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Activation estimates of the RHIC beam dump

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Electron-Ion Collider

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DISCLAIMER

Activation estimates of the RHIC beam dump

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In anticipation of the expiration of the RHIC ASE in December 2025 and the need to demonstrate compliance with nuclear facility rule (10CFR830), this study quantifies the radionuclide inventory and respective activity at the beam dumps by simulating a period of five years of operation using conservative assumptions. Simulations were performed with the Monte Carlo particle transport and interaction code FLUKA and its dosimetry results were compared with measured dose rate data, showing good agreement. The beam dump was deemed to constitute the main hotspot of residual radiation and also representative of a worst case scenario in terms of induced activation. The activation levels calculated indicate that the RHIC tunnel will be well below the thresholds of a DOE's category-3 nuclear facility classification.

ACRONYMS

ALARA As low as reasonably achievable.

ASE Accelerator Safety Envelope.

DOE Department of Energy

EIC Electron Ion Collider

EOB End of Bombardment

FLUKA FLUktuierende KAskade Monte Carlo particle transport and interaction code

MC Monte Carlo

RHIC Relativistic Heavy Ion Collider

SAR Safety Analysis Report

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I. INTRODUCTION

In between the time that the RHIC ASE expires, at the end of 2025, and the approval of the first EIC ASE the possibility exists that the RHIC Tunnel will not be eligible to be authorized under the DOE Accelerator Safety Order. In that case, the tunnel will be managed as a DOE radiological/nuclear facility, which requires a full characterization of the tunnel's radioactivity.

In this work, the Monte Carlo particle transport and interaction code FLUKA [1, 2] (development version 2024.0) was used to calculate the specific activity in the "yellow" and "blue" beam dumps, after a 5 year operation period from 2013-17. These activity values were subsequently analysed to determine whether they would fall below the DOE's Category-3 nuclear facility classification. The choice of the beam dumps as the main foci of this study was supported by existing radiation survey data, from 2017 and also recent surveys from 2021 up to August 2023 [3]. To ensure the validity of the activity estimates, residual radiation levels were simulated for the beam dump and compared with the survey data collected in 2017.

II. MATERIAL AND METHODS

A. Simulated geometry and materials

The beam dump geometry was reproduced in FLUKA for the radiological calculations and its inner structure is described in figure 1.

Longitudinally, the beam dump is approximately 5 m long and is surrounded laterally and vertically by at least 15 cm of steel shielding. In addition, the lateral steel shielding is enclosed between two 15 cm thick marble walls along its whole length. Due to the dump's design and shielding configuration the radiation fields are the highest longitudinally, particularly at the entrance (figure 2).

Material composition of the beam dump itself consisted of solid carbon, graphite and steel with 0.5, 2.6 and 2 m thicknesses respectively [5]. Most of the surrounding shielding was made of steel and the material composition adopted in this study was adapted from a previous RHIC work [6, 7] to ensure the validity of the activity estimates. Marble chemical composition can also differ greatly, this work employed a relatively common marble chemical composition [8].

B. Source term details

Since RHIC operation is quite complex, some approximations were used to create a FLUKA irradiation profile representative of the 2013-17 period. This time range was chosen because it was a particularly intense research period in which high energy ion beams were employed, hence there exists an expectation to observe relatively elevated radioactivity levels in the dumps post bombardment.

Species injected into the ring in the 2013-17 operation period consisted mainly of protons and Au ions, but included deuterons, helions and Al ions of various energies as well. For ease of computation, the source term was defined considering the maximum energy per nucleon of each species during a given run.

Besides the variable energy of the particles delivered to the ring, RHIC's runs can differ greatly in terms of number of particles injected. This is because the ring is filled with several particle bunches and beam is kept stored until its quality degrades and/or the decision is taken to dump the beam. Morevoer, this beam "lifetime" can vary widely due to various physics processes such as, for instance, beam-beam interactions [9]. To create an irradiation profile for the whole 5 year period it was assumed that the total number of particles injected for each species/energies in a run were delivered to the dump at a constant rate throughout the run's beam operation period. The data for the total number of particles is compiled in table I

TABLE I. *Summary of total particles delivered to the ring and assumed to be dumped throughout 2013-17. Note that these values do not reflect the beam loss factors, which were later applied in the FLUKA calculations.*

	Blue dump			Yellow dump		
Run	ion	E [GeV/n]	# [$\times 10^{12}$]	ion	E [GeV/n]	# [$\times 10^{12}$]
13	p	259.4	11000	p	259.4	11000
14	Au	100	46	Au	100	57
"	h	103.5	410			
15	p	100.2	12000	p	100.2	7800
"				Au	100.2	32
"				Al	100	83
16	Au	100	96	Au	100.9	140
"	d	100	6800			
17	p	259.4	11000	p	259.4	8900
"	Au	27.2	32	Au	27.2	30
"	p	259.4	110[a]	p	259.4	89[a]

[a] The number of protons in mode 1B of run 17 was estimated as 1% from the run total based on the relatively few physics days and reported high number of failures

Since the beam dumps are almost identical, the same beam dump geometry model was used in the radiological calculations but with either the blue or yellow irradiation profiles detailed in table I.

