Broad Lane, Sheffield, S3 7HQ
Telephone:0114 289 2000
Facsimile:0114 289 2500

HEALTH & SAFETY LABORATORY

Thematic network on the analysis of thorium and its isotopes in workplace materials

(Contract nr SMT4-CT98-7516)

Synthesis report

IEAS/02/02

Network co-ordinator: A M Howe

C Bernot (EC), O T Butler and A M Howe

HEALTH AND SAFETY LABORATORY
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Summary

Background

Accurate measurements of workplace exposure to ^{232}Th and its progeny are required to estimate internal radiation doses received by persons working with thorium-containing materials. However, a small intercomparison carried out in 1995 in the United Kingdom raised doubts about the reliability of results obtained by methods available for measurement of thorium.[1] Further work was deemed to be necessary.

Work Programme

An EC-funded thematic network was established to bring together experts in the field of thorium analysis in order to co-ordinate research activity and identify best analytical practice, requirements for reference materials, etc. The work programme of the network included (i) a survey of past, current and proposed research to determine future research needs; (ii) a series of intercomparison exercises to test the performance of methods for measuring thorium in workplace materials; and (iii) a workshop to promote best practice and transfer information to regulatory authorities and industry.

Outcome

Three interlaboratory comparisons were carried out, as planned, to test the performance of techniques and methodologies available for measurement of thorium. Test solutions containing ^{232}Th and ^{228}Th in equilibrium, test solutions containing ^{232}Th and ^{228}Th in disequilibrium and solid test samples containing ^{232}Th and ^{228}Th in equilibrium were supplied to participants. These were analysed by a variety of techniques. Full details of the three laboratory intercomparisons are given in a series of HSL reports[2,3,4] and in other publications.[5,6]

The main findings were that:

- there was a clear improvement in the accuracy of ^{232}Th measurements compared to earlier UK intercomparison;
- results from the 1st and 2nd intercomparisons showed that whilst there was no significant difference in the performance of the various methods at high activity levels, several laboratories using γ-spectrometry had insufficient sensitivity for measurement of low level test solutions;
- results from the 2nd intercomparison gave little indication that the presence of impurities has a detrimental effect on thorium measurements for any of the analytical techniques tested;
- results from the 3rd intercomparison revealed that many participants experienced difficulty with dissolution of the solid samples, which were introduced in this final exercise. Sample dissolution is required for α-spectrometry and inductively coupled plasma techniques. Neutron activation analysis (NAA) and γ-spectrometry can be used directly on solid materials. However NAA facilities are relatively scarce and the quality of results returned by laboratories using γ-spectrometry was generally poorer than those obtained by the other techniques. Poorer quality results were attributed to difficulties with instrumental calibration.

On the basis of the results of the literature review and survey of research activity, the Network identified two key areas of priority for further research. These were (i) sample preparation methods for the analysis of thorium in bulk materials using techniques that require sample dissolution, and (ii) the development of suitable traceable standards and certified reference materials for thorium analysis.

A workshop to promote best practice and transfer information to regulatory authorities and industry was held at the Studiecentrum voor Kernenergie/Centre d'Etude de l'Energie Nucleaire (SCK-CEN), Mol, Belgium on 27/28 March 2001. SCK-CEN and the Institute for Reference Materials and Measurement (IRMM) jointly hosted this workshop, which was entitled the 1st European workshop on the analysis of thorium in workplace materials. A dedicated issue of Radiation Protection Dosimetry entitled *Thorium in the workplace,* was published in November 2001[(7)] was published in November 2001. This issue contains twenty papers arising from the oral and poster presentations given at the workshop. Six of these papers describe the aforementioned work carried out by the network.

Future initiatives

The Health and Safety Laboratory has submitted a research proposal to the UK Health and Safety Executive seeking funding for the initial work on sample preparation methods for bulk materials. If this is supported and the resulting research work is successful it is intended to seek EC funding under the 6th Framework Programme for a reconstituted Thorium Network to test the methods developed.

