THE PILASTER DEPLOYMENT

MURUROA 1973

A RADIOLOGICAL REVIEW

PREPARED FOR: VETERANS' AFFAIRS NEW ZEALAND

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DISCLAIMER

CONTENTS

EXECUTIVE SUMMARY

The French nuclear weapon testing programme at Mururoa during 1973 involved five tests with explosive yields in the range of less than 1 to 20 kiloton (kt) TNT equivalent. The New Zealand Government mounted a protest mission involving the two Navy frigates, HMNZS OTAGO and HMNZS CANTERBURY. Each ship spent a month at sea, with much of that time being in the vicinity of Mururoa, and respectively witnessed the first (~ 6 kt) and second (~ 0.05 kt) tests. Because nuclear weapons were to be involved, radiological preparedness was undertaken with a comprehensive radiation monitoring programme for each ship, backed up by plans for emergency evacuation and treatment should the need have arisen.

A Radiation Officer from the National Radiation Laboratory (NRL), Mr J. F. McCahon, accompanied the ships and assumed responsibility for the on-board monitoring.

The monitoring involved continuous environmental external (gamma) radiation measurements using either equipment provided by NRL for HMNZS OTAGO, or the Ships Installed Radiac System (SIRS) for HMNZS CANTERBURY; atmospheric radioactivity monitoring; surface contamination monitoring; and personal monitoring (using thermoluminescent devices (TLDs) and film badges, and pocket dosemeters). Preparations were in place for seawater, food and drinking water monitoring if the need had arisen, which it did not. Rainwater was collected when possible for analysis later.

The only radiological record available for the deployment is McCahon's report, with other information contained in ships messages (such as news-media releases) being based on McCahon's reporting of on-board monitoring. Problems were encountered with the handling of personal dosimetry badges but these did not preclude meaningful assessments.

The on-board monitoring results indicate that crews of neither ship were exposed to significant radiation attributable to the weapon tests. The HMNZS OTAGO crew was exposed to none; with external radiation levels, atmospheric radioactivity levels, and contamination levels being essentially zero. The only difference for HMNZS CANTERBURY was that traces of atmospheric radioactivity were detected a day after the test, with this potentially delivering a small dose of less than 0.05 milliSievert. Drinking water contamination, arising from the distillation of seawater, has been discounted as a possible route of exposure.

The report concludes that due to the lower natural background radiation levels over the oceans and the lack of exposure to other sources of radiation, the crews of HMNZS OTAGO and HMNZS CANTERBURY received no more radiation exposure during their one-month deployments to Mururoa than their families did at home, and possibly less.

1. INTRODUCTION

This report was researched and prepared for Veterans' Affairs New Zealand at the request of the Hon Craig Foss, Minister of Veterans Affairs with the aim of recording, to the most accurate extent possible, details of any radiation exposure incurred by crews of HMNZS OTAGO and HMNZS CANTERBURY during their "protest voyages" to Mururoa in 1973 under an operation codenamed "PILASTER".

The report was expected to be for general rather than specialist readership, so technical detail and jargon have been limited, although some concepts and units concerning radioactivity and dose are explained.

The report does not provide general details of the voyages because those have already been thoroughly documented (Wright, 2008, 2015). It focuses strictly on issues of radiological interest.

Background information on radioactivity and radiation doses is provided in Appendix A in order to facilitate understanding of some of the concepts in the report. It is recommended that the reader becomes familiar with that material before reading further.

1.1 INFORMATION SOURCES

The following information sources were used in compilation of this report, with all references given in the References section.

Radiological data:

- The report by J F McCahon, National Radiation Laboratory (NRL) scientist on board as a radiological advisor, and official correspondence concerning that report;
- Ship-to-shore signals recorded at the time and giving details of explosions and radiation readings;
- Logbook for HMNZS OTAGO and Captain's Report (OTAGO, 1973);
- Logbook for HMNZS CANTERBURY and Captain's Report (CANTERBURY, 1973);
- Declassified Navy orders regarding radiological protection;
- NRL Environmental Radioactivity Reports;
- Various scientific reports as referenced.

General information of ships' deployment:

- Declassified Navy orders concerning the PILASTER deployment;
- Published information (Wright, 2008, 2015);
- Anecdotal information (Pearce 1973), and discussions with Cdr Peter Cozens and Dr L. Moffatt (ships' Medical Officer).

Places visited during research:

- Office of the Minister of Veterans Affairs, Parliament Buildings, Wellington;
- Defence Library, HQ NZDF, Wellington;
- Navy Museum and Archives, Devonport;
- National Radiation Laboratory;
- National Archives.

1.2 SHIPS' ORDERS

A number of zones were established in order to facilitate positioning of ships and reporting of progress, as follows (NZDF, 1973):

- Test area: centred on Mururoa test site (21°50'S 138°47'W) to a radius of 120 nautical miles.
- Observation area: A ten-mile-wide sector outside the territorial sea around Mururoa, which the ships entered when ordered to do so.
- Intermediate zone: The sea area to the west of Mururoa bordered by the true bearings 200° and 260° centred on 21°50'S, 138°47'W, and between radii 68 and 120 miles. This was the zone in which the ships "loitered" while awaiting orders to proceed to the observation area in preparation for a test.

To ensure the safety of ships and crew, instructions were issued to the effect that "*Should it be assessed that a nuclear detonation is imminent the Frigate is to select the most advantageous position in the up wind sector of the observation area to witness the detonation….The ship and her company are not to be placed in any danger from the effects of the detonation and proper NBCD precautions are to be taken*".

"France claims a territorial sea of 12 miles. This claim is accepted by New Zealand….You are not to enter French territorial waters…"

"NBCD readiness is to be such that should a nuclear explosion take place and fallout subsequently be detected in the ship's vicinity, shelter stations can be assumed and pre-wetting activated without delay".

"For a ship at a minimum distance of 12 miles up-wind from the nuclear detonation expected in the current series, the only real hazard is from thermal radiation which can produce chorioretinal burns". (Protective measures against this were detailed within the orders.)

Restriction to the above areas ensured that there was always a separation of at least 12 nautical miles between the ships and Ground Zero although, in the events, the distance was more than 20 miles.

2. WEAPON TESTS OBSERVED

Two tests were conducted at Mururoa during the operation – one observed by each ship.

The first test of the five in the 1973 series occurred on 21 July, and was observed by HMNZS OTAGO, which reported the event as follows.

Orders required that *“On detonation of a nuclear device as much as is practicable of the following information is to be reported:*

a. Time of detonation

b. Height of balloon on detonation

c. Meteorological conditions

d. Radiation levels

e. Position of other forces and protest vessels

f. Diameter of the fireball

g. Height of the nuclear cloud

h. Ship’s position course and speed.”

HMNZS OTAGO’s response on 21 July was (Ship Message 1):

A: 2211800Z

B: Estimate 2000 ft

C: Good

D: Nil

E: West of area range 20 NM from bomb

F: not known

G: 20,000 ft approx.

H: 280EE8.0

Estimate yield six kiloton.

Official French yield information was restricted to yield ranges (kt; Matthews, 1992) of:

< 1

1 – 20

20 – 200

200 – 1000

> 1000.

The test observed by HMNZS OTAGO was thus a “small” one on the yield scale, with the official yield being in the range 1 – 20 kt, later estimated at about 6 kt.

The second test occurred on 28 July during HMNZS CANTERBURY’s deployment near the observation zone. It was neither seen nor heard by those on board because it was of extremely low yield (< 1 kt, later estimated as 0.05 kt; NRL File 19/0) and obscured by low cloud (Wright, 2015). There was even doubt that a test had actually occurred, until a small uplift cloud was observed. The yield was so small that, if it were not for the fact that traces of radioactivity were detected later on HMNZS CANTERBURY, it might not have been considered to be a “nuclear” test at all. Interception of confusing signals at the time suggested that events might not have gone according to plan on the atoll (Wright, 2008, 2015); but as far as is known, it was a test of a nuclear trigger device, detonated over the north of the atoll at site “Denise”, a distance of ~40 nautical miles from HMNZS CANTERBURY (Fig. 4).

The crew were evidently disappointed because there was some expectation that they might witness a large “H-bomb” detonation, which would have been rather more spectacular.

Tests observed	
HMNZS OTAGO:	08:00, 21 July. Yield 6 kiloton
HMNZS CANTERBURY:	13:00, 28 July. Yield 0.05 kiloton

3. NUCLEAR WEAPON EFFECTS

The energy of a nuclear explosion is released with approximately 50% as blast, 35% as light (the “flash”) and thermal radiation, and 15% as “ionizing” radiation (Eisenbud, 1987). The ionizing radiation includes prompt gamma radiation and radiation arising later from fallout. Possible sources of radiation exposure following an above-ground nuclear weapon explosion are as follows:

- Prompt gamma and neutron radiation. At the instant of detonation, ionizing radiation is released in the form of gamma and x-rays, plus neutrons. This radiation is intense and hazardous but its range is limited to less than 3 km (USAEC, 1950). There were no ships within range of this radiation at Mururoa. A common misconception among some test observers is that if the flash was seen brilliantly there must have been radiation exposure too. From large tests, as witnessed during Operation Grapple, witnesses recorded they could “see the bones in their hands”. This should not be confused with radiation exposure however. Light (visible or infrared) is not absorbed appreciably by air so it travels great distances. Ionizing radiation, on the other hand, reacts with air and is absorbed by it, limiting its range. There is thus no relationship between seeing the flash and prompt radiation exposure, beyond 2-3 km from detonation.

- External radiation due to radioactive materials contained in an airborne plume downwind of the detonation. Many fission products emit gamma radiation so external exposure results from the plume containing them.

- External radiation from fallout deposited on surfaces.

- Internal exposure due to inhalation or ingestion of radioactive materials. Food ingestion was not a factor in the PILASTER deployment because all food was supplied from HMAS SUPPLY, rather than being obtained locally. The issue of drinking water is discussed in Section 6.

Regarding exposure to airborne radioactivity and fallout, it should be noted that this material decays rapidly, diminishing by a factor of about 40 between 1 and 24 hours after detonation. In addition, it disperses rapidly as the air mass containing the debris disperses and is carried downwind. Local impact depends on height of detonation and explosive yield. If the detonation occurs at ground-level, or so low that the fireball touches the ground, there is more local fallout because vaporised surface materials condense and fall out of the atmosphere locally, carrying radioactive material. In a “normal” weapon test, as conducted at Mururoa in 1973, the radioactive debris are carried aloft by the fireball, to the upper troposphere in the case of kiloton-sized detonations, or high into the stratosphere for megaton detonations. From there, for these respective cases, the material circulates to the lower atmosphere over periods of days to years, and is there subjected to removal by precipitation. It is therefore understandable that HMNZS OTAGO would not have been exposed to fallout because the yield was sufficient to ensure the cloud was well elevated. For the test viewed by HMNZS CANTERBURY, however, this would not necessarily have been the case. There, the very small yield would have resulted in little fireball lift, and the relatively small amount of radioactivity produced could well have been circulated in low altitude wind eddies before being caught in prevailing eastward winds, as indeed seems to have been the case (Section 7).