To avoid overly conservative estimates, the irradiation profile was further corrected to account for beam losses. In relative terms, during operation, beam losses are the greatest at the collimators (e.g. $\sim 45\%$ in 2023) [10]. However, these numbers do not account for the dump events and the fact that the vast majority of the particles in the ring are eventually lost in the dump by design. These annual beam losses, including aperture losses, intra-beam losses and beam-gas effects were estimated in the 90's to be relatively low resulting in $\sim 97\%$

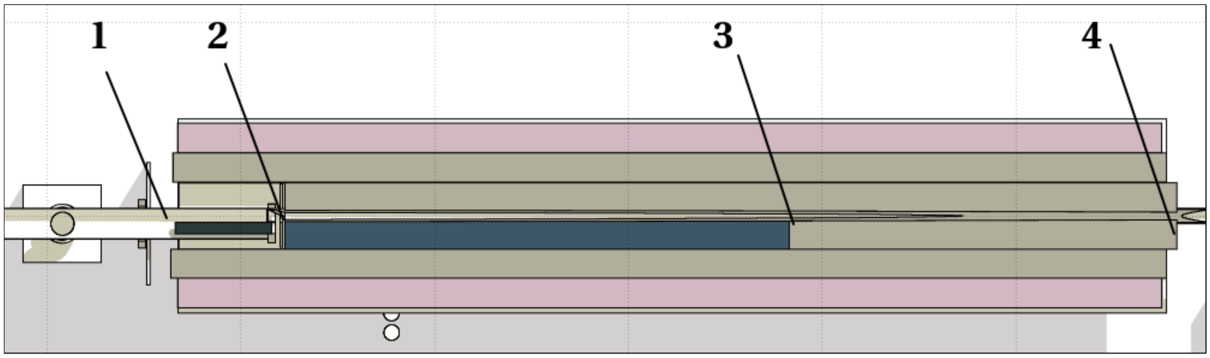

FIG. 1. *Top view of the RHIC beam dump model in flair Geoviewer [4] at beam elevation. Beam direction is from left to right and the beam is "kicked" so as to interact with the core of the dump in the following sequence: 1) entrance of the dump and solid carbon section; 2) window and beginning of the graphite dump core; 3) steel section and; 4) end of the dump. The distance between 1-4 is* ~ 5 m *long.*

FIG. 2. *Upstream side of the beam dump (5 January 2024).*

of the protons and $\sim$ 82% of the gold ions effectively "dumped" [11]. In time, as RHIC operation's luminosity increased and operation became overall more complex, the beam loss mechanisms related to beam–beam interaction played a more relevant role leading to large tune spread, emittance growth, and short beam and luminosity lifetimes [12]. Therefore, in a compromise between a credible and conservative result, this study will consider a baseline of 5% loss outside of the beam dump for the proton, deuteron, helion and 25% for the Al and Au ions.

C. Survey Data

Survey data collected at both beam dumps during run 17 was provided by the Radiological Control Division and consisted of a series of reports with measurements performed with either a RO-20 Ion Chamber and a Telepole (GM-based detector) at: 12 February; 1, 9, 16 and 30 March; 20 April; 30 May; 14, 21, 28, 29 and 30 June.

The 2017 RHIC operation campaign lasted from 12 February until 27 June hence the first measurement took place prior to operation and the last three dates correspond to measurements post EOB.

In these reports, general dose area measurements were performed at the dump's inboard and outboard areas, as well as downstream and upstream of it. In the latter two cases the results would also be complemented with contact readings.

D. Nuclear Facility designation thresholds

DOE's Order 5480.23, Nuclear Safety Analysis Reports, specifies requirements for "safety analyses involving DOE nuclear facilities, and for submittal, review, and approval of contractor plans and programs to meet these requirements." One of such requirements is that, as part of the methodology for hazard categorization, threshold quantities of hazardous materials are not exceeded, otherwise this would mandate the creation of a SAR [13].