An expression of interest entitled "A feasibility study for the preparation of certified reference materials for the analysis of thorium in workplace materials in the non-nuclear industry" was submitted to the Growth Programme of the 5th Framework Programme by the Institute of Reference Materials and Measurements, Geel, Belgium on behalf of the Network. Unfortunately the evaluation committee rejected the proposal. Consideration will be given to its resubmission, in due course, to the 6th Framework Programme.

Contents

1 BACKGROUND, OBJECTIVES, WORK PROGRAMME AND DELIVERABLES

1.1 Background

Interest in methods for measuring workplace exposure to ^{232}Th and its progeny stems from concern about the magnitude of internal radiation doses received by persons working with thorium-containing materials. This is of particular concern in non-nuclear industries, where awareness of the health risks and control measures may not be so great as in the nuclear sector.

Since 1985, control of workers' exposure to ionising radiation has been regulated in the United Kingdom (UK) by the Ionising Radiation Regulations. These regulations, made in 1985[(8)] and subsequently revised in 1999,[(9)] implicitly require workplace monitoring regimes that are capable of achieving the measurement accuracy needed to demonstrate compliance. However, it was not until a proposal was made to update the former European basic radiation protection standards,[(10,11)] now superseded,[(12)] that a decision was taken to review methods available for measurement of ^{232}Th and its progeny. This review was commissioned in 1990 by the UK regulatory authority, the Health and Safety Executive (HSE).

The conclusion of the review[(13)] was that further work was needed to establish the accuracy and suitability of measurement methods for thorium. The UK National Physical Laboratory (NPL) was therefore commissioned to conduct a suitable intercomparison amongst those analytical laboratories known to offer a thorium measurement service. This exercise was funded by the UK Department of Trade and Industry. Three laboratories took part using alpha, gamma spectrometry and neutron activation analysis. Two solution samples were provided one with ^{232}Th and ^{228}Th in equilibrium and the second with a known degree of disequilibrium.

It was clear from the results that, although the equilibrium sample presented few problems, this was not the case for the disequilibrium sample. The following conclusions were reached:

- there were significant difficulties in achieving acceptable results for disequilibrium samples;
- uncertainty estimates were generally over-optimistic or incomplete;
- no evidence was available to judge the measurement capabilities for more complex matrices such as solids; and
- further comparisons and investigations were required on a European basis.

Full details of the results have been published.[(1)]

These conclusions led to the idea of organising a network to bring together experts in the field of thorium analysis in order to co-ordinate research activity, determine best analytical practice, identify requirements for reference materials, etc.

HSE asked the Health and Safety Laboratory (HSL) to take the lead on establishing a thorium network in 1997. HSL worked closely with NPL to put together the proposal for a thematic network on 'The analysis of thorium and its isotopes in workplace materials', referred to in short as 'The EC Thorium Network'. The successful proposal was submitted to the Fourth Framework Programme in December 1997 and work commenced in October 1998.

The objectives of the Thorium Network were:

- To identify common research areas and provide a focus for co-ordinating future research activity for better management of resources
- To make recommendations about future requirements for reference materials for the accurate analysis of ^{232}Th and to encourage their provision, traceability and equivalence at the appropriate levels and environments
- To evaluate appropriate techniques and determine best practice for analysis of ^{232}Th at workplace levels and environments
- To hold a workshop to promote best practice and transfer information to regulatory authorities and industry

1.2 Work Programme

A technical work programme was agreed to reflect the planned route to achieving the objectives of the project. This was broken down into three work packages:

Work Package 1"Inventory of current research activities concerning thorium analysis in the workplace and environment"

Work Package 2"Examination and comparison of analytical techniques for the determination of thorium and its progeny in bulk materials and the development of reference materials"

Work Package 3"Technology transfer"

2 NETWORK COMPOSITION

2.1 Details of Network partners

The project was carried out involving the following partners:

- The Health and Safety Laboratory, referred to as "the co-ordinator" or "HSL" or "Partner 1";
- Commissariat a L'Energie Atomique, referred to as "CEA" or "Partner 2";
- Studiecentrum voor kernenergie Centre d'Etude de l'Energy Nucleaire, referred to as "SCK-CEN" or "Partner 3"
- Forschungszentrum Jülich GmbH, referred to as "FZL" or "Partner 4"

- Ente Per Le Nuove Tecnologie, l’Energia E l’Ambiente, referred to as “ENEA” or “Partner 5”

- European Commission, Joint Research Centre, Institute for Reference Materials and Measurements, referred to as “CEC-JRC-IRMM” or “Partner 6”

- Micromass UK Ltd, referred to as “MICROMASS” or “Partner 7”

- Siempelkamp Nuklear-und-Umwelttechnik GmbH & Co; referred to as, “SNU GmbH & Co” or “Partner 8”

- University of Innsbruck, Institut for Analytical Chemistry and Radiochemistry, referred to as “UNI INNSBRUCK - RADIOCHEMIE” or “Partner 9”

- Fachhochschule Aachen referred to as “FHAC” or “Partner 10”

- The National Physical Laboratory, referred to as “NPL” or subcontractor

2.2 Role of Network partners

The major responsibilities of the Network partners were:

Partner 1: To act as co-ordinator: to carry out general administration of the network (writing of reports, dissemination of information amongst participants etc), to organise meetings and to evaluate the results of intercomparison exercises.

Partner 2: To provide technical expertise in environmental and trace analysis of radioactive isotopes, to actively participate in the intercomparison exercises, to attend meetings, and to act as a link between the network and other laboratories in France.

Partner 3: To provide technical expertise in analysis of radioactive isotopes, to actively participate in the intercomparison exercises, and to attend meetings, and to act as a link between the network and other laboratories in Belgium.

Partner 4: To provide technical expertise in environmental, waste and trace analysis of radioactive isotopes, to actively participate in the intercomparison exercises, to attend meetings, to act as a link with the network for quality control of radioactive waste packages and to act as a link between the network and other laboratories in Germany.

Partner 5: To provide technical expertise in radiochemical analysis of environmental materials, to actively participate in the intercomparison exercises, to attend meetings, and to act as a link between the network and other laboratories in Italy.

Partner 6: To provide technical expertise in radiochemical analysis and preparation of reference materials, to actively participate in the intercomparison exercises, and to attend meetings.

Partner 7: To provide technical expertise in development of applications for mass spectrometers, to actively participate in the intercomparison exercises, and to attend meetings.

Partner 8: To provide technical expertise in processing and analysis of radioactive, to actively participate in the intercomparison exercises, and to attend meetings.

Partner 9: To provide technical expertise in radiochemical analysis for regulatory purposes, to actively participate in the intercomparison exercises, to attend meetings, and to act as a link between the network and other laboratories in Austria.

Partner 10: To provide technical expertise in radiochemical analysis, to actively participate in the intercomparison exercises, and to attend meetings.

Subcontractor: To prepare, characterise and supplying test materials to the participants and any other laboratories identified by the co-ordinator as being appropriate laboratories to participate in the intercomparison exercise.

Contact details are at Annex 1.

3 MAIN RESULTS OF THE WORK

3.1 Work Package 1

In Work Package 1, a survey of national and international laboratories was carried out to establish the extent of current and proposed research activity in the field of thorium analysis.

A report was subsequently produced containing the results of the survey, together with some preliminary conclusions concerning future research requirements. This report[14] was distributed to interested parties in December 1999. Its findings were also presented at the 1st European Workshop on the Analysis of Thorium in Workplace Materials and subsequently published [15].

The report identified two key areas considered to be a priority for future activity, namely research into sample preparation methods for thorium analysis and provision of traceable standards and certified reference materials.

