M E M O R A N D U M

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SUBJECT: NMC source term evaluation

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1 INTRODUCTION

The NMC cyclotron was shutdown in September 2009. By the end of 2010 it is scheduled to be dismantled and transported to ANSTO.

The scope of this report is to assess the levels of activation of the main cyclotron components in order to provide a transport package category.

The assessment consists of analysing different measured data. The analysis was done with suitable radiation transport models and codes intending to match calculated and experimental data and producing a final bounded source term. The values of specific activities of the estimated source term are then compared against the limits for transport of radioactive material Ref/1/ to determine the proper transport package category.

2 METHOD

The evaluation was made on the basis of two types of measured data:

- A radiological survey of the cyclotron and vault Ref/4/
- Gamma spectrometry on samples from several components Ref/5/

From the gamma spectrometry we have produced a list with all the identified long lived radioisotopes, shown in table 1. These isotopes in the material components may have originated from:

- Direct interaction of the protons with the cyclotron components (p, x) reactions; and
- Interaction of the secondary neutrons generated on (p,n) reactions with all the materials of the tank exterior, such as shields, yoke and magnet structures

Given these two main sources of activation, a set of samples were taken from different accessible regions of the cyclotron. The pole faces are areas where there was direct proton interaction. The remainder of the structure was assumed under neutron activation.

The level of specific activity in each of the main components was determined from the results of the gamma spectrometry and then scaled to the rest of the structure with the following methodology:

Firstly, the results of the external sample (sample #04) were assumed to be the minimum and will correspond to all the exterior of the cyclotron. This assumption is based on the lowest neutron flux according section 3.2.

Secondly, those values obtained from the processing of the samples taken from the pole face area and the side tank interior (samples #09 & #10) were chosen as the maximum values for the isotope specific activities. This is due to the fact that over those areas there were the maximum combined proton and neutron reaction rates.

Finally, a remaining task is to determine the internal distribution of the specific activities of the identified isotopes. Given that in the bulk of the cyclotron structure, the main cause of activation were neutron reaction, the task would include an estimation of the neutron fluence distribution over it.

Once the specific activity has been assigned over the different regions of the cyclotron, two checks were done: first, to evaluate the dose rates outside the tank in a closed position and compare them against the cyclotron vault survey and second, to assess on the dose rate field inside the tank in an open position and contrast them with the cyclotron tank survey. These two checks are shown in sections 3.1 and 3.3.

