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ARTICLE

Development of Nuclear Instruments to Measure Power Distribution of HTGR (1) Development of Ex-Core Detector

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Japan Atomic Energy Agency, ANSeeN, and Shizuoka University has been conducted a joint-research to develop nuclear instrument for High Temperature Gas-cooled Reactor (HTGR) core power distribution In the project, we developed the ex-core detector system to avoid heigh temperature environment of the HTGR core. The system achieves the measurement by taking advantage of the HTGR core feature of long flight length neutron due to the graphite moderated core with Computed Tomography (CT) technologies. The theory is demonstrated by calculation in HTTR (High Temperature Engineering Test Reactor) and criticality experiment in KUCA (Kyoto University Criticality Assembly). These technologies are expected to be applied to other reactors.

KEYWORDS: HTGR, ex-core detector, power distribution measurement

I. Introduction

Japan Atomic Energy Agency, ANSeeN, and Shizuoka University has been conducted a joint-research to develop nuclear instrument for High Temperature Gas-cooled Reactor (HTGR) core power distribution from 2021. Inside of HTGR core is high temperature environment from 400℃ to 1,000℃. Therefore, it is difficult to measure the power distribution by in-core detector. Hence, we tried two approaches, an ex-core detector and in-core detector. As for the ex-core detector, JAEA proposed and developed power distribution measurement technologies by using ex-core detector based on Computed Tomography (CT) technologies. Shizuoka University developed a high-temperature and high-dose durable in-core semi-conductor detector. ANSeeN developed detector systems for both of ex-core detector and in-core detector. These plan of development are accepted and supported by“Nuclear Energy System R&D Project” in MEXT. The three years project was finished in FY2023, and the present report describes a part of“Development of ex-core detector”

II. Concept of Ex-core Detector System and Development

Figure 1 shows the concept of the detector system. The spiral curve is an orbit of a moving ex-core detector with computed tomography theory. That is a case of the implementation to obtain detector signals at each measurement point. The detector signals obtained at measurement point r_d is expressed as follows,

$$\mathrm{R}(\mathrm{r}_d) = \int_{core} w(\mathrm{r}_d, r,) S(r) dr^3, \quad (1)$$

where, w(r): spatial weighting functions for a detector (-), S(r): fission neutron source ($s^{-1}cm^{-3}$), r_d: detector position (-). In the case of HTGR, because of the long neutron flight length, the neutron yielded in the center of core reaches to ex-core detector unlike Light Water Reactor (LWR).

First, the neutron transport equation in this system can be expressed as follows,

$$\mathrm{L}\phi(\mathrm{r}) = \mathrm{S}(\mathrm{r}), \quad (2)$$

where, L: neutron loss operator (cm^{-1}), ϕ(r): neutron flux ($cm^{-2}s^{-1}$). Here, the fission neutron source is replaced as follows,

$$\mathrm{S}(\mathrm{r}) = \chi(r, E)\delta(\mathrm{r} - \mathrm{r}_i), \quad (3)$$

where, χ(r,E): fission spectrum (-), r_i: a certain fuel position (-). The neutron source is limited to neutron release from a certain fuel position r_i. With the neutron flux obtained from Eq. (2) with the source of Eq. (3). The weighting function can be evaluated as follows,

$$w(\mathrm{r}_d, \mathrm{r}_i) = \int \Sigma_d \delta(\mathrm{r} - \mathrm{r}_d)\phi(r, E)\, dE, \quad (4)$$

where, Σ_d: response cross-section of detector (cm^{-1}). Here, the adjoint equation is defined as follows,

$$\mathrm{L}^\dagger \phi^\dagger(\mathrm{r}_d, r) = \Sigma_d \delta(\mathrm{r} - \mathrm{r}_d), \quad (5)$$

where, $L^\dagger$: adjoint neutron loss operator (cm^{-1}), $\phi^\dagger$ (r): adjoint neutron flux (-).

