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Evaluation of neutron dose rates at the HBS prototype target station

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ABSTRACT

At Forschungszentrum Jülich, the High Brilliance Neutron Source (HBS) project aims to provide a efficient source for various scattering, analytical and imaging applications in science and industry under the concept of High-Current Accelerator-driven Neutron Sources (HiCANS). To ensure the radiation safety, the shielding design of the source is of great importance. In this work, neutron dose rates were evaluated at the JULIC neutron test platform, which was designed to test key components of the HBS. In the vicinity of the target station the measured neutron dose rates were below 5 mSv/h for proton currents up to 0.11 μA. Monte Carlo simulation using PHITS confirmed these results, with the calculated dose rates generally agreeing with the experimental data. It demonstrates the effectiveness of the multilayered shielding of the target station design for HBS.

1. Introduction

Over the last years, High-Current Accelerator-driven Neutron Sources (HiCANS) have been met with increasing interest and represent a viable option for the next generation of neutron sources (Zakalek et al., 2025). The High Brilliance Neutron Source (HBS) developed by the Jülich Centre for Neutron Science at Forschungszentrum Jülich, is designed to provide high neutron brightness for various scattering, analytical, and imaging instruments (Gutberlet et al., 2023; Brückel et al., 2020, 2023a,b).

The HBS design in its final upgrade features a linear particle accelerator that generates a pulsed proton beam with a proton energy of 70 MeV, a peak current of 90 mA and a duty cycle of 1.6% resulting in an average current of 1.44 mA and an average thermal load of 100 kW at the neutron target. The latter is made of tantalum and cooled by microchannel technology (Baggemann et al., 2024; Ding et al., 2023). The primary neutron emission reaches 10^{15} s^{-1} in $4\pi \cdot sr$ with a broad neutron energy spectrum and a peak value around 1 MeV. The generated high-energy neutrons are moderated for effective utilization with light water as a thermal moderator. Optional cryogenic coolant like solid methane or liquid hydrogen are available as one dimensional cold moderators (Eisenhut et al., 2020). The water moderator is surrounded by a neutron reflector made of lead due to its high scattering and $(n, 2n)$ cross sections for fast neutrons and its low moderation effect (Rücker et al., 2024). With all the nuclear reactions in the Target Moderator Reflector (TMR) unit, a high neutron/gamma radiation field is generated.

A critical component of the HBS design is the shielding of the TMR unit, which together with the walls of the bunker of the neutron source must ensure neutron and gamma dose rates as low as is reasonably achievable to avoid unnecessary radiation exposure of personal working in adjacent rooms during neutron source operation. Furthermore, the shielding should allow various maintenance work in the bunker of the neutron source after shutdown of the accelerator. Compared to conventional nuclear reactors, which typically operate with well-characterized thermal neutron energy spectra, the neutron spectrum of the TMR unit in the HBS design is much broader and contains a large number of fast neutrons in addition to thermal neutrons. The shielding must take into account both the broad neutron spectrum and the gamma radiation, which requires a multi-layer structure to effectively attenuate the radiation fields. In addition, the dimensions of the TMR shielding should be optimized so that optical elements such as neutron guides, choppers, or slits of the various instruments can be positioned as close as possible to the neutron source in order to make optimum use of the neutrons produced. Furthermore, thermal management is important in such a compact system, and cooling and material performance under irradiation need also to be considered.

The shielding concept of the TMR units consists of alternating layers of pure lead (8 cm thickness) and Borotron (polyethylene blended with

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B_2O_3 containing 5 weight% elemental boron) with thickness varying between 11.5 and 31 cm placed in a steel housing. The walls of the bunker are considered of ordinary concrete with 50 weight% iron aggregate and a thickness of 140 cm. The detailed geometry of the shielding of the TMR unit, the dimension of the bunker as well as the total (neutron and gamma) dose rate distribution determined with the transport code PHITS (Sato et al., 2024) are given in Gutberlet et al. (2023). During operation the average dose rate at the outer surface of the shielding of the TMR unit is calculated to be 0.9 Sv h^{-1} and 0.3 Sv h^{-1} at the top. The average value at the outer surface of the bunker wall is calculated to be 2.2 μSv h^{-1} and at the roof 1.9 μSv h^{-1}. The dose rate at the surface of the TMR unit after shut down of the accelerator remains below 2 μSv h^{-1}.

