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**THE LONG RANGE DIFFUSION OF THE EFFLUENT
CLOUD FROM THE PHOEBUS 1B EP-IV REACTOR TEST
OF FEBRUARY 23, 1967**

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THE LONG RANGE DIFFUSION OF THE EFFLUENT CLOUD FROM THE PHOEBUS 1B EP-IV REACTOR TEST OF FEBRUARY 23, 1967

Abstract

This report discusses the movement and diffusion of the effluent cloud produced by the Phoebus 1B EP-IV Event of February 23, 1967. This cloud was tracked by aircraft for almost three days, and useful concentration measurements were obtained for almost two days.

Pre- and post-run calculations were done with a computer code for large cloud diffusion using climatology and observed meteorology respectively. Calculations of concentrations and cloud size are compared with the available measurements. Calculations agree well with measurement for the first few hours.

At later times, comparisons of measured and calculated concentrations and

cloud size indicate that calculations yielded concentrations a factor of 2 to 5 higher than observed. The most likely explanation is the presence of a large amount of change with height through the depth of the cloud of the mean wind direction. The increased dilution rate due to this effect is not included in the calculational model. In this sense calculations will be conservative. A contributing cause of this difference may also be insufficient resolution in the aircraft data at late time. All these factors would bias observations towards low values.

During the two days of interest, decay and diffusion decreased radioactive concentration more than eight orders of magnitude.

Introduction

The Phoebus 1B EP-IV reactor test was conducted at the Nuclear Rocket Development Station (NRDS), 90 miles northwest of Las Vegas, Nevada on February 23, 1967. The reactor was operated from 1354 to 1435 PST on February 23, 1967. Power levels between 1250 and 1500 megawatts were maintained

between 1400 and 1428 PST.¹ For purposes of discussing the time dependent behavior of the effluent cloud in this report, H-hour was taken as 1420 PST.

The purpose of this report is to discuss the available data on cloud concentrations and size, the associated meteorology and to make comparisons with calculations,

done with the computer code for large cloud diffusion, 2BPUFF,² over the three days that the effluent cloud was tracked by aircraft.

SOURCE

Integration of the power level curve given by Weiss¹ and data given by Thalgott³ indicate a total integrated power for this reactor run of 2.9×10^6 megawatt seconds. Using the 100 Ci/megawatt-second conversion factor⁴ to obtain gross gamma at H+1 hours gives 2.9×10^8 Ci. Estimates of percent released from the reactor range from 0.7 to 3 percent. Using the round number of a 1-percent release gives a total cloud burden at H+1 of 2.9×10^6 Ci. From aircraft sampling of the cloud and an estimate of the cloud volume, the Public Health Service estimated a total cloud burden (gross β) at H+1.6 of about 2×10^6 Ci.⁵ Decaying this back to H+1 with $n = 1.2$,^{5,6} in a t^{-n} decay scheme, gives a cloud burden of 3.5×10^6 Ci at H+1. It should be noted that these aircraft data were only for particulate samples (IPC 1478 filter paper and charcoal) and that about 85 percent of the activity was on particles less than 1μ . The aerial mapping of the fallout pattern by the EG&G aircraft indicates about 7450 Ci at H+24 in the fallout pattern.⁷ Decaying this back to H+1, with $n = 1.2$, gives 3.4×10^5 Ci or approximately 10 percent of that which is thought to have been (H+1) released; the rest was in the cloud. Some of this activity would have still been airborne at H+1, and some would have already been deposited. In any case it appears that a reasonable number to use for the nonfalling cloud

burden at H+1 is 3×10^6 Ci. The difference between the Public Health Service estimate⁵ and the other estimates of release probably cannot be resolved; the differences are within the accuracies of the determinations.

INITIAL CLOUD GEOMETRY AND METEOROLOGY

The effluent cloud was generated by the high velocity and high temperature radioactive gases (and small particles) exiting the nozzle of the reactor. This nozzle or "tail pipe" was pointed upwards. The effluent rose several thousand feet above the Jackass Flats (NRDS is located on Jackass Flats) ground surface (about 3800 feet above sea level) and was carried downwind by the prevailing winds. The reactor was run for 41 minutes; the effluent, while close to the reactor during the initial time period, looked more like a plume than a cloud. At distances downwind, where the time between generation of the effluent and its arrival at the downwind location was about ten times generation time, the effluent looked more like a cloud than a plume. For Phoebus 1B EP-IV this meant a travel time of about 6.7 hours or about 80 miles downwind (with a wind velocity of 12 miles per hour).