In the Eq. (5), the response cross-section of detector is given as an adjoint neutron source. In this condition, the adjoint neutron flux means neutron importance for detector

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response. Then, the spatial weighting functions can be expressed as follow,

$$w(\mathrm{r}_d, r) = \int \phi^{\dagger}(\mathrm{r}_d, r, E)\chi(r, E)\, dE, \tag{6}$$

To estimate the power distribution, the Eq. (1) is reduced by discretization to as follows,

$$R_j = \sum_{i=1}^{n} w_{j,i} S_i, \tag{7}$$

where, R_j: detector response in j-th detector position (-), $w_{j,i}$: spatial weighting functions for j-th detector position and i-th core region (-), S_i: fission neutron source for i-th core region (s^{-1}), n: number of core regions.

Finally, the power distribution is determined by the least square method. Then the sum of square errors J is expressed as follows,

$$\mathrm{J} = \frac{1}{2}\|WS - R\|^2. \tag{8}$$

The vector stands for a series for power density regions and detector positions, respectively for S and R. To minimize the error, the deviation for each fission rate should be zero as follows,

$$\nabla \mathrm{J} = 0. \tag{9}$$

The eq. (9) can be reduced to as follows,

$$S = W^{+}R, \tag{10}$$

$$W^{+} = (W^{T}W)^{-1}W^{T}. \tag{11}$$

The power distribution can be unfolded by Eq. (10). W^{+} is called pseudo-inverse matrix. When the weighting functions for each detector position, namely the row vector of W, are linearly independent, and a number of detector positions coincide with that of power density. Therefore, many detectors should be installed or one or several detectors should be moved as shown in Fig. 1. The subjects which should be solved in this project to reach Technology Readiness Level (TRL) 4 are listed as follows:

- Demonstrate the unfolding technology
- Develop the detector system

In addition, according to the plan described in Fig. 1, we aim to be implemented by 2030.

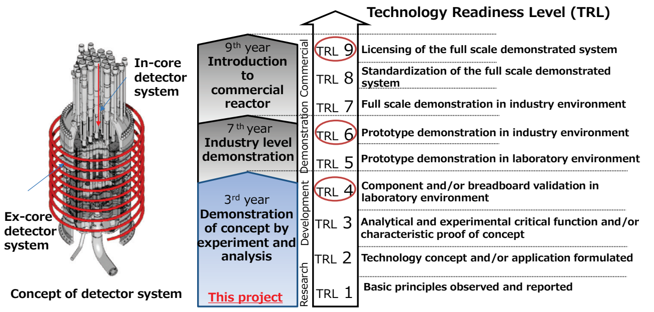

Fig. 1 Concept of detector system and development target

III. Demonstration of the Unfolding Technology

1. Numerical Demonstration

To demonstrate the unfolding technology, numerical demonstration was performed using the HTTR [1] geometry. The geometry is shown in **Fig. 2.**[2] The power density is set for each fuel block calculated by neutron diffusion code SRAC-COREBN,[3] and the detector efficiency is calculated by neutron transport calculation code PARTISN.[4] By using the power distribution and detector efficiency, the detector signals for each position described in Fig. 2 is evaluated. With the signals and the detector efficiency, the power distribution is unfolded by Eq.(10). The unfolded power distribution was compared with power distribution calculated by neutron diffusion code. The number of fuel block is 150, and the number of detector position is 180. The result of the comparison is listed in **Table 1**. The maximum error is 1.1×10^{-8}%, and the averaged error is 1.2×10^{-9}%. It is completely coincided.[2]

Table 1 Comparison of unfolded power

Items	Values
Whole core error	
Averaged error (%)	1.2×10^{-9}
Standard deviation (%)	1.8×10^{-9}
Maximum local error	
Error (%)	1.1×10^{-8}
Column	1D1
Layer	4
Rank of inverse matrix	150

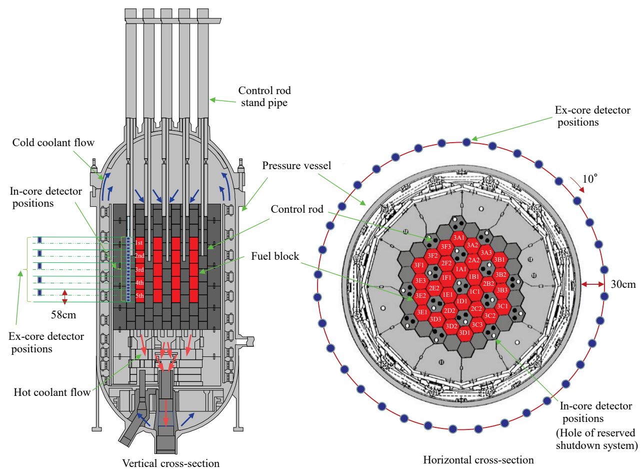

Fig. 2 HTTR geometry

2. Experimental Demonstration

To demonstrate the unfolding technology, experimental demonstration was performed in the Kyoto University Criticality Assembly (KUCA).[5] To obtain basic core characteristics data for a graphite-moderated system, We configured a graphite-moderated core in the B-rack of the

KUCA as a reference core.

