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## ABSTRACT

In order to assess the impact of a potential atmospheric release of radionuclides from the National Medical Cyclotron facility in Camperdown, N.S.W., an atmospheric tracer release, sampling and analysis system using $SF_6$ was developed. During eight experiments conducted in a variety of meteorological conditions, ten samplers were located in the vicinity of the Cyclotron building in order to sample the 15 minute $SF_6$ release. The experiments indicated a strong influence of the Cyclotron building and other nearby buildings on the rapid downward movement of the tracer gas plume. The atmospheric dilution factors which lead to the highest observed air concentrations were then applied to the releases of $I^{123}$ and $Xe^{123}$ from a potential accident scenario in order to assess the impact on nearby receptors. Even given the conservative assumptions about the release of $I^{123}$, the estimated radiation doses were at least an order of magnitude below the international standards for doses to members of the public.

CONTENTS

## 1. INTRODUCTION

The National Medical Cyclotron is located close to the Royal Prince Alfred Hospital (RPAH) in Camperdown, N.S.W. in order to produce short-lived medical radio-isotopes for use in Positron Emission Tomography (PET). Surrounding the Cyclotron building there is a complexity of other buildings of differing heights and at various distances (Figure 1) which will exert influences on the local atmospheric dispersion meteorology. It is the purpose of this report to discuss the attempts to measure the local atmospheric dilution factors as a function of the prevailing meteorology and to apply these factors to potential accidental releases from the Cyclotron in order to assess the radiological impacts on the surrounding community.

In attempting to define an experimental methodology to allow measurement of atmospheric dilution factors in a complex urban area there are a number of different approaches which have been used. One option is try to use numerical or other computer models adapted from simpler environments to predict the atmospheric dispersion. An investigation is currently underway to use one such numerical model with information on the building locations around the Cyclotron. Another option is to construct a physical model of the site and to undertake wind tunnel tests with tracer release simulations and sampling downwind at critical receptor locations (e.g. Hosker 1984, Meroney et al 1980). Wind tunnel tests have been used for study of dispersion around individual buildings as well as in more complex building environments. Usually they are quite expensive to undertake, mainly due to the labour intensive model construction. In any case it is also necessary to conduct *in-situ* meteorological measurements in order to define the climatological influences on wind and atmospheric dispersion meteorology parameters.

For these reasons, it was decided to undertake *in-situ* atmospheric dilution measurements using the atmospheric tracer gas, sulphur hexafluoride ($SF_6$). At the same time a longer term meteorological monitoring program was established (Clark and Bartsch 1994). The background wind flows were measured using a station on the Queen Mary Nursing Home (QMNH) (Figure 1) and the local winds were monitored above the Cyclotron with a second station. In the following discussion it will be shown that while this approach allows measurements of real normalised concentrations, without any assumptions being required for translation of wind tunnel derived results to the actual real-world situation, there are still questions about how representative a relatively small number of experiments is in terms of all possible meteorological conditions.

In the following report there will be a discussion on the influences of buildings on wind flow and atmospheric dilution patterns. Then a description of the experimental methodology used at the Cyclotron will precede a more detailed discussion of the eight field experiments. In the final section there will be an assessment of the radiological impact of a potential accidental release of radionuclides from the Cyclotron.

## 2. BUILDING INFLUENCES ON WIND AND ATMOSPHERIC DILUTION MEASUREMENTS

There is an extensive literature on the behaviour of wind and turbulence patterns around simplified building shapes which has been well summarised by Hosker (1984), among others. When wind profiles typical of the atmospheric boundary layer are incident on sharp edged three-dimensional buildings, turbulent wakes, cavity zones and vortices are generated. These are schematically represented in Figure 2 (Hosker 1984). This building induced turbulence is also illustrated by Wilson (1977) who emphasized the importance of the location of the chimney relative to the roof circulation zone in which there can be a reverse direction of air movements compared to the incident wind direction (Figure 3). The length of the cavity zone downwind of an obstacle varies according to the the shape of the building and its orientation to the wind. In some cases the wake cavity extended to downwind distances of 80 times the building height (H). Hansen and Cermak (1975) have also shown that an observed maximum mean velocity defect (compared to the incident wind speed) decays downwind (x) of the building as $(x/H)^{-\frac{3}{2}}$. It is obvious that the modifications to free flow conditions with the generation of wakes, cavities and vortices will have important effects on effluent dispersion in the vicinity of the National Medical Cyclotron building, given the proximity of other buildings (Figure 1).

Koga and Way (1979) have investigated the influence of chimney stack height, stack location on the building and effluent discharge velocity on downwind patterns of plume behaviour. They identified four different patterns ranging from an escaped to a fully downwashed plume using smoke visualisation and helium releases in wind tunnel experiments. It was shown that variation of the stack location on the roof from the leading edge to leeward position can cause variations of factors of three in the maximum ground level concentration. A general conclusion for squat buildings was to position the stack near the centre of the building in order to minimise the impact on downwind ground level locations. If the stack needs to be near the building edge then it is best that the stack be at least 2 to 2.5 times the building height. This rule would overcome the real-world problem of variable wind directions and the requirement of identification of a leeward side to the building in determination of optimum stack location. Given the height and location of the chimney stack on the NMC building, it is likely there could be significant plume downwash under particular wind direction regimes.

The reports above refer to flow around single buildings but when clusters of buildings are studied then the situation becomes extremely complex. Cermak, Lombardi and Thompson (1974) have measured pollutant concentration profiles in a urban street canyon with the wind incident at different angles. They found that aligning a street canyon at 45° to the incident wind direction could lower concentrations in the lee of the upwind building by up to a factor of two. Atmospheric stability also may have an important influence both in terms of the effect of convective turbulence on the persistence of mechanical turbulence effects downwind of a building and the possible thermal/convective impacts of buildings heated by the solar radiation during the day. Under stable atmospheric conditions when there is significant horizontal meandering of the wind, the effect of building wake phenomena may be masked by the ambient turbulence (Start et al 1977). With building clusters Cagnetti (1975) found that at sites downwind of the building wake effects, effluent air concentrations were decreased by factors of between two and four over open terrain values.

In a study very similar to the current study, Scofield (1986) used wind tunnel measurements and *in-situ* $SF_6$ atmospheric tracer gas releases to investigate the atmospheric dispersion of emissions from the University of Michigan cyclotron building. The air concentration measurements at ventilation system intakes and at ground level revealed that stack concentrations were reduced by factors of between $10^3$ and $1.3x10^4$ respectively. It was speculated that building turbulence and heat island circulation systems could have lead to these observations. Of course each site has its own unique building geometry and influences and the direction of the wind will be important in determining how the structures interact with the chimney stack emissions. Reference will also be made to the Scofield (1986) studies in the following description of the field studies conducted at the National Medical Cyclotron.

## 3. ATMOSPHERIC TRACER TEST METHODOLOGY

After discussions with personnel from the National Medical Cyclotron (NMC) about possible accident scenarios (Barnes 1993a), it was decided to release $SF_6$ into the chimney stack for a period of 15 minutes in order to simulate an accident; this will be discussed in more detail in a following section. It was also stated that the medical isotope production schedule which would result in a Maximum Credible Accident (MCA) was likely to occur sometime between 1200 and 2400 EST. This scenario determined when most of the tracer release experiments were conducted.

The 15 minute releases were timed to coincide with the averaging times of the meteorological data acquisition systems (Clark and Bartsch 1994). The $SF_6$ gas cylinder was placed on an electronic balance with a sensitivity of 20g and the weight changes noted during the release. A Bronkhorst High-Tech electronic mass flow controller was used to control the flow of $SF_6$ from the cylinder. In order to purge the release lines of any residual $SF_6$ and to allow the mass flow controller to reach equilibrium, high purity, oxygen free dry nitrogen gas was attached to the controller for some minutes prior to the start of each release and for some time after the conclusion of the experiment. A rotameter in the output line allowed the amount of $SF_6$ to be determined during each experiment and was compared to the balance measurements. In general, about 0.64kg of $SF_6$ was released during each 15 minute experiment. The temperature and efflux velocity of the stack gases were measured during some of the tests. It was observed that there was quite turbulent mixing in the chimney with velocities varying from 16 to 20 m $s^{-1}$. The temperatures were near environmental values and for the purposes of subsequent plume rise calulations the chimney stack gases were considered to be of neutral buoyancy.

Ten samplers with pump rates of the order of 1.5 l $min^{-1}$ were deployed at a number of locations and pre-programmed simultaneously with the $SF_6$ release to start pumping air into Tedlar bags for a period of 20 minutes. A sampling time of 20 minutes was used to allow the tracer to clear the sampling network. Also the programmable Gilian HFS 513 air samplers had only a minimum time resolution of 10 minutes; the SKC air samplers (Model No. SKC 224-PCEX7) which were also used could be programmed to a resolution of one minute. The range and number of the sampler locations [as indicated in Figure 4 by an asterisk (*)] were determined by the wind direction prevailing at the time of the release and the presence of so-called critical receptors, where people are present for long periods of time. At the conclusion of each release the bags were collected and returned to the laboratory in the NMC building for immediate analysis.

A Varian 3400 gas chromatograph with electron capture detector was used to analyse the bag samples for $SF_6$. Samples are introduced via a loop onto a GS-Molesieve PLOT column (30m x 0.53mm) (J & W Scientific, Folsom, California, U.S.A.) operating at 50°C with a linear flow rate (Helium) of 24 cm $s^{-1}$. The chromatograph was calibrated by dilution of a 10 ppm standard $SF_6$ gas sample into Tedlar bags. The gas release rates were determined so that the ~110 μL sampling loop on the chromatograph could be used to give air concentrations between approximately 10 ppt and 0.1 ppm. The upper range of concentrations (0.1 ppm) was not exceeded during the field tests. The lower limit of 10 ppt determined with the current settings of the GC will hereafter be referred to in this report as the GC threshold. The method of analysis was to initially calibrate the chromatograph using three standards and then to proceed through the bag samples before repeating the calibrations at the end of a batch. Before each new sample containing $SF_6$, the sample loop was purged with about 100 ml of oxygen free dry nitrogen gas using a hypodermic syringe. At least two analyses of each sample were completed to ensure consistency. Using the computer software supplied by Delta Systems, at the end of each 60 minute analysis period a chromatogram [GC reponse (V) versus time (seconds)] was produced with quantitative information on the $SF_6$ peak areas (V sec). These were averaged for each bag and calibration factors were applied at the end of the day in order that $SF_6$ concentrations (ppt) could be determined. It usually took at least two to three hours to analyse ten bag samples. During this period, previously exposed bags were emptied of gas and flushed with at least 80 litres of dry nitrogen gas in order to clean them or to return the concentrations to levels below the minimum detectable limits of the gas chromatograph. With these procedures only two releases were possible each study day.