3.2 Work Package 2

Work Package 2 featured a series of three laboratory intercomparisons designed to test the performance of the various techniques and methodologies available for measurement of thorium. Test solutions containing ^{232}Th and ^{228}Th in equilibrium, test solutions containing ^{232}Th and ^{228}Th in disequilibrium and solid test samples containing ^{232}Th and ^{228}Th in equilibrium were provided to participants. Samples were prepared and characterised by NPL

Tables 1, 2 and 3 give a summary of how the reported results compared to the NPL target values for each of the three intercomparisons.

Table 1 – Summary of results from 1st intercomparison

Sample	*Technique (number of data sets)*	*Nuclide measured*	*NPL target value*	*Deviation of reported results from NPL target value* *Individual or mean result*	*Deviation of reported results from NPL target value* *Range*
Equilibrium Solution	ASC (1)	^{232}Th	10.72 Bq/g	- 16 %	-
	AS (3)	228+ 230 + ^{232}Th		- 4 %	- 11 % ↔ 0 %
	GS (5)	various		+ 3 %	- 39 % ↔ + 72 %
	NAA (2)	^{232}Th		0 % , + 2%	-
	ICP-MS (6)	^{232}Th		+ 2 %	- 12 % ↔ + 3 %
	ICP-AES (2)	Th		+ 3 %, - 4 %	-
Non-equilibrium solution	ASC (1)	^{232}Th	^{232}Th 36.90 Bq/g ^{228}Ra 12.66 Bq/g ^{228}Th 9.70 Bq/g	- 18 %	-
	AS (3)	228+ 230 + ^{232}Th		- 2 %	- 4 % ↔ + 8 %
	GS (5)	various		+ 17 %	- 36 % ↔ + 79 %
	NAA (2)	^{232}Th		0 % , + 4%	-
	ICP-MS (6)	^{232}Th		- 2 %	- 12 % ↔ + 2 %
	ICP-AES (2)	Th		0 %, +2 %	-

Table 2 – Summary of results from 2nd intercomparison

Sample	*Technique (number of data sets)*	*Nuclide measured*	*NPL target value*	*Deviation of reported results from NPL target value* *Individual or mean result*	*Deviation of reported results from NPL target value* *Range*
Equilibrium Solution	ASC (1)	^{232}Th	10.72 Bq/g	+ 1 %	-
	AS (5)	$^{228+230+232}Th$		- 5 %	- 34 % ↔ + 4 %
	GS (8)	various		+ 2 %	- 37 % ↔ +166 %
	NAA (3)	^{232}Th		- 3 %	- 4 % ↔ + 2 %
	ICP-MS (5)	^{232}Th		0 %	- 5 % ↔ + 7 %
	ICP-AES (2)	Th		- 3 %, + 1 %	-
Non-equilibrium solutions ***Results for solution with impurities in brackets***	ASC (1)	^{232}Th	^{232}Th 0.0130 Bq/g ^{228}Ra 0.0001 Bq/g ^{228}Th 0.0036 Bq/g	- 40 % (- 6 %)	-
	AS (5)	$^{228+230+232}Th$		+ 6 % (0 %)	- 13 % ↔ + 65 % (- 43 % ↔ + 60 %)
	GS (2)	various		+ 6 % (+ 20 %)	- 37 % ↔ +58 % (-13 % ↔ +108 %)
	NAA (3)	^{232}Th		- 5 % (+ 3 %)	- 5 % ↔ + 29 % (- 4 % ↔ + 13 %)
	ICP-MS (6)	^{232}Th		- 2 % (- 4 %)	- 4 % ↔ - 1 % (- 11 % ↔ - 1 %)
	ICP-AES (2)	Th		- 1 %, + 3 % (- 1 %, + 7 %)	- -