In order to test the interaction of all the critical components developed at the HBS project, a prototype of the HBS target station was realized at the Jülich Light Ion Cyclotron (JULIC) neutron test platform on the premises of the Nuclear Physics Institute of Forschungszentrum Jülich (Felden et al., 2019; Lehrach et al., 2024). It allows a comprehensive evaluation of moderator-reflector configurations, cold moderator performance, shielding, etc. in a controlled area (Paulin et al., 2023). In this work, the performance of the shielding of the target-station prototype is investigated by measuring neutron dose rates at different positions around the shielding. Furthermore, numerical simulations of the dose rates are carried out and compared with the experimental values. These results help to access the effectiveness of the HBS shielding and serve as basis for further optimization.

2. Experiment

2.1. JULIC neutron test platform

JULIC can deliver a low current (about 100 nA in average) pulsed proton beam with variable frequency and length i.e. with a variable duty cycle and a maximum proton energy of 42 MeV. Negative hydrogen ions (H^-) generated from an ion source are stripped by a thin carbon film prior injection into JULIC and the resulting protons accelerated to 42 ± 1 MeV and further transport towards the neutron target. The average proton current is determined from the measured H^- ion current. The proton beam enters the target station horizontally at a height of 1.40 m from the ground floor. The primary neutrons are produced from the interaction of the protons with a 6 mm thick tantalum target and moderated within a thermal moderator made of polyethylene surrounded by a lead reflector. The entire TMR unit is housed within a modular shielding consisting of 30 interlocking steel boxes arranged in an octagonal structure. These boxes create a "maze" effect with multiple bends, effectively reducing neutron leakage through the shielding. The complete TMR shielding is about 3 m wide and 3 m high and has a total weight of about 78 tons. It consists of three multi-layers, consisting of 8 cm thick lead to slow down fast neutrons and to reduce gamma radiation and 27 cm thick borated polyethylene to moderate fast neutrons and to absorb thermal neutrons (Zakalek et al., 2024; May et al., 2017). The structure is divided into three vertical sections: the lower level (Block-L), extraction/target channel level (Block-M), and upper level (Block-H), with respective heights of 0.90, 1.00, and 0.90 m. Additionally a top plug level (Block-T) with a rectangular shape is set above the multi-layers, with a thickness of 0.37 m and a surface of 1.81×1.81 m^2 (Patent, 2023).

A sketch of the JULIC neutron platform setup is shown in Fig. 1. The proton beam line is partially shielded with heavy concrete to reduced interference from background neutrons and gamma radiation. The detailed shielding layout is also shown in Figs. 2 and 3.

2.2. Calibration of the neutron monitor

The neutron monitors (Type MAB REM 0201) used are ^{3}He gas proportional counters encased in polyethylene cylinders (length: 25 cm, diameter: 22 cm). They are sensitive to neutron energies up to 10 MeV and can measure dose rates up to 1 Sv h^{-1}. The calibration of the neutron monitors was performed using a 10 mCi AmBe source with a neutron emission of 2.8×10^4 s^{-1} that delivers a neutron dose rate of 23.5 μSv h^{-1} at a distance of 11 cm from the source (Forschungszentrum Jülich, 2003). The calibration factors of the neutron monitors are given in column 3 of Table 1.

2.3. Position of the neutron monitors

Neutron dose rates were measured at eleven positions around the TMR shielding. These positions were divided into four groups.

The group S-1 refers to two neutron monitors positioned at the surface of the shielding facing the proton beam line and placed at the heights of 0.82 m and 2.23 m from the floor i.e. below and above the proton beam line. The group S-2 contains two neutron monitors positioned at the surface of the shielding on the opposite side of the proton beam line. The monitors are placed at the heights of 0.82 m and 2.23 m. The group S-3 is composed of three neutron monitors located at the junction between Block E and F (see Fig. 2), next to the group S-2. This position was chosen to evaluate the attenuation effect of the stepped interface between horizontal shielding segments, where potential leakage paths may exist. The monitors were placed at heights of 0.82 m, 1.53 m and 2.23 m. All the neutron monitors are positioned approximately 15 cm from the outer surface of the TMR shielding.

