SOR/RF Type Testing:

Final Report

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Final Report

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1. INTRODUCTION

As part of project 06df, “Improved Operational Dosimetry”, being conducted under the Defence Research and Development Canada (DRDC) Hazard Protection Program, DRDC Ottawa Research Centre has determined that DND’s current in-service electronic dosimeter, the MGP SOR/RF, should undergo the type testing process for external photon dosimetry, in accordance with the civilian standard S-106, in order to have a better understanding and characterization of its performance. To fulfill this need, DRDC, Ottawa Research Centre tasked Bubble Technology Industries (BTI) to develop and execute a type testing plan for the SOR/RF. New task authorizations, Task 10 and 11, were added to the Scientific Services contract (Contract #: W7714-071044/001/TOR) so that BTI could perform this work.

The SOR/RF is an electronic dosimeter which measures exposure to X-rays and gamma rays and calculates and displays an integrated dose and instantaneous dose rate to the user. The SOR/RF is designed for military use, and is intended to be resistant to harsh environments and to electrical/magnetic interference. SOR/RF dosimeters are used in conjunction with a reader. The reader unit retrieves dose records from multiple dosimeters and can be used to reset dosimeters as needed.

A type testing plan was developed by BTI in accordance with Canadian Nuclear Safety Commission (CNSC) Standard S-106 under Task 10. The type testing plan was executed, with previously agreed-upon limitations, under Task 11. This report describes the work completed under Task 11 and includes the results from the type testing executed.

2. WORK PERFORMED

In preparation for testing, several experimental apparatuses were constructed. These include jigs for holding dosimeters in an upright orientation, and for holding multiple dosimeters at equal distances from a radioactive source. For magnetic field testing, an apparatus was assembled to suspend a single dosimeter between two solenoids, through which DC or AC electric current could be run to generate an appropriate magnetic field. In addition, a water-in-PMMA phantom, having the dimensions given in Canadian Nuclear Safety Commission (CNSC) Standard S-106, was constructed. After completion of necessary experimental apparatuses, gamma and neutron dose measurements were completed where necessary to determine unknown dose rates in test geometries. Communication between BTI and DRDC was maintained throughout testing to ensure that testing proceeded according to DRDC requirements. During these communications, it was determined that BTI should not complete the electric field test specified in the test plan, due to an inability to generate AC frequencies required to complete a meaningful test. The remaining tests proceeded as defined in the test plan, and are described below in this document. Deviations from the test plan in these tests have been noted when necessary.

3. TYPE TESTING RESULTS

The following sections describe the results of the type testing executed under Task 11. The type testing work has been completed according to CNSC Standard S-106. The type testing work described in this document was performed by Bubble Technology Industries (BTI).

3.1. TEST OVERVIEW

The purpose of type testing is to assess the degree to which certain influence quantities (e.g. dose rate, angle of incidence, temperature, humidity, etc.) create uncertainty in the dose measurements assigned to users of a dosimetry system. The overall amount of uncertainty which can be tolerated is defined by CNSC Standard S-106, in Equation 14 of Appendix A. DRDC, Ottawa Research Centre, is investigating the possibility of using the Mirion SOR/RF electronic dosimeter as a legal dose of record for Canadian Armed Forces (CAF) personnel deployed in overseas operations. A subset of these dosimeters was tested to determine the overall uncertainty in the dose measurements reported by this type of unit. The goal is to determine whether the SOR/RF dosimeter meets the requirements set out in S-106 when subjected to the conditions of use potentially encountered by the Canadian Armed Forces. A total of 19 tests were defined that were determined to be necessary to perform on SOR/RF dosimeters during a type testing campaign based on S-106. The full results from 11 of these tests, and partial results from an additional 5, are reported on in this document. Based on these results, an analysis of the overall uncertainty in the dosimetry system is presented.

Due to the nature of the functionality of the SOR/RF dosimeter and its use by the Canadian Armed Forces, the following assumptions were made in the interpretation of CNSC Standard S-106 for the development of this test plan:

1. Only requirements for external dosimetry have been considered.
2. Only whole body dose $H_p(10)$ has been considered. Skin dose $H_p(0.07)$ is not being assessed.
3. Only dose to the torso has been considered. Dose to extremities has not been assessed.

Only photon dose response has been considered, but with beta and neutron radiation fields included as quantities influencing the photon dose response.

The objective of the test campaign is to demonstrate that the CAF dosimetry system using SOR/RF dosimeters meets the dose response uncertainty specifications of CNSC Standard S-106 when subjected to the expected conditions of use.

