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Author(s)	Nakashima Hiroshi, Sakamoto Yukio, Iwamoto Yosuke, Matsuda Norihiro, Kasugai Yoshimi, Nakane Yoshihiro, Masukawa Fumihiro, Mokhov N., Leveling A., Boehnlein D., Vaziri K., Sanami Toshiya, Matsumura Hiroshi, Hagiwara Masayuki, Iwase Hiroshi, Kinoshita Norikazu, Hirayama Hideo, Oishi Koji, Nakamura Takashi, Arakawa Hiroyuki, Shigyo Nobuhiro, Ishibashi Kenji, Yashima Hiroshi, Nakao Noriaki, Niita Koji
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Title: EXPERIMENTAL STUDIES OF SHIELDING AND IRRADIATION EFFECTS AT HIGH ENERGY ACCELERATOR FACILITIES

Authors: H. Nakashima, Y. Sakamoto, Y. Iwamoto, N. Matsuda, Y. Kasugai, Y. Nakane, F. Masukawa (Japan Atomic Energy Agency),
N. V. Mokhov, A. F. Leveling, D. J. Boehnlein, K. Vaziri (Fermi National Accelerator Laboratory),
T. Sanami, H. Matsumura, M. Hagiwara, H. Iwase, N. Kinoshita, H. Hirayama (High Energy Accelerator Research Organization),
K. Oishi (Shimizu Corporation),
T. Nakamura (Tohoku Unversity),
H. Arakawa, N. Shigyo, K. Ishibashi (Kyushu University),
H. Yashima (Kyoto University),
N. Nakao (Aurora, Illinois)
K. Niita (Research Organization for Information Science & Technology)

Corresponding author:
H. Nakashima,
J-PARC center, Japan Atomic Energy Agency,
Shirakata-Shirane 2-4, Tokai, Naka, Ibaraki, 319-1195 Japan
e-mail: nakashima.hiroshi@jaea.go.jp

List of contents:
Pages: 4
Tables: 0
Figures: 4

Abstract

Experimental studies of shielding and radiation effects are carried out at Fermi National Accelerator Laboratory (FNAL) under collaboration between FNAL and Japan, aiming at benchmarking simulation codes and studying irradiation effects for upgrade and design of new high-energy accelerator facilities. The purposes of this collaboration are (1) acquisition of shielding data in a proton beam energy region above 100-GeV; (2) further evaluation of predictive accuracy of the PHITS and MARS codes; (3) modification of physics models and data in these codes if needed; (4) characterization of radiation fields for studies of radiation effects; and (5) development of a code module for an improved description of radiation effects.

The first campaign of the experiment was carried out at the Pbar target station and NuMI experimental station at FNAL, which use irradiation of targets with 120-GeV protons for antiproton and neutrino production, respectively. The generated secondary particles passing through steel, concrete and rock were measured by activation methods as well as by other detectors such as a scintillator with a veto counter, phoswich detector and a Bonner ball counter on trial. Preliminary experimental and calculated results are presented.

1. Background of Experiment

Several reliable multi-purpose high-energy radiation transport codes are now in use worldwide.[1, 2, 3, 4, 5] These codes have been used for accelerator facility shielding design and high-energy physics, and recently the utilization of the codes has widely spread to various fields such as space, biological and medical sciences, and nuclear and material engineering.

In order to compare the calculation results from an aspect of accelerator shielding, an international comparison has been carried out as one of the activities of the SATIF (Shielding Aspects of Target, Irradiation Facilities) meeting under OECD/NEA/NSC (Organization for Economic Co-operation and Development /Nuclear Energy Agency /Nuclear Science Committee). In the activity, neutron attenuation in iron and concrete has been compared, and it is pointed out that some discrepancies among the codes have been observed in the energy region above a few tens of GeV.[6, 7]

Benchmarking calculations against measurements is the way to understand possible reasons for these discrepancies. Many shielding experiments have been carried out below 1 GeV[8), 9), 10), 11)], while only a few studies were performed in the energy region above a few tens of GeV.[12), 13), 14)] The shielding experiment at CERF of CERN[14)] gave good information for benchmarking of the codes for a 120-GeV beam comprised of protons and pions.

