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# Proceedings of the FNCA 2004 Workshop on the Utilization of Research Reactors

January 13-21, 2005
Bangkok, Thailand
(Contract Research)

Nuclear Technology and Education Center

July 2006

Japan Atomic Energy Agency

日本原子力研究開発機構

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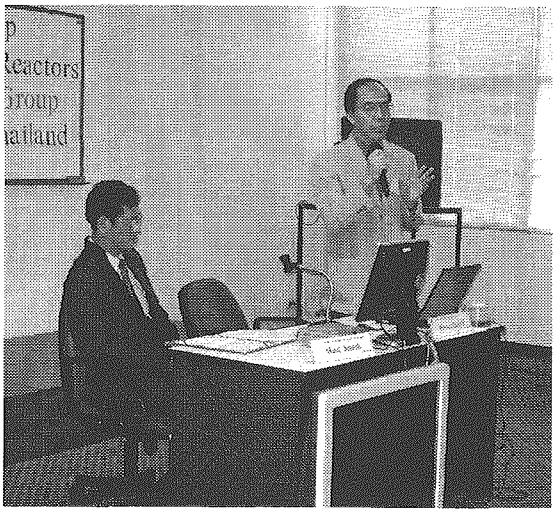
# The FNCA 2004 Workshop on the Utilization of Research Reactors

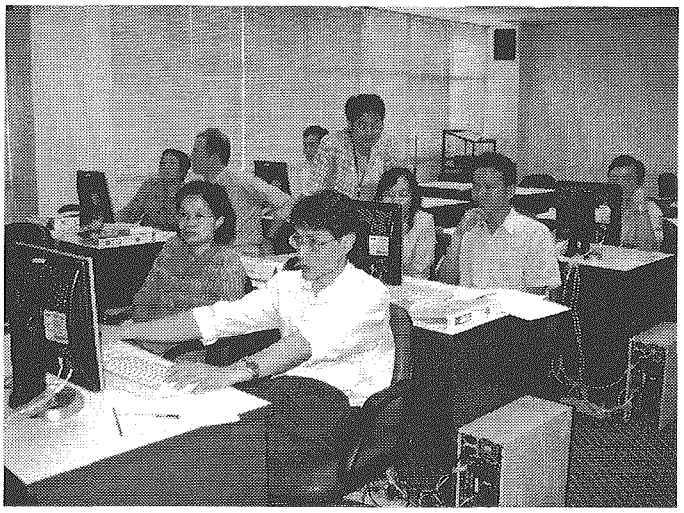
January13-21, 2005 Bangkok, Thailand

## Sub-workshop

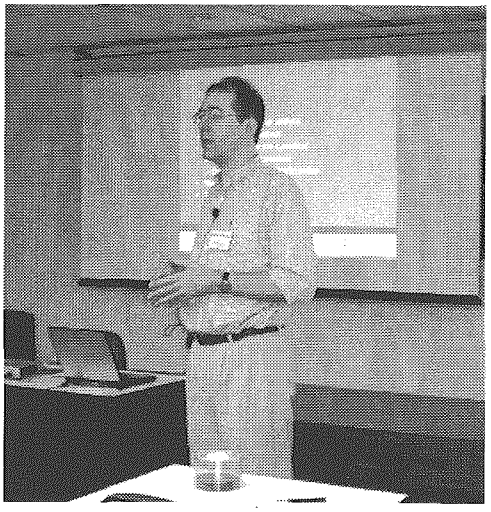
OAP

Group Photo

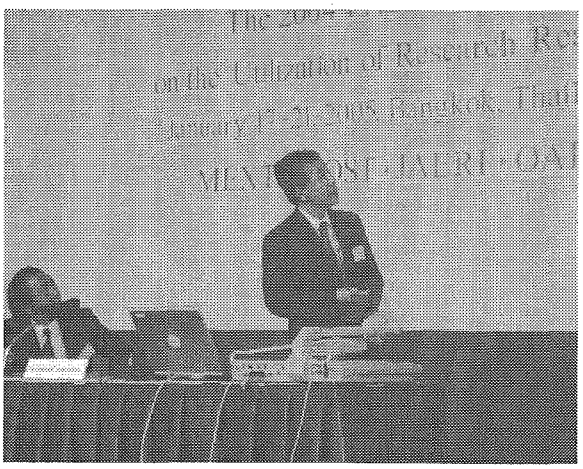


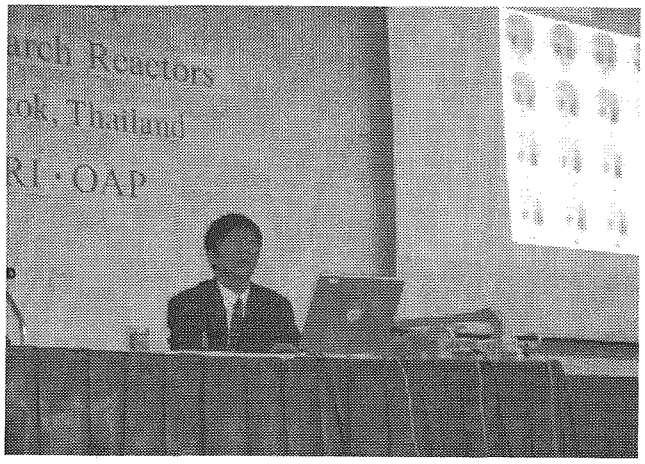


$K_0$ Method Evaluation



### Workshop - Plenary Session

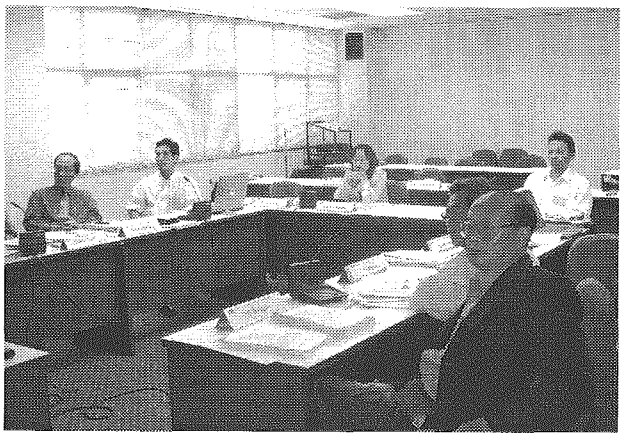


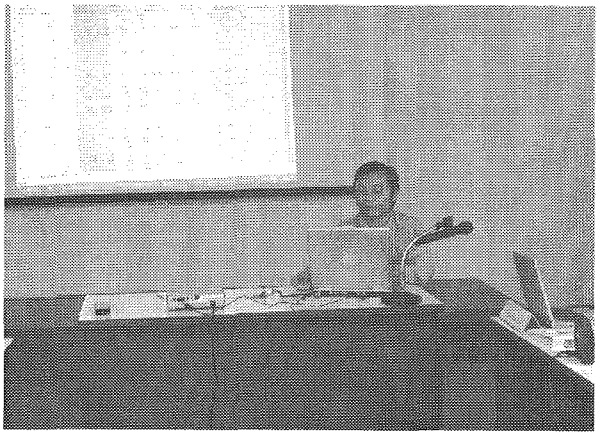



Group Photo

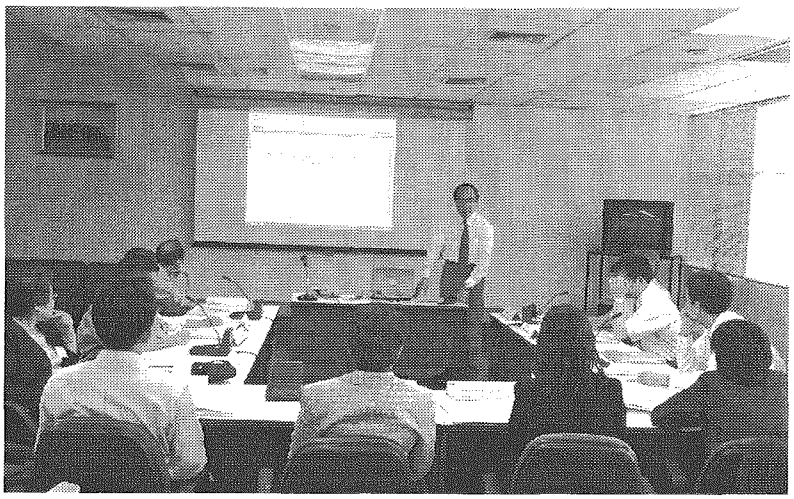
Press Conference

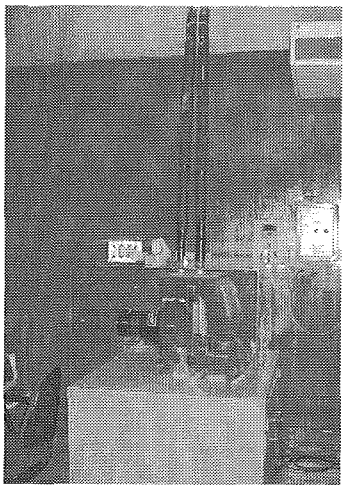
**Parallel Session – Neutron Activation Analysis Group**



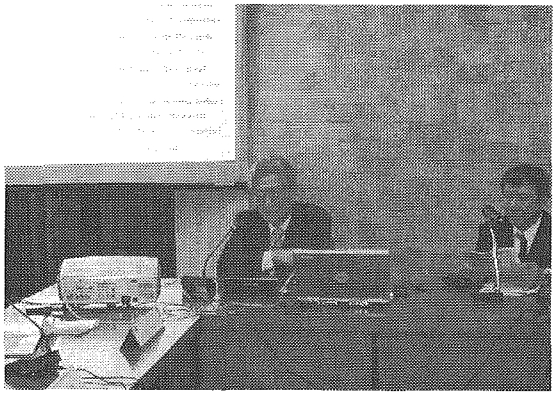


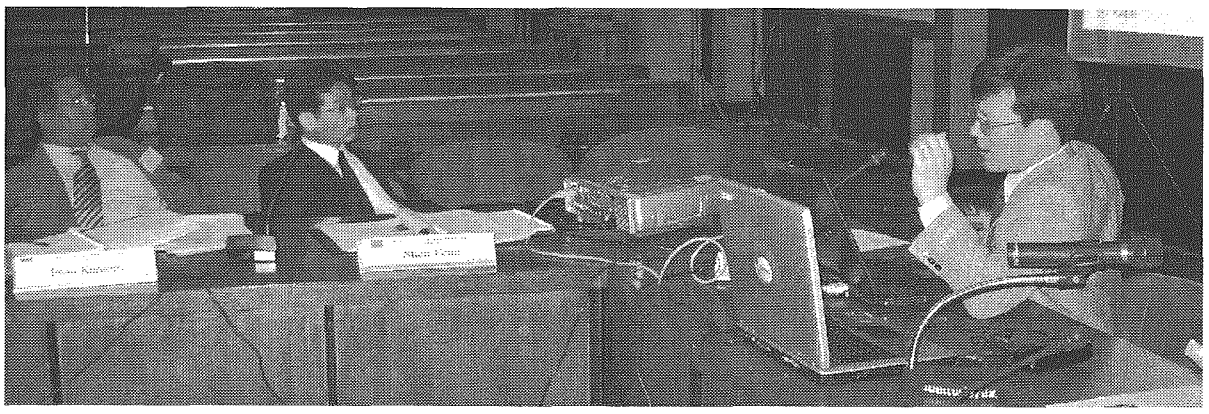
Neutron Activation Analysis Group

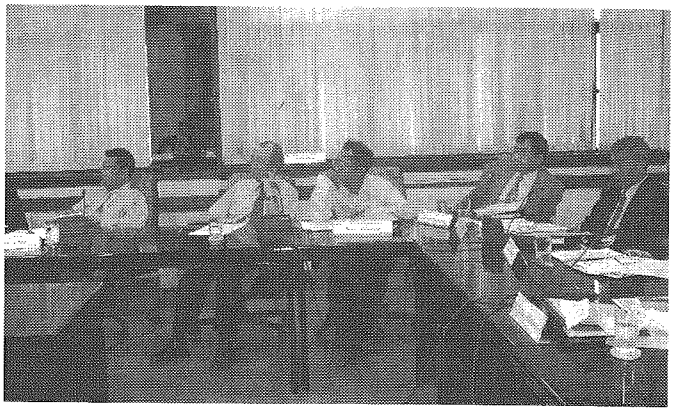




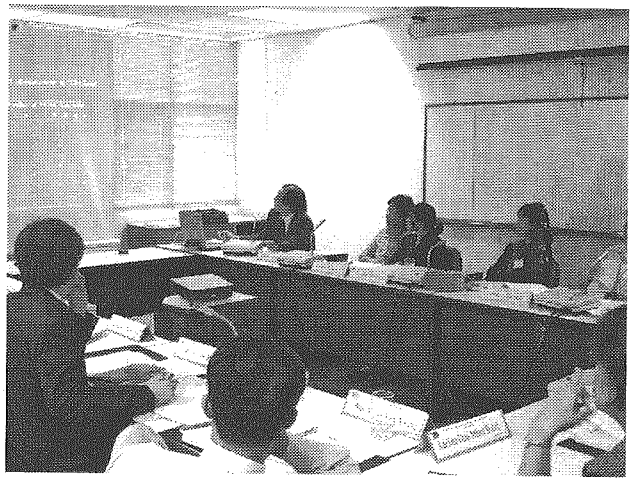
**Parallel Session – Research Reactor Group**

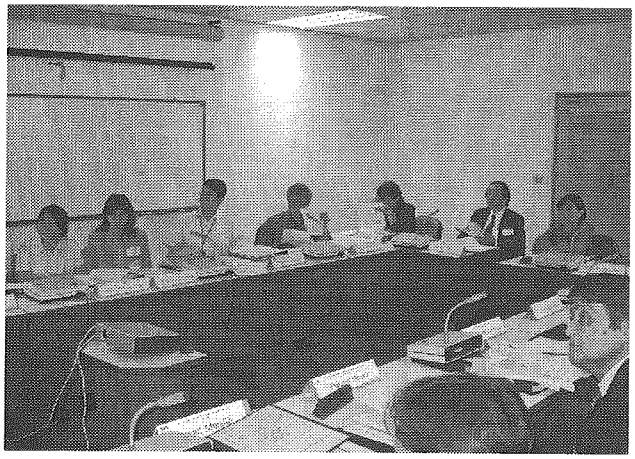


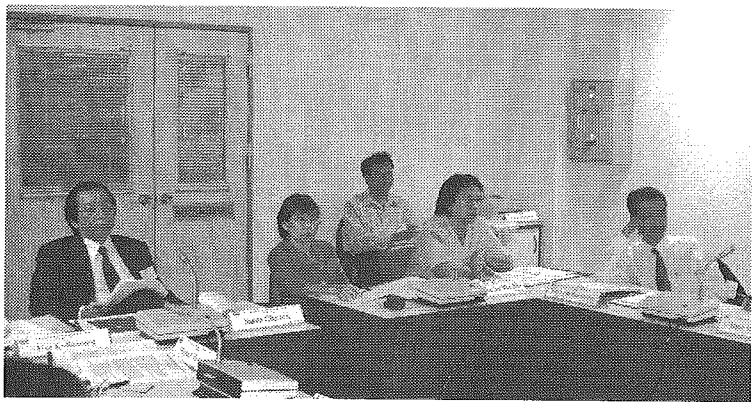




**Parallel Session – Tc Generator Group**







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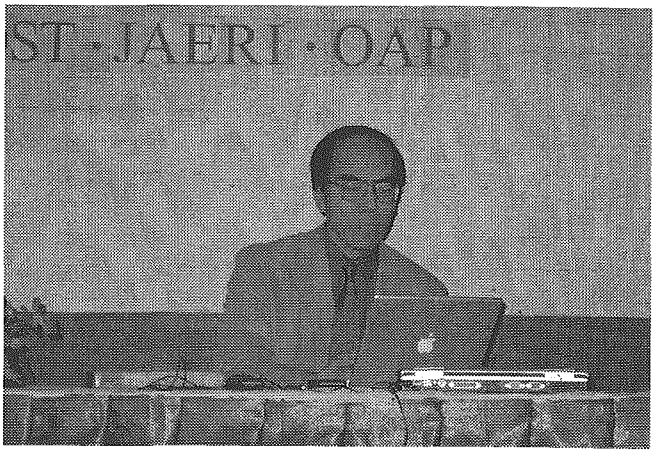
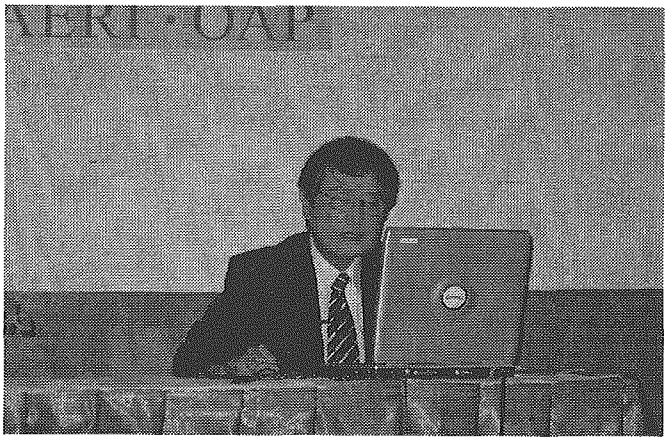
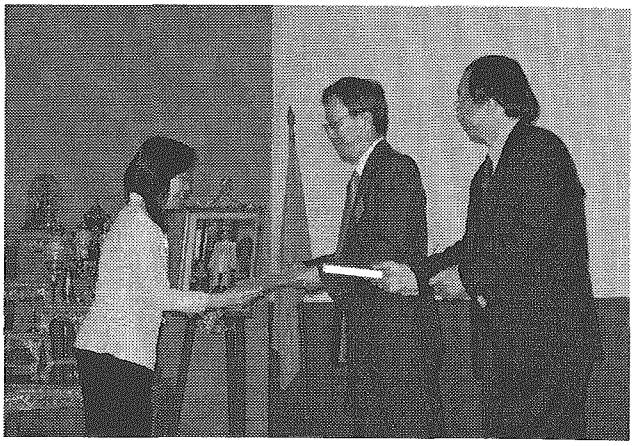
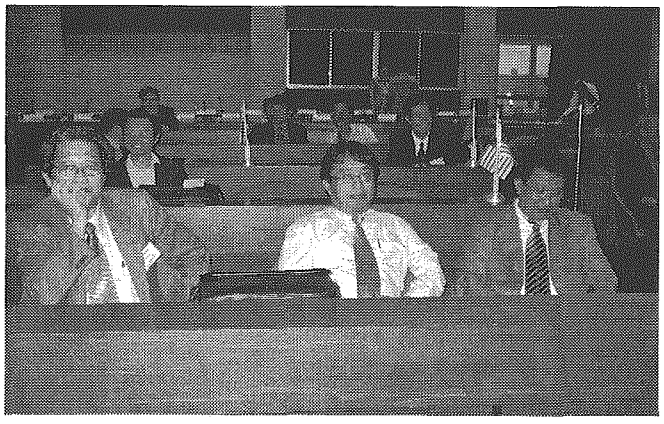
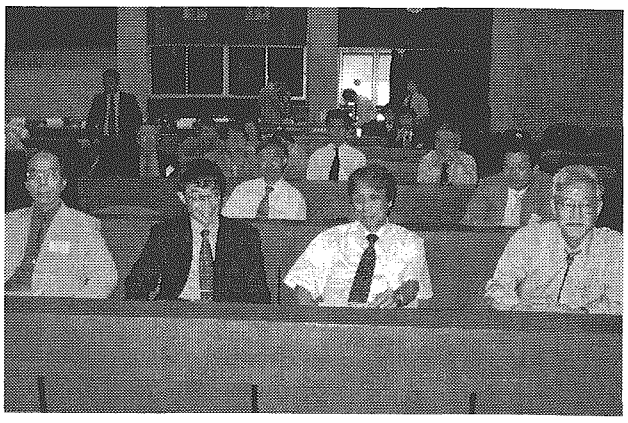



**Closing Ceremony**





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January13-21, 2005
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Nuclear Technology and Education Center

Japan Atomic Energy Agency
Tokai-mura, Naka-gun, Ibaraki-ken

(Received May 1, 2006)

The FNCA 2004 Workshop on the Utilization of Research Reactors, which is the twelfth workshop on the theme of research reactor utilization, was held in Bangkok, Thailand from January 13 to 21, 2005. This workshop was executed based on the agreement in the fifth Coordinator's Meeting of Forum for Nuclear Cooperation in Asia (FNCA) held in Tokyo, March 2004.

The workshop consisted of three groups under the themes of the following fields; 1) Neutron Activation Analysis, 2) Research Reactor Technology and 3) Tc-99m Generator Technology. The total number of participants for the workshop was 59 people from 8 countries; China, Indonesia, Korea, Malaysia, the Philippines, Thailand, Vietnam and Japan.

This report consists of 6 papers for Neutron Activation Analysis, 5 papers for Research Reactor Technology, 5 Papers for Tc-99m Generator Technology and a summary report.

Keywords: Utilization, Neutron Activation Analysis, Research Reactor Technology, Tc Generator Technology, and FNCA

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This Workshop was sponsored by the Ministry of Education, Culture, Sports, Science and Technology (MEXT), and Ministry of Science and Technology, Thailand, and the Japan Atomic Energy Research Institute (JAERI) had been assigned by MEXT as the responsible organization for holding the Workshop. This report includes the results carried out under the contract between JAERI and MEXT under the auspices of the special account law for electric power development promotion.

# FNCA 2004 年度　研究炉利用ワークショップ　論文集

2004 年 1 月 13 日～21 日

バンコク　タイ

(受託研究)

日本原子力研究開発機構

原子力研修センター

(2006 年 5 月 1 日受理)

研究炉利用ワークショップは、2004 年 3 月に東京で開催されたアジア原子力協力フォーラム第 5 回コーディネータ会合での合意に基づいて、文部科学省からの受託として 2005 年 1 月 13 日から 21 日まで、タイのバンコクで開催されたものである。

中性子放射化分析、研究炉基盤技術及び Tc-99m ジェネレータ技術の 3 つのテーマについてワークショップを開催し、中国、インドネシア、韓国、マレーシア、フィリピン、タイ、ベトナム及び日本の 8 か国から 59 名が参加した。

本論文集は、6 編の中性子放射化分析分野の報告、5 編の研究炉基盤技術分野の報告、5 編の Tc-99m ジェネレータ分野の報告及び 1 編のサマリー報告を収録したものである。

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本ワークショップは、文部科学省とタイ科学技術省の共催として、文部科学省から原研が受託して実施したものである。この論文集は、電源開発促進対策特別会計法に基づき、文部科学省から受託して行なった研究の結果を含む。

原子力科学研究所(駐在)：〒319-1195 茨城県那珂郡東海村白方白根 2-4

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# 1. Workshop

## Neutron Activation Analysis

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# 1.1 ANALYSIS OF AIRBORNE PARTICULATE MATTER COLLECTED IN URBAN AND RURAL AREA BY INSTRUMENTAL NEUTRON ACTIVATION ANALYSIS*)

Sutisna[1], Muhayatun[2]
[1)]Center for R & D of Materials Science and Technology
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National Nuclear Energy Agency of the Republic of Indonesia

**ABSTRACT**

ANALYSIS OF AIRBORNE PARTICULATE MATTER COLLECTED IN URBAND AND RURAL AREA BY INSTRUMENTAL NEUTRON ACTIVATION ANALYSIS. This report presents the work of monitoring study on air particulate matter (PMs) in Indonesia on the period of 2002 to 2004. The PMs were collected at two sampling site that represented an urban and rural area using Gent stacked air sampler for 24 hours, once a month for each sampling point. Fine and coarse fractions of PMs were collected. The PMs deposited on a filter were measured for mass concentration and were analyzed for elemental concentration by using INAA. Irradiations of filters were carried out at GA. Siwabessy reactor and were counted by high-resolution HPGe detector coupled to a multichanel analyzer. The $PM_{10}$ analysis resulted shows that the range of $PM_{10}$ for rural site was 5.5 $\mu g.m^{-3}$ to 46.9 $\mu g.m^{-3}$ while $PM_{10}$ for urban site was 12.0 $\mu g.m^{-3}$ to 93.1 $\mu g.m^{-3}$. About 17 elements of Al, Br, Cl, Cr, Co, Cs, Fe, I, La, Mn, Na, Sb, Sc, Se, Sm, V and Zn were analyzed through short and long irradiation of INAA. Among , the elements of Al, Br, Cl, Fe and Na were found at mayor component. The pollutants of Fe, V, Sb, Cr, Zn and Co were higher at urban site compare to the rural site. It could be conclude that the mean of 24 hours $PM_{10}$ and mean annual of fine fraction were still below the PMs National Standard for both sampling sites. The INAA technique could be used to control the pollutant concentration on environmental sample.

***Keywords***: PMs, Fine and coarse fraction, INAA, filter.

## INTRODUCTION

Utilization of nuclear technique on the environmental study was carried out under the FNCA program for the period of 2002 – 2004. The nuclear analytical technique was considered as a technique that has a good capability for elemental quantification on a trace elements level analysis. Regarding to that program, the INAA was used to determine the element quantity on air particulate matter sample. This technique is very

*) *Presented in The 2004 Workshop on the Utilization of Research Reactors, Bangkok, Thailand, January 13-22, 2005*

suitable for air particulate matter sample obtained by GANT stacked air sampler. The INAA has a high sensitivity and accuracy.

Air particulate sample was taken from two sampling point located at Lembang and Bandung that represented rural and an urban region. Sampling was carried out once a month for the period of 2002–2004 by using GANT stacked air sampler. Elemental quantification on $PM_{10}$ and $PM_{2.5}$ was performed by using INAA.

This paper will report the analytical result obtained, mass concentration of fine and coarse fraction and the elemental distribution as function of sampling time.

## METHODOLOGIES

***Sampling:*** Air particulate sample have been collected from two sampling points that represent of urban (Bandung) and rural (Lembang) area. Samplings were carried out for 24 hours using GANT Stacked Filter Unit Sampler with two kinds of filter (Nucleopore, $\phi$ = 47 mm, 0.45 μm and 8 μm pore size). Airborne particulate matter will be deposited on 0.45 μm and 8 μm pore size filter for fine and coarse particulate respectively. Exposed and unexposed filters were equilibrated in the chamber of 45-55 % of humidity and weighed in semi microbalance before using.

***Irradiation:*** Samples irradiations were carried out at rabbit facility of the GA. Siwabessy multipurpose reactors of National Nuclear Energy Agency (BATAN) at a thermal neutron flux of about $10^{13}$ $n.cm^{-2}.sec^{-1}$. Sample and standard were irradiated simultaneously at same position. Irradiation time ($T_i$), Cooling time ($T_d$) and Counting time ($T_c$) as typical values were as follow: 1). For short half life radionuclide determination: $T_i$ = 2 minutes, $T_d$ = 2-3 minutes and 1 hours, and $T_c$ = 60 seconds and 900 seconds. 2) For long half life radionuclide determination: $T_i$ = 3 hours, $T_d$ = 1 – 4 weeks and $T_c$ = 1800 -14400 seconds.

***Data Acquisition:*** Data acquisition of gamma-ray emitted were carried out using a high purity Ge detector (Efficiency of 20%, resolution of 1.8 keV at 1332 keV of $^{60}Co$ and P/C = 40) coupled to the Multiport II equipped with the GENIE 2000 software. The gamma rays spectra were then analyzed using peak search of GENIE 2000 software provided by Canberra.

***Data Analysis:*** Mass concentrations of fine and coarse particles were determined using weighed for both sampling point. Meanwhile the elemental concentration on each fraction was determined using a comparative method of INAA to home standard.

# RESULT AND DISCUSSION

## PMs concentration

Analysis of mass concentration deposited on filter taken from both samplings sites is very important to know the contamination level occurred on urban and rural site. The quantity of PMs represented the level of pollution that coming from urban or industrial activity. Figure 1 and 2 below shows the distribution of $PM_{10}$ for both sampling site as a function of sampling time. In general, the quantity of $PM_{10}$ taken from Bandung site is

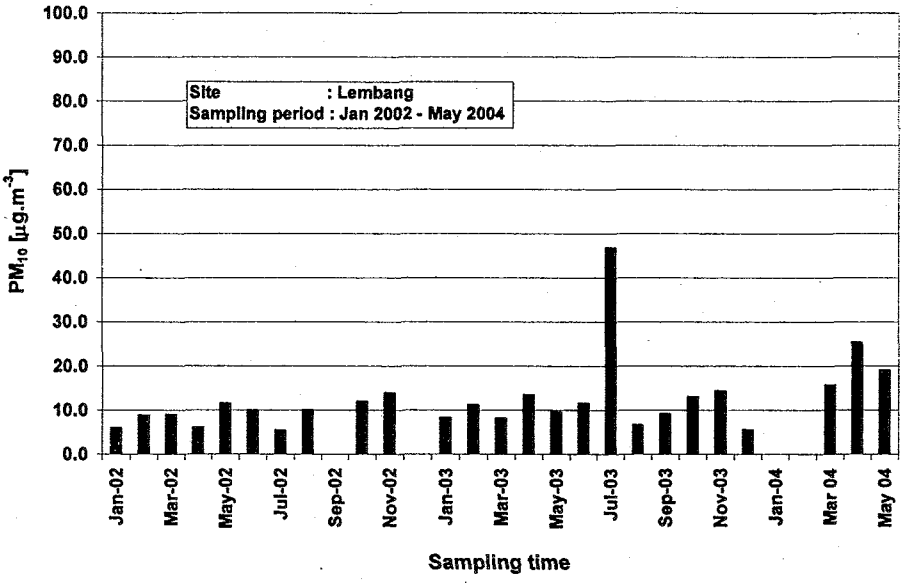


**Figure 1.** $PM_{10}$ concentration at Lembang site.

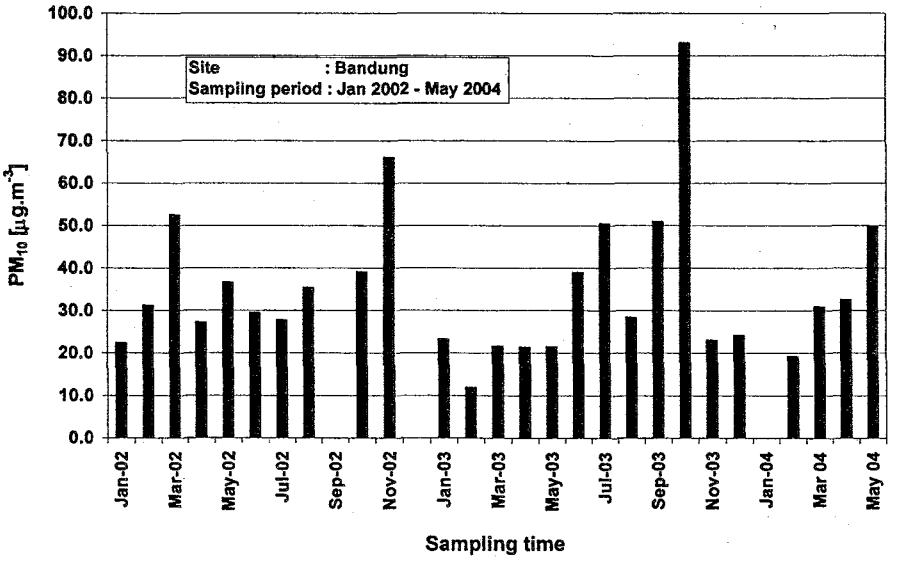


**Figure 2.** $PM_{10}$ concentration at Bandung site.

higher that that from Lembang site. This phenomenon show that the Bandung site, as urban region, more pollute compare to Lembang site.

Range of $PM_{10}$ concentration is 5.5 $\mu g.m^{-3}$ to 46.9 $\mu g.m^{-3}$ for rural site, and 12.0 $\mu g.m^{-3}$ to 93.1 $\mu g.m^{-3}$ for urban site. At rural site, 32 % of $PM_{10}$ is contributed from fine

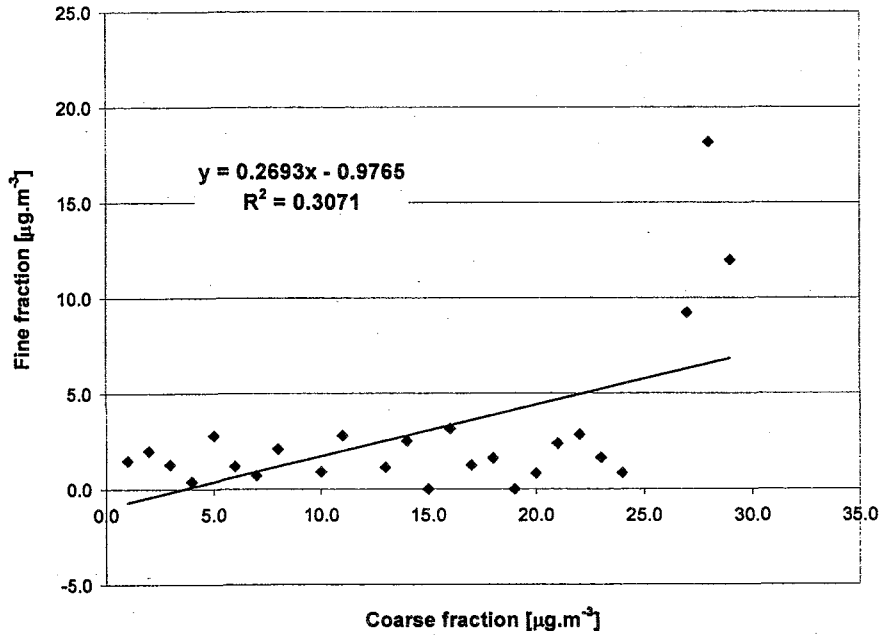


**Figure 3.** Correlation of fine fraction to coarse fraction for Bandung site.

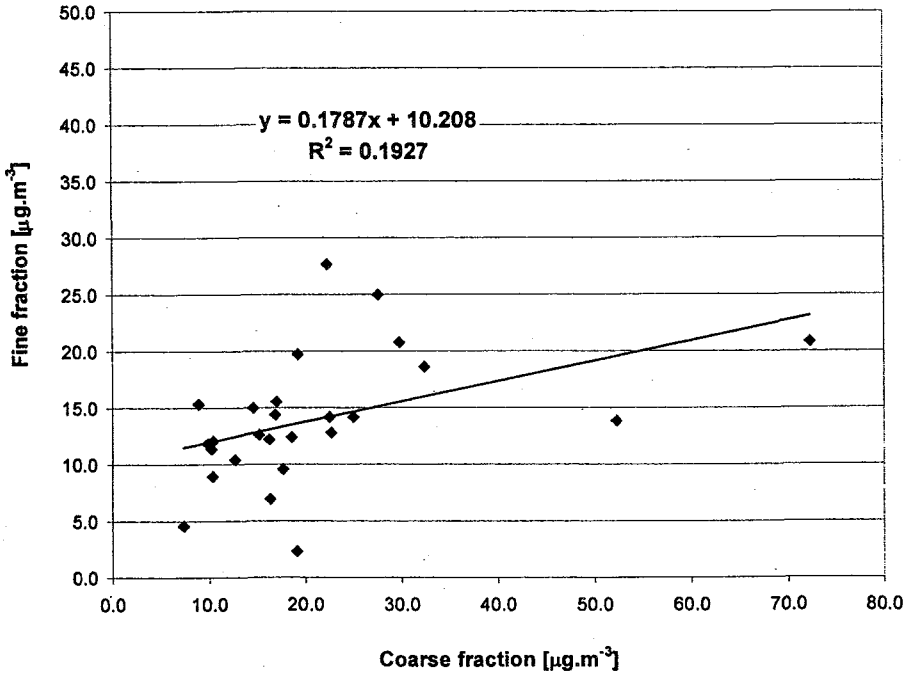


**Figure 4.** Correlation of fine fraction to coarse fraction for Lembang site.

fraction, while at urban site the contribution of fine fraction to $PM_{10}$ is of about 60 %. Mean of 24 hours $PM_{10}$ was still below the $PM_{10}$ National Standard of 150 $\mu g.m^{-3}$ for both sampling sites. Mean annual of fine particle at rural site was 7.8 $\mu g.m^{-3}$ at 2002 and 12.0 $\mu g.m^{-3}$ at 2003. Meanwhile the mean annual of fine particle at urban site was 14.4 $\mu g.m^{-3}$ and 12.9 $\mu g.m^{-3}$ for 2002 and 2003 respectively. They were still below the $PM_{2.5}$ National Standard of 15 $\mu g.m^{-3}$. Figure 3 and 4 shows the regression analysis to identify the relationship between fine and coarse fraction for both sampling site. As indicate by R factor obtained, the correlation of fine to coarse fraction is not significant.

## ELEMENTAL COMPOSITION

Table 1 to 4 shows the average concentration of elements measured for both sampling site (rural and urban) in the sampling period of Jan 2002 to Aug 2004. The 17 elements of Al, Br, Cl, Cr, Co, Ce, Fe, I, La, Mn, Na, Sb, Sc, Se, Sm, V and Zn have been analyzed. The table presents the analytical result of element concentration at fine and coarse fraction for each sample. However, the mean value was calculated based on population, and so the element which have a concentration under its limit detection, exclude in mean calculation. Among those elements concerned, Al, Br, Cl, Fe and Na, were found to be grouped as major component for both sampling site and all fraction. Some elements concentration increase with time, but the other was not significant difference.

The mean annual concentration of Fe, V, Sb, Cr, Zn and Co pollutants is relatively high at urban site compare to rural site. This pollutant could be contributed from metal industry located at west and east of urban sampling site.

Br is an interesting element because it's used as indicator for air pollution coming from vehicle utilization. The Br concentration is higher in fine fraction of PMs for both sampling site. Its concentration at urban site was higher than that at rural site. It could be contributed from the utilization of leaded petrol that is still used in Indonesia.

## CONCLUTION

The elements and mass concentration at urban site were generally higher than that at rural site. Mean of 24 hours $PM_{10}$ and mean annual of fine fraction were still below the PMs National Standard for both sampling sites. The INAA technique could be used to control the pollutant on environmental sample.

## ACKNOWLEGMENT

I would like to express special thank to MEXT and JAERI that supported this work. Special thank are due Mr. Iman Kuntoro and Mr. Gunandjar for their support to this project. Thank you very much to my colleagues at Center for Research and Development for Nuclear Technique for their support on the sampling of environmental sample. Thank you very much for my colleagues at Center for Development of Research Reactor for their assistant on sample irradiation.

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**Table 1.** Average concentration of elements measured in coarse fraction of rural site for the sampling period of 2002-2004 [Unit in ng.m$^{-3}$].

| Elements | 2002 | | | 2003 | | | 2004 | | |
|---|---|---|---|---|---|---|---|---|---|
| | n | Mean | Range | n | Mean | Range | n | Mean | Range |
| Al | 11 | 78.5 | 9 - 162 | 11 | 683.2 | 46 1727 | 3 | 163.7 | 136 - 216 |
| Br | 11 | 28.1 | 6 - 49 | 4 | 28.6 | 3.8 - 51.3 | 3 | 5.4 | 4.6 5.9 |
| Cl | 11 | 101 | 18 - 328 | 10 | 32.7 | 8 - 58 | 3 | 71.0 | 27 - 145. |
| Cr | 11 | 5.6 | 0.2 - 12.9 | 6 | 2.0 | 0.2 - 5.9 | 3 | 17.1 | 15.7 - 18.7 |
| Co | 11 | 0.13 | 0.01 - 0.28 | 5 | 2.0 | 0.01 8.54 | 3 | 0.18 | 0.17 0.19 |
| Ce | | | | 6 | 0.25 | 0.02 - 0.76 | | | |
| Fe | 11 | 86 | 12 - 165 | 8 | 38.9 | 3.1 - 68.6 | 3 | 120.2 | 100 - 152 |
| I | 11 | 5.6 | 0.4 - 36.3 | 3 | 7.7 | 6 9 | 3 | 0.36 | 0.27 - 0.49 |
| La | 11 | 1.3 | 0.05 - 4.04 | 5 | 0.6 | 0.01 - 1.50 | 3 | 0.15 | 0.11 - 0.21 |
| Mn | 11 | 1.3 | 0.1 - 2.8 | 5 | 6.03 | 0.18 - 27.8 | 3 | 3.16 | 2.63 - 4.11 |
| Na | 11 | 78.5 | 9 - 162 | 6 | 35.6 | 11.4 - 79.2 | 3 | 289.8 | 215 - 384 |
| Sb | 11 | 0.2 | 0.06 - 0.30 | 5 | 0.35 | 0.02 - 1.21 | | | |
| Sc | 11 | 0.012 | 0.001 - 0.089 | | | | 3 | 0.02 | 0.01 - 0.04 |
| Sm | 11 | 0.11 | 0.001 - 0.988 | 2 | 0.04 | 0.01 0.07 | 3 | 0.02 | 0.01 - 0.02 |
| V | 11 | 0.6 | 0.1 2.3 | 2 | 0.27 | 0.06 - 0.48 | 3 | 0.39 | 0.26 - 0.47 |
| Zn | 11 | 10.4 | 1.6 - 23.9 | 7 | 1.67 | 0.02 5.47 | 3 | 7.04 | 6.28 - 8.15 |

**Table 2.** Average concentration of elements measured in fine fraction of rural site for the sampling period of 2002-2004 [Unit in ng.m$^{-3}$].

| Elements | 2002 | | | 2003 | | | 2004 | | |
|---|---|---|---|---|---|---|---|---|---|
| | n | Mean | Range | n | Mean | Range | n | Mean | Range |
| Al | 11 | 39 | 10 - 95 | 11 | 1065.1 | 19 - 9550 | 6 | 40.1 | 16 - 64 |
| Br | 11 | 41 | 17 - 84 | 8 | 33.4 | 5.36 - 145 | 6 | 42.95 | 13.5 - 77.9 |
| Cl | 11 | 78.6 | 33 - 140 | 10 | 40.0 | 0.06 - 109 | 6 | 95.62 | 26.1 - 173 |
| Cr | 11 | 8.2 | 0.2 - 29.9 | 9 | 6.48 | 0.05 - 19.80 | 6 | 3.87 | 1.80 - 6.31 |
| Co | 11 | 0.2 | 0.01 - 0.34 | 7 | 0.70 | 0.07 - 3.06 | 4 | 0.16 | 0.14 - 0.20 |
| Ce | | | - | 3 | 0.15 | 0.05 - 0.32 | | | |
| Fe | 11 | 111.2 | 14 - 266 | 10 | 37.8 | 5.6 - 105.2 | 6 | 47.26 | 25.04 - 80.24 |
| I | 11 | 4.4 | 0.4 - 29 | 4 | 19.9 | 11.7 - 33.20 | 6 | 2.47 | 1.24 - 4.57 |
| La | 11 | 1.4 | 0.1 - 4.2 | 4 | 0.42 | 0.11 - 1.20 | 6 | 0.12 | 0.05 - 0.27 |
| Mn | 11 | 1.2 | 0.3 - 2.9 | 5 | 2.16 | 0.25 - 8.40 | 6 | 1.09 | 0.52 - 1.65 |
| Na | 11 | 41.5 | 18 - 100 | 7 | 48.05 | 1.87 - 187.5 | 6 | 92.85 | 30.9 - 221.5 |
| Sb | 11 | 0.5 | 0.3 - 1.2 | 7 | 0.49 | 0.03 - 1.51 | | | |
| Sc | 11 | 0.005 | 0.001 - 0.02 | | | | | | |
| Se | | | | 6 | 0.37 | 0.09 - 1.66 | | | |
| Sm | 11 | 0.3 | 0.001 - 2.405 | 2 | 0.17 | 0.02 - 0.32 | 6 | 0.001 | 0.005 - 0..04 |
| V | 11 | 0.4 | 0.2 - 1.4 | 7 | 1.77 | 0.17 - 4043 | 6 | 0.54 | 0.16 - 0.95 |
| Zn | 11 | 7.9 | 1.6 24.0 | 3 | 36.2 | 5.9 - 85.3 | 6 | 10.01 | 6.42 - 13.1 |

**Table 3.** Average concentration of elements measured in coarse fraction of urban site for the sampling period of 2002-2004 [Unit in ng.m$^{-3}$].

| Elements | 2002 | | | 2003 | | | 2004 | | |
|---|---|---|---|---|---|---|---|---|---|
| | n | Mean | Range | n | Mean | Range | n | Mean | Range |
| Al | 11 | 525 | 53 - 1040 | 9 | 14211 | 654 - 82146 | 5 | 717 | 269 - 1073 |
| Br | 11 | 39.3 | 12 - 82 | 10 | 56.4 | 5.35 - 220.9 | 5 | 32.52 | 27.2 - 46.4 |
| Cl | 11 | 199.3 | 59 - 483 | 9 | 265.7 | 7.92 - 690.4 | 5 | 231.2 | 64.9 - 421.8 |
| Cr | 11 | 17.0 | 4.3 - 40 | 10 | 6.81 | 0.6 - 24.2 | 5 | 19.6 | 14.4 - 28.7 |
| Co | 11 | 0.89 | 0.02 - 3.59 | 7 | 0.39 | 0.06 - 1.3 | 5 | 0.43 | 0.24 - 0.63 |
| Ce | | | - | 6 | 0.33 | 0.07 - 0.97 | 5 | | |
| Fe | 11 | 1011 | 111 - 3015 | 11 | 574.9 | 29.4 - 2244 | 5 | 493.7 | 182. - 772 |
| I | 11 | 7.9 | 0.5 - 38.1 | | | | | | |
| La | 11 | 1.0 | 0.1 - 4.2 | 6 | 0.25 | 0.06 - 0.58 | 5 | 0.32 | 0.14 - 0.49 |
| Mn | 11 | 16.4 | 4.5 - 32.7 | 11 | 7.1 | 0.96 - 22.24 | 5 | 10.64 | 5.0 - 15.9 |
| Na | 11 | 266.7 | 47 - 484 | 11 | 296.9 | 15.02 - 852.1 | 5 | 356.1 | 72.6 - 930 |
| Sb | 11 | 1.1 | 0.05 - 6.5 | 8 | 1.10 | 0.07 - 5.02 | 5 | | |
| Sc | 11 | 0.06 | 0.002 - 0.151 | | | | 5 | 0.12 | 0.01 - 0.31 |
| Se | | | | 3 | 2.0 | 0.05 - 3.95 | 5 | | |
| Sm | 11 | 0.05 | 0.003 - 0.283 | 6 | 0.17 | 0.012 - 0.63 | 5 | 0.05 | 0.019 - 0.08 |
| V | 11 | 1.2 | 0.7 - 3.1 | 8 | 18.19 | 0.38 - 82.7 | 5 | 2.81 | 0.635 - 5.19 |
| Zn | 11 | 13.6 | 4.8 - 21.9 | 10 | 10.08 | 0.26 - 27.8 | 5 | 27.8 | 10.2 - 38.0 |

**Table 4.** Average concentration of elements measured in fine fraction of urban site for the sampling period of 2002-2004 [Unit in ng.m$^{-3}$]

| Elements | 2002 | | | 2003 | | | 2004 | | |
|---|---|---|---|---|---|---|---|---|---|
| | n | Mean | Range | n | Mean | Range | n | Mean | Range |
| Al | 11 | 113 | 42 - 216 | 11 | 969.1 | 81.50 - 4336 | 7 | 103.4 | 37 - 163 |
| Br | 11 | 46.2 | 20 - 90 | 10 | 213.7 | 12.75 - 1786 | 7 | 85.8 | 33 - 169 |
| Cl | 11 | 118.7 | 33 - 285 | 12 | 46.17 | 5.50 - 121.2 | 7 | 90.1 | 36. - 175 |
| Cr | 11 | 16.0 | 3.2 - 49.8 | 10 | 18.81 | 1.2 - 86.6 | 7 | 5.8 | 2.70 - 12.2 |
| Co | 11 | 0.6 | 0.01 - 2.17 | 8 | 8.0 | 0.14 - 36.60 | 5 | 0.3 | 0.12 - 0.57 |
| Ce | | | - | 6 | 0.54 | 0.04 - 1.45 | | | |
| Fe | 11 | 202.6 | 20 - 616 | 12 | 373.7 | 15.72 - 3732 | 7 | 207.1 | 50 - 568 |
| I | 11 | 4.7 | 0.5 - 22.6 | 5 | 138.05 | 3.80 - 617.0 | 7 | 2.3 | 0.7 - 3.4 |
| La | 11 | 1.0 | 0.04 - 2.3 | 5 | 0.14 | 0.03 - 0.31 | 7 | 0.2 | 0.06 - 0.27 |
| Mn | 11 | 2.9 | 1.0 - 5.7 | 10 | 1.54 | 0.16 - 3.47 | 7 | 2.9 | 1.11 - 7.47 |
| Na | 11 | 108.0 | 42 - 237 | 11 | 63.88 | 12.68 - 109.7 | 7 | 102.1 | 24.8 - 203.5 |
| Sb | 11 | 1.2 | 0.06 - 6.72 | 7 | 2.11 | 0.20 - 12.01 | | | |
| Sc | 11 | 0.03 | 0.01 - 0.11 | | | - | | | |
| Se | | | | 5 | 0.65 | 0.16 - 2.51 | | | |
| Sm | 11 | 0.05 | 0.003 - 0.203 | 4 | 0.01 | 0.003 - 0.02 | 7 | 0.02 | 0.006 - 0.040 |
| V | 11 | 0.9 | 0.3 - 2.1 | 9 | 3.08 | 0.004 - 7.70 | 7 | 1.9 | 0.3 - 4.9 |
| Zn | 11 | 13.8 | 4.1 - 26.9 | 9 | 84.9 | 3.5 - 286.8 | 7 | 28.7 | 10 - 55.0 |

# 1.2 CHEMICAL CHARACTERIZATION OF URBAN AIR PARTICULATE MATTER OF KUALA LUMPUR 2002 – 2004

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**Abstract**

Urban air particulate samples of Kuala Lumpur ambient air have been collected and characterize according to fine and coarse airborne particulates. The air filters containing particulate matter were collected using GENT stack filter unit fitted with appropriate polycarbonate filters. The sampling location site (Lat: 03° 10'30"; Long: 101° 43' 24.2") is approximately 1 km from the Kuala Lumpur city center. All the sampling conducted from January 2002 until October 2004 was included in the analysis and results were reported. The mass loading for finest air particulate matter (PM 2.5) in Kuala Lumpur are 199 ± 55 μg (2002), 171 ± 53 μg (2003), and 171 ± 61 μg (2004), respectively. The mass loading for coarse air particulate matter (PM 10) in Kuala Lumpur were 125 ± 29 μg (2002), 134 ± 48 μg (2003), and 137 ± 57 μg (2004), respectively. The elemental concentration of the air filters were determined using INAA technique utilizing both short and long irradiation facilities at MINT's TRIGA MKII reactor. Upon irradiation the air filters were counted at suitable counting time using HPGe gamma-ray detectors. The elements reported for this monitoring are Al, As, Br, Co, Cr, K, Lu, Mn, Na, Sb, Sc, Ti, V, and Zn. Certified reference materials were also included in the sample analysis function as quality control materials.