The configuration of the fuel assembly is shown in **Fig. 3**. The fuel assembly (74“G2/8”p8EU) is composed of eight unit cells, which include a 1/16-in.-thick 93% EU plate, three 1/2-in.-thick graphite plates, a 1/4-in.-thick graphite plate, and two 1/8-in. polyethylene (PE) plates with axial graphite reflectors. The driver fuel assembly (3/8”p38EU) is composed of 38 unit cells, which include a 1/16-in.-thick EU plate and three 1/8-in.-thick PE plates with axial graphite reflectors. The driver fuel assembly (3/8”p10EU), which is used for fine-tuning criticality, is composed of 10 unit cells. They include a 1/16-in.-thick EU plate and three 1/8-in.-thick PE plates with axial graphite reflectors. The bulk density of the graphite plates is 1.7 g/cm. The porosity is 25% where the theoretical density of ideal crystalline graphite is 2.25 g/cm. The measured impurities of the graphite plates are summarized in **Table 2**. The configuration of the core named [B7/4“G2/8”p8EU(3)+3/8”p38EU] is shown in **Fig. 4**. The core temperature is equal to room temperature (approximately 25°C). The fuel assemblies and the driver fuel assemblies are surrounded by the graphite and PE reflectors.

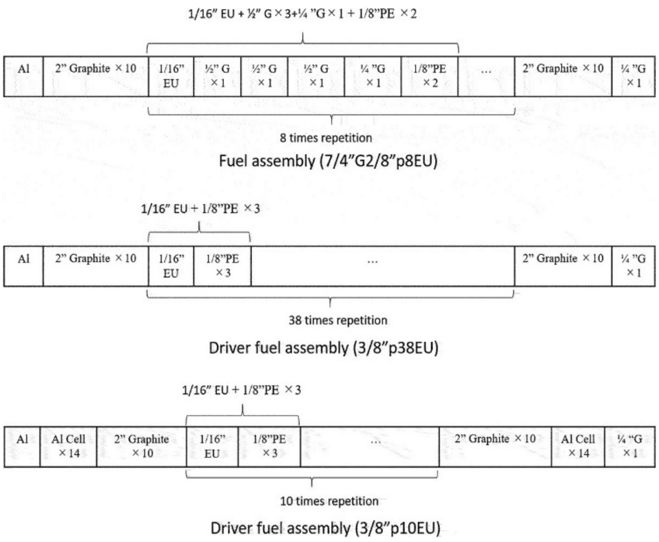

Fig. 3 Configuration of fuel assembly

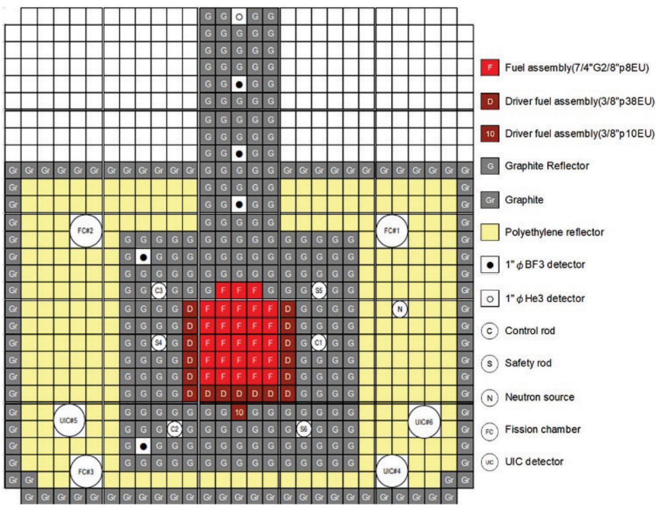

Fig. 4 Configuration of the core B7/4“G2/8”p8EU(3)+3/8”p38EU

To measure the leaked neutron from core, the moving detector system with stepping more was deployed for each direction as shown in **Figs. 5** and **6**.