In order to start a cloud calculation with 2BPUFF² it is necessary to have an estimate of initial cloud size, shape, and height. In this section such estimates are developed from photographic, meteorological, and aircraft data.

Figures 1-3 show the 1300 PST surface weather chart, the 1400 PST second standard level streamline analysis (winds 1000 to 2000 ft above the ground surface) and the 1400 PST 10,000 ft MSL (above

Fig. 1. Surface analysis for 1300 PST, February 23, 1967.

Fig. 3. Local analysis 10,000 feet MSL streamlines for 1400 PST, February 23, 1967.

mean sea level) streamline analysis⁸ for February 23, 1967. These figures indicate a high pressure area to the east of Jackass Flats and a low pressure area to west. The ridge aloft had gradually moved from west to east across NRDS during the day. The surface low over California was a thermal low. The low pressure system off the coast of Washington and Oregon moved on shore and caused precipitation west of the Rockies and as far south as central Nevada by February

25, 1967. During the reactor operation the winds were light southerly, see Fig. 4 for a time section of the winds near reactor run time. There was a wind direction change from south near the surface to southwest at higher altitudes but there was little time change in the winds during the 41 minutes of the reactor operation. There were no restrictions to visibility but there was an overcast cirrostratus cloud layer. The effluent cloud did not reach the altitude of the cirrostratus but

Fig. 4. NRDS wind time section from 0600 PST February 23 to 0700 PST, February 24, 1967.

this cloud layer did increase the background problem for infrared photographs of the effluent cloud.

The radiosonde data obtained at the time of reactor start up (see Fig 5) indicates super adiabatic and dry adiabatic lapse rates from the ground surface to a weak, shallow inversion at 7800 ft MSL. Above this inversion the atmosphere was stable although there were no more significant inversions below the height of the 500 MB (millibars) surface. With an adiabatic lapse rate there would be little to stop the rise of the effluent cloud, even if entrainment reduced the effluent temperature close to ambient, until the effluent reached the 7800 ft MSL inversion. This height was high enough so that it is reasonable to expect conditions close to ambient within the rising effluent. Consequently, the weak inversion at around 7800 ft MSL would be sufficient to restrict further vertical motion.

Weiss¹ took infrared photographs of the effluent cloud. These photographs indicate a top of about 4400 ft above the ground surface (or 8200 ft MSL) for the effluent. This is consistent with the radiosonde data. Weiss' observations were during full power (around 1500 megawatts) operation of the reactor. During lower power levels (i.e. during start up and shut down) the effluent height was less well defined and was lower.

The infrared vidicon camera system used by Boquist⁹ indicated an effluent height around 400 ft above the ground. This value is too low to be reasonable and must be a consequence of poor sensitivity of the infrared vidicon camera system.

The effluent cloud was sampled by aircraft within a distance of a few miles of the reactor location (i.e. over the Jackass Flats area). These data indicated that the altitude of maximum activity was about 7000 ft MSL.¹⁰ Most of the activity was in the 5,000 to 10,500 ft MSL altitude range.¹⁰

Within about 8 to 10 miles of the reactor location, along the effluent trajectory, the ground elevation increases almost 3000 ft because of the transition from Jackass Flats to the Shoshone Mountains. With a dry adiabatic lapse rate capped by a weak, shallow temperature inversion (see Fig. 5) it is reasonable to expect this increase in ground elevation to cause an increase in cloud elevation. Consequently, the finding of activity at 10,000 ft MSL is not surprising. This is particularly true when one considers that there is no information on the precise position of the aircraft when the observation was made. Activity lower than the height of the inversion (see Fig. 5) is, of course, consistent with reactor operation at low power levels during start up and shut down.

The hypothesis of an altitude increase of the effluent cloud over the Shoshone Mountains is substantiated by the observation made by the Public Health Service at H+2 27 (hr min)⁵ of the height of maximum activity at 10,000 ft MSL, with the effluent extending from 7,000 to 13,000 ft MSL. By this time the effluent was over the northern part of Yucca Flats.

This increase in cloud altitude over the Shoshone Mountains raised the bulk of the effluent from a regime of southerly winds to one of stronger southwesterly winds (see Fig. 4). Because this altitude

Fig. 5. Radiosonde observations from Jackass Flats, Nevada on February 23, 1967.

transition for the whole cloud took place over a time period equivalent to the duration of reactor operation, the orientation of the effluent cloud was changed from one initially being along a north-south line to one being along an east northeast-west southwest line. Aircraft observations^{3,5} support this picture for approximately the first two hours. Observations of this author, flying aboard the NATS operated by EG&G, and the unpublished cloud tracking maps of EG&G, indicate a cloud oriented more or less east-west at H+5 to 6 and moving towards the northeast.