## 4. EXPERIMENTAL RESULTS

In tables which summarise each experiment dealing with the $SF_6$ tracer releases the following data are presented :

1. The experiment number.

2. Cyclotron chimney location.
3. The release date, start and end times.
4. $SF_6$ release rate.
5. Average wind speed (designated ubar - $ms^{-1}$), wind direction (°), standard deviation of wind direction ($\sigma_\theta$) (designated sigma - °) and temperature (°C) for both the Cylotron and QMNH meteorological stations during the 15 minute release.
6. Pasquill stability category based on measurements of the average wind speed (ubar) and $\sigma_\theta$ (sigma) on QMNH using the Mitchell and Timbre (1979) method; see Clark and Bartsch (1994) for a more detailed discussion on the climatology of $\sigma_\theta$ at this site.
7. Sampler number and location with respect to the co-odinate system in Figure 4.
8. The direct (line-of-sight) distance between the chimney and sampler location.
9. $SF_6$ air concentration (g $m^{-3}$) and normalised concentration ($m^{-2}$) - see below.
10. Plume rise (m) due to no building influences (Briggs 1984) and building influences (Wilson 1977) - see below.

The normalised concentration in the Tables is given by :

$$\frac{\chi u}{Q}$$

where : $\chi$ = air concentration (g $m^{-3}$).
u = wind speed (m $s^{-1}$)
Q = release rate (g $s^{-1}$)

Normalisation of the air concentration with respect to the release rate and wind speed is a convenient concept (Turner 1970, Draxler 1984) which allows actual air concentrations to be calculated provided Q and u are known. The normalised concentration will be used later in assessment of the impact of a potential accident at the Cyclotron.

The indicative rise of the plume from the Cyclotron chimney is given by formula 8.56 in Briggs (1984) where the plume is considered to be a bent over jet (no buoyancy) rising into a cross wind without any building influences. The building influenced plume rise in the tables is taken from formula 6 in Wilson (1977) which was adapted from Briggs (1969).

Unfortunately it was only discovered after the experiments (when the anemometer was removed for calibration) that there was a problem with the wind direction measurements on the Cyclotron; the wind vane shaft had loosened from the 360° rotating potentiometer. For this reason, the values appearing in the following tables for the average wind direction and $\sigma_\theta$ have been coded as 999.

**4.1 Experiment No. 1 : 300893 - 2100 to 2115 EST**

The wind during Experiment No. 1 was generally from the north-east sector with low speeds on both the Cyclotron building roof ($1.5 ms^{-1}$) and Queen Mary Nursing Home (QMNH) roof ($2.5\ ms^{-1}$) (Table 1). The bag at the location 1 (see Figure 4) proved to have a leak and there was a valve opening problem with a bag at the upwind location 25 which lead to no data being available from these positions. A comparison of sampler positions 3 (5th floor of the QMNH, at Cyclotron chimney stack level) and position 4 (15th floor on QMNH) indicates that the initial plume rise with the prevailing winds took the tracer to quite high altitudes which is confirmed by the plume rise calculations in Table 1. During this test the highest concentration was observed at the upper location on QMNH. However, within 150 m after interaction of the plume with the Nursing Home there was significant downwash of $SF_6$ in the wake of the building with the second highest concentrations being observed at location 10 near the corner of Grose and Church Streets to the west-south-west of the Cyclotron. There was also a reasonably high air concentration at the entrance to QMNH which indicates that this location was beyond the separation zone for eddies being formed on the south-east corner of the building and moving westwards. A significant downwards movement of the plume was also necessary. There was a small air concentration of $SF_6$ observed at location number 2 but a surprising fifth highest ranking at location number 5, directly upwind. This suggests that there was some downward movement of the plume to the west of the Cyclotron which was then advected eastwards along the street/car park to the north of the building. Similar observations will be reported in a later experiment for winds from another sector. The lowest concentration was observed at location number 8 which was positioned south-east of the chimney.

**4.2 Experiment No. 2 : 310893 - 1545 to 1600 EST**

On the following day a wind from the north-east sector prevailed with neutral (type D) atmospheric stability conditions (Table 2). With the wind speed higher at 4.6 m $s^{-1}$ on the Cyclotron and 5.9 m $s^{-1}$ on QMNH the predicted values for plume rise were much lower. This is reflected in the observed value of $SF_6$ being higher at the lower position (No. 3) on QMNH than that on the 15th floor (No. 4). On this occasion the maximum air concentrations were observed along Grose Street near the corner with Church St and outside the entrance to the QMNH. There was very little $SF_6$ observed on the north-west side of QMNH near the Child Care Centre which is one of the critical receptor locations. The main impact area was in and around QMNH. It should be noted that the occurrence of a zero air concentration in any of these tables indicates a value below the minimum detectable limit, or threshold, of the current sample loop and settings on the gas chromatograph (GC).

**4.3 Experiment No. 3 : 310893 - 2030 to 2045 EST**

A moderate north-east wind with near neutral conditions were observed during this experiment which commenced at 2030 EST (Table 2). At three locations (Nos. 1, 2 and 7) there were bags with bad leaks which meant no data were retrievable; these bags were not used previously or for any subsequent experiments. On this occasion upwind locations (Nos. 5 and 8) detected $SF_6$ values below the GC threshold. With similar winds (Cyclotron 3.8 $ms^{-1}$; QMNH 5.5 $ms^{-1}$) than earlier in the afternoon, there was slightly greater plume rise. The $SF_6$ concentrations were higher at location 4 (15th floor) than location 3 (5th floor) on QMNH. Samplers were placed at two locations judged to be directly downwind of the chimney stack, locations 11 and 14. These indicated that ground level $SF_6$ concentrations were highest at the most distant location (No.14) and lower closer to the Cyclotron. However, the concentrations were lower than those recorded earlier in the day at locations no. 9 and 10. The fourth highest concentration observed during this experiment was recorded near the Walkway at Location No.6. Once again the upwind locations (Nos. 5 and 8) recorded below threshold values.

**4.4 Experiment No. 4 : 020993 - 1500 to 1515 EST**

There were strong, gusty north-west winds observed during this experiment (Table 3). The large value of $\sigma_\theta$ (20.7°) which is more typical of light wind conditions in a non-urban environment was observed at the QMNH station with a very strong wind (9.8 m $s^{-1}$). Using the Mitchell and Timbre (1979) method this lead to a classification of the relatively unstable Pasquill stability class B during experiment no. 4. Even though the QMNH is west of the Cyclotron and somewhat upwind of the release point during this experiment, there was sufficient transport of $SF_6$ in the lee of the building for moderate air concentrations to be observed on the 5th and 15th floors. However, below threshold values were observed further upwind at both the Child Care and Endocrine Centres (Nos. 1 and also 2) and at position 7 on No. 1 Store. With a predicted plume rise of between 11.2 and 40 m the highest $SF_6$ concentration would not have been expected at location 8, in the lee of the Cyclotron building. Instead it is apparent that there is a significant interaction of the turbulent eddies generated by both the QMNH and Cyclotron buildings in rapidly mixing the $SF_6$ to near ground level at location No.8. The air concentration observed at the special location No. 16 was the second highest for this experiment. With the prevailing gusty winds there was a two orders of magnitude dilution of $SF_6$ at location No.25, within 100m downwind of location No. 8.

**4.5 Experiment No. 5 : 020993 - 2030 to 2045 EST**

Winds near ground level had moderated to 2.4 $ms^{-1}$ and were observed to be from the west-south-west whereas on QMNH were measured from the west-north-west at 4.7 $ms^{-1}$ (Table 3). The vertical stability category had become more stable to a neutral class D with the horizontal dispersion category remaining at type B from earlier in the afternoon. The permanently located samplers at positions 1 to 4 all detected below the GC threshold levels. With QMNH being directly upwind of the Cyclotron chimney on this occasion, there appeared to be no interaction of the turbulent eddies with the plume which lead to the upwind measurements of $SF_6$ observed in previous experiments. The highest air concentration was observed at location No.5 just 60 m to the north-east of the chimney. This $SF_6$ concentration was a factor of two lower than that observed earlier in the day at location No.8 when the wind speed was a factor of two higher from the north-west direction. In the evening experiment this suggests that the plume was still rising when passing over location

No.5. The third highest air concentration at location No.17 could probably be attributed to a wake cavity in the lee of the Cyclotron building. The idea of a plume rising over the closer samplers could also explain the observation of the $SF_6$ air concentration at location no. 25 being higher than that at location 8, some 100 m closer to the chimney. Turbulent dispersion and/or channeling of the plume down the carpark/road between the chimney and location 21 on Missenden Road could also account for the relatively low air concentration of $SF_6$ at this site.

**4.6 Experiment No. 6 : 060993 - 1315 to 1330 EST**

During this experiment, general observations of the Cyclotron anemometer indicated that winds were light and fluctuated from the east to south-west with the predominate direction from the south to south-east. The wind directions at chimney stack level were observed to be similar to those station on top of QMNH (Table 4). The large value of $\sigma_\theta$ on QMNH (52.8°) indicates a classification of the most dispersive Pasquill stability category type A using the Mitchell and Timbre (1979) method. These large horizontal fluctuations in the wind direction have important implications for the following discussion on the $SF_6$ measurements. By contrast, with winds from the south-south-east sector there are no building structures upwind of the Cyclotron which could cause rapid downward movement of the tracer plume.

The large fluctuations in wind direction caused all samplers to record $SF_6$ air concentrations above the threshold level on the GC. The top two concentrations were recorded on the QMNH with the highest on the 15th floor. This suggests that the occasional swing of the wind to the east may have coincided with the maximum plume rise to this level thus leading to a high instantaneous dose of $SF_6$ which integrated over 15 minutes still lead to the highest concentration. Significant near ground level concentrations were also observed at the Queen Elizabeth II Rehabilitation Centre (no. 22) and the Endocrine (no. 2) and Child Care (no. 1) Centres. The sixth highest reading during this experiment was observed across the large car park on Dunblane Street (no. 24), some 150 m from the chimney stack.