The only possible source of radiation exposure for ships in the vicinity of distant nuclear explosions would therefore be radioactive materials transported in the atmosphere or deposited on ships' decks. This could lead to internal exposure to inhaled radioactive particulates and external exposure to deposited material. For safety purposes, a monitoring programme was instituted on HMNZS OTAGO and HMNZS CANTERBURY to ensure protection against these possibilities.

Possible exposure routes:

Inhalation of airborne radioactivity

External radiation from deposited fallout

4. RADIOLOGICAL MONITORING DURING THE DEPLOYMENT

Official radiological preparations are given in Appendix B. It is clear that the radiological security of the ships and their crews was considered by the Government, and precautions were taken against even the most unlikely scenarios whereby some radiological event might have resulted in a need for evacuation and medical treatment. A Radiation Safety Officer, Mr Jim McCahon, was provided by NRL with responsibility for radiation monitoring and advisory functions. By all accounts, Mr McCahon conducted this work with the utmost thoroughness.

An intensive on-board monitoring programme was planned as detailed in Appendix B, using the following monitoring equipment for the purposes indicated:

- **External gamma radiation** monitoring on HMNZS OTAGO utilised a Geiger-Mueller gamma monitor supplied by NRL; mounted on the roof of the bridge and connected to a MK3 NRM meter (McCahon 1973). HMNZS CANTERBURY, being a more modern ship with better Chemical/Biological/Radiological/Nuclear (CBRN) protective facilities, was equipped with a **Ship's Installed Radiac System** (SIRS) of external radiation sensors. A cobalt-60 gamma-radiation source was carried for the purposes of detector calibrations, and McCahon used this to check all radiation sensors, including the SIRS.

  The detection limit for the equipment was 0.001 mSv/h (see Appendix A for unit descriptions).

  An agreed "action level" was set at 0.2 mSv/h, and McCahon considered the ships' systems to be adequate for meeting this requirement.

  Daily background readings were taken throughout the voyage, with continual monitoring after each test.

- **Airborne radioactivity** was monitored using two portable air samplers provided by NRL. The samplers were Staplex units, which drew air through glass-fibre filters (GF/A), with a sampling rate of 14 cubic feet per minute (cfm) or 0.4 m^3/min, to collect airborne particulates. These air samplers were used intermittently and on occasions for up to 48h continuously, causing motor burnout – which was overcome by kiwi ingenuity through which a vacuum cleaner was attached to the filter head, achieving about the same flow rate (NRL file, 1973). The filters were analysed using a "Radiac Set MD2", possibly with second more sensitive measurements using the "Mk 6 NHA water contamination assembly", although no separate results were given for that.

  The detection limit was 2 Bq/m^3 (50 pCi/m^3).

  Navy instructions required background readings at 24 hour intervals prior to detonation; while after detonation, readings were to be taken at intervals not exceeding 1 hour until all danger of fallout was over. Accordingly, McCahon reported that prior to the first test (21 July) one air sample was taken each day to establish background levels, and after each test a continuous series of air samples was taken for three days.

The McCahon report mentions filters being returned to NRL later for more sensitive analysis. Evidence was found that the filters were indeed returned to NRL (Yeabsley, 1973), and that there was Intelligence interest in levels of (non-radioactive) materials on the filters (which might have indicated bomb design features), but results of radiological analyses have not been found. With the passage of time after sampling, much of the fission-product radioactivity would have decayed away by the time the filters reached NRL.

- **Fresh water, seawater and food** monitoring was to be carried "out at the discretion of the NRL Officer". For this purpose Radiac Sets MD2 were available, together with Accessory Kit MK3 NAK and a Water Contamination Assembly MK6 NHA

  There is no record of such monitoring having been performed, which is not surprising considering the lack of radioactivity detected.

- **Rainwater** was collected when possible during the voyages, from exposed areas of both ships, and returned later to NRL for analysis. Although there was no fallout deposition on the ships (Section 5.3), collection of rainwater was of scientific interest to NRL as an adjunct to its routine monitoring of rainwater throughout the South Pacific (Section 8). There is no record of such analyses having been performed however. Nor is there any record in the ships' logbooks of rainfall during the days immediately before and after the tests. Anecdotal information indicates the weather was fine (Moffatt, pers. comm.).

- **Surface contamination monitoring** utilized the Radiac MD2 units in checks for surface contamination monitoring on various parts of the ships following each test (McCahon 1973).

- **Personal monitoring**: Two types of personal monitoring were conducted:

  - **Pocket dosemeters** were supplied by the Navy to be carried by selected passengers and crew, and to be read following detection of elevated radiation levels. Such dosemeters are normally carried when handling significant quantities of radioactivity or in emergency situations. They are not usually low-level environmental monitors appropriate for measuring background radiation levels. Two of the three types had ranges of up to 50 mSv or 500 mSv as mentioned in Appendix B. The underlying purpose behind their distribution might have been that they were available and already deployed if an emergency had arisen, although they were supposed to be read in "the presence of fallout or direct radiation above background". McCahon did not report readings taken from them, but did make a note in his report concerning a need for training in their use.

  - All on board were provided with personal monitors in the form of **thermoluminescent (TLD) badges** to monitor external radiation exposure. Seventy people wore **film badges** provided by NRL as well. The TLD was used with an on-board measurement system (TLD Disc Reader MK 2NDR) to provide immediate results, while the film badges were returned to NRL for measurement later. Instructions concerning analysis of the TLD badges required that if the presence of fallout or direct radiation above background level was detected, by air samplers or otherwise, following the detonation of a nuclear device, 25 TLDs were to be analysed, with selection from throughout the ship, but particularly from those who were on the upper deck or in engine room compartments. Although no such instance occurred, McCahon analysed all badges while on HMNZS CANTERBURY, at the end of the mission.

Detection limits were:	TLD: 0.2 mSv;
	Film: 0.12 mSv.

It should be noted that these types of personal monitors are not appropriate or particularly useful for monitoring low-level radiation at environmental background levels, because such levels are below the threshold for measurement. Furthermore, they record the cumulative dose from all external radiation, from whatever source, natural or otherwise, from the time they leave the laboratory until they are analysed. As with the pocket dosemeters, they are worn to record elevated doses, should such occur, and were therefore deployed during the voyage as a contingency against such an occurrence. Here, the only positive readings arose through exposure to radiation from the calibration source, as described in Section 5.4.

- **Thyroid monitoring:** Two GM counters, type MX 115, were taken on the voyage for thyroid monitoring, as a precaution against iodine-131 contamination in the event of a major incident (McCahon 1973). Potassium iodide tablets were also carried for use as a “thyroid blocker”. They were not needed.

As indicated in Appendix B, most on-board monitoring made use of equipment formerly known “Radiac” instruments. These instruments were designed primarily for military use for the purposes of alerting to and monitoring of radiation hazards in a military operational environment. They were not intended for normal Health and Safety use, such as assessing doses to individuals (MoD, 2009). Rather they were to be used by the chain of command for assessment of hazard in a military operation. Naturally, the Navy made use of such equipment and, indeed, HMNZS CANTERBURY’s SIRS was a Radiac system. Use of such equipment on the PILASTER deployment would have been deemed appropriate, and McCahon was satisfied that all systems met the requirements of the radiation protection protocols adopted for the deployment (McCahon, 1973).

Dose limits applied on the voyages are described in Appendix A.

Monitoring conducted on board:

External radiation (gamma radiation)

Atmospheric radioactivity (beta radiation)

Fallout deposition (surface contamination)

Personal dosimetry (TLD and Film)

In addition to the monitoring, full radiological precautions were taken on board. For example, on HMNZS CANTERBURY it was recorded (Cheney, 1973): "*Preparations for the test had been completed on board with the ship at action stations and N.B.C.D. State 1 Condition ZA*".

5. MONITORING RESULTS

Radiological information for the PILASTER deployment is limited to that contained in the McCahon Report (1973), based on the measurements described above. No separate radiation-related records from ships' documents were found. Cdr Cozens was of the opinion that readings from the HMNZS CANTERBURY SIRS may have been recorded in an Engineer's Logbook - the "HQ1 Logbook" (Cozens, pers. comm.). Attempts to find such a logbook in National Archives and Navy records were unsuccessful. If it did exist, it is now deemed lost. It is apparently common for extraneous logbooks and documents to be discarded over the years. McCahon made use of SIRS readings in his assessment and report, however, so the essential information is available as reported here.

The present report is thus based entirely on the McCahon report and associated correspondence, together with a reassessment of the dose calculation for the airborne radioactivity detected by HMNZS CANTERBURY. Results of radiation monitoring recorded by McCahon (1973) were as follows.

5.1 EXTERNAL RADIATION

No external gamma radiation was detected on either ship, at any time, either by the specially installed detector on HMNZS OTAGO or the SIRS on HMNZS CANTERBURY.

The dose rate from any such radiation can therefore only be expressed in terms of the detection limit of the equipment, as:

External radiation dose never exceeded 0.001 mSv/h.

This upper limit represents 0.5% of the set Action Level (0.2 mSv/h).

5.2 AIRBORNE RADIOACTIVITY

No airborne radioactivity was detected on air filters throughout the voyages of both ships except those described below. For scientific interest, McCahon arranged for all air filters to be returned to NRL for more sensitive measurements but the results of any such analyses are no longer available.

On the HMNZS CANTERBURY, traces of airborne residues of the test of 28 July were detected due to an evident circulation in the wind field such that debris were briefly carried in a south-westerly direction from the test site. This detection is likely to have resulted from insufficient buoyant plume rise (because of the very low explosive yield) to escape surface wind eddies.

McCahon reported readings as follows:

21.00 28/7 to 10.00 29/7:	average concentration 26 Bq/m^3 (700 pCi/m^3)
10.00 29/7 to 14.00 29/7:	average concentration < 0.2 Bq/m^3 (50 pCi/m^3)
14.00 29/7 to 19.00 29/7:	average concentration about 6 Bq/m^3 (150 pCi/m^3)
03.00 30/7 to 07.30 30/7:	average concentration 41 Bq/m^3 (1100 pCi/m^3)

The average concentration for the 34-hour period, 22 Bq/m^3, represents only 0.06% of the set Action Level (Appendix A.8), so there was no concern on the ship.

It was estimated that a person on the deck throughout the entire period, 21.00 on 28/7 to 07.30 on 30/7, would have received a total internal dose (due to inhaled radioactive particulates) of the order of 0.017 mSv, better expressed as < 0.02 mSv. The atmospheric radioactivity level was so low that external radiation was not of concern, with inhalation being the only vector of interest. Measurements taken after 07.30 on 30/7 showed insufficient radioactivity to change this dose estimate significantly. This estimate would, of course, have been a conservative over-estimate because crew would not have been on deck for the 34 hour period.

As part of the present review, this dose estimate was reassessed by ESR's National Centre for Radiation Science (Hermanspahn, 2015) and found to be reliable within the range of uncertainties which exists concerning the exact nature of the device, likely time spent on deck, and the analyses themselves. The new dose assessment is 0.005 mSv with a maximum based on pessimistic assumptions, of 0.05 mSv, providing a range which encompasses the initial assessment of < 0.02 mSv.

Airborne radioactivity dose (HMNZS CANTERBURY only): 0.005 – 0.05 mSv

This dose range is similar to the normal range of onshore radon exposure (Appendix A.6) for a 34-hour period, of 0.001 – 0.04 mSv. It could be said, therefore, that any dose received from the airborne radioactivity on HMNZS CANTERBURY was similar to natural doses incurred in the same time interval by people on shore.