## 1.0 INTRODUCTION

Air pollution in urban areas has been the concern of many governments in relation to its impact on the health of the population living within the vicinity. Many health related problems such as respiratory illness and decrease of lung functions are linked to the exposure of air particles (PM 2.5 and PM 10) presence in the air that we breathe. Hence, monitoring of the ambient air by collecting air particulate samples gives indication on the level of pollution within the city and provides information for further action by policymakers to enhance the air quality of urban areas. Kuala Lumpur being the capital of Malaysia has also faced the problems of air pollution. Increase of mobile sources, stationary sources and open burning sources would increase the level of air pollution in Malaysia (Afroz *et al.*, 2003).

The collaboration between research institutions facilitates and improves the monitoring of regional air pollution levels. Methods have been developed to analyze chemical constituents of fine and coarse air particulates. Neutron activation analysis being one of the accurate analytical methods has been playing important role in determination of multiple elements in air particulate samples.

In this report, data obtained from monthly collection of air filter samples from the year 2002 up to 2004 at Kuala Lumpur were presented. Chemical constituents (Al, As, Br,

Co, Cr, K, Lu, Mn, Na, Sb, Sc, Ti, V, and Zn) of the fine and coarse air particulates have been determined.

## 2.0 EXPERIMENTAL

The sampling station is located at University Technology Malaysia campus (Lat: 03° 10' 30", Long: 101° 43' 24.2"), about 1 km northeast of the city center of Kuala Lumpur. The site is chosen due to the fact that various types of properties including residential and commercial which is surrounded by various industrial estates within the Klang Valley. The valley is the most densely populated and industrialized area in the country which comprises total area of about 3,000 $km^2$ with estimated 3 million people living in its vicinity. Its climate is typical of the humid tropics with mean daily temperature of between 26° and 30° C, the average precipitation is about 2,500 mm. The winds are generally light throughout the year between 0.5 m $s^{-1}$ and 1.0 m $s^{-1}$.

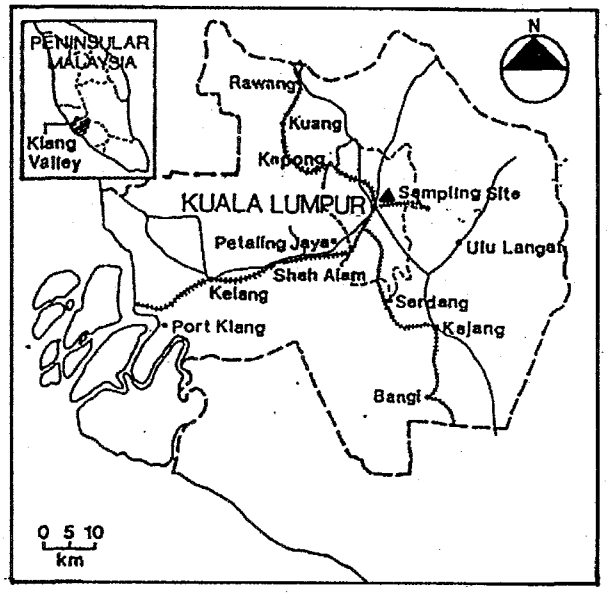


Fig. 1 Sampling location at Kuala Lumpur.

The sampling has been done once every month using Gent air sampler at flow rate of about 15 $cm^3$/min on a 24 hours average (morning-to-morning) throughout the year 2002 until October 2004. A total of 42 pairs of filters were used where each pair consists of finest and coarse airborne particulate matter which was collected for the study. All air filters were kept in desiccators and conditioned for about 24 hours before and after sampling prior to weighing to ensure no effect of moisture in the quantification of the mass of the airborne particulate matter. The mass of the air particulate matter was gravimetrically determined using microbalance. The total mass was divided by the volume of air passing through the filter to provide micrograms of the atmospheric air particulate per cubic meter of air sampled.

The elemental analysis (except black carbon) has been done using INAA technique. The air particulate samples, standard solutions and CRM were irradiated at the MINT TRIGA Mark II reactor at 750 kW with neutron flux in the order of $10^{12}$ $n \cdot cm^{-2}s^{-1}$. The irradiation time was 3 minute for short half-live nuclides and 12 hours for long half-live nuclides. All samples and standards were left for appropriate time after irradiation

prior to counting using HPGe γ-ray spectrometry systems. Counting times were set for 1 – 2 hours at counting geometry of 1 cm from the γ-ray detector. All samples and standards were counted at different cooling time to determine nuclides of interest. The efficiency of the HPGe γ-ray detector is and resolution of 1.8 keV (at 1332 keV). The elements determined include Al, As, Br, Co, Cr, K, Mn, Na, Sb, Ti, V, and Zn. The NBS 1633a have been used as the quality assurance material for the analytical procedure.

## 3.0 RESULTS & DISCUSSIONS

The results of air particulate analysis for year 2002, 2003 and 2004 were present in Table 2 and 3. However, due to the busy schedule of the reactor, the elemental concentrations of air filters in the year 2004 were based on coarse particulate collected from January until October. At present, analytical work is pending due to reactor maintenance and will complete the analysis in the near future.

The mass loading for finest air particulate matter (PM 2.5) in Kuala Lumpur are 199 ± 55 μg (2002), 171 ± 23 μg (2003), and 171 ± 61 μg (2004), respectively. The mass loading for coarse air particulate matter (PM 10) in Kuala Lumpur were 125 ± 29 μg (2002), 134 ± 48 μg (2003), and 137 ± 57 μg (2004), respectively. The slight decrease of PM 2.5 from the year 2002 until 2004 has been very encouraging as it is the major cause of respiratory disease. There are some increase of PM 10 for the period mentioned.

The mass concentration of air particulates are shown in Fig. 2 with finest air particulate tends to be having higher concentration than coarse air particulate matter. From January to July each year showed air particulate concentration below 30μg/m$^3$. However, in between August and September registered a slightly higher air particulate concentration well about 30μg/m$^3$. This might be due to the dry season along with exhaust fumes and expose soil surface tends to increase the air particulates around the city. In the following months from October to December, a slight decrease can be seen as rainy season approaches. The effects of rainfall to air particulate in 2003 was shown in Fig. 3 where increase of rainfall showed some effect in lessen the mass concentration of fine and coarse air particulates collected in the air filters. In general, the monthly average fine and coarse air particulate matter has a concentration which fluctuates between 5 – 50 μg/m$^3$ as indicated in Fig. 2. The current PM10 level of Kuala Lumpur which is still below 90 μg/m$^3$ as stated in the Malaysia Air Quality Guideline.

Elemental concentration of the finest and coarse air particulates were shown in Table 2. Elements such as Ti, Al, and Cr showed some increase in the recent years however As, Sb, Co, Zn showed stable results throughout. The increase of Ti and Al concentration in both finest and coarse air particulate might attribute to industrial activities surrounding the Klang Valley.

In accordance with quality control measures, certified reference material was used namely NIST SRM 1633a (coal fly ash). The result of the analysis (13 elements) was compared to certified value as in Table 1 and found to be satisfactory for elements of interest.

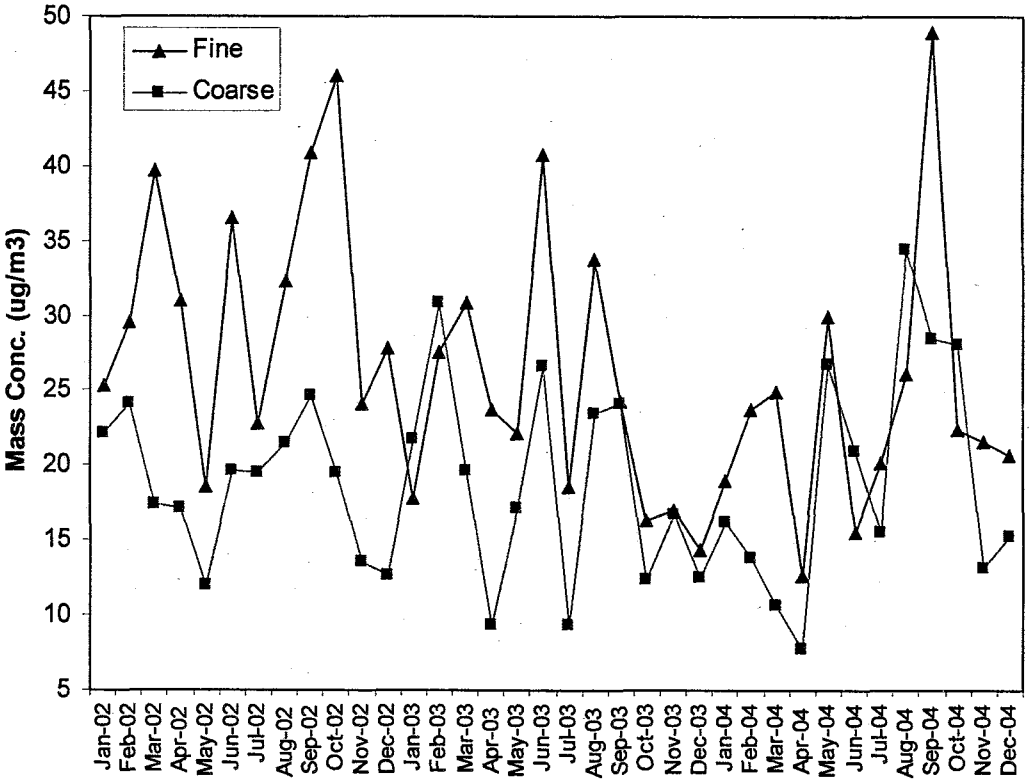


Fig. 2 Mass concentration of air particulates of Kuala Lumpur from 2002 until 2004.

Table 1: Analytical results of analysis of quality assurance material NMS SRM1633a (Trace elements in coal fly ash).

| Elements | Certified Values (ug/g) | Measured Values (ug/g) |
|---|---|---|
| Dy | 15.6 ± 1.2 | 14.7 ± 2.0 |
| Ti | 8000 | 7568 |
| V | 297 ± 16 | 234 ± 21 |
| Al | 14.3 ± 1.0 (%) | 12.1 ± 0.7 (%) |
| Mn | 179 ± 8 | 182 ± 1 |
| Sm | 17.0 | 17.4 |
| Na | 1700 ± 100 | 1692 ± 136 |
| K | 1.88 ± 0.06 (%) | 1.96 ± 0.13 (%) |
| Eu | 4.0 | 3.25 ± 0.16 |
| As | 145 ± 15 | 152 ± 8 |
| Ca | 1.11 ± 0.01 (%) | 0.95 ± 0.12 (%) |
| Lu | 1.12 ± 0.18 | 1.18 ± 0.19 |
| Br | 2.3 | 2.4 |

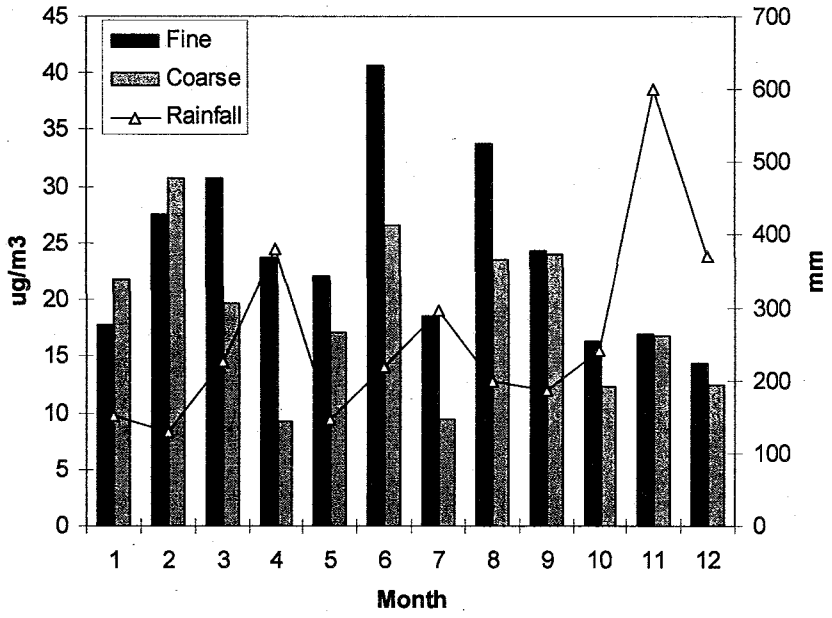


Fig. 3 Monthly rainfall and mass concentration of air particulates of Kuala Lumpur in 2003.

## 4.0 CONCLUSION

The chemical characterization of air particulates has been quantified using INAA technique and yield comprehensive data on the current air quality at Kuala Lumpur which is useful indicators for the pollution level in the city. These results are particularly important for policymakers where community health and environmental protection is concerned. Thus, continuous effort of the project would be very beneficial in long-term monitoring of air particulates in this region as trans-boundary air pollution can be a serious problem to the health of the population.

## 5.0 ACKNOWLEDGEMENTS

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## 6.0 REFERENCES

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Table 2: Mass Concentration of APM at sampling site in Kuala Lumpur for 2002 – 2004.

| | | 2002 | | 2003 | | 2004 | |
|---|---|---|---|---|---|---|---|
| Month | Particulate | Weight (ug) | Conc (ug/m3) | Weight (ug) | Conc (ug/m3) | Weight (ug) | Conc (ug/m3) |
| January | Fine | 177.0 ± 2.1 | 25.2 ± 0.3 | 142.0 ± 3.4 | 17.75 ± 1.2 | 132.7 ± 9.6 | 18.95 ± 0.4 |
| | Coarse | 154.8 ± 2.4 | 22.1 ± 0.3 | 137.7 ± 5.2 | 21.7 ± 1.3 | 113.7 ± 5.8 | 16.2 ± 1.2 |
| February | Fine | 206.3 ± 3.4 | 29.4 ± 0.4 | 206.33 ± 2.1 | 27.6 ± 1.4 | 166.0 ± 9.3 | 23.7 ± 0.9 |
| | Coarse | 169.0 ± 1.1 | 24.1 ± 0.1 | 215.7 ± 9.2 | 30.8 ± 0.6 | 97.3 ± 7.2 | 13.9 ± 0.3 |
| March | Fine | 277.6 ± 2.6 | 39.6 ± 0.3 | 215.7 ± 2.4 | 30.8 ± 1.3 | 174.3 ± 6.9 | 24.9 ± 0.5 |
| | Coarse | 122.0 ± 3.1 | 17.4 ± 0.4 | 137.7 ± 4.1 | 19.7 ± 3.6 | 74.3 ± 5.9 | 10.6 ± 1.1 |
| April | Fine | 216.6 ± 2.7 | 30.9 ± 0.3 | 166.3 ± 3.1 | 23.8 ± 0.9 | 101.0 ± 4.6 | 12.6 ± 1.2 |
| | Coarse | 120.3 ± 2.9 | 17.1 ± 0.4 | 65.0 ± 4.5 | 9.29 ± 3.3 | 54.3 ± 7.2 | 7.75 ± 1.0 |
| May | Fine | 149.0 ± 2.7 | 18.6 ± 0.3 | 155.0 ± 5.3 | 22.1 ± 2.7 | 210.0 ± 9.0 | 30.0 ± 0.3 |
| | Coarse | 95.6 ± 8.1 | 11.9 ± 0.1 | 120.0 ± 6.1 | 17.1 ± 0.6 | 187.7 ± 8.4 | 26.8 ± 0.8 |
| June | Fine | 255.3 ± 2.0 | 36.4 ± 0.2 | 285.0 ± 4.4 | 40.7 ± 4.8 | 109.0 ± 8.5 | 15.6 ± 1.9 |
| | Coarse | 138.0 ± 4.0 | 19.7 ± 0.5 | 186.3 ± 8.4 | 26.6 ± 0.8 | 146.7 ± 3.6 | 20.9 ± 0.6 |
| July | Fine | 159.3 ± 3.5 | 22.7 ± 0.5 | 149.0 ± 5.9 | 18.6 ± 1.0 | 161.8 ± 6.7 | 20.2 ± 0.7 |
| | Coarse | 137.0 ± 2.1 | 19.5 ± 0.3 | 75.0 ± 3.8 | 9.4 ± 0.8 | 124.7 ± 9.7 | 15.6 ± 2.1 |
| August | Fine | 226.0 ± 1.5 | 32.2 ± 0.2 | 236.0 ± 4.2 | 33.7 ± 0.5 | 183.0 ± 5.7 | 26.1 ± 1.6 |
| | Coarse | 150.3 ± 1.9 | 21.4 ± 0.2 | 164.4 ± 3.6 | 23.5 ± 1.8 | 241.0 ± 4.9 | 34.4 ± 0.8 |
| September | Fine | 286.6 ± 2.7 | 40.9 ± 0.39 | 170.3 ± 5.0 | 24.3 ± 1.5 | 342.3 ± 9.5 | 48.9 ± 1.8 |
| | Coarse | 173.0 ± 2.1 | 24.7 ± 0.3 | 168.7 ± 4.8 | 24.1 ± 2.1 | 199.0 ± 5.3 | 28.4 ± 1.5 |
| October | Fine | 322.6 ± 3.0 | 46.10 ± 0.43 | 114.3 ± 5.9 | 16.3 ± 0.9 | 156.7 ± 4.5 | 22.4 ± 2.6 |
| | Coarse | 136.6 ± 3.5 | 19.52 ± 0.50 | 86.7 ± 8.7 | 12.4 ± 1.7 | 197.0 ± 6.9 | 28.1 ± 3.1 |
| November | Fine | 169.3 ± 8.6 | 24.19 ± 0.12 | 119.0 ± 9.6 | 17.0 ± 1.4 | 151.3 ± 8.1 | 21.6 ± 1.3 |
| | Coarse | 94.6 ± 3.9 | 13.52 ± 0.56 | 117.7 ± 4.7 | 16.8 ± 1.1 | 92.0 ± 7.0 | 13.1 ± 1.8 |
| December | Fine | 250.3 ± 3.8 | 27.81 ± 0.43 | 115.4 ± 7.7 | 14.4 ± 8.3 | 165.4 ± 8.3 | 20.7 ± 2.3 |
| | Coarse | 113.6 ± 2.3 | 12.63 ± 2.60 | 100.0 ± 8.2 | 12.5 ± 0.3 | 122.6 ± 6.4 | 15.3 ± 3.0 |
| **Average** | **Fine** | **199.4 ± 55.0** | **30.5 ± 7.8** | **171.7 ± 52.5** | **23.9 ± 8.0** | **171.1 ± 61.8** | **23.8 ± 9.1** |
| | **Coarse** | **125.2 ± 28.7** | **19.1 ± 3.7** | **134.2 ± 47.9** | **18.7 ± 7.0** | **137.5 ± 57.4** | **19.3 ± 8.3** |

Table 3: Elemental concentration in air filters analyzed by NAA (ng/m$^3$).

| Element | 2002 | | | | 2003 | | | | 2004 | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Fine (ng/m3) | | Coarse (ng/m3) | | Fine (ng/m3) | | Coarse (ng/m3) | | Coarse (ng/m3) | |
| | Range | Average ± SD | Range | Average ± SD | Range | Average ± SD | Range | Average ± SD | Range | Average ± SD |
| Ti | 0 – 704 | 117 ± 287 | 477 – 877 | 611 ± 169 | 0 – 1348 | 350 ± 530 | 0 – 1909 | 502 ± 662 | 0 – 1375 | 849 ± 423 |
| Al* | 0.56 - 1.79 | 1.23 ± 0.14 | 3.29 - 13.70 | 6.83 ± 3.48 | 0 – 1.12 | 0.23 ± 0.38 | 3.69 – 8.53 | 2.36 ± 3.63 | 4.19 - 24.38 | 13 ± 6 |
| V | 25.50 – 61.57 | 40.3 ± 13.09 | 10.29 - 18.29 | 17.72 ± 3.25 | 0 – 39 | 11 ± 13 | 0 – 35 | 10 ± 11 | 9 – 37 | 20 ± 8 |
| Mn | 60.29 – 673 | 244 ± 253 | 71.38 – 176 | 121 ± 42.44 | 0 – 550 | 133 ± 210 | 0 – 102 | 22 ± 32 | - | - |
| Na | 93.29 – 749 | 277 ± 259 | 107 – 1037 | 385 ± 361 | 0 – 747 | 246 ± 224 | 0 – 1436 | 452 ± 418 | 147 – 2059 | 567 ± 551 |
| K | 0 – 1000 | 432 ± 401 | 0 – 720 | 196 ± 289 | 0 – 1200 | 324 ± 435 | 0 – 983 | 305 ± 304 | 0 – 755 | 414 ± 252 |
| Br | 7.88 - 20.14 | 12.29 ± 4.42 | 2.00 - 4.75 | 3.62 ± 2.54 | 0 – 13 | 7 ± 5 | 0 – 12 | 5 ± 4 | - | - |
| As | 0 - 4.38 | 1.90 ± 2.10 | 0 - 7.00 | 2.11 ± 3.39 | 0 – 2 | 1 ± 1 | 0 – 7 | 1 ± 2 | - | - |
| Sb | 0.57 - 7.71 | 1.85 ± 4.06 | 0.71 - 2.43 | 1.23 ± 1.02 | 1 – 5 | 3 ± 1 | 1 – 2 | 2 ± 1 | - | - |
| Cr | 3.14 - 11.86 | 2.58 ± 7.37 | 0 - 1.25 | 0.21 | 0 – 408 | 119 ± 158 | 0 – 30 | 15 ± 10 | 22 - 265.5 | 74 ± 74 |
| Zn | 53.71 - 76.43 | 36.82 ± 47.30 | 0 - 98.86 | 38.59 ± 44.49 | 0 – 134 | 37 ± 45 | 0 – 105 | 50 ± 38 | - | - |
| Co | 2 - 5.43 | 3.12 ± 1.22 | 0.75 - 4.43 | 2.29 ± 1.34 | 0 – 6 | 1 ± 2 | 0 – 6 | 2 ± 2 | - | - |
| Black C | 3.55 – 8.31 | 6.87 ± 1.20 | 1.50 – 2.03 | 1.67 ± 0.14 | 2.45 –7.15 | 4.53 ±1.46 | 0.08 – 0.90 | 0.43 ± 0.27 | 0.10 – 0.94 | 0.41± 0.27 |

* in μg/m$^3$

# 1.3 Roadside Air Particulate Monitoring in the PM10 range at the Poveda Learning Center, EDSA, Metro Manila

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## ABSTRACT

The Philippine Nuclear Research Institute undertakes air particulate matter monitoring in the PM10 range using a Gent-type dichotomous sampler. Samples are collected in 2 fractions: fine, having a mean aerodynamic diameter below 2.2 microns and coarse, with mean aerodynamic diameter of 2.2-10 microns. The PNRI station at Poveda Learning Center, Mandaluyong, Metro Manila was identified for sample collection under this project. The sampler is located about 100 m. away from the major highway, Epifanio delos Santos Avenue (EDSA), on the roof-deck of a three – story building.

Mean annual and 24-hour PM10 levels were found to be below the national standards: 60 ug/cu m annual mean and 150 ug/cu m 24-hour value. Using the Gent sampler, the weight of the fine fraction underestimates PM2.5 by 15%. The sum of the coarse and fine fractions is equal to PM10. The 24-hour value for PM2.2 is generally below the US EPA standard of 65 ug./cu m while the annual mean is generally in exceedance of the long-term standard of 15 ug/cu m. This indicates the need to study current standards and its efficacy in protecting the general population from adverse health effects due to fine particulate pollution.

Correlation plots of coarse and fine fractions with PM10 show greater contribution of the coarse fraction to PM10. Contribution of the fine fraction is found to decrease from 36% in 2002, to 29 % in 2003 and 20% in 2004. Fine fraction contribution to PM10 at another station, the Ateneo de Manila is 40% for both years. The station at the Ateneo is farther from the road and is exposed to a lower volume of vehicular traffic. High coarse particle contribution to PM10 at the Poveda station could be due to particles resuspended from the road by the vehicles. An increase in the concentration of coarse particles is observed in 2003 which remains at the same level in 2004. Fine particle concentration also increases in 2003 but decreases in 2004, possibly reflecting the impact of government drive against smoke belching vehicles. Black C was determined for the fine fraction by reflectommetry. It is found to be highly correlated to fine mass confirming the significant contribution of combustion processes to the fine fraction. Due to the delay in the repair of the PNRI XRF spectrometer, no analysis of samples was done in 2003.

## INTRODUCTION

Since 1997, the Philippine Nuclear Research Institute has implemented an air pollution project which has as basic objective the identification and apportionment of air particulate pollution sources. This uses nuclear and related techniques with multielement capability for elemental characterization of air particulate samples. The Gent dichotomous sampler is used to collect samples in the PM10 range, fractionated to coarse and fine fractions. The PNRI air pollution project generated benchmark data on fine and coarse air particulate levels and composition, being the first long term monitoring program for PM10 to be conducted locally.

So far, the PNRI has conducted air particulate monitoring at seven sites in Metro Manila. Sampling stations are located from major thoroughfares and other direct sources of pollution in order not to introduce any bias in the source apportionment results. However, in the last quarter of 2001, the PNRI set up its first roadside air monitoring station at Poveda

Learning Center along the Epifanio delos Santos Avenue, a major highway running from the South to the Northwestern part of Metro Manila. Samples were collected at this station for comparative analysis by INAA and XRF spectrometry. This paper will present some trends obtained for the station as well as results of the comparative analysis performed under the project.

## METHODOLOGY

### *Sample collection and weighing*

The sampler at the Poveda Learning Center is located about 100 m. away from EDSA, on the roof deck of a three story building. Sampling is performed twice weekly using the Gent sampler, fabricated at Clarkson University, U.S.A and provided by the IAEA. Air particulate matter is collected on Nuclepore filters in the PM10 range using a stacked filter unit, giving a fine (2.2 microns and below) and a coarse (2.2- 10 microns) fraction. The cut-off for the fine fraction is at 2.2 microns and is therefore underestimated by 15%. However the total of the coarse and fine fractions gives the mass of PM10.

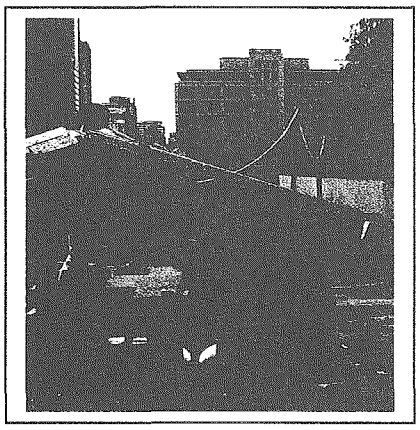

**Figure 1. PNRI station at Poveda Learning Center**

### *Particulate mass determination*

Particulate mass is determined from the difference of the equilibrated weight of the filter before and after sampling. Equilibration is done in a desiccator kept at a relative humidity of 60 %. Weighing is done with a Mettler MT5 microbalance.

### *X-ray fluorescence spectrometry*

Air filters are analyzed with a KEVEX 771 Secondary target X-ray fluorescence spectrometer using three secondary targets, Ti in vacuum, Ge and Zr. The air filter sample is placed in an EPA-type sample holder, a 4 x 4 $cm^2$ plastic cassette and mounted on a sample position of the 16-position sample wheel. The IAEA software AXIL is used for spectrum processing and quantitation by the method of Elemental Sensitivities. Instrument calibration is done using Micromatter thin film standards. Due to malfunction of PNRI XRF spectrometer, no analysis of samples was done in 2003.

### *Black Carbon analysis*

Black Carbon analysis is done on the fine fraction using a Digital Smoke Stain Reflectometer. The following formula is used to calculate for the Black C:

$$\text{Black C } (ug/cm^2) = \frac{1}{2\varepsilon} \ln \left[\frac{R_o}{R}\right]$$

where $\varepsilon$ is the mass absorption coefficient of Black C, $R_o$ is the reflectance from a blank filter and R is the reflectance from a loaded filter. $\varepsilon = 7\ cm^2/g$.

## RESULTS AND DISCUSSION

### *Annual summary data for PM10 and PM2.2*

Annual summary data from 2002-2004 are given in Figure 2 in the form of Box-Whisker plots showing the distribution of the data as well as the mean and the median values. The rectangular part extends from the lower to the upper quartile, covering the center half of the data. The center lines within the box represents the median and the plus sign the sample mean. The whiskers extend from the rectangle to the maximum and minimum values. Outside points, represented by small squares, lie more than 1.5 times the interquartile range above or below the box. Points exceeding 3 times the interquartile range are represented by small squares with a plus sign at the center.

PM10 values are found to be below the short term national standard of 150 ug/cu m and the long-term standard of 65 ug/cu m. The mean values represented by the cross in the Box-Whisker plot show that PM10 values would comply with the long-term standard of 60 ug/cu m. With respect to PM2.5, 24-hour values are within the 60 ug/cu m standard of the USEPA, which is used for reference in the absence of local standards. Annual values are above the 15 ug/cu m standard of the USEPA. The data indicate that Philippine fine particulate standards may not effectively protect the public from adverse health impacts of air pollution and that a policy review may be required to introduce fine particle standards.

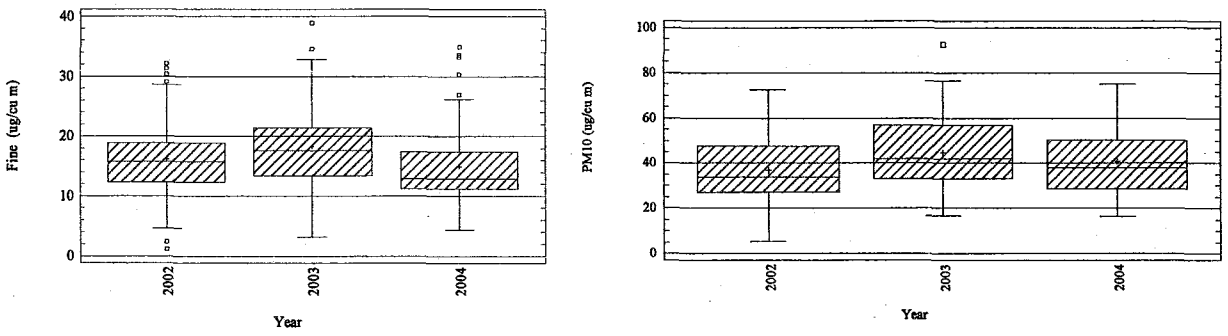


**Figure 2. Annual summary data for Fine fraction and PM10.**

### *Seasonal variation of coarse and fine fractions*

The Box – Whisker plots of pooled monthly data for coarse and fine fractions (Figure 3) show difference in the impact of rainfall on the coarse and the fine fractions. The difference in particulate levels between the rainy months, June to September and the dry months November to April is pronounced for the coarse fraction but not for the fine fraction. In other stations such as the Ateneo de Manila University Campus, where vehicular volume is smaller, pronounced seasonal variation is observed both for the coarse and the fine fractions. Increased precipitation of chemical species emitted by vehicles stalled in heavy traffic resulting from heavy rain may increase fine particulate levels.

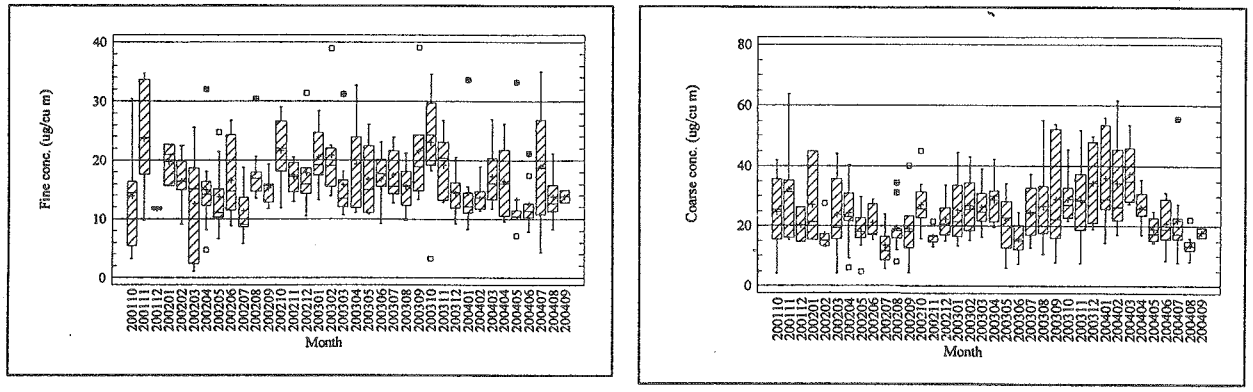


**Figure 3. Monthly summary data for fine and coarse particulate concentration at Poveda Learning Center**

*Correlation between coarse and fine fractions and PM10*

The multiyear correlation plots for coarse and fine particulate fractions presented in Figure 4 show varying contribution of coarse and fine fraction to PM10 with time. Fine contribution in 2002 is 36%, decreasing to 29% in 2003 and to 20% in 2004. Increase in coarse contribution could come from increasing volume of vehicles causing re-suspension of soil or debris from the roads due to vehicles. The large decrease in fine concentration observed in 2004 could reflect the impact of stricter implementation of controls on smoke emitting vehicles.

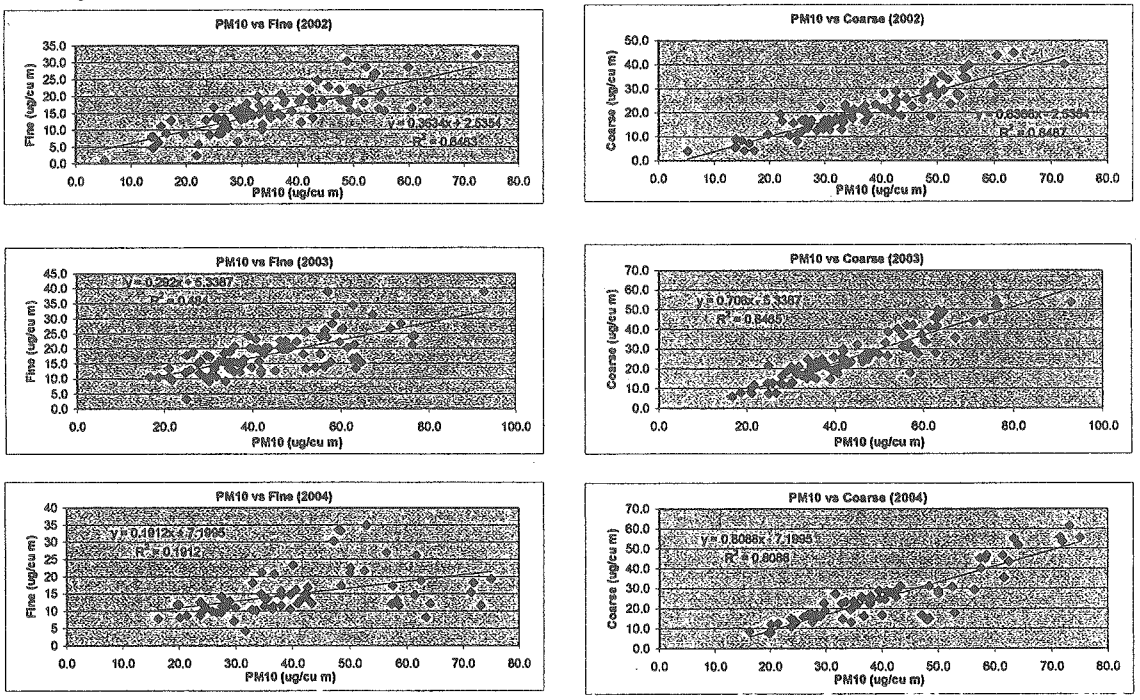


**Figure 4. Multiyear correlation plots for the coarse and the fine fractions against PM10**

*Black Carbon contribution to fine mass*

The time series plots (Figure 5) for fine particulate mass and Black C show the magnitude of Black C contribution to fine mass and their close correspondence. Figure 6 shows good correlation between fine mass and Black C. Black C makes up 50% of fine mass.

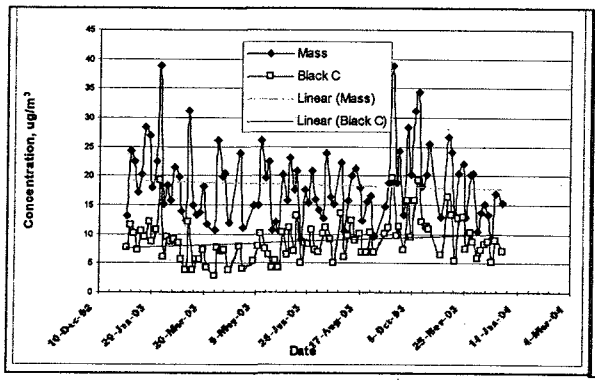


**Figure 5. Time series for fine mass and Black C**

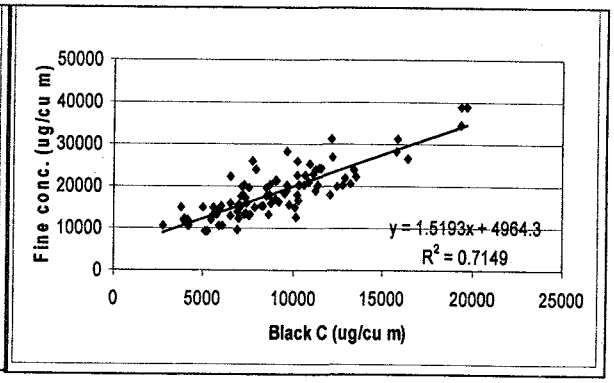


**Figure 6. Correlation between Black C and fine mass**

Figure 7 demonstrates the difference between weekend and weekday fine concentration levels. Fine weekday mean concentration is 20.7 ug/cu m and 16.4 ug/cu m for the weekend where volume of traffic is lower.

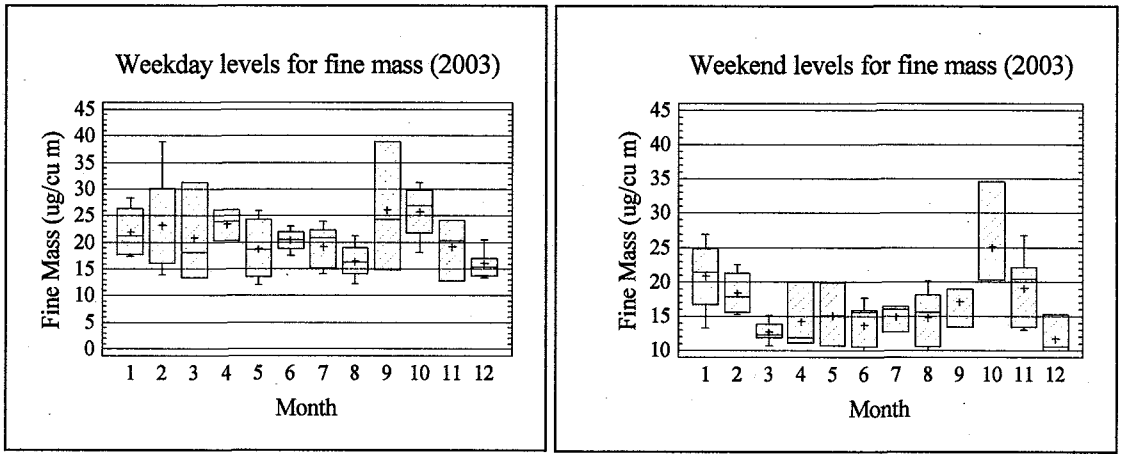


**Figure 7. Weekday-weekend levels for fine mass**

*Elemental Analysis*

Due to malfunction of the PNRI XRF spectrometer, elemental analysis was done only for samples collected from January to August 2002. Results are summarized in Table 1. For these samples, 15 elements are measured in the coarse fraction and 10 in the fine. Additional elements were measured in samples analyzed by NAA at JAERI through the Japanese project participants. It also allowed detection of possible systematic errors in analysis of some elements such as V and Fe. Performance of the PNRI secondary target XRF spectrometer could have been better with a larger sample size. Large instrumental Al and Si blanks resulted in a big number of negative values. This prevented optimum use of capability of the spectrometer for enhanced detection of light elements through analysis in vacuum.

**Table 1. Elemental data for Poveda Learning Center 2002 (ug/cu m)**

| | | Coarse | | | | | Fine | | |
|---|---|---|---|---|---|---|---|---|---|
| | Mean | Max | Min | n | | Mean | Max | Min | n |
| Na | 452.11 | 887.50 | 155.82 | 30 | | | | | |
| Si | 808.33 | 4,222.31 | 85.17 | 57 | | | | | |
| S | 510.97 | 1,174.96 | 118.12 | 57 | | 612.93 | 1,506.57 | 25.13 | 57 |
| Cl | 643.64 | 1,537.81 | 12.57 | 56 | | | | | |
| K | 139.05 | 287.46 | 50.27 | 56 | | 96.58 | 254.12 | 18.85 | 55 |
| Ca | 641.16 | 1,434.14 | 128.18 | 56 | | 89.71 | 198.27 | 11.31 | 54 |
| Ti | 31.75 | 45.55 | 8.80 | 51 | | | | | |
| V | 20.40 | 31.42 | 7.54 | 56 | | 13.80 | 29.32 | 1.26 | 55 |
| Mn | 11.08 | 31.42 | 3.77 | 51 | | | | | |
| Fe | 383.52 | 738.28 | 50.27 | 56 | | 79.67 | 301.59 | 2.79 | 56 |
| Ni | 2.61 | 4.71 | 1.26 | 33 | | 3.29 | 6.28 | 1.26 | 46 |
| Cu | 4.58 | 18.15 | 1.26 | 43 | | 4.33 | 39.10 | 1.26 | 33 |
| Zn | 74.19 | 326.73 | 4.19 | 56 | | 52.38 | 296.01 | 6.28 | 55 |
| Br | 3.17 | 7.85 | 1.26 | 35 | | 7.29 | 64.23 | 1.26 | 54 |
| Pb | 28.67 | 244.35 | 3.77 | 52 | | 30.64 | 131.25 | 5.59 | 51 |

## CONCLUSION:

PNRI monitoring conducted at the Poveda Learning Center in EDSA has produced data characterizing air particulate matter level and composition along a major highway in Metro Manila. Data showed that at 100 m from the road, PM10 values are compliant to national standards. Fine particulate matter is compliant to the USEPA short term standard for PM2.5 but not to the long-term standard. Graphical examination of the data provide information useful for air quality management. A multitechnique approach in the elemental characterization of the samples can provide a wider range elements for use in pollutant source apportionment.

1.4

# $k_0$-INAA for APM samples collected in period of June 2004 – March 2005 and some marine certified reference materials

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## ABSTRACT

The airborne particulate matter (APM) samples have been collected in 2004 using two types of polycarbonate membrane filter $PM_{2.5}$ and $PM_{2.5-10}$ at two sites of industrial (Ho Chi Minh City) and rural (Dateh) regions in south of Vietnam. Three marine certified reference materials have been selected to establish a k0-NAA procedure for marine samples. The concentration of trace multi-element in the samples has been determined by the $k_0$-INAA procedure using Ko-DALAT software developed in Dalat NRI. About 28 elements in 224 APM samples collected at two areas of Dateh and HCMC of Vietnam in period from June, 2004 to March, 2005 were presented in report. The statistical analysis was applied to the data set to investigate the pollution source at sampling sites. The results proved that the $k_0$-NAA on the Dalat research reactor is a reliable and effective analytical technique for characterization of trace multi-element in APM and marine samples for air and marine environmental pollution study in Vietnam.

*Keywords:* Air pollution; Airborne particulate matter; Neutron activation analysis; $k_0$-standardization method.

## INTRODUCTION

In the air pollution study in Vietnam, two sampling sites have been selected to collect the airborne particulate samples (APM) using two types of polycarbonate membrane filter $PM_{2.5}$ and $PM_{2.5-10}$. The two sampling sites with different characteristics selected for the study are Dateh district (Lam Dong Province) and Ho Chi Minh City representing for rural and industrial regions, respectively. The first site is freely from industrial activities with a low population density. Compared to the first site, Ho Chi Minh City (HCMC) is an high population density and big traffic intense site. About 15 km northward, there is a small industrial complex consisting, in particular one old thermal power station consuming 2000 tones of oil per day and two ferrous smelters. Further northward about 35 km from HCMC is the major industrial zone of South of Vietnam.

The number of interested elements in the APM samples is of about 30 elements, so in order to cover all the interested elements with using conventional relative NAA method some different reference materials must be applied. This leds to two problems: (i) the systematical error of analytical results for all interested elements depend on the different reference materials to be affected to the interpretation of emission sources; (ii) the analysis productivity of short-lived nuclides is low because each irradiation container only contains maximum of 3-4 samples including 1-2 reference materials.

The $k_0$-standardization method of neutron activation analysis ($k_0$-NAA) is capable to satisfy the above mentioned requirements i.e. multi-element, stable in systematical error, less consuming for reference materials and high capacity for short-lived nuclides analysis of APM samples. This report briefly describes the application of the $k_0$-NAA method for determination of multi-element in the APM samples collected in 2004 as a demonstration.

The marine samples including sediments and biotas will be subject to continue in application of $k_0$-NAA method for monitoring marine environmental pollution in the next stage of the NAA group in the framework of the FNCA activities. Therefore, this report briefly also presents preliminary results in establishment the $k_0$-NAA procedure for several selected reference materials of marine samples, i.e. Sargasso (NIES-9), Oyster Tissue (NIST-1566b) and Marine Sediment (NMIJ-7302a).

## EXPERIMENTAL

### The air particulate matter samples,

*Sampling and sample preparation*

Sampling sites: Industrial (Ho Chi Minh City) and Rural (Dateh) regions

Sampling period: June 2004 - March 2005

Sampling frequency: Each week for two times (Tuesday and Friday)

Sampling time: 24 h (flow rate: start ~18 lpm, stop ~15 lpm)

Coarse fraction: $PM_{2.5-10}$ and Fine fraction: $PM_{2.5}$

Filter: Polycarbonate membrane filter 47 mm diameter, 8 μm and 0.4 μm pore size for coarse and fine respectively.

Weighing: Maintain the same condition before and after sampling.

Sampling address: (1) Dateh District, Lamdong Province (Vietnam), latitude: 11°31' N, longitude: 107°28' E, altitude: 800 m; (2) Truong Dinh Street, 1st District, Ho Chi Minh City (Vietnam), latitude: 10°46' N, longitude: 106°41' E, altitude: 9 m. The rough maps of Dateh and HCMC are shown in Figs 1 & 2, respectively.

The flux monitors used are sheet of Zr (99.8%, thickness 0.125 mm, ADVENT Research Materials Ltd.), wire of Al-0.11%Au (dia. 0.5 mm, IRMM), and Ni (99.98%, dia. 0.076 mm for determination of thermal/fast neutron ratio).

*The $k_0$-NAA procedure*

Neutron source: Dalat research reactor of 500 kW power.

Irradiation facilities: Dry channel 7-1 using pneumatic transfer system for short irradiation down to 45 seconds and 40 wet irradiation holes in rotary rack using manual for long irradiation up to 20 hours.

Thermal neutron flux: ~ $4.6 \times 10^{12}$ n/cm$^2$.sec and ~ $3.5 \times 10^{12}$ n/cm$^2$.sec for channel 7-1 and rotary rack, respectively.

Counting system: Ortec GMX-30190 detector using automatic sample changer (model ASC2) possibly for 40 samples in a measurement batch, and Canberra GX-1520 detector using manual for changing sample. Acquisition and analysis software using Ortec

GammaVision 5.32 for both gamma-ray spectrometers connected to an Ortec 919E MCB with four inputs.

Data processing: The Ko-DALAT software, a $k_0$-based neutron activation analysis program on PC developed in Dalat NRI.

Quality control: Urban Particulate (NIST SRM 1648), Coal Fly Ash (NIST SRM 1632c) and Vehicle Exhaust Particulates (NIES CRM No.8). Data intercomparison work by IAEA.

Trace element analysis of three marine samples, i.e. Sargasso (NIES CRM No. 9), Oyster Tissue (NIST SRM 1566b) and Sediment (NMIJ CRM No. 7302a) has been carried out to establish a proper procedure on the Dalat research reactor (DRR).

A set of irradiation, decay and counting times established for the APM and the marine samples on the DRR are showed in Tables 1 & 2.

The measurements are performed on the calibrated $\gamma$-ray spectrometers at the positions where the dead time of system is controlled as less than 5%.

## RESULTS AND DISCUSSION

The concentration range of elements and particulate matter (PM) in fine and coarse fractions of APM samples collected at HCMC and Dateh are shown in Table 3. The mean concentration distribution of elements in fine and coarse fractions of APM samples collected at HCMC and Dateh is displayed in Figure 3.

The results have indicated that (i) mean concentration of elements such as As, Co, Cr, Hg, Sb, Se, V & Zn at HCMC is higher than Dateh from 1.6 to 7.0 times. These elements are regarded as discharging by thermal power stations using coal and petroleum, metallurgical factories and/or rubbish burning; (ii) mean concentration of elements such as Al, K, Mg & Ti discharged by soil dust, road dust, biomass buring and forest burning at Dateh is higher than at HCMC from 1.5 to 2.5 times. The results are also suitable with the factor analysis presented below.

The factor analysis was done by STATGRAPHICS Plus 3.3 software for the source identification of elemental composition in particulate matter. The results of factor analysis in fine and coarse fractions of APM samples collected at HCMC and Dateh are displayed in Tables 4-7. In the tables, models of 4, 5 & 6 factors were applied to investigate the correlation between source and sampling site. The results of factor analysis have indicated that besides of normal sources as soil dust, road dust and rubbish burning, the main sources given rise air pollution at HCMC are industrial activities and vehicles. As for Dateh site, besides of normal sources the remaining sources contributing to air pollution are biomass burning and seaspray.

The analysis results of elemental concentration for three marine samples in comparison with certified values are shown in Table 8. As for Sargasso (NIES CRM No. 9), 16 elements were determined. the Oyster Tissue (NIST SRM 1566b) and the Marine Sediment (NMIJ CRM No. 7302a), 12 elements were determined.

## CONCLUSION

The concentration of about 28 elements (Al, As, Ba, Br, Ca, Ce, Cl, Co, Cr, Cs, Cu, Eu, Fe, Hg, I, K, La, Mg, Mn, Na, Sb, Sc, Se, Sm, Ti, U, V, Zn) in about 224 APM samples collected by filters from June 2004 to March 2005 at rural (Dateh) and industrial (HCMC) sites was determined by the $k_0$-INAA on the Dalat research reactor. Three marine certified reference materials were used to establish the k0-NAA procedure for about 17 elements (Al, As, Br, Ca, Cl, Co, Fe, I, K, Mg, Mn, Na, Rb, Sb, Sc, Sr, Zn) in marine samples. The results proved that the $k_0$-NAA using "Ko-DALAT" software can be regarded as a reliable and effective analytical technique for the air and marine environmental pollution study.

## ACKNOWLEDGEMENTS

This work has been carried out in the combination with national projects of Ministry of Science & Technology (MOST) of Vietnam.

The organizers of the 2004 FNCA Workshop (MEXT of Japan and OAP of Thailand) on Utilization of Research Reactors are gratefully acknowledged.