3.2. TEST RESULTS

3.2.1. INFLUENCE OF PHOTON ENERGY AND ANGLE OF INCIDENCE

DESCRIPTION

A SOR/RF unit was attached to the front face of a water-in-PMMA phantom, as defined by S-106. The phantom was positioned so that the SOR/RF point of test was located at a distance of 30 cm from a ~100 mCi Cs-137 source, and so that the SOR/RF was oriented relative to the source at angles of 0˚, 20˚, 40˚, 60˚ and 80˚. In each of these positions, the SOR/RF was irradiated for a period of 5 min. Five (5) SOR/RF units were tested in this manner, one at a time. **Note:** This test was performed with a 1 cm spacing between the dosimeter and the phantom, rather than the 0 cm spacing described in the test plan, due to geometrical limitations of the apparatus securing the dosimeter to the phantom.

RESULTS

Dosimeter angle of incidence relative response, with reference to the response at 0˚, are presented below in *Table 1*.

Table 1: Dosimeter Relative Response with Respect to Angle of Incidence

Angle (°)	0	20	40	60	80
Relative response	1.00	1.00	1.02	1.03	1.06

3.2.2. INFLUENCE OF DISTANCE BETWEEN DOSIMETER AND PHANTOM

DESCRIPTION

A SOR/RF unit was attached to the front face of a water-in-PMMA phantom, as defined by S-106. The attachment of the dosimeter to the phantom was made to provide a spacing between the front face of the phantom and the back face of the dosimeter. Tests were performed with spacings of 1 cm, 2 cm, 3 cm, and 4 cm. For each of these spacings, the position of the phantom was adjusted such that a distance of 30 cm was maintained between the point of test on the dosimeter and a ~100 mCi Cs-137 source. In each of these configurations, the dosimeter was irradiated by the source for periods of 5 minutes. Five (5) SOR/RF units were tested in this manner, one at a time. Tests were also completed for each dosimeter with the dosimeter in the same position but the phantom removed entirely. **Note:** a 4 cm test was substituted for the 0 cm test called for in the test plan because of geometric limitations of the apparatus securing the dosimeter to the phantom.

RESULTS

Dosimeter relative response when varying distances between the dosimeter and the phantom, with reference to the 1 cm distance, are presented below in *Table 2*.

Table 2: Dosimeter Relative Response with Respect to Distance between Dosimeter and Phantom

Distance to phantom (cm)	1	2	3	4	no phantom
Relative response	1.00	1.00	0.99	0.98	0.96

3.2.3. DOSE LINEARITY

DESCRIPTION

Five (5) SOR/RF units were exposed simultaneously to a ~100 mCi Cs-137 source, each at a distance of 30 cm. The units were also exposed simultaneously to a ~450 µCi Cs-137 source, again at 30 cm. For both sources, exposures were completed for durations of 1 min, 10 min, and 60 min.

RESULTS

Dosimeter dose linearity results, with reference to the 5.22 mSv dose response, are presented in *Table 3*. Relative responses for the three lowest dose measurements have been marked with an "*", due to their relatively high uncertainties given that SOR/RF reports doses to a precision of only 0.001 mSv. For this reason, a relative response for the lowest dose measurement (< 0.001 mSv) is not reported here.

Table 3: Dosimeter Relative Response with Respect to Magnitude of Dose

Expected integrated dose (mSv)	0.000371	0.00371	0.02226	0.087	0.87	5.22
Relative response	*	0.8*	0.9*	0.98	0.99	1.00

3.2.4. INFLUENCE OF DOSE RATE

DESCRIPTION

Five (5) SOR/RF units were exposed simultaneously to ~100 mCi Cs-137 source at distances of 30 cm, 100 cm, and 200 cm, and to a ~500 µCi Cs-137 source at distances of 40 cm, and 150 cm. Durations of exposure were 5 min, 15 min, 45 min, 1200 min, and 6000 min respectively.

RESULTS

Dosimeter relative response as a function of dose rate, with reference to a dose rate of 5220 µSv/hr, is presented below in *Table 4*.

Table 4: Dosimeter Relative Response with Respect to Dose Rate

Dose rate (µSv/hr)	0.95	11.6	147	540	5220
Relative response	1.07*	1.07*	0.99	0.99	1.00

*The two lowest dose rate measurements took place in a different geometry than the other measurements to facilitate longer tests, taking place over several days. The low magnitude of these dose rates introduces uncertainty in accurately relating measured dose rates in this geometry to calibrated dose rates in the BTI calibration facility where the higher dose rate tests were performed. This uncertainty is on the same order of magnitude as the dose rate effect reported here; consequently the two low dose rate relative responses have been omitted from the calculation of the overall accuracy of the dosimeter.

3.2.5. INFLUENCE OF MAGNETIC FIELD

DESCRIPTION

A SOR/RF unit was positioned in the centre of a magnetic field, generated by an electric current running through 2 solenoids positioned on either side of the unit. AC and DC fields were generated at strengths of 5 G and 10 G respectively. For each of these 4 fields, the unit was tested in 2 orthogonal orientations relative to the direction of the field. Tests were also conducted in the same apparatus at both orientations with zero magnetic field. For each of these test scenarios, the unit was positioned facing a ~100 mCi Cs-137 source, with the point of test at a 30 cm distance from the source. Five (5) units were tested, one at a time.