Decay calculations and map plotting on board indicated that the debris had followed a roughly circular path of radius 60 nautical miles, travelling west, south, and east over a period of 36 hours. This can also be inferred from the chart provided in Fig. 4.

The detection of radioactivity was reported by Capt. Cheney, of HMNZS CANTERBURY (Cheney, 1973), as follows: *"At about 1000 on Sunday 29th the NRL air sampler detected radioactivity at extremely low levels. This provided excitement for the press representatives but amusement of the ship's company. The levels, which have been reported in detail by signal, reduced at about 1600 then increased once more during the night of 29th/30th. The ship proceeded to the southern part of the intermediate area on Sunday."*

The signal referred to contained the above detection details. The matter was not referred to again in the Report of Proceedings.

5.3 SURFACE CONTAMINATION

Following the above detection of airborne radioactivity, McCahon checked for surface contamination on HMNZS CANTERBURY (as would have arisen if fallout had actually been deposited on the ship). No radioactivity was detected on surfaces, indicating no deposition. “Barely detectable and harmless” traces of radioactivity were found on some intake filters for the air conditioning system, as would be expected if the filters were indeed cleaning the air properly, as evidently they were.

The filter in compartment 01G Forward showed more radioactivity than other filters – which McCahon attributed to its intake being in the highest, most exposed position, on the side of the main mast.

Because no surface contamination was detected on either ship, both were declared “clean” to the satisfaction of the Auckland Harbour Board on the ships’ return to Devonport.

Local fallout deposition: not detectable

5.4 PERSONAL MONITORING

Unfortunately, personal dosimetry by TLD badge was fraught with practical problems during the voyage. After the rendezvous with HMNZS CANTERBURY, McCahon found to his dismay that badges worn by crew of that ship had been tampered with due to lack of training, rendering most unusable. For example, badges had been taken out of their plastic envelopes, chips removed, and badges put through the laundry. In fact, only 35 of the original HMNZS CANTERBURY issue could be used. Badges worn by HMNZS OTAGO crew were transferred by helicopter to HMNZS CANTERBURY for reading there on completion of the mission. On processing, these badges were found to record doses in the range of 0.2 mSv to 2 mSv. It transpired that during the transfer by helicopter between ships, the badges travelled together with the calibration source. McCahon calculated that in one hour badges closest to the source would have received doses of “several hundred millirad” (several mSv), while those at the other end of the transport container would have received 0.2 mSv to 0.3 mSv, thus accounting for the entire dose recorded by the badges and rendering all helicoptered HMNZS OTAGO badge results invalid. The only HMNZS OTAGO badges not exposed during transfer were those worn by personnel during their own transfers. There were six of these and, of these, only two were uncompromised by exposure at some time during the voyage to the calibration source, x-ray equipment, or chemical contamination. All badges were called in for reading on 7 August, and read on 8 August. The uncertainty in readings was ± 0.2 mSv.

The only uncompromised TLD readings available were as follows:

HMNZS OTAGO: two discs, worn by Coleman and Daykin during their transfer, which gave readings of “no significant dose” (less than 0.2 mSv).

HMNZS CANTERBURY: 33 of the original issue, which gave readings of less than 0.2 mSv (the minimum reliable reading for the instrument) and averaging 0.04 mSv, which is "not significantly different from zero" (McCahon 1973). Statistics were not given for the average, so the instrument uncertainty is adopted here; i.e., the average was 0.04 ± 0.2 mSv. (Two HMNZS CANTERBURY discs, worn by Robertson and Bennetts, recorded doses of 0.20 mSv, and McCahon concluded that these were probably accurate readings, with the dose delivered while assisting with the calibration source during checking of the SIRS.) McCahon's own badge registered 1.34 mSv due to his repeated handling of the calibration source.

As McCahon noted, in spite of the above problems, and including even the highest extra dose received during transfer between ships, no dose was recorded which was more than a small fraction of the 30 mSv dose permitted for persons occupationally exposed to radiation, as adopted by the radiological protocol for the deployment (see Appendix A.8). That conclusion is valid.

In this report, it is considered that the HMNZS CANTERBURY reading of 0.04 ± 0.2 mSv is a meaningful estimate of external dose received by anyone on board either ship (other than those exposed to the calibration source).

Neither badge type distinguishes between external radiation sources, so natural background radiation was included in the final readings. A one-month voyage would result in a natural cosmic radiation dose of about 0.03 mSv (see Appendix A) so, even with the uncertainties involved, it is evident that the of 0.04 ± 0.2 mSv dose equates with normal background (cosmic radiation) exposure, and that no additional external radiation dose was contributed by the weapon tests themselves.

The film badges were duly analysed at NRL, and all were found to have no readings above the detection limit of 0.12 mSv (Faulkner, 1973). This is consistent with the above conclusion.

Given the "average" dose calculated, of 0.04 ± 0.2 mSv, and the detection limit of the film badges (0.12 mSv), it is reasonable to conclude that the total external dose, received from all sources including natural background (cosmic), was as follows:

Total one-month external exposure: < 0.12 mSv

Monitoring results

- No external radiation attributable to the tests was detected on either ship (less than 0.001 mSv/h);
- Maximum possible internal dose received by the HMNZS CANTERBURY crew during transit of the plume was less than 0.05 mSv, which is within the range of natural radon exposure on shore for the same time interval;
- There was no fallout deposition on either ship;
- The total month's external radiation dose, including natural background, was less than 0.12 mSv, with the average measured level of 0.04 mSv being accounted for by natural cosmic radiation exposure.

6. SEAWATER CONTAMINATION

Concern has been expressed over the possibility that drinking water obtained by distillation of seawater might have been contaminated by fallout radioactivity.

There are a number of factors counting against such a concern:

1. The distillation process itself safeguards against transfer of contaminants to the distillate;

2. Only traces of radioactivity were detected in the atmosphere by HMNZS CANTERBURY, for a short period;

3. No fallout deposition on the ship was detected, indicating no fallout there or in the vicinity. There was thus no contamination of intake seawater associated with the airborne radioactivity detection;

4. By the time any local fallout which might have occurred downwind of ground zero had circulated in ocean currents to where the ships had been, they would long since have departed the area; and, furthermore, significant dilution would have occurred in the process. Ocean current from the downwind “fallout zone” moved only at 2 knots (Figs 3 and 4), requiring two days or more to reach the Observation Area;

5. Due to low test yields, small amounts of local fallout (if any), mixing and dilution, any weapon-related radioactivity measureable in seawater in the Mururoa region in 1973 would have been entirely due to global fallout from earlier Northern Hemisphere tests as discussed below.

This issue can be explored by consideration of the fission product caesium-137 (^{137}Cs), which is often used as a tracer of weapons-test debris in seawater because it is produced in high yield during the nuclear fission process, is long-lived (30 year half-life), and remains in solution in salt form. Data on concentrations of ^{137}Cs in seawater in the Mururoa region are considered here, with comparisons made between different regions. Data are from the International Atomic Energy Agency (IAEA) marine studies programme (IAEA, 2005).

Concentrations of ^{137}Cs in seawater in the Mururoa region (defined here as spanning the region between about 13° - 28° S, and 122° - 152° W) over the period 1962 to 1990 are shown in Fig. 1 below, where it can be seen that the average concentration for 1973 was within the normal range for the period. The average for the entire 29-year period was 3.4 ± 1.6 Bq/m^3, while the 1973 level was 1.0 ± 1.2 Bq/m^3.

The Mururoa region is compared with other oceanic areas in Table 1 below.

The data presented here indicate that HMNZS OTAGO and HMNZS CANTERBURY would not have encountered seawater contaminated by radioactivity at levels atypical of those encountered by ships sailing in any ocean

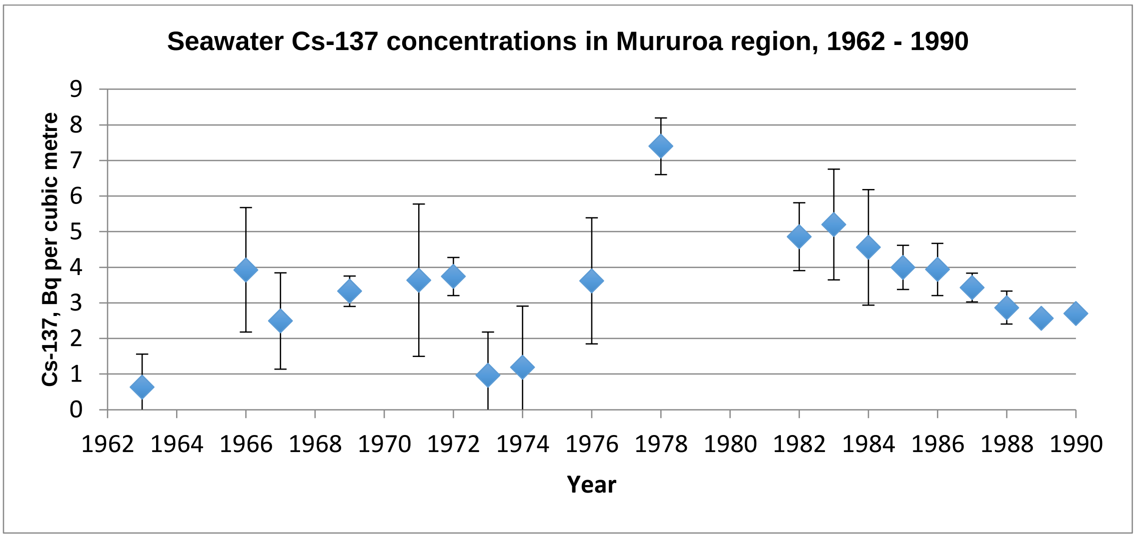

Fig. 1. Average (± standard deviation) ^{137}Cs concentrations recorded in the Mururoa region, 1962 – 1990.

Seawater ^{137}Cs concentrations during 1973		
	Average	**Standard deviation**
South Pacific	1.4	1.6
North Pacific	4.4	4.2
South Atlantic	0.4	0.8
North Atlantic	2.0	2.4
All regions (global)	3.6	4.1
Mururoa region	1.0	1.2

Table 1: A comparison of seawater ^{137}Cs concentrations between different oceanic regions in 1973.

Normal drinking water consumption of two litres per day, with a dose conversion factor of 0.000013 mSv per Bq ^{137}Cs via ingestion (Delacroix et al 2002), and a seawater ^{137}Cs concentration of 1 Bq/m^3, would result in an immeasurably small radiation dose. The following conclusion therefore applies.

Exposure to fallout radionuclides in drinking water is not a credible concern.

7. DETAILS OF SHIP MOVEMENTS

French expectations for restricted zones are indicated in Fig. 2, copied from an official French chart released when testing at Mururoa began. Movements of HMNZS OTAGO and HMNZS CANTERBURY during their respective test observations are shown in the charts reproduced in reduced format in Figs 3 and 4 (Wright, 2015a).