**4.7 Experiment No. 7 : 060993 - 1915 to 1930 EST**

A sea breeze from the north-east developed between Experiments 6 and 7. As the sea breeze began to wane, winds became generally light to moderate from the north-east with a speed of 2.8 m $s^{-1}$ recorded above the Cyclotron and 4.0 m $s^{-1}$ atop QMNH (Table 4). The atmospheric stability categories of type D (vertical dispersion) and type B (horizontal dispersion) indicated continuing good atmospheric dispersion conditions. The highest air concentrations of the series of $SF_6$ releases were observed during this experiment. Even though there were no larger buildings upwind of the Cyclotron, the interaction of the north-east winds with the QNMH building caused strong downward mixing of the plume so that the highest readings were measured on the Walkway within 70m, and at the entrance to QMNH, about 115m from the chimney. Without the interaction with QMNH, plume rise calculations suggest the plume should have been between 17 and 65 metres above. Samplers at location nos. 12 and 13, chosen to pick up the near centreline air concentrations recorded the third and fourth highest values during this experiment. Even though location no.6 was well south of the plume centreline, relatively high values were also recorded there. The plume apparently did not directly impact the 5th floor and 15th floor samplers on QMNH as these concentrations were lower than at the ground level samplers. However, there was still sufficient horizontal movement in eddies around the building nearer to ground level for values of $SF_6$ significantly above threshold to be recorded at locations 1 and 2.

**4.8 Experiment No. 8 : 120993 - 1100 to 1115 EST**

There was broken cloud with light to moderate south to south-west winds observed during this experiment (Table 5); there was a problem with the QMNH data acquisition system during this period which lead to a loss of data from this station. With a wind from this sector the Cyclotron chimney is near the downwind edge of the building. Under these circumstances it is possible that part of the plume could be entrained into the lee wave eddy which brings significant amounts of $SF_6$ to near ground level close to the Cyclotron building (see Figure 1). Such a scenario is supported by the observations at location no.18 and also no. 20 which is only 40m away to the north-west. Otherwise, the highest concentrations were observed near the Queen Elizabeth II Rehabilitation Centre in Lucas Street after dispersion across a complexity of building and tree surfaces.

Normally with a wind direction from the south to south-west no $SF_6$ should have been detected at locations nos. 1 and 2. However, observations at ground level in the car park immediately to the north of the Cyclotron indicated that there was a definite easterly component to the wind. This could have resulted from a funnelling effect and eddying around the north-north-east corner of the Cyclotron building with winds from the south to south-west. Similar levels of $SF_6$ were observed at locations 1, 2 and 5. The air concentrations of $SF_6$ on the QMNH building (locations 3 and 4) were about an order of magnitude lower. The GC threshold level was not exceeded at location no. 8.

**5. SUMMARY**

In order to identify trends from the atmospheric tracer studies, in Table 6 there is a summary of the first fifty observations sorted in order of air concentrations from highest to lowest. This table represents a collation of Tables 1 to 5 with the sampler location numbers the same as in Figure 4 and the meteorological data as measured by the Cyclotron and QMNH stations. The majority of the high observed air concentrations occurred with QMNH winds from the north-east direction. There are no large buildings upwind from the Cyclotron in this sector but downwind there is the influence of the Cyclotron building and the large QMNH building to cause the downward movement of the tracer gas. The normalised concentrations observed at the National Medical Cyclotron were much higher than those recorded by Scofield (1986) in a similar study at the University of Michigan Cyclotron. There the factors for near ground level receptors varied between $4 \times 10^{-6}$ and $1.3 \times 10^{-4}$, whereas with the different local geography and building influences at the NMC, the maximum normalised concentrations of $1.89 \times 10^{-3}$ at location numbers 9 and 19 were an order of magnitude higher. It is apparent in Table 5 that unless the plume impacts directly on the QMNH, with almost all wind directions observed during these studies there is downward transport of the airborne discharges to near ground level in the proximity to the Cyclotron. This observation appears to negate the idea that high stack discharge velocities (18 m $s^{-1}$) at the NMC would lead to significant plume rise and thus little chance of impaction on nearby ground level receptors.

There appears to be a major influence of turbulence induced by the Cyclotron building itself and the large QMNH building. It is apparent that these building influences can occur under light to moderate wind speeds (<3 m $s^{-1}$). The range of atmospheric stabilities encountered during these eight experiments was mainly in the neutral to unstable classes (D tc A) which probably reflects the influence of the building structures in determining the local mechanical and convective atmospheric turbulence and dispersion conditions. Even though the number of experiments was restricted, it is thought that a sufficient representation of conditions was sampled to allow an analysis of the consequences of a hypothetical accident at the NMC facility.

## 6. POTENTIAL ACCIDENT SCENARIO AND RADIOLOGICAL IMPACT ASSESSMENT

A Maximum Credible Accident (MCA) scenario has been formulated by Barnes (1993a). The following are features of the MCA :

a. A target load of 310kPa is ruptured in the Cyclotron beam room and gas is released into the vacuum system.

b. The time of release is between 1200 and 2400 EST.

c. Initially 25 Ci (9.25 x $10^{11}$ Bq) of $Xe^{123}$ and 4.8 Ci (1.78 x $10^{11}$ Bq) of $I^{123}$ are available for release.

d. All activity would be removed from the beam room and discharged to the atmosphere through the Cyclotron chimney stack within 15 minutes.

Several additional points can be made concerning the inventory of radionuclides available for release in such a scenario. In Fig.5 (Barnes 1993b) there is a plot of the decay and in-growth of radionuclides at the end of a 6 hour target irradiation in the Cyclotron. Initially in addition to 9.25 x $10^{11}$ Bq of $Xe^{123}$ and 1.78 x $10^{11}$ Bq of $I^{123}$ there is 18 Ci (6.66 x $10^{11}$ Bq) of $Cs^{123}$. Because $Cs^{123}$ has a very short half life (0.34 h) and is not listed in ICRP 30 (1979), it is considered to have no radiological impact on downwind receptors. A peak is reached in the $I^{123}$ production in the target four hours following the End of Bombardment (EOB) [see the $I^{123}$ production line in Fig. 5] when the inventory is 6.5 Ci (2.4 x $10^{11}$ Bq) of $I^{123}$ due to the in-growth from $Xe^{123}$ and decay of $I^{123}$ and 6.5 Ci (2.4 x $10^{11}$ Bq of $Xe^{123}$ itself (half life = 2.14 h). The assumption that the full inventory of radionuclides is available for release to the atmosphere is highly conservative for the following reasons :

i. Due to the severe economic penalty resulting from a loss of $Xe^{123}$ there is a system in place designed to capture >99% of any release of this gas from the ruptured target.

ii. When $I^{123}$ is released to the room it would consist of approximately equal parts of organic, elemental and other undefined chemical forms. In this situation it is likely to quickly "plate-out" or be adsorbed to walls and other surfaces in the beam room. May (1993) states that it is probable that much less than 10% of the $I^{123}$ released to the room would be available for discharge to the atmosphere.

When considering the impact of any routine or accidental release of radionuclides, it is necessary to identify the major pathways the nuclides would follow between a particular release point and the receptors. In the case of an accidental release from the Cyclotron, the major radiation doses will be received from the inhalation of radionuclides, exposure of the external whole body due to the cloud of gases in the vicinity and exposure of the skin. Till and Meyer (1983), Healy (1984), Petersen (1985) and others have discussed all the pathways which lead to total exposure of human receptors. However, at the Cyclotron, due to the short half lives of the radionuclides released ($I^{123}$ - 13.13 h; $Xe^{123}$ - 2.14h), long term exposure due to ground deposition was considered to be negligible. Also, again because of the short half lives of the radionuclides there is no possibility of biological uptake in the terrestial or aquatic food chains which could result in a significant radiation dose due to the ingestion pathway.

In order to calculate the radiation doses it is necessary to estimate the atmospheric dilution between the release point and the receptors. For this purpose the maximum normalised concentrations measured from the $SF_6$ tracer releases were used together with the prevailing meteorological parameters (Table 6). The amount of radionuclide activity available for release enabled the release rate over 15 minutes (Q) to be determined; the release rate was assumed to be uniform during this period. With a maximum normalised concentration ($\chi u/Q$) of $1.89 \times 10^{-3}$ [$m^{-2}$] and average wind speed observed at 2.8 m $s^{-1}$, the air concentration for each nuclide released could be determined. These concentrations strictly apply to locations nos. 9 and 19 but it is assumed these are the worst cases and any other location will have lower observed air concentrations. It was also assumed that the receptors are exposed for the same time as the release i.e. 15 minutes.

In order to calculate the amount of radionuclide inhaled into the body the breathing rate was taken to be $2.66 \times 10^{-4}$ $m^3s^{-1}$ (ICRP 1975). In terms of the inhalation of radioactive iodine, Petersen (1985) makes the point that a correction may be required to account for the different organ size and metabolic rates of a child when compared to an adult. Thus an enhancement factor of 1.92 was suggested for the child thyroid dose based on ICRP (1975). With knowledge of these factors together with the radionuclides which are available for release, the total activity inhaled into the body can be calculated. The inhalation dose conversion factors of $I^{123}$ (Sv $Bq^{-1}$) for individual organs (e.g. thyroid, lung, etc.) and the total effective dose conversion factor determined from tissue weighting factors (see ICRP 1992) were taken from ICRP 30 (1979). The inhalation dose rate conversion factors for $Xe^{123}$ for the individual organs and total effective dose rate conversion factors [(Sv $h^{-1}$)/(Bq $m^{-3}$)] were taken from

ICRP [1980]. The whole body dose rate conversion factors [(Sv $h^{-1}$)/(Bq $m^{-3}$)] were taken from Kocher (1983) and the skin dose rate conversion factor for $Xe^{123}$ was taken from ICRP (1980).

The results of the radiological dose assessments for an accident occurring immediately following the target irradiation and four hours after target irradiation are shown in Tables 7 and 8 respectively. The total doses at the bottom of these tables result from the addition of the contributions due to both the $I^{123}$ and $Xe^{123}$ releases. The highest total doses were observed to occur in Table 7 for the case of target rupture immediately after irradiation. The highest dose of 3.85 x $10^{-2}$ mSv to a child (from the inhalation and whole body pathways in the Cyclotron accident scenario) should be compared to the annual effective dose limit of 1 mSv which has been set for continual exposure of a member of the public (ICRP 1991). A separate dose limit of 15 mSv has been set for exposure of the skin (ICRP 1991). This can be compared to the maximum skin dose of 2.95 x $10^{-2}$ mSv from Table 7.

## 7. CONCLUSIONS

An atmospheric tracer release, sampling and analysis methodology using $SF_6$ gas has been developed and applied to study atmospheric dispersion patterns around the National Medical Cyclotron. The influence of the Cyclotron building and nearby buildings, in particular the Queen Mary Nursing Home, has caused significant downward dispersion of the tracer leading to relatively high air concentrations near ground level. However, when the measured atmospheric dilution factors are applied to a potential accident scenario which could lead to a release of $I^{123}$ and $Xe^{123}$ from the Cyclotron chimney stack, the impact on nearby receptors was calculated to be more than an order of magnitude lower than the ICRP (1991) standards for radiation doses. Even lower radiation doses might have been expected if possible mechanisms which lead to a significant reduction in the release of $I^{123}$, such as adsorption on building surfaces, had not been ignored in the calculations.