For purposes of starting a calculation with 2BPUFF² it is necessary to know the initial cloud geometry. From the sources of data mentioned above it was decided to use 7800 ft MSL as the initial cloud center elevation. During the calculations this was raised to 10,000 ft MSL as the cloud went over the Shoshone Mountains.

The aircraft data within the first hour indicate a cloud thickness (or vertical extent) of about 5500 ft.¹⁰ However, this measurement is a function of the radioactivity concentration in the cloud and the sensitivity of the airborne instrumentation. It is assumed that the 5500 ft (1680 m) represents the distance from $+4\sigma_z$ to $-4\sigma_z$ of a Gaussian shaped cloud whose peak is at the cloud center. In the end of this section it will be shown that this is consistent with the sensitivity of the airborne instrumentation on the B-57's and the 6000 ft thickness measured by PHS⁵ at H+2.27.

NATS stands for Nevada Aerial Tracking System and is a highly instrumented Martin 404 aircraft.

An estimate of the cross wind width of the cloud is obtained by calculating the spread of a turbulent jet over a distance of 4400 ft (Weiss¹ distance above ground). Several authors^{11,12} have reported the spread of a turbulent jet (distance from jet center to where the jet velocity was one tenth the velocity on the jet axis) as being represented by a line at an angle of 12° from the jet axis. Taking the tangent of 12° , multiplying by the distance above ground, and then doubling, gives a total cross wind width of 536 m.

The reactor was at power levels ≥ 500 megawatt for 39 minutes.¹ During this time the 6 m/sec winds at 8000 ft MSL would have moved the leading edge of the effluent cloud 14,050 m downwind. Plume meandering and diffusion would make the downwind width of this trapezoidally shaped (in the horizontal) cloud wider than the upwind edge. Using an included angle of 30° from Pasquill,¹³ for meandering and diffusion, taking the tangent, multiplying by the travel distance and adding the upwind width gives 8636 m for the downwind edge. Both the turbulent jet and the plume diffusion studies which provide the basis for Pasquill's¹³ estimates are to the one-tenth concentration, that is, the definition of the edge. For a Gaussian cross wind distribution this is approximately equal to the 2σ from the center, or a total width of 4σ .

The cross wind σ 's are plotted (see Fig. 6) as determined from particle concentrations at the ground surface.⁶ It is seen that the cloud width estimates prepared in this report are consistent with the ground measurements. Within the first hour after the reactor was started several aircraft^{3,5} reported cloud widths

of 5 to 10 miles (8-16 km). Although somewhat larger than the values in Fig. 6, these aircraft data are comparable within the constraints of this report.

This trapezoidal cloud had a horizontal area of $6.45 \times 10^7 \text{ m}^2$ and an equivalent circular radius of $4.53 \times 10^3 \text{ m}$. It was this radius and a half cloud thickness of 420 m which was taken as $2\sigma_r$ and $2\sigma_z$ for an initial Gaussian shaped cloud in the 2BPUFF computer code calculation. The subscripts r and z indicate radial (horizontal) and vertical direction respectively. The total cloud burden, with an initial concentration of unity per m^3 at the cloud

Fig. 6. Cloud width as a function of time as determined from ground deposition measurements at different distances downwind.

center, is 1.72×10^{10} . Decaying the $3 \times 10^6 \text{ Ci}$ at H+1 back to H+0.1 hr (the starting time for the diffusion calculations is 2BPUFF) gives $4.75 \times 10^7 \text{ Ci}$. Dividing by the 1.72×10^{10} burden results in a center point concentration of $2.75 \times 10^9 \text{ pCi/m}^3$ at H+0.1.

With an average gamma energy of 0.7 Mev⁴ and assuming an infinite cloud of uniform concentration gives a conversion factor for concentration to exposure rate of about 1300 R/hr/Ci/m³¹⁴. Applying this conversion to the center point concentration results in an exposure rate of 3.6 R/hr. Peak exposure rate readings obtained from B-57 aircraft penetrating the cloud between 1410 and 1430 PST were 1, 4, and 4.6 R/hr respectively.³ There was also a reading of 0.8 R/hr above the cloud.³

If we go $4\sigma_z$ vertically from the cloud center the exposure rate is 1.2 mR/hr. The threshold of sensitivity for airborne exposure rate meter is one half to a few mR/hr. Thus, the use of a $\sigma_z = 210 \text{ m}$ in the 2BPUFF calculations is consistent with the early B-57 observations of a total thickness of 1680 m ($8\sigma_z$).