Several high-intensity high-energy accelerator facilities are being constructed and planned in the world.[15), 16), 17)] Radiation damage to the structural materials is a critical design issue for such accelerator facilities. The life of the materials is mainly decided by the Displacement-per-Atom (DPA) in materials. Some codes have the capability of estimating radiation effects on materials via DPA calculation, and this is one of the reasons why these codes are used so widely in numerous applications. The accuracy of the estimations of radiation effects, however, has not yet comprehensively been evaluated by experiments in realistic radiation fields.

Thus, an experiment on shielding and radiation effects using accelerator complex at FNAL has been proposed at the 7th SATIF meeting, and planned under collaboration among many institutes and universities of Japan and U.S.A.

2. Purposes

The purposes of the collaboration are (1) acquiring shielding data in a proton beam energy region above 100 GeV; (2) further evaluation of predictive accuracy of the PHITS and MARS codes; (3) modification of physics models and data in these codes if needed; (4) characterization of radiation fields for studies of radiation effects; and (5) development of a code module for an improved description of radiation effects.

In order to acquire the shielding data and characterize the radiation field for study of radiation effects, the experimental targets and detectors were set to measure (1) the transmitted particle fluxes and their reaction rates through and inside shields, (2) the streaming particles fluxes and reaction rates through ducts set inside shields, and (3) the residual activities and mass distribution around targets and shields, as well as (4) to analyze air around target chemically.

3. Experimental Setups

The first campaign of the experiment was carried out at the Pbar target station and NuMI experimental station at FNAL, that use irradiation of targets with 120 GeV protons for antiproton and neutrino production, respectively[18), 19)]

3. 1. Pbar target station

A cross sectional view of the Pbar target station is shown in Fig. 1. At this station, an antiproton production target, consisted of copper and Inconel disks, is irradiated by 120-GeV protons with a 1.6-μs pulse width and a 2.2-sec repetition period. The number of protons in the pulse is up to 7×10^{12}, and the resultant beam power corresponds to about 61 kW. After the target, a collection lithium lens, collimator and a pulsed magnet are placed to focus, collimate and extract the produced antiprotons. The remaining proton and secondary particles are absorbed in a dump placed after the pulsed magnet. The dump consists of a graphite cylinder 20 cm in diameter and 120 cm long encapsulated in a 20-cm thick aluminum shell. Shields made of iron and concrete are placed on the upper side of the target and magnets. The thickness of iron and concrete above the target are 6 and 4 feet, respectively. A 6-foot air gap is between the iron and concrete shields.

3. 2. NuMI experimental station

Secondary particles are produced in a 1-m long graphite target irradiated with 120-GeV protons at the NuMI experimental station. The secondary particles, mainly pions, are focused in the direction of a neutrino detector with two magnetic horns and lead to a 675-m-long decay pipe, in which pions are decayed into muons and neutrinos. The muons are passed through an iron absorber located downstream of the decay pipe in order to remove protons, neutrons and pions from the beam axis. Figure 2 shows a downstream view of the decay pipe of the course. Behind the absorber, there are four rooms at depths of 0, 13.7, 33.5, and 67.1 m from the rock surface, named as “Alcove-1,” “Alcove-2,” “Alcove-3,” and “Alcove-4,” respectively. In the first campaign, activation detectors were installed in every room along the beam axis and were irradiated with the secondary particles for 22.8 hours. The integrated number of primary protons on the graphite target was 6.26×10^{17}.

4. Preliminary Results

4.1 Pbar target station

The first measurement of the transmitted particle fluxes and corresponding reaction rates through shields of concrete and iron was done at the Pbar station. In the measurements, various techniques were used: activation method, activation method with chemical separation, Bonner sphere counters (current mode, pulse mode), NE213 scintillation counter, phoswitch detector test, neutron and gamma survey meters, thermo-luminescence detectors, and solid state nuclear track detectors. Because of the high intensity of the secondary particles, mainly neutron, at the top of the target station, it was very difficult to use some counters there.