## 8. ACKNOWLEDGEMENTS

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## 9. REFERENCES

Barnes, R.K. [1993a] - Personal communication.

Barnes, R.K. [1993b] - Commercial-in-confidence.

Clark, G.H., Bartsch, F.J.K. [1994] - General aspects of the meteorology and wind flow patterns at the National Medical Cyclotron site, Camperdown, N.S.W., Australia. Report in preparation.

Briggs, G.A. [1969] - Plume rise. USAEC Critical Review Series. TID-25075.

Briggs, G.A. [1984] - Plume rise and buoyancy effects. In *Atmospheric Science and Power Production*, ed. by D. Randerson. USDOE/TIC-27601.

Cagnetti, P. [1975] - Downwind concentrations of an airborne tracer released in the neighbourhood of a building. *Atmos. Enviro.* Vol. 9, pp.739-747.

Cermak, J.E., Lombardi, D.J., Thompson, R.S. [1974] - Applications of physical modeling to the investigations of air pollution problems in urban areas. Presented at the 67th Annual Meeting of the Air Pollution Control Assocn., June 9-13, Paper No. 74-160, Denver, Colo..

Draxler, R.R. [1984] - Diffusion and transport experiments. Chapt. 9 in *Atmospheric Science and Power Production*, U.S. Dept. of Energy Report No. DOE/TIC-27601. Edited by D. Randerson.

Hansen, A.C., Cermak, J.E. [1975] - Vortex-containing wakes of surface obstacles. Colorado State Univ. Fluid Dynamics and Diffusion Laboratory Report CER75-76ACH-JEC16, Colorado State Univ., Fort Collins, Colo., U.S.A..

Healy, J.W. [1984] - Radioactive cloud dose calculations. Chapter 16 in *Atmospheric Science and Power Production.* U.S. Dept. of Energy Report No. DOE/TIC-27601. Edited by D. Randerson.

Hosker, R.P.,Jr [1984] - Flow and diffusion near obstacles. Chapter 7 in *Atmospheric Science and Power Production*, United States Dept. of Energy, DOE/TIC-27601.

ICRP [1975] - Reference man : anatomical, physiological and metabolic characteristics. International Commission on Radiological Protection, Publication 23.

ICRP [1979] - Limits for intakes of radionuclides by workers. International Commission for Radiological Protection, Publication 30, Supplement to Part 1 (Annals of the ICRP 3(1-4)).

ICRP [1980] - Limits for intakes of radionuclides by workers. International Commission for Radiological Protection, Publication 30, Supplement to Part 2 (Annals of the ICRP 5(1-6)).

ICRP [1991] - 1990 recommendations of the International Commission on Radiological Protection. Publication 60.

ICRP [1992] - 1990 recommendations of the International Commission on Radiological Protection. Users edition. Publication 60.

Kocher, D.C. [1983] - Dose-rate conversion factors for external exposure to photons and electrons. *Health Physics* **45**(3), 665-686.

Koga, D.J., Way, J.L. [1979] - Effects of stack height and position on pollutant dispersion in building wakes. Wind Eng., Proc. of the Int. Conf, 5th, Vol.2, Colo. State Uni., Fort Collins, Jul 8-14, 1979, pp1003-1017. Pergamon Press.

May, F.G. [1993] - personal communication.

Meroney, R.N., Peterka, J.A., Kothari, K.M. [1980] - Wind-tunnel measurements of dispersion and turbulence in the wakes of nuclear reactor plants. United States Regulatory Commission Report NUREG/CR-1475.

Mitchell, A.E. Jr., Timbre, K.O. [1979] - Atmospheric stability class from horizontal wind fluctuation. *Air Pollution Control Association Annual Meeting*, Cincinnati, Ohio. Paper 79-29.2.

Petersen, M.C.E. [1985] - Some dose conversion factors for airborne activity. Ansto ESD/TN-12.

Scofield, P.A [1986] - Atmospheric tracer study of the emissions from the University of Michigan Cyclotron/PET facility. Masters Thesis, University of Michigan. DOE/OR/00033 T308.

Start, G.E., Cate, J.H., Dickson, R., Ricks, N.R., Ackermann, G.R., Sagendorf, J.F. [1977] - Rancho Seko building wake effects on atmospheric diffusion. NOAA Tech. Memo. ERL-ARL-69.

Till, J.E., Meyer, H.R. [1983] - Radiological assessment. A textbook on environmental dose analysis. NUREG/CR-3332, ORNL-5968.

Turner, D.B. [1970] - Workbook of atmospheric dispersion estimates. U.S. Dept. of Health, Education and Welfare , Public Health Service Publication No. 999-AP-26.

Wilson, D.J. [1977] - Effect of vent stack height and exit velocity on exhaust gas dilution. American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE) Trans. Vol.83 (Part1).

Experiment No. 1

Cyclotron chimney map location = ( 194.2, 136.2)

Date : 300893 Start time : 2100 End time : 2115
Sulphur hexafluoride release rate = 0.738 g/s
Cyclotron Met. data : ubar = 1.5 Wind dirn. = 999.9 Sigma = 999.9 T = 14.6 deg.C
QMNH Met. data : ubar = 2.5 Wind dirn. = 38.2 Sigma = 23.0 T = 14.1 deg.C
QMNH Pasquill stability category - vertical : F horizontal : A

| | Sampler Location | | Chimn to Samp | | | Plume Rise | |
|---|---|---|---|---|---|---|---|
| No. | x(m) | y(m) | Dist. (m) | Concentration (g/m**3) | Normalised Conc (/m**2) | No Bldg. | Building |
| 2 | 142.5 | 166.1 | 59.7 | 0.344e-06 | 0.700e-06 | 28.5 | 65.7 |
| 3 | 143.3 | 136.8 | 50.9 | 0.541e-06 | 0.110e-05 | 27.2 | 62.5 |
| 4 | 143.3 | 136.8 | 50.9 | 0.412e-04 | 0.838e-04 | 27.2 | 62.5 |
| 5 | 242.0 | 160.8 | 53.8 | 0.836e-06 | 0.170e-05 | 27.6 | 63.6 |
| 6 | 193.5 | 84.4 | 51.8 | 0.110e-05 | 0.224e-05 | 27.3 | 62.8 |
| 10 | 12.7 | 118.9 | 182.3 | 0.317e-04 | 0.644e-04 | 40.0 | 94.0 |
| 8 | 237.5 | 107.2 | 52.1 | 0.191e-06 | 0.388e-06 | 27.3 | 62.9 |
| 9 | 83.4 | 120.9 | 111.8 | 0.246e-04 | 0.500e-04 | 34.4 | 80.3 |

Experiment No. 1, 30 August 1993 - $SF_6$ air concentrations and meteorological data.

Table 1

Experiment No. 2

Cyclotron chimney map location = ( 194.2, 136.2)

Date : 310893 Start time : 1545 End time : 1600
Sulphur hexafluoride release rate = 0.724 g/s
Cyclotron Met. data : ubar = 4.6 Wind dirn. = 999.9 Sigma = 999.9 T = 19.3 deg.C
QMNH Met. data : ubar = 5.9 Wind dirn. = 59.5 Sigma = 11.4 T = 17.7 deg.C
QMNH Pasquill stability category - vertical : D horizontal : D

| | Sampler Location | | Chimn to Samp | | | Plume Rise | |
|---|---|---|---|---|---|---|---|
| No. | x(m) | y(m) | Dist. (m) | Concentration (g/m**3) | Normalised Conc (/m**2) | No Bldg. | Building |
| 1 | 108.4 | 166.5 | 91.0 | 0.720e-05 | 0.457e-04 | 14.0 | 37.2 |
| 2 | 142.5 | 166.1 | 59.7 | 0.185e-04 | 0.117e-03 | 12.6 | 32.7 |
| 3 | 143.3 | 136.8 | 50.9 | 0.105e-03 | 0.664e-03 | 12.1 | 31.2 |
| 4 | 143.3 | 136.8 | 50.9 | 0.750e-04 | 0.477e-03 | 12.1 | 31.2 |
| 6 | 193.5 | 84.4 | 51.8 | 0.455e-04 | 0.289e-03 | 12.1 | 31.3 |
| 7 | 141.4 | 24.1 | 124.0 | 0.264e-04 | 0.168e-03 | 15.2 | 40.9 |
| 8 | 237.5 | 107.2 | 52.1 | 0.000e+00 | 0.000e+00 | 12.2 | 31.4 |
| 10 | 12.7 | 118.9 | 182.3 | 0.185e-03 | 0.117e-02 | 16.9 | 46.1 |
| 9 | 83.4 | 120.9 | 111.8 | 0.295e-03 | 0.188e-02 | 14.8 | 39.6 |

Experiment No. 3

Date : 310893 Start time : 2030 End time : 2045
Sulphur hexafluoride release rate = 0.724 g/s
Cyclotron Met. data : ubar = 3.8 Wind dirn. = 999.9 Sigma = 999.9 T = 18.6 deg.C
QMNH Met. data : ubar = 5.5 Wind dirn. = 40.9 Sigma = 13.2 T = 17.6 deg.C
QMNH Pasquill stability category - vertical : D horizontal : C

| | Sampler Location | | Chimn to Samp | | | Plume Rise | |
|---|---|---|---|---|---|---|---|
| No. | x(m) | y(m) | Dist. (m) | Concentration (g/m**3) | Normalised Conc (/m**2) | No Bldg. | Building |
| 3 | 143.3 | 136.8 | 50.9 | 0.879e-05 | 0.462e-04 | 13.9 | 35.0 |
| 4 | 143.3 | 136.8 | 50.9 | 0.308e-04 | 0.161e-03 | 13.9 | 35.0 |
| 5 | 242.0 | 160.8 | 53.8 | 0.000e+00 | 0.000e+00 | 14.1 | 35.6 |
| 6 | 193.5 | 84.4 | 51.8 | 0.646e-05 | 0.339e-04 | 13.9 | 35.2 |
| 8 | 237.5 | 107.2 | 52.1 | 0.000e+00 | 0.000e+00 | 14.0 | 35.3 |
| 11 | 129.5 | 70.3 | 92.4 | 0.283e-04 | 0.148e-03 | 16.3 | 42.0 |
| 14 | 36.2 | 57.1 | 176.7 | 0.178e-03 | 0.936e-03 | 19.5 | 51.5 |

Experiment Nos. 2 and 3, 31 August 1993 - $SF_6$ air concentrations and meteorological data.