The ships' charts (Figs 3 and 4) indicate the following:

- At no time did either ship breach the 12-mile French territorial limit (as ordered)
- Neither ship entered the French-designated hazard zone to the east of Mururoa (Fig. 2);
- HMNZS OTAGO was 20 nautical miles (37 km) from Ground Zero at the time of detonation (Fig. 3);

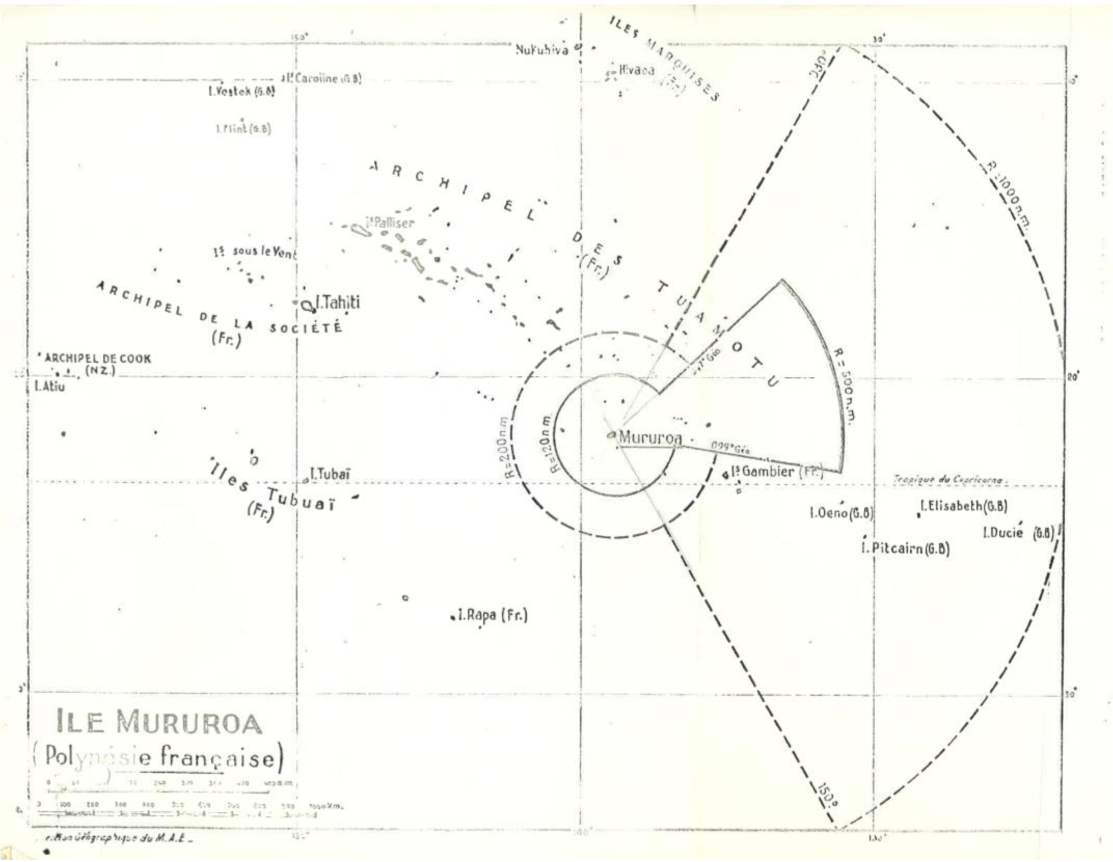

Fig. 2: A copy of the official French chart showing restricted zones, and highlighting the "fallout zone" to the east of Mururoa.

- HMNZS CANTERBURY was 41 nautical miles (76 km) from Ground Zero at the time of detonation (Fig. 4);
- Both ships were well beyond the range of prompt gamma radiation from the weapons (Section 3);
- Both ships were in surface upwind positions at the time of the detonations;
- The position of HMNZS CANTERBURY at detonation, outside the Observation Zone, is explained by the prudent decision of the Captain to follow the French ships to their own designated safe area, it having become apparent that a problem had arisen at the test site – HMNZS CANTERBURY thus joined the ships clustered in a safe zone, at action stations (CANTERBURY, 1973);
- At the time HMNZS CANTERBURY encountered the test plume it was about 90 nautical miles (170 km) from Ground Zero, about 20 – 40 hours after the test.

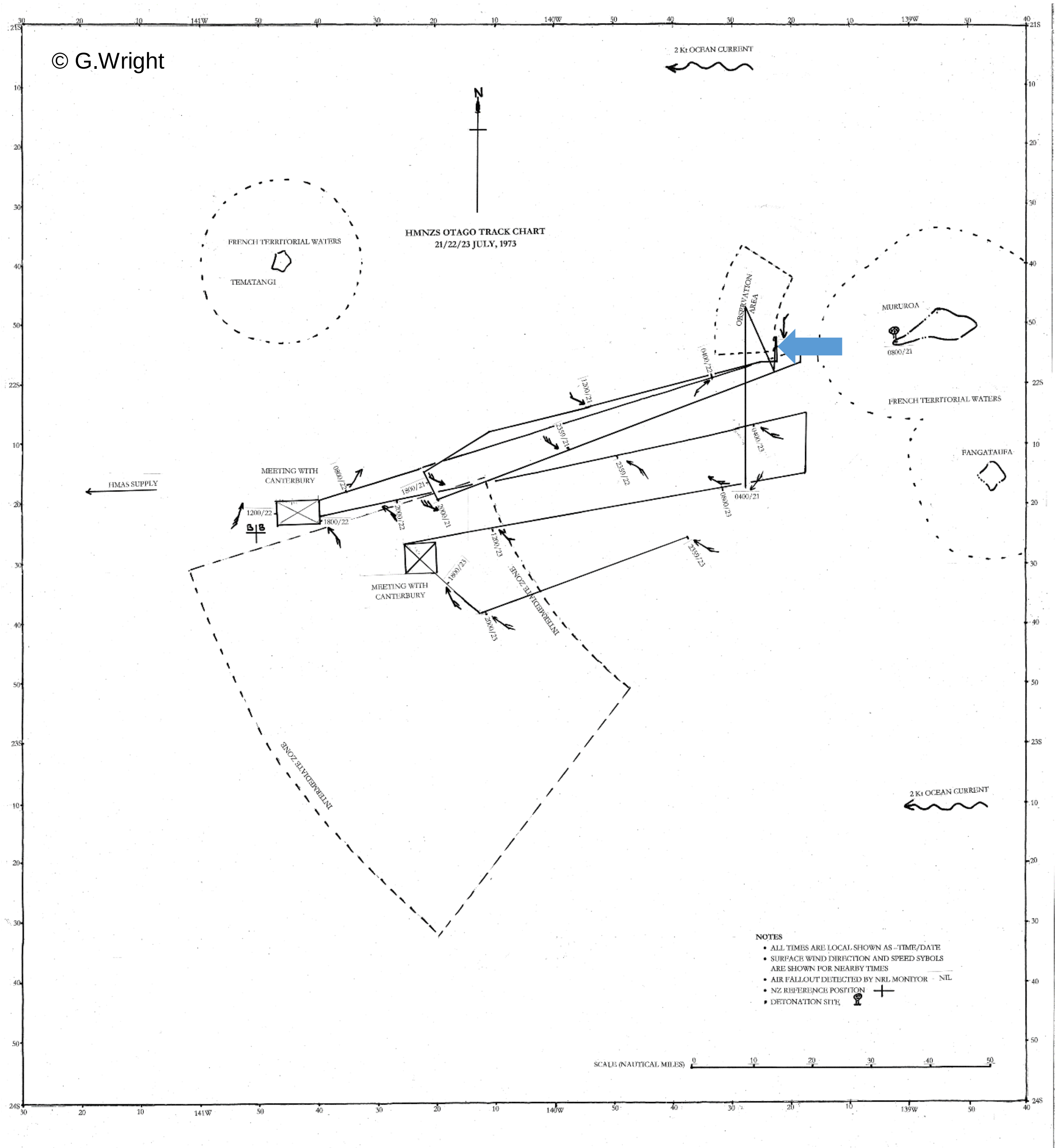

Fig. 3: Chart of the manoeuvres of HMNZS OTAGO, 21 to 23 July, 1973. The position of the ship at detonation (08.00, 21 July) is indicated by the arrow. Surface winds, ocean current, and Ground Zero position are indicated. Segments of the designated Observation and Intermediate Zones are shown to indicate relative positions.

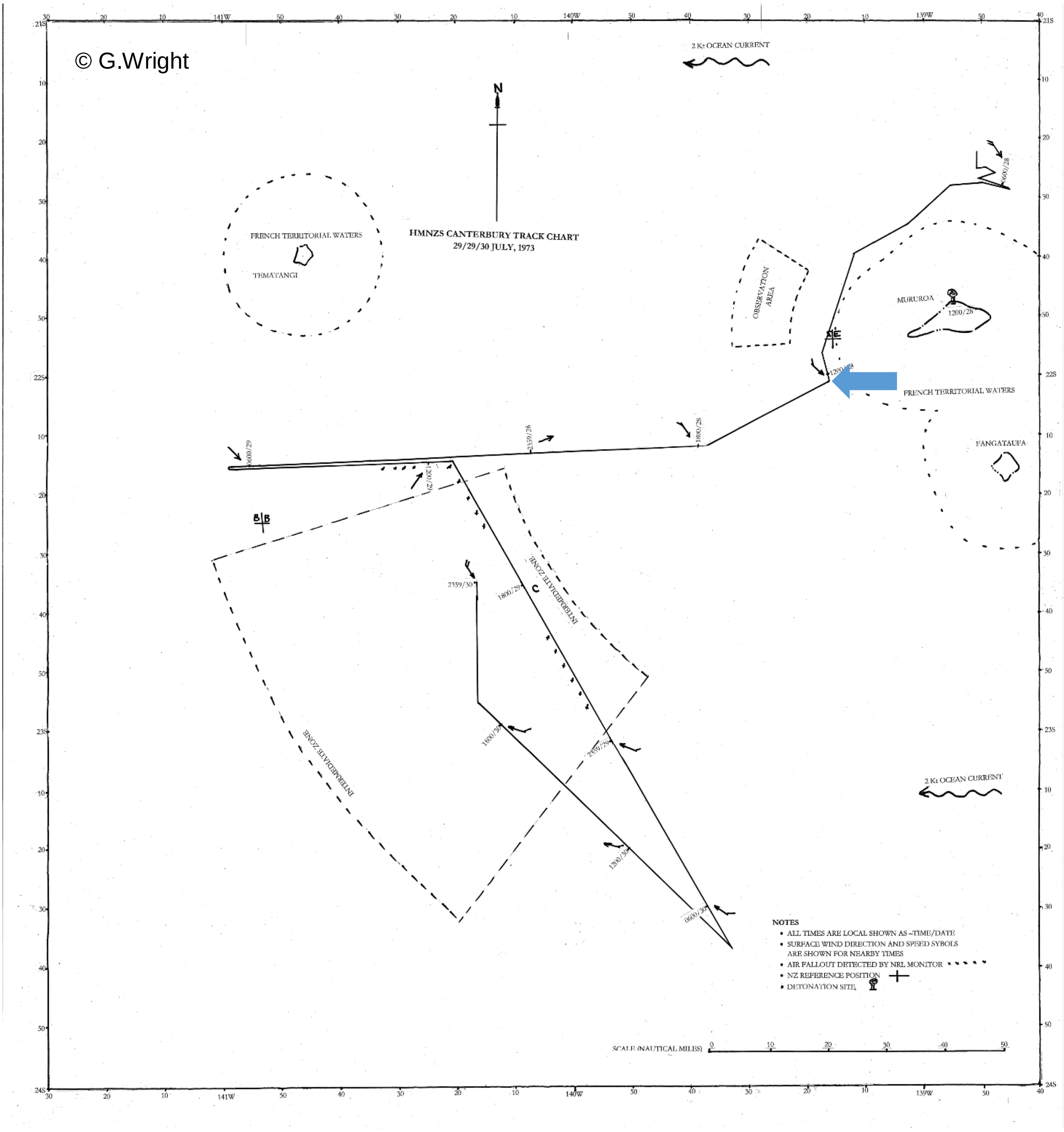

Fig. 4: Chart of the manoeuvres of HMNZS CANTERBURY, 28 to 30 July, 1973. The position of the ship at detonation (13.00, 28 July) is indicated by the arrow. Surface winds, ocean current, and Ground Zero position are indicated. The areas where the ship encountered the test plume are indicated by "x" symbols within the Intermediate Zone. (Correction: time of detonation was 13.00, not 12.00 as shown).