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## TABLES AND FIGURES

**Table 1.** Irradiation, decay and counting time for the Airborne Particulate Matter.

| Types | Irradiation time | Decay time | Counting time | Nuclides |
|---|---|---|---|---|
| Short | 5 m | 5 m | 300 s | Al, Ca, Cu, Mg, Ti, V. |
| (Channel 7-1) | | 30 m | 900 s | Ba, Cl, I, In, K, Mn, Na. |
| Long | 10 h | 2-3 d | 1800 s | Au, Br, La, $^{122}$Sb, Sm. |
| (Rotary rack) | | 3 w | 7200 s | As, Au, Ce, Co, Cr, Cs, Fe, Hf, Lu, Rb, $^{124}$Sb, Sc, Se, Th, Yb, Zn. |

**Table 2.** Irradiation, decay and counting time for marine samples, i.e. Sargasso NIES CRM (N-9), Oyster Tissue NIST SRM (1566b) and Marine Sediment NMIJ CRM (7302a).

| Types | Irradiation time | | | Decay time | | | Counting time | | | Nuclides |
|---|---|---|---|---|---|---|---|---|---|---|
| | N-9 | 1566b | 7302a | N-9 | 1566b | 7302a | N-9 | 1566b | 7302a | |
| Short (Channel 7-1) | 45 s | 5 m | 45 s | 5 m | 10 m | 5 m | 200 s | | | Al, Ca, Cu, Mg, Ti, V. |
| | | | | 1 h | | | 600 s | 900s | 600s | Ba, Cl, I, K, Mn, Na, $^{239}$U, $^{69m}$Zn. |
| Medium (Channel 7-1) | 15 m | | | 1-2 d | | | 20-30 m | | | As, Ba, Br, Cl, K, La, Na. |
| Long (Rotary Rack) | 3 h | | | 3 d | | | 30 m | | | As, Br, La, $^{122}$Sb, Sm. |
| | | | | 2-3 w | | | 2-3 h | | | Ag, Ce, Co, Cr, Cs, Fe, Hf, Hg, Rb, $^{124}$Sb, Sc, Se, U, Th, Yb, $^{65}$Zn. |

**Table 3.** Concentration range of elements in fine and coarse fractions of airborne particulate matter collected at Ho Chi Minh City (HCMC) and Dateh.

| Elements | HCMC [ng/m$^3$] (based-on 52 pairs of sample) | | | | Dateh [ng/m$^3$] (based-on 59 pairs of sample) | | | |
|---|---|---|---|---|---|---|---|---|
| | *Fine* | | *Coarse* | | *Fine* | | *Coarse* | |
| **Al** | 4 - 471 | | 3 - 2110 | | 18 - 1292 | | 65 - 4960 | |
| **As** | 0.58 - 14.82 | | 0.16 - 30.07 | | 0.10 - 7.92 | | 0.019 - 3.882 | |
| **Ba** | | | 5.92 - 54.87 | | | | 1.11 - 22.63 | |
| **Br** | 0.68 - 10.65 | | 0.02 - 5.78 | | 0.72 - 18.59 | | 0.13 - 5.72 | |
| **Ca** | 22 - 752 | | 224 - 10651 | | 22.4 - 294,5 | | 38 - 1173 | |
| **Ce** | 0.492 | 0.892 | 0.25 - 2.81 | | | | 0.13 - 8.05 | |
| **Cl** | 9 - 412 | | 29 - 4165 | | 1.93 - 308.44 | | 7 - 1485 | |
| **Co** | 0.035 - 2.749 | | 0.080 - 5.157 | | 0.014 - 0.725 | | 0.033 - 1.037 | |
| **Cr** | 1.53 - 13.01 | | 1.2 - 194.4 | | 1.82 - 37.62 | | 1.26 - 23.37 | |
| **Cs** | 0.04 - 2.63 | | 0.029 - 3.229 | | 0.012 - 0.914 | | 0.027 - 0.827 | |
| **Cu** | 0.10 - 12.06 | | 0.22 - 16.36 | | 0.78 - 30.58 | | 0.56 - 12.32 | |
| **Eu** | 0.002 - 0.606 | | 0.002 - 0.646 | | 0.007 - 0.626 | | 0.007 - 0.414 | |
| **Fe** | 34 - 631 | | 24 - 14237 | | 34 - 995 | | 30 - 2713 | |
| **Hg** | 0.087 - 1.915 | | 0.024 - 0.339 | | 0.135 - 0.401 | | | |
| **I** | 0.068 - 3.720 | | 0.013 - 0.930 | | 0.41 - 6.14 | | 0.033 - 3.084 | |
| **K** | 28 - 944 | | 2 - 1143 | | 77 - 1583 | | 3 - 2740 | |
| **La** | 0.044 - 0.880 | | 0.04 - 12.76 | | 0.036 - 1.134 | | 0.077 - 4.903 | |
| **Mg** | 0.44 - 36.60 | | 2.5 - 267.0 | | 1.87 - 60.60 | | 2.7 - 226.3 | |
| **Mn** | 0.1 - 35.9 | | 0.07 - 64.45 | | 0.35 - 19.86 | | 0.6 - 46.4 | |
| **Na** | 10 - 948 | | 4 - 3545 | | 34 - 801 | | 22 - 5602 | |
| **Sb** | 0.26 - 16.53 | | 0.03 - 26.89 | | 0.062 - 4.635 | | 0.015 - 1.005 | |
| **Sc** | 0.006 - 0.125 | | 0.006 5.742 | | 0.007 - 0.236 | | 0.020 - 0.764 | |
| **Se** | 0.46 - 16.61 | | 0.048 - 0.588 | | 0.550 - 2.872 | | | |
| **Sm** | 0.01 - 49.58 | | 0.012 - 1.195 | | 0.003 - 0.120 | | 0.006 - 0.423 | |
| **Ti** | 11.6 - 84.0 | | - | | 2.41 - 81.52 | | 9 - 351 | |
| **U** | | | 0.009 - 0.209 | | | | 0.006 - 0.246 | |
| **V** | 0.08 - 34.31 | | 0.02 - 10.20 | | 0.18 - 10.93 | | 0.11 - 8.91 | |
| **Zn** | 4 - 1134 | | 2 - 1024 | | 1.74 - 290.62 | | 1.2 - 134.2 | |
| **PM** | 455 - 35833 | | 750 - 68542 | | 1923 - 55000 | | 192 - 105769 | |

**Table 4.** Factors, $h^2$ (communalities) in five-factor model for fine fraction at HCMC.

| | Eigen val | F1 | F2 | F3 | F4 | F5 | Com. |
|---|---|---|---|---|---|---|---|
| FPM | 7.48 | 0.64 | 0.54 | | | 0.36 | 0.89 |
| Al | 3.15 | | 0.96 | | | | 0.98 |
| As | 2.27 | | 0.23 | | 0.41 | 0.60 | 0.76 |
| Br | 1.74 | | 0.38 | | 0.46 | 0.68 | 0.83 |
| Ca | 0.68 | | 0.63 | 0.73 | | | 0.95 |
| Cl | 0.57 | | | 0.96 | | | 0.93 |
| Cr | 0.42 | | | 0.33 | 0.79 | 0.32 | 0.86 |
| Cu | 0.28 | 0.53 | | 0.40 | | 0.59 | 0.84 |
| Fe | 0.17 | 0.30 | 0.72 | 0.47 | 0.29 | | 0.92 |
| K | 0.12 | 0.97 | | | | | 0.98 |
| I | 0.06 | 0.71 | 0.52 | | | | 0.83 |
| Mn | 0.02 | 0.75 | | 0.59 | | | 0.93 |
| Na | 0.02 | 0.91 | | 0.30 | | | 0.98 |
| Sb | 0.02 | | | | 0.95 | | 0.94 |
| Sc | 0.01 | | 0.90 | | 0.34 | | 0.96 |
| V | 0.00 | 0.78 | | | 0.42 | | 0.82 |
| Zn | 0.00 | 0.64 | | 0.71 | | | 0.95 |
| Sources | | Biomass and oil burning | Road dust | Rubbish burning, construction | Oil burning | Coal + Vehicle | |

**Table 5.** Factors, $h^2$ (communalities) in six-factor model for coarse fraction at HCMC.

| | Eigen val | F1 | F2 | F3 | F4 | F5 | F6 | Com |
|---|---|---|---|---|---|---|---|---|
| CPM | 10.72 | 0.59 | 0.54 | 0.41 | | | 0.37 | 0.95 |
| Al | 2.35 | 0.64 | 0.37 | 0.37 | 0.48 | | 0.26 | 0.98 |
| As | 1.81 | | 0.96 | | | | | 0.99 |
| Br | 0.92 | 0.59 | 0.38 | 0.34 | 0.43 | | | 0.81 |
| Ca | 0.61 | 0.80 | 0.45 | | | | 0.26 | 0.90 |
| Cl | 0.48 | | | 0.97 | | | | 0.97 |
| Cr | 0.43 | | | | | 0.96 | | 0.99 |
| Cu | 0.26 | 0.58 | | 0.62 | 0.40 | | | 0.94 |
| Fe | 0.20 | 0.84 | 0.34 | | 0.30 | | | 0.97 |
| K | 0.08 | 0.44 | | 0.31 | 0.24 | | 0.75 | 0.94 |
| La | 0.06 | 0.25 | 0.94 | | | | | 0.99 |
| Mg | 0.04 | 0.65 | | 0.29 | 0.54 | 0.24 | | 0.90 |
| Mn | 0.02 | 0.30 | 0.33 | 0.34 | 0.70 | | 0.35 | 0.92 |
| Na | 0.01 | | | 0.87 | | | 0.22 | 0.89 |
| Sb | 0.00 | 0.41 | 0.89 | | | | | 0.99 |
| Sc | 0.00 | 0.89 | 0.32 | | | | | 0.98 |
| V | 0.00 | 0.37 | 0.35 | 0.45 | 0.66 | | | 0.94 |
| Zn | 0.00 | 0.81 | | | | | 0.27 | 0.83 |
| Sources | | Soil dust + vehicles | Coal | Seaspray | Petroleum | Industry | Biomass burning | |

**Table 6.** Factors, $h^2$ (communalities) in five-factor model for fine fraction at Dateh.

| | Eigen val | F1 | F2 | F3 | F4 | F5 | Com |
|---|---|---|---|---|---|---|---|
| FPM | 9.66 | | 0.55 | 0.53 | | | 0.82 |
| Al | 4.07 | | 0.97 | | | | 0.95 |
| As | 1.65 | 0.99 | | | | | 0.99 |
| Br | 1.41 | 0.94 | | | 0.22 | | 0.96 |
| Ca | 0.53 | | 0.67 | 0.39 | | 0.58 | 0.96 |
| Cl | 0.30 | | | | 0.88 | 0.23 | 0.96 |
| Cr | 0.17 | 0.95 | | | | | 0.95 |
| Cs | 0.07 | 0.99 | | | | | 0.99 |
| Fe | 0.06 | | 0.97 | | | | 0.98 |
| K | 0.04 | | 0.85 | 0.34 | | | 0.94 |
| La | 0.03 | 0.99 | | | | | 0.99 |
| Mg | 0.02 | 0.71 | 0.65 | | | | 0.98 |
| Mn | 0.01 | 0.96 | | 0.23 | | | 0.98 |
| Na | 0.00 | | | 0.29 | 0.85 | | 0.93 |
| Sb | 0.00 | 0.99 | | | | | 0.99 |
| Sc | 0.00 | 0.99 | | | | | 0.99 |
| V | 0.00 | 0.98 | | | | | 0.98 |
| Zn | 0.00 | | | 0.96 | | | 0.96 |
| Sources | | Coal, Petroleum | Soil dust | Biomass burning | Seaspray | Construction | |

**Table 7.** Factors, $h^2$ (communalities) in four-factor model for coarse fraction at Dateh.

| | Eigen val | F1 | F2 | F3 | F4 | Com |
|---|---|---|---|---|---|---|
| CPM | 11.79 | 0.86 | 0.48 | | | 0.96 |
| Al | 2.08 | 0.87 | 0.24 | 0.29 | 0.26 | 0.97 |
| As | 1.11 | 0.85 | 0.31 | 0.24 | | 0.89 |
| Br | 0.73 | 0.49 | 0.82 | | | 0.92 |
| Ca | 0.41 | 0.58 | 0.70 | | | 0.87 |
| Cl | 0.27 | | 0.97 | | | 0.96 |
| Cr | 0.18 | 0.24 | | 0.95 | | 0.97 |
| Fe | 0.18 | 0.87 | | 0.32 | | 0.91 |
| K | 0.10 | 0.84 | 0.43 | | | 0.92 |
| La | 0.06 | 0.74 | | 0.57 | | 0.87 |
| Mg | 0.04 | 0.87 | | | 0.30 | 0.88 |
| Mn | 0.03 | 0.94 | 0.23 | | | 0.97 |
| Na | 0.02 | 0.56 | 0.69 | | | 0.92 |
| Sb | 0.01 | 0.73 | 0.28 | 0.42 | | 0.79 |
| Sc | 0.01 | 0.83 | 0.26 | 0.41 | 0.21 | 0.98 |
| V | 0.00 | 0.85 | 0.36 | 0.27 | | 0.97 |
| Zn | 0.00 | | | | -0.93 | 0.96 |
| Sources | | Soil dust, Biomass burning | Seaspray | Road dust | Rubbish burning | |

**Table 8.** Analysis result of three marine samples in comparison with certified values.

| Elem-ments | Sargasso CRM (NIES-9) | | | | Oyster Tissue SRM (NIST-1566b) | | | | Marine Sediment CRM (NMIJ-7302a) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Mean | SD | Certified | Unc. | Mean | SD | Certified | Unc. | Mean | SD | Certified | Unc. |
| Ag | | | 0.31 | 0.02 | | | 0.666 | 0.009 | | | 0.49 | 0.24 |
| Al | 197 | 16 | 215 | | 228 | 4 | 197.2 | 6 | 72100 | 132 | 78000 | |
| As | 104 | 12 | 115 | 9 | 6.74 | 1.00 | 7.65 | 0.65 | 20.4 | 1.2 | 22.1 | 1.4 |
| B | | | - | | | | 4.5 | 1.9 | | | - | |
| Ba | | | - | | | | 8.6 | 0.3 | | | - | |
| Br | 231 | 28 | 270 | | 41 | 9 | - | | | | - | |
| %Ca | 1.17 | 0.07 | 1.34 | 0.05 | | | 0.0838 | 0.002 | | | 4.2 | |
| Cd | | | 0.15 | 0.02 | | | 2.48 | 0.08 | | | 1.82 | 0.04 |
| %Cl | 4.3 | 0.2 | 5.1 | | 0.520 | 0.050 | 0.514 | 0.01 | | | - | |
| Co | 0.17 | 0.04 | 0.12 | 0.01 | 0.410 | 0.014 | 0.371 | 0.009 | 11.4 | 1.6 | 12.4 | 1.5 |
| Cr | | | 0.2 | | | | - | | | | - | |
| Cs | | | 0.04 | | | | - | | | | - | |
| Cu | | | 4.9 | 0.2 | | | 71.6 | 1.6 | | | 57.8 | 2.8 |
| Fe | 189 | 20 | 187 | 6 | 183.4 | 7.6 | 205.8 | 6.8 | 53200 | | 54000 | |
| H | | | - | | | | 7.2 | 0.4 | | | - | |
| Hg | | | 0.04 | | | | 0.0371 | 0.001 | | | - | |
| I | 432 | 35 | 520 | | | | - | | | | - | |
| %K | 5.3 | 0.56 | 6.1 | 0.2 | 0.62 | 0.04 | 0.652 | 0.009 | 1.5 | 0.2 | 1.6 | |
| MeHg | | | - | | | | 0.013 | 0.007 | | | - | |
| %Mg | | | 0.65 | 0.03 | | | 0.1085 | 0.002 | 1.4 | 0.3 | 1.2 | |
| Mn | 17.6 | 1.6 | 21.2 | 1 | 16.9 | 0.6 | 18.5 | 0.2 | 690 | 37 | 710 | |
| Mo | | | - | | | | - | | | | 1.98 | 0.24 |
| %N | | | - | | | | 7.6 | 0.4 | | | - | |
| %Na | 1.52 | 0.15 | 1.7 | 0.08 | 0.302 | 0.003 | 0.3297 | 0.005 | 1.85 | 0.17 | 1.9 | |
| Ni | | | - | | | | 1.04 | 0.09 | | | 25.8 | 1.2 |
| %P | | | 0.26 | | | | - | | | | 0.65 | |
| Pb | | | 1.35 | 0.05 | | | 0.308 | 0.009 | | | 82.7 | 8.8 |
| Rb | 23 | 6 | 24 | 2 | 3.101 | 0.136 | 3.262 | 0.145 | 76 | 6 | 74 | |
| %S | | | 1.2 | | | | 0.6887 | 0.014 | | | - | |
| Sb | | | 0.04 | | | | 0.011 | 0.002 | 1.08 | 0.11 | 1.22 | 0.05 |
| Sc | 0.10 | 0.01 | 0.09 | | | | - | | | | - | |
| Se | | | 0.05 | | 1.87 | 0.11 | 2.06 | 0.15 | | | - | |
| Sm | | | - | | | | - | | | | - | |
| Sn | 261 | 100 | - | | | | 0.031 | 0.008 | | | 18.5 | 0.8 |
| Sr | 0.083 | 0.010 | 0.100 | 0.003 | | | 6.8 | 0.2 | 795 | 67 | 880 | |
| Th | | | - | | | | 0.0367 | 0.004 | | | - | |
| Ti | | | 9 | | | | - | | | | 4200 | |
| U | | | 0.4 | | | | 0.255 | 0.001 | | | - | |
| V | | | 1 | 0.1 | | | 0.577 | 0.023 | | | 166 | |
| Zn | 18.6 | 2.3 | 15.6 | 1.2 | 1506 | 54 | 1424 | 46 | 387 | 54 | 401 | 16 |
| *Total* | *16 elements* | | *30 elements* | | *12 elements* | | *31 elements* | | *12 elements* | | *23 elements* | |

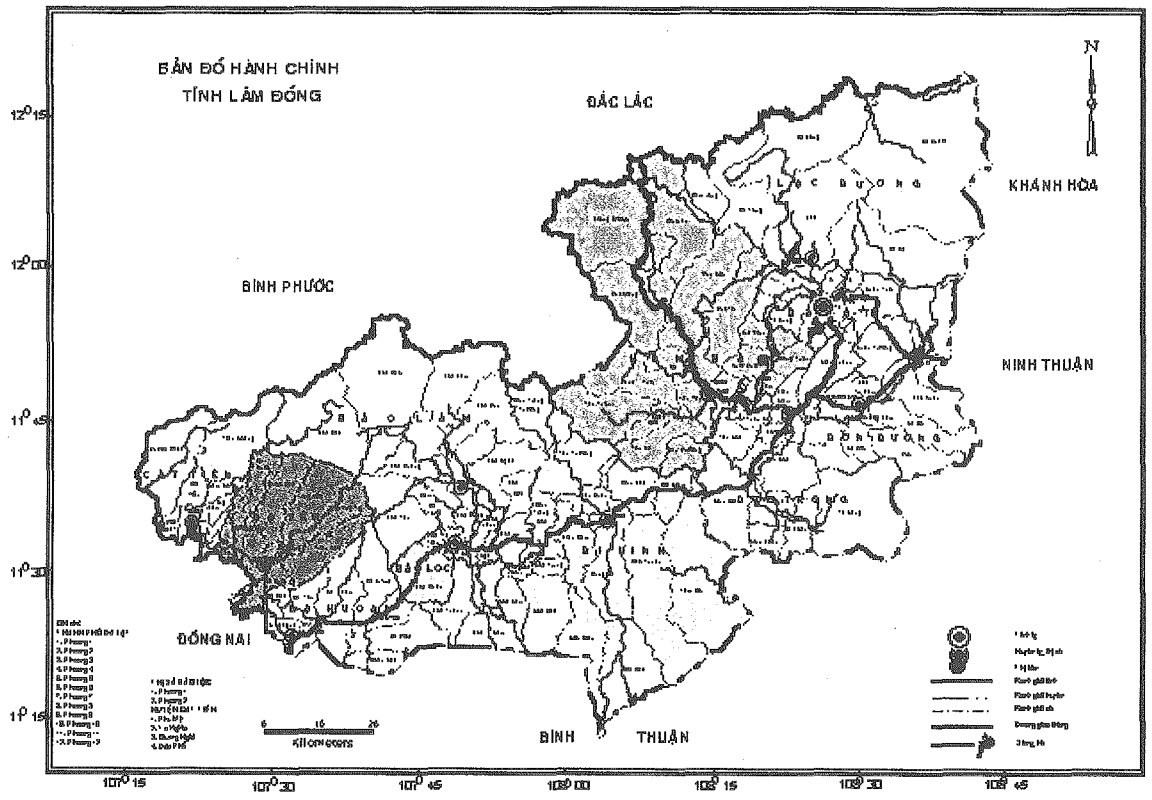


**Fig 1.** The rough map of Dateh site

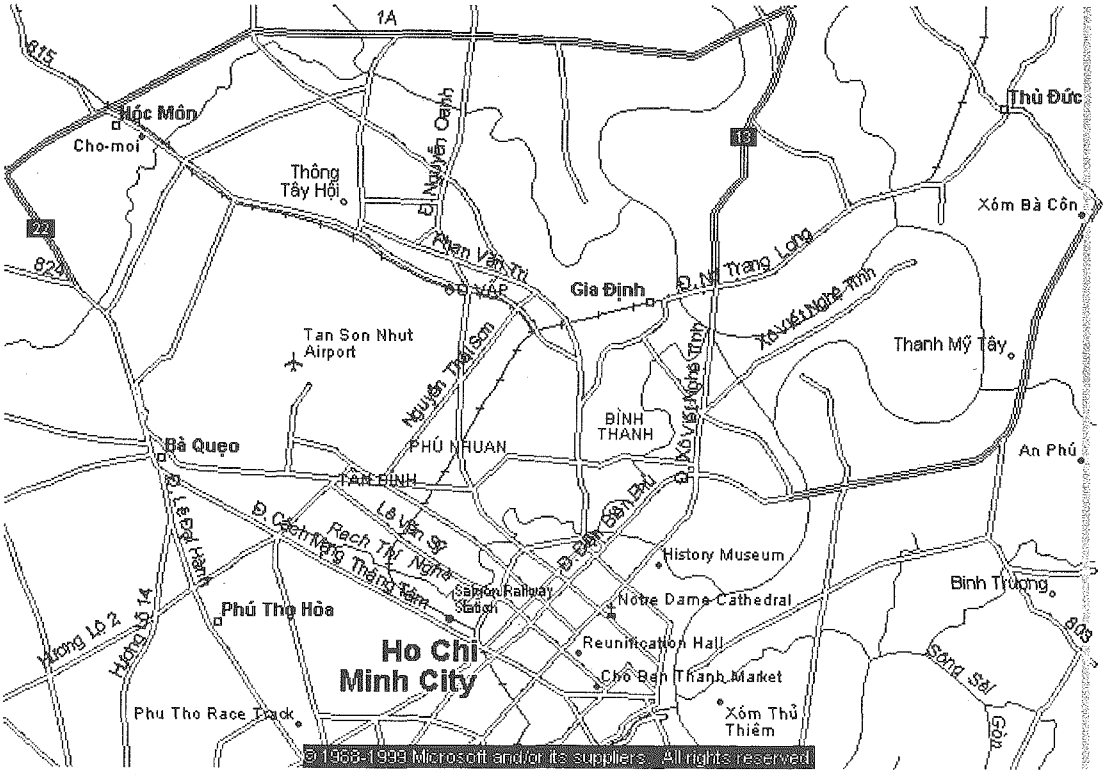


**Fig 2.** The rough map of Ho Chi Minh City site

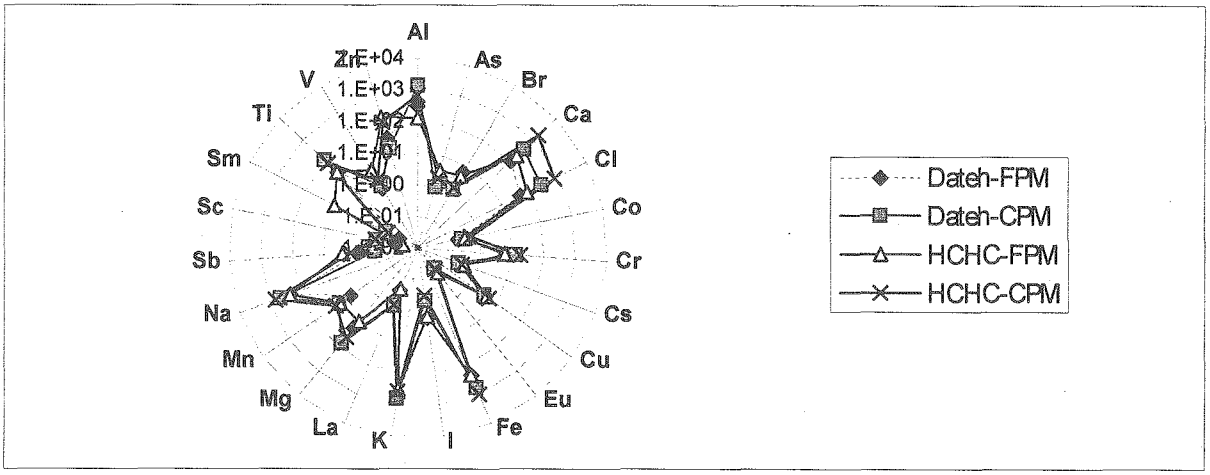


**Fig 3.** Mean concentration distribution (unit ng/m$^3$) of elements in fine and coarse fractions of APM samples collected at HCMC and Dateh

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# 1.5 INAA of Airborne Particulate Matter Collected in Bangkok 2002-2004

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## Abstract

This paper presents the summary report of the monitoring study on ambient air quality in Bangkok metropolis and its boundary covering the period from 2002 to 2004. The work performed included sampling of fine and coarse fractions of particulate matter at the sites representing urban and suburban areas; measurement of particle mass concentration and elemental concentration; and data interpretation. Instrumental neutron activation by use of research reactor facilities at Office of Atoms for Peace was carried out for multielemental analysis of all filter samples collected. Twenty elements were determined. The database of the three consecutive years are summarized and reviewed in this paper.

*Key words:* Air pollution in Thailand; INAA; Particulate matter

## 1. Introduction

The Environmental Research Group, Chemistry and Material Science Research Program, Office of Atoms for Peace (OAP) has conducted the monitoring study on ambient air quality in Bangkok since 1994. The primarily objective was toward application of instrumental neutron activation analysis (INAA) on elemental determination of airborne particulate matter (APM or PM).

As of interest in FNCA-NAA group, a collaborative project for air pollution study was designed for the three-year plan covering the period from 2002 to 2004. The scheme was to collect fine and coarse particulate matter (FPM and CPM) at the specific sites once a month and to analyze those collected samples for multielements by use of neutron activation technique. The results were examined concerned to air pollution as of local and also regional areas.

Since the current-phase project on air pollution study using INAA is completed this year, the results obtained from the three years are concluded and presented in this final report.

## 2. Methodologies

### 2.1. Aerosol sampling

The study areas covered in this project are shown in Figure 1. Site [1] and [2] are in the inner areas of Bangkok Metropolitan. Both sites thus represent urban areas. While site [3] representing a suburban residential area is in Pathumthani Province, a Bangkok's boundary in the north approximately 40 km from Bangkok City center. The Gent air samplers were set up at these sites to collect fine and coarse particles (FPM: $PM_{2.2}$ and CPM: $PM_{2.2\text{-}10}$) on two sequential 47 mm diameter Nuclepore polycarbonate filters (0.4 μm and 8 μm pore size). The sampling was generally operated at flow rate about 16 lpm for 24 hours basis once a month from January 2002 to December 2004. The numbers of samples collected are given in Table 1.

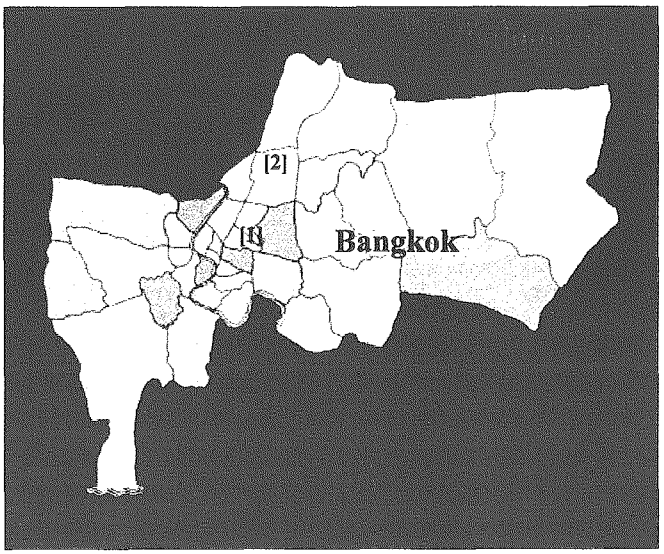



Figure 1 Map of Bangkok and sampling sites at [1] Pathumwan, Bangkok; [2] Chatuchak, Bangkok; and [3] Klongha, Pathumthani.

Table 1 Samples collected during 2002 and 2004

| Sampling sites / Year | Bangkok Site* (Urban) | | Pathumthani Site (Suburban) | |
|---|---|---|---|---|
| | No. of Sample | | No. of Sample | |
| | Fine fraction | Coarse fraction | Fine fraction | Coarse fraction |
| 2002 | 12 | 12 | - | - |
| 2003 | 12 | 12 | 12 | 12 |
| 2004 | 12 | 12 | 12 | 12 |
| Total | 36 | 36 | 24 | 24 |

* Site [1] in 2002
Site [2] in 2003 and 2004

### 2.2. Analytical technique

Although the objective of the project is to utilize INAA for elemental analysis, it is important to measure the air filter samples for mass concentration. Therefore, the measurements of PM mass using a Microbalance were first performed. Then, the filter samples were analyzed for elemental concentrations by INAA. All compositions determined were compiled for data report.

For INAA, the air filter samples including standards and filter blanks were packed in polyethylene vials and were irradiated in 1.2 MW TRIGA MARK III Research Reactor at the thermal neutron flux in the order of $10^{12}$ n/cm$^2$.sec. All irradiated samples were then transferred to new vials and counted for gamma ray activities. Two different irradiations and four gamma ray counts after appropriate decay times were conducted in order to determine short-, medium-, and long-lived radionuclides[1]. 20 elemental concentrations, their uncertainties and detection limits were obtained.

## 3. Results and discussion

The three-year database of mass and elemental compositions of fine and course particles collected from both urban and suburban sites are summarized and interpreted as shown in Tables 2 to 4 and Figures 2 to 5.

Statistics of mass concentrations of fine and coarse particles collected at Bangkok and Pathumthani during 2002 and 2004 are summarized in Table 2 and Figure 2. Apparently, there is not significant difference between PM masses at different years. However, PM masses at urban were much higher than at suburban site especially for coarse fractions. Time variations of fine and coarse particle masses at both sites are presented graphically in Figure 3. It can be observed the similar patterns of which PM were higher during dry season. PM in urban Bangkok was obviously higher than PM in suburban Pathumthani corresponding to the higher pollution in the city. To compare with national ambient air quality standard of $PM_{10}$[(2)], fine and coarse fractions were added together to obtain derived $PM_{10}$. Consequently, derived $PM_{10}$ was plotted versus $PM_{10}$ standards as shown in Figure 4. Data of only two years, i.e., 2003 and 2004 were used so that derived $PM_{10}$ of both sites can be collated. The two-year averages of derived $PM_{10}$ were 58.8 $\mu g/m^3$ and 37.0 $\mu g/m^3$ for Bangkok and Pathumthani respectively while $PM_{10}$ standard is 50 $\mu g/m^3$ for annual average. Besides, there were very high values of derived $PM_{10}$ in Bangkok during dry seasons which once exceeded the 24-hour $PM_{10}$ standard, i.e., 120 $\mu g/m^3$. Derived $PM_{10}$ in Pathumthani was corresponding but in lower level and no value exceeded the standard.

Statistical data of elemental concentrations are summarized in Tables 3 and 4 for Bangkok and Pathumthani database accordingly. It can be concluded that, in general, CPM contained most elements in higher concentrations than FPM. Furthermore, elemental contents of both CPM and FPM at urban area were found to be higher than at suburb. Greater information can be obtained from their correlations and time variations. As examples, time series plots of those selected key elements for sea, soil, and pollutants are given in Figures 5 (a) to (d).

From the results above, it can be inferred that air pollution in urban area like Bangkok metropolitan are more serious than at its boundaries as Pathumthani, particularly with concern to PM. The monitoring study on air pollution and trends in urban and suburban areas are still needed to be carried on.

## 4. Conclusion

A collaborative project for INAA application on air pollution study set up among FNCA members has accomplished in 2004 as planned. The results of the study can be made use for monitoring of air pollution and its trend both in country and regional scales.

In Thailand, the data/information generated from this work will be a part of long-term database that OAP contribute to national authorized agent who has direct responsibility in air quality assessment/management. It will be an advantage from this FNCA collaboration if APM database/information outputs from each member state can be compiled and provided to their end-users. Nevertheless, this issue may need further discussion and agreement in specific.

## References

1. Chueinta, S. Bunprapob, and S. Tedthong (2004). INAA of Airborne Particulate Matter Collected in Bangkok and Pathumthani, Thailand. Proceeding in The 2003 Workshop on the Utilization of Research Reactors, Dalat, Vietnam, January 12-16, 2004

2. Ambient air standards of Thailand (1995). Pollution Control Department, Ministry of Natural Resource and Environment.

Table2 Statistical summary of mass concentrations of FPM and CPM collected at Bangkok (2002-2004) and Pathumthani (2003-2004)

| Sampling sites: Size fractions | Particle mass ($\mu g/m^3$) | | | | | |
|---|---|---|---|---|---|---|
| | 2002 | | 2003 | | 2004 | |
| | Range | Mean | Range | Mean | Range | Mean |
| Bangkok: urban area | | | | | | |
| FPM | 5.50 – 38.6 | 28.4 | 2.17 – 26.19 | 18.3 | 8.32 – 45.0 | 20.0 |
| CPM | 21.7 – 75.8 | 36.8 | 16.7 – 86.3 | 32.9 | 19.2 – 85.4 | 46.4 |
| Pathumthani: suburb | | | | | | |
| FPM | - | - | 1.71 – 25.0 | 15.0 | 7.00 – 42.1 | 18.2 |
| CPM | - | - | 3.39 – 36.7 | 15.5 | 7.15 – 57.5 | 25.3 |

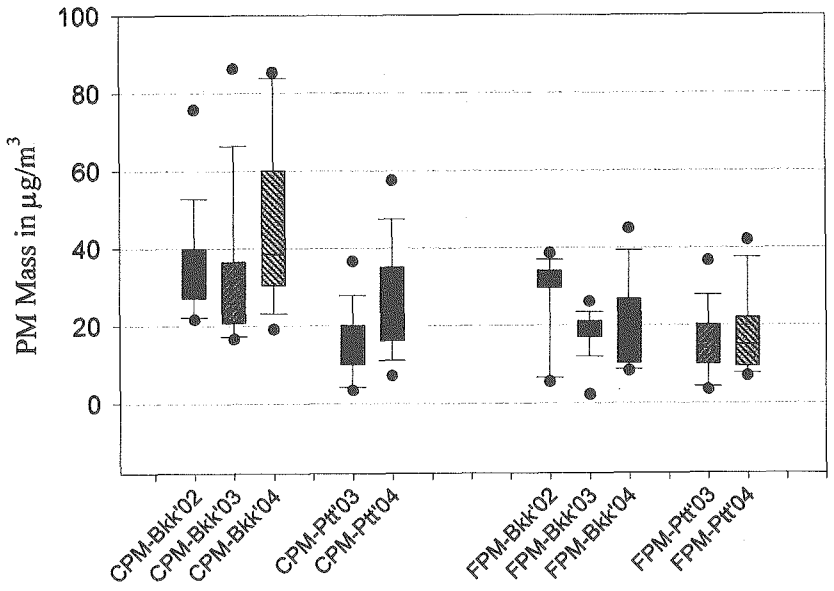
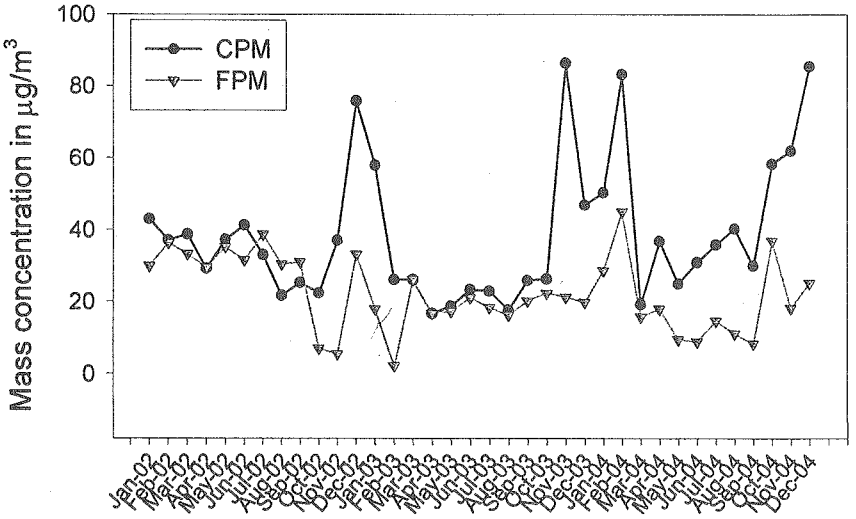
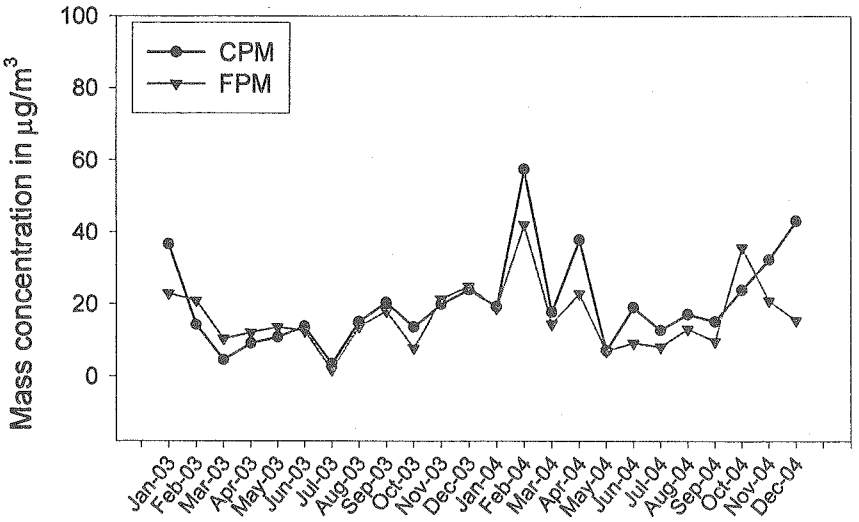



Figure 2 Comparison of PM mass at different sites and times.




(a) Bangkok




(b) Pathumthani

Figure 3 Time variations of fine and coarse particle masses at (a) Bangkok and (b) Pathumthani.

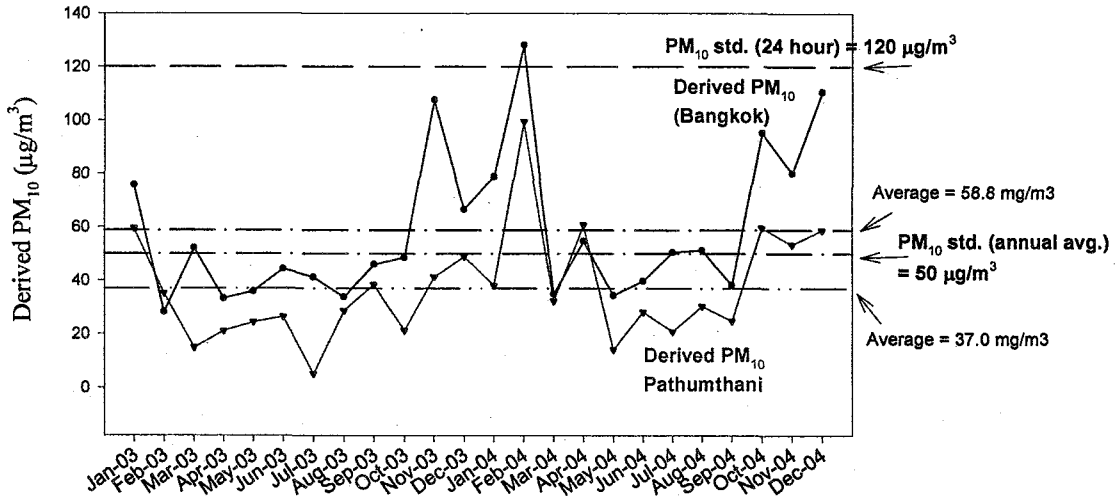



Figure 4 Time series plots of derived $PM_{10}$ vs. $PM_{10}$ standards.

Table 3 Mean and standard deviation (in ng/m$^3$) of elemental concentrations of FPM and CPM collected at Bangkok in 2002-2004

| Element | Bangkok, urban residential area | | | | | |
|---|---|---|---|---|---|---|
| | 2002 | | 2003 | | 2004 | |
| | Mean ± SD | | Mean ± SD | | Mean ± SD | |
| | FPM | CPM | FPM | CPM | FPM | CPM |
| Al | 73.2 ± 47.4 | 564 ± 282 | 94.5 ± 65.5 | 761 ± 609 | 139 ± 73 | 1022 ± 474 |
| As | 1.17 ± 1.02 | 1.98 ± 1.53 | 1.89 ± 1.74 | 3.07 ± 2.66 | 2.29 ± 2.28 | 3.22 ± 2.39 |
| Br | 2.52 ± 1.72 | 3.35 ± 1.61 | 8.71 ± 2.44 | 10.4 ± 3.67 | 5.16 ± 2.39 | 6.06 ± 3.08 |
| Ca | 370 ± 277 | 1563 ± 109 | 133 ± 87.6 | 1585 ± 1034 | 163 ± 63 | 1989 ± 715 |
| Cl | 65.3 ± 58.8 | 683 ± 702 | 21.3 ± 12.9 | 309 ± 148 | 45.0 ± 34.4 | 706 ± 752 |
| Cr | 2.25 ± 1.43 | 2.46 ± 1.14 | 2.01 ± 1.69 | 2.62 ± 0.86 | 2.08 ± 1.12 | 4.31 ± 2.29 |
| Cu | 5.25 ± 3.08 | 18.7 ± 12.6 | 4.33 ± 1.33 | 10.4 ± 3.91 | 6.47 ± 2.64 | 17.7 ± 7.0 |
| Fe | 150 ± 82 | 680 ± 247 | 131 ± 67 | 641 ± 450 | 207 ± 68 | 899 ± 305 |
| K | 245 ± 130 | 365 ± 128 | 217 ± 134 | 508 ± 430 | 334 ± 201 | 628 ± 353 |
| La | 0.17 ± 0.07 | 0.52 ± 0.29 | 0.088 ± 0.050 | 0.48 ± 0.33 | 0.13 ± 0.06 | 0.69 ± 0.30 |
| Mg | 46.9 ± 35.9 | 161 ± 110 | 27.9 ± 12.9 | 183 ± 135 | 51.7 ± 22.6 | 295 ± 91 |
| Mn | 3.59 ± 1.86 | 59.1 ± 54.3 | 4.52 ± 2.11 | 15.8 ± 9.77 | 12.4 ± 12.4 | 26.4 ± 14.7 |
| Na | 78.1 ± 48.6 | 652 ± 553 | 71.7 ± 34.3 | 481 ± 185 | 130 ± 86 | 678 ± 519 |
| Sb | 1.01 ± 0.78 | 3.55 ± 1.85 | 1.09 ± 0.58 | 2.29 ± 1.77 | 1.91 ± 1.59 | 3.75 ± 3.15 |
| Sc | 0.015 ± 0.011 | 0.096 ± 0.041 | 0.017 ± 0.013 | 0.13 ± 0.10 | 0.033 ± 0.017 | 0.19 ± 0.09 |
| Se | 0.71 ± 0.40 | 0.50 ± 0.28 | 0.87 ± 1.37 | 0.67 ± 0.25 | - | - |
| Sm | 0.013 ± 0.007 | 0.065 ± 0.029 | 0.010 ± 0.006 | 0.064 ± 0.052 | 0.016 ± 0.006 | 0.089 ± 0.038 |
| Ti | 16.6 ± 8.7 | 61.3 ± 51.6 | 8.04 ± 3.13 | 53.4 ± 35.5 | 13.4 ± 5.5 | 73.3 ± 29.7 |
| V | 0.92 ± 0.40 | 2.51 ± 1.13 | 1.55 ± 0.93 | 3.32 ± 2.10 | 2.43 ± 1.25 | 4.76 ± 2.35 |
| Zn | 39.6 ± 29.8 | 69.3 ± 21.0 | 46.2 ± 27.9 | 97.7 ± 37.2 | 71.1 ± 40.0 | 136 ± 70 |

Table 4 Mean and standard deviation (in ng/m$^3$) of elemental concentrations of FPM and CPM collected at Pathumthani in 2003-2004

| Element | Pathumthani, suburban residential area | | | |
|---|---|---|---|---|
| | 2003 | | 2004 | |
| | Mean ± SD | | Mean ± SD | |
| | FPM | CPM | FPM | CPM |
| Al | 55.2 ± 52.9 | 488 ± 329 | 151 ± 83 | 724 ± 421 |
| As | 1.29 ± 1.33 | 0.73 ± 0.63 | 2.00 ± 2.07 | 1.40 ± 1.37 |
| Br | 8.84 ± 4.54 | 7.36 ± 3.01 | 5.41 ± 3.80 | 4.19 ± 3.84 |
| Ca | 83.9 ± 69.9 | 811 ± 426 | 149 ± 60 | 1106 ± 441 |
| Cl | 13.1 ± 12.0 | 178 ± 109 | 34.2 ± 26.3 | 371 ± 289 |
| Cr | 1.67 ± 1.88 | 1.41 ± 0.89 | 1.58 ± 1.59 | 2.53 ± 1.95 |
| Cu | 3.77 ± 4.31 | 4.18 ± 2.53 | 5.95 ± 4.36 | 4.83 ± 1.82 |
| Fe | 103 ± 60.4 | 308 ± 177 | 144 ± 58 | 437 ± 221 |
| K | 279 ± 220 | 201 ± 128 | 395 ± 229 | 406 ± 223 |
| La | 0.081 ± 0.044 | 0.32 ± 0.15 | 0.12 ± 0.04 | 0.48 ± 0.22 |
| Mg | 30.4 ± 28.0 | 102 ± 66.2 | 53.0 ± 28.8 | 180 ± 80 |
| Mn | 3.09 ± 2.16 | 8.41 ± 5.93 | 10.2 ± 16.0 | 15.0 ± 10.4 |
| Na | 81.6 ± 44.0 | 230 ± 81.4 | 139 ± 82 | 417 ± 313 |
| Sb | 1.17 ± 1.35 | 0.49 ± 0.38 | 1.66 ± 1.56 | 0.90 ± 0.84 |
| Sc | 0.018 ± 0.016 | 0.081 ± 0.055 | 0.034 ± 0.018 | 0.13 ± 0.08 |
| Se | 0.47 ± 0.34 | 0.35 ± 0.32 | - | - |
| Sm | 0.011 ± 0.008 | 0.044 ± 0.023 | 0.018 ± 0.007 | 0.070 ± 0.033 |
| Ti | 7.61 ± 4.77 | 31.0 ± 17.5 | 13.1 ± 6.1 | 44.9 ± 21.8 |
| V | 1.09 ± 0.79 | 1.40 ± 0.67 | 1.91 ± 0.61 | 2.28 ± 0.89 |
| Zn | 30.6 ± 24.5 | 34.3 ± 24.1 | 55.2 ± 29.4 | 48.1 ± 21.8 |

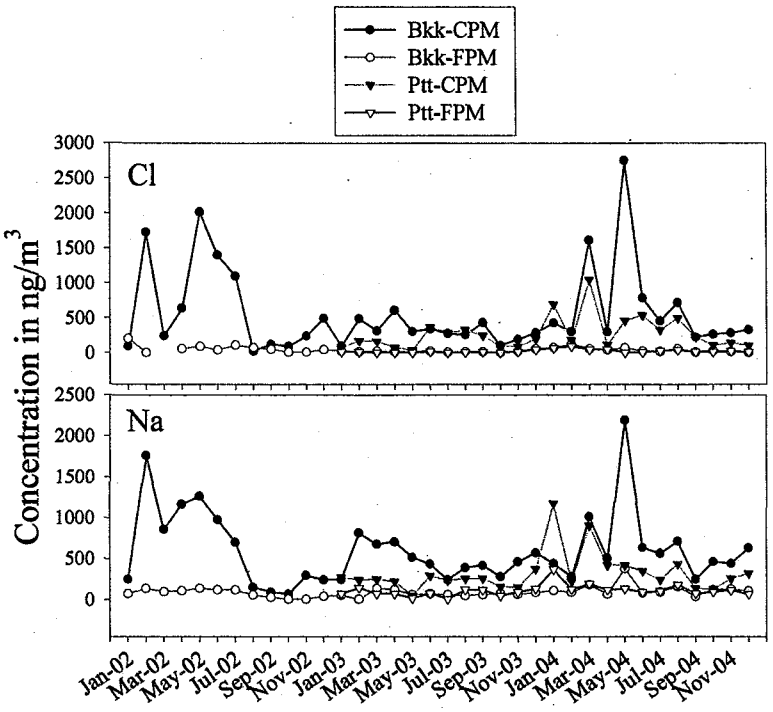



Figure 5 (a)

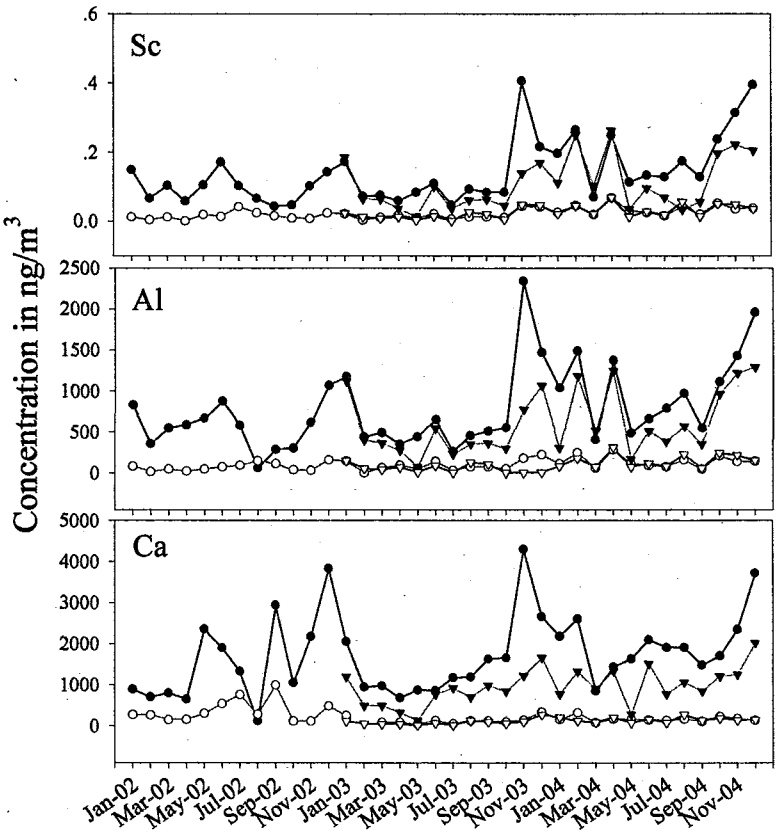



Figure 5(b)

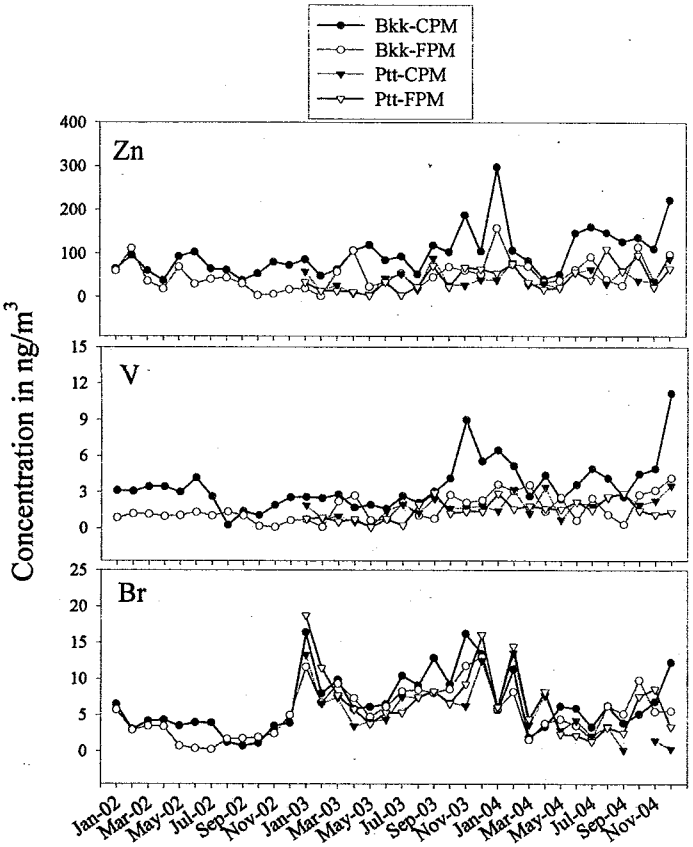



Figure 5 (c)

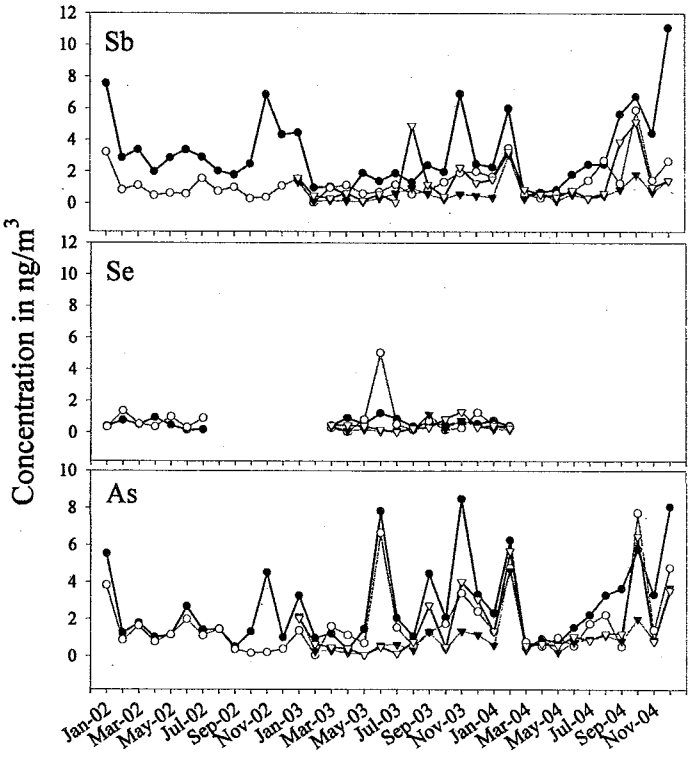



Figure 5 (d)

Figure 5 Time variations of selected key elements for (a) sea; (b) soil; (c) and (d) pollutants.

