Head will first strike land near Horseshoe Cove (see Fig. 6) at which point the surface currents will be strongly deflected by the roughly 100-ft seacliff rising nearly perpendicularly from the sea. Next, the air must flow over the principal eminence of the Head, the 265-ft dome at the north end of the Head, after which it passes near a secondary summit of about 240-ft elevation and then sweeps down across the saddle of 100-ft elevation at the swale of which the reactor will be located. Finally, the air must then ascend the side of the 200-ft dome south of the reactor complex and then pass out across (or plunge down over?) a 100-ft seacliff at the extreme southern tip of the Head. In Fig. 7 the profile of the terrain along section AA' through the proposed stack location is displayed and, to be certain that the distortion of vertical scale in that figure does not mislead the reader, a photograph of the Head profile is shown in Fig. 8. Few industrial plant designers have had to confront flow boundary conditions as aerodynamically complex as these, so previous experience can offer little help in

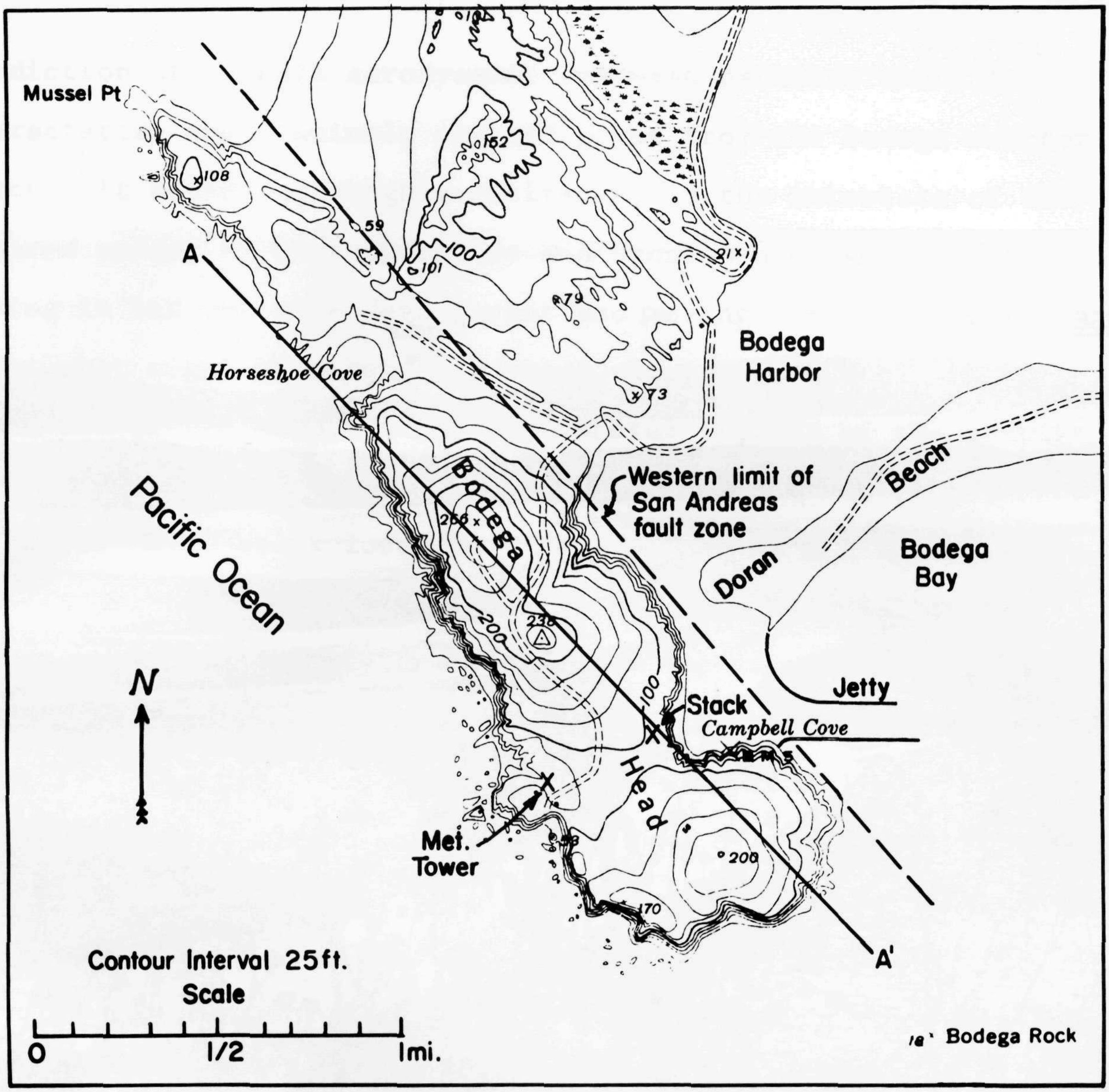

Fig. 6. Topographic chart of Bodega Head.