Neutron reaction rate distributions of the Cu (n, x) ^{56}Co reaction (threshold energy E_{th} about 20 MeV) along the proton beam line behind the concrete shield are shown in Fig. 3 as a typical experimental data. Experimental errors range from ± 5% to several tens of % depending on the activation counting statistics. The data were preliminary analyzed with the PHITS code and compared with the measurement in Fig. 3. Calculations are in agreement with data within about 50% except for the position of 275 cm. At that position, details of the downstream components not included in the preliminary simplified PHITS model, result in an underestimation of the data by a factor of 3. The work is underway to implement all the details of the Pbar station into the model as well as to repeat the measurements behind and inside the shields of concrete and iron in the next campaign.

4.2 NuMI experimental station

As a typical experimental data at the NuMI experimental station, the average values of the yield ratios normalized to the value at Alcove-2 are plotted in Fig. 4 as a function of the depth from the rock surface. [19] A variation of these ratios for the nuclides studied is within a factor of two. In the measurement, the yields of ^{24}Na on aluminum and 18 nuclides (^{64}Cu, ^{57}Ni, ^{58}Co, ^{57}Co, ^{56}Co, ^{55}Co, ^{59}Fe, ^{54}Mn, ^{52}Mn, ^{51}Cr, ^{48}V, ^{48}Sc, ^{47}Sc, ^{46}Sc, ^{44m}Sc, ^{43}K, ^{42}K, and ^{24}Na) on copper samples were measured by the activation method. While the yields decrease steeply between Alcove-1 and Alcove-2, the yields from Alcove -2 show a gradual exponential decrease. The profile of the yields is similar to the attenuation of the muons, and the data is under detailed analyses using the MARS and PHITS codes.

5. Summary

Preliminary experiments with the 120-GeV proton beams were carried out at the two Fermilab facilities and the results on the secondary particle fluxes and mass distributions were obtained. Analyses for all the measurements and preparation for the next experiment are underway. The next experiment is planned based on analyses of the results. First comparisons with the data revealed a need for more detailed descriptions of the realistic setups in the PHITS and MARS calculation models. Survey counter developments will start soon for measurements of radiation damage induced by high-energy high-intensity beams.

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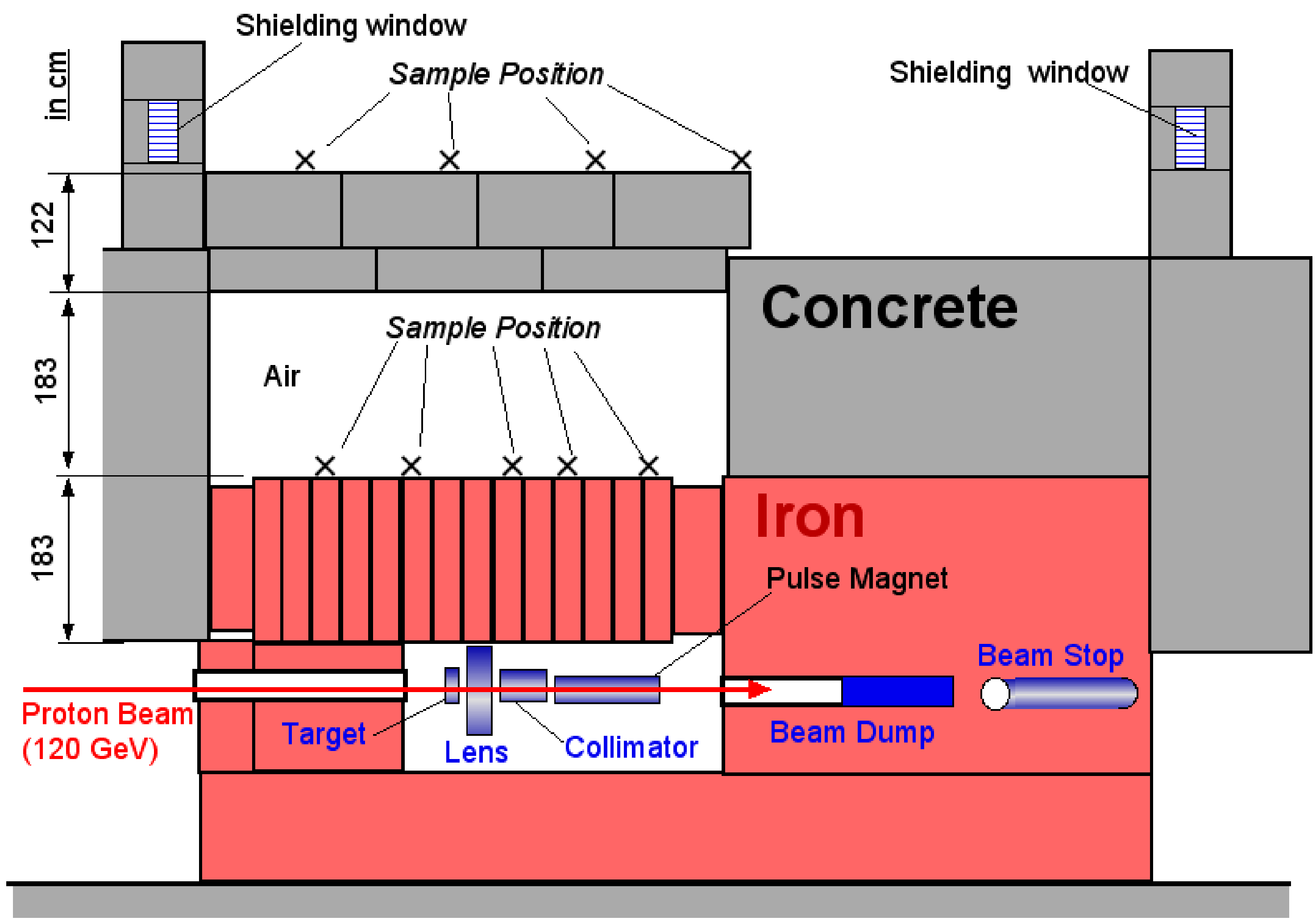
Figure captions