RESULTS

Dosimeter relative response as a function of magnetic field strength, frequency of alternation, and dosimeter orientation, with reference to zero magnetic field is provided in Table 5 and Table 6.

Table 5: Dosimeter Relative Response – 0 Hz

Magnetic field strength (G)	0	0	5	5	10	10
Current frequency (Hz)	0	0	0	0	0	0
Dosimeter orientation (°)*	0	90	0	90	0	90
Relative response	1.00	1.02	0.99	1.03	0.99	0.86

Table 6: Dosimeter Relative Response – 60 Hz

Magnetic field strength (G)	5	5	10	10
Current frequency (Hz)	60	60	60	60
Dosimeter orientation (°)*	0	90	0	90
Relative response	0.99	1.03	0.99	1.02

*angle between the axis of the magnetic field and the direction in which the dosimeter faces.

It is noteworthy that while most of the magnetic field tests did not produce significant effects in the results, the SOR/RF units did show a significant susceptibility to a static magnetic field of 10 G when the face of the dosimeter was oriented sideways relative to the direction of the field. Information from the manufacturer suggests that SOR/RF may not previously have been tested in DC magnetic fields.

3.2.6. INFLUENCE OF ELECTRIC FIELD

DESCRIPTION

As per the test plan, this test would have involved exposing five (5) SOR/RF units, one at a time, to a ~100 mCi Cs-137 source at 30 cm distance while being exposed to static and alternating electric fields of varying strengths. During preparations for the completion of this test, it was determined that BTI could not generate an electric field of sufficient strength and AC frequency to affect SOR/RF performance. Consequently, it was agreed with DRDC that this test would not be completed by BTI under this contract.

RESULTS

Test not completed, as per agreement with DRDC.

3.2.7. INFLUENCE OF IMMERSION IN WATER

DESCRIPTION

A SOR/RF unit was positioned facing a ~100 mCi Cs-137 source at a distance of 30 cm, and irradiated for 5 min. It was then submerged in a water bath for 60 sec, and re-irradiated under the same conditions as previously. Five (5) units were tested, one at a time.

RESULTS

Dosimeter relative response with respect to immersion of the dosimeter in water, with reference to the response prior to immersion is presented in Table 7.

Table 7: Dosimeter Relative Response with Respect to Immersion in Water

Immersion status	Before	After
Relative response	1.00	1.00

3.2.8. SENSITIVITY TO BETA RADIATION

DESCRIPTION

A SOR/RF unit was positioned at a distance of 25 cm from a ~46.7 MBq Sr-90 source and irradiated for 5 min. Five (5) units were tested, one at a time. The tests were repeated with a ~2.5 mCi Pm-147 source. **Note:** The test plan originally called for the use of a 55.5 MBq Sr-90 source as the beta emitter for this test. 55.5 MBq is the nominal strength of the Sr-90 source used for the test; its actual activity at the time testing took place was approximately 46.7 MBq. However, when SOR/RF demonstrated a sensitivity to Sr-90 in the course of testing, it was suspected that units might be responding specifically because of the high energy nature of the beta particles emitted by Sr-90. Pm-147 has a lower-energy beta ray, and so testing was completed with both Sr-90 and Pm-147. The results of both tests are presented here.

RESULTS

None of the SOR/RF units tested in this manner showed any response to beta radiation from Pm-147. However, during a 5 min exposure to Sr-90, the SOR/RF units tested on average registered a dose of 0.042 mSv. This figure is much too large to have been generated by Bremstrahlung X-ray photons, and so is likely caused directly by interactions with betas. Influence of both Pm-147 and Sr-90 beta radiation on the relative response of SOR/RF to a gamma source is discussed in the context of the Mixed Gamma + Beta Field test in Section 3.2.11 of this document.

3.2.9. SENSITIVITY TO NEUTRON RADIATION

DESCRIPTION

A SOR/RF unit was positioned facing a ~0.59 mCi Cf-252 source at a distance of 25 cm. The position of the SOR/RF was shielded from the source by 10 cm of lead to attenuate the gamma rays being emitted by the source. In this configuration, the unit was exposed to the source for a duration of 1 hour. Five (5) units were tested, one at a time. **Note:** The test plan called for durations of exposure of 5 min; however, this was increased to 1 hour to provide for better comparability of results with the Mixed Neutron and Gamma Field test (described in Section 3.2.12 of this document), which underwent a similar change. The test plan also called for a distance between dosimeter and neutron source of 30 cm; this was moved in to 25 cm to take advantage of higher neutron rates in that position.