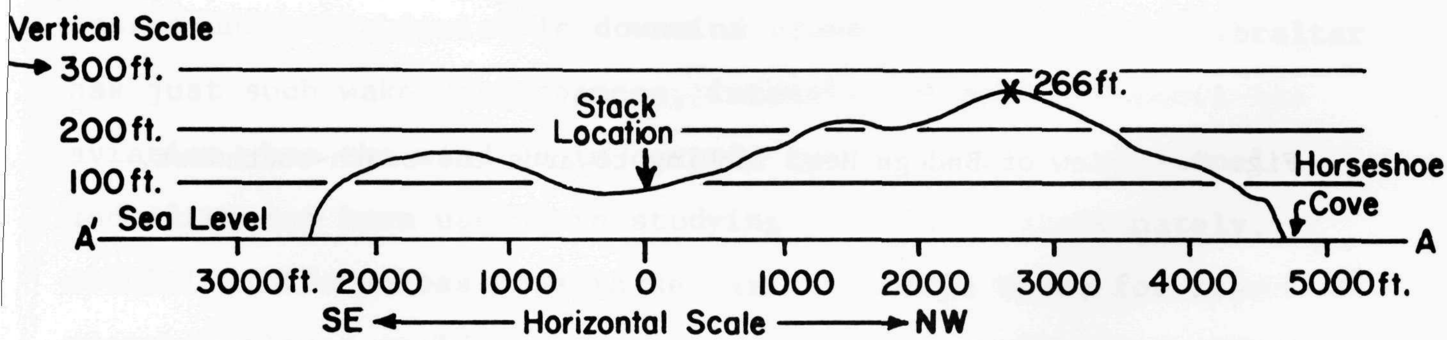

Fig. 7. Cross-section through Bodega Head along section AA' of Fig. 6.

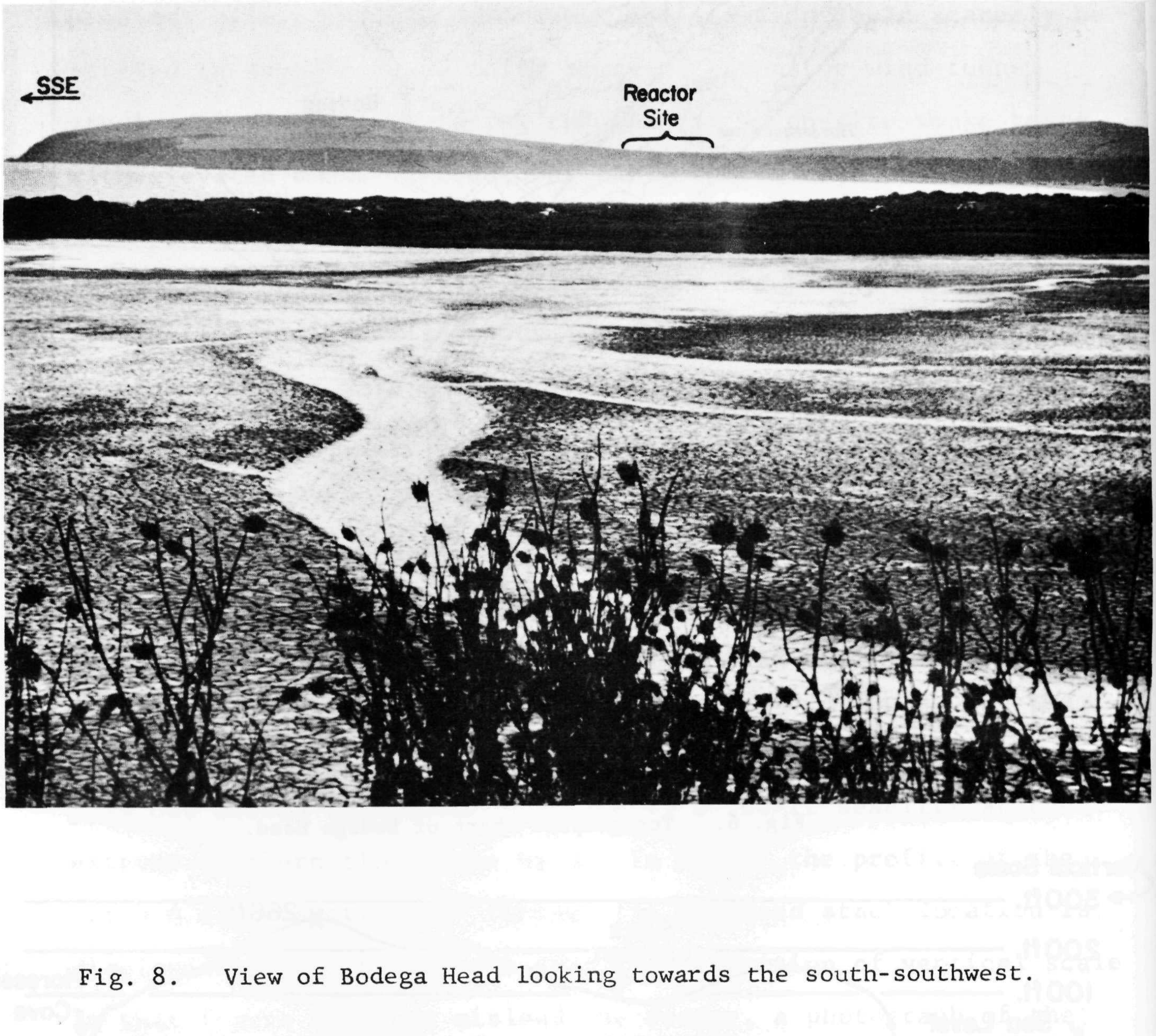

Fig. 8. View of Bodega Head looking towards the south-southwest.