8. SOUTH PACIFIC RADIOACTIVITY MONITORING

Nuclear weapons were tested in the atmosphere throughout the period 1945 to 1980. Testing in the Pacific region was conducted by the USA in the Marshall Islands during the period 1946 – 1958, and in the Line Islands of the Republic of Kiribati in 1962. The United Kingdom tested weapons on Christmas and Malden Islands during the period 1956 – 1958. The French above-ground testing programme in the Tuamotu Archipelago, at Mururoa and Fangataufa, commenced in 1966 and continued through to September 1974.

NRL commenced environmental radioactivity monitoring in the New Zealand and South Pacific regions in 1962. The monitoring programme was expanded in 1966 and involved sample collections and/or continuous monitoring for various periods at Penrhyn, Manihiki, Pukapuka, Nukunonu, Funafuti, Tarawa, Fiji (Nadi and Suva), Samoa (Apia, Faleolo and Sataua), Niue and Cook Islands (Rarotonga, Aitutkai and Mangaia) and Raoul Island, as shown in Fig.5. Monitoring involved measurement of radioactivity in air and rainwater (gross beta activity), strontium-89/90 deposition, iodine-131 in milk, and environmental gamma radiation at the various monitoring stations. Foodstuffs were collected periodically as well.

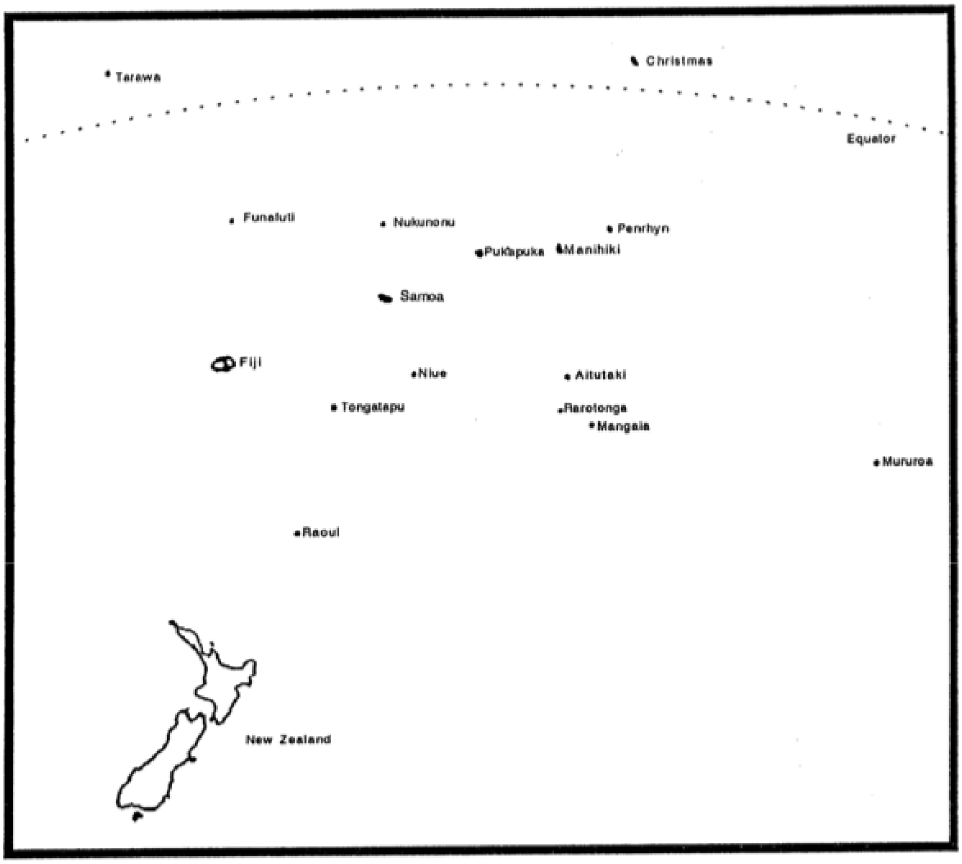

Fig. 5: Environmental radioactivity monitoring stations in the South Pacific region.

During the 1973 French testing programme, monitoring included:

- Rainwater radioactivity at Tarawa, Funafuti, Suva, Samoa, Niue, Tonga, Aitutaki and Rarotonga;
- Atmospheric radioactivity at Nadi, Samoa and Tonga;
- Strontium-90 deposition at Suva and Rarotonga;
- Iodine-131 in milk at Suva and Apia;
- Environmental radiation at Penrhyn, Aitutaki, Rarotonga, Samoa, Niue and Tonga;
- Migratory fish collected in the Samoa and New Zealand regions.

The programme was summarized by Matthews (1992).

There were five French tests during 1973 with yields (as announced by the French) as follows:

- A 21 July: 1 – 20 kt (estimated at ~5kt by HMNZS OTAGO)
- B 28 July: < 1 kt (estimated later at 0.05 kt)
- C 18 August: 1 – 20 kt
- D 24 August: < 1 kt
- E 28 August: 1 – 20 kt

HMNZS OTAGO witnessed test A (21 July), while HMNZS CANTERBURY witnessed the smaller test B (28 July). NRL observed that these first two tests had negligible, if any, radiological impact at any monitoring station.

Tests C and E, on the other hand, were easily detected in the atmosphere at Samoa and Tonga as shown in Fig. 5. This detection arose through westward transport of debris, whereas for the other tests, debris evidently drifted eastward as per the normal pattern. The detection of a trace of debris to the west by HMNZS CANTERBURY would have been due to a transitory low-altitude wind eddy. Had there been significant westward transport from test A, it is likely to have been detected at westward stations as for tests C and E which were in the same yield range.

The purpose of mentioning this monitoring here is to put the two observed tests into perspective in terms of their radiological impact, and to indicate the sensitivity of monitoring systems in operation throughout the South Pacific during the deployment of HMNZS OTAGO and HMNZS CANTERBURY. The radioactivity status of the region was thus well understood at the time.

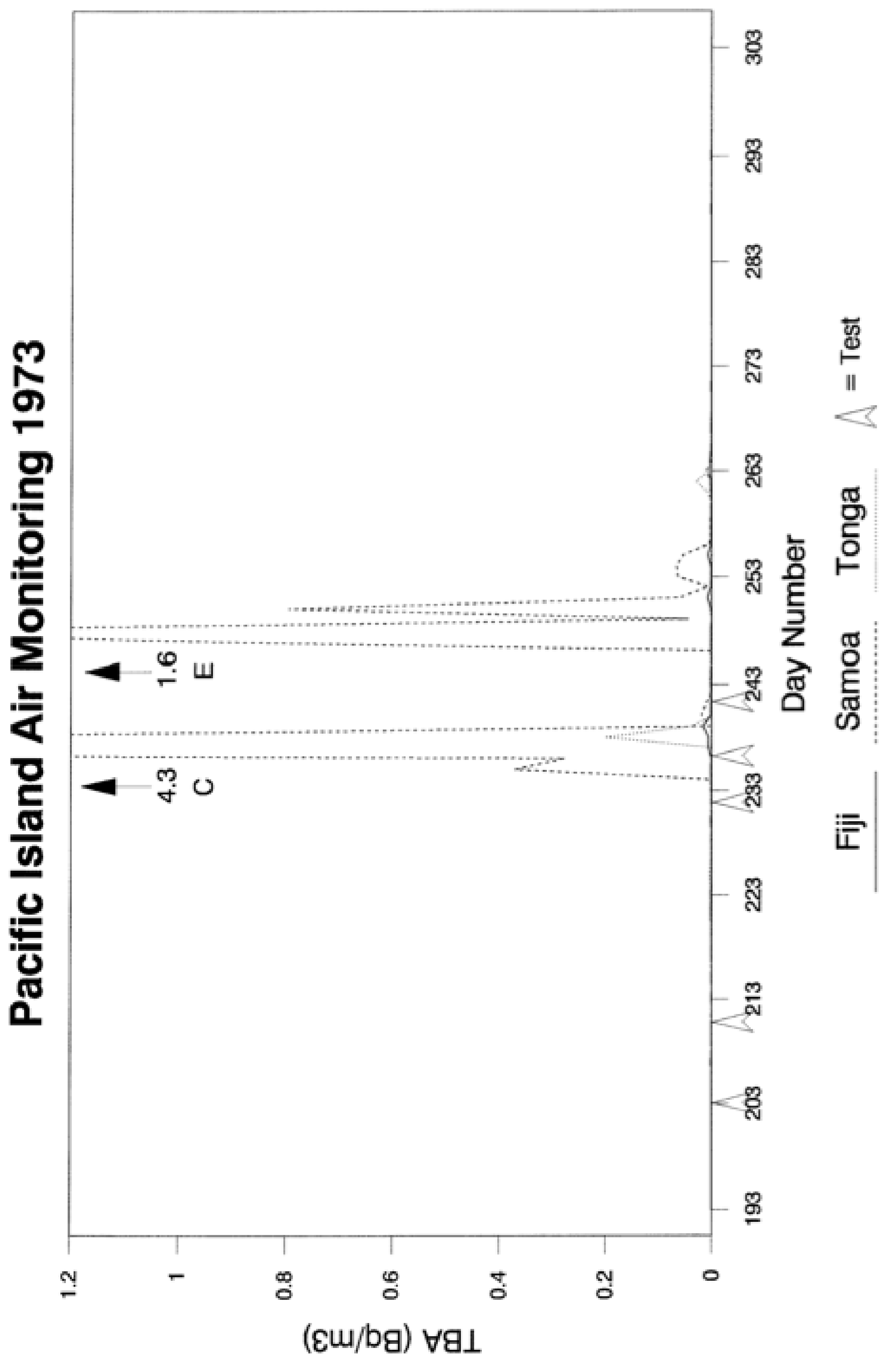

Fig. 6: Total beta activity (TBA), Bq/m^3, at Fiji, Samoa and Tonga during the 1973 monitoring period (Matthews, 1992). On this scale, test A (HMNZS OTAGO) occurred on day 203; and test B (HMNZS CANTERBURY) on day 210, as shown.

9. CONCLUSION

Radiological preparations for the voyage were of a very high standard.

