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Radioactivity of the Closed Loop Cooling Water of the Main Injector Beam Abort Dump

C. M. BHAT

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C.M. Bhat

Fermi National Accelerator Laboratory

P.O. Box 500, Batavia, Illinois 60510 [1]

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I. INTRODUCTION

The design aspects of the MI beam-abort dump and a study from the point of view of radiation shielding have been made very recently [1]. An estimated yearly operational beam abort on this beam dump will be about 3.8E18@120GeV (this is obtained by scaling the 8GeV and 150GeV aborted beam intensities to 120GeV as $E^{.75}$). This gives an average 3.4kW power dump over a year. While in an accidental beam abort on the beam dump there will be as high as about 3E13 to 1E14 per pulse at 150GeV during fixed target runs and gives about 0.3MW to 1.0MW power dump. Hence it has been decided to have an efficient core cooling system using water. The carbon core being highest radiation region of the beam dump the water flowing very near to it will also become radioactive due to the contamination of tritium and other radioactive nuclei. In this report an attempt has been made to develop a model to estimate the total increase in the tritium level activity of the water used for cooling the MI beam dump.

The MI beam dump is designed on the similar lines as the Fermilab TEV C0 beam dump[2]. In the case of TEV beam dump the core cooling water (LCW) is connected to the main MR magnet cooling LCW system with an intermediate storage tank. The purpose of this storage tank is to allow short-lived isotopes to decay before the water reaches the nearest serice building. Finally, the LCW is passed through a central de-ionizing system to keep the conductivity of the water low and to remove the heavier radioactive contaminations. Since the de-ionizing system is incapable of separating the tritium contamination, the tritium will slowly buildup in the water. Since the activated water from the dump is being mixed up with other LCW (i.e. with about 6000 gallon of LCW) the dilution factor is considerably large and the radioactivity

[1] Operated by the Universities Research Association, Inc., under contract with U.S. Department of Energy

is low. For MI beam dump it has been planned [3] to have a closed loop water with a separate heat exchanger to reduce the added tritium contamination in MI magnet cooling LCW. The closed loop cooling water need not be LCW. To keep water clean a filter may be enough. The out going water temperature is expected to be 175°F and incoming water will be at 130°F with a water flow rate of 156gal/min. The 95°F water from the MI magnet cooling system will be used in this heat exchanger to absorb the heat energy from the warm water coming from the beam dump.

II. CALCULATION OF TRITIUM ACTIVATION IN COOLING WATER AND DISCUSSIONS OF THE RESULTS

The interaction of high energy particles with a beam dump will develop hadronic and electromagnetic showers which will produce residual radioactivity in the dump material and the water used to cool it. One of main radioactive contamination in the water is tritium which are produced by the nuclear reactions like, O(x,^{3}H)Y1 and Al(x,^{3}H)Y2. The oxygen nuclei are from water and the Al target is from the core cooling aluminum box. The induced radioactivity C_{tri}, arising from the tritons in the water after it has been exposed to the beam spill for time 't' is given by,

$$C_{tri} = \frac{N_{tri}}{\tau_{tri}}$$

where τ_{tri} is the mean life of tritons in seconds. N_{tri} is total number of tritons produced in the water by pulsed beam. (See Appendix I for detailed derivation for N_{tri} for both pulsed and continuous beams. Some comparison with observations are also given.) The number of tritons, N_{tri}, has the form,

$$N_{tri} = N\sigma_{tri}S(1-\frac{dt}{\tau_{tri}})\frac{\tau_{tri}}{dt}\{1-(1-\frac{dt}{\tau_{tri}})^m\}.$$

N is the average number of primary protons on the beam dump per pulse. σ_{tri} is the probability of tritium production per one star in the water. S is the total number of stars produced in the water per one primary proton. m = $\frac{t}{dt}$. dt is an average time gap between successive beam aborts. The mean life of triton is 17.79 years.

To evaluate the number of stars, S, produced in the water flowing through the aluminum box we used a cylindrical geometry in the Monte Carlo code CASIM[5]. The carbon core of 3.4in radius (which has same cross sectional area as 6inX6in carbon core [1]) is assumed to be surrounded by 1.3in thick water symmetrically. The aluminum box extends radially up to about 6.7in and finally steel is added.