The group T includes four neutron monitors installed directly at the top of the shielding. The monitors labeled T-1, T-2 and T-4 were placed above the upper level of the shielding (Block-H) at a height of 2.9 m from the floor. The monitor labeled T-3 is placed above the top plug level (Block-T) at a height of 3.2 m from the floor.

Fig. 2 illustrates the arrangement of the neutron monitor groups from a top view of the TMR shielding. The proton beam enters the target station from the side where the neutron monitor group S-1 is located.

2.4. Dose rate measurement

Due to the limited availability of neutron monitors with respect to the number of measurement positions, the dose rate measurements were carried out at different time periods during neutron experiments. The proton pulse currents were between 8.3 μA and 8.8 μA and duty cycles between 1% and 3%, resulting in average proton currents between 33 nA and 105 nA. The count rates of the neutron monitors recorded at the various positions and the associated average proton currents are given in Table 1 with the resulting dose rates, absolute values and values normalized to a current of 1 mA.

3. Simulation

The neutron dose rates were simulated with the Particle and Heavy Ion Transport code System (PHITS 3.24) (Sato et al., 2024) using the reaction cross sections from the Japanese Evaluated Nuclear Data library (JENDL-4.0) (Shibata et al., 2011) for neutron energies up to 20 MeV and JENDL-4.0/HE (Kunieda et al., 2016) for proton energies up to 200 MeV. A total of 1.27×10^9 particle histories were simulated using parallel computing with distributed memory. Neutron dose rates were evaluated using the [T-Track] tally in PHITS, using the multiplier function. Effective dose was calculated based on the ICRP Publication 103 recommendation (Otto, 2021). To improve the statistics of the tally results, the weight window method was applied as a variance reduction technique.

Fig. 1. The sketch of the JULIC neutron platform. The heavy concrete wall around the proton beam tube in a partially transparent green color.

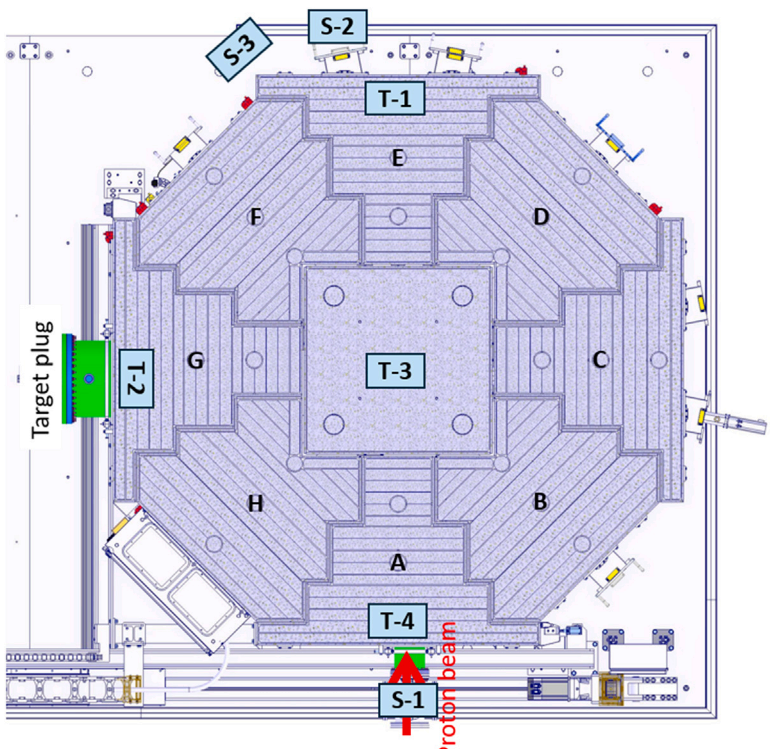

Fig. 2. Top view of the TMR shielding with 7 neutron monitor positions in horizontal cross-section (S-1, S-2, S-3 and T).