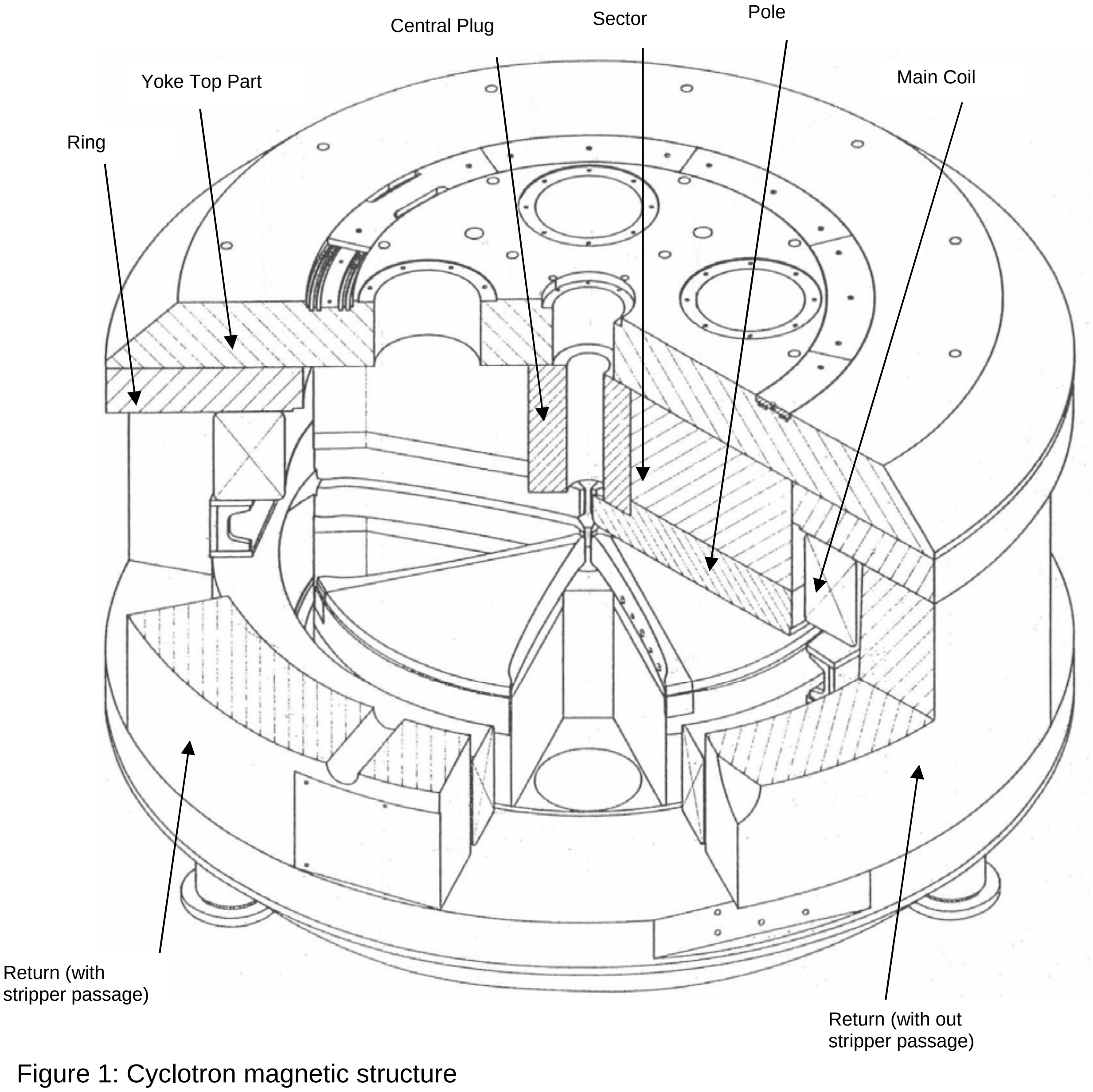

Figure 1: Cyclotron magnetic structure

Target nuclide	Reaction	Product
Li7	(p,n)	Be7
Fe56	(p,n)	Co56
Fe57	(p,n)	Co57
Fe58	(p,n)	Co58
Fe58	(n,γ)	Fe59 β^- decay --> Co59
Co59	(n,γ)	Co60
Fe54	(n,p)	Mn54
Pb207	(p,n)	Bi207
Cu65	(p,n)	Zn65
Mg25	(p,α)	Na22

Table 1. Identified isotopes and their most probable origin

3 RESULTS

The results for the different models are the following:

3.1 *Dose rates outside the closed tank*

The specific activity measured on the sample from the external surface of the yoke was taken as representative of the whole cyclotron structure. Based on this assumption and to estimate the dose rates produced outside the cyclotron we made a 3D model using MicroShield /2/. The results for dose rates at 50 cm from the external surface are in good agreement with those from the health physic survey, Ref/4/.

On the one hand, the calculated value from MicroShield using the source of table 3 (column Yoke exterior) distributed over the whole cyclotron structure was 10 microSv/hr at 50 cm. On the other hand, the values from Ref/4/ measured in the health physics survey were under 10 microSvhr far from detected hot spots. This is a conservative assumption not considering the higher activation of the internal structure.

This means that specific activity assigned to the region named yoke external is appropriate.

However, from the same calculation set it was observed that the specific activity in the yoke interior region could be even bigger without modifying the external dose rates values due to self shielding effect of the cyclotron structure. This is possible because the levels of the neutron flux were higher in the interior of the cyclotron, reaching its maximum over the region where the protons reaction occurred. An estimation of the neutron flux distribution will show a limit of the maximum internal specific activity. We now should compare the relative neutron fluxes from the exterior with that from the interior of the cyclotron, and this would give us a maximum value for the specific activity of the internal components.