# 1.6 Roles of Environmental Monitoring Toward the Better Environment

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**Abstract**

Generally, highly populated and/or industrialized areas face serious air pollution. Particularly in developing countries, without effective measures to control emission from automobiles and industries, millions of dwellers will exposed to unhealthy and dangerous levels of air pollution. The first step toward the better environment is to utilize good quality of monitoring data. State of the environment can be assessed based on the environmental monitoring data. This paper describes the roles of environmental monitoring toward the better environment with successful example of improvement of serious air pollution.

## 1. Introduction

Local governments in many countries have been monitoring hazardous air pollutants to maintain healthy air for a human being and ecosystem. Monitoring parameters include traditional air pollutants such as $SO_2$, $NO_2$, CO, SPM, $O_3$, Pb and rather newly focused pollutants like heavy metals, VOCs, and other organic compounds. States of the environment can be assessed by the observed concentration of individual parameter comparing with the air quality standard. From these monitoring activities, important pollutants are identified, and inferences impacting upon people are reviewed. Mitigation of the effects by the air pollutants are planed by various ways to lower the concentration of pollutants, such as modification of industrial process, purification of raw materials, and various types of end of pipe treatments. Air pollution control strategies are very important; targeted concentration level, option of regulation such as emission standard, tax, and financial support to encourage emission control. During implementation of pollution control, monitoring data of the air pollutants can be used again for assessing progress of control the pollutants in living environment. As mention here, environmental monitoring has various roles toward the better environment.

## 2. Air pollution of the world

Urban air pollution is a major environmental problem in the developing countries of the world. WHO(World Health Organization) and UNEP(United Nations Environment Programme) collected air pollution monitoring data from many cities in 35 developing and

developed countries[1]. As shown in Fig.1, ambient air pollution in 20 of the 24 megacities of the world (over 10 million people by year 2000) is at level where serious health effects are reported.

| Parameter / Cities | $SO_2$ | SPM | Pb | CO | $NO_2$ | $O_3$ |
|---|---|---|---|---|---|---|
| Bangkok | ○ | ● | ● | ○ | ○ | ○ |
| Beijing | ● | ● | ○ | ○ | ○ | ● |
| Bombay | ○ | ● | ○ | ○ | ○ | ○ |
| Buenos Aires | ○ | ● | ○ | ○ | ○ | ○ |
| Cairo | ○ | ● | ● | ● | ○ | ○ |
| Calcutta | ○ | ● | ○ | ○ | ○ | ○ |
| Delhi | ○ | ● | ○ | ○ | ○ | ○ |
| Jakarta | ○ | ● | ● | ● | ○ | ● |
| Karachi | ○ | ● | ● | ○ | ○ | ○ |
| London | ○ | ○ | ○ | ● | ○ | ○ |
| Los Angeles | ○ | ● | ○ | ● | ● | ● |
| Manila | ○ | ● | ● | ○ | ○ | ○ |
| Mexico City | ● | ● | ● | ● | ● | ● |
| Moscow | ○ | ● | ○ | ● | ● | ○ |
| New York | ● | ● | ○ | ● | ● | ● |
| Rio de Janeiro | ● | ● | ○ | ○ | ○ | ○ |
| Sao Paulo | ○ | ● | ○ | ● | ● | ● |
| Seoul | ● | ● | ○ | ○ | ○ | ○ |
| Shanghai | ● | ● | ○ | ○ | ○ | ○ |
| Tokyo | ○ | ○ | ○ | ○ | ○ | ● |

**Fig.1** Overview of air quality in 20 megacities based on a subjective assessment of monitoring data and emissions inventories [1].

● Serious problem. WHO guidelines exceeded by more than factor of two.

● Moderate to low pollution. WHO guidelines exceed by up to a factor of two. (Short-term guidelines exceeded on a regular basis at certain locations).

○ Low pollution. WHO guidelines are normally met. (Short-term guidelines may be exceeded occasionally).

The first observation is that air pollution is widespread across the megacities and is often most severe in cities in developing countries. But even in developed countries, air quality standards are being exceeded, although to a lesser degree. Each of the 20 megacities has at least one major air pollutant which occurs at levels that exceed WHO health protection guidelines. 14 of these megacities have two such pollutants and 7 have three or more. The last group consists of Beijing, Cairo, Jakarta, Los Angeles, Mexico City, Moscow and Sao Paulo.

### 3. Contribution of environmental monitoring system to the air quality prevention

Air quality monitoring is part of initial strategy in the pollution prevention programs[2]. In a case of Malaysia, the government established Malaysian Air Quality Guidelines, Air Pollution Index, and Haze Action Plan to improve air quality. The first "long-term" air quality monitoring project emphasizing particulate matter and sulfur dioxide was carried out by the Department of Environment (DOE) and the Malaysia Meteorological Service (MMS) at the industrial and residential zones in Petaling Jaya in 1978. Results of the study suggested that the particulate matter exceeded 93% of the time in the industrial zone (the previously proposed standard was 24-hour average of 0.1mg/m$^3$) and 95% of the time in the residential zone. In 1996, 10 new fully automated ambient air quality monitoring stations with telemetric system were installed, bringing the total number of stations up to 31. The monitoring system contributes to the prevention of air quality in Malaysia.

Early 1960's in Japan, large scale petrochemical complex operations began in Yokkaichi city, and the air pollution in the city reached its worst level around 1963-1964[3]. As heavy oil sulfur content rates at the time measured around 3%, annual sulfur dioxide emissions of the city are estimated at 130,000-140,000 tons. Annual average sulfur dioxide concentration in this area was 0.075ppm (almost four times more than the current environmental quality standards). Residents complaining of asthmatic symptoms began to appear around 1961. Among many symptoms, a correlation between symptoms such as dyspnea (shortness of breath) and sulfur dioxide concentration was recognized. Statistical data indicates that the number of certified sufferers called "Yokkaichi Asthma" in the city totaled 1,738. The National Air Surveillance Network (NASN) was first established in 1965 at three sites located in Tokyo and Osaka areas. The network measured not only gaseous pollutants but also particulate matter and its components. Concentration of sulfur dioxide was gradually decreased (national annual average of sulfur dioxide dropped from 0.030ppm in 1973 to 0.010ppm in 1987) and the main focus of air pollution moved to nitrogen dioxide and fine particles ($PM_{10}$). The network now covers whole nation and measures various parameters including hazardous air pollutants. The

activities of the network obviously contribute to the prevention of the air quality.

## 4. Example of air quality improvement – phase out of leaded gasoline

Most of the countries once used leaded gasoline and some of them faced serious air pollution by combustion products of the leaded gasoline. Organic tetraalkyl lead (tetraethyl- and tetramethyl-lead) was added to gasoline as the most convenient and economical way to increase the octane ratings of all grades of gasoline. Lead is known as a hazardous heavy metal that has a damaging impact on human health, in particular on children and pregnant women. The main symptoms include difficulties in mental development (e.g. reading and learning disabilities) and in concentration, adverse effects on kidney function, blood chemistry and cardiovascular system, and hearing degradation. For example, by medical survey in Jakarta, lead in blood of highly exposed people disturbs ALA-D activities to interrupt the synthesis of coproporphyrinogen from ALA (Fig.2) [4]. Same kind of episode of lead poisoning in Japan was called "Yanagi-cho Lead Poisoning" emerged in 1968 in a small area with busy traffic in Tokyo.

In a case of Thailand, air pollution is one of the major environmental problems in the Bangkok Metropolitan Administration (BMA)[5]. Air quality in BMA was worst in 1992 during the period of rapid economic growth when the highest concentration of Total Suspended Particulate (TSP) raised up to 10 times exceeding the ambient standard, including lead particulate and carbon monoxide which were also exceeded the standard several folds. However, air quality in Bangkok has been gradually improved since 1995 when law enforcement on construction activities, strengthening the emission standard, phasing out leaded gasoline, and public campaign became more effective. As lead is considered hazardous to human health, the government made a decision to phase out leaded gasoline step by step. In 1989, reduction of lead in gasoline was made from 0.45g/l to 0.4g/l, and gradually dropped to 0.15g/l in 1992. In 1994, unleaded premium gasoline was introduced, and lead free gasoline was made mandatory in 1997, leading to a dramatic decline in lead in the air, as shown in Fig.3.

In other countries, phase-out of leaded gasoline drastically decreased concentration of atmospheric lead[6].

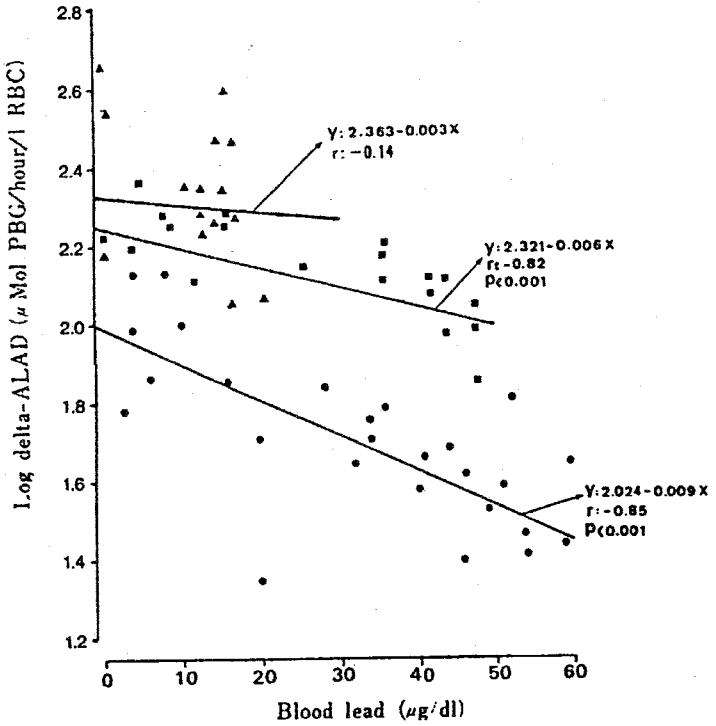


**Fig.2** Relationship between concentration of lead in blood and δ-aminolevulinic acid dehydrase activity in the three subject groups: rural people, drivers, and policemen in Bandung in 1983-84. (▲:rural people, ■:drivers, ●:policeman)[4]

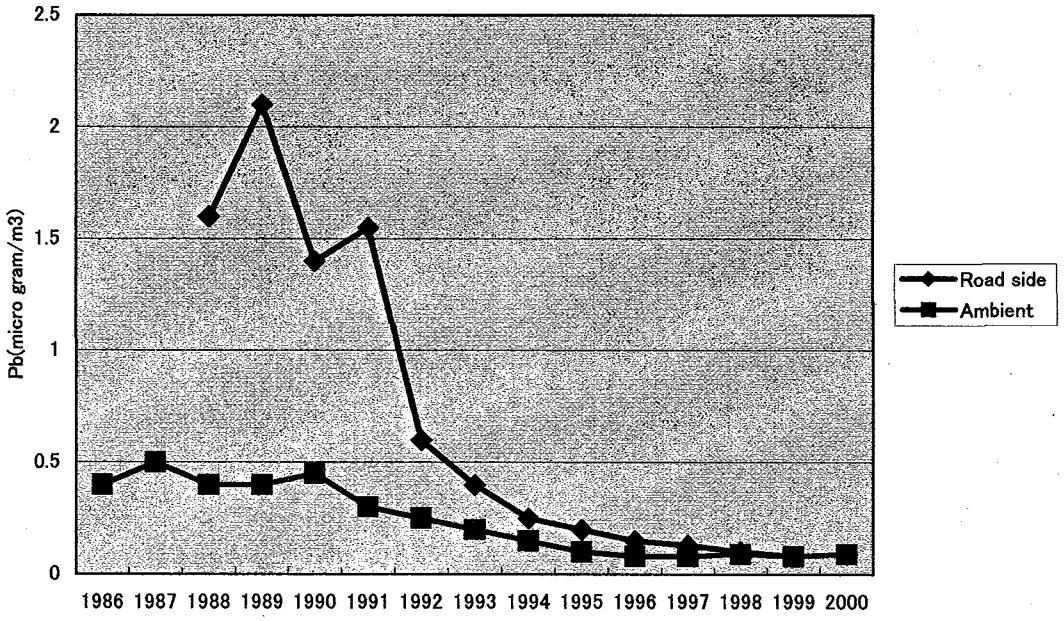


**Fig.3** Annual average of lead concentration in Bangkok during 1986-2000.[5]

## 5. Health effects and air quality standard for some hazardous elements – a new trend

In this section, health risk evaluation of two carcinogens, arsenic (As) and nickel (Ni) by WHO is introduced[7]. Because of the possible long-term health effect of these elements, guideline of new air quality standard is being set up in some developed countries.

As is released to the atmosphere from both natural and anthropogenic sources. The principal natural source is volcanic activities, with minor contributions by exudates from vegetation and windblown dusts. Man-made emissions to air arise from the smelting of metals, the combustion of fuels, especially of low-grade brown coal, and the use of pesticides. There are three population groups at high exposure risk: the occupationally exposed, people drinking water with abnormally high concentrations of arsenic, and children living in the close vicinity of copper smelters. There is sufficient evidence that inorganic arsenic compounds are skin and lung carcinogens in humans. Present risk estimates have been derived from studies in exposed human populations in the United States and Sweden. When assuming a linear dose-response relation, a safe level for inhalation exposure cannot be recommended. At an air concentration of 1 microgram/$m^3$ of As, an estimate of lifetime risk is $1.5 \times 10^{-3}$. This means that the excess lifetime risk level is 1:10,000, 1:100,000 or 1:1,000,000 at an air concentration of As of about 66 ng/$m^3$ or 6.6 ng/$m^3$, or 0.66 ng/$m^3$, respectively.

Ni content is enriched in coal and crude oil. Ni in coals ranges up to 300 mg/kg; most samples contain less than 100 mg/kg but there is a large variation by region. The Ni content of crude oil is in the range <1-80 mg/kg. Little is known about risk groups in the general population, although smokers and those exposed at work have higher exposures than other groups within the population. Exposure to Ni levels of 10-100 mg/$m^3$ have been reported for occupational groups, with documented increased cancer risk. On the basis of the most recent information of exposure and risk estimated in industrial populations, an incremental risk of $3.8 \times 10^{-4}$ can be given for a concentration of Ni in air of 1 microgram/$m^3$. The concentrations corresponding to an excess lifetime risk of 1:10,000, 1:100,000 and 1:1,000,000 are about 250, 25 and 2.5 ng/$m^3$, respectively.

At present, the air quality guideline for Ni is enacted in Japan; annual Ni concentration of 25ng/$m^3$ which corresponds to $10^{-5}$ risk level.

## 6. Conclusion

Air pollution is still serious in many large cities and industrial areas. Though, some pollutants such as atmospheric lead and sulfur dioxide drastically decreased their concentration in certain areas of the world. There are new trends of control of hazardous air pollutants which

is possible cause of cancer. Monitoring system of these air pollutants obviously contributes to the prevention of the air quality.

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# 1. Workshop

## Research Reactor Technology

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1.7

# Utilization of MCNP code in the research and design for China Advanced Research Reactor

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**Abstract:** MCNP, which is the internationalized neutronics code, is used for nuclear research and design in China Advanced Research Reactor (CARR). MCNP is an important neutronics code in the research and design for CARR since many calculation tasks could be undertaken by it. Many nuclear parameters on reactor core, the design and optimization research for many reactor utilizations, much verification for other nuclear calculation code and so on are conducted with help of MCNP.

Keywords: MCNP, CARR, Neutonics code

## 1 Introduction

### 1.1 Introduction to MCNP code

MCNP, developed by various government and private organizations (as Los Alamos National Laboratory) and collected by Radiation Safety Information Computational Center (RSICC), is a general-purpose Monte Carlo N-Particle code that can be used for neutron, photon, electron, or coupled neutron/photon/electron transport. This code is widely used in many areas, especially in research reactor, which include radiation protection and dosimetry, radiation shielding, radiography, medical physics, nuclear criticality safety, detector design and analysis, nuclear oil well logging, Accelerator target design, Fission and fusion reactor design, decontamination and decommissioning and so on.

The code treats an arbitrary three-dimensional configuration of materials. Point-wise cross-section data typically are used, although group-wise data also are available.

For neutrons, all reactions given in a particular cross-section evaluation (such as ENDF/B-X) are provided. Thermal neutrons are described by both the free gas and S(alpha, beta) models. For photons, the code accounts for incoherent and coherent scattering, the possibility of fluorescent emission after photoelectric absorption, absorption in pair production with local emission of

annihilation radiation, and bremsstrahlung.

### 1.2 Introduction to CARR

The CARR Project was set up for meeting the need of science and technology development in the 21st century. Having incorporated the successful experience in construction of research reactors in China and foreign countries as reference and also with its own innovations and technical features, CARR is a safe, reliable, multipurpose research reactor of high performance. It will provide an important platform of further development for science researches in China.

CARR is cooled and moderated by light water and reflected by heavy water. This reactor is of inverse neutron trap design and of tank-in-pool type with a power of 60MW. Its maximum thermal neutron flux reaches $1.0\times10^{15}$ n/cm$^2$/s in central position when the central fuel assembly is replaced by experimental channel. The peak flux in heavy water reflector is about $8.0\times10^{14}$ n/cm$^2$/s where the main applications for intense neutrons is available.

A large fraction of fast neutrons leak out from cylinder tube because the reactor has a rather compact core that possesses a low slowing down ability for fast neutrons. Then the thermal neutron flux peak occurs in heavy water reflector because of its good quality of slowing down ability and very small absorption.

The reactor has a quite pure thermal neutron spectrum and much more space available for arrangement of many vertical and horizontal channels. There are nine horizontal beam channels, seventeen vertical irradiation channels, one vertical CNS channel and one vertical hot neutron source in heavy water reflector (see Fig.1).

The design and construction work is undergoing now with the schedule of 52 months' construction period and it will be completed at the end of 2006.

### 1.3 Major applications of CARR

Vertical and horizontal channels with associated equipment and instruments are installed in reactor core and in heavy water reflector for various applications and make it possible for full use of the intense neutron source created by the reactor for neutron scattering experiments, radioisotope (RI) production, setting up ionization and radiation metrological standards, study on nuclear power development and neutron activation analysis and so forth.

### 1.4 Utilization of MCNP in CARR

There are many neutronic codes that are used in research and design of CARR. They can be generally divided into two groups. One is the group of integral transport method, which includes MCNP code. The difference is that MCNP is grounded on probability theory, compared with other integral transport code. The other is of diffusion method, which is to resolve the diffusion equation by differential or nodal after the group parameters were approached.

The role of MCNP is an important and indispensable code in the research and design of CARR in many areas. It is available to the situation of calculation the effective multiplication factor (which

can produce the reactivity, further to the excess reactivity, shut margin and so on), the average of neutron flux or photon flux over the specified volume or across the specified surface or with designated degree of angle (which can produce many results such as the reaction rate, the nuclear heating, radiation exposure and so on), the arbitrary energy segment, and so forth.

From viewpoint of the utilization, it is better to divided into three parts which include the research and design of CARR complex (reactor core and heavy water tank for CARR), many applications for CARR like CNS, the verification task such as the criticality, flux and group parameters.

## 2 Design of CARR complex

### 2.1 Effective Multiplication Factor

The effective multiplication factor ($k_{eff}$) is a basic result from the output file of MCNP calculation except other information like neutron tracks. For the reason of exact geometry configuration and point-wise cross-section of nuclides, the result of effective multiplication factor is one of the best values among the calculation codes such as CITATION, KENO, and so on, especially for the case of abnormal neutron energy spectrum and core structure in the reactor. The typical example in CARR is $k_{eff}$ with the insertion of control rods or safety rods. As well known, the diffusion theory can't be used well in the region near the material with strong absorption. So, MCNP is the perfect code for it.

With the ability of good result of $k_{eff}$, many important parameters can be calculated from the criticality simulation. These parameters include excess reactivity, shutdown margin, control rod worth under different combination, fuel assembly worth in different location, power coefficient of reactivity, fuel temperature coefficient, moderator temperature coefficient, and so on. In CARR case, all these parameters are calculated by MCNP and CITATION from which the result of MCNP is more believable. Fig.2 shows the control rod worth under different situation.

By the way, the good results must be with good standard deviation and in good valid confidence intervals. Even though with a good standard deviation, the real result may be not as good as calculation. The result from criticality calculation should have a good space and energy distribution of neutron source as the beginning stage. It's better to calculate with the source come from several continuous calculation steps and with a large history at one time.

### 2.2 Flux and Power Distribution

Flux and power distribution is the major ability of normal neutronic codes, based on diffusion theory, from which it was showed directly. For MCNP, it is indirect and necessary to tally the flux and power with special descriptions and requirements in the input file prepared for the calculation. It can be thought that the tally is little bit complicated than other codes. But one coin has two sides. MCNP code has more powerful ability than others to calculate the parameter if it is relate to flux or power. For example, the tally relates to the different energy partition, or different volume and

different location, or different incidence angle.

Diffusion code is adept at the flux and power distribution calculation for fuel assembly with fissionable materials. MCNP can also do this job if the divided space is available in the input file with the required cards as F4:N and F7:N. Because the good result from diffusion code is related to the accuracy of group parameters and the dimensional model, it is also need to be verified for the flux and power distribution results in CARR reactor core. Tab.1 shows the compared results between two methods.

Outside of the fuel assembly lattice and inside the core vessel, there is an aluminum insert for the purpose of limiting the flow area and increasing the flow rate. But this insert should be resolved with two problems, i.e., radiation damage and cooling down to the expected temperature. MCNP code could have a good application for it, compared with the diffusion codes. As far as radiation damage is concerned, the fast neutron flux is more important parameter than the others. It is an exclusive resort to MCNP for the special shape and peculiar energy range of fast neutron flux. As for the nuclear heating, MCNP is also the only method if the exact heating is necessary. The example of nuclear heating calculation is showed in CNS application. Whether the aluminum insert is safe or not can be decided by the nuclear heating, cooling condition, mechanical structure with the help of thermal-hydraulic analysis.

### 2.3 Neutron Energy Spectrum

Neutron energy spectrum is also a vital parameter in research reactor. CARR is of inverse neutron trap design and more lack-of-moderated inside the core vessel, so the good result is approached for high thermal neutron flux in the heavy water tank that is outside the core vessel. With the point-wise nuclide cross-sections and the probability model, the neutron energy spectrum is effortless obtained by the tally result from MCNP. Another point is most experienced user for neutronic calculation always analyzes the parameter and judges it good or not in the diffusion calculation by the hardness of spectrum. Sometimes, that is very useful for distinguishing the inconspicuous mistakes when any contradiction occurs.

In order to get better comparison observably among the spectrums with different hardness, more detailed neutron energy spectrum is treated as N(E), where N is neutron number (not the flux) and E(neutron energy) is the variable. This format of spectrum can be facile to be compared with standard thermal neutron energy spectrum, which is called "Maxwell" spectrum. The corresponding calculation is put into practice in analyzing inside the core vessel. The digital calculation method is neglected here and its application example for CNS is showed in the Fig.3.

### 2.4 Radiation Shielding

Normally, shielding calculation is the necessary work for the reactor design and is implemented by some special shielding codes like DOT. The results from the shielding code always have the large error and are commonly acceptable when the error is not too large as several times. If the flux-to-dose rate conversion factor provided, the human biological equivalent rate can be easily

attained when the neutron and photon flux is ready by way of flux tallying. MCNP provided the convenient multipliers (DE and DF) for the conversion from flux to dose. With the help of the function of MCNP, the radiation exposure is handy to reach.

But the disadvantage of MCNP code is the more remote distance from reactor core, the larger error will happen, i.e., the more difficult to calculate. Many effective tips can be used by the proficient user in which how to increasing the accuracy. But sometimes the low efficiency is appeared because it is necessary to check output of MCNP calculation in detail. Even more, the bad ending is come forth even though a small mistake. Fortunately, the calculation speed of modern computer is speed up almost every month. By combination between the higher speed of modern computer and some trustful tips, the case of remote distance from reactor core is also possible resolved by MCNP.

**2.5 Others Utilizations in CARR**

In the procession of design of CARR reactor core, there are some other interesting utilizations of MCNP showed as follows. This includes the method of dealing with the flux in heavy water tank by the $k_{eff}$, the design of storage lattice of spent or fresh fuel assembly and so on.

CARR is of inverse neutron trap type design and of tank-in-pool type research reactor. The heavy water tank is located outside the core vessel and its flux in it should be validated by the MCNP. The flux in heavy water should be valued with the depletion of fuel. How it is changed is also an important parameter when the complex is designed. But it hasn't been of more confidence about the neutron flux outside the reactor core by diffusion method for the largest absorption inside the reactor code. That is to simulate the different control rod insert and to keep the reactor on criticality when the fuel is with any depletion. But it's not easy to simulate the burn-up of fuel. In order to analyze the changed tendency of flux, the approximate method was considered by way of MCNP code. At last, the real flux in the heavy water tank is treated as the flux calculated from MCNP multiplied by the $k_{eff}$, whenever the reactor is under criticality and wherever control rod is inserted. The example is showed in Fig.4 where the distance from reactor core is 46 cm. The integral of neutron flux along the vertical direction is showed in Tab.2 with different insert cases.

Another example is the design for the storage lattice of spent or fresh fuel assembly to prevent the criticality in fuel assembly pool. The distance between each other on the horizontal dimension is more significant parameter when the single layer is required. Obviously, the smallest distance for the case of fresh fuel assembly to prevent criticality is also suitable to spent fuel assembly since the conversion factor of breeding is less than 1.0 for CARR case. It's extraordinary difficult to simulate the whole fuel assembly pool with full loading of large number of fresh fuel assemblies. It is necessary to simplify the model of storage pool based on the single layer design. It's very easy to evaluate the smallest distance with MCNP by introducing the model of infinite boundary in horizontal dimension and the real model in vertical dimension. Fuel assembly of CARR is of square cross section, so tip is the surface written with "*", which means the reflection surface and is induced with infinite boundary.Tab.3 is the calculation results for this model of CARR storage pool.

The best lattice distance is available for 13.5 cm.

MCNP has been used as a crucial code in the design of CARR complex besides diffusion codes as CITATION. The above items are focus on the effective multiplication factor, flux and power distribution, neutron energy spectrum, radiation exposure, and some tips. Even from this example, it can be concluded that MCNP is a powerful code for the research and design of CARR complex.

## 3 Applications of CARR

CARR is a multipurpose research reactor which include many application plans such as radioisotope (RI) production, neutron scattering experiment, Neutron Activation Analysis (NAA), Neutron Transmutation Doping (NTD) and so on. The previous started work includes the design of Cold Neutron Source (CNS) and its beam tube. Other applications of CARR haven't been commenced until the detailed design of CARR is finished.

Not only is MCNP widely applied in the design of CNS already commenced, but also it's exclusively employed in the design of almost all the applications in the future. The explanation of main applications is listed here.

### 3.1 The Design of CNS

The liquid hydrogen and liquid deuterium are always used as cold moderator for the temperature of it is as low as 20K approximately. But the cold moderator will be added the nuclear heating by way of gamma rays and neutron collision. Gamma rays, normally entitled as photon in MCNP, are mainly nuclear heating source by effect of incoherent (Compton) scatter, pair production, and photoelectric absorption. The nuclear heating will be also released when the thermal neutron encounter cold hydrogen or deuterium by the course of collision.

Two most significant problems for physics design of CNS are the nuclear heating and the gain factor of CNS. Nuclear heating should be removed from the cryostat to the environment by the cold moderator circulation loop and helium refrigeration system. So firstly the nuclear heating should be decided exactly for the circulation loop and helium refrigeration system. At the same time, the effect of CNS should be carefully designed for good gain factor at the same condition of reactor. General speaking, the effect of CNS is described as the gain factor, which is the ratio of state with cold moderator to without it. Hence, the gain factor is an indicator of the performance of CNS. According to the characteristic of CNS and further device as beam tube, the brightness of cold neutron is introduced into the research of CNS. The brightness is defined as the second derivative of flux with respect to the wavelength (angstrom) and angle.

Heat load includes the nuclear heating of neutrons and prompt gamma rays, beta particles from $^{28}$Al, the delayed photons from $^{28}$Al and delayed fission product gamma rays for aluminum material. The total nuclear heating in CNS is listed in Tab.4.

After the design is optimized with the size and shape of moderator cell and thickness and shape of liquid cold moderator, the better design is achieved. The brightness of cold neutron, with respect to energy of cold neutron, is showed in Fig.5 for the nominal power of 60 MW in the reactor,

compared with NBSR (nominal power of 20MW) of NIST. The gain factor, with respect to wavelength of cold neutron, is also showed here on Fig.6 in comparison with ORPHEE and NBSR.

### 3.2 The Irradiation Design of RI

In order to design the suitable RI irradiation target, the RI characteristics of production and disappear should be considered at length. Normally, it should be established for the differential equation or equation group of production (decay or absorption or fission reaction from other nuclides) and disappear (decay or absorption to other nuclides) included the process of in-pile or out-pile. From the equation or equation group, the quantity of the nuclide involved can be easily found with the relationship of time. Among those parameters, the nuclide reaction rate (can be varied with the time) is a more important parameter in production of RI. The optimization of nuclide reaction rate is also the process of optimization for target, irradiation condition, irradiation time and their combinations.

As well known, MCNP is very suitable to sum up the reaction rate with the more accurate result in the reactor especially for the particular shape (not cuboidal or cylinder). Various reaction rates can be tallied and normalized by reactor power after the assumption configuration is input. From this perfect function of MCNP, it's a good code in the design of RI production.

### 3.3 Neutron Activation Analysis

Neutron Activation Analysis (NAA) has been rapidly extended its application in various scientific and technological areas included material science, life science, geological science, environmental science, agriculture and marine science, archaeology and forensic science. The applications of NAA are scheduled as one of the most central utilizations in CARR reactor.

MCNP code can carry out the research and design very well in advanced study. The important parameter for NAA is the quantity of active nuclide and its decay character. As introduced above for the RI production, MCNP is good at this calculation. In addition, the analysis of epithermal NAA (formed by the Cd plate to remove the thermal neutron) and other series are also good job of MCNP. The research and design of pneumatic transfer system (rabbit system) will be designed and achieved by MCNP by estimation in near future.

### 3.4 Other applications

Other than above applications of CNS and NAA, there are many planned applications such as neutron transmutation doping (NTD), experimental loop of fuel assembly irradiation, hot source and so on. It's also available and suitable to be researched and designed by MCNP code. For example, in order to improve the quality of NTD, the good neutron energy spectrum and better neutron distribution over the irradiation area are necessary. The adjustment for the spectrum and distribution could be studied with the help of MCNP.

## 4 Verification

It's a necessary step of the verification for other codes and some research results by the quality assurance system. Normally, neutronic codes and the important design should be verified by different calculation methods. Because of the defect of diffusion theory for strong absorption in the reactor, the transportation theory is more available method to verify them.

The group parameters of fuel assemblies and control rods should be checked by the MCNP code. With the help of tallying of flux in specified volume and multiplying the cross section on the flux, the necessary group parameters can be easily approached such as $\Sigma a, \Sigma s, \upsilon \Sigma f$ and so forth. The model of the whole reactor core is necessary for MCNP unlike other codes for group parameters.

They are necessary to be verified for some researches and designs that are important parameters for CARR. For example, the control rod worth and safety rod worth should be reviewed by different code carefully. Fig.3 is already showed the results of calculation.

Generally, the MCNP code is a very famous code based on ideal theory and can be used to verify for the group parameters and other neutronic codes.

## 5 Conclusion

MCNP is an excellent neutronic code with special characteristics since its model is based on the probability and transportation theory, compared with other method. It has been widely used in the research and study in the process of CARR design, and will be extensively used in the future design for the CARR applications. Until now, it has been an indispensable nuclear calculation code and already been used to resolve the design of CARR complex, CARR applications and verifications.

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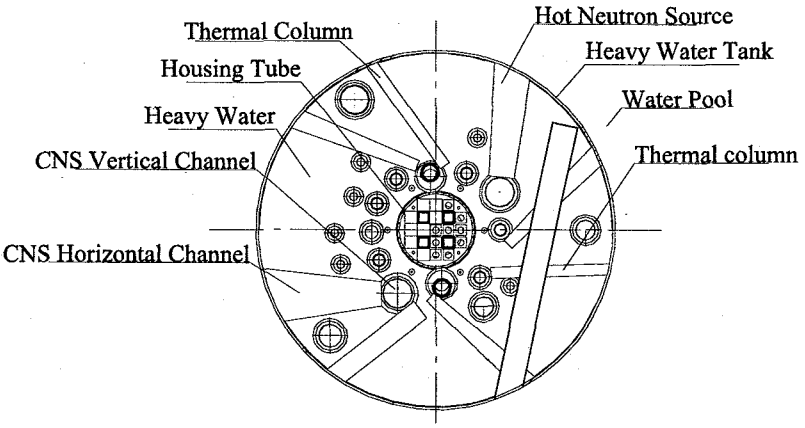



Fig.1 the sketch map of CARR reactor core

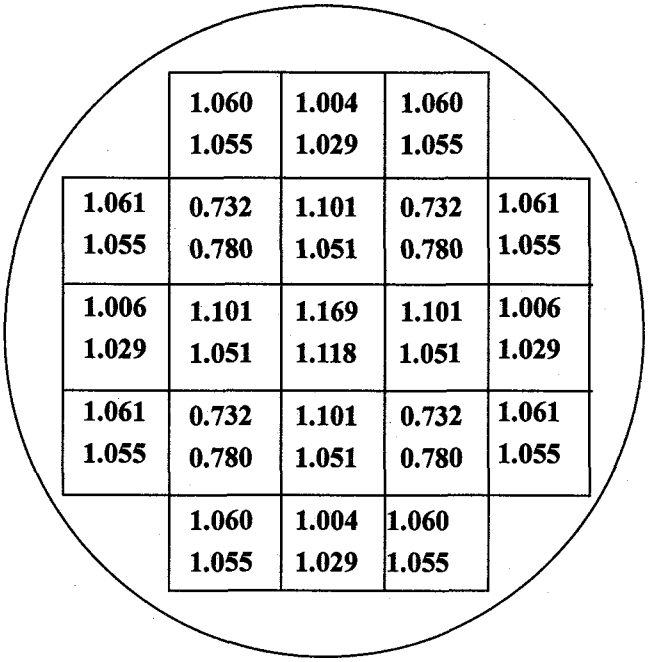



Fig.2 the comparison of radial nuclear factor by two methods
Up is calculated by CITATION, down MCNP

Tab.1 The control rods and safety rods worth under different insertion combination

| Safety rods | | Shim rods | | | Regulate rod | Worth |
|---|---|---|---|---|---|---|
| (1) | (2) | (1) | (2) | (3) | (1) | (ΔK/K) |
| I | I | I | I | I | I | 36.175 |
| O | I | I | I | I | I | 35.005 |
| I | I | O | I | I | I | 22.541 |
| I | I | I | I | I | O | 22.294 |
| O | O | O | O | O | O | 0 |
| I | O | O | O | O | O | 1.171 |
| O | O | I | O | O | O | 4.744 |
| O | O | O | O | O | I | 4.859 |

| | | | | | | |
|---|---|---|---|---|---|---|
| O | O | O | O | I | I | 12.145 |
| O | O | I | I | O | O | 12.356 |
| I | I | O | O | O | O | 2.348 |
| O | O | I | I | I | I | 30.619 |
| O | O | I | I | O | I | 18.344 |

Notes: I—the condition of fully insert(IN) of rod
O—the condition of fully withdraw(OUT) of rod

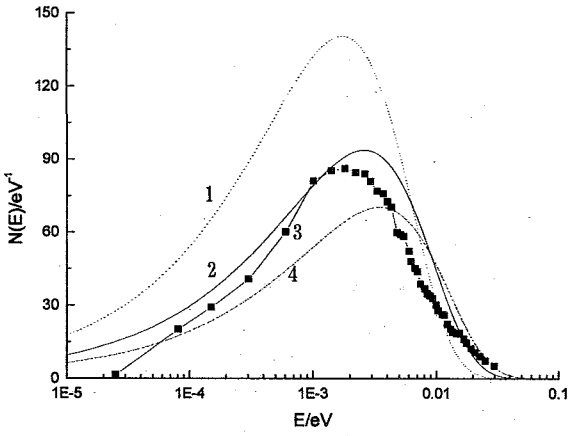
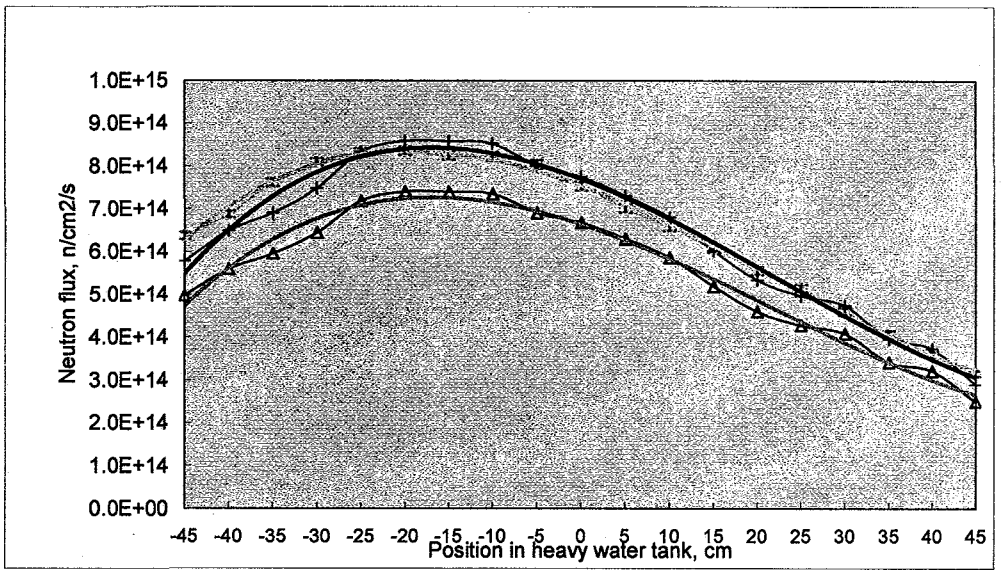



Fig.3 Comparison among calculation example and Maxwell distributions under different temperature, T
1—40K; 2—60K; 3—CNS; 4—80K

Fig.4 the comparison flux between different insertion depth of control rod
Δ - flux for designated position H=42.5 cm and Keff=1.16
O - flux multiplied with 1.16 for designated position H=42.5 cm and Keff=1.16
+- flux for Keff=1.16



Tab.2 the integral neutron flux along vertical direction with different insert depth of control rods

| $k_{eff}$ | Integral flux | $\times k_{eff}$ | Normalization |
|---|---|---|---|
| 1.0 | 6.20E16 | 6.20E16 | 1.000 |
| 1.161 | 5.25E16 | 6.10E16 | 0.984 |
| 1.235 | 4.95E16 | 6.11E16 | 0.985 |
| 1.265 | 4.80E16 | 6.07E16 | 0.979 |

Tab.3 the keff with different distance for storage pool

| Lattice distance（cm） | $K_{eff}$ | Standard deviation(‰) |
|---|---|---|
| 7.72 | 1.65619 | 1.84 |
| 7.9 | 1.65586 | 1.46 |
| 8 | 1.65861 | 4.41 |
| 10 | 1.45950 | 2.33 |
| 12 | 1.15632 | 4.88 |
| 13 | 1.03677 | 4.86 |
| 13.5 | 0.96522 | 4.84 |
| 14 | 0.88038 | 4.92 |
| 15 | 0.82549 | 3.39 |
| 16 | 0.74581 | 5.34 |

Tab.4 Total heat load in Watt for one case of CNS in CARR

| Material | kind | Heating rate, W/g | Heat load, W |
|---|---|---|---|
| Al | Neutron collision | 0.0034 | 2.91 |
| | γ rays | 0.744 | 636.99 |
| | β rays | 0.801 | 685.79 |
| | Total | 1.55 | 1327.06 |
| H2 | Neutron collision | 0.85 | 195.33 |
| | γ rays | 1.23 | 282.65 |
| | Total | 2.08 | 477.98 |

Fig.5 the comparison of brightness between CARR and NBSR

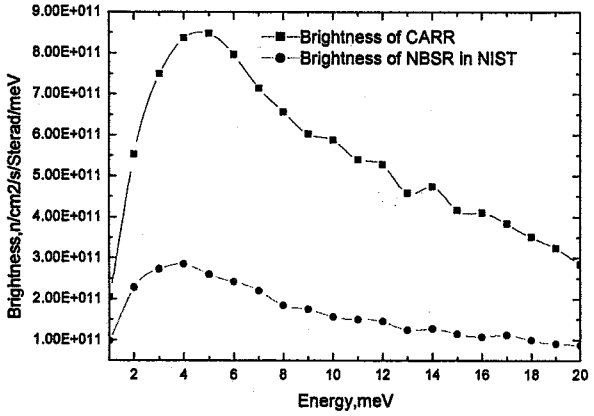
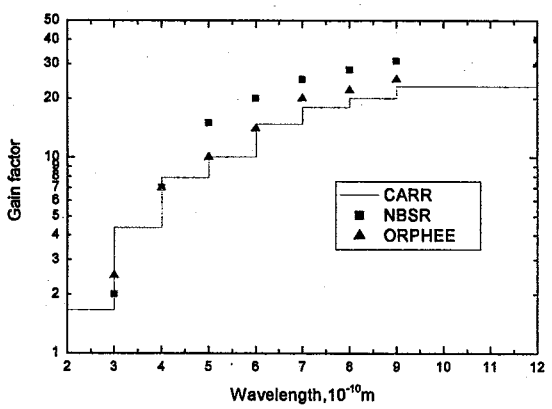



Fig.6 the comparison of gain factor among CARR, NBSR and ORPHEE



# 1.8 HANARO Operation Experience in the Year 2004

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**Abstract**

*The experiences of the HANARO operation and maintenance in the year 2004 are presented in this article. The operation of HANARO, a 30 MW research reactor operated by the Korea Atomic Energy Research Institute (KAERI), aims at a safe and effective operation to enhance its utilization in various fields of scientific research and industry. Regardless of its importance of the routine operation, this article is devoted to rather unusual matters such as irregular maintenance events and incidents.*

*Since the first criticality in 1995, it has been a long-cherished task to reach the designed power level of 30 MW from the temporarily approved 24 MW. By resolving the concern on the fuel integrity, the designed level could be licensed and, eventually, it was achieved last November. On the other hand, after its 9 years of operation, the mechanical integrity of the heavy water reflector tank was checked. The measurement of the vertical straightness of the tank inner shell indicated its integrity. Meanwhile, the HANARO fuel production facility was completed at the KAERI site, and it will begin to supply centrifugally atomized fuels, instead of conventional comminuted fuels, to HANARO shortly.*

*There were several incidents in 2004, which have all been cleared, including a leak of heavy water, melting of a sample in an irradiation hole for the neutron activation analysis, and a condensation problem in a horizontal beam tube. The progress of and lessons from each incident are presented.*

*The utilization of HANARO is expanding every year and the trend will also continue in 2005. The operation mode has been changed from an 18-day continuous operation and 10-day shutdown (18-10 mode) to the 23-12 mode since the end of 2004, and a further extension is planned to the 30-12 mode. Thanks to this extended operation term, an increased power level and, most importantly, a reliable operation, the HANARO is gaining more and more credit from the end users.*

***Keywords**: HANARO, Operation experience, Power uprating, Straightness, Incident, Leak, Melting, Condensation, Operation mode*

## 1. Introduction

The HANARO reactor is a 30 MW, multipurpose research reactor which is operated by the Korea Atomic Energy research Institute, Daejeon, Korea. Since the first criticality in 1995, the HANARO has become as one of the highest grade reactors in the world in terms of the thermal neutron flux level as well as various fields of utilization. According to a study on the contribution of HANARO to the national economy,[1] it was estimated that the contribution in monetary terms would be, roughly speaking, seven times larger than the amount of the research fund invested every year.

In this article, we present the HANARO operation experiences in the year 2004. The operation aims at a safe and effective operation to enhance its utilization in various fields of scientific research and industry. Regarding the performance and utilization of HANARO, we have introduced the reactor to FNCA countries elsewhere.[2]

A routine operation covers various kinds of hardware works such as a reactor start-up and shut-down, fuel reloading, regular maintenance of components and systems, management of the water quality and of the gaseous radioactive waste, and so on. It covers software works as well, such as the fuel management calculation and the analyses of the impact of irradiation tests. The importance of the routine operation cannot be overemphasized in achieving the operation goal. However, because a routine operation has become so common that most readers are familiar with, we devote this article to rather unusual matters such as irregular maintenance events and incidents.

## 2. HANARO Reactor

Before to advance, we will briefly describe the reactor for a better understanding of the following sections. Interested readers should visit the internet site *http://hanaro.kaeri.re.kr*.

Table 1 lists the design features of the HANARO, which is self-explanatory. Figs. 1 and 2 show its structure and the core layout, respectively. The primary coolant, which cools the core region, enters the inlet plenum and flows upward through fuel channels. The coolant is gathered in the chimney, and then exits through two outlet nozzles. The two loops combine at a returning line into the core. 10% of the returning flow is bypassed to the bottom of the reactor pool. The reflector tank surrounding the reactor core is made of Zircaloy 4 and filled with heavy water, which is circulated in a closed loop. Regarding the safety, the reactor has inherent safety characteristics such as a smooth transition to the natural circulation in case of the cooling pump failure, redundancy in keeping the coolant inventory against a loss of coolant, reactor trip by the gravity drop of shut-off rods, and the negative reactivity feedback. In addition, a layer of hot water is formed at the pool surface to protect workers and visitors from the radiation exposure around the pool surface.

The reactor has three regions; an inner core region which consists of 31 honeycomb flow tubes, an outer core with eight circular holes outside the inner core, and a heavy water reflector region which surrounds the core. The inner core consists of 20 positions accommodating hexagonal 36-rod fuel bundles, four shut-off rods (SOR's), four control absorber rods (CAR's), and three flux traps. Each SOR or CAR is, in fact, in a cylindrical shape, and it embraces a circular 18-rod fuel bundle. Among the eight holes in the outer core, four holes are loaded with circular fuel bundles and the remaining are reserved as irradiation holes. The reflector region provides a large area for various vertical holes and horizontal beam tubes, as shown in Fig. 2, with the order of a $10^{14}$ thermal neutron flux at the peak region.