Table 2

Experiment No. 4

Cyclotron chimney map location = ( 194.2, 136.2)

Date : 020993 Start time : 1500 End time : 1515
Sulphur hexafluoride End rate = 0.718 g/s
Cyclotron Met. data : ubar = 5.1 Wind dirn. = 999.9 Sigma = 999.9 T = 18.7 deg.C
QMNH Met. data : ubar = 9.8 Wind dirn. = 306.9 Sigma = 20.7 T = 16.6 deg.C
QMNH Pasquill stability category - vertical : B horizontal : B

| Sampler Location No. | x(m) | y(m) | Chimn to Samp Dist. (m) | Concentration (g/m**3) | Normalised Conc (/m**2) | Plume Rise No Bldg. | Plume Rise Building |
|---|---|---|---|---|---|---|---|
| 1 | 108.4 | 166.5 | 91.0 | 0.000e+00 | 0.000e+00 | 13.0 | 34.9 |
| 2 | 142.5 | 166.1 | 59.7 | 0.000e+00 | 0.000e+00 | 11.7 | 30.7 |
| 3 | 143.3 | 136.8 | 50.9 | 0.769e-05 | 0.546e-04 | 11.2 | 29.3 |
| 4 | 143.3 | 136.8 | 50.9 | 0.400e-05 | 0.284e-04 | 11.2 | 29.3 |
| 5 | 242.0 | 160.8 | 53.8 | 0.308e-05 | 0.218e-04 | 11.4 | 29.8 |
| 6 | 193.5 | 84.4 | 51.8 | 0.108e-04 | 0.764e-04 | 11.3 | 29.5 |
| 7 | 141.4 | 24.1 | 124.0 | 0.000e+00 | 0.000e+00 | 14.1 | 38.4 |
| 8 | 237.5 | 107.2 | 52.1 | 0.108e-03 | 0.764e-03 | 11.3 | 29.5 |
| 25 | 332.3 | 101.4 | 142.4 | 0.192e-05 | 0.136e-04 | 14.6 | 40.1 |
| 16 | 246.7 | 55.2 | 96.6 | 0.320e-04 | 0.227e-03 | 13.2 | 35.6 |

Experiment No. 5

Date : 020993 Start time : 2030 End time : 2045
Sulphur hexafluoride End rate = 0.724 g/s
Cyclotron Met. data : ubar = 2.4 Wind dirn. = 999.9 Sigma = 999.9 T = 13.6 deg.C
QMNH Met. data : ubar = 4.7 Wind dirn. = 283.0 Sigma = 18.4 T = 12.8 deg.C
QMNH Pasquill stability category - vertical : D horizontal : B

| Sampler Location No. | x(m) | y(m) | Chimn to Samp Dist. (m) | Concentration (g/m**3) | Normalised Conc (/m**2) | Plume Rise No Bldg. | Plume Rise Building |
|---|---|---|---|---|---|---|---|
| 1 | 108.4 | 166.5 | 91.0 | 0.000e+00 | 0.000e+00 | 22.9 | 55.8 |
| 2 | 142.5 | 166.1 | 59.7 | 0.000e+00 | 0.000e+00 | 20.3 | 48.8 |
| 3 | 143.3 | 136.8 | 50.9 | 0.000e+00 | 0.000e+00 | 19.4 | 46.5 |
| 4 | 143.3 | 136.8 | 50.9 | 0.000e+00 | 0.000e+00 | 19.4 | 46.5 |
| 5 | 242.0 | 160.8 | 53.8 | 0.560e-04 | 0.186e-03 | 19.7 | 47.3 |
| 6 | 193.5 | 84.4 | 51.8 | 0.000e+00 | 0.000e+00 | 19.5 | 46.7 |
| 21 | 255.9 | 206.8 | 93.8 | 0.203e-06 | 0.673e-06 | 23.1 | 56.3 |
| 8 | 237.5 | 107.2 | 52.1 | 0.108e-04 | 0.357e-04 | 19.5 | 46.8 |
| 25 | 332.3 | 101.4 | 142.4 | 0.228e-04 | 0.754e-04 | 26.1 | 64.3 |
| 17 | 219.5 | 139.7 | 25.6 | 0.126e-04 | 0.418e-04 | 16.0 | 37.6 |

Experiment Nos. 4 and 5, 2 September 1993 - $SF_6$ air concentrations and meteorological data.

Table 3

Experiment No. 6

Cyclotron chimney map location = ( 194.2, 136.2)

Date : 060993 Start time : 1315 End time : 1330
Sulphur hexafluoride End rate = 0.718 g/s
Cyclotron Met. data : ubar = 1.6 Wind dirn. = 999.9 Sigma = 999.9 T = 17.6 deg.C
QMNH Met. data : ubar = 1.7 Wind dirn. = 153.0 Sigma = 52.8 T = 15.6 deg.C
QMNH Pasquill stability category - vertical : A horizontal : A

| No. | Sampler Location x(m) | y(m) | Chimn to Samp Dist. (m) | Concentration (g/m**3) | Normalised Conc (/m**2) | Plume Rise No Bldg. | Building |
|---|---|---|---|---|---|---|---|
| 1 | 108.4 | 166.5 | 91.0 | 0.160e-03 | 0.356e-03 | 30.8 | 72.1 |
| 2 | 142.5 | 166.1 | 59.7 | 0.221e-03 | 0.493e-03 | 27.2 | 63.1 |
| 3 | 143.3 | 136.8 | 50.9 | 0.295e-03 | 0.658e-03 | 25.9 | 60.0 |
| 4 | 143.3 | 136.8 | 50.9 | 0.338e-03 | 0.754e-03 | 25.9 | 60.0 |
| 6 | 193.5 | 84.4 | 51.8 | 0.615e-07 | 0.137e-06 | 26.1 | 60.3 |
| 22 | 182.3 | 200.8 | 65.6 | 0.271e-03 | 0.603e-03 | 28.0 | 65.0 |
| 8 | 237.5 | 107.2 | 52.1 | 0.326e-06 | 0.726e-06 | 26.1 | 60.4 |
| 15 | 86.3 | 70.6 | 126.2 | 0.756e-05 | 0.169e-04 | 34.0 | 80.1 |
| 24 | 85.4 | 253.3 | 159.8 | 0.172e-04 | 0.384e-04 | 36.6 | 86.4 |

Experiment No. 7

Date : 060993 Start time : 1915 End time : 1930
Sulphur hexafluoride End rate = 0.711 g/s
Cyclotron Met. data : ubar = 2.8 Wind dirn. = 999.9 Sigma = 999.9 T = 14.2 deg.C
QMNH Met. data : ubar = 4.0 Wind dirn. = 58.9 Sigma = 17.6 T = 13.6 deg.C
QMNH Pasquill stability category - vertical : D horizontal : B

| No. | Sampler Location x(m) | y(m) | Chimn to Samp Dist. (m) | Concentration (g/m**3) | Normalised Conc (/m**2) | Plume Rise No Bldg. | Building |
|---|---|---|---|---|---|---|---|
| 1 | 108.4 | 166.5 | 91.0 | 0.131e-04 | 0.516e-04 | 20.4 | 50.6 |
| 2 | 142.5 | 166.1 | 59.7 | 0.461e-04 | 0.182e-03 | 18.1 | 44.4 |
| 3 | 143.3 | 136.8 | 50.9 | 0.146e-03 | 0.574e-03 | 17.3 | 42.2 |
| 4 | 143.3 | 136.8 | 50.9 | 0.160e-03 | 0.630e-03 | 17.3 | 42.2 |
| 5 | 242.0 | 160.8 | 53.8 | 0.861e-07 | 0.339e-06 | 17.6 | 43.0 |
| 6 | 193.5 | 84.4 | 51.8 | 0.235e-04 | 0.925e-04 | 17.4 | 42.5 |
| 19 | 141.4 | 98.2 | 65.0 | 0.480e-03 | 0.189e-02 | 18.5 | 45.6 |
| 9 | 83.4 | 120.9 | 111.8 | 0.480e-03 | 0.189e-02 | 21.6 | 54.0 |
| 12 | 103.8 | 71.0 | 111.4 | 0.357e-03 | 0.140e-02 | 21.6 | 53.9 |
| 13 | 32.2 | 13.7 | 203.1 | 0.308e-03 | 0.121e-02 | 25.7 | 65.2 |

Experiment Nos. 6 and 7, 6 September 1993 - $SF_6$ air concentrations and meteorological data.

Table 4

Experiment No. 8

Cyclotron chimney map location = ( 194.2, 136.2)

Date : 120993 Start time : 1100 End time : 1115
Sulphur hexafluoride release rate = 0.724 g/s
Cyclotron Met. data : ubar = 5.4 Wind dirn. = 999.9 Sigma = 999.9 T = 15.5 deg.C
QMNH Met. data : ubar = 999.9 Wind dirn. = 999.9 Sigma = 999.9 T = 999.9 deg.C
QMNH Pasquill stability category - vertical : * horizontal : *

| | Sampler Location | | Chimn to Samp | | | Plume Rise | |
|---|---|---|---|---|---|---|---|
| No. | x(m) | y(m) | Dist. (m) | Concentration (g/m**3) | Normalised Conc (/m**2) | No Bldg. | Building |
| 1 | 108.4 | 166.5 | 91.0 | 0.191e-04 | 0.142e-03 | 12.4 | 33.7 |
| 2 | 142.5 | 166.1 | 59.7 | 0.101e-04 | 0.757e-04 | 11.2 | 29.7 |
| 3 | 143.3 | 136.8 | 50.9 | 0.154e-05 | 0.115e-04 | 10.8 | 28.3 |
| 4 | 143.3 | 136.8 | 50.9 | 0.185e-06 | 0.138e-05 | 10.8 | 28.3 |
| 5 | 242.0 | 160.8 | 53.8 | 0.138e-04 | 0.103e-03 | 10.9 | 28.8 |
| 13 | 203.2 | 142.8 | 11.1 | 0.221e-03 | 0.165e-02 | 7.7 | 18.3 |
| 20 | 200.3 | 176.7 | 41.0 | 0.295e-03 | 0.220e-02 | 10.2 | 26.6 |
| 8 | 237.5 | 107.2 | 52.1 | 0.000e+00 | 0.000e+00 | 10.8 | 28.5 |
| 23 | 171.3 | 196.3 | 64.3 | 0.326e-03 | 0.243e-02 | 11.4 | 30.4 |
| 21 | 255.9 | 206.8 | 93.8 | 0.246e-03 | 0.183e-02 | 12.5 | 34.0 |

Experiment No. 8, 12 September 1993 - $SF_6$ air concentrations and meteorological data.