3.2 *Neutron flux distribution*

In order to estimate the neutron flux distribution over the whole cyclotron we made another 3D model using MCNP /3/.

This model includes a neutron source over the pole faces, as shown in figure 2.

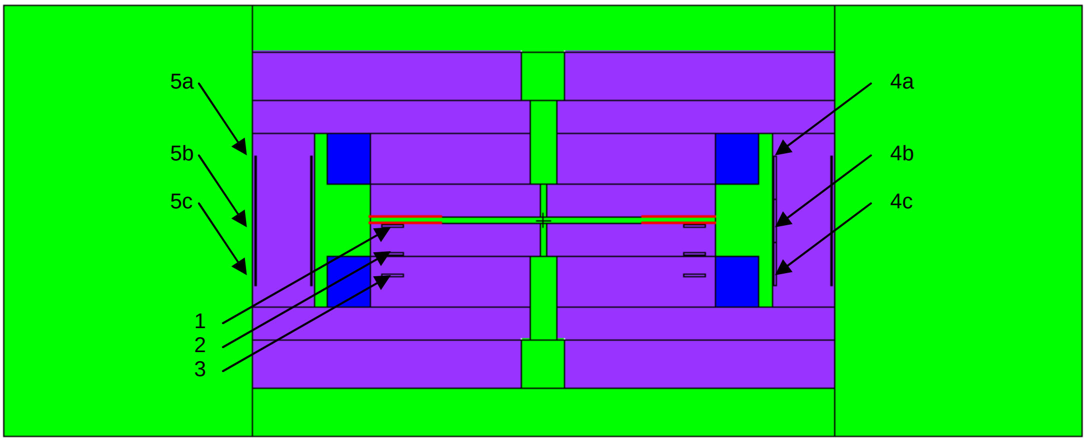

Figure 2: Neutron source on bottom and top pole faces (shown in red)

The neutron source energy was assumed to be homogeneously distributed over the range 0-10 MeV (range of possible neutron energies from the (p,n) reactions). The spatial distribution was supposed over an annular cylinder of 30 cm thickness, in accordance with the sampling region, and 0.1 cm height coincident with the maximum range of protons of energy lower than 30 MeV in steel, see fig 3 shown in red.

The small rectangles show the tally regions where the neutron fluxes were evaluated. The results are presented in table 2.

Tally Point	Relative neutron flux	Position
1	1.00	Pole surface
2	0.41	Pole 15cm
3	0.22	Pole 25cm
4a	0.22	Yoke interior
4b	0.31	
4c	0.25	
5a	0.02	Yoke exterior
5b	0.03	
5c	0.02	
Average	0.10	Magnetic structure

Table 2: Relative neutron flux distribution over the cyclotron volume

3.3 Dose rate inside the open tank

In order to verify if the assigned values for the pole face specific activity are acceptable we developed a 3D model of the open tank using MCNP. This model is presented in figure 3.

The model consist of a representation of the cyclotron structure with a gamma source distributed over the pole upper and lower surfaces faces and over the vacuum tank as indicated in figure 3. The intensity of that gamma source is given by the identified isotopes from samples taken from those regions.

A set of detectors (volume tallies from the MCNP code) were located within the region between the two halves of the open cyclotron in order to calculate the values of dose rate produced by the proposed maximum gamma source.