Table 1. Design Features of HANARO

| | |
|---|---|
| Reactor Type | Open-Tank-In-Pool |
| Thermal Power (MW) | 30 |
| Max. Thermal Neutron Flux ($n/cm^2 \cdot sec$) | $4.4\times10^{14}$ in the inner core<br>$2.7\times10^{14}$ in the reflector region |
| Fuel | 19.75% enrichment, $U_3Si$ in Al matrix, Al Clad |
| Coolant | $H_2O$ |
| Moderator | $H_2O$ / $D_2O$ |
| Reflector | $D_2O$ |
| Core Cooling | Upward, Forced Convection Flow |
| Absorber Material | Hafnium |

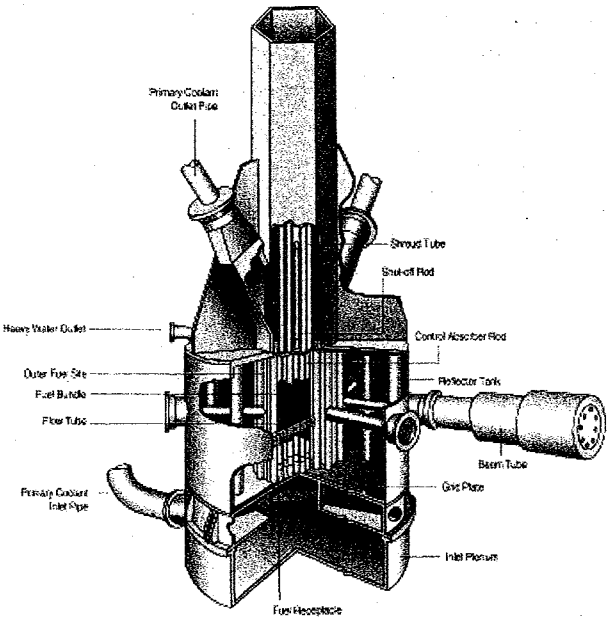


Fig. 1. Structure of the HANARO Reactor

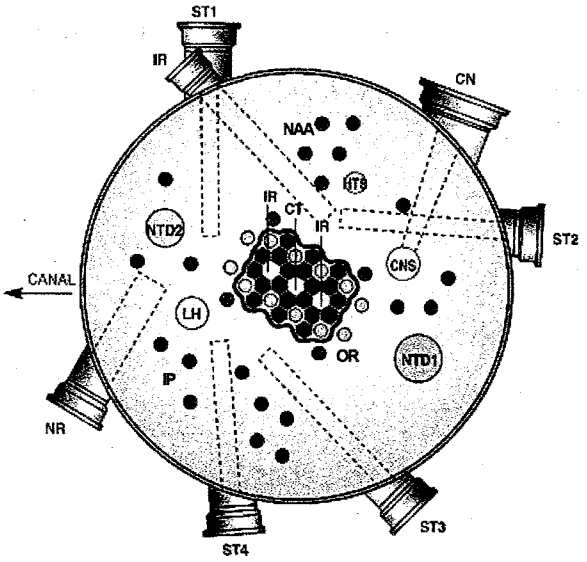


Fig. 2. Layout of the HANARO Core and Experimental Holes

Abbreviations in Fig. 2
Vertical holes: CNS (Cold Neutron Source), CT (Central Thimble), HTS (Hydraulic Transfer System), IP (Isotope Production), IR (Inner Region), LH (Large Hole), NAA (Neutron Activation Analysis), NTD (Neutron Transmutation Doping), OR (Outer Region)
Horizontal beam ports: CN (Cold Neutron), IR (Irradiation), NR (Neutron Radiography), ST (Standard Tube)

## 3. Operation and Maintenance Issues

### 3.1 Power Uprating

Since the first criticality in 1995, it has been a long-cherished task to reach the design power level of 30 MW from the temporarily approved 24 MW. Although the power limitation imposed by the government had been cleared by the end of Sept. 2003, one more year was required to pass all the Preoperational Inspections superintended by the Korea Institute of Nuclear Safety (KINS), the regulatory body. After several kinds of system performance tests and physics tests, we officially achieved the design power last November.

The limitation on the power level had been imposed because of a concern about the reactor safety. What the regulatory body wanted to be confident of was the integrity of the fuel and the DNB margin. With respect to the limiting condition related to the fuel integrity, the regulatory body requested more experimental evidence on the integrity of the fuel under as high local power and burn-up condition as in the HANARO core at 30 MW. It arose because the HANARO fuel had not been used anywhere before. As the fuel irradiation tests per the request confirmed the integrity of the fuel under the power even higher than 30 MW, the limiting condition was cleared. We conducted the tests at KAERI with three fuel bundles along with the post irradiation examinations. Meanwhile, only a limited number of experimental critical heat flux (CHF) data of the HANARO fuel bundles was the most critical issue for the DNB concern. To resolve the issue, we carried out several CHF experiments at the AECL, Canada, and modified the computer codes by, for example, implementing the updated CHF correlation. Accordingly we validated the calculation of the DNB margin and could clear the limiting condition.

The operation at 30 MW means the completion of the HANARO construction project which has lasted for about 20 years from the beginning of its basic design in 1985. In addition to the pride of a

successful operation for the last nine years even though the power level was only 80% of the designed power, we are proud of completing the project by ourselves.

### 3.2 Measurement of the Inner Shell Deformation

According to an analysis on the deformation of the inner shell of the reflector tank,[3] it was estimated that the inner shell would deform by a maximum of 0.84 mm toward the core center due to the creep and growth during a reactor operation for 20 years at the power level of 30 MW. To confirm the safety of the reactor and the validity of the analysis as well, we decided to measure the straightness of the inner shell, and then developed tools to measure it remotely. Note that the shell is located 12 m under the top surface of the pool.

The most important component of the measurement tool assembly is a dial gauge moving on a linear motion guide. The performance and the accuracy of the assembly were verified through tests using a dummy inner shell and a steel straight edge.

The measurement work in Aug. 2004, the first measurement ever, began with the removal of some reactor components such as flow tubes, absorbers, and shrouds to install the measurement tool. Maintaining the level of the pool water as normal, we measured the straightness of the two inner shell surfaces. The measurement points are on the center lines of the two long-sides of the inner shell, as shown in Fig. 3. The measurement showed the deformation of a maximum of 0.26 mm at the center of the west side toward the core center, the direction same to the prediction. The magnitude of deformation was much smaller than the estimated by the analysis, taking into consideration that the growth due to irradiation saturates in the early stage of the reactor operation.

As a conclusion, we confirmed that the inner shell keeps the integrity and there are enough clearances with adjacent absorber rods or fuel channels. We are going to measure the straightness of the inner shell every ten years, and we are using a similar tool to measure the straightness and diameter of the vertical holes.

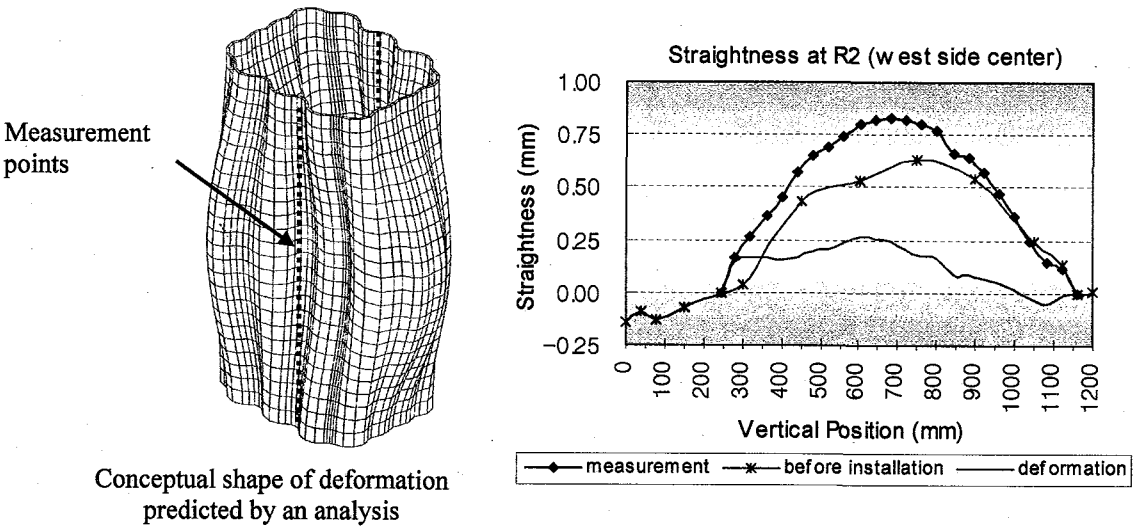


Fig. 3. Result of the Inner Shell Straightness Measurement

### 3.3 Fuel Supply

R&D on $U_3Si$ dispersion fuel has been carried out since 1987 aiming at a localization of the HANARO fuel. Its work scope includes basic research on the fabrication technology, its property characterization, preliminary fabrication, parameters optimization, and so on. As a result, a unique fuel fabrication process was established and its performance was confirmed through hydraulic tests

and two irradiation tests. The in-core performance of the new KAERI-developed atomized fuel has been known much better than the previous one. Details of the test results as well as the fabrication process are found elsewhere.[4]

In the middle of 2004, the HANARO fuel production facility was completed at the KAERI site. The use of atomized fuel, which will be produced in the facility, was permitted by the government as well. The facility was designed and constructed with special attention being paid to safety such as its nuclear criticality. Most of the process equipment was manufactured domestically, and a quality control system was established to guarantee the performance of the fuels. The facility is equipped with various measuring devices and detectors.

The facility can produce up to 45 fuel bundles a year, which is sufficient to meet the demand of around 40 bundles in the HANARO fuel management scheme. It will begin to provide the HANARO reactor with new fuels at the end of Feb. this year, 2005.

## 4. Incidents

### 4.1 Leak of Heavy Water

On May 3rd, it was noticed that the tritium radioactivity in the exhaust air at the top of the reactor stack, and then in the air sampled at a post on the site boundary, increased abnormally. Even though the measured tritium concentrations were far below the regulatory limiting value, several due actions were subsequently taken including the shut down of the reactor. For the next four weeks, the KAERI and KINS investigated this leak of heavy water incident. The conclusions of the investigation were as follows. Maximum 50 L of heavy water was evaporated into the atmosphere, the incident did not affect the safety of the reactor, and the impact of the incident in terms of radioactivity was negligible to either the workers or the environment.

The initiation went back eleven days. On April 22nd, a water pump among the two pumps of the heavy water cooling system was removed from the system for maintenance, and both open ends of the pipeline were sealed with flanges and silicon gaskets. On the 27th, it was noticed that the water level of the heavy water expansion tank began to drop, but the reactor operation continued until May 3rd. Actually operators were thinking that such a gradual drop was due to a leak of heavy water filling the emptied part of the pipe from the isolation valve to the sealed end, but not due to a leak to the atmosphere. On May 3rd, an unusual high tritium radioactivity confirmed the leak to the atmosphere as mentioned above. In fact, the tritium measurement was conducted to identify a reason for the low level alarm in the expansion tank the day before. When the component room was accessible, the day after the reactor shut down, a leak over the floor of the room was observed. After replacing the gasket of the leaking end with a metal gasket, the leak stopped and the tritium concentration was recovered to its usual level.

Lessons from the incident are: A silicon gasket is not appropriate; an improvement of a leak detecting system, especially a continuous monitoring of tritium at the stack exhaust, is needed; and an explicit criterion for judging a leak of heavy water is needed. In addition, because the tritium builds up in the heavy water as the operation time accumulates, an overall re-assessment of the heavy water management plan will be required.

### 4.2 Melting of a Sample in the NAA hole

It was in the afternoon, Oct. 12th when the area radiation monitor alarmed in the PTS room. The PTS (Pneumatic Transfer System) is a system for taking a sample in and out of a NAA (Neutron Activation Analysis) hole. What caused the alarm was identified as Na-24 which was produced from Na-23 in the sample.

In the morning of that day, a series of irradiations was being carried out, but there was trouble with the third rabbit in inserting into the irradiation position. From a couple of hours searching for the reason and trouble shooting, it seemed that a rabbit which had been irradiated before was stuck in the hole. So the staff tried to withdraw the rabbit by increasing the pressure of the nitrogen gas by

twice its usual level. After the second try with a doubled pressure, the alarm sounded, so the room was evacuated and isolated, and then the reactor was shut down.

In terms of radiation safety, several actions followed such as measurements of the radiation levels in various places, identification of contaminating nuclide(s), assessment of the radioactivity release to the environment, assessment of the external and internal exposures of three staffs, and the decontamination. Other actions include an estimation of the sample temperature, reporting to the regulatory body, estimation of the integrity of the hole, and searching for a way to prevent a similar incident.

The sample was a flux monitor surrounded by borated plastic containing borax ($Na_2B_4O_7$) as a thermal neutron shield, and it was contained in a rabbit made of polyethylene. Based on the calculations, it was presumed that the heat from the nuclear reaction of B-10 with neutrons melted the shield first and then the polyethylene rabbit. The melted stuff could have got stuck inside the hole.

The irradiation in trouble was one of the irradiations for a study on the alpha track using the boron steel. Actually, boron steels used to be irradiated before, but without the borax shield. In the irradiation request sheet, the requester did not change the title of the irradiation from a usual boron steel irradiation and failed to fully describe the special shield that was newly added for some reason. What was worse, the NAA staff thought the irradiation as usual regardless of the client's verbal explanation on the sample. The lesson is simple. There must be a clear and detailed description on the sample to be irradiated. By revising the irradiation request form as well as by recommending close communication between clients and irradiation staffs, now we pay special attention to any irradiation sample that contains materials easily heated up such as boron, uranium, lithium, cadmium, and gadolinium. This incident also shows the importance of the experiment planning by the users; high heating materials should not be irradiated in a high flux region.

### 4.3 Wetting of a Beam Tube

In the evening of July 5$^{th}$ while the reactor was on power, the leak detector attached to the ST3 beam tube alarmed the control room for a leak of water. However, no other symptom indicating a leak of pool water, such as bubbles in the pool, was found. One hour later, staff drained yellowish brown water of about 260 cc from the tube, and shortly the emergency ventilation system of the reactor hall was activated by a radioactivity level four times higher than the normal level. The major source of the radioactivity was, as analyzed later, Ar-41 from the activation of Ar-40 in the air. Eight hours later, the radiation level in the hall was recovered to the normal level.

There were three major concerns about this incident; what the source of the drained water was, whether the beam tube is intact, and how to dry out the beam tube. We carried out many kinds of experimental analyses; analyses of the drained water, analyses of gas purged three times from the beam tube, and several analyses during the drying-out work using the He gas which started two weeks after the incident. Such analyses included analyses of the chemical constituent and tritium concentration, comparison of the nuclides in drained water and purged gas with those in the pool water, and so on.

Based on the analyses which were continued for about one month, we reached a conclusion on the source of the water- it was the water condensed from the moisture in the air inside the beam tube, but neither the pool water nor the heavy water. It is supposed that any beam tube ready to be used is filled with He gas. However, it was estimated that the ST3 tube contained not only He but also air of 14% in volume. The reason was presumed to be an incomplete purge of air after maintenance work sometime before. Identifying where the moisture in the tube came from, we could confirm the integrity of the tube.

## 5. Beyond 2004

The number of operation days is generally increasing every year, 170 days in the year 2001, 209 days in 2002, 217 days 2003, and 184 days in last year. The total power production shows the same

trend to that of the operation days; 3,771 MWD in 2001, 4,852 in 2002, 5,119 in 2003, and 4,523 MWD in 2004. Because there were several incidents as presented above and preoperational inspections for the power uprating last year, the situation was somewhat different from that in an ordinary year. In addition to the quantitative growth, the utilization of HANARO is expanding every year from a qualitative point of view.

The operation mode has been changed from an 18-day continuous operation and 10-day shutdown (18-10 mode) to a 23-12 mode since the end of 2004, and further extension is planned to a 30-12 mode. Thanks to this extended operation term and increased power level to 30 MW, a quantitative jump is expected in 2005 in the utilization of HANARO. Moreover, as several additional facilities such as a cold neutron source facility and a fuel test loop are under design, we expect another qualitative jump within a few years.

It is worth to note here that such a rosy expectation assumes the availability of the reactor on demand. From the reliable operation up to now, the HANARO has gained credit from its end users, thus the expectation seems to be very realistic.

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# 1.9 Operation and Maintenance of 1MW PUSPATI TRIGA Reactor

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**Abstract**

*The Malaysian Research Reactor, Reactor TRIGA PUSPATI (RTP) has been successfully operated for 22 years for various experiments. Since its commissioning in June 1982 until December 2004, the 1MW pool-type reactor has accumulated more than 21143 hours of operation, corresponding to cumulative thermal energy release of about 14083 MW-hours. The reactor is currently in operation and normally operates on demand, which is normally up to 6 hours a day. Presently the reactor core is made up of standard TRIAGA fuel element consists of 8.5 wt%, 12 wt% and 20 wt% types; 20%-enriched and stainless steel clad. Several measures such as routine preventive maintenance and improving the reactor support systems have been taken toward achieving this long successful operation. Besides normal routine utilization like other TRIGA reactors, new strategies are implemented for effective increase in utilization.*

## 1. Introduction

The TRIGA Mark 11 reactor, Reactor TRIGA PUSPATI was installed by General Atomic (San Diego, U.S.A)) in the years 1981 and 1982. The reactor, with a maximum steady state power of 1 MWth, consists of a circular core containing a circular grid plate and a graphite assembly surrounding the core. To facilitate neutron beam experiments, the reactor is equipped with four beam ports installed at mid-core height and a thermal column. The different designs of the ports give rise to differences in the neutron beams obtainable. The flux available at the entrance to the beam ports are approximately ranges from 1 x $10^{12}$ n/cm$^2$/s to 2 x $10^{12}$ n/cm$^2$/s. Presently, only two beam ports are utilized for the neutron beam experiments, namely neutron radiography and small angle neutron scattering.

Since its first criticality in June 1982 until end of December 2004, the reactor has accumulated a total of 21143.62 hours of operation, corresponding to cumulative thermal energy released of 14092.96 MW-hours. Figure 1 shows a summary of the operational history of RTP since commissioning.

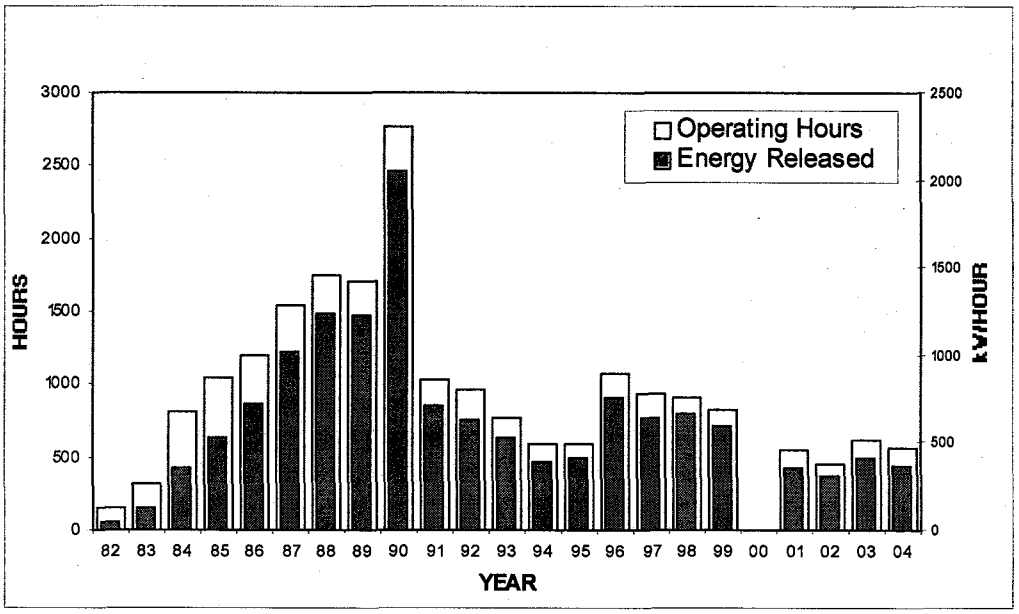


**Figure 1: Operating Data of RTP (June 1982 – December 2004)**

Reactor main systems as water purification circuit, secondary coolant circuit and reactor hall ventilation system are important support systems for the safe operation of research reactors and they need as much maintenance as any other safety related system. The most important components of the systems are inspected in regular intervals especially during the scheduled period of annual and semiannual maintenance.

## 2. Reactor Utilization

It is clear that during the lifetime RTP the utilization areas have not been changed. The reactor has been used mainly for neutron activation analysis, isotope production, beam experiments and training of human resources. Presently, the reactor operation is generally geared toward the neutron activation analysis activity. The neutron activation analysis comprised trace element analysis for environmental, biological, geological and food. A total number of 3186 sample irradiations were performed in the year 2004. Approximately 70% of this irradiation was performed in a 40 position annular rack that rotate slowly around the core. The rest of the samples were irradiated using the pneumatic transfer system.

Production of radioisotopes is currently not carried out due to maintenance job of the radioisotope handling facilities. The facilities are being upgraded as to make compliance with the assurance quality requirement.

In trying to revitalize the reactor utilization in Malaysia, new strategies are implemented. As part of the strategy, MINT has initiated the forming of Reactor Interest Group (RIG), which made of parties who has interest in reactor utilization. With main objectives to arrest the decline of interest in reactor

utilization for research and development as well as educational purposes, this grouping comprised of staffs from MINT, universities academics and other research institutes in Malaysia.

In promoting the uses of reactor at MINT, RIG has launched a series of discussion sessions with the universities academic staffs and other research institutes. Seminars and workshop were also conducted to identify various areas of reactor utilization where collaboration works between MINT, universities academic staffs and research institutes are possible.

To date, RIG has identified a few potential collaboration areas related to reactor utilizations. Amongst these areas are preliminary studies of new irradiation facilities such as Boron Neutron Capture Therapy (BNCT) and Prompt Gamma Neutron Activation Analysis (PGNAA), as well as enhancing and upgrading the present facilities i.e. the Neutron Radiography (NR) and Small Angle Neutron Scattering (SANS). Research and development (R&D) areas related reactor utilizations identified includes instrumentation of irradiation facilities, software engineering, bulk and advance material studies, etc.

## 3. Core management

Since commissioning, the RTP core has undergone 11 different core configurations. Only the first core consisted of all standard 8.5 wt% fuel supplied by General Atomic. Subsequently, the next seven cores consisted of mixed cores of 8.5 wt% and 12 wt%. Today the reactor core consists of the 8.5 wt%, 12.0 wt% and 20 wt% types. Because of the low reactor power level, the burn-up of the fuel is very small and all the fuel loaded into the core in 1982 is still there. A properly administered reactor program to provide core management function has been established RTP. The ultimate goal of core management is the effective long term of the reactor to provide same experimental services as well as to prolong the lifespan of the fuel. TRIGAM code, which is adapted from TRIGAP code, is mostly used in the fuel management calculation at RTP.

The irradiated fuel is stored in racks, located in the reactor pool. It is interesting to mention that six underground storage pits is available for the interim storage of spent fuel .At this moment, RTP does not intend to take part in the US policy of acceptance the spent fuel from the foreign research reactors.

## 4. Upgrading And Refurbishment Activities

The following description of activities is some of the actions carried out in the year 2004 to prolong the lifetime of the reactor and related systems.

4.1 Electric and electronically system

- Replacement of uninterrupted power supply system to avoid automatic scram of the reactor during power failure
- Replacement of the normal power supply with essential power supply to the reactor main systems.

4.2 Physical Protection

- A new monitoring system at the entrance of the reactor building has been installed.

4.3 Measures against heat exchanger performance

A few years ago, during cleaning of the heat exchanger, some corrosion was found on the outside of the tubes in side the heat exchanger. After cleaning several leakage were found and all the tube concern were plugged. As results of that, the efficiency of the heat exchanger was reduced and the process of replacing the heat exchanger has been initiated. A tender for a replacement with a new plate type heat exchanger has been issued and replacement job will be carried out this year.

## 5. Licensing of MINT Reactor

One of the significant events happening to the RTP in the year 2004 was the issuance of license by the regulatory body. Prior to September 2004, the Atomic Energy Licensing Board (AELB) exempted RTP from direct regulatory control. During this time responsibility for safe operation of RTP rested with the Safety and Health Committee of MINT with the assistance of the Major Facility Safety Sub-committee. However Rules and Regulations established by the AELB, established in 1985, with the enactment of the Atomic Energy Licensing Act are also applicable to the reactor. Initially, the activities of the AELB are primarily concentrated on the regulation of nuclear materials and ionizing radiation sources. As part of the IAEA recommendation, which requires the operation of the facility to be independent of the regulator, a temporary Operating License for RTP was issued by the (AELB) in September 2004. The issuance of the licence is based on the current SAR. Extensive interaction between RTP and AELB is currently in progress on how best to regulate and monitor site compliance with site license condition.

## 6. Conclusion

The reactor is operating very satisfactorily. All these activities in refurbishment and upgrading will hopefully prolong the lifetime of the reactor for several more years.

Several efforts have instated toward increasing direct utilization of the reactor especially in the utilization of neutron beams. The upgrading of the radioisotope handling facilities hopefully will increase the request for the radioisotope production at the reactor. With the provision of the financial and human resources, clearly demonstrate the national commitment in supporting the activities related to the nuclear reactor

# 1.10 CURRENT STATUS OF OPERATION AND UTILIZATION OF THE DALAT RESEARCH REACTOR

*(The 2004 FNCA Workshop on the Utilization of Research Reactors, Bangkok, Thailand, 17-21 January 2005)*

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## ABSTRACT

The Dalat Nuclear Research Reactor (DNRR) is a 500 kW pool-type reactor using the HEU (36% enrichment) WWR-M2 fuel assemblies. It was renovated and upgraded from the USA 250 kW TRIGA Mark-II reactor. The first criticality of the renovated reactor was in the 1st November 1983 and its regular operation at nominal power of 500 kW has been since March 1984.

The DNRR is operated mainly in continuous runs of 100 hrs, once every 4 weeks, for radioisotope production, neutron activation analysis, scientific research and training. The remaining time between two continuous runs is devoted to maintenance activities and also to short run for reactor physics and thermal hydraulics experiments. From the first start-up to the end of December 2004, it totaled about 27,253 hrs of operation and the total energy released was about 543 MWd.

The first fuel reloading was executed in April 1994 after more than 10 years of operation with 89 fuel assemblies (FA). The 11 new FAs were added in the core periphery, at previous beryllium element locations. After reloading the working configuration of reactor core consisted of 100 FAs. The second fuel reloading was executed in March 2002. The 4 new FAs were added in the core periphery, at previous beryllium element locations. The working configuration of 104 FAs ensured efficient exploitation of the DNRR at nominal power for about 3000 hrs since March 2002. In order to provide excess reactivity for the reactor operation without the need to discharge high burned FAs, in June 2004, the fuel shuffling of the reactor core was done. 16 FAs with low burn-up from the core periphery were moved toward the core center and 16 FAs with high burn-up from the core center were moved toward the core periphery. This operation provided additional reactivity of about 0.85 $\beta_{eff}$ that the current reactor configuration using re-shuffled HEU fuel is expected to allow normal operation until June 2006.

In 1999, the request of returning to Russia HEU fuels from foreign research reactors used Russian fuels was submitted to Russian Government though IAEA. After that, the Russian Research Reactor Fuel Return (RRRFR) Program was established and trilateral discussions among the United State, the Russian Federation and the IAEA started. In this aspect, the Dalat reactor core has been considered to insert fresh LEU FAs instead of fresh HEU FAs. It means the mixed core of HEU and LEU FAs may be used in the coming years. For these purposes, neutronics and thermal hydraulics calculations and safety analyses should be done.

The current status of the reactor operation and utilization as well as some results on in-core fuel management of the DNRR are presented in this paper. Some activities to participating in the project on Research Reactor Technology for Effective Utilization are proposed for discussions.

## I. REACTOR DESCRIPTION AND ITS OPERATION

The DNRR is a pool-type reactor, moderated and cooled by light water. It was renovated and upgraded from the TRIGA Mark-II reactor built in early 1960's. First criticality of the renovated reactor was in November 1983 and since March 1984, its regular operation has been done. Main specifications of the DNRR are shown in Table 1.

*Table 1. Reactor Specifications*

| | |
|---|---|
| - Reactor type | Swimming pool, TRIGA Mark II, modified to Russian type of IVV-9 |
| - Nominal thermal power | 500 kW, steady state |
| - Coolant and moderator | Light water |
| - Core cooling mechanism | Natural convection |
| - Reflector | Beryllium and Graphite |
| - Fuel type | WWR-M2, U-Al alloy, 36% enrichment |
| - Number of control rods | 7 (2 safety rods, 4 shim rods, 1 regulating rod) |
| - Control rod material | $B_4C$ for safety and shim rods, Stainless steel for automatic regulating rod |
| - Neutron measuring channels | 9 (6 CFC, 3 CIC) |
| - Vertical irradiation channels | 4 (neutron trap, 1 wet channel, 2 dry channels) and 40 holes at the rotary rack |
| - Horizontal beam-ports | 4 (1 tangential, 3 radial) |
| - Thermal column | 1 |
| - Spent fuel storage (temporary) | inside reactor building, next to the reactor shielding |
| - Maximum thermal neutron flux in the reactor core (neutron trap) | $2.1 \times 10^{13}$ n.cm$^{-2}$.s$^{-1}$ |
| - Utilisation | RI, NAA, PGNAA, NR, basic researches on neutron beam, manpower training |

From the first run at the power of 500 kW in February 1984 to the present time, the reactor has proved to be safe and reliable, as it has never suffered from any incident, which significantly affected the environment, and annual operation schedules have been rigorously respected (see in Table 2 and Fig. 1).

*Table 2. Operation data of the DNRR*

| ***Year*** | ***Operation time (hrs)*** | ***Released Energy (MWd)*** | ***Accumulated released energy (MWd)*** | ***Number of scram*** | | |
|---|---|---|---|---|---|---|
| | | | | *Electric network failure* | *Other reasons* | *Total* |
| 1984 | 1120 | 18.6 | 18.6 | 11 | 17 | 28 |
| 1985 | 1771 | 31.7 | 50.3 | 5 | 8 | 13 |
| 1986 | 1387 | 26.9 | 77.2 | 6 | 4 | 10 |
| 1987 | 993 | 17.9 | 95.2 | 6 | 4 | 10 |
| 1988 | 1287 | 25.2 | 120.3 | 14 | 4 | 18 |
| 1989 | 1343 | 26.3 | 146.6 | 9 | 2 | 11 |
| 1990 | 1505 | 30.4 | 177.0 | 13 | 5 | 18 |
| 1991 | 1654 | 33.9 | 210.9 | 8 | 2 | 10 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 1992 | 1486 | 30.4 | 241.3 | 8 | 2 | 10 |
| 1993 | 966 | 19.7 | 261.0 | 1 | 2 | 3 |
| 1994 | 1302 | 26.8 | 287.8 | 11 | 1 | 12 |
| 1995 | 1351 | 27.9 | 315.7 | 9 | 2 | 11 |
| 1996 | 1370 | 28.1 | 343.8 | 7 | 3 | 10 |
| 1997 | 1205 | 24.7 | 368.5 | 9 | 1 | 10 |
| 1998 | 1205 | 24.9 | 393.4 | 2 | 4 | 6 |
| 1999 | 1215 | 25.1 | 418.5 | 9 | 4 | 13 |
| 2000 | 1113 | 22.9 | 441.5 | 8 | 0 | 8 |
| 2001 | 1231 | 25.3 | 466.8 | 4 | 2 | 6 |
| 2002 | 1220 | 25.0 | 491.8 | 1 | 3 | 4 |
| 2003 | 1298 | 26.1 | 518.0 | 3 | 7 | 10 |
| 2004 | 1231 | 25.1 | 543.1 | 18 | 1 | 19 |
| ***Total*** | ***27,253*** | | ***543.1*** | ***162*** | ***78*** | ***240*** |

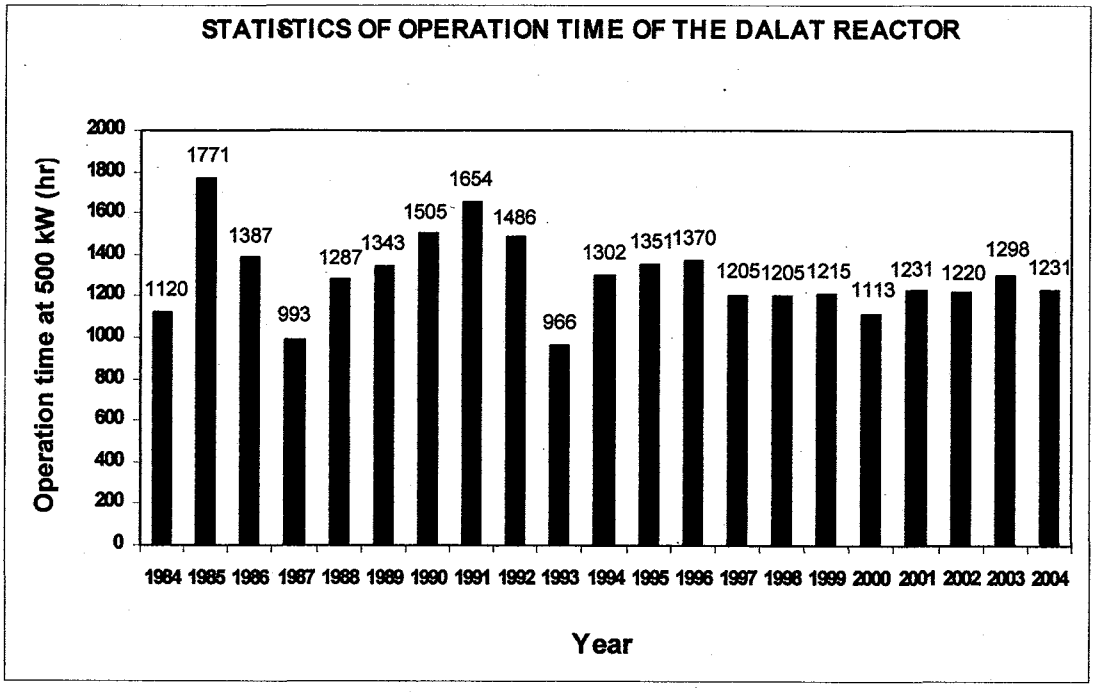


*Figure 1. Statistics of reactor operation time from 2/1984 to 12/2004*

## II. REACTOR MANAGEMENT

### II.1. Core Management

The fuel assemblies of the DNRR are of Soviet-designed standard type WWR-M2, enriched to 36% in U-235. Each fuel assembly composes of 3 concentric layers: 2 circular inner tubes and one hexagonal outer tube. The fuel layer with a thickness of 0.7 mm is wrapped between two-aluminum alloy cladding layers of 0.9-mm thickness.

After 10 years of operation with the core of 89-fuel assembly configuration, in April 1994, refueling work was done by adding 11 fresh FAs in the core periphery at previous

beryllium rod locations. The second refueling work was done in March 2002 by adding 4 fresh FAs more in the core periphery. In order to provide excess reactivity for the reactor operation without the need to discharge high burned FAs, in June 2004, the fuel shuffling of the reactor core was done. 16 FAs with low burn-up from the core periphery were moved toward the core center and 16 FAs with high burn-up from the core center were moved toward the core periphery. The current reactor configuration using re-shuffled HEU fuels is expected to allow normal operation until around June 2006. At present, the reactor has been working with 104-fuel assembly configuration (Fig. 2).

For core management, some computer codes have been used so far. For neutronics calculation, WIMSD-5B, HEXNOD, HEXA-BURN-UP, HEXAGA, SRAC (Pij, TWOTRAN, CITATION), MCNP4C2 have been used and for thermal hydraulics calculation and safety analysis, PARET, RELAP5, NATCON, DRSIM, COOLOD, EUREKA, DRTETH codes have been used.

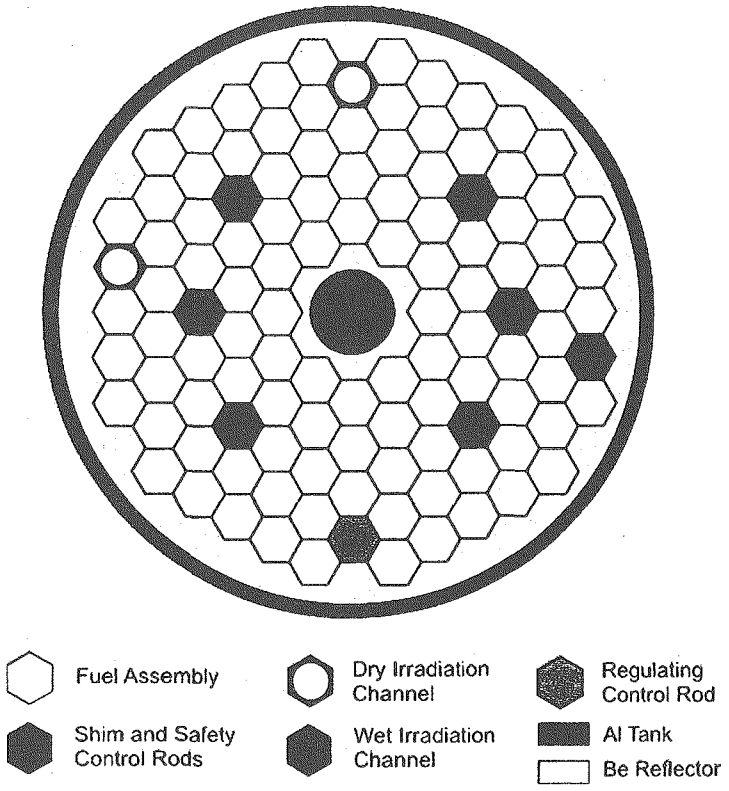


*Figure 2. Cross-section view of the reactor core*

## II.2. Ageing Management

In order to carry out the visual inspection of reactor aluminium tank and in-side components, an home-made high-resolution camera system has been designed and installed.

In the past years, using the designed camera system, inspections have been done regularly time per year. The upper cylindrical shell prevented visual access to the major part of the reactor tank's surface, both because it covers the upper part of the tank and because its

horizontal bottom plate prevents from easy immersion of video camera. Thus, only about 20% of the total reactor tank's surface could be visually inspected. Based on the results obtained, it could be noted that most of the pits seem to have initiated from mechanical defects (scratches on the aluminum surfaces during commissioning and re-commissioning time). It seems to us that the pitting corrosions are now stopping.

### II.3. Modification study

The study on modification of the reactor control and instrumentation system has been carried out in the framework of a national project. Obtained results showed that, replacement of an existing I&C system by a new one should be implemented under an IAEA TC project VIE/4/014 and national support during 2005-2006 period. The new I&C system will be purchased from Russian SNIIP System Atom Co. Estimated budget for the I&C modification is about 600,000 US$.

## III. REACTOR UTILIZATION

### III.1. Radioisotopes Production

Radioisotopes and radiopharmaceuticals have been produced serving nuclear medicine departments and other users such as in industry, agriculture, hydrology, scientific research, etc. For medicine applications, our products are routinely delivered to more than twenty hospitals in the country. The main products are $^{32}P$ applicators, $^{99m}Tc$ generator and its label, $^{131}I$ solution/capsules and others (Fig. 3). It is totaled about 2,468 Ci of radioisotopes have been produced and supplied to medical users so far, giving a yearly average of about 170 Ci.

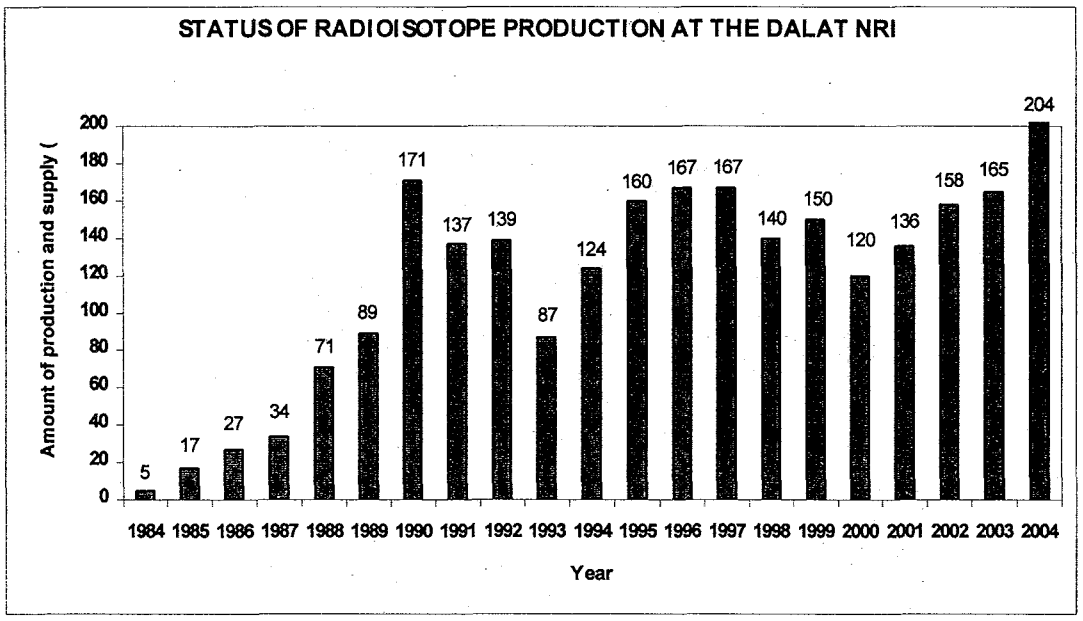


*Figure 3. Status of radioisotope production for medical use from 3/1984 to 12/2004*

### III.2. Neutron Activation Analysis

Different methods of NAA are used for element analysis, including Instrumental NAA, Radiochemical NAA and Prompt gamma NAA.

During the last years, the K-zero method has been developed to analyse airborne particulate samples for investigation of air pollution; crude oil samples and base rock samples for oil field study.

In the nuclear analytical field, requests of many branches of the national economy for various types of samples have been answered. Nuclear technique is of advantage in serving geology exploration, oil prospecting, agriculture, biology, etc. Environmental studies are carried out efficiently with nuclear and associated methods. Environmental pollution studies especially at big cities and industrial centers have contributed to implementing the environment control mission of the Government. About 3000 samples have been irradiated and analysed every year.

### III.3. Neutron Beam Utilisation

The reactor has four horizontal beam tubes, which provide beams of neutron and gamma radiation for a variety of experiments. In configuration, three of the beam tubes are oriented radically with respect to the center of the core, and one beam tube is tangential to the outer edge of the core. Besides, there is a large thermal column with outside dimensions of 1.2m by 1.2m in cross section and 1.6m in length.

During the last two years, some activities related to neutron beam utilization have been carried out, such as improvement of PGNAA system, nuclear data measurements, and preparation for setting up a measurement system for studying of (n, 2γ) reactions.

A new PGNAA facility has been designed and now is under construction for replacement of the old one, which was constructed about 20 years ago. It consists of the collimation components, the beam shutter, the shielded sample room and the beam catcher. The design of the new facility has been performed using computer simulation to optimize the collimator geometry and shielding. A thermal neutron flux density in the order of $5.10^6$ n.cm$^{-2}$ s$^{-1}$ and cadmium ratio of 150 are expected at the sample position.

Measurement of neutron spectrum in the channel (at the distance of 1.5 m from surface of reactor wall) was realized by neutron activation technique. The thermal neutron spectrum, medium neutron spectrum and fast neutron spectrum were measured using gold foils, 1/v foils and threshold metal foils, respectively. For the design of the PGNAA facility, the MCNP code has been used to evaluate the filters, shutters and shielding. The results of the neutron spectrum measurement above were used as input for the evaluation.

Design and construction of neutron beam at the channel No. 3 of the reactor for studying of (n, 2γ) reactions have been done. The facility consists of neutron beam collimator, beam shutter, sample table and beam catcher. Thermal neutron flux density in the order of $10^6$ n.cm$^{-2}$ s$^{-1}$ and the cadmium ratio of 200 are expected at the sample position. The two HPGe detector gamma spectrometers will be set up for data acquisition.

## IV. PROPOSED ACTIVITIES FOR THE NEXT TWO YEARS

The current core of the Dalat reactor used with 104 FAs of 36% U-235 enrichment. In June 2004, the fuel shuffling of the reactor core was done. This operation provided additional reactivity of about 0.85 $\beta_{eff}$ that will allow the core to operate two years more. Around June 2006, additional reactivity will be required for continued operation.

In order to meet the requirement of the Reduced Enrichment for Research and Test Reactors (RERTR) Program co-ordinated by the United State, it could be accomplished either by further shuffling of the reactor core or by replacement of the highest burned HEU FAs with fresh LEU FAs. For these purposes, neutronics and thermal hydraulics calculations and safety analyses should be done during the next two years.

Computer codes used for neutronics analysis included:
Nuclear cross sections: WIMSD-5B, Pij (SRAC), TWOTRAN (SRAC);
Diffusion theory: HEXNOD, CITATION (SRAC);
Monte Carlo transport theory: MCNP4C2.

We assumed that neutronics and thermal hydraulics calculations should be performed by two ways: further shuffling the existing burned HEU FAs of the core after June 2006 and fresh LEU FAs would be loaded to replace with the highest burned HEU FAs. Because of that calculations done to compare the behavior of the reactor core with only HEU FAs and HEU mixed LEU FAs are necessary.

For participating in the new project on Research Reactor Technology for Effective Utilization, we propose the activities for 2005 as follows:

- Calculations to find out the optimal options for refueling with inserting fresh LEU FAs instead of high burned HEU FAs using MCNP and SRAC codes.
- The working core configurations of the Dalat reactor with the mixed core are modeled using MCNP and SRAC codes. For MCNP code, ENDF cross section library is used. The neutron cross sections for use in SRAC code are generated using PIJ (SRAC).
- The reactor physics and kinetic parameters with reactor mixed core are also determined by using SRAC code.
- Determination of radioactivity of the reactor core using SRAC and ORIGEN2 codes.
- Thermal hydraulics calculations and safety analysis for the Dalat reactor in case of mixed core using COOLOD, DRSIM and RELAP5 codes.
- Preparation of Safety Analysis Report (SAR) for conversion of reactor core from HEU FAs to mixed core of HEU and LEU FAs.

The study on reactor core management would help the operating staffs in planning their reactor utilisation in a better and optimum way. Selection of appropriate core configurations and reactor cycle planning according to the irradiation requirements would not only enhance the reactor utilisation but also optimise the fuel consumption.

## CONCLUSION

The Dalat research reactor has been safely operated and effectively utilized for 21 years. To achieve that, maintaining and upgrading the reactor technological facilities have been done with a high quality. The reactor physics and thermal hydraulics studies have also provided the important bases for safety evaluation and in-core fuel management to ensure its safe operation and effective exploitation.

Core analysis and measuring techniques have been developed in the existing reactors to give on evaluation of irradiation requirements, analysis of reactor utilisation, core configuration selection procedures and optimisation of flux and burn-up. Based on this research programme the reactor operating staffs could share their experience regarding the safe operation and effective utilization of their research reactors.

Taking this opportunity, we would like to express our thanks to Japanese Government for co-ordination and financial support for this collaboration program.

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JP0650495

# 1.11 Current Status of the Thai Research Reactor (TRR-1/M1)

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**ABSTRACT**

The first Thai Research Reactor, TRR-1 went critical on 27 Octerber 1962 at the maximum power of 1 MW. It was located at Office of Atoms for Peace (OAP) in Bangkok. Since then, TRR-1 was continuously operated and eventually shut down in 1975. Plate type, high-enriched uranium (HEU) and $U_3O_8$-Al cladding were used as the reactor fuel. Light water was used as moderator and coolant as well. In 1975, because of the problem from fuel supplier and also to supporting the Treaty of Non Proliferation of Nuclear Weapon or NPT, TRR-1 was shut down for modification. The reactor core and control system were disassembled and replaced by TRIGA Mark III. A new core was a hexagonal core shape designed by General Atomics (GA). Afterwards, TRR-1 was officially renamed to the Thai Research Reactor-1/Modification 1 (TRR-1/M1).

TRR-1/M1 is a multipurpose swimming pool type reactor with nominal power of 2 MW. The TRR-1/M1 uses uranium enriched at 20% in U-235 (LEU) and ZrH alloy as fuel. Light water is also used as coolant and moderator. At present, the reactor is operating with core No.14. The reactor has been serving for various kinds of utilization namely, radioisotipe production, neutron activation analysis, beam experiments and reactor physics experiments.

Keywords: TRR-1, HEU, TRR-1/M1, LEU,

## 1. Introduction

TRR-1/M1 is a movable-core TRIGA Mark III reactor. It is a light water-cooled and reflected pool-typed reactor using uranium zirconium hydride (UzrH) fuel-moderater elements developed by General Atomics. This reactor is designed for continuous steady-state operation up to 2 MW at any positions in the pool. Moreover, this reactor can be operated in pulsing mode at around 23 MW –sec, the peak power of 2000 MW and a pulsed width at a half of maximum of 10 msec.

The initial criticality of TRR-1/M1 was reached on Nov.7, 1977. At the beginning, the whole core was composed of 8.5 wt-%/20% enriched U-235 fuel elements. In 1980, some fuel elements were replaced by 20 wt-%/20% enriched U-235 resulting in mixed core operation until now.

## 2. Aging Management of TRR-1/M1

2.1 Reactor Pool Refurbishment

The reactor pool is one of the major parts of the swimming pool typed reactor. During 1975-1977, the reactor pool was repainted while TRR-1 was changed to TRR-1/M1. During 1990-1991, the reactor pool was refurbished again. The fuel elements of TRR-1/M1 core were removed and transferred to spent fuel storage pool. Irradiation and experimental facilities were dismantled. The surface of the pool wall was removed by sandblasting. After that, painting and epoxy aradite coating were performed. From this refurbishment, the reactor pool can be operated in a good condition more than 10 years.

2.2 TRR-1/M1 Decommissioning plan

After a long period of services, aging problems of the reactor pool, IC system and obsolete equipment of the supporting system has recently been taken into accout. On December 27, 1989, it was assigned by the cabinet the relocation of TRR-1/M1 to the new suitable site. OAP then established the work plan for the new nuclear research center. In the meantime, a working group on decommissioning plan has been appointed.

## 3. Current Status of TRR-1/M1

3.1 Reactor Operations

At present, TRR-1/M1 is operating with the core No.14 with the released power of 1586.6 MWD (as of Nov. 2003). The reactor is operated at the power of 1.2 Mw, 4 days a week or 46 hours per week. In 2003, the total reactor operating time is 1960 hours.