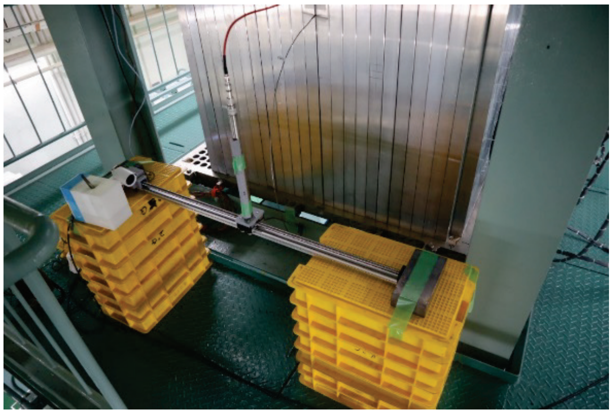

Fig. 5 Moving detector system

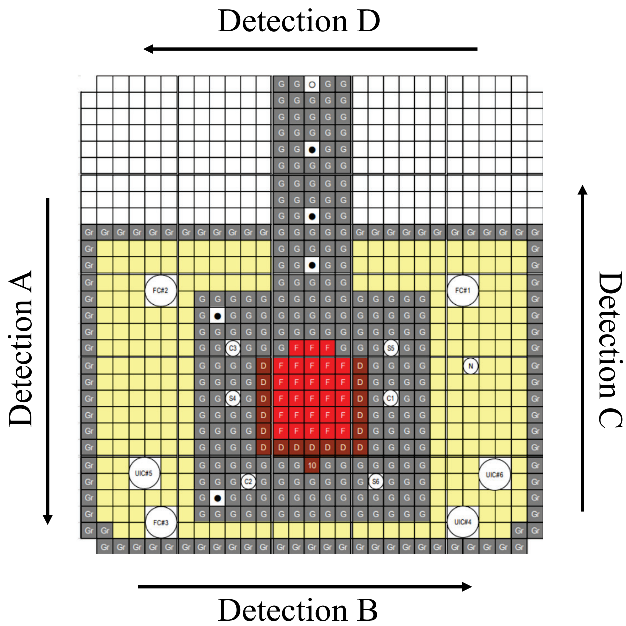

Fig. 6 Moving direction of detector system

The core composed of 880 high enrichment uranium plates. The detector position is discretized to 86 points in each direction. The total measurement positions are 344 points.

To unfold the power distribution, first, we should evaluate the weighting function as shown in Eq.(11). In this evaluation, we used forward method unlike the Eq.(6). Because, the MVP code could not apply the adjoint calculation in the contentious energy mode. The source is set to each fuel plate, The calculation is performed 880 times. The detector is modeled by cylindrical shape at the 344 points. The calculation results are shown in **Figs. 7** to **10**, respectively for the direction A to D.

There are two types of calculated detector signals; Direct calculation and the signals obtained by the product of weighting factor and power distribution. The “direct calculation” stands for the data are calculated by reaction in the detector with the neutron flux obtained by an Eigen-value problem. Next, the “calculation with