Table 5

| Date | Times EST. | | Samp. Loc. No. | Concn. (g/m**3) | Norm. Conc. (/m**2) | NMC Ubar m/s | QMNH Ubar m/s | QMNH Dirn. deg. | QMNH Sigma deg. | Pasq. Horiz | cat Vert |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 060993 | 1915 | 1930 | 9 | 0.4797e-03 | 0.1889e-02 | 2.8 | 4.0 | 58.9 | 17.6 | B | D |
| 060993 | 1915 | 1930 | 19 | 0.4797e-03 | 0.1889e-02 | 2.8 | 4.0 | 58.9 | 17.6 | B | D |
| 060993 | 1915 | 1930 | 12 | 0.3567e-03 | 0.1405e-02 | 2.8 | 4.0 | 58.9 | 17.6 | B | D |
| 060993 | 1315 | 1330 | 4 | 0.3382e-03 | 0.7538e-03 | 1.6 | 1.7 | 153.0 | 52.8 | A | A |
| 120993 | 1100 | 1115 | 23 | 0.3259e-03 | 0.2431e-02 | 5.4 | 999.9 | 999.9 | 999.9 | * | * |
| 060993 | 1915 | 1930 | 13 | 0.3075e-03 | 0.1211e-02 | 2.8 | 4.0 | 58.9 | 17.6 | B | D |
| 120993 | 1100 | 1115 | 20 | 0.2952e-03 | 0.2202e-02 | 5.4 | 999.9 | 999.9 | 999.9 | * | * |
| 060993 | 1315 | 1330 | 3 | 0.2952e-03 | 0.6578e-03 | 1.6 | 1.7 | 153.0 | 52.8 | A | A |
| 310893 | 1545 | 1600 | 9 | 0.2952e-03 | 0.1876e-02 | 4.6 | 5.9 | 59.5 | 11.4 | D | D |
| 060993 | 1315 | 1330 | 22 | 0.2706e-03 | 0.6030e-03 | 1.6 | 1.7 | 153.0 | 52.8 | A | A |
| 120993 | 1100 | 1115 | 21 | 0.2460e-03 | 0.1835e-02 | 5.4 | 999.9 | 999.9 | 999.9 | * | * |
| 120993 | 1100 | 1115 | 18 | 0.2214e-03 | 0.1651e-02 | 5.4 | 999.9 | 999.9 | 999.9 | * | * |
| 060993 | 1315 | 1330 | 2 | 0.2214e-03 | 0.4934e-03 | 1.6 | 1.7 | 153.0 | 52.8 | A | A |
| 310893 | 1545 | 1600 | 10 | 0.1845e-03 | 0.1172e-02 | 4.6 | 5.9 | 59.5 | 11.4 | D | D |
| 310893 | 2030 | 2045 | 14 | 0.1784e-03 | 0.9361e-03 | 3.8 | 5.5 | 40.9 | 13.2 | C | D |
| 060993 | 1915 | 1930 | 4 | 0.1599e-03 | 0.6297e-03 | 2.8 | 4.0 | 58.9 | 17.6 | B | D |
| 060993 | 1315 | 1330 | 1 | 0.1599e-03 | 0.3563e-03 | 1.6 | 1.7 | 153.0 | 52.8 | A | A |
| 060993 | 1915 | 1930 | 3 | 0.1458e-03 | 0.5740e-03 | 2.8 | 4.0 | 58.9 | 17.6 | B | D |
| 020993 | 1500 | 1515 | 8 | 0.1076e-03 | 0.7645e-03 | 5.1 | 9.8 | 306.9 | 20.7 | B | B |
| 310893 | 1545 | 1600 | 3 | 0.1046e-03 | 0.6643e-03 | 4.6 | 5.9 | 59.5 | 11.4 | D | D |
| 310893 | 1545 | 1600 | 4 | 0.7503e-04 | 0.4767e-03 | 4.6 | 5.9 | 59.5 | 11.4 | D | D |
| 020993 | 2030 | 2045 | 5 | 0.5597e-04 | 0.1855e-03 | 2.4 | 4.7 | 283.0 | 18.4 | B | D |
| 060993 | 1915 | 1930 | 2 | 0.4612e-04 | 0.1816e-03 | 2.8 | 4.0 | 58.9 | 17.6 | B | D |
| 310893 | 1545 | 1600 | 6 | 0.4551e-04 | 0.2892e-03 | 4.6 | 5.9 | 59.5 | 11.4 | D | D |
| 300893 | 2100 | 2115 | 4 | 0.4120e-04 | 0.8375e-04 | 1.5 | 2.5 | 38.2 | 23.0 | A | F |
| 020993 | 1500 | 1515 | 16 | 0.3198e-04 | 0.2272e-03 | 5.1 | 9.8 | 306.9 | 20.7 | B | B |
| 300893 | 2100 | 2115 | 10 | 0.3167e-04 | 0.6437e-04 | 1.5 | 2.5 | 38.2 | 23.0 | A | F |
| 310893 | 2030 | 2045 | 4 | 0.3075e-04 | 0.1614e-03 | 3.8 | 5.5 | 40.9 | 13.2 | C | D |
| 310893 | 2030 | 2045 | 11 | 0.2829e-04 | 0.1485e-03 | 3.8 | 5.5 | 40.9 | 13.2 | C | D |
| 310893 | 1545 | 1600 | 7 | 0.2644e-04 | 0.1680e-03 | 4.6 | 5.9 | 59.5 | 11.4 | D | D |
| 300893 | 2100 | 2115 | 9 | 0.2460e-04 | 0.5000e-04 | 1.5 | 2.5 | 38.2 | 23.0 | A | F |
| 060993 | 1915 | 1930 | 6 | 0.2349e-04 | 0.9252e-04 | 2.8 | 4.0 | 58.9 | 17.6 | B | D |
| 020993 | 2030 | 2045 | 25 | 0.2275e-04 | 0.7543e-04 | 2.4 | 4.7 | 283.0 | 18.4 | B | D |
| 120993 | 1100 | 1115 | 1 | 0.1906e-04 | 0.1422e-03 | 5.4 | 999.9 | 999.9 | 999.9 | * | * |
| 310893 | 1545 | 1600 | 2 | 0.1845e-04 | 0.1172e-03 | 4.6 | 5.9 | 59.5 | 11.4 | D | D |
| 060993 | 1315 | 1330 | 24 | 0.1722e-04 | 0.3837e-04 | 1.6 | 1.7 | 153.0 | 52.8 | A | A |
| 120993 | 1100 | 1115 | 5 | 0.1384e-04 | 0.1032e-03 | 5.4 | 999.9 | 999.9 | 999.9 | * | * |
| 060993 | 1915 | 1930 | 1 | 0.1310e-04 | 0.5159e-04 | 2.8 | 4.0 | 58.9 | 17.6 | B | D |
| 020993 | 2030 | 2045 | 17 | 0.1261e-04 | 0.4179e-04 | 2.4 | 4.7 | 283.0 | 18.4 | B | D |
| 020993 | 2030 | 2045 | 8 | 0.1076e-04 | 0.3568e-04 | 2.4 | 4.7 | 283.0 | 18.4 | B | D |
| 020993 | 1500 | 1515 | 6 | 0.1076e-04 | 0.7645e-04 | 5.1 | 9.8 | 306.9 | 20.7 | B | B |
| 120993 | 1100 | 1115 | 2 | 0.1015e-04 | 0.7569e-04 | 5.4 | 999.9 | 999.9 | 999.9 | * | * |
| 310893 | 2030 | 2045 | 3 | 0.8795e-05 | 0.4616e-04 | 3.8 | 5.5 | 40.9 | 13.2 | C | D |
| 020993 | 1500 | 1515 | 3 | 0.7688e-05 | 0.5460e-04 | 5.1 | 9.8 | 306.9 | 20.7 | B | B |
| 060993 | 1315 | 1330 | 15 | 0.7565e-05 | 0.1686e-04 | 1.6 | 1.7 | 153.0 | 52.8 | A | A |
| 310893 | 1545 | 1600 | 1 | 0.7196e-05 | 0.4572e-04 | 4.6 | 5.9 | 59.5 | 11.4 | D | D |
| 310893 | 2030 | 2045 | 6 | 0.6458e-05 | 0.3389e-04 | 3.8 | 5.5 | 40.9 | 13.2 | C | D |
| 020993 | 1500 | 1515 | 4 | 0.3998e-05 | 0.2839e-04 | 5.1 | 9.8 | 306.9 | 20.7 | B | B |
| 020993 | 1500 | 1515 | 5 | 0.3075e-05 | 0.2184e-04 | 5.1 | 9.8 | 306.9 | 20.7 | B | B |
| 020993 | 1500 | 1515 | 25 | 0.1919e-05 | 0.1363e-04 | 5.1 | 9.8 | 306.9 | 20.7 | B | B |

$SF_6$ air concentrations ranked from highest to lowest for all experiments combined, together with meteorological data.

Table 6

Accident scenario : 0 hours after target irradiation

RADIONUCLIDE : I123 Activity = 1.78e+11 Bq
Air concentration = 1.33e+05 Bq/m**3

| Dose Pathway | Receptor | | Dose Conversion Factor | Dose (mSv) |
|---|---|---|---|---|
| Inhalation | Lungs | | 0.790e-11 [Sv/Bq] | 2.52e-04 |
| | Thyroid | Adult | 0.110e-09 [Sv/Bq] | 3.51e-03 |
| | | Child | 0.110e-09 [Sv/Bq] | 6.75e-03 |
| | Total Effective | | 0.118e-09 [Sv/Bq] | 3.77e-03 |
| Whole Body | | | 0.252e-10 [(Sv/h)/(Bq/m**3)] | 8.41e-04 |
| TOTAL (Inhalation & Whole Body) | | Adult | | 4.61e-03 |
| | | Child | | 7.84e-03 |
| Skin | | | 0.000e+00 [Sv/h)/(Bq/m**3)] | 0.00e+00 |

RADIONUCLIDE : Xe123 Activity = 9.25e+11 Bq
Air concentration = 6.93e+05 Bq/m**3

| Dose Pathway | Receptor | | Dose Conversion Factor | Dose (mSv) |
|---|---|---|---|---|
| Inhalation | Lungs | | 0.120e-10 [(Sv/h)/(Bq/m**3)] | 2.08e-03 |
| | Thyroid | Adult | 0.000e+00 [(Sv/h)/(Bq/m**3)] | 0.00e+00 |
| | | Child | 0.000e+00 [(Sv/h)/(Bq/m**3)] | 0.00e+00 |
| | Total Effective | | 0.770e-10 [(Sv/h)/(Bq/m**3)] | 1.33e-02 |
| Whole Body | | | 0.997e-10 [(Sv/h)/(Bq/m**3)] | 1.73e-02 |
| TOTAL (Inhalation & Whole Body) | | Adult | | 3.06e-02 |
| | | Child | | 3.06e-02 |
| Skin | | | 0.170e-09 [Sv/h)/(Bq/m**3)] | 2.95e-02 |

TOTAL DOSES due to I123 and Xe123 via the Inhalation and Whole Body pathways is : Adult 3.52e-02 mSv
Child 3.85e-02 mSv

TOTAL Skin dose : 2.95e-02 mSv

Radiation doses for a potential accidental release from the Cyclotron - immediately after target irradiation.