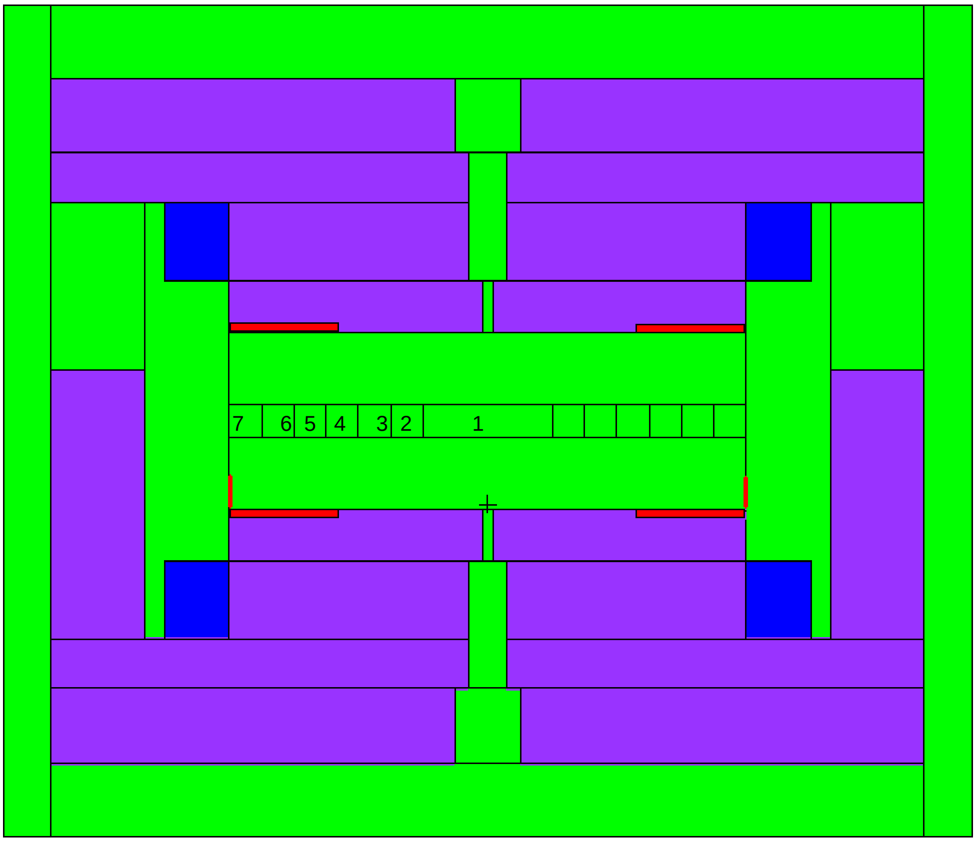

Figure 3: Gamma source on bottom and top pole faces and vacuum tank

The intensity of the gamma source due to the isotopes decay is given in 11 energy groups as shown in table 3

Energy group [MeV]	Intensity Apr/10 [γ/cm^3/sec]	Intensity Novr/10 [γ/cm^3/sec]	Intensity Apr/11 [γ/cm^3/sec]
0.015	4.76E+06	2.97E+06	1.86E+06
0.1	6.09E+06	3.82E+06	2.39E+06
0.15	7.55E+05	4.73E+05	2.97E+05
0.5	8.49E+04	2.09E+04	1.01E+04
0.6	1.14E+04	7.14E+03	4.47E+03
0.8	1.40E+05	3.38E+04	1.15E+04
1	7.85E+04	2.75E+04	1.65E+04
1.5	2.56E+04	2.06E+04	1.84E+04
2	2.10E+04	4.21E+03	8.45E+02
3	2.33E+04	4.68E+03	9.37E+02
4	1.40E+02	2.80E+01	5.62E+00
Total	1.20E+07	7.38E+06	4.61E+06
[MeV/cm^3/sec]	1.18E+06	6.20E+05	3.77E+05

Table 3: Gamma source

All the calculations were done using the data for Apr/10; the columns corresponding to Nov/10 and Apr/11 show that the total energy emitted will approximately halve every 6 month.

The results are presented in table 4.

Position	Tallies inside open tank	Calculated Dose Rate [mSv/hr]	Measured Dose Rate [mSv/hr]
1	1.26	0.5	0.2
2	1.44	0.6	
3	1.74	0.7	
4	2.17	0.9	0.6
5	2.71	1.2	
6	3.04	1.3	1.1
7	2.85	1.2	

Table 4: Dose rates inside the open tank. Comparison between measured and calculated values.