prediction of overall aerodynamic downwash patterns that will characterize the routinely emitted plume from the Bodega reactor stack. It would seem highly desirable, in the interests of the assured safety of boat operators and sportsmen on small craft moving in and out of Bodega Harbor and passing almost directly under what might be a semi-permanent plume-downwash off the south end of the Head, to conduct careful studies of the complex problem of aerodynamic downwash from a simulated elevated source at the proposed stack location. In addition to the foregoing aerodynamic difficulty, I believe it is entirely possible that a vortex-pair system may trail off quasi-horizontally from the lee of the Head when the wind blows from the prevailingly north-westerly direction across Bodega, since wind-tunnel work has disclosed similar vortex-pairs in the wake of many other obstacles of roughly similar shape. Such vortices might, either separately or in combination with downwash induced by the south seacliff, serve to mix down onto the sea-surface radioactive emissions that could conceivably constitute a quite undesirable source of contamination for operators of fishing craft making frequent passes under the invisible downwind plume. The Island of Gibraltar has just such wake disturbances, intensive enough to imperil aviation when the wind is in certain quarters, and wind-tunnel modelling has been useful in studying it (38). Unfortunately, modelling offers less hope in the case of Bodega Head, for its smooth outlines would imply strong dependence on flow Reynolds number, unlike the simpler case of a sharp-edged obstacle like Gibraltar.

The complexities of the interaction between Bodege Head and ambient winds have bearing on another matter concerned with long-term hazard-monitoring at any reactor built there. At Bodega, even more than at most other sites of currently-proposed power reactors, lack of past local meteorological data dictates establishment of a program of routine measurement of all parameters influencing local diffusion climatology. Wind-profile data are the most important ingredients in the semi-theoretical calculations now used at nuclear facilities to make predictions of diffusion climatology for use in planning officially acceptable levels of routine stack emission of radioactive gases and particulates. On Bodega Head, PG&E has erected a 250 ft meteorological tower for that purpose, and automatically-recording anemometers have been located at three levels, namely 7 feet, 50 feet, and 250 feet above terrain (1). I have examined the tower site and its exposure and have serious doubts as to the representativeness of wind data gathered from that tower when used for predictions of diffusion climatology for the downwind area. All turbulence theories underlying standard computational procedures for converting tower wind-data into diffusion coefficients (see reference 36, for example) assume a turbulence field in a <u>quasi-steady state</u>; but the lower two levels (7 ft and 50 ft) of the present Bodega Head tower can surely not be expected to sample winds characterized by anything like steady-state turbulence, since the air currents arriving at the base of the tower have just been forcibly deflected some 50-60 feet (considering only the <u>most favorable</u> direction of

NW-SE flow) up the steep slope that borders the Head at that point. The latter sudden deflection will alter the wind profile in some complex way defying subsequent deduction of representative diffusion coefficients from the tower data. Evidently the tower has been put at a spot (near the old Stroh Ranch buildings) where the prevailing northwesterly winds have the least precipitous path up the seacliff (west winds will confront a nearly vertical cliff of about 80 ft just upwind of the tower!), which suggests that perhaps some recognition of the above problem influenced the shift of the tower site from the still less desirable location indicated on earlier site plans. But even with the tower in this perhaps optimum spot on the Head, diffusion-coefficients computed from the tower data can scarcely be relied on to give a true picture of conditions representative of the airflows into which the stack will be emitting its effluents. The specific error I would anticipate from use of wind-profile data taken from the present tower is an (ultimate) error of inferring more favorable turbulent diffusion than the true value. This conclusion follows because the disturbance of the Head will tend to increase the wind speeds recorded at the lower two anemometer levels, giving a spurious indication of a too-high degree of turbulent smoothing of the profile. That error will then be carried into subsequent over-optimistic estimates of turbulent dispersion of radioactive stack effluents. I am unaware of any precise way of allowing for such errors due to poor tower exposure. In so complex a site, prudence would have dictated erecting at least two or three towers to cross-check the representativeness of the main tower location. The preceding error-prediction applies to the prevailing wind directi of northwest. For the case of west or southwest winds I would not hazard a guess as to the precise nature of the error, for then the lowest anemometer may well be in a wake region below a separating stream surface attached to the very sharp lip of the 80-ft seacliff just west of the tower site. Between this serious tower-exposure problem and the aforementioned uncertainties as to aerodynamic downwash induced by the Head itself, I see very serious difficulties in reliable prediction of diffusion climatology at Bodega Head from the measurement program presently in use by PG&E.