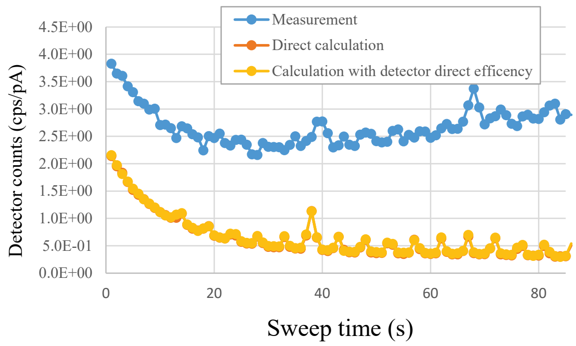

Fig. 7 Detector signals in the direction A

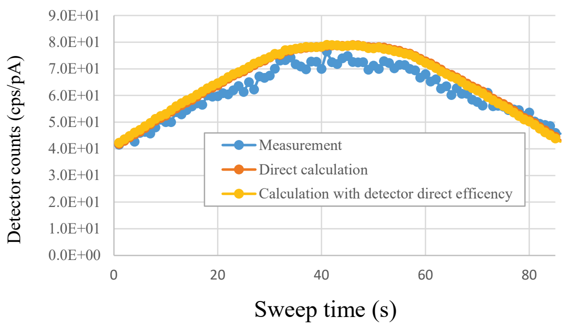

Fig. 8 Detector signals in the direction B

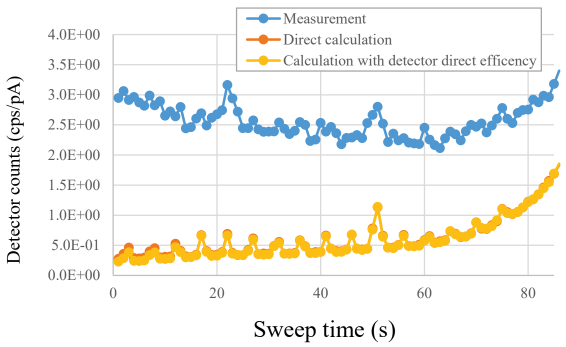

Fig. 9 Detector signals in the direction C

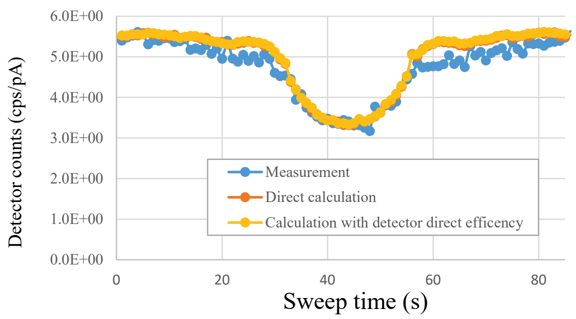

Fig. 10 Detector signals in the direction D

detector direct efficiency" stands for the data are calculated by Eq. (7). The detector efficiency is evaluated not by Eq. (6) but by Eq. (2) and Eq. (3) with a fixed source problem and power distribution with an Eigen-value problem. The calculated detector signals show good agreement, this means the weighting function is accurate.

On the contrary, there are deference between measurement and calculated signals in the directions A and C, unlike in B and D, because of normalization by amplitude.

Even the number of measurement position is 344, but, it is guessed that the linearly independent element is few, because the elevation of detector is not changed during the sweep, and by SVD analysis, it must be around 4. Then we reduced the groups to 4 as shown in **Fig. 11**. The fuel assemblies composed as shown in Fig.3 The fuel assembly (7/4"G2/8"p8EU) includes 8 enriched uranium plates. The driver fuel assembly (3/8"p38EU) includes 38 enriched uranium plates. The driver fuel assembly (3/8"p10EU) includes 10 enriched uranium plates. The whole core includes 880 enriched uranium plates. The 880 enriched uranium plates are reduced to 4 groups. The group 1 includes 230 enriched uranium plates. The group 2 includes 324 enriched uranium plates. The group 3 includes 230 enriched uranium plates. The group 4 includes 96 enriched uranium plates.

The comparison of reference power distribution and unfolded power distribution is shown in **Fig. 12**. It shows good agreement with the small errors around $2x10^{-6}$. However, the accuracy is not obtained by this unfolding method, but by the fuel group condense to 4 groups and the group number is too little. The power distribution is obtained by Eq. (10) and Eq. (11). To unfold the power distribution, here the power distribution is condensed to 4 groups, the weighting function should also be condensed to 4 groups. To condense power distribution, the power should be averaged in the fuel group volume because the power density is an extensive variable. However, the weighting function is an intensive variable. By just averaging, the intensive property is not conserved. To conserve the intensive property, the weighting function should be averaged with weighting by power distribution as follows,

$$w'_{j,I} = \sum_{i \in I} w_{j,i} S_i \Big/ \sum_{i \in I} S_i, \qquad (12)$$

where, $w'_{j,I}$: condensed spatial weighting functions for j-th detector position and I-th condensed core region (-), $w_{j,i}$: spatial weighting functions for j-th detector position and i-th core region (-), S_i: fission neutron source for i-th core region (s^{-1}), n: number of core regions.