Table 3 – Summary of results from 3rd intercomparison

Sample	*Technique (number of data sets)*	*Nuclide measured*	*NPL target value*	*Deviation of reported results from NPL target value* *Individual or mean result*	*Deviation of reported results from NPL target value* *Range*
Equilibrium Solution	ATS (1)	^{232}Th	10.72 Bq/g	- 8 %	-
	AS (1)	$^{228+230+232}Th$		- 3 %, 0 %	-
	GS (6)	various		- 6 %	- 18 % ↔ + 3 %
	NAA (2)	^{232}Th		0 % , + 2%	-
	ICP-MS (2)	^{232}Th		- 2 %, - 3 %	-
	ICP-AES (1)	Th		- 6 %	-
Thorium ore	AS (2)	$^{228+230+232}Th$		- 11 %, + 2 %	-
	GS (4)	various		+ 12 %	- 12 % ↔ + 86 %
	NAA (3)	^{232}Th		0 %	- 6 % ↔ + 3 %
	ICP-MS (2)	^{232}Th		- 1 %, - 1 %	-
Zircon sand	AS (2)	$^{228+230+232}Th$		- 11 %, + 2 %	-
	GS (4)	various		+ 33 %	- 46 % ↔ + 584 %
	NAA (3)	^{232}Th		- 11 %	- 20 % ↔ + 7 %
	ICP-MS (2)	^{232}Th		+ 2 %, + 8 %	-

Full details of the three laboratory intercomparisons are given in a series of HSL reports.(2,3,4) and summarised in a subsequent publication(5). These cover the work carried out, together with the results and the recommendations arising out of them. A summary of the findings is given below.

All participants obtained creditable results for the high activity level samples tested in the 1st intercomparison exercise and there were no significant differences in the performance of the various methods they used. The 2nd intercomparison exercise tested performance at a significantly lower activity level and in the presence of various impurities that could potentially affect analytical accuracy. Overall, participants performed well, but several laboratories using γ-spectrometry had insufficient sensitivity for measurement of low level samples and did not report results. The presence of impurities was found not to have a detrimental effect on measurements made using α- and γ-spectrometry and inductively coupled plasma mass spectrometry.

In the 3rd intercomparison exercise two bulk materials were distributed to test the effectiveness of sample dissolution procedures. One sample was a zircon sand material and the second was a thorium containing certified reference ore material supplied as a blind sample to participants. In general participants obtained creditable results. However, results obtained by laboratories using γ-spectrometry were generally poorer than those reported by laboratories using other techniques. This could have been due to difficulties associated with instrument calibration and, in particular, the problem of finding or producing a suitable calibration standard. However, the ease of use of the technique (no sample preparation) and its relative low cost make it suitable as a routine screening technique. For application of techniques such as α- spectrometry and inductively coupled plasma mass spectrometry to the analysis of bulk materials, experience in sample preparation skills is necessary. For that reason a number of laboratories declined to take part in the 3rd intercomparison exercise.

Laboratories participating in the 3rd intercomparison were asked to provide a best estimate of instrumental and analysis costs. A general summary is presented in the Table 4.

Table 4 – Analytical attributes (key advantages in bold)

Technique	*ICP-AES*	*QICP-MS*	*PERALS*	*α-spectrometry*	*γ-spectrometry*	*NAA*
Typical sample size used	0.1 – 0.5 g	0. 1 g	< 1 g	0.5 – 2 g	1 – 150 g	1- 5 g
Sample pre-treatment	yes	yes	yes	yes	No	No
Isotopes measured	232	232, 230	232, 230, 228[1]	232, 230, 228	(232)[2], 228	232
Analysis time	< 5 min (analysis) 2 – 5 hr (preparation)	< 5 min (analysis) 2 – 5 hr (preparation)	Up to 48 hr (analysis) 2 – 5 hr (preparation)	Up to 48 hr (analysis) 2 – 5 hr (preparation)	0.5 – 15 hr	Up to 3 weeks
Relative uncertainty % (k = 1)	2 - 10	2 - 3	5	5	15	2 - 7
Detection limit [4] Th-232 (Bq/g)	4×10^{-2}	2×10^{-5}	10^{-3}	10^{-3}	2×10^{-3}	10^{-6}
Instrument cost	€50–150 k	€150–250 k	€15–25 k	€30–40 k	€50 k	€50 k [3]
Analysis cost [5]	€300–600	€300–600	€160	€300–600	€50–200	€150[3]