Fig. 1. Cross sectional view of the Pbar target station.

Fig. 2. Schematic view of the NuMI experimental station.

Fig. 3. Comparison between the data and PHITS calculation of neutron reaction rate distributions of Cu (n, x) ^{56}Co reaction along to the proton beam line behind the Pbar target station concrete shield.

Fig. 4. The average values of the yield ratios on aluminum and copper, normalized to the value at Alcove-2, as a function of the depth from the rock surface at NuMI.



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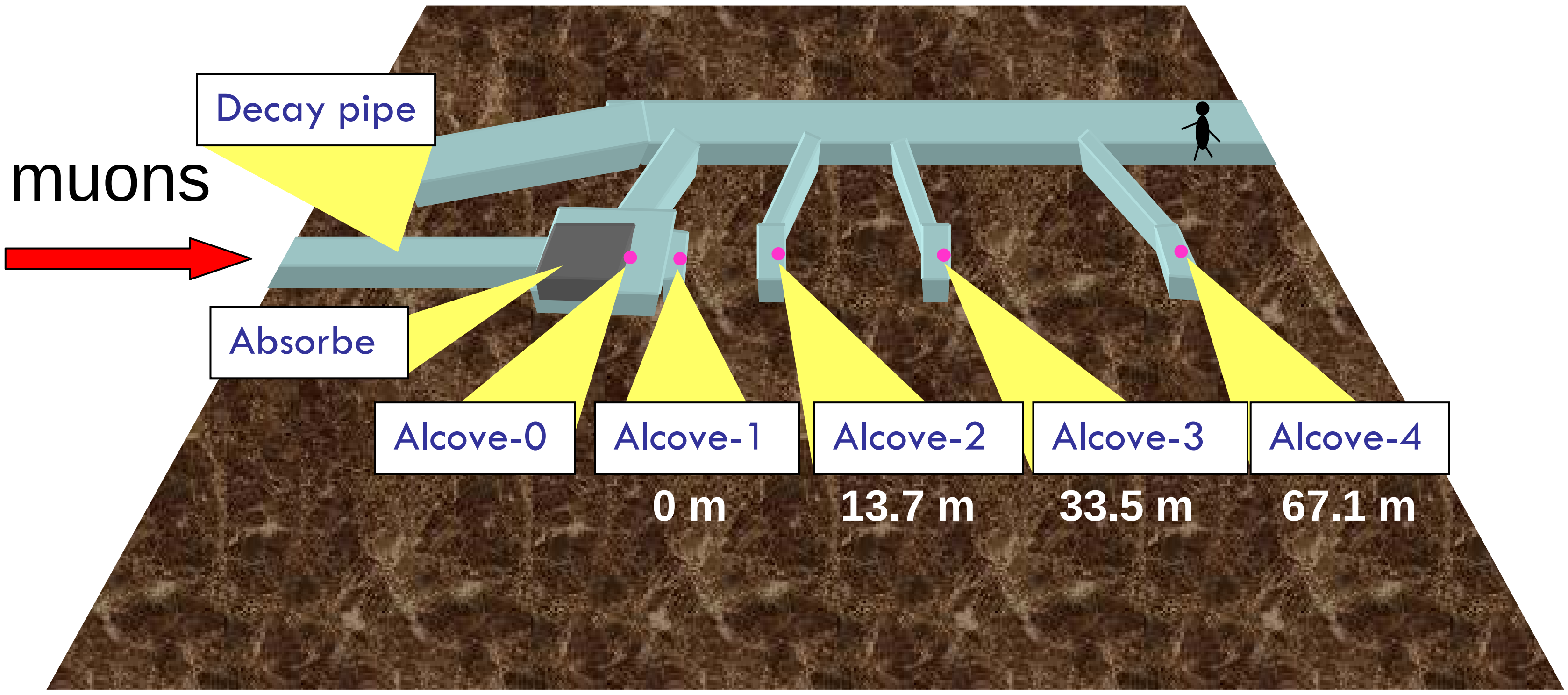
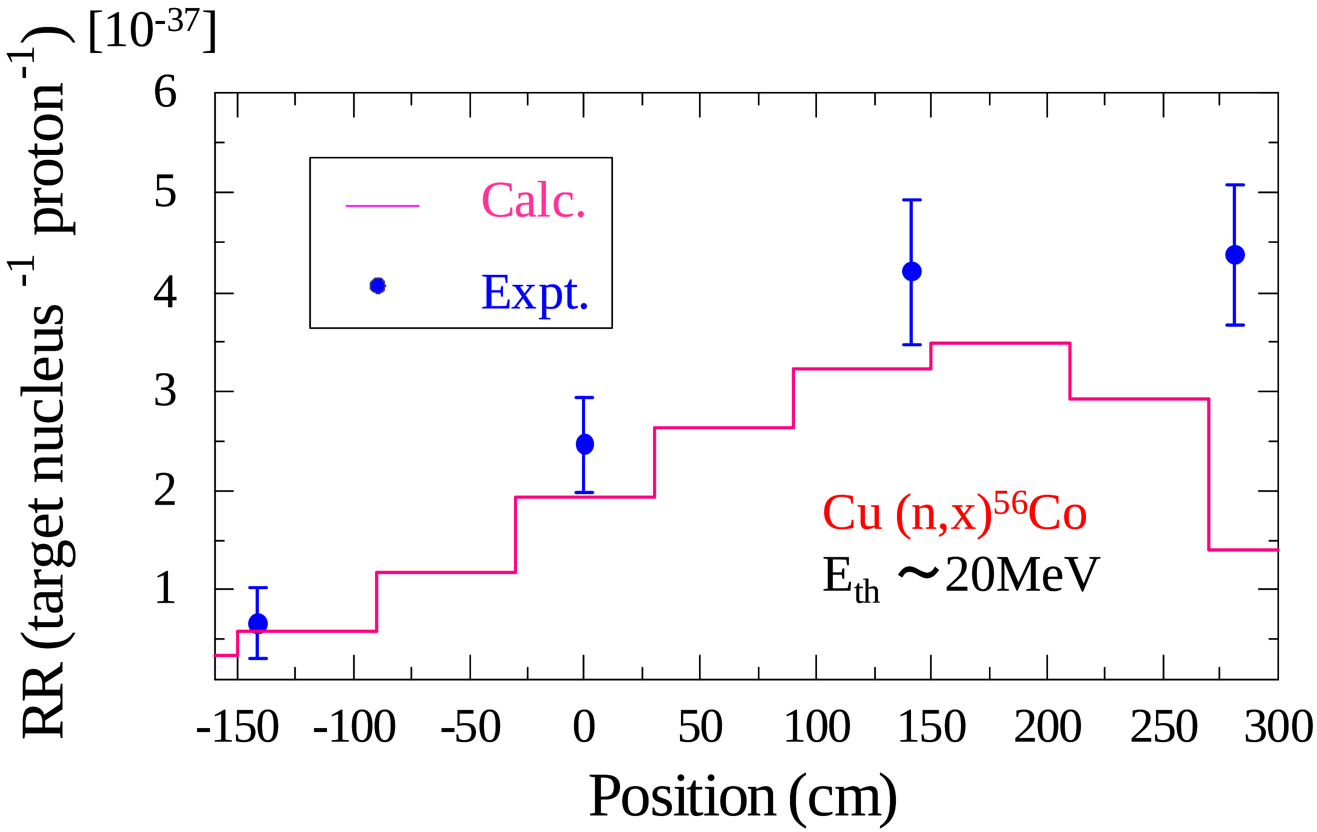