RESULTS

At the end of one hour of exposure, 4 of the 5 dosimeters showed zero dose. The 5^{th} dosimeter recorded a dose of 0.001 mSv. The independently-measured gamma dose rate behind the lead shielding at the position of the SOR/RF units was 1.40 µSv/hr. Neutron dose rate at the same position was 187 µSv/hr. The response of the dosimeters is therefore consistent with neutron insensitivity. Influence of neutron radiation on the relative response of SOR/RF to a gamma source is discussed in the context of the Mixed Gamma + Neutron Field test in Section 3.2.12 of this document.

3.2.10. INFLUENCE OF MECHANICAL SHOCK CAUSED BY DROPPING

DESCRIPTION

A SOR/RF unit was positioned facing a ~100 mCi Cs-137 source at a distance of 30 cm, and irradiated for 5 min. It was then dropped 6 times, once onto each of its faces. It was dropped from a height of 1 m onto a concrete surface. It was then re-irradiated under the same conditions as previously. Five (5) units were tested, one at a time.

RESULTS

Dosimeter relative response with respect to dropping the dosimeter onto concrete, with reference to the response prior to dropping, is presented in Table 8.

Table 8: Dosimeter Relative Response with Respect to Dropping

Drop status	Before	After
Relative response	1.00	1.00

3.2.11. RESPONSE TO MIXED BETA AND GAMMA FIELDS

DESCRIPTION

A SOR/RF unit was positioned at a distance of 25 cm from a ~46.7 MBq Sr-90 source, and at a distance of 30 cm from a ~100 mCi Cs-137 source, and irradiated by both sources for a duration of 5 min. Five (5) units were tested, one at a time. The tests were repeated with a ~2.5 mCi Pm-147 source. **Note:** The test plan originally called for the use of a 55.5 MBq Sr-90 source as the beta emitter for this test. 55.5 MBq is the nominal strength of the Sr-90 source used for the test; its actual activity at the time testing took place was approximately 46.7 MBq. However, when SOR/RF demonstrated a sensitivity to Sr-90 in the course of testing, it was suspected that units might be responding specifically because of the high energy nature of the beta particles emitted by Sr-90. Pm-147 has a lower-energy beta ray, and so testing was completed with both Sr-90 and Pm-147. The results of both tests are presented here.

RESULTS

Dosimeter relative response with respect to exposure to the Pm-147 beta radiation field, with reference to the pure gamma field response, is presented in *Table 9*.

Table 9: Dosimeter Relative Response with Respect to Presence of a Pm-147 Beta Radiation Field

Radiation field	gamma only	beta + gamma
Relative response	1.00	0.99

Dosimeter relative response with respect to exposure to the Sr-90 beta radiation field, with reference to the pure gamma field response, is presented in *Table 10*.

Table 10: Dosimeter Relative Response with Respect to Presence of a Sr-90 Beta Radiation Field

Radiation field	gamma only	beta + gamma
Relative response	1.00	1.05

Consistent with the beta sensitivity tests, SOR/RF appears to be relatively unaffected by Pm-147 but significantly influenced by Sr-90. This is reasonable given that Sr-90 emits higher energy beta rays than Pm-147; Pm-147 beta rays are likely being absorbed within SOR/RF before they can trigger counts.

3.2.12. RESPONSE TO MIXED NEUTRON AND GAMMA FIELDS

DESCRIPTION

A SOR/RF unit was positioned facing a ~0.59 mCi Cf-252 source at a distance of 25 cm. The position of the SOR/RF was shielded from the Cf-252 source by 10 cm of lead to attenuate the gamma rays being emitted by that source. Simultaneously, the SOR/RF was positioned at a 30 cm distance from an unshielded ~500 µCi Cs-137 source. In this configuration, the unit was exposed to the source for a duration of 1 hour. Five (5) units were tested, one at a time. **Note:** The test plan called for durations of exposure of 5 min; however, this was increased to 1 hour to provide for a more precise dose measurement, given the strength of the Cs-137 source. The test plan also called for a distance between dosimeter and neutron source of 30 cm; this was moved in to 25 cm to take advantage of higher neutron rates in that position.

RESULTS

Dosimeter relative response with respect to a neutron radiation field, with reference to the pure gamma field response, is presented in *Table 11*.

Table 11: Dosimeter Relative Response with Respect to Presence of Neutron Field.

Neutron field	No	Yes
Relative response	1.00	1.00

3.2.13. INFLUENCE OF GRADUAL TEMPERATURE VARIATIONS

DESCRIPTION

Five (5) dosimeters were positioned facing a ~500 µCi Cs-137 source at a distance of 25 cm, inside an environmental chamber. The dosimeters were brought from room temperature to an extreme temperature at a rate of 10°C/min. They were then left at the extreme temperature for 4 hours, and then brought back to room temperature at a rate of 10 °C/min. The dosimeters were exposed to the source for the duration of the test.