[1]measured but not separately, [2] indirectly, [3] reactor costs not included, [4] typical detection limit, improvements possible with more efficient sample introduction systems, newer instruments, preconcentration, longer counting times etc, [5]participants asked to provide cost for one off/small batch of samples, reductions anticipated for work of a higher throughput

3.3 Work Package 3

The focal point of Work Package 3 was the organisation of the 1st European Workshop on the Analysis of Thorium in Workplace Materials. Its principal aim was to disseminate the work carried out by the network, and to discuss the implications arising from it. This workshop was held at SCK•CEN, Mol, Belgium, 27-28 March 2001 A special issue of Radiation Protection Dosimetry was dedicated to this workshop(7) and a listing of papers can be found in Annex 2.

Requirements for reference and quality control materials and for standardisation of analytical methodology were reviewed at the workshop, and consideration was given to the feasibility of establishing a proficiency testing scheme for thorium analysis. Recommendations concerning key areas for future work in this field were agreed. These reflected the key areas for future work already identified in Work Package 1.

4 EXPLOITATION OF RESULTS

4.1 Dissemination of results

The proceedings of the workshop were disseminated in a special issue of Radiation Protection Dosimetry(7). This issue consists of twenty articles arising from oral and poster presentations (see Annex 2). Three papers are dedicated to the interlaboratory trials conducted by the network. Copies of this issue have been distributed to workshop delegates with further copies to DG research and interested individuals that could not attend the workshop. The publishers have marketed this special issue through normal channels to the wider radiological community e.g. website, CD-ROM fliers. Reprints of individual articles are available from named authors.

Network reports detailing the activities of the network over its lifetime are available from the network co-ordinator, the Health and Safety Laboratory or via the British Library.

4.2 Future initiatives

4.2.1 Sample preparation procedures

From the results of the literature review, the survey of research activity and discussions at the open forum in the workshop, the Network identified two key areas of priority for further research, the first of which was development of sample preparation methods for thorium analysis. The initial thoughts of the network were to seek EC funding with the aim to further investigate sample preparation procedures and standardisation thereof. On reflection it was felt that initial sample preparation studies should be conducted in one or two laboratories given organisational complexities of conducting work in multiple laboratories in different countries. Draft working procedures could then be tested within a reinstated network prior to possible transfer to a relevant standards body.

The network co-ordinators, the Health and Safety Laboratory now propose to carry out the initial studies in-house, and a proposal has been submitted to the Health and Safety Executive seeking funding for this work. If this is successful it is intended in due course to seek EC funding under the 6th Framework Programme to reinstate the network.

4.2.2 Reference materials for thorium analysis

The second priority area for further work identified from the literature review and workshop discussions was the development of reference materials for thorium analysis that are traceable to national standards. The use of reference materials is essential when measurements are performed to ensure compliance with legislation. It has been shown that whilst a number of thorium containing reference materials exist, very few if any are suitable for the measurement of samples derived from the workplace.

An expression of interest entitled "A feasibility study for the preparation of certified reference materials for the analysis of thorium in workplace materials in the non-nuclear industry" was submitted by JRC-IRMM, Geel (network partner 6) to the Growth Programme (5^{th} Framework) on behalf of the network. This proposal involved identifying the commonly handled workplace materials containing thorium and subsequently identifying a subset of materials that could form the basis for the subsequent production of a set of potential reference materials.