The radiological monitoring programme conducted on board was soundly based, with good use made of available equipment. Although errors were made, particularly with the personal monitoring, this did not compromise safety or alter the radiological outcome.

Emergency preparations for all possible contingencies were thorough and well planned.

The on-board Radiation Officer, Mr J. F. McCahon from NRL, evidently conducted his duties thoroughly under unfamiliar, and therefore difficult, conditions. It is a credit to his efforts that the information contained in this report was available.

This review has made use of all available radiation-related information pertaining to the voyages. Retrospective assessment of historic radiation exposure is always challenging, but the conclusions in this instance are clear.

Conclusions related to possible radiation exposure of the crews of HMNZS OTAGO and HMNZS CANTERBURY during the PILASTER deployment are as follows:

1. The weapons tests conducted were in the yield range of extremely small (HMNZS CANTERBURY) to small (HMNZS OTAGO) on the scale of such tests;

2. Neither test had notable radiological impact in the South Pacific region (beyond the Mururoa atoll itself at least);

3. Crew of the HMNZS OTAGO were exposed to NO radiation resulting from the observed weapon test:

    - No external radiation was detected above background;
    - No airborne radioactivity was detected above background;
    - No surface contamination was detected;
    - Personal dosimetry measurements were consistent to natural (cosmic) background.

4. Crew of the HMNZS CANTERBURY were exposed to NO SIGNIFICANT radiation resulting from the observed weapon test:

    - No external radiation was detected above background;
    - A trace of airborne radioactivity was detected;
    - No surface contamination was detected;
    - Personal dosimetry measurements were consistent to natural (cosmic) background.

5. There was no exposure to contaminated drinking water on either ship.

6. The small radiation exposure due to inhaled radioactivity on HMNZS CANTERBURY was conservatively estimated to be within the range of onshore radon exposure, at 0.005 – 0.05 mSv. In reality, it is likely that the dose obtained was at the lower limit of this range.

7. Personal dosimetry measurements indicated exposure to radiation levels consistent with natural cosmic radiation only.

The possible radiation exposure of those on board HMNZS CANTERBURY due to airborne radioactivity is compared with exposure from other radiation sources in Fig. 7 and 8 below.

Summary. On the basis of information obtained during this review it is likely that, due to lower natural background radiation levels over the oceans and the lack of significant exposure to other sources of radiation, the crews of HMNZS OTAGO and HMNZS CANTERBURY received less radiation exposure during their one-month deployments to Mururoa than their families did at home (in spite of detection of traces of airborne radioactivity by HMNZS CANTERBURY).

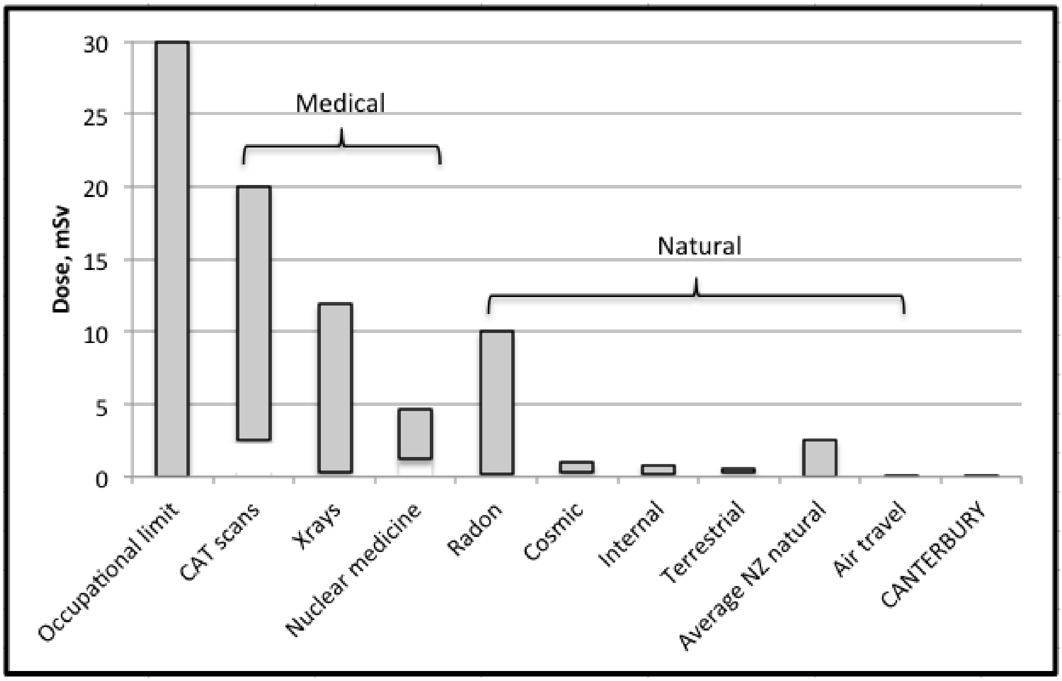

Fig. 7: Comparison of possible radiation dose received aboard HMNZS CANTERBURY **due to inhalation of airborne radioactivity** (pessimistic maximum) with ranges of doses commonly received from other sources (comparative data are from Tables A3, A4 and A5, Appendix A). Natural radiation doses are received every year, and the Occupational limit is for a three-month period.

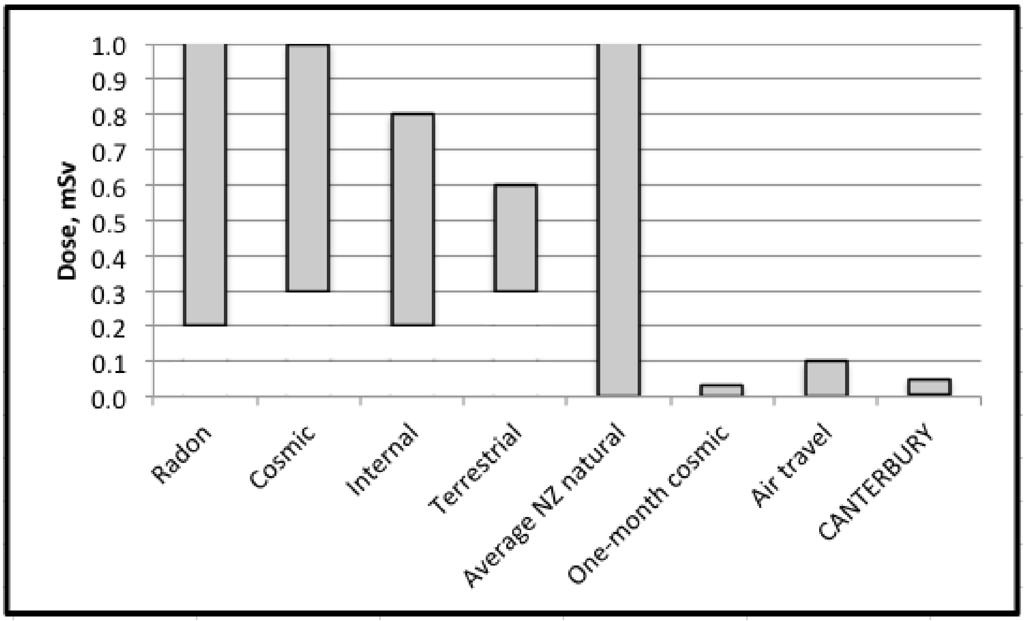

Fig. 8: Expanded view of the lower-dose portion from figure 7. The one-month cosmic dose is the natural dose incurred during one month at sea. The “Air travel” referred to corresponds to cosmic radiation received on a return Melbourne-London flight (ARPANSA, 2015). Any remaining exposure, on either ship, approximated the one-month natural cosmic radiation dose. The plotted inhalation dose on HMNZS CANTERBURY is an upper bound – i.e., dose was less than 0.05 mSv; and more likely of the order of 0.005 mSv.

APPENDIX A: DEFINITIONS AND UNITS

Understanding of the science behind radiation and radiological protection is not helped by the plethora of units used throughout history. This report adopts the currently accepted International System of Units, and an explanation of radioactivity, dose, and the various units of measurement are provided here.

A.1 RADIOACTIVITY

Every atom contains a nucleus comprising particles called protons and neutrons. The numbers of these particles define the element and, for nuclear stability, they have to be present in set ratios. Too many of either one causes instability. An unstable atom naturally seeks to improve its stability (i.e., lower its energy), and the process by which it does this is called “radioactivity”. Such an atom is called a “radionuclide”. During the radioactive process the number of protons or neutrons is adjusted, often with transformation of the original atom into that of another element. During this process “radiation” is emitted, as a means of shedding energy. This radiation may be in the form of “beta particles” (electrons emitted by the nucleus), alpha particles (comprising two protons plus two neutrons), and/or electromagnetic radiation (x-rays or gamma rays). This process is called “radioactive decay”, with each event being a “disintegration” or, more accurately, a “nuclear transformation”. The degree of instability of the atom governs how quickly this process occurs, with a very unstable atom “decaying” within seconds, while one that is only marginally unstable might last for millions of years, with everything possible between these extremes. The time taken for half of the unstable atoms to decay is called the “half-life”, which is a fixed constant for every particular radioactive species. Some radionuclides have half-lives of less than a second, while others are billions of years.

We live in a radioactive world in which most materials contain radioactive atoms. During the formation of the elements of the universe, all possible atoms were formed, with many being radioactive. In fact, the majority of known element atoms are unstable. Obviously, the short-lived have long since decayed to stable forms; but some long-lived ones remain in nature. Uranium and thorium, for example, have half-lives of billions of years and still exist in nature (these long-lived species called “primordial” radionuclides). All soils and rocks contain them, and during their decay process they produce other radioactive species such as radon gas. Some of these products are short lived (half-lives of minutes or days), and so are decaying as rapidly as they are produced. Another long-lived atom is potassium-40 (^{40}K), which comprises about 0.01% of all potassium. Our bodies contain a lot of potassium, and therefore also radioactive ^{40}K, and we are thus radioactive ourselves.

Nuclear fission, as occurs in nuclear weapons and reactors, involves the breaking apart of uranium or plutonium atoms into smaller atoms called “fission products”. At the time of their production, these fission products are unstable and therefore radioactive. They decay mainly with the emission of beta particles and gamma radiation, with half-lives ranging from less than one second to years. About 5% of the energy of a nuclear explosion is carried by these unstable atoms. In the weapons case, they collectively comprise “fallout”, i.e., radioactive species distributed throughout the atmosphere and deposited on the ground under the influence of gravity and rain.

The degree of radioactivity of any unstable element is defined by the rate at which the atoms undergo transformation, i.e., how many atoms transform (decay or disintegrate) per second. This gives rise to the units by which radioactivity is understood.

A.2 RADIOACTIVITY UNITS

The radioactive decay rate was originally named after Marie and Pierre Curie, the discoverers of several radioactive species including radium and polonium. A "Curie" (symbol Ci) was defined as the rate of decay of one gram of radium-226 (^{226}Ra), which happens to be 3.7 x 10^{10} disintegrations per second.

1 Ci = 3.7 x 10^{10} disintegrations per second (s^{-1}).

This is a high decay rate because one gram of radium contains a lot of radium atoms (2.7 x 10^{21} in fact).

In environmental radioactivity monitoring, as described in this report, it was more common to use the picoCurie (symbol pCi) or 10^{-12} Curie.