Table 7

Accident scenario : 4 hours after target irradiation

RADIONUCLIDE : I123 Activity = 2.40e+11 Bq
Air concentration = 1.80e+05 Bq/m**3

| Dose Pathway | Receptor | | Dose Conversion Factor | Dose (mSv) |
|---|---|---|---|---|
| Inhalation | Lungs | | 0.790e-11 [Sv/Bq] | 3.40e-04 |
| | Thyroid | Adult | 0.110e-09 [Sv/Bq] | 4.74e-03 |
| | | Child | 0.110e-09 [Sv/Bq] | 9.10e-03 |
| | Total Effective | | 0.118e-09 [Sv/Bq] | 5.08e-03 |
| Whole Body | | | 0.252e-10 [(Sv/h)/(Bq/m**3)] | 1.13e-03 |
| TOTAL (Inhalation & Whole Body) | | Adult | | 6.22e-03 |
| | | Child | | 1.06e-02 |
| Skin | | | 0.000e+00 [Sv/h)/(Bq/m**3)] | 0.00e+00 |

RADIONUCLIDE : Xe123 Activity = 2.40e+11 Bq
Air concentration = 1.80e+05 Bq/m**3

| Dose Pathway | Receptor | | Dose Conversion Factor | Dose (mSv) |
|---|---|---|---|---|
| Inhalation | Lungs | | 0.120e-10 [(Sv/h)/(Bq/m**3)] | 5.40e-04 |
| | Thyroid | Adult | 0.000e+00 [(Sv/h)/(Bq/m**3)] | 0.00e+00 |
| | | Child | 0.000e+00 [(Sv/h)/(Bq/m**3)] | 0.00e+00 |
| | Total Effective | | 0.770e-10 [(Sv/h)/(Bq/m**3)] | 3.46e-03 |
| Whole Body | | | 0.997e-10 [(Sv/h)/(Bq/m**3)] | 4.48e-03 |
| TOTAL (Inhalation & Whole Body) | | Adult | | 7.95e-03 |
| | | Child | | 7.95e-03 |
| Skin | | | 0.170e-09 [Sv/h)/(Bq/m**3)] | 7.65e-03 |

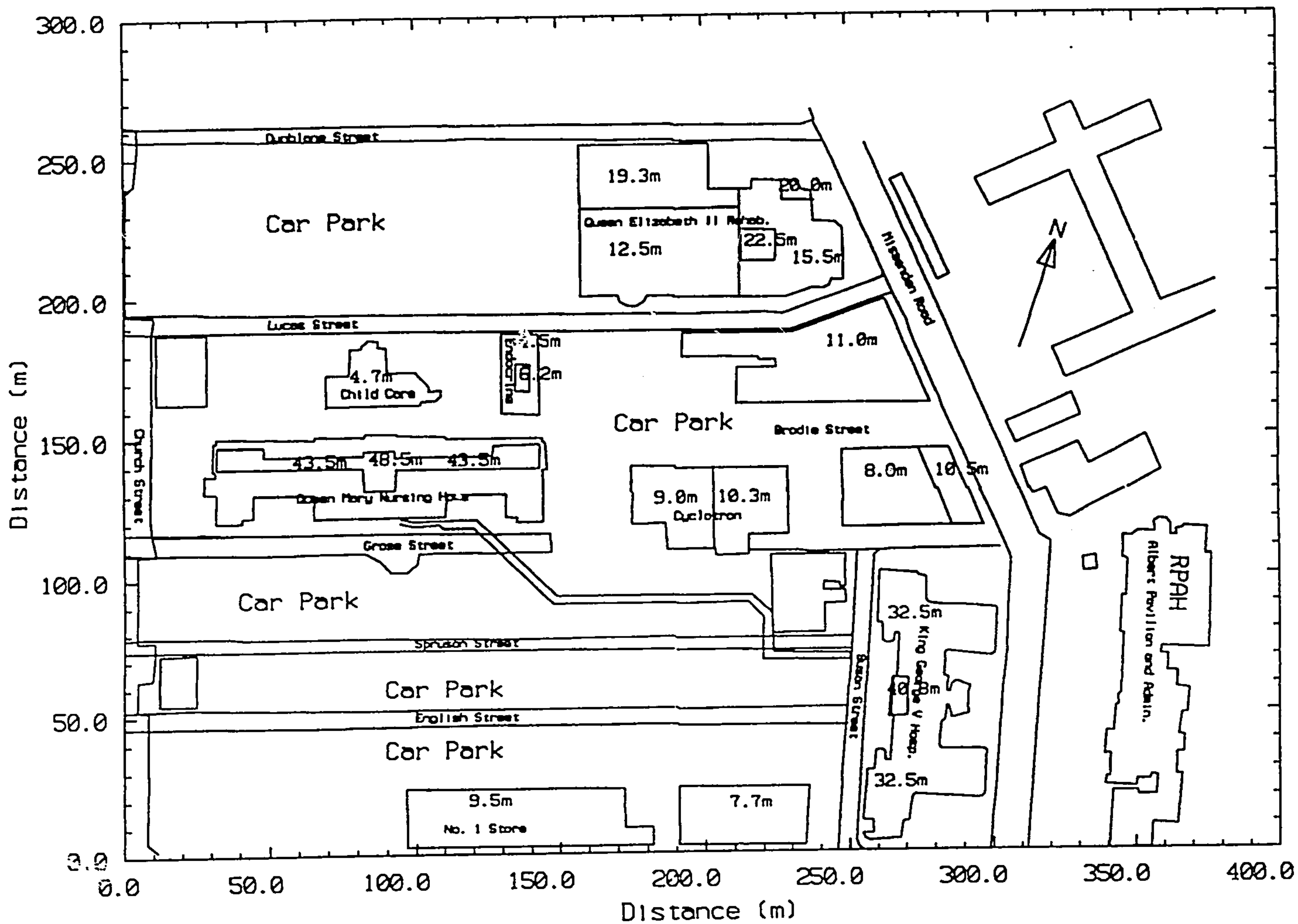
TOTAL DOSES due to I123 and Xe123 via the Inhalation and Whole Body pathways is :
Adult 1.42e-02 mSv
Child 1.85e-02 mSv

TOTAL Skin dose : 7.65e-03 mSv

Radiation doses for a potential accidental release from the Cyclotron - 4 hours after target irradiation.

Table 8

Site Plan and Building Heights




Site plan and building heights surrounding the National Medical Cyclotron

Figure 1

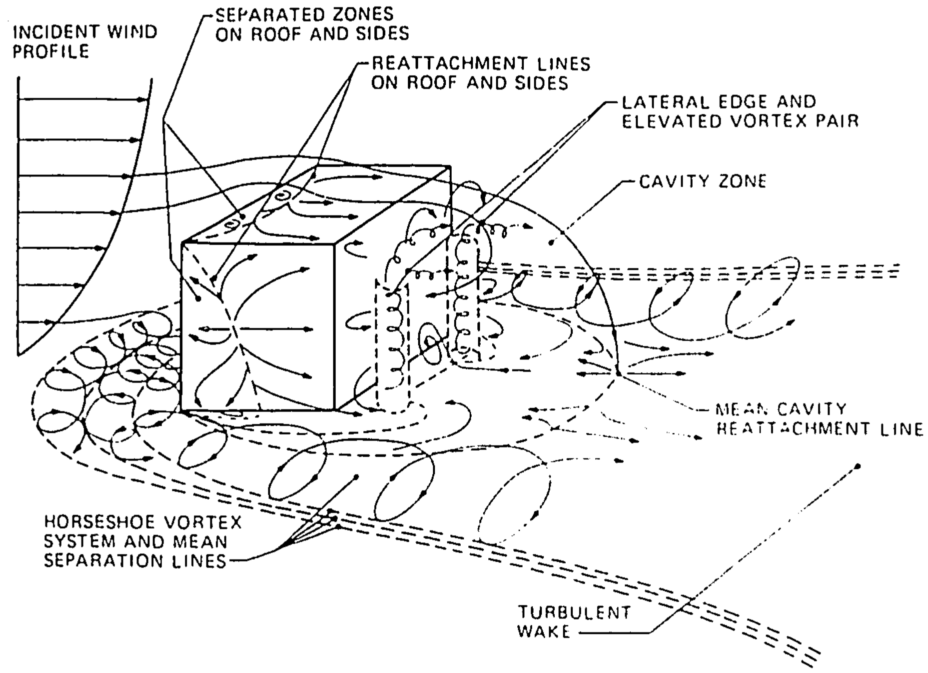



Fig. 7.15 Recent model of flow near a sharp-edged three-dimensional building in a deep boundary layer. [Based on H. G. C. Woo, J. A. Peterka, and J. E. Cermak, *Wind-Tunnel Measurements in the Wakes of Structures*, NASA Contractor Report NASA CR-2806, National Space and Aeronautics Administration, 1977; and on J. C. R. Hunt, W. H. Snyder, and R. E. Lawson, Jr., Flow Structure and Turbulent Diffusion Around a Three-Dimensional Hill, in *Fluid Modeling Study on Effects of Stratification, Part I. Flow Structure*, Report EPA-600/4-78-041, U. S. Environmental Protection Agency, 1978.]

Flow around a three-dimensional building - Figure 7.15 from Hosker (1984).