Prior to the reactor run a similar initial cloud height, thickness and equivalent circular radius was predicted using climatological data for cloud height and downwind travel during reactor operation. The same approach was used then as is used above to obtain the horizontal area of the cloud. Table I summarizes these pre- and post-run predictions.

CLOUD TRAJECTORY AND METEOROLOGY

As mentioned previously the effluent initially moved towards the north and then

Table I. Initial cloud size parameters.

	Pre-Run	Post-Run
Height above ground	1700 m	1340 m
Thickness ($-2\sigma_z$ to $+2\sigma_z$)	500 m	840 m
Radius (center to $2\sigma_r$)	4750 m	4530 m

to the north-northeast as it rose over the Shoshone mountains. The Environmental Scientific Services Administration (ESSA) personnel at Jackass Flats prepared trajectory predictions from observed wind data for several different altitudes.⁸ Figure 7 gives these trajectories for the vicinity of the test site. The trajectories began at the time of reactor start up. The change in wind direction from 8,000 to 10,000 ft is quite evident on this figure. From spot observations of exposure rate measurements made in aircraft and on the ground,^{3,5} this author has drawn approximate cloud boundaries for several different times.

The long range meteorological trajectories are given in Fig. 8.⁸ Several tetrons (constant level balloons) were released from NRDS prior to and during the full power run. Two of these were tracked by FAA radars in Utah. The balloons were inflated to fly at 12,000 ft MSL but NRDS radar measurement indicated that they were flying at about 11,500 ft MSL. The two tetrons followed quite closely the 12,000 ft trajectory on Fig. 8 until they were lost in ground clutter in southwestern Wyoming at 1600 PST on February 24.

The best record of where the effluent cloud actually went is from the tracking data from the NATS aircraft. Figure 9 from the EG&G report⁷ summarizes these

data on the effluent trajectory and cloud size. Comparison of Figs. 8 and 9 indicates that the cloud followed the path of the 10,000 ft trajectory quite closely until the Dakotas were reached. At this point the effluent moved toward the east-northeast while the meteorological trajectory moved towards the southeast. Comparison of the times on Fig. 8 and 9 (remember H-hr $\simeq$ 1420 PST) indicates that the cloud moved somewhat faster than the meteorological trajectories.

Lifting the effluent over the Shoshone Mountains probably put the effluent at a potential temperature surface of about 30°C. Examination of Fig. 5 and the Ely, Nevada radiosonde data (which is not presented in this report) from 1600 PST on February 23, 1967 are consistent with this statement. In order to obtain an idea of likely effluent heights along the trajectory, the heights of the 30°C and 32°C potential temperature surfaces from nearby radiosondes are plotted on Fig. 10. Aircraft altitude-spirals and the flight altitude of the NATS are also indicated. For the most part, aircraft data were obtained at heights consistent with the radiosonde data.

The weather along the trajectory was ideal for tracking and sampling the effluent. On February 23 and during the morning of February 24 there were high cirrus clouds. Skies were clear the rest of the way to Minnesota. There were no clouds or precipitation associated with the arctic front along the east side of the Rockies in Fig. 1. Temperatures in the cold arctic air were 15 to 20°C colder than in Nevada, and this cold air extended up to 5000 to 7000 ft MSL over the plains states. The effluent would therefore tend to ride up

Fig. 7. On-site meteorological trajectories and approximate cloud boundaries.

Fig. 8. Long range meteorological trajectories.

Fig. 9. The effluent trajectory and diffusion pattern measured from the NATS aircraft between the altitudes of 9500-10500 feet MSL.

over the cold dome of air instead of penetrating it.

The 7000 ft MSL trajectory on Fig. 8 must have been carried through the frontal surface; this is not physically consistent.

DIFFUSION CALCULATIONS

Two calculations have been done for this event; one was done pre-run using

February climatology to prepare meteorological input and the other was done post-run using observed meteorology. Neither calculation, not the cloud, had any interaction with precipitation. Table II gives input parameters that do not change with time throughout the calculation.

The basis for the initial cloud size has been previously discussed. An averaging

path of 100 to 120 km is consistent with the distance flown by a sampling aircraft during one filter exposure at times after several hours. In the calculation this distance is used to compute an average concentration over a horizontal path length centered on the cloud center. Mean transport velocities are consistent with climatological data at around 700 MB

(pre-run) or observed winds (post-run). This velocity is only used in the calculation to move the effluent down wind, with respect to ground zero, in order to present dry deposition as a function of distance. The deposition velocity and maximum horizontal diffusivity are consistent with our knowledge of these values for this kind of a calculation.²

Fig. 10. Effluent height as a function of time. Organization symbol is plotted at height of maximum activity; bar indicates altitude range of cloud. Letters indicate radiosonde observations from that station; the upper station identification at any time is at the height of the 32°C potential temperature surface and the lower is the height of the 30°C surface.