Before concluding this section on winds and their bearing on Bodega reactor hazards, one warning is addressed to the meteorologically uninitiated reader: Several wind patterns and drifts have been discussed above in over-simplified terms that may leave in the minds of non-meteorologists a rather too well-defined impression of expected wind patterns. Anyone who has worked closely with mesoscale circulation problems (above all in areas of such complex topography and land-sea geography as that found near Bodega Head) knows that a bewildering variety of departures from over-simplified models is almost the rule rather than the exception. It is dangerous, in assessing reactor hazards, to think too narrowly in terms of two or three attractively simple models of flow, lest attention be diverted from the hazards associated with unusual combinations of events. Were the costs of such neglect not so serious, it would only be sensible to ignore all but the principal features of local flow patterns; but in assessing hazards of a large power reactor, perspicacity is at a premium. The Windscale accident in England in 1957 is an excellent lesson in this direction; an odd sequence of wind changes led to considerable confusion in the midst of the Windscale accident and subsequently led to a peculiar pattern of dispersion of the radioactive materials emitted from the Windscale plant. Real wind-flow patterns are seldom as simple as we envisage in our models.

3.4 Precipitation. Annual amounts of precipitation ranging from 30 to 40 inches are typical of the coastal area near Bodega, increasing upslope towards the Coast Range summits. The marked division into a nearly dry summer season and a wet winter season is so well-known as to need no elaboration. Some representative data for stations near Bodega have been given by Eberly and Robinsion (1), but will not be reproduced here. Of interest, however, is the fact that the 32-year record for Pt. Reyes indicates 77 days per year with more than a trace of precipitation with 61 of these days occurring in the winter half-year (Nov.-Apr.). Roughly one day in five, for the year as a whole, has at least light precipitation, the average amount per rain-day being about 0.5 inch. In winter one-third of all days has some rain. This is chiefly drizzle and light rain, with essentially no thunderstorm precipitation, an important point in that it implies small drop sizes and large drop concentrations, conditions maximizing washout of contaminated particulates in the subcloud layer or in low stratus below the main precipitation deck (26, 27, 31, 39). This climatological characteristic of frequent light drizzles and rains in the winter half-year along the northern California coast introduces an adverse factor in winter that offsets the advantage then enjoyed as a consequence of absence of strong subsidence inversions. Briefly, one has the coastal inversions holding reactor effluents under a lid at 1500 ft in the summer half-year, and one has frequent situations favoring rain-scavenging in winter. However, the direct hazards to humans is likely to be greater in summer, inasmuch as inhalation hazards could be extensive in summer, whereas winter-rain washout would offset chiefly iodine hazards on milksheds.

Rain scavenging (40, 41) involves both "rainout" of contaminants deposited (chiefly by Brownian motion) on cloud droplets and then carried down in the general precipitation process, and also "washout" by aerodynamic impaction in the subcloud layer. Reactor effluents would not be found on particles large enough to be subject to direct aerodynamic impaction by rain except in the event of an explosive release in which fuel-element particles were blown out into the atmosphere. But gaseous emissions, both of routine and accidental types, can go into solution in available droplets (41, 42) or, after they decay to non-gaseous daughter products (rubidium, strontium, cesium, barium), can attach to particles of the prevailing aerosol (43) and can then be cloud-scavenged and ultimately rain-scavenged. The California coastal weather of the winter half-year should be almost unexcelled in favoring all such scavenging processes, which calls for careful consideration of hazards resulting from rain deposition of fission products on the rolling grasslands downwind of the Bodega site. Particularly important is, of course, deposition of 8-day radioiodine, I-131 (see 44 for a recent summary on I-131 deposition), on pastures of the milksheds of Sonoma and Marin Counties during the wet season. Radioiodine enters the food chain via milk and is then selectively deposited in thyroid tissues, posing hazards especially serious to infants fed on market milk. Unusually stringent monitoring of wet-season radioiodine deposition on pasturelands downwind of any nuclear reactors constructed on the California coast and also on the Oregon and Washington coasts will be indispensable for the reasons cited above. Indeed, nowhere in the country will reactor-hazards-planning face such adverse precipitation-scavenging conditions as prevail in the winter half-year along the West Coast.

3.5 Fog and Stratus. Another salient feature of the climatology of the West Coast in general and the Bodega area in particular is the frequent occurrence of fog and low stratus. These, like the frequent winter drizzles, pose adverse scavenging hazards. Fog and stratus are predominantly a summer half-year phenomenon as are the inversions that confine them to the lower layers. Maximum coastal fogginess occurs north of Bodega, in the Eureka area, where U.S. Weather Bureau data (45) indicate an average of about 50 days per year with dense fog. This is the foggiest area of the United States. Southward near Bodega, the frequency falls below 20 days per year in the Golden Gate area. Fog and low stratus are essentially the same phenomenon, fog being convertible to a low stratus overcast by strong wind-stirring. Stratus bases of less than a few hundred feet are common along the California coast; and since the foothills of the coastal range are frequently shrouded by stratus that would be described as fog by an observer on the beclouded slopes, fog and stratus will be discussed together here. Eberly and Robinson (1) summarize a 1.5-year record of ceiling heights at Jenner, Calif., about 12 miles north of Bodega. Some 39 per cent of all days had ceilings below 450 ft. Of that amount 34/39 of all cases were contributed by the summer dry season, 5/39 by the wet winter season, documenting the predominance of stratus and fog in the summer half-year in the Bodega area.