3.4 Source term evaluation

Finally, once the models have been compared against the measurements, and showed to be conservative, the source term is evaluated as follow:

The cyclotron structure is divided in several regions and each one has been assigned a maximum specific activity. This maximum specific activity was selected from the samples result in those sampled region where it was possible to access and from the estimated according to the methodology depicted in this report from those region where the access to sampling was impossible i.e. the interior of the bulk structure.

These maximum specific activities were then multiplied by the mass of the corresponding region from which a mass-weighted average could be determined.

The regions are:

- Pole Surface: The outer annular sector of the poles surfaces. 50 cm wide and 0.1 cm thick.
- Vacuum tank: the 5 cm height and 0.1 cm thick region of the vacuum tank, exposed to protons, between the upper and bottom pole surfaces.
- Magnetic structure: Corresponding to the bulk of the tank. It includes the yoke, the return, the ring, the sector , the central plug, etc all weighting 55 tons
- Yoke external: Corresponding to the outer region where the samples were taken Ref/5/. These values, see table 5, were used together with the neutron fluxes, to obtain the average specific activity of the Magnetic structure region.

Then the process, to compare against the limits, was done according to Ref/1/ paragraph 404. It states that for mixtures of radionuclides, the determination of the basic radionuclide values referred to in para. 401 may be determined as follows:

$$Xm = 1 / SUM [f(i)/X(i)]$$

Where:
f(i) is the fraction of activity or activity concentration of radionuclide i in the mixture;

X(i) is the appropriate value of A1 or A2, or the activity concentration for exempt material or the activity limit for an exempt consignment as appropriate for the radionuclide i; and
Xm is the derived value of A1 or A2, or the activity concentration for exempt material or the activity limit for an exempt consignment in the case of a mixture.

The values corresponding to LSA-I, the X(i) values, were calculated also as per Ref/1/ which establishes that the limits have to be lower than 30 times those for exempt materials.

In the one hand, using the f(i)'s and X(i)'s values from table 5, the obtained limit for the mixture is:

Xm = 604 Bq/gr;

On the other hand, the average specific activity for the cyclotron, XNMC, obtained from the total activity and the total mass is:

XNMC = Total Activity / total mass = 28740 MBq / 55 tons = 523 Bq/gr; which is lower than the applicable limit Xm.

The results show that the bulk of the cyclotron structure is rated as LSA-I material (Low Specific Activity) Ref/1/. Beside this, the maximum dose rate at 3 meters of the cyclotron does not exceed the value 2 mSv/hr, see health physics survey in Ref/4/. With these two conditions the package could be categorized as Industrial Package type 1 (IP-1).

The results are shown in table 5.

isotope	Pole surface	Vacuum tank	Magnetic Structure	Yoke external	Total Activity [MBq]	f(i)	X(i) [Bq/gr]
Be7	35000	52000	0	0	1883	0.07	30000
Co56	9200	15000	0	0	531	0.02	300
Co57	890000	74000	0	0	14004	0.49	3000
Co58	6200	220	0	0	90	0.00	300
Co60	2000	0	50	7	2780	0.10	300
Mn54	2000	79000	50	7	4924	0.17	300
Na22	680	95000	0	0	2588	0.09	300
Zn65	48	10000	30	4.2	1924	0.07	300
Bi207	11	570	0	0	16	0.00	300
Fe59	2	0	0	0	0	0.00	300
Mass [ton]	0.013477	0.027143	55	**Total Activity [MBq]**	**28740**		

Table 5: Specific activities in Bq/gr over the different regions of the cyclotron. Activity concentration factors f(i) and activity limits for exempt material X(i).

4 CONCLUSIONS

Considering all the conservative assumptions we have bounded the maximum possible specific activities over the cyclotron in order to rating the package as Industrial Package Type 1 (IP-1).

With regards to the potential collective dose that the personnel could receive during the dismantling works of the cyclotron, table 3 from section 3.3 shows that the intensity of the gamma source due to activation will half every 6 months which would lead to a proportional reduction of the dose rates.

5 REFERENCES

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