RESULTS

In each of these temperature cycles, the dosimeters are assumed to reach temperature equilibrium with their environment at 2 hours after the extreme temperature is reached. Only data collected at that extreme temperature and after that equilibrium point are used in calculating the dosimeter relative responses presented below in *Table 12*. Relative responses are calculated with reference to the 25°C test.

Table 12: Dosimeter Relative Response with Respect to Gradual Temperature Variation

Temperature (°C)	-25	0	25	50
Relative response	*	1.12	1.00	0.89

* Note that a relative response for the -25 °C test could not be determined: long term exposure to low temperatures rendered the displays of the devices unreadable. At -5 °C, low battery indicators started to show on some of the devices. By -15 °C (four hours into the cycle), displays on four of the five units under test were unreadable. The gradual temperature cycle was allowed to be completed, and it was observed that dosimeters recovered at room temperature. Doses displayed on the units at that time indicated that the dosimeters had continued to count and accumulate dose throughout the temperature cycle, and that dose readings were inflated by exposure to cold, but without information on dose response during the period of temperature equilibrium, it is not possible to determine how severe the effect is.

3.2.14. INFLUENCE OF ABRUPT TEMPERATURE VARIATIONS

DESCRIPTION

Five (5) dosimeters were positioned facing a ~500 µCi Cs-137 source at a distance of 25 cm, inside an environmental chamber. The dosimeters were exposed to the source for a duration of 2 hours. At the start of the exposure, the dosimeters were brought from room temperature to an extreme temperature in under 5 min.

RESULTS

Dosimeter relative response as a function of operational temperature after temperature shock, with reference to 25˚C temperature, is given in Table 13.

Table 13: Dosimeter Relative Response as a Function of Temperature

Temperature (˚C)	-25	0	25	50
Relative response	1.16	1.06	1.00	0.94

3.2.15. BATCH HOMOGENEITY TESTING

DESCRIPTION

Thirty-eight (38) SOR/RF units were exposed to a ~100 mCi Cs-137 source at a distance of 30 cm for 5 min. The units were exposed to the source 5 at a time. **Note:** The test plan called for forty (40) units to be subjected to this test. However, 1 unit was non-functional at the time that this test was completed, and another was in-use elsewhere in preparation for other tests taking place. In the circumstances, it was determined that 38 units would be sufficient to complete the test.

RESULTS

Results from this test were used to calculate a K1 statistic, as in the 1999 Technical Specifications of the Health Canada National Dosimetry Service (NDS) [1], according to the equation below:

$$K1 = \frac{H(max) - H(\min)}{H(min)} \times 100 \qquad (1)$$

Where H(max) and H(min) are the maximum and minimum recorded doses respectively. The expected dose for a dosimeter tested for the duration and geometry defined above was 0.435 mSv. The maximum dose displayed by a unit after the test was 0.450 mSv, and the minimum reported dose was 0.425 mSv. Thus, K1 was calculated to be 5.88%.

3.2.16. RESPONSE STABILITY TESTING

DESCRIPTION

Five (5) SOR/RF units were exposed to a ~100 mCi Cs-137 source at a distance of 30 cm for 5 min. This source exposure for was repeated 5 times for each unit. The units were exposed to the source simultaneously.

RESULTS

Results from this test were used to calculate K2 statistics for each of the five testing cycles, as in the NDS Technical Specifications [1]. These were then averaged to obtain an overall K2 statistic. K2 is calculated according to the formula below:

$$K2 = \frac{S + S \times t_n \sqrt{2/(n-1)}}{H(avg)} \times 100 \qquad (2)$$

Where H(avg) is the average recorded dose, S is the sample standard deviation, n is the number of dosimeters tested and t_n is the 95% confidence t statistic for n dosimeters. For each of the five tests, n = 5 and t_n = 2.015. Based on this equation, the overall average K2 statistic for the dosimeters was calculated to be 3.51%.

3.2.17. ZERO DOSE VARIATION

DESCRIPTION

Thirty-eight (38) SOR/RF units were exposed to a ~100 mCi Cs-137 source at distances of 200 cm, 100 cm, and 30 cm. Source exposures were completed for durations of 45 min, 15 min, and 5 min respectively. The units were exposed to the source 5 at a time. **Note:** The test plan called for forty (40) units to be subjected to this test. However, 1 unit was non-functional at the time that this test was completed, and another was in-use elsewhere in preparation for other tests taking place. In the circumstances, it was determined that 38 units would be sufficient to complete the test.

RESULTS

For each dosimeter, using the 3 doses at each distance and the expected doses for each distance and exposure duration, a zero dose response was extrapolated using linear regression. The average extrapolated zero dose response for the 38 units was -9.66×10^{-6} mSv, and the standard deviation for that extrapolated response was 0.00271 mSv.