There appear to be no published data on fog and stratus drop-sizes made in the immediate vicinity of Bodega, but Neiburger's work (46) and also the work of Neiburger and Wurtele (47), on southern California stratus is probably applicable for the northern coast, too. Neiburger found rather narrow stratus drop-size distributions, usually peaked near diameters of about 15 microns. Liquid water contents increased upward from cloud base to near the cloud top, maxima usually lying near 0.4 - 0.5 grams cm^3. Fogs would probably have considerably lower liquid water contents and probably somewhat broader drop-size distributions. Here, again, we encounter meteorological parameters of importance in the reactor hazards problem for which extant data are pitifully sparse. Indeed, it is quite remarkable how little work of any sort has been done on West Coast fog-meteorology. Extrapolation and inference, guided by information gained elsewhere, must suffice in making certain general predictions as to hazards.

That fogs (and here stratus) can exert an important "scrubbing" action on soluble gases and small particulates is well known from a number of lines of research. Chamberlain's work (42) is directly concerned with scrubbing of radioactive airborne materials, and Junge (41) discusses a number of aspects relevant to the present problem. Fog-scrubbing is effective enough that artificial fog-spray systems are under current study as a means of removing radioactive halogens from reactors and perhaps for taking out volatile fission products in event of accidental releases. Droplet-scrubbing of radioactive effluents from the Windscale accident was implicated in the deposition of a narrow band of high activity just downwind of the Windscale pile in the 1957 accident, according to Chamberlain (48). Droplets of water rising from the cooling towers of the nearby Calder A power station scavenged Windscale effluents and led to rapid deposition in the downwind areas. On the foggy, cloudy hills downwind from Bodega, a ready-made scrubbing system will be operative through a large fraction of each summer day.

Once entrained into a fog, radioactive gases or particulates can be deposited on ground vegetation and particularly on leaves of trees and on conifer needles by aerodynamic impaction. At typical wind speeds and for fog- and stratus-drop-sizes of the magnitude indicated by Neiburger's work, impaction will be fairly efficient. The surface layers of a fog or a stratus deck intersecting a hilltop pasture, blowing past the individual blades of grass, will have a fraction of its droplets removed aerodynamically, adding appreciably to direct turbulent deposition of vapor-form radioactivity. The solubility of iodine in water is sufficiently large to make this process a factor of importance in total iodine deposition from routine stack emissions and must be studied carefully as part of any adequate planning of a monitoring program for a reactor at Bodega or at any other site along the coast near which pasture lands are found.

Fog-drip from conifers is a very effective mechanism of removal of large amounts of water from fogs, as shown by the work of Grunow (49), Nagel (50), Twomey (51) and others. In any pasturelands where conifers border grazing areas in the coastal range, radioiodine could get into the food chain by a sequence involving fog-scavenging of gaseous iodine, aerodynamic impaction on conifer needles, fog-drip precipitation to the grasses below, and biological uptake by dairy cattle.

If conifers are seldom interspersed with grazing areas, fog-drip will not be a serious cause of milkshed contamination, of course. By contrast, the process of impaction on pasture grasses in the fog or stratus zones could be a very common process and demands careful study, both with respect to routine-emission hazards and major-accident hazards. It is beyond the scope of this report to examine that problem, however.

4. HAZARD IMPLICATIONS

4.1. General Remarks. Much of the detail concerning meteorological aspects of radiological hazards associated with operation of a 1000 Mw (thermal) reactor on Bodega Head has been elaborated in Section 3. Here, a brief summary of those hazard implications will be given.

Meteorological conditions along the northern California coast are decidely unfavorable with respect to reactor hazards. The peculiar combination of strong, low-level inversion over much of the dry season plus sea-breeze circulations capable of transporting marine air inland to nearby population centers makes the dry season of the summer half-year distinctly more hazardous than the winter wet season. However, the high frequency of light showers and drizzles during the wet season carries the danger of efficient deposition of airborne effluents on the downwind milkshed in event of a major accident.

It must be reiterated that this report has been principally concerned with radiological hazards resulting from a reactor core-meltdown, a major accident that could conceivably result from a series of equipment malfunctions triggered by seismic activity on the nearby San Andreas fault zone. The present study sheds no new light on the probability of such an accident; but the consequences of any such accident could be so catastrophic that one must examine carefully the way in which meteorological factors might minimize or aggravate the hazards of such an event. Briefly, it is clear that meteorological conditions near and downwind of Bodega would frequently tend to seriously aggravate radiological hazards accompanying an accident.