The vertical cross section of the geometrical model used in the simulation is shown in Fig. 3. The proton beam tube was simplified as a cylindrical aluminum tube with an external diameter of 15 cm and a wall thickness 2 mm. A beam of 42 MeV protons was set to impinge uniformly on the surface of the tantalum target, which was modeled with a thickness of 6.4 mm and an area of 8.7×8.7 cm^2. The polyethylene thermal moderator with a thickness of 13 cm facing the target was embedded in the lead reflector with a thickness of 5 cm. The shielding was modeled according to the physical setup of stepped interlocking shielding blocks made of lead and Borotron including 5 mm vertical and 10 mm horizontal gaps between the blocks. The neutron monitors were modeled in the form of cylinders. Some of them are shown in Fig. 3 at positions S-1, S-2, S-3, T-1 and T-4. The concrete walls (thickness of 70 cm) of the experimental hall and concrete walls (thickness of 50 cm) surrounding the proton beam line were also taken into account. Nonetheless, the roof of the experimental hall was not included in the model due to the absence of structure information and neutron extraction channels were not considered in the dose rate calculation.

The simulated neutron dose rates at each measured position are given in column 8 and 9 of Table 1. The relative statistical errors of the tally results for positions S-1, S-2 and S-3 are approximately 2% and for positions T-1, T-2, T-3 and T-4 less than 8%. The one standard deviation statistical uncertainties (σ) listed in Table 1 were obtained

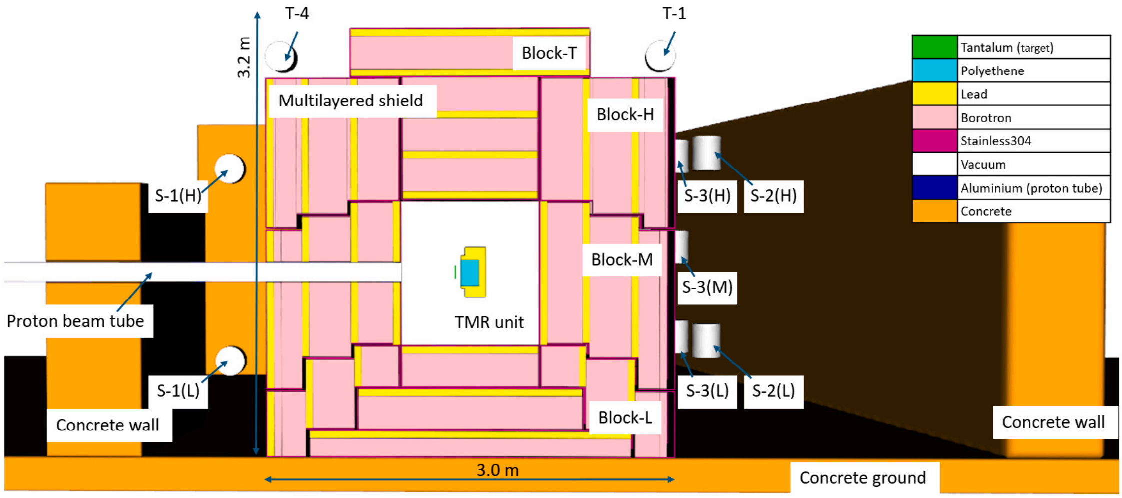

Fig. 3. The Monte Carlo model of the prototype target station. All the components are in relative scale. The neutron monitors situated at positions S-1, S-2, S-3, T-1 and T-4 are depicted in cylindrical form.

by multiplying the tally results by the relative statistical errors. To allow easier comparison, the measured and simulated dose rates are also normalized to a proton current of 1 mA and are shown in Table 1.

4. Results and discussion

As the dose rates were measured at different proton currents, the values normalized to a current of 1 mA (column 7 and 9 in Table 1) are considered for discussion. In order to evaluate the reliability of the calculated to experimental (C/E) neutron dose rate, the combined uncertainty in C/E was calculated by reusing the uncertainties of both the experimental and simulation results (column 10 in Table 1). For most positions, the calculated C/E ratios lie within their combined uncertainties.