When multiple radionuclides are featured in a facility source term inventory it shall be designated as Category 3 if the sum of the ratios of the quantity of each n material Activity (A) to the Category 3 thresholds (T3) exceeds one, e.g.:

$$\frac{A_1}{T3_1} + \frac{A_2}{T3_2} + (...) + \frac{A_n}{T3_n} > 1$$

The DOE Hazard Category-3 (CAT-3) Nuclear Facility isotope thresholds were retrieved from "DOE-STD-1027-92, Chg. 1" and the LANL Fact Sheet containing Hazard Category 3 Threshold Quantities for the ICRP-30 List of 757 Radionuclides [14].

III. RESULTS

1. *Dosimetry assessment*

An example of the distribution of residual ambient dose equivalent rates calculated with FLUKA 1 day post EOB (28 June 2017) after 5 years of operation starting in run 13, is depicted in figure 3.

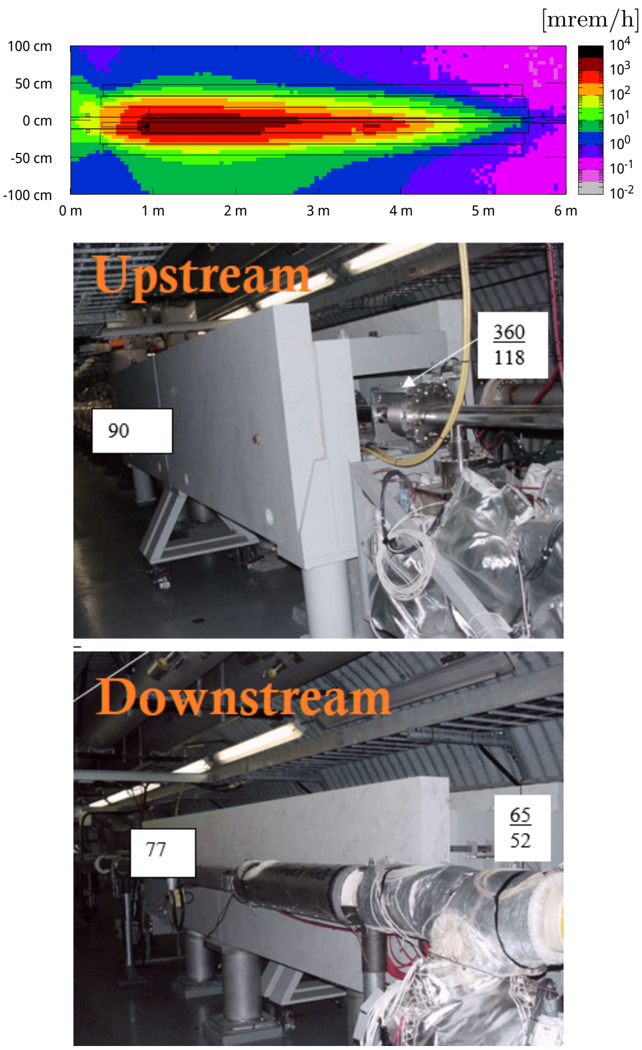

FIG. 3. *Top panel: Plan view of H*(10) [mrem/h] for the blue dump at 1 day post EOB calculated with FLUKA. Beam travelled from left to right and the dose rates are averaged over 10* cm*, centered at beam level. Lower panels: excepted from the radiological survey report at 1 day post EOB, all survey values are in mR/h and general area doses except for the values underlined, which are contact readings.*

A comparison between the simulated H*(10) rates, accounting for beam losses, and the data acquired during surveys throughout and immediately after run 17 is shown in table II. The symbol $\mathfrak{F}$ denotes the FLUKA results calculated in this work whereas $\mathfrak{S}$ indicates the survey data. Only the general area dose rates' survey results upstream of the beam dump were compared with the simulation data to mitigate the impact of artifacts related to: 1) self-shielding of non-modeled components, 2) low statistics, and 3) inconsistent locations of contact readings. The effect of the difference in units (i.e., mrem versus mR) in the comparison was also neglected

TABLE II. *FLUKA H*(10) simulation ($\mathfrak{F}$) and survey ($\mathfrak{S}$) data for general area dose rates upstream of each beam dump at different times both during the run 17 period and shortly afterwards. The EOB date (27 June) is underlined.*