This simulation predicts about 10.3stars/protons @150GeV. The probability for triton production per star is 0.075 from Ref. 6.

Here we have made calculations for normal operational beam abort as well as an accidental beam loss. For operational losses, we estimate the radioactivity for irradiation period of 1 year and 10 years. The results for tritium contamination are summarized in the Table I below. The total amount of water in the closed loop system is assumed to be about 210 gallon[4]. The water capacity of the core cooling aluminum box is 10 gallon (i.e. about 5% of the total aluminum box volume). At any time only this amount of water is exposed to the direct hadronic and electromagnetic showers.

Table I. The radioactivity of the cooling water of the MI beam abort dump arising from tritium contamination. The total amount of the water in the closed loop is about 210 gallons.

Conditions	N, Protons/pulse	Time of Irradiation	Radioactivity due to tritium
Operational* Beam Abort	4E18 @150GeV/year	1 year	.18μCi/ml of LCW
	4E18 @150GeV/year	10 year	1.44μCi/ml of LCW
Accidental Beam Abort	5.6E16/hour High Intensity Fast Spill (1spill/1.9sec)	1 hour	2.6nCi/ml

* dt = 2sec. For calculation purpose we have assumed that the aborted beam is distributed over a period of one year. In reality the abort will occur in a random fashion. For example during accelerator study time the beam abort will be very often but of low intensity. For accidental beam abort the intensity of the beam may be quite high but generally for shorter duration.

The results shown in the Table I use the Monte Carlo estimations of the stars in the water which is flowing through the aluminum box at the time of beam spill and we neglect the stars produced in other volume of the water. In the closed loop cooling water system the same water will be circulating approximately once in 1.34min if the total amount of the water is about 210 gallon. Hence the tritium will slowly build up. Besides the tritium production, many other radioactive nuclei will also be produced. A list of radioactive nuclei identified in the samples of LCW from pbar beam dump is listed in Table II in the Appendix I. If we have a de-ionizing system attached to the water line then the heavier radioactive nuclei can be removed from the water almost continuously and the radioactivity can be kept lower atleast by about 30%.

The errors in the above estimation has two sources. First, the errors in Monte Carlo calculations of star/proton. We believe that the actual number of stars are larger than the one obtained from CASIM calculations. This might arise from the fact that a) the threshold for hadronic production in CASIM is 50MeV and hence the tritons produced at lower energy are neglected and b) approximations to the geometry of the beam dump. Besides these errors, there is some uncertainty in the triton production cross section per star, i.e. σ_{tri}. A σ_{tri} of .113/star [7] is used at CERN which is about 50% larger than the value quoted in Ref. 6. Hence with all these errors taken into account we may have to design a close loop water system with a safety factor of about two builtin. The Fermilab sets a specific activity to be below .67μCi/ml for closed loop LCW[6]. From the Table I we find that if the total amount of closed loop water is kept at 210 gallons for MI beam abort dump and total amount of beam aborted per year maintained the same then the water has be replaced approximately once in every two years which is not unreasonable.

REFERENCES

1. C.M. Bhat, MI Note-86, July, 1993.
2. C.T. Murphy et al, Fermilab TM-1196
3. Title 1 Design Report FERMILAB MAIN INJECTOR, August 1992.
4. J. A. Satti (Private communication)(1993).
5. A. Van Ginneken, CASIM Fermilab,FN-272 (1975).
6. ESH Radiological Control Manual FERMILAB, (1992).
7. Radiological Considerations for the Environment around the LHC edited by G.R. Stevenson and R.H. Thomas, May 1989, CERN-TIS/89-19
8. A. F. Leveling, (private communication) 1993.