4. ANALYSIS OF TYPE TESTING RESULTS

4.1. ESTIMATION OF PROBABILITIES

The first step in the analysis of type testing results following standard S-106 is to define intervals of values for each influence quantity, for which each tested value is considered representative. Then, the probability that each influence quantity will take on a value in each interval must be estimated according to the intended conditions of use of the dosimeter. The intended use of the SOR/RF dosimeter is by Canadian Armed Forces personnel on missions to which they have been assigned. The probabilities of SOR/RF units being exposed to different values of influence quantities have been assigned on this basis.

For Angle of Incidence, since dosimeters are equally likely to be exposed to sources from all tested angles, all angles of incidence have been assumed to be equally probable, following the example of the Uranium Mines Dosimeters discussed in the NDS Technical Specifications [1]. Probabilities have been adjusted from the values listed in the Technical Specifications to match the angles of incidence tested here, and the intervals of angles of which they are taken to be representative, following the guidance of S-106. The probabilities are presented below in *Table 14*.

Table 14: Probabilities of Intervals of Angles of Incidence

Angle (°)	Interval (°)	Probability
0	0 - 10	0.111
20	10 - 30	0.222
40	30 - 50	0.222
60	50 - 70	0.222
80	70 - 90	0.222

Note that the first interval listed above includes half as many angles of incidence as the others, and has therefore been assigned half the probability of occurrence of the others.

For distance between dosimeter and phantom, probabilities have again been defined following the example of the NDS Technical Specifications [1]. Again, the probabilities have been adjusted to reflect the intervals defined by the tests performed in this testing campaign. The probabilities are shown below in *Table 15*.

Table 15: Probabilities of Intervals of Distance between Dosimeter and Phantom

Distance (cm)	Interval (cm)	Probability
1	0 - 1.5	0.5
2	1.5 - 2.5	0.3
3	2.5 - 3.5	0.2
4	3.5 - 4.5	0

For each of the remaining influence quantities, since mission requirements for Canadian Armed Forces are not predictable, it has been assumed that it is equally probable that each influence quantity will take on any value within the whole range of values assessed. For dose linearity, dose rate, magnetic field strength, and the temperature tests, intervals and probabilities have been defined as shown in the tables below.

Table 16: Probabilities of Intervals of Dose

Dose (mSv)	Interval (mSv)	Probability
0.087	0.001 - 0.2	0.004
0.87	0.2 - 2	0.036
5.22	2 - 50	0.960

Table 17: Probabilities of Intervals of Dose Rate

Dose Rate (mSv/hr)	Interval (mSv/hr)	Probability
0.110	0.001 - 0.12	0.001
0.135	0.12 - 0.2	0.000
0.435	0.2 - 200	0.999

Table 18: Probabilities of Magnetic Field Characteristics

Strength (G)	Interval (G)	Frequency (Hz)	Orientation (°)	Probability
0	0 - 2.5	0	0	0.125
0	0 - 2.5	0	90	0.125
5	2.5 - 7.5	0	0	0.125
5	2.5 - 7.5	0	90	0.125
5	2.5 - 7.5	60	0	0.125
5	2.5 - 7.5	60	90	0.125
10	7.5 - 10	0	0	0.0625
10	7.5 - 10	0	90	0.0625
10	7.5 - 10	60	0	0.0625
10	7.5 - 10	60	90	0.0625

Note that for magnetic field orientation and DC/AC, the tests performed have not been assumed to be representative of a continuum of values other than the specific values tested; probabilities have been distributed considering each orientation and each of static and alternating magnetic fields to be equally likely.

Table 19: Probabilities of Intervals of Temperature (Gradual Test)

Temperature (°C)	Interval (°C)	Probability
0	(-12.5) - 12.5	0.400
25	12.5 - 37.5	0.400
50	37.5 - 50	0.200

Table 20: Probabilities of Intervals of Temperature (Shock Test)

Temperature (°C)	Interval (°C)	Probability
-25	(-37.5) - (-12.5)	0.286
0	(-12.5) - 12.5	0.286
25	12.5 - 37.5	0.286
50	37.5 - 50	0.143

For the remaining tests, including the drop test, the immersion test, and the mixed radiation field tests (beta + gamma, and neutron + gamma), the tests performed have not been assumed to be representative of a continuous spectrum of values. Therefore, intervals have not been defined for these tests, and the results of each test have been considered to be equally likely to occur.

4.2. CALCULATION OF MEAN RELATIVE RESPONSES OF DOSIMETER FOR EACH INFLUENCE QUANTITY

Each influence quantity assessed by the tests reported on in this document has been treated as an independent influence quantity for the purposes of this analysis. Some of the influence quantities, such as temperature and angle of incidence, are known to be composite influence quantities according to the definitions of S-106; however, the other influence quantities with which they are to be treated compositely (humidity and energy respectively) have not yet been assessed through this phase of testing. For independent influence quantities, the equation specified by S-106 for calculating mean relative response is as shown below in Equation 3:

$$\overline{r_q} = \sum_{s=1}^{M_q} r_{q,s} p_{q,s} \qquad (3)$$

where M_q is the number of measured relative responses for influence quantity q, $r_{q,s}$ is the sth measured relative response, and $p_{q,s}$ is the probability of the influence quantity taking on the sth value. As defined by this equation, the mean relative response is the average of the measured relative responses of the dosimeter with respect a given influence quantity, as weighted by the probabilities for the corresponding influence quantity intervals which have been defined above.