A second type of radiological hazard that must be considered in safe siting of nuclear reactors, the hazard associated with routine emissions of radioactive off-gases from the plant, has received only passing attention above because this is a hazard much more subject to engineering control. Nevertheless, emphasis must again be placed on the strong doubts expressed above concerning meteorological adequacy of the presênt tower equipment being used in securing data on local diffusion climatology near the Head. There will be serious errors in the eddy diffusion coefficients deduced from wind profiles indicated by the present tower. Those errors are almost certain to be in the direction of indicating safer diffusion conditions than will actually prevail. To get adequate turbulence information from a tower located on such a rugged promontory will be impossible without check-data from other adjacent sites free from transient disturbance effects of the Head itself. A further difficulty influencing dispersion of the routine emissions from the Bodega reactor has been cited: High probability of strong aerodynamic downwash effects produced by the Head itself. Because such downwash might render contamination conditions on Bodega Bay much more serious than would be inferred from data obtained with the present meteorological tower on the Head, it seems quite important that a special study be made of this downwash problem to be sure that local boat operators repeatedly entering and leaving Bodega Harbor via the waters immediately downwind (southeast) of the Head not be exposed to dangerous dosages. A widely used rule of thumb in stack design is to make the stack at least 2.5 times higher than the highest adjacent obstacles to level airflow. With a 265-foot summit directly upwind of the proposed reactor site, this would call for a stack in excess of 650 feet. Finally, a last factor demanding much more thorough study than seems to have been made to date is the role of fog and stratus in scavenging routine effluents and depositing them on downwind pasture lands in Marin and Sonoma Counties. If routine emissions are planned without quantitative allowance made for each of those three cited disturbing factors, actual dosages could exceed Company estimates.

It is, however, the consequences of a major accidental release of volatile radioactive fission products from a core meltdown that have been chiefly of interest in this study. With approximately 200 million curies of volatile fission products in the core of the Bodega No. 1 reactor at equilibrium, the question of seismically induced accidents assumes crucial importance. Despite the fact that no large cities or towns are closer to Bodega than about 25 miles, the frequent occurrence of meteorological conditions that could ensure transport of radioactive gases over considerable distances makes the accident hazard-potential very serious for this particular site.

The hazard-potential of the Bodega site has attained substantially increased credibility as a result of findings of U. S. Geological Survey investigators (29, 30). These findings appear to have led to a significant design change, PG&E Amendment No. 7 of March 31, 1964 (52), that would ostensibly accommodate seismic displacements of subjacent bedrock amounting to up to two feet in magnitude. Amendment No. 7 states that "with a two foot horizontal movement along this fault, the Company's analysis indicates that a part of the lower portion of the reactor containment structure may be crushed inwards up to twelve inches but the steel lining of the pressure suppression chamber, though distorted, would remain intact." Prospect of release of gaseous fission products following a major seismic accident at Bodega is not changed to certainty by such altered conception of the degree of seismic damage that might be sustained; but a breached reactor building and a "deformed" drywell shell can reasonably be viewed as vitiating about one and a half out of three of the containment barriers whose presence has been stressed by PG&E as assuring impossibility of emission of any fission products.

That the conception of multiple barriers to volatile fission-product escape has, in fact, been altered even further as a consequence of the U.S.G.S. findings and the recognition of possibility of bedrock displacements seems clear from testimony (53) presented at the May 19, 1964 hearings in San Francisco before the San Francisco Board of Supervisors by Mr. L. H. McEwen, a spokesman for the General Electric Company, contractor to PG&E

in design of the Bodega reactor. In his submitted statement (53, p. 17), McEwen notes that "significant motion of part of the foundation could cause a breach in the wall of the reactor building, but consequences of this would not be harmful because the air in the reactor building is itself quite suitable for breathing -- people work there -- and thus its release to the environment would be of no consequence. Further motion of part of the foundation could cause distorting (denting) of the containment, but this would not impair it. Even greater motion, which could perforate the containment (emphasis added), would not itself comprise a severe accident because the containment itself contains only air. Accident possibilities only begin with foundation movements which would cause an opening in the reactor vessel or the process piping system within the containment." By these statements of the reactor manufacturer's spokesman, the triple barrier to escape of volatiles is admitted to be, potentially, reduced to a single barrier (the reactor vessel itself) in event of major seismic displacements. Such an admission of possibility of containment perforation clearly demands that very serious consideration be given to the here-discussed meteorological aspects of the consequences of fission-product release at Bodega and represents a substantial change in the claimed integrity of the over-all system.

This substantial change in claimed integrity, already implicit in Amendment No. 7, has, on May 19, 1964, led the Atomic Energy Commission's Director of Regulation, Harold L. Price, to request from PG&E much more definitive specifications of structural design features and system safeguard details than have previously been supplied the AEC. Price's query (54) notes that "the amendment further states that offsets up to 2 feet would damage the building but would not impair containment. It is not clear to us from the information submitted how your design plan would achieve this objective." The Director of Regulation further asks PG&E how it proposes to modify its design so that "(i) the structure and leak tightness of the containment building would not be impaired? (ii) the ability to shut down the reactor and maintain it in the shut-down condition would not be impaired? (iii) primary systems would remain intact? and (iv) supply of power to the facility would not be interrupted?" Price proceeds to still more specific queries about location and safeguards proposed for "vital internal components" and especially about the emergency cooling system. The latter query is directed to a crucial point, for with the original triple containment barrier potentially reduced (by major seismic accident) to the single barrier of the reactor vessel, the question of reliability of the emergency cooling system required to dispose of post-accident fission decay heat assumes major importance. Possibility of a whole series of seismically induced malfunctions in the complex automatic control systems that must swing into operation in event of accident draws attention to the possibility of failure of the standby systems design to deliver emergency cooling to the reactor core. Such a failure would insure meltdown of the core, a prerequisite to escape of the volatile fission products. With the outer two containment barriers breached, core meltdown would leave only the reactor vessel as the sole containment barrier. The further possibility (admitted by PG&E in its estimate of the "maximum credible accident" specified in its 1962 Preliminary Hazards Summary Report) that seismically induced failures of other components of the safety system might eventuate in breaching of that one last barrier returns our attention to the meteorological factors that would govern radiological exposure hazards in event of such an accident.