	Blue dump		Yellow dump	
Day	$\mathfrak{F}$ [mrem/h]	$\mathfrak{S}$ [mR/h]	$\mathfrak{F}$ [mrem/h]	$\mathfrak{S}$ [mR/h]
30 Jun 17	*104.2*	*84*[a]	*89.1*	*16*[a]
29 Jun 17	*107.4*	*74*[a]	*92.0*	*22*[a]
28 Jun 17	*111.3*	*118*[a]	*95.4*	*23*[a]
<u>27 Jun 17</u>	*222.0*	–	*183.7*	–
21 Jun 17	–	–	*117.1*	*43*[a]
12 Feb 17	*21.2*	*2.5*[b]	*15.2*	*2.0*[b]

[a] Telepole
[b] RO-20

2. *Activation analysis*

The activity levels in the steel core of the blue dump at EOB can be visualized in figure 4 (isomers were excluded for ease of visualization purposes). Note that due to material and volume considerations it is reasonable to expect that the steel core of the dump contains the bulk of activity.

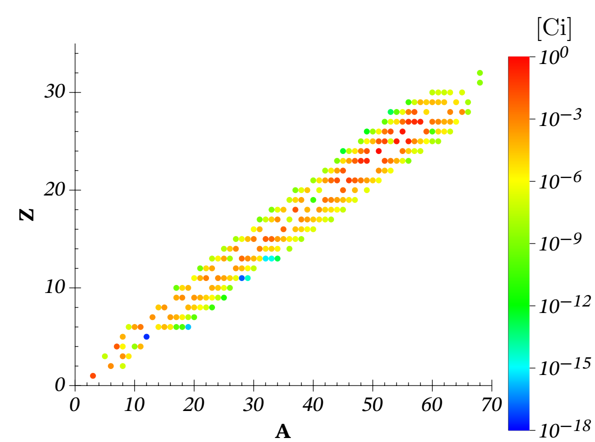

FIG. 4. *Activity levels [Ci] scored in the blue beam dump steel core at EOB.*

Specific activities of relatively long-lived cobalt isotopes ($^{56-58,60}$Co) were scored at EOB as well, their distribution throughout the blue beam dump can be visualized in figure 5.

For all sections of the blue beam dump, including its core (C-C, graphite, steel), the W window, pipe, as well as the marble shielding and structural steel components

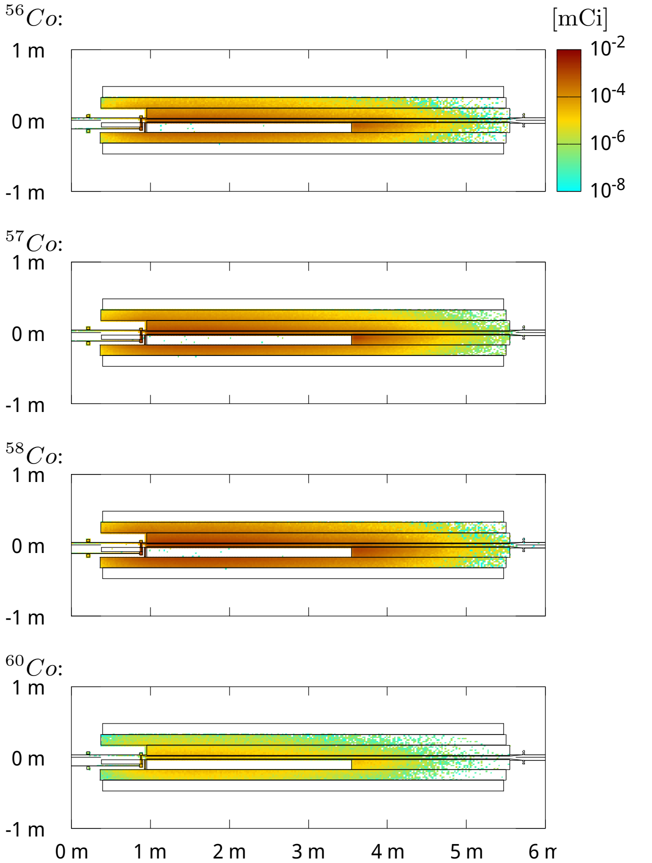

FIG. 5. *Distribution of FLUKA calculated Activity [mCi] at EOB for selected Co isotopes. The values are averaged over a 10* cm *thickness centered at beam line elevation. Beam direction is left to right.*