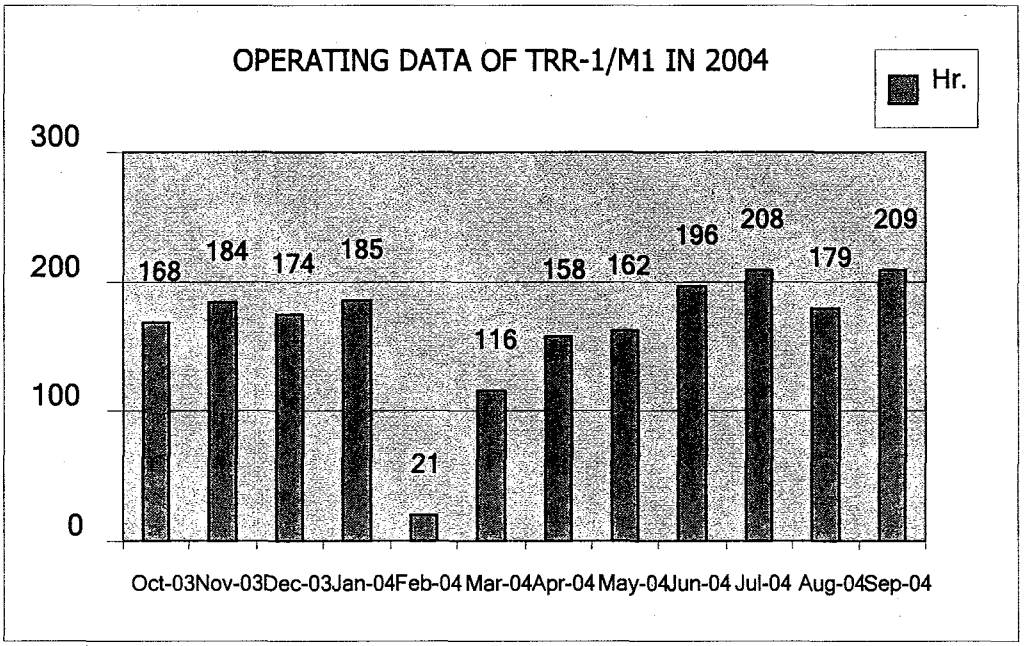


Fig.1 OPERATING DATA OF TRR-1/M1 IN 2004

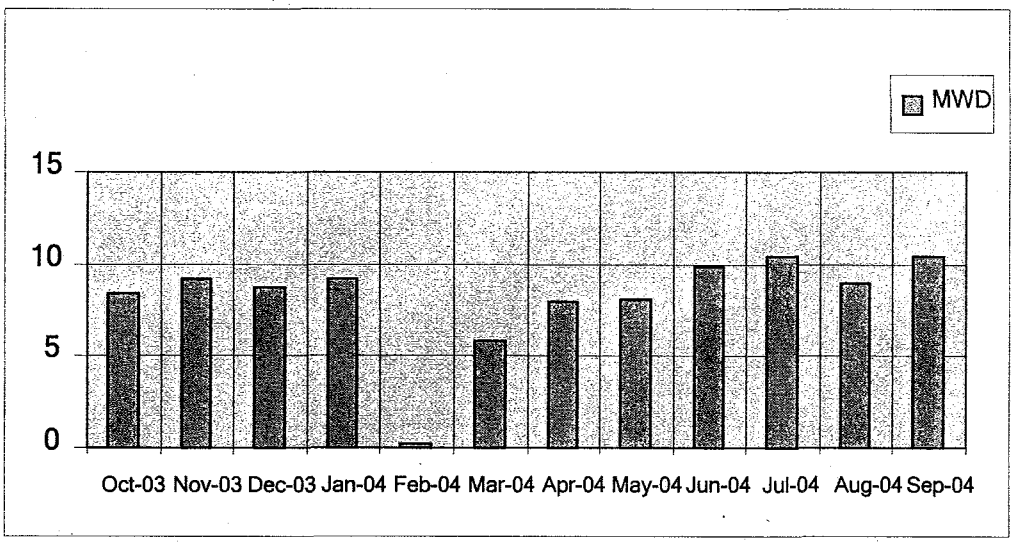


FIG.2 ENERGY RELEASED OF TRR-/M1 IN 2004

3.2 Reactor Utilization

Reactor utilization can be divided into 3 main areas: reactor physics studies, isotope production and chemistry and other researches as the following

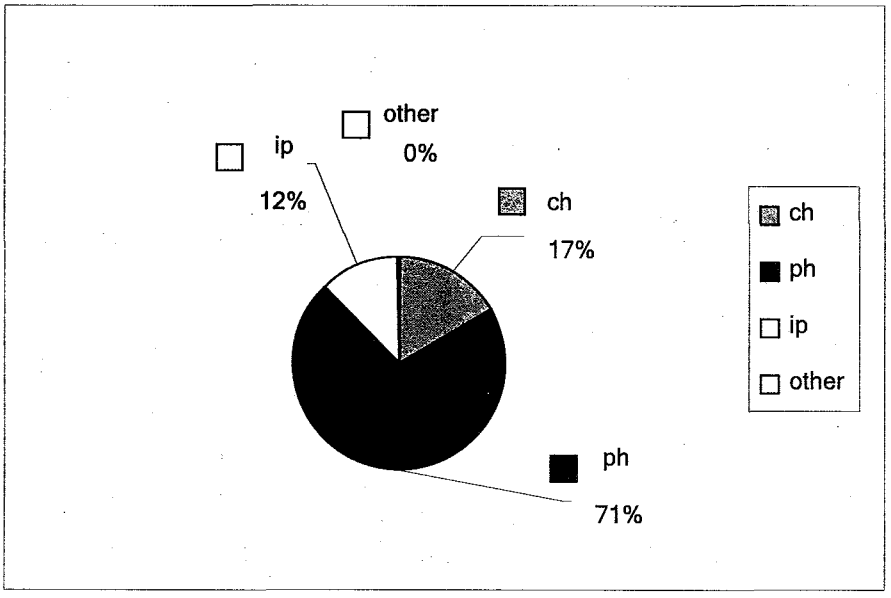


FIG.3 NUMBER OF IRRADIATED SAMPLES IN TRR-1/M1 IN 2004

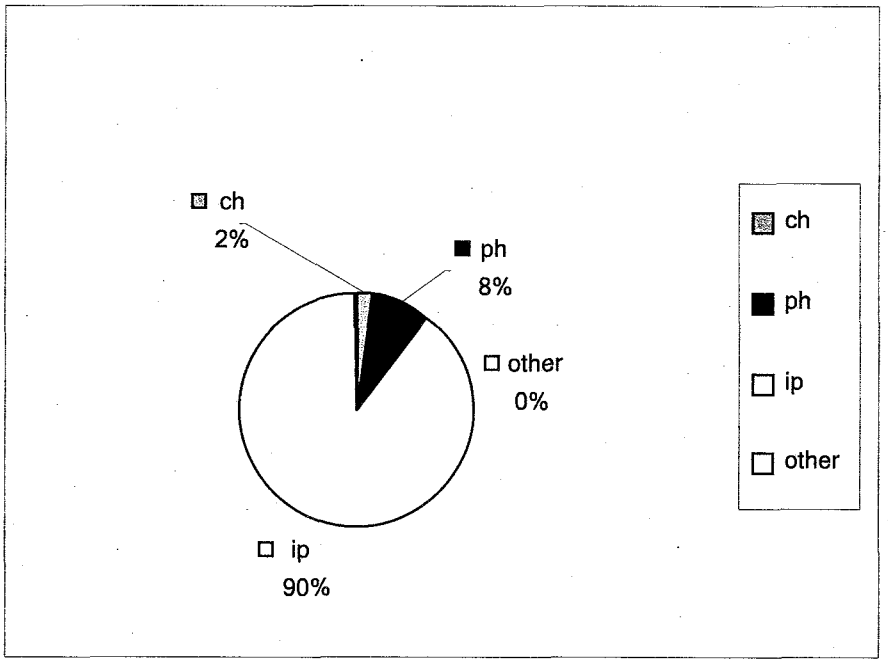


FIG.4 NUMBER OF SAMPLE-HOURS OF USERS

a) Neutron Activation Analysis such as:
- Determination of Zirconium and Arsenic in slag
- Determination of elements in human hair
- Determination of Uranium in Tantalite
- Analysis Th in monazite

b) Irradiating the isotope targets mainly for production of I-313 and Sm-153
c) Nuclear Physics and Reactor Engineering Experiments such as Neutron Radiography

3.3 Reactor maintenance

The maintenance program of TRR-1/M1 has been considered with high priority since 10 years of operation. In order to improve the reliability and availability of the reactor, the preventive maintenance schedule has been performed weekly and yearly. This includes inspection, testing, surveillance, repair and replacement activities. Inspection and testing are routinely applied on Monday, mainly for the safety of reactor component and primary and secondary cooling system.

Annual maintenance is normally carried out in February. It takes around 2 months to complete the maintenance activities. The main purposes of annual maintenance are to inspect, monitor and diagnose and evaluate the condition of machine or component. Since the reactor is gradually oldre, condition monitoring of component has played an important role to predict the robustness of the system. This monitoring has leaded to assurance of safety of the reactor operation. By condition monitoring technique, the status of component could be evaluated as early as possible and take action to avoid further deterioration. Eight systems required for annual maintenance as listed:

1. Electrical system
2. Reactor Instrumentation and Control system

3. Cooling system
4. Air compressor and Ventilation Control System
5. Irradiation Facility
6. Reactor Pool Purification System
7. Emergency Core Cooling System
8. Reactor Core configuration and Testing

## 4. Establishment plan of the new research reactor

4.1 Siting

The project area is The Ongkharak Nuclear Research Center (ONRC) is located about 60 Km. North of Bangkok at Ongkharak District, NakhonNayok Province. The area around 500,000$m^2$(~ 126 acres) planed to comprise a research reactor-isotope production-waste management complex, a visitor center, general utility systems, residential area and recreation parks.

4.2 General description of the new research reactor

As designed, the new reactor to be a multipurpose, pool-typed TRIGA reactor with a steady-state thermal power output rating of 10 MW. Low-enriched Uranium (LEU) 19.7% wt as fuel and light water as coolant and moderator whereas heavy water ($D_2O$) and beryllium as the reflector.

The arrangement of the ractor, auxiliary pool, transfer canal and isotope transfer hot cell designed to allows underwater and pneumatic transferring of irradiated targets from irradiated locations to isotope production hot cell.

4.3 Utilization plan

As planed, the main purposes of this reactor to be for radioisotope production, R&D in the nuclear science, nuclear engineering as listed:

a.)Beam experiments such as:
- Prompt Gamma neutron Activation Analysis (**PGNAA**)
- High Resolution Powder Diffractometry (**HRPD**)
- Small Angle Neutron Scattering (**SANS**)
- Neutron Radiography (**NR**)

b.) Boron Neutron Capture Therapy (**BNCT**).
c.) Radioisotope Production for medical, industrial and agricultural uses. (**RI**)
d.) Neutron Transmutation Silicon Doping (**NTD**)
e.) Applied research and technology development in the nuclear field
f.) Reactor operation training.
g.)Training in reactor physics (neutron physics, thermal hydraulics, reactor experiments etc.)

## 5. Conclusion

Te TRR-1/M1 has been operated since 1977 to serve radioisotope production, research and development in nuclear and related sciences and other utilizations. Efforts have been carried out to maintain the efficiency in both reactor operations and utilizations in accordance with the IAEA safety guideline. However, aging has also been concerned after several years of services. Establish plan of a new research reactor has recently been carried out.

# 1. Workshop

## Tc Generator Technology

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JP0650496

# 1.12 Performance of PZC-Mo Generator and labeling results Prepared with its Eluate and MDP Kit

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**Abstract**

This paper described the performance of Tc-99m generator prepared with Mo adsorbent PZC and irradiated nature $MoO_3$, and the labeling results of MDP kit prepared with Tc-99m eluted from PZC-Mo generator and MDP was report as well. ThreeTc-99m generators was prepared with different batches of PZC and reactor irradiated nature Mo. The adsorption efficiency of two batches of the PZC is good (96.4% and 93.4%)and that of one batch of PZC is not satisfy (77.8%). The elution efficiency is not so high, and it increases along with the elution date. The elution file is very broad till to 30 ml and the Mo breakthrough is high to unacceptable.

The labeling efficiency of MDP kit, prepared with Tc-99m eluate eluted with saline containing 0.05% NaClO from Mo-PZC generator, is approximately 77~84% and it can reach to >98% labeling with eluate without containing 0.05%HClO in eluate.

## 1. Introduction

According to the arrangement of FNCA Tc-99m generator project, three batches of Mo adsorbent material PZC was distributed to the member country of FNCA as chromatographic material for preparation of Tc-99m generator with reactor irradiated nature Mo. Experimental results of performance of $^{99m}Tc$ generator prepared with the Mo adsorbent PZC and reactor irradiated $MoO_3$ is reported in this paper. As the Japanese experiment instruction, 1g irradiated $MoO_3$ (Irradiated in MJTR with the neutron flux of $\sim 6\times 10^{13}$ n • $cm^{-2}$ • $s^{-1}$) and 1g non-irradiated $MoO_3$ was dissolved with 5mL 6mol/L NaOH . After being diluted and adjusted pH, 1g PZC was added to 8ml solution to adsorb Mo and the PZC adsorbed $^{99}Mo$ was packed in glass column to prepare $^{99m}Tc$ generator. Five MDP kits were labeled with eluates eluted from PZC-Mo generator in different elution day.

## 2. Experiment

2.1 Mo-PZC generator preparation

2.1.1 Preparation of original $^{99}Mo$ solution

*a)* 1g nature $MoO_3$ irradiated in MJTR for 9 days and1g non-irradiated $MoO_3$ was dissolved in 5mL 6mol/L NaOH.

*b)* Adjust pH of the solution with 1mol/mL HCl to pH=7

*c)* Diluted the solution with water *to 50mL.* The concentration of Molybdenum is 26.7mgMo/mL. It is called **original $^{99}Mo$ solution**.

d) Pipette out 5.0 mL of original $^{99}Mo$ solution into a penicillin type vial of 10 mL volume to measure the radioactivity of $^{99}Mo$ (noted as $a_0$) and calculate the $^{99}Mo$ radioactivity of 8mL original solution (noted as $A_0$).

$$A_0=8\times a_0/5$$

2.1.2 $^{99}$Mo adsorption on PZC

a) Pipette 8.0ml original solution into a flask for PZC adsorption. Adjust the volume of this solution with water to 25mL.

b) Add 1g PZC to the solution and cap the flask. Keep the mixture at 80-90℃ for 3 hours in a water bath. During this process shake the flask slowly by hand several times.

c) Take out the mixture from the water bath and cool it to room temperature.

d) Neutralize this solution to pH=7 with 1 mol/L NaOH solution

e) Suck out 6-7mL of the supernatant solution from the Mo-PZC mixture and filter it through a G4 sintered glass filter to get a clear supernatant solution.

f) Pipette 5.0 mL of above prepared clear supernatant solution to measure its $^{99}$Mo radioactivity (noted as $\mathbf{a_1}$) with dose calibrator, pour this clear supernate into a waste container.

g) Calculate the $^{99}$Mo radioactivity non-adsorbed on PZC (noted as $\mathbf{A_1}$).

$$A_1=(25Xa_1)/(5xf_1)$$

$f_1$—The decay factor of $^{99}$Mo for the time period from $^{99}$Mo radioactivity measurement of the original solution to that of the supernatant solution of $^{99}$Mo adsorption mixture

h) Calculate the Mo adsorption capacity and total $^{99}$Mo radioactivity of PZC adsorbent (noted as $\mathbf{A_t}$).

$$A_t\,(\text{mCi } ^{99}\text{Mo})=A_0-A_1$$

i) Calculate the specific of PZC (noted as **s**)

$$s\,(\text{mCi } ^{99}\text{Mo /g PZC})=A_t/1$$

j) Calculate the Mo adsorption capacity of PZC Noted as $\mathbf{K_{Mo}}$)

$$K_{Mo}(\text{mgMo/gPZC})=\frac{A_0-A_1}{A_0}\ X\frac{8\times 26.7}{1}$$

2.1.3 Loading and conditioning $^{99}$Mo-PZC generator column

a) Remove the fine powder from the adsorption solution by the decantation of supernatant solution and washing water of 40 ml, and collect all the fine powder, supernate and washing solution into the waste container as above.

b) Pack the PZC adsorbing $^{99}$Mo into a glass column (10mm in inner diameter 80mm in length with $G_3$ fritted glass filter).

c) Elute the $^{99}$Mo-PZC-column with 10ml 0.9% saline solution containing 0.05% NaClO by sucking the eluate completely into an evacuated bottle and measure its $^{99}$Mo radioactivity with dose calibrator.

d) Measure the total volume of liquid (noted as $\mathbf{V_w}$) collected in waste container.

e) After vigorously shaking, take out 5 ml into penicillin vial to measure the $^{99}$Mo radioactivity (noted as $\mathbf{a_3}$) with dose calibrator at t=0. This time is noted as **Reference time** t=0

f) Measure the $^{99}$Mo radioactivity of $^{99}$Mo-PZC column (noted as $\mathbf{A_m}$) with dose calibrator at t=0.

2.1.4 Hydrated Zirconium Oxide (HZO) column assembling

Connect a pre-pared 0.5 grams Hydrated Zirconium oxide column with $^{99}$Mo-PZC columns to assembly a $^{99m}$Tc generator system. (PZC lot No. B040527-30M is not connected HZO column from the third elution day)

2.1.5 Calculation of $^{99}$Mo radioactivity of $^{99}$Mo-PZC column, its deviation and loss of fine PZC powder

a) Calculated $^{99}$Mo radioactivity of column (noted as $A_{cc}$) at t=0

$$A_{cc}=(A_0xf_0)-(a_3xV_w/5)$$

$f_0$---- The decay factor of $^{99}$Mo for the time period from $^{99}$Mo radioactivity measurement of the $^{99}$Mo original solution to the reference time t=0)

b) Measure the $^{99}$Mo radioactivity of column (noted as Amc) at t=0

$$A_{mc}=A_m$$

c) $^{99}$Mo-PZC-column radioactivity deviation (noted as $\delta$ %)

$$\delta\ \%=[100\times(A_{mc}-A_{cc})/A_{cc}]$$

d) Loss of the fine powder (noted as $\sigma$ %)

$$\sigma\ \%=100x(A_t-A_{cc}/f_0)/(s)=100x[1-\{A_{cc}/(f_0xA_t)\}]$$

2.1.6 Elution of $^{99m}$Tc

a) After 24 hours of standing from the reference time t=0 (from the end of loading and conditioning step), elute the generator with 10ml 0.9% saline by sucking Tc-99m eluate completely into an evacuated vial three times.

b) measure the Tc-99m radioactivity (noted as $\mathbf{a_{Tc}}$) and the Mo-99 radioactivity (noted as $\mathbf{a_{Mo}}$) of this portion of 10ml eluate with a radioisotope dose calibrator.

c) Repeat this elution every 24 hours and collect all the measurement data for calculation.

d) Calculation of Tc-99m radioactivity, Tc-99m elution yield, Mo-99 breakthrough and Molybdenum content in Tc-99m eluate.

e) Total Tc-99m radioactivity of Tc-99m eluate (noted as $\mathbf{A_{Tc}}$)

$$A_{Tc}=a_{Tc}$$

f) Elution yield of Tc-99m generator system (noted as Y%)

$$Y\%=(100xA_{Tc})/(A_{cc}x0.86xf_e)$$

fe----Mo-99 decay factor for the time period from present Tc-99m elution of generator to the reference time.

g) Mo-99 breakthrough in Tc-99m eluate (noted as B%)

$$B\%=[100xa_{Mo}/a_{Tc}]$$

h) Molybdenum content in Tc-99m eluate [noted as M($\mu$g Mo/ml)]

$$M(\mu g\ Mo/ml)=(267000/(A_0Xf_0))x[a_{Mo}xf_t/10]$$

$f_t$----- Mo-99 decay factor for the time period from present Tc-99m elution of generator to the Mo-99 radioactivity measurement of original solution.

2.2 The labeling of MDP kit

2.2.1 pipette 4ml eluate eluted from Tc-99m generator and infuse lyophilized MDP kit and shake it to make it completely dissolved.

2.2.2 Measure the Tc-99m activity of labeled MDP kits.

2.2.3 After 5 minutes, measure the labeling efficiency by paper chromatography using 85% methyl alcohol as developing solvent.

## 3. Results and Discussion

3.1 The preparation of Mo-PZC generator

Three Mo-PZC generator were prepared bu mostly following the distributing document 'Standard procedure for the preparation of PZC based chromatographic $^{99m}$Tc generator using (n, γ)$^{99}$Mo'.

The 1g Alumina safe columns assembling with $^{99m}$Tc-PZC generator system was replaced with 0.5g hydrate Zirconia (HZO). Because the high Mo breakthrough was found in the experiments, the HZO safe column of one generator was disconnected after two elution days.

The color of Mo-PZC mixture solution is colorless (PZC lot No. B040527-30M and No. B040527-35M) and one is light blue (PZC lot No. B040527-45M). The PZC swelled little in the process of Mo adsorption and the frangibility has been obviously improved.

The preparation experimental data of $^{99m}$Tc-PZC generators is showed in table 1.

Table1 The preparation experimental data of the $^{99}$Mo-PZC generator

| Item | Measurement data | | | Item | Calculated data | | |
|---|---|---|---|---|---|---|---|
| PZC lot No | B040527-30M | B040527-35M | B040527-45M | PZC Lot No | B040527-30M | B040527-35M | B040527-45M |
| $m_{PZC}$, g | 1.0 | | | $C_{Mo}$, mgMo/mL | 26.7 | | |
| $a_0$, mCi/5mL | 31.2 (Nov.8 9:44) | | | $A_0$, mCi/5mL | 49.9(9:44) | | |
| $a_1$, mCi/5mL | 0.344 (14:40) | 0.620 (15:17) | 2.30 (13:54) | $A_1$, mCi | 1.81 (9:44) | 3.29 (9:44) | 12.02 (9:44) |
| $a_3$, mCi/5mL | 0.069 (15:52, t=0) | 0.115 (16:05, t=0) | 0.261 (16:15, t=0) | $A_t$, mCi/5mL | 48.1(9:44) | 46.61(9:44) | 37.9(9:44) |
| $V_w$, mL | 206 | 192 | 169 | E*, % | 96.4 | 93.4 | 76.0 |
| $a_m$, mCi $^{99}$Mo | 19.0 Nov.1016:54 | 8.85 Nov.13 16:55 | 12.6 Nov.11 16:50 | $K_{Mo}$, gMo/gPZC | 205.9 | 199.6 | 166.2 |
| $A_m$,mCi | 32.8(t=0) | 36.2(t=0) | 30.0(t=0) | s, Ci$^{99}$Mo/gPZC | 48.1 | 46.61 | 37.9 |
| $a_{Tc}$, Ci$^{99m}$Tc | - | | | $A_{cc}$, mCi $^{99}$Mo | 43.6 (t=0) | 41.6 (t=0) | 35.5(t=0) |
| $a_{Mo}$ mCi$^{99}$Mo | | | | $A_{mc}$, mCi $^{99}$Mo | 32.8(t=0) | 36.2(t=0) | 30.0(t=0) |
| | | | | δ,% | -24.8 | -13.0 | -15.6 |
| | | | | σ,% | 3.36 | 4.52 | -0.28 |
| | | | | $A_{Tc}$, mCi $^{99m}$Tc | See table 2 | See table 3 | See table 4 |
| | | | | Y%,B%,MgMo/mL | | | |

*Adsorption efficiency

3.2 The elution of Mo-PZC generator

In the first two elution days, 10 ml saline containing 0.05% NaClO were used to elute each generators, and 4ml eluate of each generator was used to label three MDP kits. In the last two elution days, saline without NaClO was used to elute the generators, and 4ml eluates of two generators were used to label two MDP kits.

Because of the lower elution efficiency of every generator in 10 ml eluate for the first elution day, three elutions were carried out every day for every generator with three10ml

eluents to check the activity of Tc-99m and Mo-99 distributed in every 10 ml eluate. The elution efficiency (y%)and Mo-99 breakthrough (B%) are calculated by these data. The elution results of $^{99m}$Tc-PZC generators are showed in table2, and table3 and table 4.

Table 2 Elution performance of $^{99}$Mo-PZC generator (PZC lot No. B040527-30M)

| Elution date | Eluent volume, | Calibration time | $f_e$ | $A_{Tc}$, mCi | *$A_{cc}$, mCi | $A_{Mo}$, Ci | Y% | | | B% |
|---|---|---|---|---|---|---|---|---|---|---|
| Nov.8 15:52 (t=0) | | | | — | 43.6 | — | — | 20ml | 30ml | — |
| Nov.9 | 10 ml | 16:26 | 0.7691 | 4.34 | 33.53 | 86.9 | 15.0 | | | 2.00 |
| Nov.10 | 10 ml | 16:24 | 0.7773 | 6.98 | 26.00 | 60.3 | 31.2 | | | 0.86 |
| | 10 ml | 16:29 | | 3.41 | | 217 | 15.2 | 46.4 | | 6.36 |
| | 10 ml | 16:35 | | 2.44 | | 303 | 10.9 | | 57.3 | 12.42 |
| Nov.11 | 10 ml | 16:27 | 0.7773 | 5.57 | 19.80 | 329 | 32.7 | | | 5.91 |
| | 10 ml | 16:29 | | 1.94 | | 364 | 11.4 | 44.1 | | 18.76 |
| | 10 ml | 16:31 | | 1.30 | | 392 | 7.6 | | 51.7 | 30.15 |
| Nov.12 | 10 ml | 17:00 | 0.7732 | 4.85 | 14.47 | 334 | 39.0 | | | 6.89 |
| | 10 ml | 17:04 | | 1.76 | | 282 | 14.1 | 53.1 | | 16.02 |
| | 10 ml | 17:01 | | 0.96 | | 295 | 7.7 | | 60.8 | 30.73 |
| Nov.13 | 10 ml | 16.33 | 0.7814 | 4.28 | 10.60 | 276 | 47.0 | | | 6.45 |
| | 10 | 16:35 | | 1.03 | | 235 | 11.3 | 58.3 | | 22.82 |
| | 10 ml | 16:40 | | 0.64 | | 245 | 7.02 | | 65.32 | 38.28 |
| Nov.14 | 10 ml | 16:18 | 0.7773 | 3.80 | 7.65 | 196 | 57.8 | | | 5.16 |
| | 10 ml | 16:33 | | 0.828 | | 110 | 12.6 | 70.4 | | 13.28 |
| | 10 ml | 16:46 | | 0.386 | | 73.5 | 5.9 | | 76.3 | 19.04 |
| Nov.15 | 10 ml | 16:16 | 0.7789 | 2.79 | 5.66 | 53.8 | 57.3 | | | 1.93 |
| | 10 ml | 16:22 | | 0.393 | | 29.1 | 8.1 | 65.4 | | 7.4 |
| | 10 ml | 16:30 | | 0.210 | | 21.0 | 4.3 | | 69.7 | 10.00 |
| Nov.16 | 10 ml | 16:13 | 0.7756 | 2.16 | 4.31 | 24.0 | 58.3 | | | 1.11 |
| | 10 ml | 16:33 | | 0.314 | | 18.5 | 8.5 | 66.8 | | 5.89 |
| | 10 ml | 16:44 | | 0.118 | | 15.0 | 3.2 | | 70.0 | 12.71 |

* The a ml ctivity of Mo-99 leaked from the column has been subtracted from $A_{cc}$.

Table 3 Elution performance of $^{99}$Mo-PZC generator (PZC lot No. B040527-35M)

| Elution date | Elution volume | Calibration time | $f_e$ | $A_{Tc}$, mCi | *$A_{cc}$, mCi | $A_{Mo}$/ uCi | Y% | | | B% |
|---|---|---|---|---|---|---|---|---|---|---|
| Nov.8 16:05(t=0) | | | | 41.6 | — | — | 10ml | 20ml | 30ml | — |
| Nov.9 | 10 ml | 16:32 | 0.7732 | 3.83 | 32.16 | 79 | 13.8 | | | 2.06 |
| Nov.10. | 10 ml | 16:46 | 0.7732 | 6.09 | 24.80 | 68 | 28.6 | | | 1.1 |
| | 10 ml | 16:57 | | 2.75 | | 160 | 12.9 | 41.5 | | 5.8 |
| | 10 ml | 17:00 | | 1.68 | | 308 | 7.9 | | 49.4 | 18.3 |
| Nov.11 | 10 ml | 16:34 | 0.7801 | 7.46 | 18.72 | 182 | 46.3 | | | 2.4 |
| | 10 ml | 16:36 | | 1.87 | | 256 | 11.6 | 57.9 | | 13.7 |
| | 10 ml | 16:38 | | 1.36 | | 313 | 8.4 | | 66.3 | 23.0 |
| Nov.12 | 10 ml | 17:16 | 0.7712 | 6.88 | 13.86 | 253 | 57.7 | | | 3.7 |
| | 10 ml | 17:23 | | 1.87 | | 247 | 15.7 | 73.4 | | 13.2 |
| | 10 ml | 17:28 | | 0.847 | | 268 | 7.1 | | 80.5 | 31.6 |
| Nov.13 | 10 ml | 17:14 | 0.7781 | 7.05 | 10.19 | 198 | 80.4 | | | 2.8 |
| | 10 | 17:18 | | 0.593 | | 206 | 6.8 | 87.2 | | 34.7 |
| | 10 ml | 17:20 | | 0.407 | | 225 | 4.6 | | 91.8 | 55.3 |
| Nov.14 | 10 ml | 16:22 | 0.7832 | 5.26 | 7.49 | 191 | 81.7 | | | 3.5 |
| | 10 ml | 16:35 | | 0.565 | | 112 | 8.8 | 90.5 | | 19.1 |
| | 10 ml | 16:47 | | 0.308 | | 72 | 4.8 | | 95.3 | 23.4 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Nov.15 | 10 ml | 16:16 | 0.7793 | 3.95 | 5.54 | 58.8 | 82.9 | | | 1.5 |
| | 10 ml | 16:22 | | 0.377 | | 38.6 | 7.9 | 90.8 | | 10.5 |
| | 10 ml | 16:30 | | 0.142 | | 24.8 | 3.0 | | 93.8 | 17.5 |
| Nov.16 | 10 ml | 16:23 | 0.7752 | 3.03 | 4.2 | 23.7 | 83.9 | | | 0.8 |
| | 10 ml | 16:35 | | 0.26 | | 20.0 | 7.2 | 91.1 | | 7.7 |
| | 10 ml | 16:47 | | 0.108 | | 16.8 | 3.0 | | 94.1 | 15.6 |

* The activity of Mo-99 leaked from the column has been subtracted from $A_{cc}$.

Table4 Elution performance of $^{99}$Mo-PZC generator (PZC lot No. B040527-45M)

| Elution date | Calibration time | $f_e$ | $A_{Tc}$/ mCi | *$A_{cc}$/ mCi | $A_{Mo}$/ uCi | Y% | | | B% |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | 10ml | 20ml | 30ml | |
| 2004.11.8 | 16:15(t=0) | | 35.5 | — | — | — | | | — |
| Nov.9 | 16:32 | 0.7748 | 1.79 | 27.5 | 319 | 7.6 | | | 1.78 |
| Nov.10 | 17:03 | 0.7732 | 2.30 | 21.02 | 184 | 12.7 | | | 8.0 |
| | 17:10 | | 0.74 | | 253 | 4.1 | 16.8 | | 34.2 |
| | 17:13 | | 0.91 | | 340 | 5.0 | | 21.8 | 37.4 |
| Nov.11 | 16:43 | 0.7797 | 3.4 | 16.02 | 240 | 24.7 | | | 7.1 |
| | 16:45 | | 0.882 | | 270 | 6.40 | 31. 1 | | 30.6 |
| | 17:17 | | 0.812 | | 316 | 5.89 | | 37.0 | 38.9 |
| Nov.12 | 17:35 | 0.7691 | 3.3 | 11.68 | 275 | 32.85 | | | 8.3 |
| | 17:40 | | 0.95 | | 204 | 9.46 | 42.3 | | 21.5 |
| | 17:46 | | 0.687 | | 236 | 6.84 | | 49.1 | 34.4 |
| Nov.13 | 16:42 | 0.7845 | 4.58 | 8.60 | 239 | 61.92 | | | 5.2 |
| | 16:48 | | 0.543 | | 176 | 7.34 | 70.3 | | 32.4 |
| | 16:50 | | 0.357 | | 186 | 4.83 | | 75.1 | 52.1 |
| Nov.14 | 16:24 | 0.7785 | 3.65 | 6.23 | 116 | 68.1 | | | 3.2 |
| | 16:37 | | 0.438 | | 102 | 8.17 | 76.3 | | 23.3 |
| | 16:50 | | 0.234 | | 71.5 | 4.37 | | 80.7 | 30.6 |
| Nov.15 | 16:17 | 0.7789 | 2.51 | 4.59 | 61.0 | 63.6 | | | 2.4 |
| | 16:25 | | 0.305 | | 33.5 | 7.73 | 71.3 | | 11.0 |
| | :16:27 | | 0.127 | | 22.0 | 3.22 | | 74.5 | 17.3 |
| Nov.16 | 16:19 | 0.7752 | 1.9 | 3.47 | 26.8 | 63.7 | | | 1.4 |
| | 16:41 | | 0.244 | | 19.6 | 8.18 | 71.9 | | 8.0 |
| | 16:48 | | 0.089 | | 14.5 | 2.98 | | 74.8 | 16.3 |

* The activity of Mo-99 leaked from the column has been subtracted from $A_{cc}$.

The elution efficiency in 10ml, 20ml and 30ml eluate listed in above table shows that the elution profile is very broad, and the elution efficiency in 10 ml is not satisfactory. The content of Mo-99 is very high and it obviously increases from the first 10ml eluate to the second 10ml eluate and the third 10ml eluate in the same elution day. The high Mo breakthrough maybe results from that the fine powder of PZC adsorbed Mo-99 is not be completely removed, and the fine powder goes through the G3 glass filter to the eluate. It can be proved by the fact that the Mo-99 in eluate cannot be removed by the HZO safe column.

3.3The labeling of MDP kit

Three kits are respectively labeled with the first eluate of each generator on November 10 (The eluent is saline containing 0.05% NaClO), and two MDP kits are labeled with the first 10 eluate of generators (PZC LOT No. B040527-30M, and No. B040527-35M), (The eluent is saline only without any NaClO). The results are listed in table 5.

Table 5 Labeling results of MDP kits

| PZC lot No. | date | time | Volume, ml | Activity of Tc-99m, | Radiochemical purity, % |
|---|---|---|---|---|---|
| B040527-30M | Nov.10 | 17:12 | 4.0 | 2.69 mCi | 76.6 |
| B040527-35M | | 17:13 | 4.0 | 2.36 mCi | 84.4 |
| B040527-45M | | 17:15 | 4.0 | 0.87mCi | 77.1 |
| B040527-30M | Nov.16 | 16:28 | 4.0 | 0.81mCi | 98.8 |
| B040527-35M | | 16:29 | 4.0 | 1.17 mCi | 98.4 |

The results listed above show that the 0.05%NaClO containing in eluate can obviously affect the labeling efficiency of MDP kit. Because of the limitation of MDP kit, no more labeling experiments were not carried out.

## 4. Conclusion

The experiments showed that the PZC distribution by Japan were prepared with different technical process has different adsorption efficiency and adsorption capacity to Mo in the process of adsorption of Mo on PZC.

The fine PZC powder, which has adsorbed Mo, should be completely removed to avoid the high Mo breakthrough in the process of Mo-PZC generator elution.

The elution efficiency for the three batches is not so high and the elution profile is broad, which can decrease the concentration of Tc-99m, and the elution efficiency obviously increase along with the elution date. The high Mo-99 breakthrough maybe is caused by the leakage of fine PZC powder, which had not been removed before generator loading.

The 0.05%NaClO containing in eluate can evidently affect the labeling yield of MDP kits.

The $^{99}$Mo-PZC generator system should be further improved, especially the quality of PZC.

1.13

# RADIOISOTOPES DEVELOPMENT AND PRODUCTION IN MALAYSIA

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## ABSTRACT

Development of radioisotopes for use in medical, industrial and agriculture sector was began in 1982 after the commissioning the 1MW TRIGA MARK II research reactor. Production of Tc-99m using Methyl Ethyl Ketone (MEK) extraction began in 1985 with the capacity about 1.2 Ci of Mo-99. By 1994, we produced Tc-99m generator using fission Molybdenum imported from Indonesia. Early 1990's, we assembled I-131 plant from Hungary for production of I-131 using TeO2 irradiated inour reactor but the yield are low. We have imported I-131 to meet the demand about 10 Ci/month. Development of Sm-153 EDTMP was began in 1994 and the trial production began in 1998. We also established the procedure for production of industrial and agriculture radioisotopes such as P-32, Na-24 and Au-198.

**Keyword : Methyl Ethyl Ketone, Fission Molybdenum**

## INTRODUCTION

Production of radioisotopes began in 1984 with the trial irradiation of certain materials using our TRIGA MARK II research reactor. The Medical Technology Division was set up to carry out production and distribution of radioisotopes. The division was equipped with the various facilities to cater this function, these facilities included; hot cell for production of Tc-99m, hot cell for I-131, glove box for production of β-emitting radioisotopes and clean room for the preparation of radiopharmaceutical kits. Under Ninth Malaysia Plan (2006 – 2010), we have proposed to the government for purchase/built of 4 new hot cell, 4 new glove box and 1unit of clean room.

## RADIOISOTOPES DEVELOPMENT

### a. Tc-99m DEVELOPMENT

Development of Tc-99m usingMethyl Ethyl Ketone (MEK) solvent extraction began in 1985 using plant developed by Bhaba Atomic Research Centre (BARC), India. From1987 – 1990, we developed semi automatic MEK (SAMEK) plant and started routine production for supplied to the hospital around Kuala Lumpur with the capacity about 1.2 Ci. However, over the years due to the constraints of the our reactor, thus was unable to carry out the usual 75 hours continuos irradiation schedule and the logistic involved, we abonded SAMEK in 1992. By 1993, we installed the Tc-99m plant from Norway with the capacity to produced 50 Tc-99m generator per batch. In 1994, we supplied the Tc-99m generator to the 11 nuclear medicine centre in Malaysia. Unfortunately, by the end of 2002, we received the notice from relevant authority to stopped the production due to the new CGMP requirement starting January 2003.

### b. I-131 DEVELOPMENT

In early 1990, we assembled I-131 plant from Hungary for production of I-131 using TeO2 irradiated in our reactor. By 1994, we started routine production, unfortunately the yield are low. To cater the demand from users, we imported I-131 about 10 Ci/month from United Kingdom and Australia in solution and capsule form.

### C. Sm – 153 EDTMP

Development of Sm – 153 EDTMP was began in 1994 under IAEA TC Project until 1998. By 2000, we started clinical trial phase 1with the cooperation of 2 hospitals.. However the production of Sm-153 EDTMP for clinical trial also affected with the closure of our facilities.

## SUPPLY AND DEMAND

Common radioisotopes used in Malaysia, are Tc-99m, I-131, Ga-67, Cr-51, Sm-153 and P-32 for medical sector and Ir-192, Co-60, Au-198, Br-82, Cs-137 and Am-242 for industrial sector. 90% of these radioisotopes are imported from other country especially from Indonesia, United Kingdom and Australia. Table 1 shown the supply and demand of radioisotopes used in medical sector.

Table 1. Supply and Demand of Radioisotopes in Medical Sector.

| ISOTOPES | ACTIVITY (mCi) | DEMAND | TYPE OF SUPPLY |
|---|---|---|---|
| Tc-99m | 1200 | 50 unit/yr | MINT |
| | 800 | 150 unit/yr | MINT |
| | 500 | 25 unit/yr | MINT |
| | 400 | 50 unit/yr | MINT |
| | 300 | 50 unit/yr | MINT |
| | 200 | 100 unit/yr | MINT |
| | | | |
| I-131 | 150 | 400 unit/yr | MINT/Import |
| | 100 | 80 unit/yr | MINT/Import |
| | 80 | 150 unit/yr | MINT/Import |
| | | | |
| Ga-67 | 10 | 50 unit/yr | Import |
| | | | |
| Cr-51 | 1 | 12 unit/yr | Import |
| | | | |
| P-32 | 10 | 6 unit/yr | Import |
| | | | |
| Sm-153 EDTMP | On request | 5 unit/yr | MINT/Import |

## NUCLEAR MEDICINE FACILITIES

In Malaysia, we have 12 nuclear medicine centre which 60% of the centre are located around Kuala Lumpur, 2 centre at the north, 1 centre at the south and 1 centre at the east of Peninsular Malaysia while 1 centre located at Sarawak in Borneo Island. Table 2 shown the users of Tc-99m generator.

Table 2. Users of Tc-99m Generator

| Nuclear Medicine Centre | Year Est. | No. of Gamma Camera | No. of SPECT |
|---|---|---|---|
| National Heart Institute | 1994 | 1 | 1 |
| UKM Hospital | 1996 | 1 | 1 |
| Pulau Pinang Hospital | 1996 | 2 | 1 |
| USM Hospital, Kelantan | 1992 | 1 | 1 |
| Sultanah Aminah Hospital, Johor | 1997 | 1 | 1 |

| | | | |
|---|---|---|---|
| Ampang Puteri Specialist Hospital | 1996 | 1 | 0 |
| University Malaya Medical Centre | 1967 | 1 | 1 |
| Kuala Lumpur Hospital | 1964 | 2 | 2 |
| Nuclear Cancer Society of Malaysia | 1997 | 1 | 0 |
| Kuching Hospital,Sarawak | 1980 | 1 | 0 |
| Penang Island Hospital, Penang | 2000 | 1 | 0 |
| Subang Jaya Medical Centre | 2005 | 1 | 0 |

## CONCLUSION

MINT is the only radioisotopes/radiopharmaceuticals producer in Malaysia. We are able to produced common radioisotopes/radiopharmaceuticals request by the users or imported the specific radioisotopes/radiopharmaceuticals.

# 1.14 Performance Testing of PZC Generators for $^{99m}$Tc Production

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**Abstract:**

The report briefly describes the performance testing done on seven batches of polyzirconium column (PZC) material. PZC is a ready-to-use high molybdenum-capacity column material for adsorbing reactor-produced $^{99}$Mo. The PZC material was manufactured by Kaken Co in Japan and was sent to PNRI for performance evaluation.

Fission molybdenum was eluted from a commercial $^{99}$Mo - $^{99m}$Tc generator. The eluted $^{99}$Mo in a molybdenum carrier solution was adsorbed on PZC through a series of procedures. The mixture was decanted to a 90 x 12 mm glass column. $^{99m}$Tc was eluted with saline solution. The parameters measured were $Tc^{99m}$ yield, %molybdenum adsorption and desorption, elution profile and radiochemical purity.

## Introduction

Tc 99m is the most widely used radioisotope in nuclear medicine. It accounts for more than 80% of the total demand for radioisotopes. Both alone or conjugated with other ligands it is very useful for in vivo medical diagnostic procedures. $^{99m}$ Tc is a decay product of its parent radioisotope, $^{99}$Mo.

The present sources of $^{99}$Mo are research reactors, produced through the (n,γ) nuclear reaction with natural molybdenum. This type of reaction produces inexpensive but low specific activity $^{99}$Mo and the technology requirement is simple and well within the capability of countries with operating research reactors. Another method of producing $^{99}$Mo is by neutron –induced fission of Uranium-235 .This process produces high specific activity $^{99}$Mo, but involves heavy shielding and requires good radioactive waste management.

Cognizant of the importance of $^{99m}$ Tc and $^{99m}$ Tc based radiopharmaceuticals, the Philippine Nuclear Research Institute has initiated research on the development of column-type generators for $^{99m}$ Tc using $^{99}$Mo in the form of gel. The use of reactor produced $^{99}$Mo will reduce the Philippines dependence on the importation of commercial generators based on fission-Molybdenum. A procedure for the incorporation of low specific activity $^{99}$Mo into zirconium molybdate gel matrix has been standardized.. The gel was characterized by its elution yield data.

The Philippines through the FNCA participates in the performance testing of the PZC, a dried form type polyzirconium compound developed by Kaken Co. in Japan. The PZC is a ready- to- use high molybdenum capacity column adsorbent material .

## Experimental Methods

### Performance Test on PZC

Seven batches of the PZC were sent to the PNRI during the year. Table 1 summarizes the data for the received PCZ materials. The performance testing was done simultaneously in December 2004, because of problems associated with the availability and acquisition of high-activity molybdenum. $^{99}$Mo was extracted from a fission molybdenum commercial generator. $^{99}$Mo activity loaded into each column was only about 2 millicurie.

Table 1. PZC Materials

| Sample Code | Quantity(grams) | Lot No. | Date Received |
|---|---|---|---|
| PCZ-1 | 5 | B040527-30M | June 2004 |
| PCZ-2 | 5 | B040527-35M | June 2004 |
| PCZ-3 | 5 | B040527-45M | June 2004 |
| PCZ-4 | 3.5 | B041112-10M | December 2004 |
| PCZ-5 | 3.5 | B041112-12.5M | December 2004 |
| PCZ-6 | 3.5 | B041112-15M | December 2004 |
| PCZ-7 | 3.5 | B041112-10M | December 2004 |

### Adsorption of Molybdenum to PZC Material

Fission molybdenum was extracted from the alumina column of an imported generator using 10 ml of 1:1 NH3 solution. The extract contains about 20 mCi.

Following the experimental flowsheet by Kaken Inc , which is shown below, four grams of molybdenum oxide was dissolved in 10 ml of 6M NaOH and diluted to 20 ml. Two ml of this Mo solution and two ml of the radioactive molybdenum solution, activity 2 mCi, were mixed with one gram of the PZC material. The pH of the mixture was adjusted to nearly neutral pH, then equilibrated in a water bath for three hours at 90° C. After the reaction, one ml of the solution from the mixture was taken for molybdenum gamma measurement. The same amount of the original $^{99}$Mo solution was counted and used as reference value for the calculation of molybdenum adsorbed by the PZC samples.

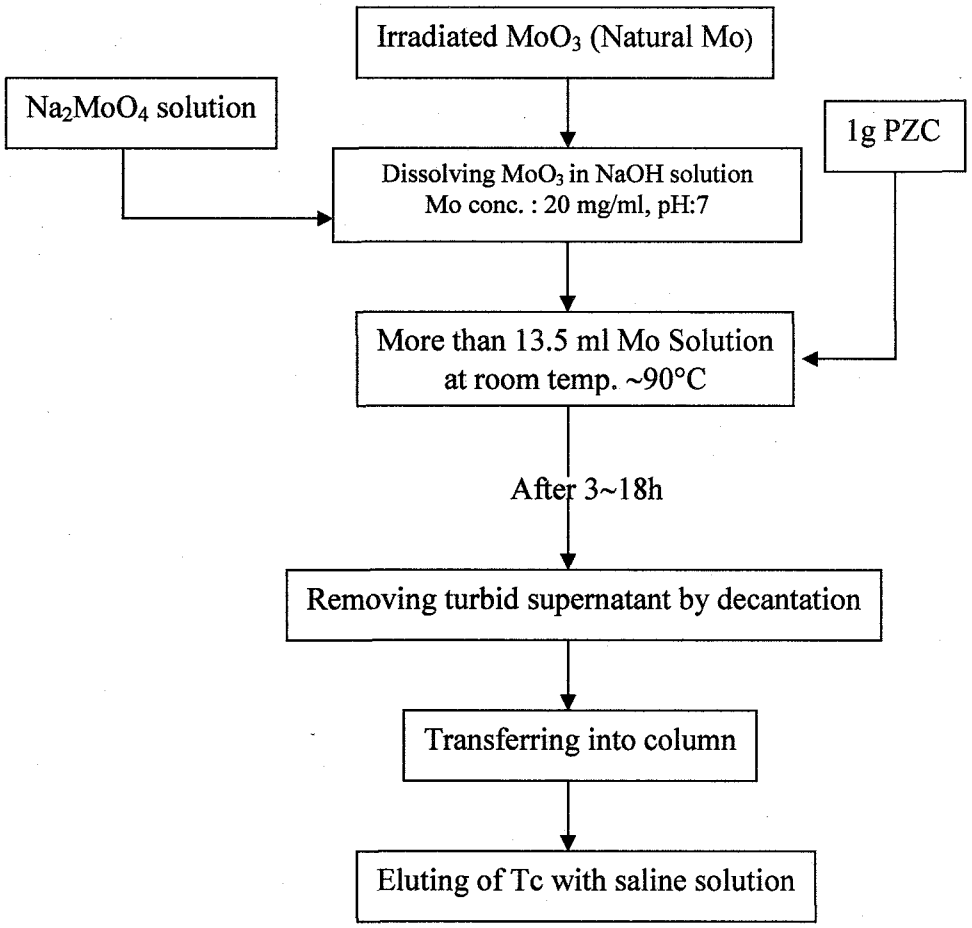


Figure 1.Experimental Flow sheet

**Column Preparation**

The fine particles were removed by decantation before packing into glass columns (size : 12mm by 90mm). The columns were washed with five 10 ml saline solution five times to remove free molybdenum and zirconium.

**Elution Yield Determination**

$^{99m}$ Tcwas eluted with 10-ml saline solution after 24 hours radioactive growth. The $^{99m}$ Tc activity was measured using an ATOMLAB Isotope Calibrator. The elution yield was calculated by comparing the activity of the $^{99m}$ Tc eluate with the theoretical amount of $^{99m}$ Tc resulting from the decay of $^{99}$ Mo adsorbed in the column. The elution yield data was measured for five days.

**Molybdenum Desorption Rate**

The desorption rate was measured in the 10ml $^{99m}$ Tc eluate. Molybdenum activity was measured using the isotope calibrator. The molybdenum activity corrected for PZC absorption factor was used as reference.

**Elution Volume**

The elution profile for each column was determined by the successive elution of 10 one-ml portions.

**Radiochemical Purity of the $^{99m}$ Tc Eluate**

Paper chromatography was done to determine the radiochemical purity of the pertechnetate solution. About 500 ul of the Tc99m eluate was spiked onto a Whatman Filter paper No.1 and then air-dried. The filter paper was then put in 75 percent methanol solution and the solvent was allowed to run through the paper. After complete running along the filter paper, it was dried again and cut into 1 cm strips. Each strip was counted for $^{99m}$ Tc activity.

**Results and discussion**

The results of the performance tests done on the seven batches of PZC materials are shown in Table 2. Only one trial per batch was performed. The tests were conducted at the same time. The results shows good values of elution yields and consistent values of daily elution yield data. Elution was done for five consecutive working days.

The elution yield data are presented in Figure 2 for the seven samples. Table 3 shows the daily elution yield values for the PZC material. Figure 3 shows the elution profile for each PZC columns

Table 2. Column Properties

| Sample Code | Percent Mo Absorption | Percent Mo Desorption | Average Percent Elution Yields | Elution Volume.ml | Percent Radiochemical Purity |
|---|---|---|---|---|---|
| PCZ-1 | 96.8 | 0.22 | 75 ± 2 | 6 | 99.3 |
| PCZ-2 | 97.0 | 0.25 | 76 ± 3 | 5 | 99.4 |
| PCZ-3 | 97.3 | 0.20 | 73 ± 3 | 6 | 99.8 |
| PCZ-4 | 98.3 | 0.29 | 81 ± 1 | 6 | 99.5 |
| PCZ-5 | 98.7 | 0.15 | 80 ± 1 | 5 | 99.6 |
| PCZ-6 | 98.6 | 0.09 | 79 ± 1 | 6 | 99.8 |
| PCZ-7 | 98.1 | 0.22 | 79 ± 2 | 6 | 99.8 |

Table 3. Elution Yield Data

| Sample Code | ELUTION DAY | | | | | Average Percent Elution Yields |
|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | |
| PCZ-1 | 76 | 76 | 72 | 74 | 75 | 75 ± 2 |
| PCZ-2 | 79 | 79 | 77 | 71 | 75 | 76 ± 3 |
| PCZ-3 | 76 | 76 | 72 | 70 | 73 | 73 ± 3 |
| PCZ-4 | 80 | 81 | 82 | 82 | 81 | 81 ± 1 |
| PCZ-5 | 81 | 82 | 80 | 79 | 79 | 80 ± 1 |
| PCZ-6 | 79 | 78 | 78 | 80 | 79 | 79 ± 1 |
| PCZ-7 | 81 | 78 | 77 | 80 | 77 | 79 ± 2 |

Based on the elution yield data that were obtained which range from 75 to 81 percent, the batch of PZC materials received and tested showed good column properties. Five ml saline solution is generally adequate to elute the available Technetium-99m from the column. The radiochemical purity of the eluate is nearly 99 percent.