The foregoing remarks have been aimed primarily at drawing attention to the fact that there has been a substantial drop in claimed integrity of the Bodega reactor as a result of recent geological and seismological findings at the site. The peculiarly adverse meteorological factors associated with the Bodega site assume much more serious proportions in the face of these reductions in claimed integrity.

No attempt to translate the meteorological factors into detailed radiological exposure estimates will be made here. Such estimates have recently been made by Mattison and Daly (55), and though they were not made in terms of some of the more specific meteorological factors stressed here, they suffice to show the dimensions of exposure hazards that would accompany a substantial release of volatile fission products from the Bodega reactor. Their estimates are based on an earlier AEC hazard study (27), and they scale the hazard estimates of that study down to match an assumed escape of 80 megacuries of volatile fission products. The latter figure was chosen by Mattison and Daly on the now quite reasonable basis that PG&E had previously accepted the possibility of escape of 80 megacuries of volatiles from reactor vessel to drywell shell as the Company's own estimate of the maximum credible accident. Since General Electric's McEwen was ready to consider (53) the possibility of drywell breaching, in his cited May 19 testimony at San Francisco, there now appears to be every reason to employ at least the 80 megacurie release assumed in the Mattison-Daly study. Details of their scaling results will not be elaborated here. It may suffice to give their figures for hazards at Santa Rosa, 20 miles from the site. External gamma doses of 72 rads on the first day and a subsequent 4600 rads in the following 90 days, plus 320-rad inhalation doses to the lungs during cloud passage and 960 rads during the entire first week were estimated. Santa Rosa thyroid dosages, largely due to the single volatile isotope Iodine-131, was put at 4700 rads by similar scaling of the AEC's 1957 hazard study. It should be noted that such serious radiological exposures are obtained for an assumed escape of only 80 megacuries of the total of approximately 200 megacuries of volatile fission products, or about one-third of all the volatiles. One-third of the volatile fission products accumulated in the Bodega reactor core at equilibrium represents, in turn, approximately 6 or 7 per cent of the total fission product inventory in the equilibrium core of Bodega No. 1 Reactor. Even that small a fractional escape of total fission products would produce catastrophic results.

The foregoing summary of seismic potential for major accident and of hazard dimensions should suffice to show that one must, indeed, weigh into the over-all assessment of desirability of constructing a complex of reactors at Bodega Head the question of the adverse meteorological features of the area, for the possibility that those features would be brought into play seems much greater now that the prospect of a major release has assumed its recently acquired credibility. Those meteorological features will be given final summary in the following two sections, separated into discussions of the quite distinct summer dry season and the winter wet season.

4.2. Summer Dry Season. We have seen that in the summer half-year the high frequency of low inversion bases poses peculiarly serious difficulties. If prevailing winds blew out to sea, the inversion factor would be of little importance. However, prevailing winds in this season are northwesterly, so the inversions have exceedingly adverse hazard implications. In addition, sea-breezes that will tend to transport effluents inland through two main gaps in the coastal ranges greatly aggravate the problem. As has been explained earlier, inland penetration of marine air by sea breeze circulations will not be accompanied by sufficiently rapid breakdown of the inversion to prevent relatively high concentrations of contaminants reaching populous areas in event of a major accident.

On a statistical basis, considering only frequency of occurrence of given airflow patterns, it seems likely that the chances of serious radiological exposures of persons in Petaluma, Santa Rosa, Sebastopol and other communities just inland from Bodega are somewhat greater than chances of exposure of persons in the San Francisco Bay area during summer. This is because during much of the morning and afternoon direct sea-breeze penetration of air from the Bodega area into those inland localities takes place. In the mere twenty-five miles of drift distance, the effluent gases would still be completely trapped under the inversion base. Increasing mixing with increasing inland penetration would finally destroy the inversion lid by the time the contaminated marine air advanced to something like 40 or 50 miles inland; beyond that distance, summer daytime hazards would be slight.

However, for hypothetical Bodega accidents occurring under certain other flow conditions, no influx of contaminated marine air would occur via the Petaluma gap. Instead, the effluents would tend to drift generally down the coast towards the Golden Gate. An accident occurring at Bodega during the nighttime hours in summer could be expected to result in effluents tending to drift out to sea in the nighttime land breeze blowing from east to west through the Petaluma gap. However, the amount of drift out to sea would be rather limited because the northwesterly flow along the coast is so strong that superposition of a local land breeze component is unlikely to lead to very strong net drift to the west. Rather, a nighttime accident is likely to lead to a flow of contaminated air moving in a generally southward direction, probably curving back in to the coast near the Golden Gate where net influx is present during most of the day, according to existing data.