Similarly, the squared mean relative responses for each influence quantity (which will be used to calculate dosimeter response variance), are calculated by Equation 4 below, as defined by S-106.

$$\overline{r_q{}^2} = \sum_{s=1}^{M_q} r_{q,s}{}^2 p_{q,s} \tag{4}$$

Again, given the probabilities defined above, this equation is average of the squared measured relative responses, weighted by the probabilities for the corresponding intervals.

The mean relative response and squared mean relative response for each influence quantity have been calculated according to the above equations, and are listed below in *Table 21*.

Table 21: SOR/RF Mean Relative Responses by Influence Quantity

Influence Quantity	Mean Relative Response	Mean Squared Relative Response
Angle of Incidence	1.03	1.05
Distance to Phantom	1.00	1.00
Dose Linearity	1.00	1.00
Dose Rate	1.00	1.00
Magnetic Field	1.00	1.00
Immersion in Water	1.00	1.00
Mechanical Shock (Drop)	1.00	1.00
Beta Radiation*	1.00	0.99
Neutron Radiation	1.00	1.00
Temperature (Gradual)	1.03	1.06
Temperature Shock	1.05	1.12

*Values presented are for Pm-147 betas. Sr-90 mean relative response is 1.05, and mean squared relative response is 1.10.

4.3. CALCULATION OF MEAN RESPONSE OF DOSIMETER

Continuing to follow the analysis set forth by S-106, the mean response of the dosimeter is calculated according to Equation 5 below.

$$\bar{R} = R_0 \overline{r_1}\,\overline{r_2} \dots \overline{r_{11}} \tag{5}$$

Where R_0 is the response of the dosimeter at reference conditions and $\overline{r_k}$ is the mean relative response for influence quantity k. Note that 11 influence quantities have been assessed in this analysis. Reference conditions for this analysis are the accumulated dose over 5 minutes in a pure gamma field at 30 cm distance from a ~100 mCi Cs-137 source, at room temperature. Based on the data collected in the Response Stability test, the response of the dosimeter at reference conditions is on average 1.01. Based on this reference response, and the mean relative responses associated with each influence quantity, the mean response of the dosimeter over the range of conditions tested is 1.12.

4.4. CALCULATION OF VARIANCE OF RESPONSE OF DOSIMETER

Continuing to follow the analysis of S-106, the variance in the dosimeter response over the conditions tested is expressed by Equation 6.

$$u^2 = R_0^2\overline{r_1^2 r_2^2} \ldots \overline{r_{11}^2} - \overline{R^2} \tag{6}$$

Where the variables are defined as previously. The variance calculated for SOR/RF based on the data and calculations presented above is 0.02.

4.5. CALCULATION OF COMBINED STANDARD UNCERTAINTY IN RESPONSE

The standard uncertainty (u) in dosimeter response is the square root of the variance calculated above. It is a measure of the uncertainty in response deriving from the influence of the influence quantities assessed in the testing of the dosimeters. In addition, there is a statistical relative uncertainty (u_s) deriving from statistical effects which are assessed through repeat measurements. Using the data from the Response Stability test above, the statistical relative uncertainty has been calculated to be 0.02. The standard uncertainty and statistical relative uncertainty are combined into a single quantity, the combined standard uncertainty (u_c), using the following formula from S-106.

$$u_c = \bar{R}\sqrt{(u/\bar{R})^2 + u_s^2} \tag{7}$$

Following this calculation, the combined standard uncertainty in the dosimeter response is 0.14.

4.6. CALCULATION OF OVERALL ACCURACY OF DOSIMETER

Using the quantities calculated above, the overall accuracy of the dosimeter may be assessed against the specifications of S-106, which is expressed by the following inequality:

$$\frac{1}{\rho} \leq \bar{R} \pm 2u_c \leq \rho \tag{8}$$

Where ρ is a constant defined by S-106. For whole body doses between 4 mSv and 10 Sv, ρ = 1.5. Thus, the S-106 upper limit on overall dosimeter accuracy is 1.50 and the lower limit is 0.67. The range of dosimeter responses represented by $\bar{R} \pm 2u_c$ is from 0.84 to 1.39. Therefore, the overall accuracy of SOR/RF meets the specification of S-106 within the range of conditions tested and analyzed so far. These results are subject to change when effects caused by any additional influence quantities are included in the analysis described above. Since further influence quantities relevant to SOR/RF remain to be tested, and since the full range of values of each influence quantity relevant to Canadian Armed Forces usage of SOR/RF remains to be tested, the results of analysis presented here should be regarded as having an **incomplete** and **provisional** nature.