Table II. Initial conditions.

	Pre-Run	Post-Run
Cloud radius ($2\sigma_r$)	4.75×10^5	4.53×10^5 cm
Cloud thickness ($4\sigma_z$)	5.0×10^4	8.4×10^4 cm
Averaging path length	1.0×10^7	1.2×10^7 cm
Mean transport velocity	1.0×10^3	9.0×10^2 cm/sec
Grid point of cloud center	12	12
Tropopause height	9.5×10^5	1.18×10^6 cm
Deposition velocity	1.0×10^0	1.0×10^0 cm/sec
Total running time	2.0×10^5	2.48×10^5 sec
n in a t^{-n} decay	1.2	1.2
Maximum value of horizontal diffusivity	1.0×10^{10}	1.0×10^{10} cm ² /sec

Table III. Climatological Input— February — Starting Time = 0800 PST.

Time (hr)	Ground surface elevation (km)	Cloud center elevation (km)	K_z at 1 m (cm ² /sec)	Depth of boundary layer (km)	K_z above boundary layer (cm ² /sec)	Top of mixed layer (km)	Base of inversion (km)	K_z above inversion (cm ² /sec)	Atmospheric dissipation (erg/g-sec)
0.0	1.16	2.86	3.0×10^3	0.3	1.0×10^4	2.35	2.85	1.0×10^3	5.0×10^{-1}
4.0	1.60	3.00	5.0×10^3	0.3	5.0×10^4	3.25	3.75	1.0×10^3	1.0×10^0
8.0	2.50	3.20	6.0×10^3	0.3	1.0×10^5	4.10	4.60	1.0×10^3	1.0×10^1
12.0	1.70	2.80	1.0×10^3	0.1	2.0×10^3	1.80	2.30	1.0×10^3	1.0×10^{-1}
22.0	2.50	3.30	1.0×10^3	0.1	2.0×10^3	1.80	2.30	1.0×10^3	1.0×10^{-1}
24.0	3.00	3.80	3.0×10^3	0.3	1.0×10^4	3.30	3.55	1.0×10^3	5.0×10^{-1}
28.0	3.00	3.80	5.0×10^3	0.3	5.0×10^4	3.60	4.10	1.0×10^3	1.0×10^0
32.0	2.00	3.40	6.0×10^3	0.3	1.0×10^5	2.50	3.00	1.0×10^3	1.0×10^1
36.0	1.40	3.00	1.0×10^3	0.1	2.0×10^3	1.50	2.00	1.0×10^3	1.0×10^{-1}
46.0	0.80	2.60	1.0×10^3	0.1	2.0×10^3	0.90	1.40	1.0×10^3	1.0×10^{-1}
48.0	0.70	2.60	3.0×10^3	0.3	1.0×10^4	1.05	1.55	1.0×10^3	5.0×10^{-1}
52.0	0.50	2.60	5.0×10^3	0.3	5.0×10^4	0.90	1.40	1.0×10^3	1.0×10^0
56.0	0.40	2.60	6.0×10^3	0.3	1.0×10^5	0.90	1.40	1.0×10^3	1.0×10^1
60.0	0.30	2.60	1.0×10^3	0.1	2.0×10^3	0.40	0.90	1.0×10^3	1.0×10^{-1}

The value of $n = 1.2$ is accepted as representing the gross radioactive decay of mixed fission products and is consistent with values found for PHOEBUS 1B EP-IV by the Public Health Service⁵ and by Van Vleck.⁶

Tables III and IV give the time dependent meteorological input along the trajectory. Because the observed trajectory of the effluent was quite close to the desired trajectory it turned out that the climatological input was for the same part of the

country as the observed meteorology input.

The choice of the parameters in Tables III and IV followed the same rationale as used in previous reports.^{2,15} For the climatological prediction the wind summaries of Crutcher¹⁶ and the mixing depth summaries of Holzworth¹⁷ were used. For the observed meteorology, winds and vertical temperature structure from the NATS aircraft and Weather Bureau observations were used.

Table IV. Observed Meteorological Input—February 23-26, 1967—Starting Time = 1420 PST.