With the exception of the values measured with the monitors positioned at the side of the proton beam (S-1 and T-4), the dose rates are ranging between 0.15 and 0.36 Sv h^{-1} mA^{-1}. The dose rates obtained for the monitors placed on the opposite side of the proton beam (S-2 and S-3) are identical taken into account the uncertainties leading to a mean value of 0.29±0.05 Sv h^{-1} mA^{-1}. The same is observed for the monitors placed at the top of the shielding (T-1, T-2 and T-3) with an average value of 0.16±0.03 Sv h^{-1} mA^{-1}. The latter value is lower than this obtained for the monitors S-2 and S-3 due the additional shielding provided by the diagonal position and therefore a larger distance from the neutron source; in addition, a top plug layer (Block-T) with additional shielding is provided for position T-3. While the simulated values for the monitors S-2 and S-3 agree reasonably with the measured values, larger discrepancies are observed for the monitors T-1, T-2 and T-3, the measured values being four and nine times higher than the simulated ones. This discrepancy could be attributed to the backscattering of neutrons from the roof of the hall, which was not implemented in the simulation model.

The dose rates measured with the monitors S-1 on the side of the proton beam are two order of magnitude higher than those obtained with the monitors S-2 and S-3. This increased dose rates suggest a strong dependence of the neutron flux on the local shielding configuration. In particular, the absence of shielding along the last 90 cm of the proton beam line (see Fig. 1) allows significant leakage of scattered neutrons resulting in higher dose rates in this region. The simulated values are ten and fourteen times lower than the measured values. For the monitor T-4 placed at the top of the shielding on the side of the proton beam line, the measured dose rate is three times higher than the simulated value and five times higher than the values measured by the other monitors (T-1, T-2 and T-3) positioned at the top of the shielding.

4.1. Local high neutron dose rate distribution caused by beam loss

In the Monte Carlo simulation, the proton beam was modeled as a uniform beam that illuminates the surface of the tantalum target homogeneously. This assumption allows for a conservative estimate of the neutron yield at the target. But proton beams typically follow a Gaussian distribution in both position and angular spread, with standard deviations between 1 and 3 cm for spatial spread and 1 to 10 mrad for angular deviation (IAEA, 2001; Pedroni et al., 1995).

To evaluate the measured neutron dose rate on the side of the proton beam, a spread beam based on experienced values in the position angle space from the JULIC cyclotron of the Jülich neutron platform was modeled. A Gaussian distribution with a spatial spread (σ) of approximately 2 cm and an angular spread (σ) of approximately 2 mrad was used. The resulting neutron dose rates at the measurement positions S-1 (height 0.82 m), S-1 (height 2.23 m) and T-4 were 81.20 ± 4.41, 59.56 ± 3.77, and 7.27±1.73 Sv h^{-1} mA^{-1}, respectively. This increase in neutron dose rate compared to the neutron dose rate determined with a uniform beam shows that a spread beam can cause a local increase in neutron dose rate in the vicinity of the proton beam.

4.2. Neutrons scattered due to the ceiling

To check the effects of the neutrons scattered from the roof of the experimental hall, an additional 10 cm thick concrete layer was modeled at a height of 10 m above the ground and a 2 cm thick mixture of steel and water was modeled underneath. The neutron dose rates at positions T-1, T-2, and T-3 are 0.043 ± 0.004, 0.019 ± 0.002, and 0.022±0.002 Sv h^{-1} mA^{-1}, respectively. The ceiling caused an increase in the neutron dose rate of about 25% at position T-3, but had no effect on positions T-1 and T-2.

Accurately simulating the distribution of scattered neutrons requires a highly detailed model of the facility that accounts for numerous structural components within the experimental hall. These components were not fully incorporated into the simulation, which may have led to an underestimation of the neutron flux.

5. Summary

The JULIC neutron test platform enabled a thorough evaluation of critical components for the HBS design. The TMR shielding of the HBS, as a very important part of the target station, was developed to ensure radiation safety and also to reduce background radiation level for measurements. The multilayered structure of the shielding with

Table 1
Neutron monitor parameters, measured and simulated neutron dose rates, C/E ratios at various positions around the TMR shielding. (DR_N stands for normalized to 1 mA).