1 pCi = 0.037 s^{-1} or 2.22 disintegrations per minute (dpm).

Partly because of the cumbersome nature of the Ci, a new unit was defined within the International System in honour of Henri Becquerel who is credited with discovery of radioactivity itself.

So now we have the Becquerel (pronounced "beckerel"), symbol Bq, with one Bq equalling one disintegration per second (dps).

1 Bq = 1 s^{-1}

The Bq is a helpful unit in environmental considerations because it is more in keeping with the levels encountered; but the reverse applies for the nuclear industry where activities are billions of times higher.

To summarise, this report uses the Bq for radioactivity:

1 Bq = 1 dps = 27 pCi.

A.3 IMPACT OF RADIATION

The impact of radiation on any material, including the human body, depends on the following factors:

- <u>The type of radiation.</u> Alpha and beta particles are not very penetrating. Alpha particles travel distances measured in millimetres in air, and cannot penetrate the human dead-skin layer. Beta particles are more penetrating and will travel distances of the order of 10 centimetres in air, and will penetrate skin. Gamma radiation is very penetrating and will travel metres in air.

- The means of exposure. Because of their minimal penetrating power, alpha radiation is harmless when its source is outside the body. If, however, alpha-emitting atoms enter the body via ingestion, inhalation or wounds they become much more hazardous because they impact directly on biological tissue. This applies to beta radiation as well, although damage from external radiation sources may also arise due to its ability to penetrate the skin. Gamma radiation penetrates the human body so is the most hazardous from an external radiation point of view.

- The organs irradiated. Inhaled materials my deposit in the lung, ingested materials may accumulate in certain organs, and external gamma radiation may irradiate the whole body. The site of exposure obviously affects health impact. Some organs are more susceptible to radiation damage than others.

- Energy deposited. The key factor in determining the likelihood of any health impact radiation has is indicated by the amount of energy deposited by the radiation. Very penetrating gamma radiation may pass right through tissues without losing much energy, so has little impact. Alpha particles, on the hand, are entirely stopped by tissues encountered and deposit all their energy there, so potentially have a bigger impact. This leads to concepts of “radiation dose”.

A.4 RADIATION DOSE

The likelihood of radiation damage is measured in terms of the “dose” received; and dose is calculated in terms of energy absorbed. A confusing array of units has been used, although fundamentally they are concerned with energy absorbed, and the impact of that energy on tissue.

Energy is considered in terms of the unit “Joule” (J), or formerly “erg” (1 erg = 10^{-7} J)

One former unit was the “**rad**” (a transliteration of “Absorbed Radiation Dose”):

1 rad = energy absorption of 100 ergs per gram, or 0.01 J/kg.

The International System of Units simplified this by redefining dose in terms of a unit called the “**Gray**” (Gy).

1 Gy = energy absorption of 1J/kg = 100 rad.

The Gray is thus the unit of radiation exposure, which is usually referred to as “dose”.

In assessing actual health impact, radiation dosimetry then becomes more complicated because it must take into account the different sensitivities of various organs to radiation and the effect irradiation of particular organs has on the whole body. This introduces concepts of “dose equivalent” (for organs), “effective dose” (for the whole body), factors such as “relative biological effectiveness" which weight dose by its effects, and tissue weighting. The effective dose is proportional to health risks and has therefore been used in this report throughout.

Dose equivalent and effective dose have the same units, and were formerly expressed in terms of the "**rem**" ("Roentgen Equivalent Man"). As would be expected, the International System of Units has brought in a new name – the **Sievert** (Sv). As in the case of the Gray above, a factor of 100 is applied.

1 Sv = 100 rem.

To summarise:

- Dose is expressed by the unit Gray: 1 Gy = 100 rad = absorption of energy of 1 Joule per kg of tissue.

- Effective dose and dose equivalent are expressed in Sieverts: 1 Sv = 100 rem.

- With external irradiation (whole-body exposure from fallout), Grays and Sievert (or rad and rem) mean the same thing; i.e., 1 Gy means the same as 1 Sv.

- With internal irradiation (from inhaled particulate matter or ingested material) dose equivalent or effective dose, Sv, would be more appropriate because of organ effects.

In this report all doses originally expressed in rad in the Mururoa voyage reports were converted to effective dose given in Sievert, specifically the milliSievert, mSv.

A dose of 1 Gy, or effective dose of 1 Sv, is a heavy dose, which would be expected to have noticeable health effects. In normal, non-emergency, situations it is therefore more appropriate to use milli or micro units:

1 mGy = 0.001 Gy; 1 μGy = 0.000001 Gy

1 mSv = 0.001 Sv; 1 μSv = 0.000001 Sv

The reason for introducing these various dose concepts here is that they provide a means of making comparisons as, in order to keep doses from any source in perspective, it is necessary to consider them relative to different radiation exposures received naturally or from other manmade sources, as discussed below.

A.5 SUMMARY OF UNITS

The above discussion of units is summarized in Table A2.

Item	Current unit	Old unit	Conversion
Radioactivity	Becquerel, Bq 1 Bq = 1 dps	picoCurie (pCi); 1 pCi = 2.2 dpm	1 Bq = 27 pCi 1 pCi = 0.037 Bq
Dose	Gray, Gy, or milliGray, mGy	rad, or millirad, mr	1 Gy = 100 rad 1 rad = 0.01 Gy 1 mr = 0.01 mGy
Effective dose	Sievert, Sv, or milliSievert, mSv	rem, or millirem, mrem	1 Sv = 100 rem 1 rem = 0.01 Sv

Note: dps = decay per second; dpm = decay per minute

Table A2: Summary of units

A.6 NATURAL RADIATION EXPOSURE

As mentioned earlier, we live in a radioactive world, and this results in unavoidable radiation exposure. Just how much each of us gets depends basically on where we live. The sources of this exposure are:

- External terrestrial radiation from primordial radionuclides in soils, rocks and building materials;

- Internal radiation from inhaled atmospheric radioactivity, principally radon gas exhaled from soils following decay of uranium and thorium;

- Cosmic radiation mainly produced through the impact on Earth's upper atmosphere of nuclear particles from outer space, but also coming directly from space. The Sun may make a small but indistinguishable contribution, though interstellar space is considered to be the primary source (the dose rate is the same at night as in the daytime). The atmosphere has a shielding effect, so the higher the altitude at which one lives, the more cosmic radiation received. Commonly, the most exposed occupational group is airline flight crews.

- Internal irradiation by materials in our bodies which contain, on average, 4000 Bq of radioactive ^{40}K, and lesser amounts of other radioactive species.

The doses contributed by these four sources are summarized in Table A3 where effective dose is expressed as mSv per year.

Average worldwide doses due to natural radiation sources (UNSCEAR 2000)		
Source of exposure	**Average, mSv/y**	**Typical range, mSv/y**
Cosmic radiation	0.4	0.3 – 1.0
Terrestrial radiation	0.5	0.3 – 0.6
Inhalation (radon)	1.3	0.2 - 10
Internal exposure	0.3	0.2 – 0.8
Total	2.5	1 - 10

Table A3: Natural radiation exposure.

Human natural background radiation exposure thus averages about 2.5 mSv/y, and this level applies in New Zealand.

It is against this background that the relative significance of any additional forms of radiation exposure can be assessed.

In the context of sea travel, it should be pointed out that sailors at sea are obviously not exposed to terrestrial radiation or radon, so during sea travel the natural exposure rate would be closer to 0.7 mSv/y, or *less than one third that received by people on shore.*

Another comparison which assists in keeping doses in perspective is the radiological implications of common medical procedures.

A.7 MEDICAL RADIATION EXPOSURE

Diagnostic x-rays, tomographic scans and nuclear medicine procedures deliver measureable radiation doses, as described in Table A4.

As can be seen in Table A4, common diagnostic procedures may incur radiation doses of an order of magnitude greater than the average natural radiation exposure.

These various types of radiation exposure result in formulation of restrictions in terms of what are deemed to be “permissible” doses to the population and to workers.

Medical radiation exposure	
Procedure	**Average dose, mSv**
X-rays (Williamson et al, 1993)	
Barium meal	6.9
Barium enema	11.9
Lumbar spine x-ray	1.4
Thoracic spine x-ray	1.1
Pelvis x-ray	1.0
Skull x-ray	0.3
Nuclear medicine (Beach, 2006)	
Bone scan	4.3
Cardiac scan	4.7
Renal scan	1.6
Lung scan	1.5
Liver scan	1.2
Thyroid scan	1.6
Gastrointestinal scan	2.1
CAT scans (Stirling, 2009)	
Head	2.5
Chest	7.9
Chest, abdomen and pelvis	20
Colonography	8.9
Abdomen and pelvis	11

Table A4: Radiation doses incurred during common medical procedures.

A.8 DOSE LIMITATION

The principal underlying all radiation exposure control is that exposure should be kept as low as is practicably achievable, and in the case of medical procedures there is obviously perceived benefit to the patient. Where no such benefit is perceived, controls must be instituted to ensure that unnecessary exposure is controlled, and limited to levels considered to have negligible hazard or, at most, no greater hazard than those incurred in everyday life or work.

There are two dose regulation systems of relevance here: public and occupational. Recommendations for these promulgated by the IAEA in its Basic Safety Standards (IAEA, 2007) are as follows.

Public exposure

The effective does limit for members of the public is 1 mSv in a year. In special circumstances a higher effective dose in a single year can be permitted, provided the effective dose over five consecutive years does not exceed 1 mSv per year.

Occupational exposure

Occupational exposure limits are set with the aim of ensuring that any risks associated with handling radioactive materials or irradiating equipment in the course of one's work are no greater than risks routinely encountered in other occupations.

For occupational exposure of workers over 18 years of age, the dose limit is 20 mSv per year averaged over five years (100 mSv in 5 y), and 50 mSv in any single year.

Additional restrictions apply to female workers who have notified of pregnancy or are breast-feeding; while for workers or students of 16 – 18 years of age, the dose limit is 6 mSv in a year.

These dose limits obviously exclude natural background radiation, which is unavoidable.

The above limits are currently adopted in radiation protection practice in New Zealand.

During the 1970s, there was an additional occupational limit such that radiation dose could not exceed 30 mSv per calendar quarter.

Mururoa deployment

Operational orders related to radiation protection during the voyages are shown in Appendix B. The Mururoa deployment was conducted in peacetime, so current occupational limits were applied, specifically the dose limit of 30 mSv in one quarter, as follows (McCahon, 1973):

- Action would be taken to prevent anyone on board receiving more than the permitted occupational exposure in any three-month period: 30 mSv (3 rad).

- Protective action would be required if the ambient radiation dose rate reached 0.2 mSv/h (20 mrad/h).

- An "Action Level" was defined for airborne radioactivity such that in the event that airborne radioactivity was detected, action would be taken to limit exposure to air containing more than 37,000 Bq/m^3 (1 μCi/m^3) of radioactivity. It was calculated that continuous breathing of air at this level for two days would give a dose of 30 mSv (the permitted three-month occupational limit). In the event that significant airborne radioactivity was encountered, preventive measures would be taken immediately, with the ship being sealed while vacating the area, such that exposure beyond a few hours, and certainly much less than two days, would be avoided.

Dose limits applying on the Muruoa voyages were thus tailored to match accepted occupational radiation exposure limits, with assurance that the dose received by any crew member would not exceed the prevailing three-month limit of 30 mSv, and less than the dose limit of 50 mSv in any one year.