Figure 2

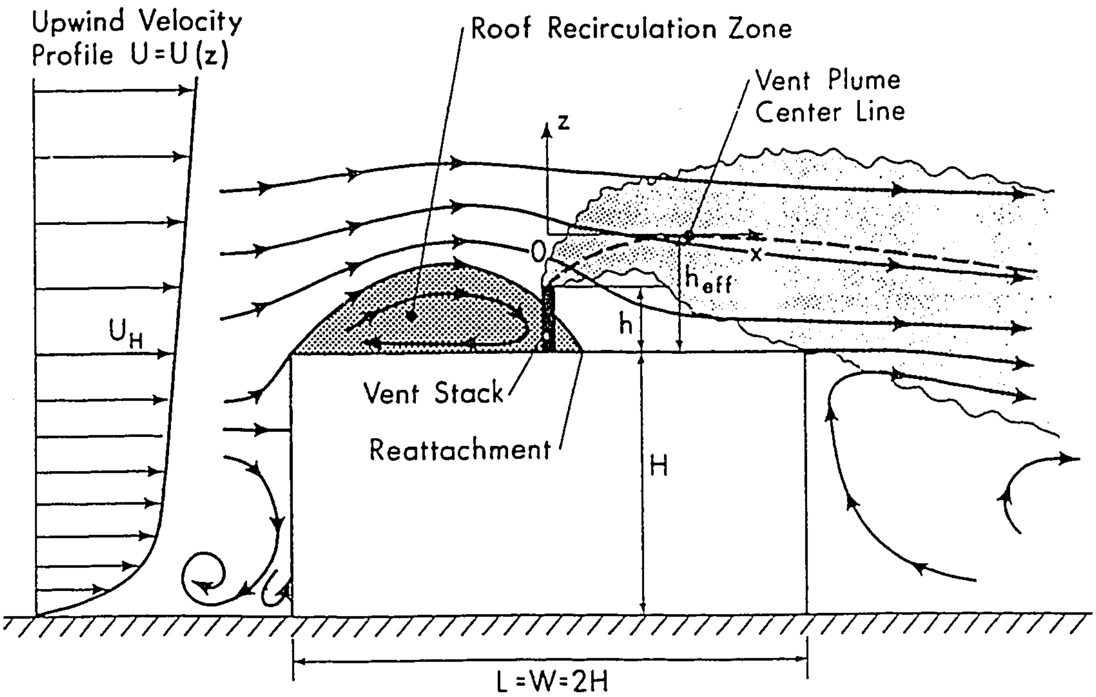



*Fig. 2 Streamlines and vent gas plume from flow visualization*

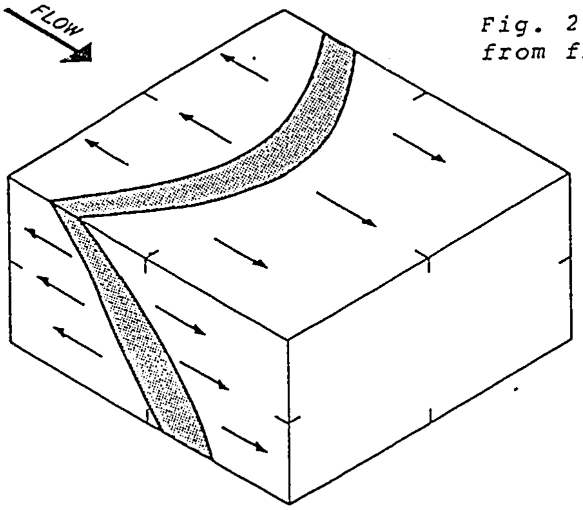
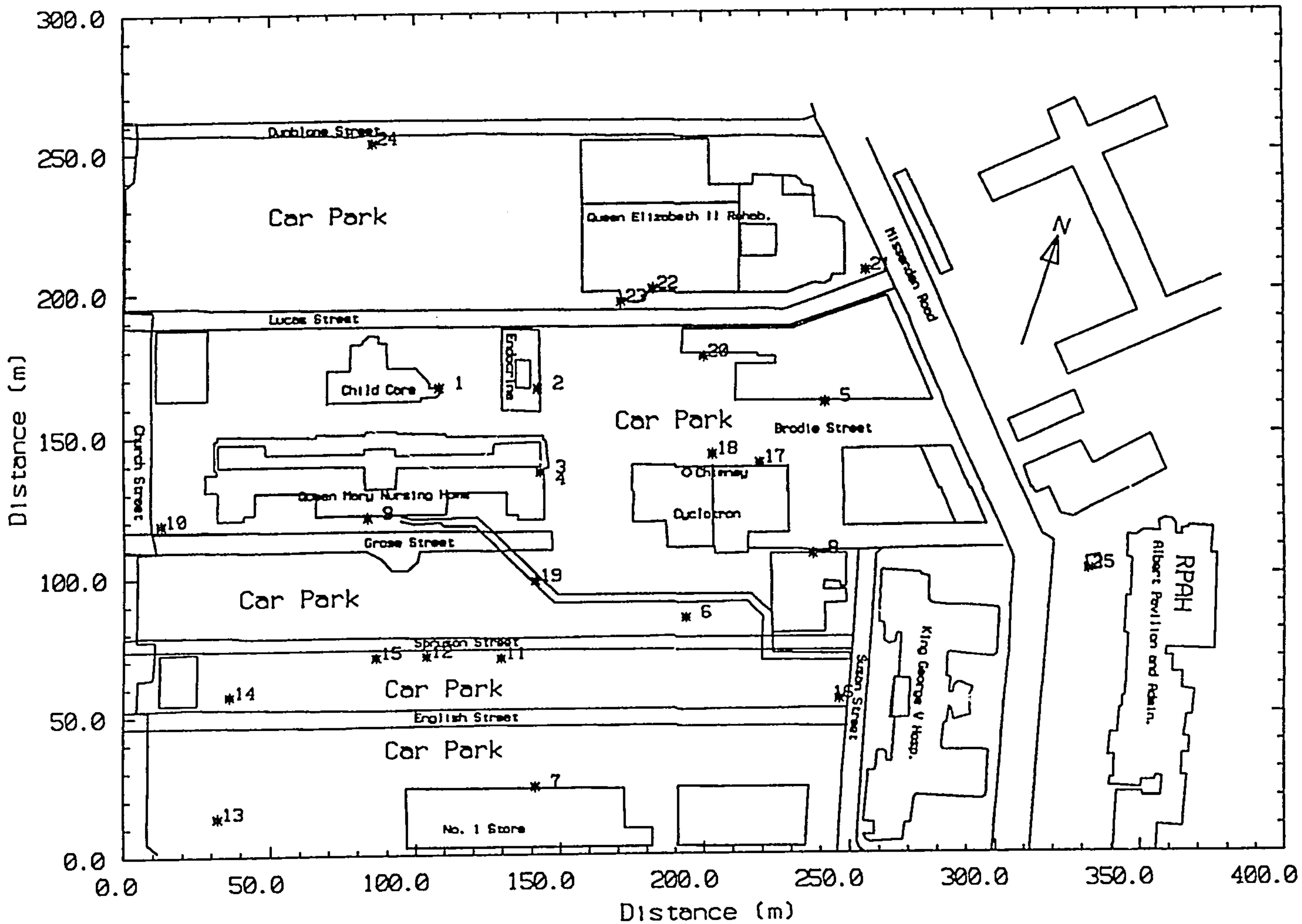



*Fig. 3 Surface flow and reattachment zones*

Streamlines and flow around buildings - Figures 2 and 3 from Wilson (1977)

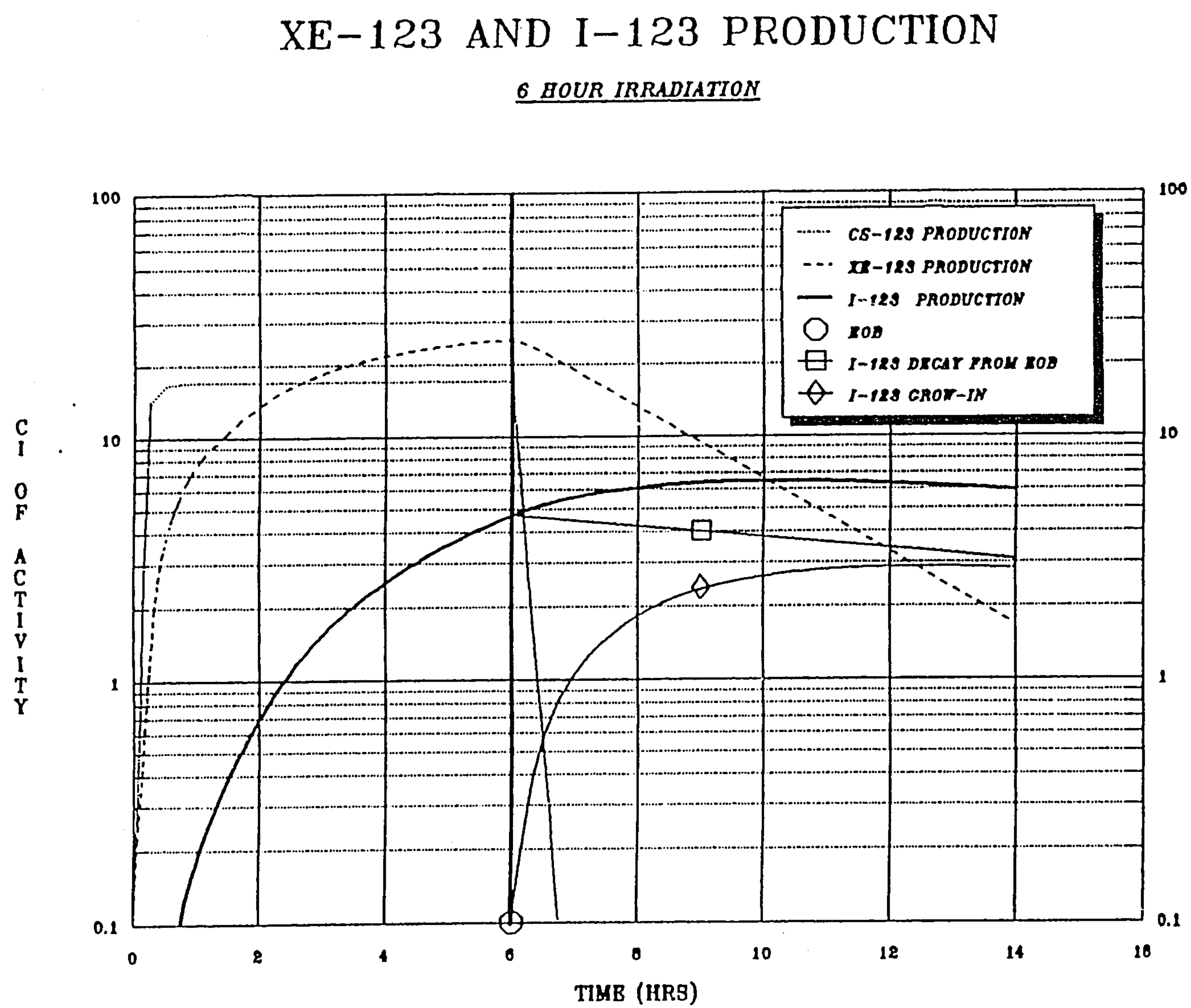
Figure 3

Site Plan and $SF_6$ Sampler Locations




Site plan and $SF_6$ sampler locations and numbers around the National Medical Cyclotron

Figure 4




$Xe^{123}$ and $I^{123}$ production in a target during and following irradiation (Barnes 1993b).

Figure 5