Fig. 2. Schematic view of the NuMI experimental station.



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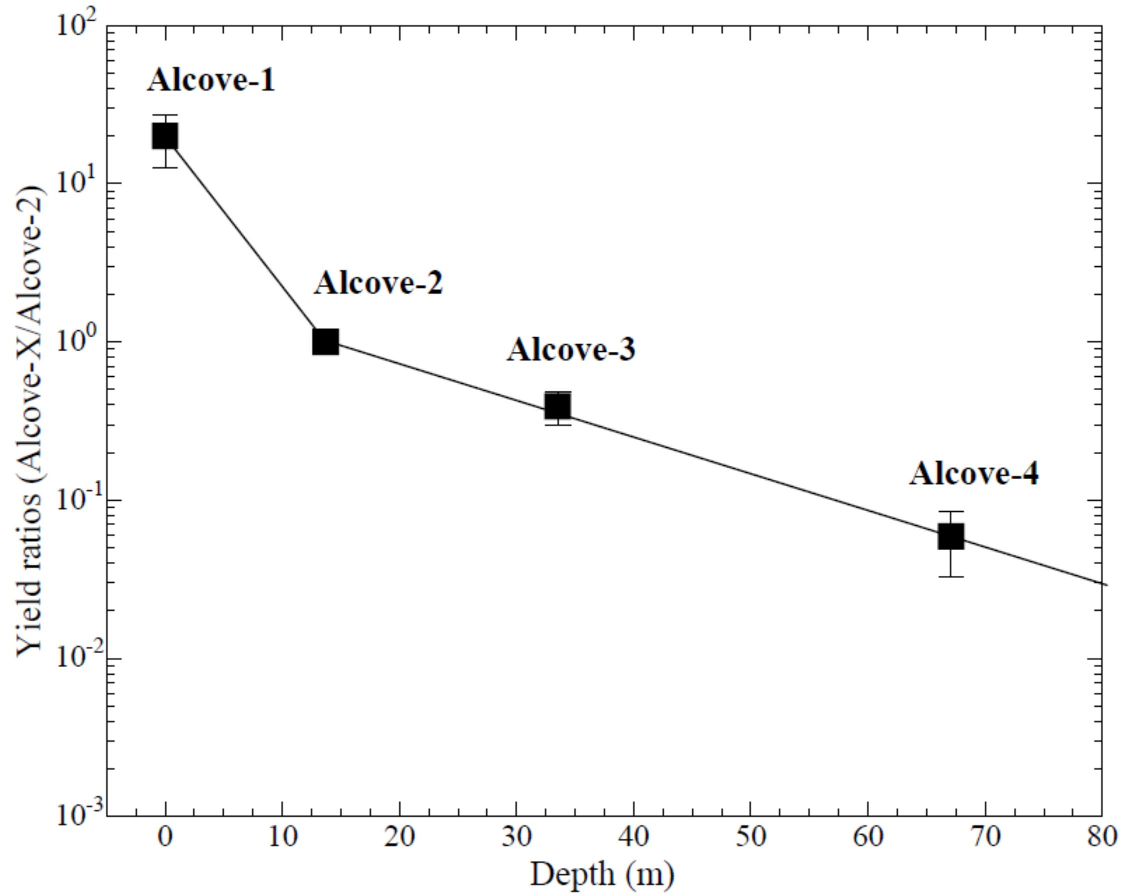

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