Thus the summer hazards to the San Francisco Bay area are chiefly nighttime hazards. Since there is no reason to believe that seismic activity is less likely to occur at night than in the day, this prospect gives San Francisco good reason to be just as concerned as, say, Santa Rosa or Petaluma, with respect to Bodega reactor hazards. In fact, the stability of the air would be even greater under such nighttime conditions than it would be under the daytime conditions posing greatest hazards to Petaluma and Santa Rosa. Hence, despite the roughly 50 miles of drift required to get effluents from Bodega Head to the San Francisco area, lateral dispersion of the effluents would be less for coastwise drift to San Francisco than for daytime drift to inland cities. Experience at the Brookhaven Laboratories (56) reveals that plumes may easily drift for many tens of miles under inversion conditions, yet suffer almost no dispersion. Plumes of fluorescent zinc sulfide were traced for over 100 miles in field tests in New Mexico, even under moderately stable conditions by Braham, Seely, and Crozier (57). I have recently completed a study (58) of an air pollution episode in the vicinity of Tucson, Arizona, in which evidence was found for nighttime drift of smelter smoke in high concentrations over distances of at least 70 miles. Other cases could be cited to show that the 50 miles separating Bodega and San Francisco do not at all preclude drift of effluents from the reactor site to the Bay area in event of a major accident at the Head. The strong winds of the California coast would typically lead to some horizontal and vertical mixing, but it is entirely possible and even likely that plume widths of less than 10 miles would be found even after 50 miles of coastwise drift from Bodega under summer nighttime conditions.

Concentrations of volatile fission products that might drift over either of the two population areas considered above would depend on inversion depth and plume width, and also on wind speed and total time of venting of the gases. If the venting of all the fission products required many days or even weeks, then emergency arrangements might be made to evacuate residents of endangered area. But, in the case of the Bodega reactor, possibility of a disastrous seismically-triggered accident in which rupture of containment systems led to rapid venting and in which an appreciable fraction of all volatile fission products might vent in times of the order of an hour or two after meltdown must be considered. If venting occurs rapidly, i.e., over a time too short to evacuate cities, then one may ignore that time because total inhalation dosages will be independent of time of passage of the cloud. Instead, for the case of rapid venting, only plume width, plume depth, and mean wind speed enter into exposure estimates. To be sure, certain volatile gases do have short enough half-lives that their own decay must be allowed for, but this can be taken into account in straightforward manner. The meteorological factors indicate that one should take a plume depth equal to the average height of the inversion-base, namely about 1200 ft. For daytime plume widths in the Petaluma and Santa Rosa area, bifurcation of the sea-breeze current suggests use of an effective width of about 25 miles. For nighttime plume widths associated with coastwise drift to Golden Gate, the greater stability and lack of any strongly divergent (bifurcating) patterns upwind of San Francisco, suggest that about the same width of 25 miles be used. It is of interest to note that a plume width of only 25 miles was found by Braham, et al, in their tracer experiment that extended out to drift distances of 107 miles in New Mexico (57). In the case of drift of effluents from Bodega to San Francisco, as compared with drift to Petaluma and Santa Rosa, the greater drift distance is likely to be more than compensated by the greater stability and consequently lesser later plume dispersion under nighttime conditions, whence exposure hazards might be somewhat greater in the case of a San Francisco fumigation than for effluent drift to the inland communities just east of Bodega. Also, under the stable conditions that would be associated with drift to San Francisco, the same kind of spotty distribution of concentrations would be expected to characterize the plume on arrival in the Bay area as was found by Braham, et al, in the New Mexico tests. This means that individual areas and persons might get radiological dosages much higher than the average value computed from the plume dimensions suggested above.

The step of translating the above meteorological estimates of summer dry season plume conditions into estimates of radiological exposure is beyond the scope of the present report. That step will be left to others more intimately familiar with the health physics aspects of the problem. It is hoped that the present assessment of meteorological factors will be of use to others attempting such estimates, just as the recent assessments of geological and seismological factors have contributed to overall understanding of the problems of the Bodega reactor site.

4.3. Winter Wet Season. It is much more difficult to attempt quantitative estimates of hazards that might result from an accident in the winter half-year. Although inversions are occasionally present in winter, they are not as intense as in summer. Also sea-breeze circulations are undoubtedly weak or absent in winter, and wind direction variability is higher than in summer. Nevertheless, the prevailing winds still blow from the northwest, and it is still the same communities that stand the greatest chance of exposure in event of accident. How much lower that chance is than in summer cannot be estimated with reliability. All that can be said by way of generalization concerning winter hazards is this: Occurrence of frequent light showers in that season increases considerably above summer levels the probability of milkshed contamination by precipitation-deposition. If dairy cattle were on native pasture under such conditions, widespread iodine contamination of market milk would probably be the greatest hazard. The Windscale accident in England led to condemnation of milk produced over an area of about 300 square miles, despite the fact that only about 20,000 curies of I-131 were released in the accident (48). Total core inventory of the Bodega reactor will be, by comparison, about 25,000,000 curies of I-131, so one can see that a major accident at Bodega could lead to consequences vastly more serious than at Windscale. Again, the crucial problem is that of estimating the probability of venting of any substantial fraction (order of a few per cent or more) of the volatile fission products in the core of the Bodega reactor as a result of a seismically-triggered malfunction. If that probability is negligible, then so are the hazards. If that probability is appreciable, then the hazard potentialities are tremendous.

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