Note: The numbers reported in the above analysis, except where otherwise indicated, are calculated using data from the beta radiation response for Pm-147. If the analysis is repeated with the Sr-90 beta radiation response substituted for the Pm-147 beta response used above, the range of dosimeter responses represented by $\bar{R} \pm 2u_c$ extends from 0.89 to 1.46. These numbers still fall within the specifications of S-106, but come much closer to breaching the upper limit defined by the standard.

4.7. DETERMINATION OF MINIMUM DETECTABLE DOSE OF DOSIMETER

The minimum detectable dose of SOR/RF was taken to be the amount of dose required for SOR/RF to register any response on its display. The smallest dose which can be displayed by SOR/RF is 0.001 mSv. The minimum detectable dose was determined by repeated testing of five (5) SOR/RF units at a distance of 30 cm from a ~450 µCi Cs-137 source, corresponding to a dose of 0.0925 µSv in every 15 seconds of exposure. In this geometry, it was found that a duration of exposure of 3 min, 30 sec caused a dose of 0.001 mSv to be displayed on all 5 devices, whereas an exposure of 3 min, 15 sec was only sufficient for 1 of the 5 units to register a dose. This corresponds to a minimum detectable dose of 1.30 µSv.

5. FOLLOW-ON WORK

BTI completed eleven of the twenty test procedures in their entirety. The following test procedures were completed within limitations at BTI, as per the Task 10 Final Report:

- Test 3.1: Influence of photon energy and angle of incidence
    - BTI is only equipped to test with Cs-137 (662 keV). BTI has access to a particle accelerator that can be used to perform testing with high-energy gamma rays
- Test 3.3: Dose linearity
    - BTI does not possess the 1 kCi Cs-137 source required for high dose tests
- Test 3.4: Influence of dose rate
    - BTI does not possess the 1 kCi Cs-137 source required for high dose-rate tests

- Test 3.16: Influence of gradual temperature variations
  - BTI's temperature chamber has a low temperature limit of -30 °C and therefore cannot complete a -50 °C test
- Test 3.17: Influence of abrupt temperature variations
  - BTI's temperature chamber has a low temperature limit of -30 °C and therefore cannot complete a -50 °C test

The remaining test procedures could not be completed at BTI because BTI does not possess the required equipment:

- Test 3.6: Influence of electric field
- Test 3.7: Influence of radio frequency (RF) electromagnetic radiation field
- Test 3.8: Influence of humidity
- Test 3.13: Influence of mechanical shock caused by vibration

Tests or partial tests that could not be completed at BTI require an external testing facility. In many cases, BTI has good contacts at suitable facilities that own the equipment required to perform the tests. BTI may be able to complete the remaining test procedures using external facilities. Costs for the remaining testing, to be performed by BTI at other locations or outsourced by BTI to external facilities, will be discussed between BTI and DRDC, Ottawa Research Centre.

6. CONCLUSION

Based on the testing that has been performed to date, and analysis that has been completed, the SOR/RF dosimeter meets the dose accuracy specifications set out by Canadian Nuclear Safety Commission Standard S-106 with respect to the influence quantities which have been assessed so far, and with respect to the range of values of those influence quantities which have been assessed so far. Further testing and analysis remains to be completed for some additional values of the influence quantities discussed in this report, and for some additional influence quantities. A final conclusion on whether SOR/RF meets the requirements of S-106 for the complete range of conditions of use anticipated for the Canadian Armed Forces remains to be determined pending the completion of this further testing and analysis.

With regard to the testing that has already been completed, SOR/RF performance was affected somewhat by angle of incidence, beta radiation at Sr-90 energy levels, and operating temperature (whether after a shock or a gradual transition). Very low operating temperatures (< 0 °C), in addition to influencing reported dose, also had the negative effect of causing the dosimeter display to dim and become unreadable after prolonged exposure. According to manufacturer information, the lower limit of operation for SOR/RF is -22 °C. Based on the testing that has been performed so far, it is not possible to define precisely the minimum temperature extreme / duration of exposure which will cause the display to become unreadable; this requires further testing. SOR/RF was also shown to be highly influenced by a 10 G static magnetic field when the direction of the magnetic field was parallel to the front face of the detector. No other magnetic field tested, including any of the other magnetic fields of the same strength, showed a significant effect like this. It appears from manufacturer documentation that SOR/RF may not have previously been tested in static magnetic fields, but only in alternating magnetic fields.

None of the other influence quantities assessed in this testing campaign appeared to significantly influence doses reported by SOR/RF.

7. REFERENCES

[1] "Technical Specifications – National Dosimetry Services, Radiation Protection Bureau, Health Canada", Health Canada, 1999.