Appendix A

A. INDUCED RADIOACTIVITY IN WATER BY A PULSED HIGH ENERGY BEAM (i.e. dt $\neq 0$)

Let N be the number of incident particles per pulse on the beam dump and let the time intervals between two successive pulses be *dt*. As a result of interaction between the beam secondary and the water many tritium nuclei are formed almost instantaneously. Let σ_{tri} be the probability that a tritium nuclei is produced per star in the water. The beam pulses, for example in MI, are of the order of 11μsec long as compared with dt ($\simeq$ 2sec). Let V_o the total volume of the water in the core of the beam dump during the beam spill and S be the number of stars produced in it. Then the number of the tritium nuclei formed per spill will be,

$$N\sigma_{tri}S$$

Now let τ_{tri} be the mean life of the tritium. Then total number of tritium nuclei left by the end of time dt, i.e. before next beam spill is,

$$N_1 = N\sigma_{tri}S(1 - \frac{dt}{\tau_{tri}}) \tag{1}$$

$$= N\sigma_{tri}Sy$$

This follows from the fact that total number of tritium decayed in time dt is proportional to number of tritium, decay constant and dt. For convenience we replace $(1-\frac{dt}{\tau_{tri}})$ by y in the above equation. Similarly by the end of 2dt the number of tritium not decayed will be

$$N_2 = N\sigma_{tri}S(y + y^2) \tag{2}$$

Continuing similar accumulation of the tritium for time t i.e. for m $= \frac{t}{dt}$ number of beam spills we get total number of tritium left will be,

$$N_m = N_{tri} = N\sigma_{tri}S(y + y^2 + y^3 + ... + y^m)$$

$$= N\sigma_{tri}Sy\frac{(1-y^m)}{(1-y)} for y^2 < 1 \tag{3}$$

Thus by the end of the time t the rate of disintegration or partial activity of the tritium is,

$$C_{tri} = \frac{N_{tri}}{\tau_{tri}}$$

B. INDUCED RADIOACTIVITY IN WATER BY HIGH ENERGY BEAM (dt $\rightarrow$ 0)

(A. Van Ginneken)

The rate of change of number of tritons in a given amount of the closed loop water is dependent upon the rate of its production and the rate at which it decays and is given by,

$$\frac{dN}{dt} = -\lambda_{tri} N + P$$

$\lambda_{tri} = \frac{1}{\tau_{tri}}$ is radioactive decay constant of the tritium. P= $N\sigma_{tri}S$ is the production rate of the tritium. By integrating from time =0 to time = t we get the total accumulation of the tritium nuclei in the water as,

$$N_{tri} = \frac{P}{\lambda_{tri}}(1 - e^{\lambda_{tri}t})$$

The rate of disintegration or specific activity of the tritium after time t is,

$$C_{tri} = \frac{N_{tri}}{\tau_{tri}}$$

It is important to note that if the time interval dt is large (e.g. relative to the life times of the radioactive nuclei) then the first method gives reliable results. Otherwise the second method is quite simple and good enough for most of the cases.

If more than one radioactive nuclei are produced their specific activity have to be added together to determine the total activity of the water.

C. A COMPARISON BETWEEN OBSERVED AND PREDICTED RADIOACTIVITY IN WATER

In this part of the report we tried to estimate the radioactivity of the Fermilab Pbar source closed loop LCW and compare it with the measurements[8]. After the 1993 1A collider run the samples of LCW from the closed loop systems of the Li-lens, newly installed pulsed magnet and the pbar source beam dump have been collected. These samples have been analyzed about two and half months after they have been collected. The Table II displays the observed radioactive contamination and their activations.

Table II. The radioactive contamination in the LCW samples collected from pbar production closed loop water systems. The primary beam was stopped in May 1993, samples were collected in June 1993 and analyzed in the month of August 1993 by TMA. (These data were supplied by A.F. Leveling of Fermilab.)