Time (hr)	Ground surface elevation (km)	Cloud center elevation (km)	K_z at 1 m (cm^2/sec)	Depth of boundary layer (km)	K_z above boundary layer (cm^2/sec)	Top of mixed layer (km)	Base of inversion (km)	K_z above inversion (cm^2/sec)	Atmospheric dissipation (erg/g-sec)
0.0	1.05	2.40	3.0×10^3	0.3	2.0×10^5	2.4	2.9	1.0×10^3	1.2
0.7	1.60	3.10	4.8×10^3	0.3	2.0×10^5	3.1	3.6	1.0×10^3	1.3
1.7	1.50	3.10	4.8×10^3	0.3	1.0×10^5	3.1	3.6	1.0×10^3	1.5
3.7	1.60	3.10	5.0×10^2	0.1	5.0×10^3	1.7	3.3	1.0×10^3	0.3
5.7	1.60	3.10	5.0×10^2	0.1	5.0×10^3	1.7	3.4	1.0×10^3	0.7
7.7	1.60	3.10	5.0×10^2	0.1	5.0×10^3	1.7	3.3	1.0×10^3	0.7
9.7	1.60	3.10	5.0×10^2	0.1	5.0×10^3	1.7	3.2	1.0×10^3	0.2
11.7	1.60	3.10	5.0×10^2	0.1	5.0×10^3	1.7	3.2	1.0×10^3	0.2
13.7	1.60	3.10	5.0×10^2	0.1	5.0×10^3	1.7	3.2	1.0×10^3	0.2
15.7	1.20	3.30	5.0×10^2	0.1	5.0×10^3	1.3	3.5	1.0×10^3	0.5
17.7	1.20	3.30	1.8×10^3	0.3	1.0×10^4	1.5	3.7	1.0×10^3	0.5
19.7	1.30	3.20	3.6×10^3	0.3	1.0×10^5	1.8	4.0	1.0×10^3	1.5
21.7	1.40	3.00	3.6×10^3	0.3	2.0×10^5	3.0	4.5	1.0×10^3	1.8
23.7	1.40	3.00	3.6×10^3	0.3	2.0×10^5	3.0	5.0	1.0×10^3	1.8
25.7	1.50	3.00	2.4×10^3	0.3	1.0×10^5	3.0	5.4	1.0×10^3	3.2
27.7	1.75	3.25	5.0×10^2	0.1	1.0×10^4	1.9	5.3	1.0×10^3	1.6
29.7	2.00	3.50	5.0×10^2	0.1	2.0×10^4	2.1	5.2	1.0×10^3	1.6
31.7	2.25	3.75	5.0×10^2	0.1	2.0×10^4	2.4	5.1	1.0×10^3	1.6
33.7	2.50	4.00	1.0×10^3	0.1	2.0×10^4	2.6	5.0	1.0×10^3	3.0
35.7	2.00	3.50	5.0×10^2	0.1	2.0×10^4	2.1	5.0	1.0×10^3	3.0
37.7	1.50	3.00	5.0×10^2	0.1	1.0×10^4	1.6	5.0	1.0×10^3	1.6
39.7	1.25	3.00	5.0×10^2	0.1	1.0×10^4	1.4	5.0	1.0×10^3	1.4
41.7	1.00	3.00	2.0×10^3	0.3	1.0×10^5	1.3	4.9	1.0×10^3	0.5
43.7	1.00	3.00	3.6×10^3	0.3	1.0×10^5	1.4	4.8	1.0×10^3	1.2
45.7	1.00	3.00	3.6×10^3	0.3	1.0×10^5	1.4	4.7	1.0×10^3	1.2
47.7	0.95	3.00	3.6×10^3	0.3	1.0×10^5	1.4	4.6	1.0×10^3	1.1
49.7	0.90	3.00	1.0×10^3	0.1	1.0×10^4	1.0	4.5	1.0×10^3	1.1
51.7	0.85	3.00	1.0×10^3	0.1	1.0×10^4	1.0	4.5	1.0×10^3	1.1
53.7	0.80	3.00	5.0×10^2	0.1	1.0×10^4	0.9	4.5	1.0×10^3	1.1
55.7	0.75	3.00	5.0×10^2	0.1	1.0×10^4	0.9	4.5	1.0×10^3	1.1
57.7	0.68	3.00	5.0×10^2	0.1	1.0×10^4	0.8	4.5	1.0×10^3	1.1
59.7	0.60	3.00	5.0×10^2	0.1	1.0×10^4	0.7	4.5	1.0×10^3	1.0
61.7	0.55	3.00	5.0×10^2	0.1	1.0×10^4	0.7	4.5	1.0×10^3	1.0
63.7	0.50	3.00	2.0×10^3	0.3	1.0×10^5	0.9	4.5	1.0×10^3	1.0
65.7	0.40	3.00	3.6×10^3	0.3	1.0×10^5	0.9	4.5	1.0×10^3	1.0
67.7	0.40	3.00	3.6×10^3	0.3	1.0×10^5	1.0	4.5	1.0×10^3	0.9
69.7	0.40	3.00	3.6×10^3	0.3	1.0×10^5	1.0	4.5	1.0×10^3	0.9