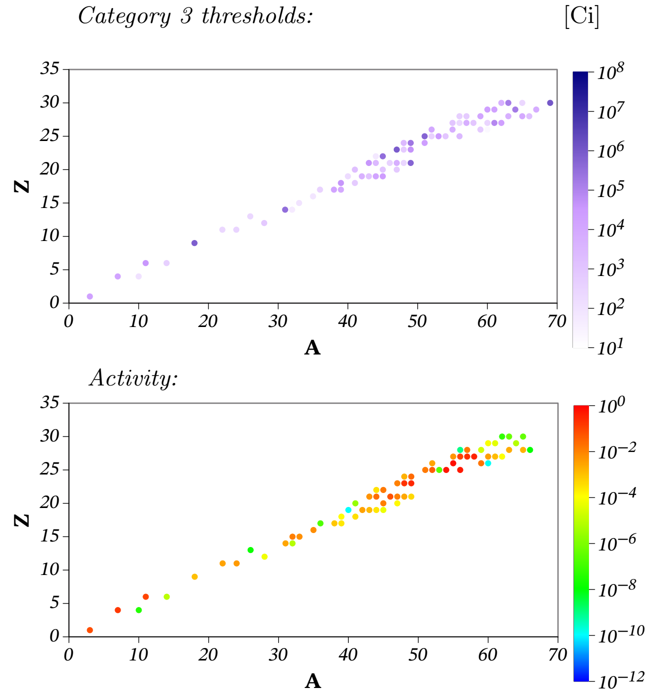

FIG. 6. *Category 3 thresholds (top panel) and Activity (bottom panel) scored in the blue dump for the isotopes for which threshold information is available. All values in Ci.*

such as pedestals, the activity levels of the isotopes of interest were compiled and are detailed in figure 6, along with the corresponding Category 3 thresholds.

The sum of ratios calculated immediately at EOB for each beam dump is listed below:

Blue dump

$$\sum_{n=1}^{n} \frac{A_n}{T3_n} \approx 0.0033$$

Yellow dump

$$\sum_{n=1}^{n} \frac{A_n}{T3_n} \approx 0.0028$$

A. Discussion

Although only a limited set of points (4) were measured in each survey report, the spatial distribution of residual radiation fields observed in figure 3 was relatively consistent with the distribution inferred from the survey records.

More importantly, the magnitude of the residual dose rates calculated with FLUKA for the blue dump was found to be within 10% of the 1 day EOB surveyed result as per the results in table II, slowly diverging afterwards but always within a factor of 2. The discrepancy between simulated and surveyed results was greater for the yellow dump, both at EOB and afterwards, at approximately a factor of 4-5. It should be noted that at the end of run's 17 mode 1A and 2 the yellow dump's survey results are relatively closer (within a factor of 3) to the simulated values. This fact points to an overestimation in the FLUKA modeling of the irradiation profile of mode 1B (21-27 June 2017) for the yellow dump, *i.e.*, the 1% indicated in table I. Survey results post EOB also differ significantly between the blue and yellow dumps.

The survey data from 12 February in table II is considerably lower than the simulated values, confirming that our estimates were systematically more conservative. This was also expected due to our modeling of a generally more conservative irradiation profile (with maximum energy beam, relatively low losses), and also perhaps a material composition of the dump that is more susceptible to long term activation. The larger difference in the 12 February results could be also ascribed to the equipment utilized for the surveys. For instance, the Telepole was found over time to over-respond at lower dose rates and, due to its shape and the beam dump's geometry, it can get closer to the hotspots upstream than the RO-20 instrument. Adding to all these variables, there are normal fluctuations related to the location at which the survey is actually performed, evidence of which can be seen in table II, where the blue dumps' 29 June surveyed value is lower than the 30 June one.

Overall Activity levels in both beam dumps at EOB were relatively high and mostly concentrated in the metallic components of the dump, particularly the steel core as shown in figure 4. The distribution of cobalt isotopes contributing to the long term activation (see figure 5) supports this statement.

Only a subset of the FLUKA calculated inventory (~ 80 out of several hundreds of isotopes species in the whole dump) are actually contributing to the radiological facility classification within the ranges of isotope masses scored. The contributing isotopes can be visualized in figure 6, along with the respective thresholds. The sum of ratios calculated for each beam dump is far lower than 1, totaling ~ 0.005 when yellow and blue beam dumps' ratios are summed up.

IV. CONCLUSION

The dosimetry simulation results obtained in this work were in good agreement with the reported dose rates from the blue beam dump survey post EOB, less so for the yellow dump but generally within a factor of ~ 5.

Since the beam dumps are the main sources of induced radioactivity in the RHIC tunnel, and even though the dosimetry results were relatively conservative, the beam dumps' combined weighted activity ratios were found to be over two orders of magnitude below the limits of DOE's category-3 nuclear facility classification.

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