Wednesday August 18, 1993

Location	Sample ID	Analysis Type	Media Type	Vendor ID	Parameter	Preanal	LLD	Result	Error	Units
AP0 DUMP RAW	930607TB03	1S	Water	TMA	Ca-45			4784.063	310.98	pCi/ml
				TMA	H-3	DIR		209840.07	13640	pCi/ml
				TMA	Be-7			844.900	3.692	pCi/ml
				TMA	Co-60			80.170	3.904	pCi/ml
				TMA	Mn-54			11.010	0.205	pCi/ml
				TMA	Na-22			33.350	0.261	pCi/ml
				TMA	Co-58			150.900	0.562	pCi/ml
				TMA	Zn-65			9.919	0.478	pCi/ml
				TMA	Cd-109			26.010	4.938	pCi/ml
				TMA	Co-56			23.610	0.313	pCi/ml
				TMA	Co-57			76.590	0.194	pCi/ml
AP0 LENS RAW	930607TB02	1S	Water	TMA	Ca-45			186.115	12.113	pCi/ml
				TMA	H-3	DIR		7475.421	486.11	pCi/ml
				TMA	Be-7			42.230	0.713	pCi/ml
				TMA	Co-60			0	0.013	pCi/ml
				TMA	Mn-54			0	0.036	pCi/ml
				TMA	Na-22			0.122	0.025	pCi/ml
				TMA	Sc-46			1.640	0.066	pCi/ml
AP0 PMAG RAW	930607TB01	1S	Water	TMA	Ca-45			600.217	39.030	pCi/ml
				TMA	H-3	DIR		20062.773	1304.3	pCi/ml
				TMA	Be-7			5890.000	8.014	pCi/ml
				TMA	Co-60			9.388	0.140	pCi/ml
				TMA	Mn-54			30.510	0.213	pCi/ml
				TMA	Na-22			1.118	0.070	pCi/ml
				TMA	Co-58			99.190	0.421	pCi/ml
				TMA	Zn-65			33.540	0.375	pCi/ml
				TMA	Cd-109			13.790	4.356	pCi/ml
				TMA	Co-56			15.850	0.207	pCi/ml
				TMA	Co-57			38.940	0.130	pCi/ml

Table III. A comparison of the predicted radioactivity of the closed loop LCW from Pbar source with the measured activity. The total amount of the LCW in each system is assumed 15 gallon.

System	LCW Exposed/ Spill (lt)	Number of Stars/ proton	Radio- active Nuclei[@]	Radio- activity Predicted* (pCi/ml)	Radio- activity Measured (pCi/ml)
Pulsed Magnet	.5	0.016	^{3}H	1.6E+4	2.0E+4
			^{7}Be	3.8E+4	5.9E+3
			^{22}Na	1.7E+4	1
Beam Dump	4.0	.21	^{3}H	2.1E+5	2.1E+5
			^{7}Be	5.0E+5	8.4E+2
			^{22}Na	2.3E+5	33

@ Mean life and production cross section per spellation :
^{3}H : $\tau = 17.8$year and $\sigma = 0.075$/star (from ref. 6)
^{7}Be : $\tau = .21$ year and $\sigma = 0.032$/star (from ref. 7)
^{22}Na : $\tau = 3.75$ year and $\sigma = 0.02$/star (from ref. 6)
* Prediction from two methods presented above agree within a fraction of a percent in this case.

To estimate the radioactivity using the models presented above one has to evaluate number of stars produced in the LCW. The pbar production system is not being cylindrically symmetric exact modeling in CASIM is rather cumbersome. However for close proximity we used cylindrical geometry and estimated total stars produced in the LCW in each of the cooling system. The results are shown in Table III. The amount of the water in the pulsed magnet and beam dump are also shown in Table III. A beam intensity of 2.1E12ppp with a duty factor of .65 is assumed. The average pulse repetition rate was once in every 2.65sec. (This comes from the fact that the maximum value of pulse repetition rate was a pulse/2.4sec and minimum rate was a pulse/3.2sec. The minimum was reached when the pbar stacking rate got lowered because of the high pbar stacks in the accumulator ring. Therefore an average pulse repetition rate of one pulse/2.65sec is taken here). Then the predictions were made only for three dominant radioactive contamination. The agreement between predicted and measured radioactivity of the LCW are reasonably good especially in the case of ^{3}H. For others the prediction is rather poor, especially in the case of ^{22}Na. Here the production cross section is taken from Fermilab radiological control manual. A value of .02/star is suggested for ground water contamination in the case of soil. Using this value may be inappropriate in this context because production cross section for ^{22}Na (which is heavier than ^{16}O) in LCW is expected to be much smaller than 0.02. The observed contamination might be coming from copper or steel. The results for Li-lens is completely omitted here because the closed loop LCW was leaking very often and new water was being added timely. Hence the data presented in Table II for Li lens can not be used in the present models.