Turbulent dissipation was estimated from wind speed, height of cloud above ground with a plus or minus factor of three for diurnal variation within the mixed layer. Values were somewhat weighted to be consistent with the diffusion data summarized by Crawford.²

There is instrumentation on the NATS aircraft to measure atmosphere dissipation¹⁸ but unfortunately, shortly after the cloud tracking activities commenced, the instrumentation became inoperative. It was not repairable during the subsequent cloud tracking activities. Thus, atmospheric

dissipation is also estimated in Table IV. However, in Table IV the values are consistent with the author's interpretation of the degree of aircraft turbulence experienced on the NATS plane and MacCready's¹⁸ relationship between aircraft turbulence, true air speed, and atmospheric dissipation.

Calculations done with 2BPUFF² start with a Gaussian distribution of activity about a center point concentration of unity.

Actual concentrations are obtained by multiplying the computer output by the Curie cloud burden at $H=0.1$ hr divided by the initial Gaussian cloud volume. This has been done in the following calculation and is consistent with a 3×10^6 Ci cloud burden at $H+1$ hr.

Figure 11 gives measured and computed concentrations as a function of time. The mR/hr ordinate on this figure is obtained

Fig. 11. Airborne concentration as a function of time. Solid symbols (x, •, ▲) are spot readings and open symbols are averaged data from filters. Dashed lines are calculations from February climatological input and solid lines are from observed meteorological input.

from the pCi/m^3 concentration on the left side of the figure and assuming one is in the middle of an infinitely large cloud (several mean free paths for the gamma radiation) with an average energy of 0.7 MeV. The X's are peak reading from the B-57 aircraft³ as they penetrated the cloud. These penetrations were between 1410 and 1430 PST. This time brackets the assumed H-hr of 1420 PST (the mid point of the period of release) and actually is during the reactor operation. Thus, it is not surprising that some actual values were above the predictions. It should be noted that time on Fig. 11 is time since start of diffusion calculation. The diffusion calculation is started at an H-hr time of 0.1 hr (the radioactive decay reference time). At this time the center point calculation was 3.6 R/hr.

The solid dots (Fig. 11) come from a hand-held mR/hr meter operated by PHS personnel in an Air Force plane.^{3,5} As none of the data were at levels below 1 mR/hr it can be inferred that 1 mR/hr is about the threshold of sensitivity of the measurements. All of the data are plotted; obviously some of the data are from the edges of the effluent.

The open circle at H+1.6 (Fig. 11) is based on a filter exposed by PHS,⁵ on an aircraft from 1452 to 1650 PST on February 23, 1967. The volume of air which passed through the filter was corrected to only that part of the aircraft flight path which indicated positive contact with the effluent. Thus, concentration is averaged over a long path length but one which is mostly within the cloud. By this time, cloud width was 10 to 20 km and so it is not surprising that this point lies above

the average concentration curves based on 100 and 120 km averaging path lengths.

The later PHS filter data (Fig. 11) were of two types: tracking and interval filters. Tracking filters (O) were exposed for about 40 minutes. If the gamma indication system on the aircraft showed above background exposure rates for only a fraction of the 40-minute exposure, then the air volume passing through, the filter was adjusted accordingly prior to calculating the concentration. If there was no positive gamma indication then the 40-minute air flow volume was used in calculating concentration. The interval filters (⊗) were exposed for 10 minutes.

These data all fall below the prediction in Fig. 11 and below the EG&G data points. Examination of the PHS and EG&G tracking information leads the author to believe that PHS was sampling the trailing edge of the cloud; PHS covered much the same territory as EG&G throughout Northern Nevada, Western Utah, and Southeastern Idaho but always seemed to be about 3 hours behind EG&G. This may explain why PHS values are low on Fig. 11.

The EG&G operational procedure was to fly along isopleths of radioactivity concentration (at a few times background) around the cloud until the entire cloud decayed and diffused to a concentration of only a fraction above background. At this late time cloud penetrations were made. During the tracking effort filters were exposed in order to "tag" the isotopic composition of the cloud.