Here, the power distribution, i.e. fission neutron source in Eq. (12), is unknown. Then, the reference power distribution obtained by the Eigen-value calculation by MVP code is used for the averaging with weighting. Moreover, the number of fuel group is too little in this case. Therefore, the accuracy of the unfolded power depends on the accuracy of the power distribution for the weighting, which is reference power distribution itself.

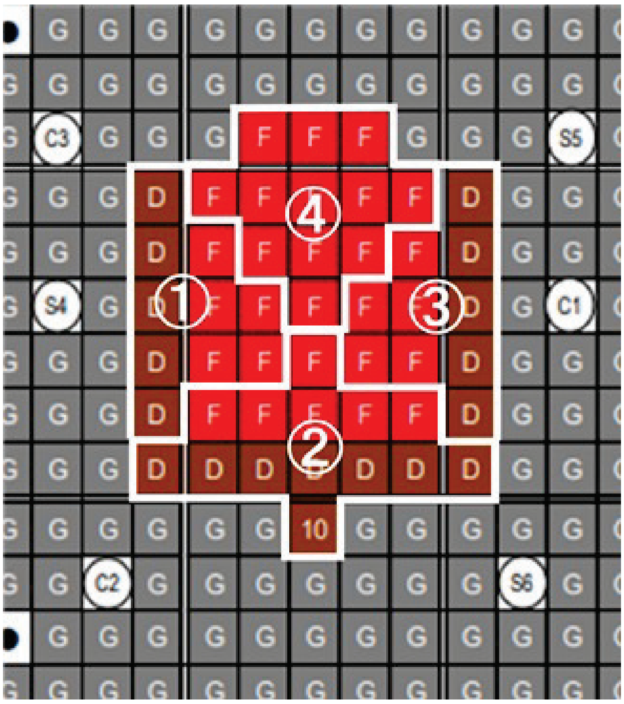

Fig. 11 Fuel element groups

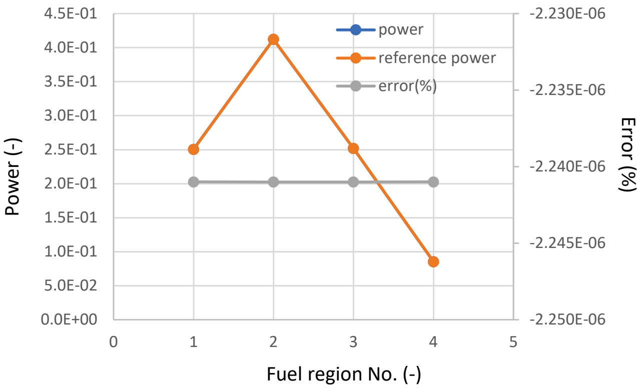

Fig. 12 Comparison between reference power distribution and that unfolded

IV. Develop the Detector System

To operate the detector movement, the conceptual design of detector system was performed as shown in **Fig. 13**. The guide tube system is composed of the guide tube and the detector robot which drives into the guide tube. A Telpher crane system is composed of a crane and a detector system moved by the crane. Multiple detector installation system is composed of many detectors installed in the guide tube. Vertical guide tube system is composed of vertical guide tubes and winched detectors on the side of the guide tube. The telpher crane system has a difficulty in electrical transmission because the cable becomes approximately 40m and it gathers electric noise. Multiple detectors installation system has a difficulty in calibration and maintenance of detectors. Then, representative candidate is spiral guide tube system and vertical guide tube system.

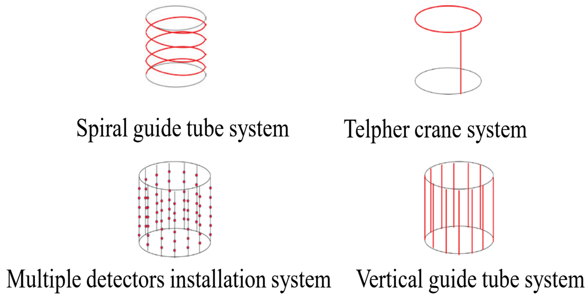

Fig. 13 Detector systems

IV. Conclusions

Japan Atomic Energy Agency and ANSeeN developed ex-core detector system to measure power distribution of HTGR core. The TRL 4 will be achieved by the following developments,

- Demonstration of the unfolding technology by analysis and experiment
- Development of the detector system and the feasibility study.

We aim to complete the technology development to be ready for deployment by 2030.

Acknowledgment

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