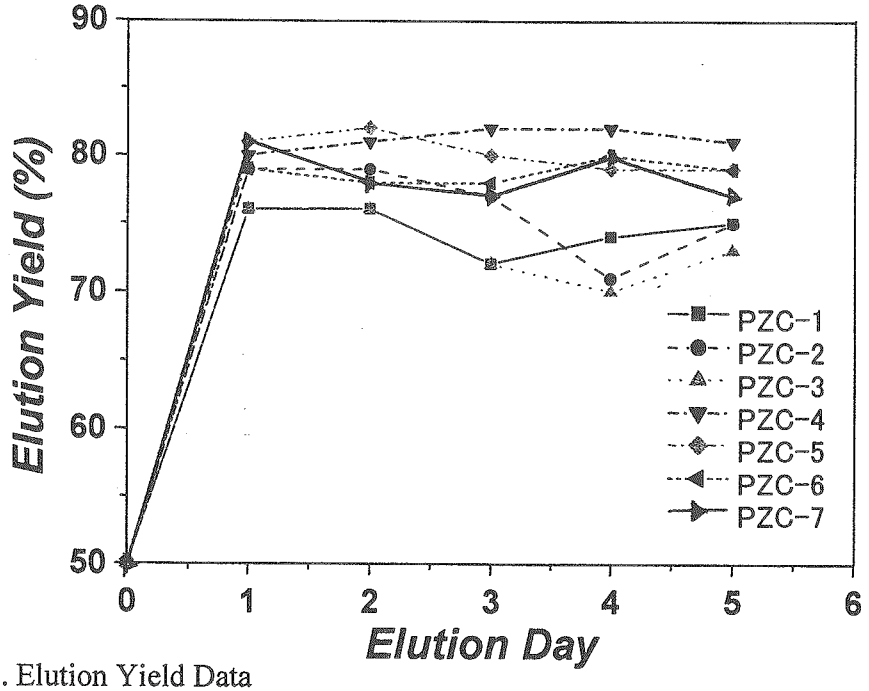


Figure 2. Elution Yield Data

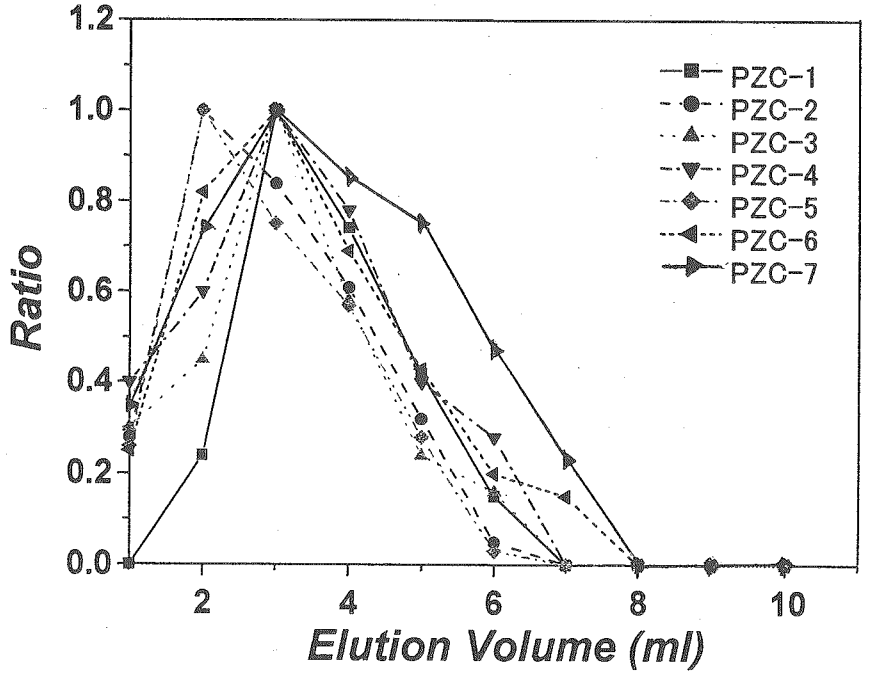


Figure 3. Elution Profile

## Conclusion and Recommendation

The results obtained for the present batches of PZC, although limited in number of trials and in the level of molybdenum activity loaded in the column showed that the PZC batches are good molybdenum adsorbent column material for $^{99m}$Tc generators.

## Acknowledgement

The Author would like to sincerely thank the Syncor, Philippines for providing the spent generators used for the study, the Irradiation Services Unit(PNRI) for the use of the ATOMLAB isotope calibrator, Mr. Ryan U. Olivares, Science Research Specialist of the Chemistry Research Section for the technical assistance and Mr. Nasser M. Kadil, (PNRI/UP Fellow) for the assistance in the extraction of the $^{99}$Mo from the spent commercial generator.

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## 1.15 Present Status of OAP Radioisotope Production

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ABSTRACT

Radioisotope Production Program (RP), Office of Atoms for Peace (OAP) is a non-profit government organization which responsible for research development and service of radioisotopes. Several research works on radioisotope production have been carried on at OAP. The radioisotope products of successful R&D have been routinely produced to supply for medical, agriculture and research application. The main products are $^{131}I$ (solution and capsule), $^{131}I$-MIBG, $^{131}I$-Hippuran, $^{153}Sm$-EDTMP, $^{153}Sm$-HA, and $^{99m}Tc$-radiopharmaceutical kits to serve local users. Radioisotopes are very beneficial for science and human welfare so as almost of our products and services are mainly utilized for medical purpose for both diagnosis and therapy. OAP has a policy to serve and response to thai community by providing radioisotopes and services with high quality but reasonable price. This policy will give the opportunity to the community to utilize these radioisotopes for their healthcare.

**Introduction**

Office of Atoms for Peace (OAP) was found on April 26, 1961. The OAP, a non-profit government organization, is responsible for research development, service of nuclear technology and regulation of nuclear technology utilization.

The OAP is located at 16 Paholyotin Road, Chatuchak destrict, Bangkok, Thailand. The OAP will be separated into 2 organizations, Office of Atoms for Peace (OAP) and Thailand Institute of Nuclear Technology (TINT). The new OAP will still be a government organization which responsible for regulatory issue, meanwhile, the TINT will be a public organization which responsible for research development and service of nuclear technology. The establishment of TINT is under processing and will be finished in the near future.

The OAP has developed such important and profitable strategic alliances with other research centers, nuclear medicine centers, universities that will enable us to cooperate, work along side with them for our research development and utilization of nuclear technology.

The institute has strong links with the IAEA, the UN agency, which is responsible for the peaceful applications of nuclear energy, isotopes and radiation. We also have bilateral agreements, with others agency such as JAERI (The Japan agency), KAERI (The Korean agency), which can give us support not only in research development work cooperation but also technical information exchange.

## ORGANIZATION STRUCTURE OF OFFICE OF ATOMS FOR PEACE

**OAP**

| | |
|---|---|
| Bureau of Radiation Safety Regulation | Bureau of Nuclear Safety Regulation |
| Bureau of Atomic Energy Administration and Management | Bureau of Technical Support for Safety Control |
| Office of the Secretary | The Radioactive Waste Management Program |
| The Radioisotope Production Program | The Radiation & Nuclear Protection Program |
| The Physics & Advanced Technology Research Program | The Reactor & Nuclear Technology Operation Program |
| The Radiation Research for Agriculture Program | The Chemistry Research & Material Science Program |

**Radioisotope production product**

The radioisotope production facilities are based on 2 MW TRIGA Mark III research reactor which operates at 1.2 MW for 55.2 MWh/week. The main radioisotope products are I-131 solution and capsule, I-131 Hippuran, I-131 MIBG, Sm-153 EDTMP. Sm-153 HA. Many Tc-99m radiopharmaceutical products are also produced such as MAA, MDP, DTPA, DISIDA, DMSA, MAG3, Phytate, Stanous, etc.

Although the production scale can not reach the whole national demand due to some limitations of the reactor, but the major parts of the nation consumption are able to fulfill.

Nowadays our products and services are focused on radioisotopes for medical, agricultural, and research applications as following:

| Product | Application |
|---|---|
| I-131 (solution and capsule) | Imaging for functional of thyroid, Treatment of hyperthyroidism, Treatment of differentiated thyroid carcinoma |
| I-131 MIBG | Imaging and therapeutic of adrenal medulla, myocardium, apheochromocytomas and neuroblastomas |
| I-131 HIPPURAN | Assessment of relative renal blood flow, differential function (tubular) and urinary tract patency |
| Sm-153 EDTMP | Palliative therapy for metastatic bone cancer pain |

| | |
|---|---|
| Sm-153 HA | Radiation synovectomy for rheumatoid arthritis |
| P-32 | Research works in agriculture |

**Tc-99m radiopharmaceutical kits**

| | |
|---|---|
| DISIDA | Hepatobiliary system imaging |
| DMSA | Scintigraphic evaluation of renal parenchyma |
| DTPA | Brain imaging, assessment of renal perfusion and estimate glomerular filtration rate |
| MDP | Bone imaging |
| MAG3 | Kidney imaging |
| MAA | Scintigraphic imaging of the pulmonary microcirculation |
| Phytate | Liver imaging |
| Stannous colloid | Gate blood pool imaging, GI bleeding and blood volume |

**Research and development**

Several research and development projects are going on such as Development of radionuclide delivery system for diagnostic or therapeutic of cancers, development of ELISA test kits for detection of milk progesterone, development of test kits for quantification of saxitoxin by receptor binding assay technique, production of no-carrier added I--131 MIBG for therapy of neuroblastoma, Yittrium-90 labeled compound for radiation synovectomy, development of Rhenium-188 HEDP as radiopharmaceutical for palliative bone pain and study of Rhenium-188 Lipiodol for hepatic tumor therapy.

**Achievement to date**

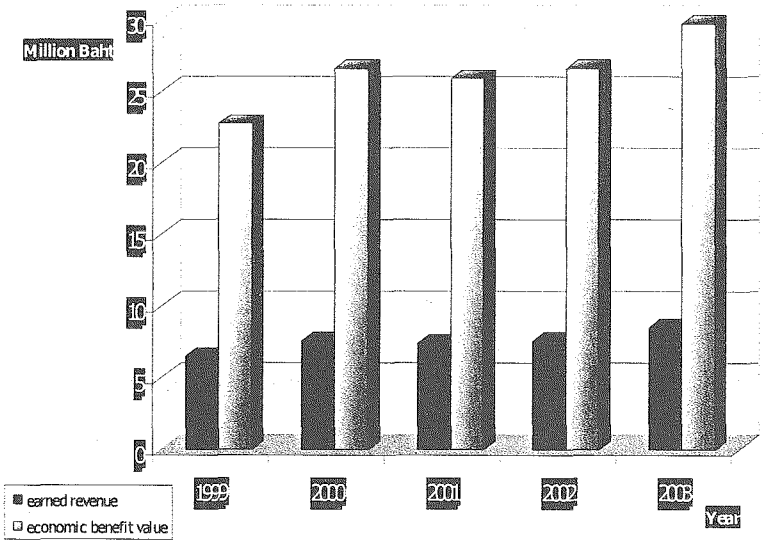
Presently, several research and development on medical radioisotopes have been carried out and the products from successful R&D have been routinely produced and supplied to the users. OAP is the only one radioisotope producer in Thailand. We have provided the products and services with high quality but reasonable price compared to other agencies and that exported from oversea to 20 nuclear medicine centers and hospitals in Thailand. As a non-profit government organization, our products and services are provided to support the Thai community mainly for healthcare. Pricing of

the products and services is based on production cost with non-profit added. The price is 2-5 times cheaper than that the imported products. The earned revenue from selling products and services during the past 5 years from 1999-2003 are 37.6 million baht. Therefore, it is estimated that the economic benefit value for saving foreign currency over the past 5 years is 131.6 million baht.

**Nuclear Medicine Center in Thailand**

| | |
|---|---|
| Government Hospitals: | 15 |
| Private Hospitals: | 5 |
| No.of SPECT: | 25 |
| No.of Gamma Camera: | 12 |
| Studies-Diagnostic | >104,000 cases |
| Therapy Administration | >90,000 cases |

**The earned revenue from selling products and services during the past 5 years**




## Conclusion

OAP, as a government organization, is responsible for research development and service of radioisotopes. Almost of the products and services are mainly utilized for medical purpose for both diagnosis and therapy. Although the production scale can not reach the whole national demand due to some limitations of the reactor, but the major parts of the nation consumption are able to fulfill. The radioisotopes and the services are provided with high quality but reasonable price. This policy will give the opportunity to the community to utilize these radioisotopes for their healthcare.

# 1.16 EVALUATION OF $^{99}Mo/^{99m}Tc$ GENERATOR EXPERIMENT USING PZC MATERIAL AND IRRADIATED NATURAL MOLYBDENUM

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ABSTRACT

Technetium-99m ($^{99m}Tc$), the most widely used radioisotope in nuclear medicine, is almost exclusively produced from the decay of its parent molybdenum-99 ($^{99}Mo$). The present sources of $^{99}Mo$ are research reactors by using the (n,γ) nuclear reaction with natural molybdenum, resulting in inexpensive but low specific activity $^{99}Mo$, or by neutron-induced fission of uranium-235, which result in expensive but high specific activity $^{99}Mo$. The technology requirement for processing of $^{99}Mo$ from the (n,γ) "activation method" is rather simple, and is within the reach of most developing countries operating research reactors. In the "fission method" the technological and infrastructure requirements are some complex, and possibly can be sustained only by countries with advanced nuclear technology. To overcome these difficulties, Japan Atomic Energy Research Institute (JAERI) and KAKEN company have developed alternative technology for $^{99}Mo/^{99m}Tc$ generator by using a molybdenum absorbent called Poly Zirconium compound (PZC) and irradiated natural molybdenum.

This paper described experiment to evaluate not only the performance of PZC as a column packing material for $^{99}Mo/^{99m}Tc$ generator from $(n,\gamma)^{99}Mo$, but also the quality of $^{99m}Tc$ obtained from PZC-based generator. Chemical and biological characteristics of $^{99m}Tc$-$NaTcO_4$ were evaluated for medical use.

It was found that some batches of PZC showed high performance for being used as a column packing material. Technetium-99m pertechnetate eluted from PZC-based generator met all the requirements for technetium-99m pertecnetate for injection as stated in pharmacopoeia. Labeling and biodistribution test of some radiopharmaceutical kits labeled with Tc-99m from both commercial and PZC-based generator showed similar pattern. It is noted that this newly developed PZC material for Tc-99m generator is promising as an alternative.

Keywords: $^{99}Mo/^{99m}Tc$ generator, polyzirconium compound, natural molybdenum

## Introduction

Technetium-99m is the most widely used radioisotope in nuclear medicine, accounting for more than 80% of all diagnostic nuclear medicine, because of its excellent physical properties which make it an ideal radioisotope in organ imaging techniques. $^{99m}Tc$ is almost exclusively produced from the decay of its parent $^{99}Mo$ and most of the commercial $^{99}Mo/^{99m}Tc$ generators are still produced based on column chromatography over aluminium oxide which adsorbed $^{99}Mo$ obtained from fission products of $^{235}U$. This type of generator has several disadvantages which limit its practical application. The major one is the limitation of the adsorption capacity for molybdate ions which requires

the use of high specific activity $^{99}Mo$ in the preparation of chromatographic generators of reasonable size which allows rapid elution in small volume because of the limitation of the adsorption capacity of alumina for molybdate ions (20 mg.Mo per gram of alumina). In countries which do not have a nuclear reactor with sufficient neutron flux and technology to handle fission products of $^{235}U$, it is almost impossible to prepare chromatographic generators suitable for medical use.

Recently, KAKEN Co. and JAERI (Japan Atomic Energy Research Institute) have developed a new inorganic adsorbent (Poly-Zirconium Compound : PZC) for $^{99m}Tc$ generator using low specific activity Mo-99 obtained from (n,γ) reaction of natural Mo. PZC synthesized from $ZrCl_4$ and isopropyl alcohol is an organic polymer with the framework of -O-Zr-O-Zr-Cl. After the dissolution of irradiated $MoO_3$ target in NaOH , $MoO_4^{-2}$ is bound to Zr through the hydrolysis of a part of Zr-Cl. As a result, $^{99}Mo$ is chemically adsorbed (bound) strongly into the PZC together with stable Mo. $^{99}Mo$ on the PZC converts to $^{99m}Tc$ through $\beta^-$ decay. Because the Zr-$^{99m}Tc$ bond is easily cut, $^{99m}Tc$ is simply eluted by normal saline.

Seven batches of PZC materials were provided by KAKEN Co., Japan. In addition to the performance of PZC-based generator such as Mo-99 adsorption, Tc-99m elution yield and Mo-99 breakthrough, the experiments in 2004 was focused on quality of $^{99m}Tc$ solution obtained from PZC-based generator in terms of labeling and biodistribution test. Labeling and biodistribution test with some radiopharmaceutical kits were conducted and the results were compared with those from kits labeled with Tc-99m from commercial generator.

## Experimentals

### 1. Preparation of PZC-based generator

The procedure for experiments was specified by KAKEN Co. Briefly, 2 g of $MoO_3$ was irradiated with thermal neutrons. Dilute the solution with water to 25 ml (53.4 mg Mo/ml), the resulting solution is called the original $^{99}Mo$ solution. A 5-ml aliquot of the original $^{99}Mo$ solution was neutralized to pH7, adjusted volume to 20 ml with water and added 1 g of PZC before incubating at 90°C for 3 hours with occasionally shaking.

After decantation of fine powder from the mixture, the $^{99}Mo$-PZC was packed into a chromotographic column and washed with 20 ml normal saline. Ten milliliters of 0.9% saline solution was used to elute Tc-99m from the column 24 hours after column packing.

Molybdenum adsorption capacity of PZC, loss of fine powder and $^{99m}Tc$ elution yield were calculated as previously described.

Irradiation condition

| | | |
|---|---|---|
| Reactor | : | Thai Research Reactor-1/Modification1(TRR-1/M1)<br>Operate at 1.2 MW. |
| Neutron flux | : | $2.0 \times 10^{13}$ n/cm$^2$-sec |
| Irradiation period | : | Tuesday 12 hrs. Wednesday 12 hrs.<br>Thursday 12 hrs. and Friday 10 hrs. |

## 2. Quality control of pertechnetate solution

Quality control of sodium pertechnetate solution was performed according to the official procedure established by Isotope Production Program, OAP. The radionuclidic purity of pertechnetate solution was analyzed by HPGe coaxial detector (EG&G ORTEC). Al, Mo-98 and Zr were determined by using mordant blue, KSCN and arsenazo III as a color-forming reagent respectively. The radiochemical purity was detected by ITLC-SG in 85% MeOH. The pH of solution was also checked.

## 3. Labeling and biodistribution test

MAG3, MDP and DTPA kits were used to evaluate the labeling efficiency of pertechnetate solution. Radiopharmaceutical kits were labeled and radiochemical purity was determined by the following chromatographic system.

| kits | Stationary phase | Mobile phase |
|---|---|---|
| MDP | ITLC-SG | 0.9% NaCl |
| | ITLC-SG | acetone |
| MAG3 | ITLC-SG | 85% MeOH |
| | Whatman no.1 | acetonitrile |
| DTPA | ITLC-SG | 0.9% NaCl |
| | ITLC-SG | MEK |

Spraque Dawley rats and Swiss albino mice were used in biodistribution test for MDP and MAG3 respectively. Approximately 500 μCi in 0.1 ml of MDP and 20 μCi in 0.1ml of MAG3 were injected through the tail vein. After a prescribed time interval has elapsed, the animals were killed for tissue samples which were weighed and counted by NaI(Tl) detector. The results of biodistribution studies were expressed as percent injected dose per gram of each organ.

## Results and discussion

In order to obtain sufficient Tc-99m for labeling and biodistribution test, 3.5-4 g of PZC were used for column packing. The Mo adsorption capacity of PZC, loss of fine PZC powder and $^{99m}$Tc elution yield were shown in table1. Technetium yield from PZC batch B040527-30M, 35M and 45M were significantly lower than that from the other four batches. PZC lot B041112-10M-TEOS exhibited very small amount of fine powder loss and gave good elution flow rate, which was probably owing to TEOS coating. In spite of high Mo adsorption capacity and $^{99m}$Tc yield of PZC B041112-10M and 12.5M, high percent loss of fine powder were observed.

Table 1 Mo adsorption capacity, loss of fine powder and $^{99m}$Tc elution yield from seven batches of PZC.

| batch no. of PZC | Mo adsorption (mg Mo/g PZC) | %Loss of fine powder | %$^{99m}$Tc elution yield |
|---|---|---|---|
| B040527-30M | 167.46 | 8.37 | 63.04 |
| B040527-35M | 170.54 | 9.37 | 69.14 |
| B040527-45M | 145.71 | 3.12 | 47.39 |
| B041112-10M | 213.53 | 10.51 | 91.72 |
| B041112-12.5M | 219.77 | 12.49 | 88.29 |
| B041112-15M | 160.41 | 8.07 | 95.03 |
| B041112-10M-TEOS | 180.96 | 0.12 | 92.88 |

Sodium pertechnetate solution obtained from PZC generator met the requirements under Sodium pertechnetate Tc-99m injection in the Specification of Primary Isotope (Isotope Production Program, OAP) as summarized in table 2.

Table 2 Chemical characteristics of $Na^{99m}TcO_4$ from PZC-based generator

| specification | requirement | $NaTcO_4$ from PZC column |
|---|---|---|
| pH | 4-7 | 5.5-5.8 |
| Radiochemical purity | ≥ 95% | ≥ 95% |
| Mo 99 breakthrough | ≤ 0.15μCi/mCi $^{99m}$Tc | ≤ 0.15μCi/mCi $^{99m}$Tc(1) |
| Mo-98 | < 5 ppm | < 5 ppm |
| Al | < 2 ppm | < 2 ppm |
| Zr | - | < 1 ppm |

(1) Mo-99 measured after passing through alumina column

The radiochemical purity of some kits labeled with Tc-99m from seven batches of PZC was more than 90%. Table 3 showed the radiochemical purity of radiopharmaceuticals which were labeled with Tc-99m from both PZC-based and commercial generator.

Table 3 Radiochemical purity of $^{99m}$Tc-labeled radiopharmaceutical kits

| Radiopharmaceutical kit | % radiochemical purity | |
|---|---|---|
| | Commercial generator | PZC-based generator(1) |
| MDP | 97.3 | 96.8-99.5 |
| MAG3 | 98.0 | 95.9-99.4 |
| DTPA | 98.5 | 96.8-98.9 |

(1)from seven batches of PZC

The biodistribution of $^{99m}$Tc-MDP in selected organs were demonstrated in figure 1. The data was obtained one hour after injection. Figure 2 showed the biodistribution data 10 minutes after $^{99m}$Tc-MAG3 injection. It was found that radiopharmaceutical kits such as MDP and MAG3 labeled with Tc-99m from both PZC-based and commercial generator showed similar biological characteristics.

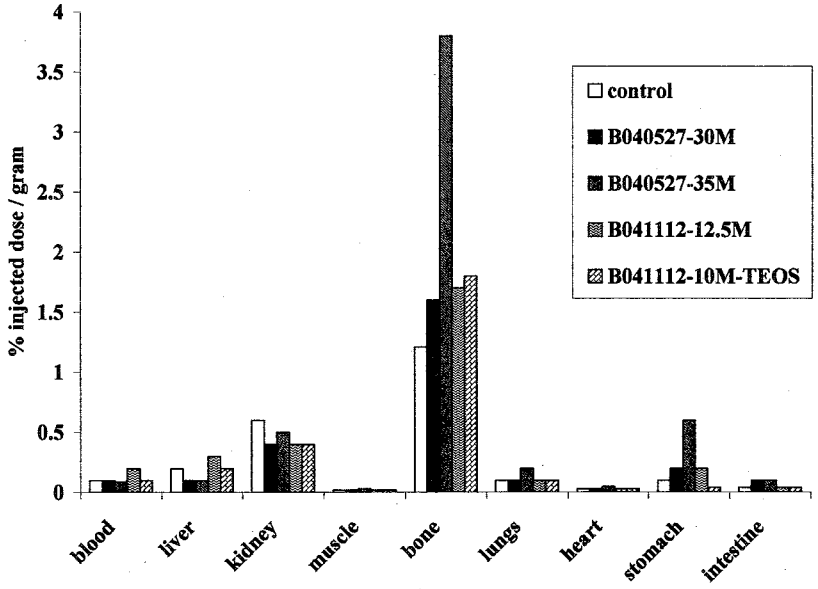


Figure 1 Biodistribution data of $^{99m}$Tc-MDP in rat 1 h after injection.

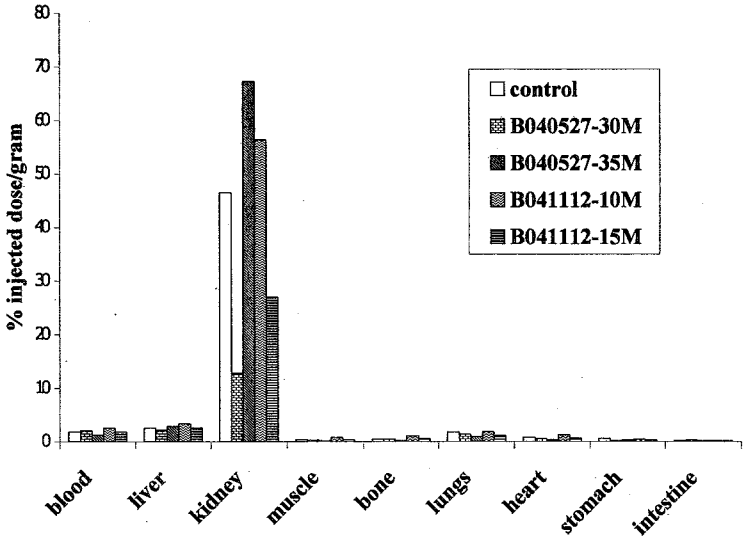


Figure 2 Biodistribution data of $^{99m}$Tc-MAG3 in mine 10 min. after injection.

## Conclusion

Although some batches of PZC showed slightly low Mo adsorption and Tc-99m yield, but all $^{99m}$Tc-$NaTcO_4$ obtained from PZC column revealed satisfactory results. It is strongly believe that $^{99m}$Tc-$NaTcO_4$ from PZC-based generator is suitable for medical use according to its chemical and biological characteristics which is comparable to those of $^{99m}$Tc-$NaTcO_4$ from (n,fission)$^{99}$Mo/$^{99m}$Tc generator.

It could be concluded that PZC exhibited high performance for (n,γ)$^{99}$Mo/$^{99m}$Tc generator and is promising as an alternative for fission $^{99}$Mo generator which will benefit the countries operating small research reactors.

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# 2. Summary Report

Neutron Activation Analysis

Research Reactor Technology

Tc Generator Technology

Round Table Discussion

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# SUMMARY REPORT OF THE FNCA 2004 WORKSHOP ON THE UTILIZATION OF RESEARCH REACTORS

***January 13 – 21, 2005***
***Bangkok, Thailand***

This document presents a summary on the implementation of the FNCA 2004 Workshop on the Utilization of Research Reactors held in Bangkok, Thailand from January 13 to 21, 2005. The workshop discussed three fields of activities, Neutron Activation Analysis (NAA), Research Reactor Technology (RR) and Tc-99m generator Technology (TCG). It was attended by scientists and technical specialists from China, Indonesia, Japan, Korea, Malaysia, the Philippines, Vietnam, and Thailand. A summary of the discussions, progress reports and future programs of each group are presented below.

## 1. Neutron Activation Analysis

This report consists of two parts; a summary of sub-workshop and a summary of workshop in which an evaluation of the 2002-2004 activity are included.

### 1.1 A summary of sub-workshop.

A sub-workshop on ko-IAEA was taken place from January 13 to January 15 at the OAP, Thailand. This sub-workshop was planned to introduce ko-IAEA software to our group countries. An expert on IAEA-ko software (Dr. Menno Blaauw, Technical University of Delft, Netherlands) was sent to us from IAEA on this occasion. A total of twelve participants from 7 countries met at the sub-workshop. During the course, some corrections and suggestions on the present version have been recommended by the group. This was the first time for ko-IAEA to be released to NAA users. Both participants and an expert shared worthwhile time.

During the workshop following the technical course on ko-IAEA, NAA group first summarized the sub-workshop in the following; (i) the FNCA sub-workshop on ko-IAEA software has been successfully implemented and (ii) participants need time to get accustomed with the software to fully experience the utilization of the software. They further confirmed the present status for the application of ko-standardization method and the intention for the use of ko-software for the future project, which are summarized in the following table.

| Country | Up to 2004 | From 2005 |
|---|---|---|
| China | ko-CIAE | ko-CIAE, ko-IAEA for comparison |
| Indonesia | | Comparison of DSM, ko-CIAE and ko-IAEA |
| Japan | DSM | Comparison of DSM and ko-IAEA |
| Korea | | (Comparison of DSM, ko-CIAE and ko-IAEA) |
| Malaysia | ko-Dalat | Comparison of ko-Dalat and ko-IAEA |
| Philippines | | ko-IAEA in collaborating research institute |
| Thailand | | ko-IAEA in comparison with other software |
| Vietnam | ko-Dalat | ko-Dalat, ko-IAEA for comparison |

Now that all countries are ready to apply ko-IAEA to NAA for routine analyses of environmental samples and will be able to use more than one software, it was agreed at the workshop that we would assess the ko-IAEA software by comparing data between ko-IAEA and other ko-software and further that we would have a session of discussion for this subject at the next workshop. Such an assessment can contribute to upgrade the ko-IAEA.

### 1.2 A summary of workshop

The workshop was taken place from January 17 to January 21, 2005 at Meeting Room 103, Building No. 4, OAP. The NAA workshop was divided into five sections; (1) reports on air particulate samples, (2) summary of the current project, (3) discussion on action items, (4) discussion on marine samples and (5) evaluation of the current project. Each section is briefly summarized as follows.

(1) Reports on air particulate samples

Reports were presented by participants from individual countries. Titles and presenters (in parentheses) of reports are shown in the following;

(i) Progress report for 2004 workshop of FNCA (Ni Bangfa, China)

(ii) Analysis of Airborne particulate matter collected in urban and rural area by instrumental neutron activation analysis (Sutisna, Indonesia)

(iii) Elemental compositions of atmospheric particulates collected in Japan in first half year of 2004 (Y. Oura, Japan)

(iv) Chemical characterization of urban air particulate matter of Kuaka Lumpur 2002-2004 (Wee B. S., Malaysia)

(v) Roadside air particulate monitoring in the PM10 range (F. L. Santos, Philippines)

(vi) Using ko-INAA for determination of trace multi-element in APM and marine samples collected in period of 2002-2004 (Ho M. D., Vietnam)

(vii) INAA of airborne particulate matter collected in Bangkok and Pathumthani 2002-2004 (W. Chueinta, Thailand)

(viii) Roles of environmental monitoring toward the better environment (T. Otoshi, Japan)

(2) Summary of the current project

As this year is the last year of the current project, we have discussed how to summarize all data for SPM obtained in 2002-2004 and came to conclude to show our activities in two different ways as described below.

(i) Compilation of all SPM data for putting on a web site.

All data for SPM are to be sent by March 31, 2005 to Wee B. S., who is then responsible for compiling these data. In addition to the data, some accompanying information needs to be sent at the same time. The format which was once prepared by W. Chueinta is to be used as a common format. Data with such information will be put on a web site. The web site of FNCA must be the most appropriate. Once the FNCA office of Japan agrees, Wee B. S. will send all compiled data to T. Mori of JAIF, who is responsible to put them on the web site.

(ii) Publication of a booklet

Comprehensive report on 2002-2004 data is prepared by each country. This report includes interpretation and discussion as well as all data (monthly data for three years for two sites). The accompanying information used for the above-mentioned compilation has to be also included in this report. A report is to be submitted by each country by no later than April 30, 2005 (hopefully in March) to T. Mori of JAIF, who is responsible to compile and edit all reports for their publication as a booklet. It is strongly requested that JAIF supports its printing and distributing. Booklets are desired to be widely sent to places such as institutions of NAA groups, government offices responsible for environmental protection policy and public organizations for monitoring environment.

(3) Discussion on action items

There are two groups of action item; action items proposed in 2002-2003 and action items proposed in 2004. The latter items were discussed in relation with sections (4) and (5) and will be individually mentioned in corresponding parts described later. Here, action items proposed in 2002-2003 were discussed separately and discussions are summarized as follows. Names in parentheses are persons in charge.

(i) Collaborative paper on 2002 data (M. Ebihara)

Final manuscript will be completed in a month and will be submitted to an appropriate journal by February 28, 2005.

(ii) QA/QC on INAA for small samples (W. Chueinta)

Data should be submitted to W. Chueinta by May 31, 2005. The draft for submission will be prepared by her by the 2005 FNCA workshop of NAA group.

(iii) QA/QC of INAA for rock samples (A. K. H. Wood)

Because this action item is almost overlapped with the above item, this item was deleted.

(iv) Comparison of SPM data between INAA and XRF (F. L. Santos and Y. Oura)

Assessment will be finished by March 31, 2005. Drafting a manuscript for submission will end by June 30, 2005.

(v) Comparison of NAA data from different ko-software (Y.-S. Chung, Ho M. D.)

Ho M. D. is responsible for contacting with Y.-S. Chung and ask of the completion of this action item.

(4) discussion on marine samples

Discussion on marine samples was made for two subjects; (i) evaluation of data for three standard reference samples and (ii) proposals for the next project.

(i) Evaluation of data for three standard reference materials of marine-related samples

Responding to the first action item proposed in 2004, analytical data for three SRM (sediment, sargasso, oyster) were submitted by all countries. These data were compiled in spreadsheets for individual samples and critically evaluated for each of them. Individual countries were asked to check their own data if there seem to be some inconsistencies in comparison with reference values. Data will be further compiled by Ho M. D. Each country is required to report final data sets for three samples to him by June 30, 2005. After compiling and editing all data, Ho M.D. may positively consider a possibility for reporting to an appropriate journal like J. Radioanal. Nucl. Chem.

(ii) Proposals for the next project (the second action item proposed in 2004)

Each country proposed detailed scheme of sampling and analyzing marine-related samples like marine biota and marine sediment, which is summarized in the following table;

| Country | Sort of samples | sampling frequency* | # of samples** | Optional |
|---|---|---|---|---|
| China | fish, mussel, clam (or sea weeds) | twice | 5 | |
| Indonesia | mussel, sea weeds, fish | quarterly | 1 | |
| Japan | mussel, oyster, clam, crab | at least once (quarterly) | 5-10 | Shells are to be samples. |
| Malaysia | clam, mussel | twice | 5 | |
| Philippines | mussel, sea weeds | twice | 5-10 | |
| Thailand | mussel, oyster, clam | twice | 5 | |
| Vietnam | mussel, clam, algae (or sea weeds), fish, sediment | quarterly | 5 | |

*per year.

**per each species and site.

The following conditions are mostly common in all countries:

(a) Sampling site: two sites

(b) Way of sampling: All countries collect samples from fisherman and/or local market. In addition, Vietnam obtain sediment samples in collaboration with ocean institute.

(c) Sample preparation: freeze-dry.

(d) Analytical technique: ko-INAA (except for Philippine, where XRF is used and comparison of data between XRF and NAA is to be done).

(e) Objective: monitoring

Mussel is analyzed by all countries as a common sample. Two sample types including mussel are to be analyzed as minimum requirement. Marine biota rather than marine sediment is targeted, considering that biota samples seem to be sensitive to the environment. The project will start from coming May if it is authorized at the next coordinators' meeting in March, 2005.

(5) Evaluation of the current project

Based on evaluation sheets submitted from all participating countries, a draft of the project evaluation report had been prepared by a project leader and its copy was distributed during the workshop. After intense discussion, the draft was revised and the final version of the evaluation report (see separate sheets) was prepared.

In relation with this subject, we have the third action item proposed in 2004; action reports for appealing of our NAA data on environmental samples to the authorities for environmental protection. Followings are summaries of presentations from individual countries.

(i) (China) NAA data for SPM are routinely sent to the data monitoring center in Beijing and used for assessing the pollution level in the city. NAA is well acknowledged to be important tool for such a purpose. Data of marine samples also are used for the same purpose.
(ii) (Indonesia) There is a good collaboration between BATAN for analyzing of SPM and other institute for collecting of SPM. NAA data of SPM are reported to environmental authorities. Analysis people often discuss with them on NAA data. NAA data of marine samples are to be reported to environmental authorities.
(iii) (Japan) There have been well organized monitoring networks for SPM throughout the land. Regrettably, NAA has not been well recognized as an important tool for monitoring the environment, possibly because the number of NAA data reported to the authorities concerned is relatively small compared to those from other analytical methods like XRF and ICP-MS. Collaboration with other governmental institutes of environmental sciences has been initiated for SPM and will be extended for marine samples. Through such a collaboration, NAA must be actively appealed to the environmental authorities.
(iv) (Malaysia) There is a highly functional structure for institutes including MINT and the authorities concerned with SPM, where NAA data can be discussed. A project for marine sample has been already launched at MINT for monitoring the marine environment. NAA data on both SPM and marine samples have been appealed to the authorities.
(v) (Philippines) There has been a strong linkage for many years between PNRI and governmental authorities in addressing the environmental issues. On many occasions, the PNRI has provided environmental data such as SPM to the authorities. The data on marine samples will also be submitted to governmental authorities.
(vi) (Thailand) Regarding SPM, OAP has been having a close connection with governmental authorities of the environmental protection, because NAA data can be obtained only at OAP and NAA is well acknowledged as an effective and reliable tool for analyzing SPM. Although there is no such a connection for marine sample at this stage, a similar connection to that for SPM must be made soon.
(vii) (Vietnam) Nowadays, only NAA data of SPM have got less effective to appeal to the authorities of the environmental protection. Such a situation has been yielding a close collaboration between NRI-Dalat and other institutes for monitoring environment as a regular duty. A similar collaboration can be established for marine samples soon.

## 2. Research Reactor Technology

### 2.1 Objective

The objectives of the Research Reactor Technology Group Workshop are to share information on the current status of research reactors among the participating countries and to determine detailed contents of the new project on "Research Reactor Technology for Effective Utilization".

### 2.2 Opening

(1) Workshop Review

Mr. Toshio Kosugi indicated the circumstances up to the present and proposed that the new project would be "Reactor Physics (Neutronics)".

(2) Special Lecture by Prof. Seiji Shiroya

"Present Status of Kyoto University Research Reactor Institute (KURRI)"

In December 2004, Kyoto University formally decided to continue the operation of a 5 MW research reactor KUR by converting the fuel loaded in the core from high enriched uranium (HEU) to low enriched uranium (LEU), although KURRI will obliged to shut down the KUR for a certain period from the beginning of fiscal year 2006 because of the regulation

procedure for the fuel conversion. This decision was made in accordance with the change in policy of the United States. It was very fortunate that the Department of Energy (DOE) decided at the end of November 2004 to extend the acceptance period for 10 years for U.S.-origin spent fuel used in the research reactors in other countries. The local governments already accepted KURRI's proposal to continue the operation of KUR. The KUR will be operated mainly for the clinical irradiation and the activation analysis for around 10 years in the future.

On the other hand, a new project called the KART&LAB (Kumatori Accelerator driven Reactor Test facility and innovation research LABoratory) project aimed at executing a feasibility study on the accelerator driven subcritical reactor (ADSR) is in progress under the financial support by Ministry of Education, Culture, Sports, Science and Technology (MEXT) of Japan. In accordance with this 5-year project from the fiscal year 2002, the construction of innovation research laboratory was completed in March 2004, where a new accelerator system of fixed field alternating gradient (FFAG) proton synchrotrons will be installed to make a series of experiments on the ADSR in combination with the Kyoto University Critical Assembly (KUCA). Now, the regulation procedure for the combination of the KUCA and the FFAG system, and the construction of FFAG complex with the capability of variable energy from 2.5 MeV up to 150 MeV are under way to realize a first experiment in the world on the ADSR at the end of this year 2005. Moreover, a series of experiments on ADSR is steadily in progress at the KUCA by using 14 MeV neutrons generated from the Cockcroft-Walton type accelerator installed in the KUCA. Valuable information on the nuclear characteristics of ADSR has already been obtained through these experiments and the conceptual neutronics design study on ADSR.

### 2.3 Country Reports

(1) China

"Utilization of MCNP Code in the Research and Design for China Advanced Research Reactor" by Mr. Shen Feng

MCNP(3B), which is the internationalized neutronics code and based on probability transport equation among neutrons, photons and electrons, is used for nuclear research and design in China Advanced Research Reactor (CARR). As an important neutronics code, many calculation tasks could be undertaken by it. Firstly, many necessary data on reactor core could be calculated by MCNP such as power distribution, reactivity, neutron energy spectrum, radiation exposure, and so on. Fuel power of any assembly can be tallied with any geometry division under certain reactor power by MCNP, so power distribution is very easy to be obtained. So is the power of any part and any location in the reactor core. The criticality calculation, which can result in many parameters such as excess criticality, shutdown margin, control rod worth, many reactivity coefficients and so on, is essential function in this code. The neutron energy spectrum can be calculated since the continuous cross-section is applied in code which maybe helpful to analyze the correctness of many results. It also can be calculated for the radiation exposure even though sometimes some special technique and tip are necessary for its intrinsic error in long penetration. Secondly, MCNP is also a useful tool to investigate and optimize the important parameters for many reactor utilizations. CARR is multipurpose research reactor which includes many application plans such as radio-isotope production, neutron scattering experiment, Neutron Activation Analysis (NAA), Neutron Transmutation Doping (NTD) and so on. Many experimental channels are located at different direction with different size and difficult to calculate its parameter by the code based on diffusion theory. MCNP have been used in study and design for the Cold Neutron Source (CNS), RI production until now on CARR. Thirdly, MCNP code could provide much verification for other nuclear calculation code that produces group parameters. This code can

compensate the disadvantage of diffusion theory and verify the group parameter for fuel assembly and control rod. Until now, MCNP is an indispensable nuclear calculation code and used to achieve many research and design tasks for CARR.

(2) Indonesia

"Aging Management and Experience in Safety Operation of the Indonesian Research Reactors" by Mr. Iman Kuntoro

BATAN operates three research reactors TRIGA-2000 at Bandung, 2 MW, KARTINI at Yogya, 100 kW and RSG-GAS at Serpong, 30 MW. The reactors operate routinely to serve R&D and radioisotope production. By now the all reactors reached ages of 40, 25 and 17 years old. Hence, aging management becomes an important activity to maintain the safe operations. Operating experience and aging management of those reactors were reported.

(3) Japan

"Current Status of Operation and Utilization of Research Reactors in JAERI" by Mr. Hisashi Sagawa

There are several research and test reactors including a critical facility in JAERI. Of these research reactors, JRR-3, JRR-4 and JMTR are utilized widely by a large number of researchers. The JMTR is a test reactor to evaluate radiation damage of structural materials in fission or a fusion reactor and behavior of nuclear fuels. The current status of research reactors in JAERI i.e. JRR-3 and JRR-4 were reported. The JRR-3 is operated in continuous runs of 26 days per cycle and 7 cycles per year for mainly neutron activation analysis, neutron scattering experiments, radioisotope production and silicon doping. From the first start-up after modification to the end of December 2004, it totaled about 58,000 hours of operation and the accumulated integrating power was about 46,000 MWd. The JRR-4 is operated in daily runs of 4 days per week and 42 weeks per year for mainly neutron activation analysis, radioisotope production, silicon doping, training and medical irradiation. From the first start-up after modification to the end of November 2004, it totaled about 5,900 hours of operation and the integrating power was about 570 MWd. With regard to utilization of JRR-3 and JRR-4 from April to December 2004, 1,996 capsules, which are used for neutron activation analysis, radioisotope production, silicon doping and so on, were irradiated, 943 experiments for neutron scattering were carried out and 6 medical irradiations were carried out.

(4) Korea

"HANARO Operation Experience in the Year 2004" by Dr. Soo-Youl Oh

The experiences of HANARO operation and maintenance in the year 2004 are presented. The operation of HANARO, a 30MW research reactor operated by the Korea Atomic Energy Research Institute (KAERI), aims at a safe and effective operation to enhance its utilization in various fields of scientific research and industry. Regardless of its importance of the routine operation, the report is devoted rather unusual matters such as irregular maintenance events and incidents. Since the first criticality in 1995, it has been a long-cherished task to reach the designed power level of 30 MW from the temporarily approved 24 MW. By resolving the concern on the fuel integrity, the designed level could be licensed and, eventually, it was achieved last November. On the other hand, after its 9 years operation, the mechanical integrity of the heavy water reflector tank was checked. The measurement of the vertical straightness of the tank inner shell indicated the integrity. Meanwhile, the HANARO fuel production facility was completed at the KAERI site, and it will begin to supply centrifugally atomized fuels, instead of conventional comminuted fuels, to HANARO shortly. There were several incidents in 2004, which have all been cleared, including a leak of heavy water,

melting of a sample in an irradiation hole for the neutron activation analysis, and a condensation problem in a horizontal beam tube. The progress of and lessons from each incident are presented. The utilization of HANARO is expanding every year and the trend will also continue in 2005. The operation mode has been changed from an 18-day continuous operation and 10-day shutdown (18-10 mode) to the 23-12 mode since the end of 2004, and a further extension is planned to the 30-12 mode. Thanks to this extended operation term, an increased power level and, most importantly, a reliable operation, the HANARO is gaining more and more credit from the end users.

(5) Malaysia

"Operation and Maintenance of the 1 MW PUSPATI TRIGA Reactor" by Mr. Adnan Bokhari

The Malaysian Research Reactor, Reactor TRIGA PUSPATI (RTP) has been successfully operated for 22 years for various experiments. Since its commissioning in June 1982 until December 2004, the 1 MW pool-type reactor has accumulated more than 21143 hours of operation, corresponding to cumulative thermal energy release of about 14083 MW-hours. The reactor is currently in operation and normally operates on demand, which is normally up to 6 hours a day. Presently the reactor core is made up of standard TRIGA fuel element consists of 8.5 wt%, 12 wt% and 20 wt% types; 20%-enriched and stainless steel clad. Several measures such as routine preventive maintenance and improving the reactor support systems have been taken toward achieving this long successful operation. Besides normal routine utilization like other TRIGA reactors, new strategies are implemented for effective increase in utilization, especially in the utilization of neutron beams. The upgrading of the radioisotope handling facilities hopefully will increase the request for the radioisotopes production at the reactor.

(6) Vietnam

"Current Status of Operation and Utilization of the Dalat Research Reactor" by Dr. Nguyen Nhi Dien

The current status of the reactor operation and utilization as well as some results on in-core fuel management of the DNRR was presented. The Dalat Nuclear Research Reactor (DNRR) is a 500 kW pool-type reactor using the Soviet WWR-M2 fuel assembly with 36% enrichment of U-235. It was renovated and upgraded from the USA 250 kW TRIGA Mark-II reactor. The first criticality of the renovated reactor was in November 1983 and its regular operation at nominal power of 500 kW has been since March 1984. The DNRR is operated mainly in continuous runs of 100 hrs, once every 4 weeks, for radioisotope production, neutron activation analysis, scientific research and training. The remaining time between two continuous runs is devoted to maintenance activities and also to short run for reactor physics and thermal hydraulics experiments. From the first start-up to the end of December 2004, it totaled about 27,500 hrs of operation and the total energy released was about 540 MWd. The first fuel reloading was executed in April 1994 after more than 10 years of operation with 89 fuel assemblies (FA). The 11 new FA were added in the core periphery, at previous beryllium element locations. After reloading the working configuration of reactor core consisted of 100 FA. The second fuel reloading was executed in March 2002. The 4 new FA were added in the core periphery, at previous beryllium element locations. The working configuration of 104 FAs ensured efficient exploitation of the DNRR at nominal power for about 3000 hrs since March 2002. In order to provide excess reactivity for the reactor operation without the need to discharge high burnup FA, in June 2004, the fuel shuffling of the reactor core was done. 16 FA with low burnup from the core periphery were moved toward the core center and 16 FA with high burnup from the core center were moved toward the core periphery. The current

reactor configuration using re-shuffled HEU fuel is expected to allow normal operation until around June 2006.

In 1999, the request of returning to Russia HEU fuels from foreign research reactors used Russian fuels was submitted to Russian Government though IAEA. After that, the Russian Research Reactor Fuel Return (RRRFR) Program was established and trilateral discussions among the United State, the Russian Federation and the IAEA started. In this aspect, the Dalat reactor core has been considered to insert fresh LEU FAs instead of fresh HEU FAs. It means that the mixed core of HEU and LEU FAs may be used in the coming years. For these purposes, neutronics and thermal hydraulics calculations and safety analyses should be done.

(7) Thailand

"Current Status of the Thai Research Reactor (TRR-1/M1)" by Mr. Dacharchai Charnbanchee

The first Thai Research Reactor, TRR-1 went critical on 27 October 1962 at the maximum power of 1 MW. It was located at Office of Atoms for Peace (OAP) in Bangkok. Since then, TRR-1 was continuously operated and eventually shut down in 1975. Plate type, high-enriched uranium (HEU) and $U_3O_8$-Al cladding were used as the reactor fuel. Light water was used as moderator and coolant as well. In 1975, because of the problem from fuel supplier and also to supporting the Treaty of Non Proliferation of Nuclear Weapon or NPT, TRR-1 was shut down for modification. The reactor core and control system were disassembled and replaced by TRIGA Mark III. A new core is a hexagonal core shape designed by General Atomics (GA). This reactor is designed for continuous steady-state operation up to 2 MW at any positions in the pool. Moreover, this reactor can be operated in pulsing mode at around 23 MW-sec, the peak power of 2000 MW and a pulsed width at a half of maximum of 10msec. The initial criticality was reached on Nov. 7, 1977. Afterwards, TRR-1 was officially renamed to the Thai Research Reactor-1/Modification 1 (TRR-1/M1). TRR-1/M1 is a multipurpose swimming pool type reactor. The TRR-1/M1 uses uranium enriched at 20% in U-235 (LEU) and ZrH alloy as fuel. Light water is also used as coolant and moderator. At present, the reactor is operating with core No.14. The reactor has been serving for various kinds of utilization namely, radioisotope production, neutron activation analysis, beam experiments and reactor physics experiments. As aging management, the reactor pool was refurbished during 1990-1991 because residual radiation existing in the pool and piping facilities after reactor shutdown is rather high. Since the TRR-1/M1 began in operations in 1977 until now, OAP tried to make every effort to improve efficiency in both reactor operations and utilizations in accordance with the IAEA safety guideline. However, aging problem of the reactor pool including the obsolete equipment of the I&C still remain the major problem for the TRR-1/M1. Therefore, depending on the above problem of the TRR-1/M1 reactor, Ongkharak Nuclear Research Center (ONRC) is established.