The H+8.5 data point (Fig. 11) comes from a filter that was on during a momentary "accidental" penetration of a fringe of the cloud at levels of 100 to 150 times background. About 1 minute was spent at

levels about 10 times background. This was used as the basis of the air volume calculation. It is more likely than not that this "fringe" of the cloud was less concentrated than the cloud center. The filter data point at H+40 was obtained within the cloud. By this time levels were low enough so cloud penetrations were being done. However, the effluent concentrations were weak enough, perhaps 25 to 50 percent above background, so that it was difficult to be certain how much of the time during exposure of a filter was in the cloud.

EG&G continued tracking the effluent by gamma spectral identification of a few isotopes in filters out to H+68. Filter data on concentrations were obtained and reported from H+31 to H+68. With the exception of the one filter at H+40 all of the data were at the 0.2 to 1 pCi/m^3 level, and there is no consistent trend with time. Hand¹⁹ believes that only the H+40 filter data were representative of airborne concentrations; the rest contain traces of the effluent but are probably not representative of airborne concentrations. Consequently the rest of the EG&G filter data have not been plotted on Fig. 11.

From an examination of the unshielded NaI crystal detection system data on the NATS aircraft during the exposure of the H+40 filter it was found that 1 pCi/m^3 gave 3.6 counts per second (CPS) on the NaI system. This relationship and the author's notes on when peak CPS above background were observed have led to the solid ($\blacktriangle$) EG&G data points on Fig. 11. Beyond H+40 the effluent CPS values were obscured by the fluctuations of natural background.

Figure 12 is cloud radius as a function of time. The lines are different isopleths of concentration. The horizontal distance from cloud center to each concentration value is computed as a function of time for the idealized circular cloud with an initial Gaussian distribution.

Measurements are airborne estimates of cloud width.^{3,5} The scatter in the PHS data probably reflect the accuracies of the estimates. However, the group of points from H+1 to H+2.5 are consistent with a cloud edge definition of a few mR/hr—the measurement threshold of the instrumentation. The one EG&G point³ is based on tracking information across the leading edge of the effluent. The EG&G tracking effort was along an isopleth of 100 to 1000 CPS above background (or about 28 to 280 pCi/m^3).

Figure 13 is circular area enclosed by an isopleth of concentration as a function of time. The data points are from an examination of the unpublished tracking maps of EG&G. Area is defined by the 28 to 280 pCi/m^3 isopleths. Thus, the data around H+21 indicate that the cloud diffused faster than the calculation from around H+10 to H+20. This is consistent with the calculations yielding higher concentrations than measurements on Fig. 11.

The most likely cause for this difference is the large amount of wind direction change with height (see Fig. 8). This shearing effect caused by the mean change in wind direction would spread the cloud horizontally and hence permit a higher vertical diffusion rate. Lower concentrations at late times would cause the cloud, as measured by instrumentation with a finite threshold of sensitivity above background, to be smaller (see Fig. 13). The

Fig. 12. Distance to an isopleth of concentration as a function of time. Calculation based on observed meteorology.

calculational model does not include the effect of mean vertical shears in wind velocity. In this sense calculations with 2BPUFF² will be conservative.

However, it should be noted that at late times there is insufficient resolution in the aircraft data to be certain how much of the sample was taken within the cloud.

Figures 14 and 15 present two altitude spirals, computations and measured.²⁰ Abscissa labelling is consistent with the

pCi concentrations throughout this report and the EG&G 3.6 CPS/pCi/m³ relationship.

As noted on Fig. 14, the aircraft was along the northeast edge of the effluent so it is not surprising that concentrations are almost two orders of magnitude below that at the cloud center. The fact that the computed profile is much smoother with height than the observed is probably related to the aircraft being at the cloud

Fig. 13. Area enclosed by an isopleth of concentration as a function of time. Calculation based on observed meteorology.

edge and because of the use of vertical diffusivities determined from previous meteorological studies using towers which had sample times larger than the time required for an altitude spiral.

The shapes on Fig. 15 are similar although the magnitudes are different. Again the altitude spiral was not in the cloud center and the earlier comment, reference Figs. 11 to 13 still applies.

Fig. 14. Concentration as a function of height at H+8.

Fig. 15. Concentration as a function of height at H+22

Conclusions

Calculations of concentrations and cloud size are generally consistent with available observations out to H+40. Beyond that time there is insufficient resolution in the data to make any definite statements. Although the details are different there is little difference in the gross calculated features from the climatological or from the observed meteorology calculations.

Calculations of concentrations and cloud size around H+20 as compared to

measurements indicate the calculated cloud may be a factor of 2 to 5 more concentrated than measurements. The most likely explanation for this difference is the large amount of change in mean wind direction (0/thousand feet) with height through the depth of the cloud. The increased dilution due to this effect is not included in the calculation. In this respect calculations with 2BPUFF² will be conservative.

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