Neutron monitors			Experiment				Simulation		C/E
Group	Height m	Calibration factor µSv h^{-1} s^{-1}	I_p nA	Count rate s^{-1}	DR µSv h^{-1}	DR_N Sv h^{-1} mA^{-1}	DR µSv h^{-1}	DR_N Sv h^{-1} mA^{-1}	
S-1	0.82	3.56 ± 0.18	105 ± 10	1227 ± 31	4367.8 ± 244.1	41.44 ± 2.32	438.6 ± 9.1	4.16 ± 0.09	0.1 ± 0.01
S-1	2.23	4.44 ± 0.22	105 ± 10	1018 ± 42	4520.1 ± 293.7	42.88 ± 2.79	313.6 ± 7.3	2.98 ± 0.07	0.1 ± 0.01
S-2	0.82	3.68 ± 0.18	105 ± 10	7.0 ± 1.1	25.9 ± 4.2	0.25 ± 0.04	51.3 ± 1.2	0.49 ± 0.01	2.0 ± 0.33
S-2	2.23	4.54 ± 0.23	105 ± 10	5.9 ± 0.9	26.6 ± 4.5	0.25 ± 0.04	25.0 ± 0.6	0.24 ± 0.01	0.9 ± 0.16
S-3	0.82	3.68 ± 0.18	60 ± 8	4.9 ± 0.7	18.0 ± 2.7	0.30 ± 0.04	22.9 ± 0.5	0.38 ± 0.01	1.3 ± 0.19
S-3	1.53	3.88 ± 0.19	60 ± 8	5.6 ± 0.9	21.6 ± 3.7	0.36 ± 0.06	32.4 ± 0.6	0.54 ± 0.01	1.5 ± 0.26
S-3	2.23	4.54 ± 0.23	60 ± 8	3.7 ± 0.6	16.7 ± 2.8	0.28 ± 0.05	11.3 ± 0.3	0.187 ± 0.005	0.7 ± 0.12
T-1	2.91	3.69 ± 0.18	33 ± 6	1.5 ± 0.3	5.6 ± 1.0	0.17 ± 0.03	1.4 ± 0.1	0.043 ± 0.003	0.3 ± 0.05
T-2	2.91	3.69 ± 0.18	105 ± 10	4.5 ± 0.9	16.4 ± 3.4	0.16 ± 0.03	1.9 ± 0.2	0.018 ± 0.001	0.1 ± 0.02
T-3	3.14	3.69 ± 0.18	55 ± 7	2.3 ± 0.3	8.3 ± 1.3	0.15 ± 0.02	0.95 ± 0.04	0.017 ± 0.001	0.1 ± 0.02
T-4	2.91	3.69 ± 0.18	47 ± 7	10.9 ± 1.6	40.4 ± 6.1	0.85 ± 0.13	13.2 ± 1.0	0.28 ± 0.02	0.3 ± 0.05

alternating lead and borated polyethylene was optimized to minimize the total dose rate at the outer surface of the target station.

The prototype of the target station was built based on this concept. Since the proton energy and proton current on the JULIC platform were lower than the HBS design parameters, the TMR shielding of the prototype was slightly scaled down, with an octagonal shape of 3 m in width and 3 m in height and a total weight of about 78 tons. The neutron dose rate distribution was measured on the platform with an average proton current up to 0.11 µA. The measured neutron dose rates in the vicinity of the target station remained below 1 Sv h^{-1} mA^{-1}, except near the proton beam tube, where scattered neutrons caused increased values.

Monte Carlo simulation based on the simplified model without additional details supported these conclusions, with the calculated-to-experimental ratios in the range of 0.1 to 2.0. With this work, the design of the TMR shielding of the HBS prototype target station was demonstrated with the dose rate on the outer surface of the target station of less than 1 Sv h^{-1} mA^{-1}. This data corroborates the configuration of the HBS shielding concept (Gutberlet et al., 2023) and can be used as a foundation for further optimizations to enhance shielding efficiency and reduce neutron leakage.

CRediT authorship contribution statement

J. Li: Writing – original draft, Validation, Data curation, Conceptualization. **T.H. Randriamalala:** Visualization, Software, Data curation. **J. Chen:** Methodology, Investigation. **N. Schmidt:** Software, Methodology, Data curation. **E. Mauerhofer:** Writing – review & editing, Writing – original draft, Conceptualization. **N. Demary:** Methodology. **O. Felden:** Methodology, Investigation. **U. Rücker:** Methodology, Investigation. **T. Gutberlet:** Writing – review & editing, Project administration. **P. Zakalek:** Writing – review & editing, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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