The Mururoa dose limits were backed up by plans for emergency evacuation and treatment in the event of a major mishap on Mururoa. Such an event might have been the accidental detonation of a megaton range weapon at ground level, which could have resulted in significant radioactive fallout in the immediate vicinity.

A.9 SUMMARY

The above radiation doses and dose limits, against which the radiological outcomes of the Mururoa voyages can be considered, are summarized in Table A5.

Comparison of doses	
Natural background	2.5 mSv per year on land
Cosmic radiation background at sea	0.4 mSv/y
X-rays	Up to 12 mSv per procedure
Nuclear medicine	Up to 5 mSv per procedure
CAT scans	Up to 20 mSv per procedure
Public dose limit	1 mSv in a year
Current occupational dose limit	20 mSv in a year, with 50 mSv in 1 year
Historical occupational limit (1970s)	30 mSv per calendar quarter
Set Mururoa voyage limit	30 mSv per calendar quarter

Table A5: A comparison of doses and dose limits.

APPENDIX B: RADIOLOGICAL PREPARATIONS FOR VOYAGES (AN EXTRACT FROM SHIPS' ORDERS)

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APPENDIX 1 TO
ANNEX D TO
OP ORD 1/73
DATED 25 JUN 73

RADIOLOGICAL PROTECTION

Air Sampling

1. Two portable air samplers (complete with filters) will be provided by the National Radiation Laboratory, and are to be read by using Radiac Set MD2.

2. The background level of natural radiation (before detonation of a nuclear device) is to be determined by the NRL Radiation Officer, and he is to take readings at 24 hour intervals prior to detonation.

3. After the detonation of any nuclear device air samples are to be taken at intervals not exceeding one hour, until all danger of radioactive fall-out is over.

Sampling of Fresh Water, Sea Water and Food

4. Sampling of sea water, fresh water and food is to be carried out by the NRL radiation officer at his discretion, using Radiac set MD2 with accessory kit MK7 NAK.

Personal Protection

5. The ship will be supplied with the following:

Item No.	Pattern No.	Description	Quantity
1	-	Dosimeter, Thermoluminescent (consisting of badge holder and TLD disc) with spare discs.	248
2	NRL Supply	Dosimeter, film badge	30
3	0552/900-7557	Dosimeter, quartz fibre, 0.200mR.	As available
4	0552/911-0101	Dosimeter, quartz fibre No.2A,0-5r.	"
5	0552/911-0003	Dosimeter, quartz fibre No.3, 0-50r.	"
6	RNZNH Supply	Tablets, potassium iodide, 200-300mgm.	1000

6. The items in paragraph 5 above are to be issued as follows:

Item 1. To all members of the ship's company and all passengers. They are to be worn at all times whilst in the test area, pinned outside clothing on the left breast, or worn around the neck on a cord.

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Item 2. To all passengers and selected members of the ship's company. Selection should cover the ship, with emphasis on personnel who normally work on the upper deck and in engine room compartments. Badges are to be worn as for Item 1 above.

Items 3. 4. 5. To be worn by selected members of the ship's company and selected passengers, as for Item 2 above. No person is to carry more than one pocket dosimeter.

Item 6. At shelter stations, when ordered, following detection of radiation significantly above background level. They are to be swallowed immediately on issue.

7. All personal dosimeters are to be numbered and the numbers recorded against those to whom they are issued.

Reading of Personal Dosimeters

8. If the presence of fall-out or direct radiation above background level is detected, by air samples or otherwise, following the detonation of a nuclear device, the following readings are to be taken and recorded:

a. 25 in number TLD's (Item 1) selected from throughout the ship, but particularly from those who were on the upper deck or in engine room compartments. These will be read by the NRL Radiation Officer, using Thermoluminescent Dosimeter Disc Reader MK 2NDR.

b. All pocket dosimeters (Items 3-5).

Subsequent Action

9. If dose rates significantly in excess of natural background level of radiation, or in any case before the level of 20 millirads per hour is detected:

a. The ship is to go to shelter stations and pre-wet and follow the normal procedures for clearing a fallout area.

b. 25 selected TLD's, and all pocket dosimeters are to be read at half-hourly or hourly intervals, depending on the rate detected. All readings are to be recorded. Any person who has received a dose approaching 3 rem, or more, to the whole body is not to be allowed subsequently into any area where dose rates exceeding 20 millirads per hour are present.

10. In the following circumstances, full details are to be reported to CNS by "operational immediate" message.

a. Any significant increase in radiation level above natural background.

b. When any personnel have received a whole body dose of more than 3 rem.

(1) If any individual dose is in the range of 25-100 rem, further instructions are to be specifically requested.

(2) If any individual dose exceeds 100 rem, the French authorities are to be contacted without further instructions, and arrangements made for the earliest evacuation of the personnel concerned to the French hospital at HAO.

11. As far as possible, exposure of personnel to radiation is to be limited so that the total accumulated whole body dose does not exceed 3 rem over the whole period the ship is in the test area. This is the maximum permissible whole body dose in a three month period, for New Zealand civilians who are exposed to ionizing radiation in the course of their employment.

12. Fission products in the form of radioactive fall-out should be washed away as soon as possible. If adherence of radioactive material to parts of the ship prevents reduction of activity to a level below 20 millirads per hour, boundaries are to be marked and personnel warned not to loiter in the area.

Additional Equipment

13. A list of additional radiac and protection equipment being supplied is at Appendix 2.

Note: Certain Service Radiac instruments are graduated in Roentgens (R), instead of rads(r). The Roentgen(R), rad(r) and rem may be considered as identical units when referred to radiation doses to the body.

APPENDIX 2 TO
ANNEX D TO
OPORD 1/73
DATED 25 JUN 73

LIST OF ADDITIONAL RADIAC AND PROTECTION EQUIPMENT AND ANCILLARIES

Pattern No.	Description	Quantity
0552/117-6663	Disc Reader Mk 2 NDR	1
0443/220-1351	Nitrogen Cylinder	1
Local Supply	Nitrogen Cylinder, charged with 220 cu ft oxygen-free dry nitrogen	1
-	Pressure Reducing Valve Type RR 8011, 0-30 PSI, with Cylinder Contents Gauge, Upstream Pressure Gauge and 4mm Tail Pipe (for Nitrogen Cylinders)	1
0552/521-5885	Radiac Set MD 2	3 (or 4) (See Note (2))
0552/114-9290	Accessory Kit Mk 7 NAK	1
0552/109-4747	Contamination Monitor Mk 3 NRM	1 (OTAGO only. See Note (1))
0552/911-0004	Dosimeter Charging Unit	As Required
8415/99-122-6631	Suits, Decontamination NBC	20
0243/521-9459	Foam Nozzle and Hose Assembly	2
0473/224-0437	Acetamide Powder, Technical	4 tins
0473/211-2324	Citric Acid, Granules	4 tins
BR 2053(8)	Handbook for Radiac Set MD 2	1+
BR 2053(11)	Handbook for Thermoluminescent Dosimeter Disc Reader Mk 2 NDR	1
Dockyard Manufacture	Low Level Dose Rate Detector Head for use with Indicator Unit of Contamination Monitor Mk 3 NRM	1 (OTAGO only. See Note (1))
-	Personal Dosimetry Equipment	See Appendix 1

Pattern No.	Description	Quantity
NRL Property	Air Sampler, 12 Volt DC	1 } See Note (2)
NRL Property	Air Sampler, 230 Volt AC	1 } See Note (2)

NOTES: (1) This instrument is not required in CANTERBURY. The Indicator Unit in conjunction with Dockyard manufactured low-level detector head mounted on GDP will perform the same function as the low-level dose rate detection system of SIRS.

(2) This instrument will also be used by the NRL Radiation Officer for testing air samples, in conjunction with NRL Air Samplers.

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ANNEX E
TO OPORD 1/73
DATED 25 JUNE 1973

OPERATING AND REPORTING AREAS

1. The following operating areas are established:

a. Observation Area

Sea area to the west of Mururoa in a sector centred on western extremity of Mururoa Atoll (21° 53S 139° 02W) between true bearings of 230 and 300 between radii 20 and 30 nautical miles.

b. Support Area

The area bounded by:

20° 51'S	141° 24'W
24° 00'S	140° 17'W
24° 27'S	142° 00'W
21° 22'S	143° 07'W

2. Incident reports

Reports of incidents in the vicinity of Mururoa are to be made with reference to lettered positions.

Appendix 1 - Declared Zones

1A.

1C. Intermediate Zone.

The sea area to the west of Mururoa in a sector bounded by the true bearings 200° and 260° centred on 21° 50'S, 138° 47°W and between Radii ~~[illegible]~~ 68 and 120 nautical miles.

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APPENDIX 1 TO
ANNEX E TO
OPORD 1/73
DATED 25 JUNE 1973

DECLARED ZONES

1. The following danger zones have been declared by French maritime and air authorities:

a. Surface Zone

(1) A circle of 120 nautical miles radius centred on Mururoa (21°50'S, 138°47'W).

(2) A circular sector of 200 nautical miles radius between true bearings 045° and 100°, through east centred on Mururoa.

b. Airspace Zone

(1) A circle of 200 nautical miles radius centred on Mururoa (21°50'S 138°47'W) to unlimited height.

(2) A circular sector of 500 nautical miles radius centred on Mururoa to unlimited height between true bearings 030° and 150° through east.

2. The Surface Zone has been promulgated in New Zealand Notice to Mariners, NZ 68(T).

Security Zone ?

c. Intermediate Zone,

68 Miles to 120 Miles.

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Item 2. To all passengers and selected members of the ship's company. Selection should cover the ship, with emphasis on personnel who normally work on the upper deck and in engine room compartments. Badges are to be worn as for Item 1 above.

Items 3. 4. 5. To be worn by selected members of the ship's company and selected passengers, as for Item 2 above. No person is to carry more than one pocket dosimeter.

Item 6. At shelter stations, when ordered, following detection of radiation significantly above background level. They are to be swallowed immediately on issue.

7. All personal dosimeters are to be numbered and the numbers recorded against those to whom they are issued.

Reading of Personal Dosimeters

8. If the presence of fall-out or direct radiation above background level is detected, by air samples or otherwise, following the detonation of a nuclear device, the following readings are to be taken and recorded:

a. 25 in number TLD's (Item 1) selected from throughout the ship, but particularly from those who were on the upper deck or in engine room compartments. These will be read by the NRL Radiation Officer, using Thermoluminescent Dosimeter Disc Reader MK 2NDR.

b. All pocket dosimeters (Items 3-5).

Subsequent Action

9. If dose rates significantly in excess of natural background level of radiation, or in any case before the level of 20 millirads per hour is detected:

a. The ship is to go to shelter stations and pre-wet and follow the normal procedures for clearing a fallout area.

b. 25 selected TLD's, and all pocket dosimeters are to be read at half-hourly or hourly intervals, depending on the rate detected. All readings are to be recorded. Any person who has received a dose approaching 3 rem, or more, to the whole body is not to be allowed subsequently into any area where dose rates exceeding 20 millirads per hour are present.

10. In the following circumstances, full details are to be reported to CNS by "operational immediate" message.

a. Any significant increase in radiation level above natural background.

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