"Ongkharak Nuclear Research Center Project" by Mr. Mongkol Julanan

The layout of the Ongkharak Nuclear Research Center and the current situation of construction are introduced. The conceptual design of the new reactor is also shown. The reactor is a pool type and its thermal power is 10MW. It has 6 neutron beam lines which are utilized for HRPD, NRG, PGNAA, BNCT and so on, and it has several vertical irradiation holes for RI production, silicon doping and pneumatic irradiation facilities.

### 2.4 Proposal for New Project from Each Country

(1) The proposal from China

The concrete plan for the new project was not indicated, but Chinese delegate indicated the items to be considered in order to implement the new project, namely aims, role of

research reactor, and so on.

(2) The proposal from Indonesia

Indonesian delegate proposed "Accuracy in neutronics calculation for a better reactor core management" to improve neutronics calculation technique for core management in each member country. In the proposal, he indicated the concrete activities for each year and also proposed of using the RSG-GAS reactor as a benchmark reactor.

(3) The proposal from Japan

Japanese delegate proposed "Sharing Neutronics Calculation Technology for the Operation Management on Research Reactors" to establish the safe and stable reactor operation, to conduct the effective fuel management and to enhance reactor utilization. In the proposal, he indicated the concrete activities for each year and also proposed of using a Monte Carlo code instead of carrying out experiments using a research reactor.

(4) The proposal from Korea

Korean delegate proposed "Enhancement of Accuracy of Reactor Physics Calculation and Sharing physics calculation technology." In the proposal, he indicated the concrete activities for each year. He also proposed to survey the status not only of core calculation methods but also of measuring techniques of reactor physics parameters.

(5) The proposal from Malaysia

The concrete plan for the new project was not indicated, but Malaysian delegate supported the use of common code for core management.

(6) The proposal from Vietnam

Vietnamese delegate proposed "Reactor core management including core analyses and measuring techniques" to optimize the fuel utilization and to enhance effective utilization of the reactor facilities. The concrete plan for each year was not indicated, but he indicated the items to be considered in order to implement the new project.

(7) The proposal from Thailand

Thai delegate proposed the core management with SRAC code system and he presented the status of neutronics calculation.

**2.5 Discussion and Summary**

Considering the importance of using research reactors for radioisotope production, neutron activation analysis, neutron radiography, Neutron Transmutation Doping (NTD), clinical irradiation (BNCT), neutron scattering experiments, and so on, the necessity of sharing common neutronics calculation codes, which enable to analyze neutronics characteristics in detail, was discussed and recognized. Utilization of the common calculation codes would contribute to improve and equalize the level of neutronics calculation among participating countries through discussions based on the common tools towards the enhancement of safe operation and effective utilization of research reactors in the participating countries.

Then the concrete contents were discussed and determined as follows:

(1) Theme Title

"Sharing Neutronics Calculation Techniques for Core Management and Utilization of Research Reactors"

(2) Objective

The objective is to share neutronics calculation techniques among the participating countries for core management on research reactors in order to assure safe and stable operation for effective utilization.

(3) Project Duration

The project duration is three years from Japanese FY2005 to FY2007.

(4) Project Activities

The detailed activities for each year are shown in the Attachment.

(5) Leading Country and Leading Organization

The leading country and the leading organization are Japan and JAERI, respectively.

(6) Common neutronics codes

SRAC system and MVP code.

**Project Activities for FY2005**

| | Preparation | 1st Workshop (January/2006) |
|---|---|---|
| **Leading country** | ● Distribute information on the minimum requirements for computer performance (standard procedure)<br>● Distribute manuals and source programs or executable modules of common code system (SRAC) & Monte Carlo code (MVP) | ● Install common code system & Monte Carlo code<br>● Demonstrate common code system<br>● Provide all information concerning the common code system<br>● Introduce candidates for imaginary cores |
| **Member countries** | ● Prepare information on current status of domestic core management (comparison between measured and calculated values)<br>● Install common code system & Monte Carlo code and execute sample problems | ● Present the current status on domestic neutronics calculation<br>● Present the installation status of the common code system & Monte Carlo code |

**Project Activities for FY2006**

| | Preparation | 2nd Workshop (January/2007) |
|---|---|---|
| **Leading country** | ● Fix imaginary core (2 type cores)<br>Geometry data<br>Material data<br>Calculation condition | ● Instruction of core burn-up calculation on imaginary core<br>● Interim evaluation of activity |
| **Member countries** | ● Core calculation on imaginary core (2 type cores) by common code system & Monte Carlo code | ● Present the results of calculations by common code system & Monte Carlo code<br>● Learn core burn-up calculation |

**Project Activities for FY2007**

| | Preparation | 3rd Workshop (January/2008) |
|---|---|---|
| **Leading country** | ● Prepare 3rd Workshop | ● Present results of calculations<br>● Evaluation of activity<br>● Discussion and proposal for the next project |
| **Member countries** | ● Domestic core calculation by common code system | |

### 3. Tc-99m Generator Technology

In the Tc-99m generator group of the 2004 Workshop, one delegate from each of China, Indonesia, Korea, Malaysia, the Philippines and two delegates from Japan were hosted by Thailand. And nine delegates of Thailand participated. Regrettably the contribution by Viet Nam was not available due to illness of the delegate. The participated delegates promoted the technology of Tc-99m generator using poly-zirconium compound (PZC) as an adsorbent for neutron activated (n, γ) Mo-99.

### 3.1 Evaluation of the collaborative experiments conducted by each country

Following the agreement of the workshop held in Indonesia in January 2004, PZC materials have been distributed to participating countries in June and November 2004 from Japan. The amount of PZC material was 15 grams for each laboratory each time. For these experiments, use of secondary column of alumina and oxidizing agent NaOCl in saline were compulsory to follow the standard protocol issued by FNCA for the production process.

Highlight of the present workshop is the quality test of Tc-99m eluted from the PZC-based generator by labeling. Prior to the workshop, the labeling efficiency for Technetium radiopharmaceutical kit (MDP, for bone diagnosis) was requested to each laboratory as a minimal implementation. The labeling results are summarized in the Table 1 together with the results of chemical purity measurement, both of which are fairly good.

Table 1. Summarization of the experimental results conducted by participating countries

| Country | Radiochemical purity | Labeling efficiency | Remarks |
|---|---|---|---|
| China | | **>98%** *(for MDP)* | |
| Indonesia | **>99%** | **>85~99%** *(for MDP, Pyrophosphate, MIBI, HMPAO,EC, HYNIC-UBI)* | Bio-distribution test using animals has been done and Clinical trial in the hospital is currently ongoing. |
| Korea | | **~100%** *(for MDP)* | |
| Philippines | **99~100%** | | |
| Thailand | **>98%** | **96~100%** *(for MDP, MAG3, DTPA)* | Bio-distribution tests using mice were done. |

The comments from each country for the experimental results are as follows.

China

The experiments showed that the PZC distributed by Japan prepared with different technical process of Mo adsorption has different adsorption efficiency. The fine PZC powder adsorbing Mo should be completely removed to avoid the high Mo breakthrough in the process of elution. The 0.05% NaOCl contained in eluate evidently affects the labeling yield of MDP kits. The $^{99}$Mo-PZC generator system should be further improved, especially the quality of PZC.

Indonesia

Radiochemical purities of $^{99m}TcO4^-$ and several kinds of radiopharmaceutical kits labeled with $^{99m}$Tc milked from fission-type generator and PZC-based generator were compared to confirm

nothing problematic difference and found each purity as high as more than 98%.

Further clinical trials of new $^{99}Mo/^{99m}Tc$ generators at several hospitals in Jakarta and Bandung are planned. Each hospital will receive 6 times of generator shipments for 6 volunteers to be tested. Each generator contains > 300 mCi $^{99}Mo$ in 1 gram of PZC.

Japan

In order to solve the remained quality problems of current PZC material related to strength of granule, pre-heating and sintering conditions were re-examined and modified. In this study a promising practical PZC with superior performance was obtained and optimal conditions for its large scale production were determined.

Korea

The performance of the PZC samples distributed in 2004 seems to be improved with a lesser breakthrough of the $^{99}Mo$, higher material stability, better elution efficiency, etc. compared to the other PZC samples provided previously.

The labeling efficiency was found to be about 100 % without free $^{99m}TcO_4^-$. This quality control study proved the property of $^{99m}TcO_4^-$ from PZC was equivalent to the $^{99m}TcO_4^-$ eluted from commercial fission type $^{99m}Tc$ generator.

Malaysia

Because of renovation of facilities in MINT, all PZC samples distributed by Japan are kept until new facility becomes available. The facility is expected to have a capacity to produce fifty Tc-99m generators per batch.

Philippines

The results obtained for the present batches of PZC, although limited in number of trials and in the level of molybdenum activity loaded in the column, showed that the PZC batches are good molybdenum adsorbent column material for $^{99m}Tc$ generators.

Thailand

Although some batches of PZC showed slightly low Mo adsorption and Tc-99m yield, all $Na^{99m}TcO_4$ obtained form PZC column revealed satisfactory results. It is strongly believed that $Na^{99m}TcO_4$ from PZC-based generator is suitable for medical use according to its chemical and biological characteristics which are comparable to those of $Na^{99m}TcO_4$ from (n, f)$^{99}Mo/^{99m}Tc$ generator.

It could be concluded that PZC exhibited high performance for $(n,\gamma)^{99}Mo/^{99m}Tc$ generator and is promising as an alternative for fission-based generator which will benefit the countries operating small research reactors.

### 3.2 Implementation of the other work plan during the FY2004

3.2.1 Trouble shooting and improvement of the loading system

BATAN, where the machine is installed, investigated (1) the cause of incomplete reaction of PZC with $^{99}Mo$ solution and (2) transfer process problems. The results of investigation and improvement were reported in the Coordinators Meeting held in March 2004 in Tokyo. After that the machine is

running without any problems.

3.2.2 Establishment of a high quality PZC synthesis procedure

Kaken Co. established the strict quality control procedure for synthesizing PZC as an exclusive manufacturer of the key material of PZC.

3.2.3. Clinical trial in hospitals

The clinical trials of PZC based $^{99m}$Tc labeled kits under cooperation with the Hasan Sadikin Hospital in Bandung already started. The trials were conducted on October 21, 2004 for testing with eluted pertechnetate itself for whole body imaging, December 17, 2004 for Myocardial perfusion diagnosis with MIBI and January 5, 2005 for Thyroid gland diagnosis with MIBI.

**3.3 Work plan for FY2005**

3.3.1 Distribution of PZC material

For the joint experiment to establish the QA/QC structure, Japan continues to distribute increased amount of PZC material for each participating laboratory.

3.3.2 Clinical trial in hospital (continued from FY2004)

Additional two hospitals in Jakarta (Cipto Mangunkusumo Hospital with $^{99m}$Tc-HMPAO and Army Hospital with $^{99m}$Tc -EC) are participating and 15 volunteers are ready for testing.

3.3.3 Commercial production and supply of PZC-based Tc-99m generator

The intensive market research, detailed cost study and QC protocols of routine production of PZC-based Tc-99m generator, as well as survey of specifications of radiopharmaceuticals of each country are to be investigated to access the present demand of Tc-99m in the region.

3.3.4 Improvement of computerized loading machine

In order to realize more efficient performance for molybdate-PZC reaction, the mechanism of Mo solution supply and the means of stirring are to be modified.

3.3.5 Publication of Comprehensive Report on PZC-based Tc-99m Generators

The authors of each chapter were nominated and the first draft will be completed by the end of March 2005.

The work plans for FY2005 is summarized in Table 2.

Table 2. Work plan for FY2005

| Items |
|---|
| 1) Distribution of PZC material |
| 2) Clinical trials in hospital |
| 3) Commercial production and supply of PZC-based Tc-99m generator |
| 4) Improvement of computerized loading machine |
| 5) Publication of comprehensive report on PZC-based Tc-99m generators |

### 3.4 Recommendations and suggestions

BATAN can provide the neutron irradiated natural Mo of high radioactivity with free of charge except the cost of container and transportation.

### 3.5 Others

1) As the invited talks, Dr. Hideaki Yokomizo, Deputy Director General, Tokai Establishment of the Japan Atomic Energy Institute made the presentation on "Neutron Sources in Japan" and Dr. Tawatchai Chaiwatanarat, Division of Nuclear Medicine of the Chulalongkorn University gave the presentation titled "Medical Application of Radioisotope in Thailand."
2) Press conference was held after the opening ceremony. Reporters from two media stations (TV and Radio) attended and the report were broadcasted within the same day.
3) Technical visit to the OAP facilities of Research Reactor, Radioisotope Production, Food Irradiation and Mutation Breeding were organized during the workshop.

## 4. Round Table Discussion

4.1 Workshop Summary

Under the chair of Mr. Sakda Charoen, PL of Thailand, and Dr. Hideaki Yokomizo, Chairman of URR field in Japan, summaries of the workshop on Neutron Activation Analysis, Research Reactor Technology and Tc-99m Generator Technology were reported by Prof. Mitsuru Ebihara, Mr. Siripone Chueinta and Dr. Tsuguo Genka respectively. All participants of the workshop agreed on the summary reports.

4.2 Additional remark at the Round Table Discussion

It was agreed to propose to the 6$^{th}$ FNCA Coordinators Meeting that Malaysia be the hosting country for the 2005 workshop by agreement of all participants at the FNCA 2004 Workshop on the Utilization of Research Reactors held in Thailand.

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# Appendix

Schedule

List of Participants

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# Schedule of
# The 2004 FNCA Workshop on the Utilization of Research Reactors
# January 13 – 21, 2005, Bangkok, Thailand

## Sub-Workshop for NAA Session

*~~~ Thursday, 13 January 2005 ~~~*

**Neutron Activation Analysis Group** Reactor Hall, Meeting Room: 103, Building No.4, OAP

| | | |
|---|---|---|
| **09:00 – 09:15** | **Registration** | |
| **09:15 – 09:30** | **Welcoming/Opening Remarks:**<br>- Mr. Manit Sonsuk, Head of the Chemistry Research and Material Science Program<br>- Prof. Mitsuru Ebihara, NAA Project Leader of Japan | |
| **09:30 – 10:30** | **Introduction of IAEA $K_0$ Software (IAEA)** | |
| **10:30 – 11:00** | ***Coffee Break*** | |
| **11:00 – 12:00** | **$K_0$ Method Experiment** | |
| **12:00 – 13:00** | ***Lunch*** | |
| **13:00 – 15:00** | ..Continued | |
| **15:00 – 15:30** | ***Coffee Break*** | |
| **15:30 – 17:00** | **Discussion** | **Chairperson**<br>**Prof. Mitsuru Ebihara** |
| **18:00 – 20:00** | **Reception hosted by MEXT at Pola-Pola Restaurant** | |

*~~~ Friday, January 14, 2005 ~~~*

**Neutron Activation Analysis Group** Reactor Hall, Meeting Room: 103, Building No.4, OAP

| | | |
|---|---|---|
| **09:00 – 10:30** | **$K_0$ Method Experiment** | |
| **10:30 – 11:00** | ***Coffee Break*** | |
| **11:00 – 12:00** | ..Continued | |
| **12:00 – 13:00** | ***Lunch*** | |
| **13:00 – 15:00** | **Discussion** | **Chairperson** |
| **15:00 – 15:30** | ***Coffee Break*** | **Dr. Ho Manh Dung** |
| **15:30 – 17:00** | ..Continued | |

*~~~ Saturday, January 15, 2004 ~~~*

**Neutron Activation Analysis Group** Meeting Room: 103, Building No.4, OAP

| | | |
|---|---|---|
| **09:00 – 10:30** | **$K_0$ Method Evaluation** | |
| **10:30 – 11:00** | ***Coffee Break*** | |
| **11:00 – 12:00** | ..Continued | |
| **12:00 – 13:00** | ***Lunch*** | |
| **13:00 – 15:00** | **Discussion** | **Chairperson** |
| **15:00 – 15:30** | ***Coffee Break*** | **Dr. Wanna Cheuinta** |
| **15:30 – 16:30** | ..Continued | |
| **16:30 – 17:00** | **Closing Remarks:**<br>-Dr. Wanna Cheuinta, NAA Project Leader of Thailand | |

## Workshop on Utilization of research Reactors

*~~~ Monday, January 17, 2005 ~~~*

**Plenary Session** Main Meeting Room, OAP

| | | |
|---|---|---|
| **09:00 – 09:30** | **Registration** | |
| **09:30 – 10:30** | **Welcoming/Opening Remarks:**<br>**Welcome Address :** Mr. Pathom Yamkate, Secretary General of OAP<br>**Remarks :** - Ms. Miwako Shimizu, Special staff of Atomic Energy Division, Research and Development Bureau, Ministry of Education, Culture, Sports, Science and Technology (MEXT)<br>- Dr. Hideaki YOKOMIZO, Chairman of Research Reactor Field<br>**Opening Speech :** Dr. Saksit Tridech, Deputy Permanent Secretary, MOST of Thailand<br>**Master of Ceremony :** Mr. Sakda Charoen , PL, Head of Radioisotope Production Program<br>**Introduction of Participants**<br>**Group Photo** | |
| **10:30 – 11:00** | **Press Conference (Meeting Room 313, OAP) / *Coffee Break*** | |
| | **General Lectures:** | **Chairperson** |
| **11:00 – 11:30** | "Neutron Sources in Japan" by Dr. Hideaki Yokomizo - Japan | **Mr. Sakda Charoen** |
| **11:30 – 12:00** | "Medical application of RI in Thailand" by Dr.Tawatchai - Thailand | |
| **12:00 – 13:30** | ***Lunch*** | |
| | ⋮ | |
| **18:30 – 20:30** | **Reception hosted by OAP at Rachada 1 Chaophya Park Hotel** | |

**Paralel Session**

**Neutron Activation Analysis Group** Meeting Room: 103, Building No.4, OAP

| | | |
|---|---|---|
| **13:30 – 14:00** | **Workshop Review, Perspectives by Prof. Mitsuru Ebihara** | |
| | **Country Report on Air Particulate Samples** | **Chairperson** |
| **14:00 – 14:30** | "Progress Report of FNCA 2004 URR Workshop of NAA Group" by Prof. Ni Bangfa - China | **Ms. Flora Lopez Santos** |
| **14:30 – 15:00** | "Analysis of Airborne Particulate Matter Collected in Urban and Rural Area by Instrumental Neutron Activation Analysis" by Mr. Sutisna - Indonesia | |
| **15:00 – 15:30** | ***Coffee Break*** | |
| **15:30 – 16:00** | "Elemental Compositions of Atmospheric Particulates Collected in Japan in First Half Year of 2004" by Dr. Yasuji Oura - Japan | **Prof. Tsunehiko Otoshi** |
| **16:00 – 16:30** | "Chemical Characterization of Urban Air Particulate Matter of Kuala Lumpur 2002 – 2004" by Mr. Wee Boon Siong - Malaysia | |
| **16:30 – 17:00** | "Roadside Air Particulate Monitoring in the PM10 range at the Poveda Learning Center, EDSA, Metro Manila" by Ms. Flora Lopez Santos - The Philippines | |

*Mon, Jan. 17 - continued*

**Paralel Session**
**Research Reactor Technology Group** Main Meeting Room, OAP

| | | |
|---|---|---|
| **13:30 – 14:00** | **Workshop Review, Perspectives by Mr. Toshio Kosugi** | |
| **14:00 – 14:30** | **"Present Status of KURRI" by Prof. Seiji Shiroya - Japan** | |
| | **Country Report on Research Reactors and Utilization** | **Chairperson** |
| **14:30 – 15:00** | "Utilization of MCNP Code in the Research and Design for China Advanced Research Reactor" by Mr. Shen Feng - China | **Mr. Siripone Chueinta** |
| **15:00 – 15:30** | "Aging Management and Experience in Safety Operation of the Indonesian Research Reactors" by Mr. Iman Kuntoro - Indonesia | |
| **15:30 – 16:00** | ***Coffee Break*** | |
| **16:00 – 16:30** | "Current Status of Operation and Utilization of Research Reactors in JAERI" by Mr. Hisashi Sagawa - Japan | **Mr. Adnan Bin Bokhari** |
| **16:30 – 17:00** | "HANARO Operation Experience in the Year 2004" by Dr. Soo-Youl Oh - Korea | |

**Paralel Session**
**Tc Generator Technology Group** Meeting Room: 122 Building No.4, OAP

| | | |
|---|---|---|
| **13:30 – 14:00** | **Workshop Review, Perspectives by Dr. Tsuguo Genka** | |
| | **Country Report on Radioisotope Production** | **Chairperson** |
| **14:00 – 14:30** | "The Labeling Results of MDP Prepared with Tc-99m Eluted from PZC Based Tc-99m Generator" by Prof. Liu Yishu - China | **Dr. Tsuguo Genka** |
| **14:30 – 15:00** | "Pre-Clinical and Clinical Trial Evaluation of Mo-99/Tc-99m Generator Based on PZC Materials and Neutron Irradiated Natural Molybdenum" by Dr. Abdul Mutalib - Indonesia | |
| **15:00 – 15:30** | "Improvement of the Characteristics of PZC Adsorbent" by Dr. Katsuyoshi Tatenuma - Japan | |
| **15:30 – 16:00** | ***Coffee Break*** | |
| **16:00 – 16:30** | "Quality Control of Tc-99m Solution Produced by PZC Generator and Production Status of Tc-99m Generator in Korea" by Mr. Hyon-Soo Han - Korea | **Ms. Adelina Dela Mines Bulos** |
| **16:30 – 17:00** | "Radioisotopes Development and Production in Malaysia" by Mr. Wan Anuar Wan Awang - Malaysia | |

~~~ *Tuesday, January 18, 2005* ~~~

**Parallel Session**

**Neutron Activation Analysis Group** Meeting Room: 103 Building No.4, OAP

| | **Country Report on Air Particulate Samples** | **Chairperson** |
|---|---|---|
| **09:00 – 09:30** | "Using of k0-INAA for Determination of Trace Multi-Element in APM and Marine Samples Collected in Period of 2002-2004" by Dr. Ho Manh Dung - Vietnam | **Mr. Wee Boon Siong** |
| **09:30 – 10:00** | "INAA of Airborne Particulate Matter Collected in Bangkok and Pathumthani 2002-2004" by Dr. Wanna Chueinta - Thailand | |
| **10:00 – 10:30** | ***Coffee Break*** | |
| **10:30 – 11:00** | "Summary of Sub-workshop on NAA-k0 Method" by Dr.Sirinart Laoharojanaphand - Thailand | **Dr. Yasuji Oura** |
| **11:00 – 11:30** | "Roles of Environmental Monitoring Toward the Better Environment" by Prof. Tsunehiko Otoshi - Japan | |
| **11:30 – 12:00** | **General Discussion on Air Particulate Sample Analysis** | **Chairperson** |
| **12:00– 13:30** | ***Lunch*** | **Prof. Mitsuru Ebihara** |
| **13:30 – 14:30** | ..Continued | |
| **14:00 – 15:00** | **Report and Discussions on "Home Works" in 2003-2004** | **Chairperson** **Prof. Mitsuru Ebihara** |
| **15:00 – 15:30** | ***Coffee Break*** | |
| **15:30 – 17:00** | **Report and Discussion on Standard Marine Sample Analysis** | **Dr. Ho Manh Dung** |

**Paralel Session**

**Research Reactor Technology Group** Main Meeting Room, OAP

| | **Country Report on Research Reactors and Utilization** | **Chairperson** |
|---|---|---|
| **09:00 – 09:30** | "Operation and Maintenance of the 1MW PUSPATI TRIGA Reactor" by Mr. Adnan Bin Bokhari - Malaysia | **Mr. Iman Kuntoro** |
| **09:30 – 10:00** | "Current Status of Operation and Utilization of the Dalat Research Reactor" by Dr. Nguyen Nhi Dien - Vietnam | |
| **10:00 – 10:30** | ***Coffee Break*** | |
| **10:30 – 11:00** | "Current Status of the Thai Research Reactor (TRR-1/M1)" by Mr. Siripone Chueinta - Thailand | |
| **11:00 – 11:30** | "Ongkharak Nuclear Research Center Project" by Mr. Mongkol Jullanan - Thailand | |
| **11:30 – 13:00** | ***Lunch*** | |
| | **Project Proposal** | **Chairperson** |
| **13:00 – 13:45** | Mr. Shen Feng - China | **Dr. Soo-Youl Oh** |
| **13:45 – 14:30** | "Project Proposal for Research Reactor Technology Group" by Mr. Iman Kuntoro - Indonesia | |
| **14:30 – 15:00** | ***Coffee Break*** | |
| **15:00 – 15:45** | "Project Proposal on Research Reactor Technology from Japan" by Mr. Tomoaki Kato - Japan | |
| **15:45 – 16:30** | Mr. Adnan Bin Bokhari - Malaysia | |
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*Tue, Jan. 18 - continued*

**Parallel Session**

**Tc Generator Technology Group** Meeting Room: 122 Building No.4, OAP

| | **Country Report on Radioisotope Production** | **Chairperson** |
|---|---|---|
| 09:00–09:30 | "Characterization of Tc99m from PZC Generators" by Ms. Adelina Dela Mines Bulos - The Philippines | Mr. Hyon-Soo Han |
| 09:30–10:00 | "Evaluation of 99Mo/99mTc Generator Experiment Using PZC Material and Irradiated Natural Molybdenum" by Mr. Sakda Charoen - Thailand | |
| 10:00–10:30 | *Coffee Break* | |
| 10:30–11:00 | "Present Status of OAP Radioisotope Production" by Mr.Sakda Charoen - Thailand | Prof. Liu Yishu |
| 11:00–11:30 | **Discussion on the work plan for FY2005** | |
| 11:30–13:00 | *Lunch* | |
| 13:00–15:00 | **Discussion on Radiopharmaceutical Labeling Test (1)** | **Chairperson** Dr. Abdul Mutalib |
| 15:00–15:30 | *Coffee Break* | |
| 15:30–17:00 | **Discussion on future program** | **Dr. Tsuguo Genka** |

*~~~ Wednesday, January 19, 2005 ~~~*

**Paralel Session**
**Neutron Activation Analysis Group** Meeting Room: 103 Building No.4, OAP

| | | |
|---|---|---|
| 09:00 –10:30 | Report and Discussion on Standard Marine Sample Analysis | Chairperson<br>Mr. Sutisna |
| 10:30 – 11:00 | *Coffee Break* | |
| 11:00 – 12:00 | ..Continued | Prof. Ni Bangfa |
| 12:00 – 13:30 | *Lunch* | |
| 13:30 – 15:00 | ..Continued | Dr. Wanna Chueinta |
| 15:00 – 15:30 | *Coffee Break* | |
| 15:30 – 17:00 | Drafting of Summary Report | Chairperson<br>Prof. Mitsuru Ebihara |

**Paralel Session**
**Research Reactor Technology Group** Main Meeting Room, OAP

| | Project Proposal | Chairperson |
|---|---|---|
| 09:00 – 09:45 | Dr. Soo-Youl Oh - Korea | Mr. Shen Feng |
| 09:45 – 10:30 | Dr. Nguyen Nhi Dien - Vietnam | |
| 10:30 – 11:00 | *Coffee Break* | |
| 11:00 – 11:45 | "Status of Neutronics Calculation for TRR-1/M1" by Mr. Siripone Chueinta - Thailand | |
| 11:45 – 13:15 | *Lunch* | |
| 13:15 – 14:45 | Discussion on the New Project | Chairperson<br>Prof. Seiji Shiroya<br>Dr. Nguyen Nhi Dien |
| 14:45 – 15:15 | *Coffee Break* | |
| 15:15 – 17:00 | Preparation of Proposal for Coordinators Meeting | Chairperson<br>Mr. Toshio Kosugi |

**Paralel Session**
**Tc Generator Technology Group** Meeting Room: 122 Building No.4, OAP

| | | |
|---|---|---|
| 09:00 – 10:30 | Discussion on Loading machine and Pre-loading System | Chairperson<br>Mr. Sakda Charoen |
| 10:30 – 11:00 | *Coffee Break* | |
| 11:00 – 11:45 | Discussion on Publication of Comprehensive Report | Chairperson<br>Dr. K.Tatenuma |
| 11:45 – 13:15 | *Lunch* | |
| 13:15 – 15:00 | Discussion on Dissemination of PZC Technology | Chairperson<br>Mr. Wan Awang |
| 15:00 – 15:30 | *Coffee Break* | |
| 15:30 – 17:00 | Drafting of Summary Report | Chairperson<br>Dr. Tsuguo Genka |

*~~~ Thursday, January 20, 2005 ~~~*

**Paralel Session**
**Neutron Activation Analysis Group** Meeting Room: 103 Building No.4, OAP

| | | |
|---|---|---|
| 09:00 –10:30 | Project Evaluation | Chairperson<br>Prof. Mitsuru Ebihara |
| 10:30 – 11:00 | *Coffee Break* | |
| 11:00 – 12:00 | Drafting of Evaluation Report | |
| 12:00 – 13:30 | *Lunch* | |

**Paralel Session**
**Research Reactor Technology Group** Main Meeting Room, OAP

| | | |
|---|---|---|
| 09:00 –10:30 | Drafting of Summary Report | Chairperson<br>Dr. Nguyen Nhi Dien |
| 10:30 – 11:00 | *Coffee Break* | |
| 11:00 – 12:00 | ..Continued | |
| 12:00 – 13:30 | *Lunch* | |

**Paralel Session**
**Tc Generator Technology Group** Meeting Room: 122 Building No.4, OAP

| | | |
|---|---|---|
| 09:00 –10:30 | Project Evaluation | Chairperson<br>Dr. Tsuguo Genka |
| 10:30 – 11:00 | *Coffee Break* | |
| 11:00 – 12:00 | Drafting of Evaluation Report | |
| 12:00 – 13:30 | *Lunch* | |

| | |
|---|---|
| 13:30 – 16:30 | Technical Visit to OAP<br>-Research Reactor<br>-Radioisotope Production<br>-Food Irradiation<br>-Plant mutation<br>-Gem Irradiation |

*~~~ Friday, January 21, 2005 ~~~*

**Paralel Sessions** Meeting Room: Main meeting room, Meeting room 103, Meeting room 122, OAP

| | |
|---|---|
| **09:00 – 09:45** | **Summary Report Draft Review** |
| **09:45 – 10:00** | ***Coffee Break*** |

**Plenary Session** Main Meeting Room, OAP

| | | |
|---|---|---|
| **10:00 – 11:30** | **Round Table Discussion**<br>**Workshop Summary**<br>NAA: Prof. Mitsuru Ebihara<br>RRT: Mr. Siripone Chueinta<br>TCG: Dr. Tsuguo Genka<br>**Discussion on Future Plans** | **Chairperson**<br>**Mr. Sakda Charoen**<br>**Dr. Hideaki Yokomizo** |
| **11:30 – 12:00** | **Closing Remarks:**<br>- Dr. Tsuguo Genka, Japan Project Leader<br>- Mr. Sakda Charoen, Thailand Project Leader | |
| **12:00 – 13:30** | ***Lunch*** | |
| **13:30 – 17:00** | **Optional Visit :** Grand Palace and Emerald Bhudda Temple | |

# List of Participants
# The FNCA 2004 Workshop on the Utilisation of Research Reactors
January 13-21, 2005 Bangkok, Thailand

| No | Name | Country | Field | Organisation & Position |
|---|---|---|---|---|
| 1 | Ni Bangfa | China | NAA | Professor, Nuclear Physics Department, CIAE |
| 2 | Shen Feng | China | RR | Design Section of Reseach Reactor, Department of Reactor Engineering Research & Design, CIAE |
| 3 | Liu Yishu | China | TCG | Associate Professor, Chengdu Gaotong Isotope Co., Ltd (CNNC), NPIC |
| 4 | Sutisna | Indonesia | NAA | Magister, Dept. of Industrial Materials, Research & Development, Center for Materials Science & Technology, BATAN |
| 5 | Iman Kuntoro | Indonesia | RR | Director, Center for Development of Research Reactor Technology, BATAN |
| 6 | Abdul Mutalib | Indonesia | TCG | Head of Division, Radiopharmaceuticals Division, Center for Development of Radioisotope and Radiopharmaceutical, BATAN |
| 7 | Soo-Youl Oh | Korea | RR | Principal Researcher, HANARO Operation Division, HANARO Center, KAERI |
| 8 | Hyon-Soo Han | Korea | TCG | Director, Division of Radioisotope Production and Applications, HANARO Center, KAERI |
| 9 | Wee Boon Siong | Malaysia | NAA | Research Officer, Industrial Technology Div., MINT |
| 10 | Adnan Bokhari | Malaysia | RR | Reactor Manager, Reactor Facility Unit, Technical Service Div., MINT |
| 11 | Wan Anuar Wan Awang | Malaysia | TCG | Research Officer, Medical Technology Division, MINT |
| 12 | Flora Lopez Santos | Philippines | NAA | Supervising Science Research Specialist, Analytical Measurements Research Unit, Atomic Research Division, PNRI |
| 13 | Adelina Dela Mines Bulos | Philippines | TCG | Senior Science Research Specialist, Chemistry Research Unit, Atomic Research Division, PNRI |
| 14 | Ho Manh Dung | Vietnam | NAA | Head of Laboratory, Department for Nuclear Physics and Technologies, Nuclear Research Institute, VAEC |
| 15 | Nguyen Nhi Dien | Vietnam | RR/M | Director, Nuclear Research Institute, VAEC |
| 16 | Miwako Shimizu | Japan | M | Special Staff, Atomic Energy Division, Research & Development Bureau MEXT |
| 17 | Hideaki Yokomizo | Japan | M | Deputy Director General, Tokai Research Establishment, JAERI |
| 18 | Mitsuru Ebihara | Japan | NAA | Professor, Dept. of Chemistry, Graduate School of Science, Tokyo Metropolitan University |
| 19 | Tsunehiko Otoshi | Japan | NAA | Professor, Tohoku Univ. of Community Service & Science |
| 20 | Yasuji Oura | Japan | NAA | Dept. of Chemistry, Graduate School of Science, Tokyo Metropolitan University |

| | | | | |
|---|---|---|---|---|
| 21 | Seiji Shiroya | Japan | RR | Professor,<br>Director General, Research Reactor Institute, Kyoto University |
| 22 | Toshio Kosugi | Japan | RR | Deputy Director,<br>Dept. of Research Reactor, Tokai Research Establishment, JAERI |
| 23 | Hisashi Sagawa | Japan | RR | General Manager,<br>Research Reactor Utilization Div., Dept. of Research Reactor, JAERI |
| 24 | Tomoaki Kato | Japan | RR | Research Engineer, JRR-3 Operation Division, Department of Research Reactor, JAERI |
| 25 | Tsuguo Genka | Japan | TCG | Project Manager, Asia Cooperation Center, JAIF |
| 26 | Katsuyoshi Tatenuma | Japan | TCG | President, Kaken Co. |
| 27 | Takeshi Mori | Japan | M | Staff, Asia Cooperation Center, JAIF |
| 28 | Akitoshi Ohtomo | Japan | M | Head, International Technology Transfer Division,<br>Nuclear Technology & Education Center, JAERI |
| 29 | Teruhisa Shiota | Japan | M | International Technology Transfer Division,<br>Nuclear Technology & Education Center, JAERI |
| 30 | Menno Blaauw | Netherlands | NAA | Applied Sciences / Reactor Institute Delft, University of Technology Delft |
| 31 | Nobuaki Onishi | Japan (Thailand) | RR | Nuclear Safety Research Association |
| 32 | Minoru Okubo | Japan (Thailand) | RR | Research Reactor and Nuclear Technology Program, OAP |
| 33 | Wanna Chueinta | Thailand | NAA | Nuclear Chemist, Chemistry & Materials Science Research Program, OAP |
| 34 | Sirinart Laoharojanaphand | Thailand | NAA | Nuclear Chemist, OAP |
| 35 | Wanchai Dharmvanij | Thailand | NAA | Nuclear Physicist, OAP |
| 36 | Supamatthree Bunprapob | Thailand | NAA | Nuclear Chemist, OAP |
| 37 | Sanya Tedthong | Thailand | NAA | Nuclear Chemist, OAP |
| 38 | Arporn Busamongkol | Thailand | NAA | Nuclear Chemist, OAP |
| 39 | Ratirot Pareepart | Thailand | NAA | Nuclear Chemist, OAP |
| 40 | Piyavadee Limvoranusorn | Thailand | NAA | Pollution Control Department, OAP |
| 41 | Pannee Pakkong | Thailand | NAA | Kasetsart University |
| 42 | Arpa Wangkiat | Thailand | NAA | Lecturer, Rangsit University |

| | | | | |
|---|---|---|---|---|
| 43 | Soontree Khuntong | Thailand | NAA | Lecturer, Kasetsart University |
| 44 | Siripone Chueinta | Thailand | RR | Head of Research Reactor and Nuclear Technology Operation, OAP |
| 45 | Dacharchai Charnbanchee | Thailand | RR | Senior Reactor Operator, OAP |
| 46 | Suthipong Boonmak | Thailand | RR | Nuclear Engineer, OAP |
| 47 | Mongkol Junlanan | Thailand | RR | Nuclear Engineer, OAP |
| 48 | Narin Klaysubun | Thailand | RR | OAP |
| 49 | Dhanaj Saengchantr | Thailand | RR | OAP |
| 50 | Saroj Srisai | Thailand | RR | Nuclear Engineer, OAP |
| 51 | Sakda Charoen | Thailand | TCG | Head of Radioisotope Production Program, Radioisotope Production Program, OAP |
| 52 | Ninnart Virawat | Thailand | TCG | Isotope Producer, Radioisotope Production Program, OAP |
| 53 | Pranom Khongpetch | Thailand | TCG | Isotope Producer, Radioisotope Production Program, OAP |
| 54 | Sumrit Chingjit | Thailand | TCG | Isotope Producer, Radioisotope Production Program, OAP |
| 55 | Wanpen Rangsawai | Thailand | TCG | Isotope Producer, Radioisotope Production Program, OAP |
| 56 | Moleephan Dangprasert | Thailand | TCG | Isotope Producer, Radioisotope Production Program, OAP |
| 57 | Usa Kullapravit | Thailand | TCG | Radioisotope Production Program, OAP |
| 58 | Prapaipit Suprarop | Thailand | TCG | Radioisotope Production Program, OAP |
| 59 | Charudech Vadwilai | Thailand | TCG | Radioisotope Production Program, OAP |

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# 国際単位系（SI）

表１．SI 基本単位

| 基本量 | SI 基本単位 | |
|---|---|---|
| | 名称 | 記号 |
| 長さ | メートル | m |
| 質量 | キログラム | kg |
| 時間 | 秒 | s |
| 電流 | アンペア | A |
| 熱力学温度 | ケルビン | K |
| 物質量 | モル | mol |
| 光度 | カンデラ | cd |

表２．基本単位を用いて表されるSI組立単位の例

| 組立量 | SI 基本単位 | |
|---|---|---|
| | 名称 | 記号 |
| 面積 | 平方メートル | $m^2$ |
| 体積 | 立法メートル | $m^3$ |
| 速さ，速度 | メートル毎秒 | m/s |
| 加速度 | メートル毎秒毎秒 | $m/s^2$ |
| 波数 | 毎メートル | $m^{-1}$ |
| 密度（質量密度） | キログラム毎立法メートル | $kg/m^3$ |
| 質量体積（比体積） | 立法メートル毎キログラム | $m^3/kg$ |
| 電流密度 | アンペア毎平方メートル | $A/m^2$ |
| 磁界の強さ | アンペア毎メートル | A/m |
| （物質量の）濃度 | モル毎立方メートル | $mol/m^3$ |
| 輝度 | カンデラ毎平方メートル | $cd/m^2$ |
| 屈折率 | （数の）1 | 1 |

表５．SI 接頭語

| 乗数 | 接頭語 | 記号 | 乗数 | 接頭語 | 記号 |
|---|---|---|---|---|---|
| $10^{24}$ | ヨタ | Y | $10^{-1}$ | デシ | d |
| $10^{21}$ | ゼタ | Z | $10^{-2}$ | センチ | c |
| $10^{18}$ | エクサ | E | $10^{-3}$ | ミリ | m |
| $10^{15}$ | ペタ | P | $10^{-6}$ | マイクロ | μ |
| $10^{12}$ | テラ | T | $10^{-9}$ | ナノ | n |
| $10^{9}$ | ギガ | G | $10^{-12}$ | ピコ | p |
| $10^{6}$ | メガ | M | $10^{-15}$ | フェムト | f |
| $10^{3}$ | キロ | k | $10^{-18}$ | アト | a |
| $10^{2}$ | ヘクト | h | $10^{-21}$ | ゼプト | z |
| $10^{1}$ | デカ | da | $10^{-24}$ | ヨクト | y |

表３．固有の名称とその独自の記号で表されるSI組立単位

| 組立量 | SI 組立単位 | | | |
|---|---|---|---|---|
| | 名称 | 記号 | 他のSI単位による表し方 | SI基本単位による表し方 |
| 平面角 | ラジアン(a) | rad | | $m \cdot m^{-1}=1$(b) |
| 立体角 | ステラジアン(a) | sr(c) | | $m^2 \cdot m^{-2}=1$(b) |
| 周波数 | ヘルツ | Hz | | $s^{-1}$ |
| 力 | ニュートン | N | | $m \cdot kg \cdot s^{-2}$ |
| 圧力，応力 | パスカル | Pa | $N/m^2$ | $m^{-1} \cdot kg \cdot s^{-2}$ |
| エネルギー，仕事，熱量 | ジュール | J | $N \cdot m$ | $m^2 \cdot kg \cdot s^{-2}$ |
| 工率，放射束 | ワット | W | J/s | $m^2 \cdot kg \cdot s^{-3}$ |
| 電荷，電気量 | クーロン | C | | $s \cdot A$ |
| 電位差（電圧），起電力 | ボルト | V | W/A | $m^2 \cdot kg \cdot s^{-3} \cdot A^{-1}$ |
| 静電容量 | ファラド | F | C/V | $m^{-2} \cdot kg^{-1} \cdot s^4 \cdot A^2$ |
| 電気抵抗 | オーム | Ω | V/A | $m^2 \cdot kg \cdot s^{-3} \cdot A^{-2}$ |
| コンダクタンス | ジーメンス | S | A/V | $m^{-2} \cdot kg^{-1} \cdot s^3 \cdot A^2$ |
| 磁束 | ウエーバ | Wb | $V \cdot s$ | $m^2 \cdot kg \cdot s^{-2} \cdot A^{-1}$ |
| 磁束密度 | テスラ | T | $Wb/m^2$ | $kg \cdot s^{-2} \cdot A^{-1}$ |
| インダクタンス | ヘンリー | H | Wb/A | $m^2 \cdot kg \cdot s^{-2} \cdot A^{-2}$ |
| セルシウス温度 | セルシウス度(d) | ℃ | | K |
| 光束 | ルーメン | lm | $cd \cdot sr$(c) | $m^2 \cdot m^{-2} \cdot cd=cd$ |
| 照度 | ルクス | lx | $lm/m^2$ | $m^2 \cdot m^{-4} \cdot cd=m^{-2} \cdot cd$ |
| （放射性核種の）放射能 | ベクレル | Bq | | $s^{-1}$ |
| 吸収線量，質量エネルギー分与，カーマ | グレイ | Gy | J/kg | $m^2 \cdot s^{-2}$ |
| 線量当量，周辺線量当量，方向性線量当量，個人線量当量，組織線量当 | シーベルト | Sv | J/kg | $m^2 \cdot s^{-2}$ |

(a)ラジアン及びステラジアンの使用は、同じ次元であっても異なった性質をもった量を区別するときの組立単位の表し方として利点がある。組立単位を形作るときのいくつかの用例は表４に示されている。
(b)実際には、使用する時には記号rad及びsrが用いられるが、習慣として組立単位としての記号“１”は明示されない。
(c)測光学では、ステラジアンの名称と記号srを単位の表し方の中にそのまま維持している。
(d)この単位は、例としてミリセルシウス度m℃のようにSI接頭語を伴って用いても良い。

表４．単位の中に固有の名称とその独自の記号を含むSI組立単位の例

| 組立量 | SI 組立単位 | | |
|---|---|---|---|
| | 名称 | 記号 | SI 基本単位による表し方 |
| 粘度 | パスカル秒 | Pa・s | $m^{-1} \cdot kg \cdot s^{-1}$ |
| 力のモーメント | ニュートンメートル | N・m | $m^2 \cdot kg \cdot s^{-2}$ |
| 表面張力 | ニュートン毎メートル | N/m | $kg \cdot s^{-2}$ |
| 角速度 | ラジアン毎秒 | rad/s | $m \cdot m^{-1} \cdot s^{-1}=s^{-1}$ |
| 角加速度 | ラジアン毎平方秒 | $rad/s^2$ | $m \cdot m^{-1} \cdot s^{-2}=s^{-2}$ |
| 熱流密度，放射照度 | ワット毎平方メートル | $W/m^2$ | $kg \cdot s^{-3}$ |
| 熱容量，エントロピー | ジュール毎ケルビン | J/K | $m^2 \cdot kg \cdot s^{-2} \cdot K^{-1}$ |
| 質量熱容量（比熱容量），質量エントロピー | ジュール毎キログラム毎ケルビン | J/(kg・K) | $m^2 \cdot s^{-2} \cdot K^{-1}$ |
| 質量エネルギー（比エネルギー） | ジュール毎キログラム | J/kg | $m^2 \cdot s^{-2} \cdot K^{-1}$ |
| 熱伝導率 | ワット毎メートル毎ケルビン | W/(m・K) | $m \cdot kg \cdot s^{-3} \cdot K^{-1}$ |
| 体積エネルギー | ジュール毎立方メートル | $J/m^3$ | $m^{-1} \cdot kg \cdot s^{-2}$ |
| 電界の強さ | ボルト毎メートル | V/m | $m \cdot kg \cdot s^{-3} \cdot A^{-1}$ |
| 体積電荷 | クーロン毎立方メートル | $C/m^3$ | $m^{-3} \cdot s \cdot A$ |
| 電気変位 | クーロン毎平方メートル | $C/m^2$ | $m^{-2} \cdot s \cdot A$ |
| 誘電率 | ファラド毎メートル | F/m | $m^{-3} \cdot kg^{-1} \cdot s^4 \cdot A^2$ |
| 透磁率 | ヘンリー毎メートル | H/m | $m \cdot kg \cdot s^{-2} \cdot A^{-2}$ |
| モルエネルギー | ジュール毎モル | J/mol | $m^2 \cdot kg \cdot s^{-2} \cdot mol^{-1}$ |
| モルエントロピー，モル熱容量 | ジュール毎モル毎ケルビン | J/(mol・K) | $m^2 \cdot kg \cdot s^{-2} \cdot K^{-1} \cdot mol^{-1}$ |
| 照射線量（X線及びγ線） | クーロン毎キログラム | C/kg | $kg^{-1} \cdot s \cdot A$ |
| 吸収線量率 | グレイ毎秒 | Gy/s | $m^2 \cdot s^{-3}$ |
| 放射強度 | ワット毎ステラジアン | W/sr | $m^4 \cdot m^{-2} \cdot kg \cdot s^{-3}=m^2 \cdot kg \cdot s^{-3}$ |
| 放射輝度 | ワット毎平方メートル毎ステラジアン | $W/(m^2 \cdot sr)$ | $m^2 \cdot m^{-2} \cdot kg \cdot s^{-3}=kg \cdot s^{-3}$ |

表６．国際単位系と併用されるが国際単位系に属さない単位

| 名称 | 記号 | SI 単位による値 |
|---|---|---|
| 分 | min | 1 min=60s |
| 時 | h | 1h =60 min=3600 s |
| 日 | d | 1 d=24 h=86400 s |
| 度 | ° | $1° =(\pi/180)$ rad |
| 分 | ’ | $1’ =(1/60)° =(\pi/10800)$ rad |
| 秒 | ” | $1” =(1/60)’ =(\pi/648000)$ rad |
| リットル | l、L | $1l=1\ dm^3=10^{-3}m^3$ |
| トン | t | $1t=10^3$ kg |
| ネーパ | Np | 1Np=1 |
| ベル | B | 1B=(1/2)ln10(Np) |

表７．国際単位系と併用されこれに属さない単位でSI単位で表される数値が実験的に得られるもの

| 名称 | 記号 | SI 単位であらわされる数値 |
|---|---|---|
| 電子ボルト | eV | $1eV=1.60217733(49)\times10^{-19}J$ |
| 統一原子質量単位 | u | $1u=1.6605402(10)\times10^{-27}kg$ |
| 天文単位 | ua | $1ua=1.49597870691(30)\times10^{11}m$ |

表８．国際単位系に属さないが国際単位系と併用されるその他の単位

| 名称 | 記号 | SI 単位であらわされる数値 |
|---|---|---|
| 海里 | | 1海里=1852m |
| ノット | | 1ノット=1海里毎時=(1852/3600)m/s |
| アール | a | $1a=1\ dam^2=10^2m^2$ |
| ヘクタール | ha | $1ha=1\ hm^2=10^4m^2$ |
| バール | bar | 1 bar=0.1MPa=100kPa=1000hPa=$10^5$Pa |
| オングストローム | Å | $1Å=0.1nm=10^{-10}m$ |
| バーン | b | $1b=100fm^2=10^{-28}m^2$ |

表９．固有の名称を含むCGS組立単位

| 名称 | 記号 | SI 単位であらわされる数値 |
|---|---|---|
| エルグ | erg | $1\ erg=10^{-7}$ J |
| ダイン | dyn | $1\ dyn=10^{-5}$N |
| ポアズ | P | $1\ P=1\ dyn \cdot s/cm^2=0.1Pa \cdot s$ |
| ストークス | St | $1\ St=1cm^2/s=10^{-4}m^2/s$ |
| ガウス | G | $1\ G\ \hat{}\ 10^{-4}T$ |
| エルステッド | Oe | $1\ Oe\ \hat{}\ (1000/4\pi)A/m$ |
| マクスウェル | Mx | $1\ Mx\ \hat{}\ 10^{-8}Wb$ |
| スチルブ | sb | $1\ sb=1cd/cm^2=10^4cd/m^2$ |
| ホト | ph | $1\ ph=10^4lx$ |
| ガル | Gal | $1\ Gal=1cm/s^2=10^{-2}m/s^2$ |

表10．国際単位に属さないその他の単位の例

| 名称 | 記号 | SI 単位であらわされる数値 |
|---|---|---|
| キュリー | Ci | $1\ Ci=3.7\times10^{10}Bq$ |
| レントゲン | R | $1\ R=2.58\times10^{-4}C/kg$ |
| ラド | rad | $1\ rad=1cGy=10^{-2}Gy$ |
| レム | rem | $1\ rem=1\ cSv=10^{-2}Sv$ |
| X線単位 | | $1X\ unit=1.002\times10^{-4}nm$ |
| ガンマ | γ | $1\gamma=1\ nT=10^{-9}T$ |
| ジャンスキー | Jy | $1\ Jy=10^{-26}W \cdot m^{-2} \cdot Hz^{-1}$ |
| フェルミ | | $1\ fermi=1\ fm=10^{-15}m$ |
| メートル系カラット | | 1 metric carat = 200 mg = $2\times10^{-4}$kg |
| トル | Torr | 1 Torr = (101 325/760) Pa |
| 標準大気圧 | atm | 1 atm = 101 325 Pa |
| カロリー | cal | |
| ミクロン | μ | $1\ \mu=1\mu m=10^{-6}m$ |

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