Unfortunately the evaluation committee rejected the proposal. It was felt that the proposal dealt with the production of certified reference materials and therefore did not contain a high research content. The network was also informed that the radiation aspects were sufficient to classify the project as "nuclear", a classification outside the remit of the Growth programme.

5 CONCLUSIONS

An EC-funded thematic network was established to address the lack of knowledge about the performance of measurement methods for thorium and its isotopes in workplace materials. The Thorium Network brought together experts in the field of thorium analysis in order to co-ordinate research activity and identify best analytical practice, requirements for reference materials, etc. The network successfully completed its work programme and made a number of recommendations concerning future needs in the field of analysis of thorium and its isotopes in workplace materials. Two key areas considered to be a priority for future activity were research into sample preparation methods for thorium analysis and provision of traceable standards and certified reference materials.

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ANNEXES

Annex 1 – Contacts

Table 5 – Network partner details

Partner	Contact and address	Tel., Fax and email	Status
1	Mr Alan Howe/Mr Owen Butler Inorganic Exposure Assessment Section Health and Safety Laboratory Broad Lane Sheffield S3 7HQ, United Kingdom	00 44 114 2892605 00 44 114 2892833 a.howe@hsl.gov.uk	Network co-ordinator
2	Dr Nicolas Baglan Commissariat à l'Énergie Atomique Direction des Applications Militaires Départment Analyse et Surveillance de l'Énvironnement Service Radioanalyses, Chimie et Énvironnement P.O. Box 91680 Bruyères-le Châtel, France	0033 1 6926 6734 0033 1 6926 7065 baglan@ldg.bruyeres.cea.fr	Network member
3	Dr Léon Vandevelde Studiecentrrum voor Kernenergie Centre d'Étude de l'Énergie Nucléaire Boeretang 200 B-2400 Mol, Belgium	0032 14 33 32 00 0032 14 32 07 55 lvandeve@sckcen.be	Network member
4	Dr Gottffried Küppers Forschungszentrum Jülich GmbH D-52425 Jülich Germany	0049 2461 614663 0049 2461 612460 g.kueppers@fz-juelich.de	Network member
5	Dr Sparaciono Natale Ente per le Nuove Tecnologie L'Energia e l'Ambiente Laboratorio Nazionale per la Caratterizzazione dei Rifiuti Radioattivi Via Crescentino, Saluggia (Vercelli), Italy	0039 0 161 483529 0039 0 161 483381 spara@alpha2000.saluggia.enea.it	Network member
6	Dr Leigh Holmes/Dr Michael Bickel European Commission Joint Research Centre Institute for Reference Materials and Measurement Retieseweg B-2440 Geel, Belgium	0032 14 571 805 0032 14 584 273 holmes@irmm.jrc.be	Network member

Partner	Contact and address	Tel., Fax and email	Status
7	Dr Zenon Palacz Micromass UK Ltd Floats Road Withenshawe Manchester M23 9LE, United Kingdom	0044 161 945 4170 0044 161 998 8915 zenon.palacz@micromass.co.uk	Network member
8	Mr Rainer Kreh Siempelkamp Nuklear und Umwelttechnik GmbH & Co Siempelkampstrasse 45 D-47803 Krefeld Germany	0049 21 51 8948 400 0049 21 51 8948 402 rainer.kreh@siempelkemp.com	Network member
9	Dr Peter Brunner Institut für Analytische Chemie und Radiochemie Leopold-Franzens-Universität Innsbruck Innrain 52a A-6020 Innsbruck, Austria	0043 512 507 5080 0043 512 507 2915 pierre.brunner@uibk.ac.at	Network member
10	Prof Friedrich Hoyler Fachhochschule Aachen Kalverbenden 6 Aachen 52066 Germany	0049 2467 993763 0049 2467 993799 hoyler@fh-aachen.de	Network member
11	Dr Mike J Woods/Dr Simon Jerome/Dr Dagmar Tyler Centre for Ionising Radiation Metrology National Physical Laboratory Teddington Middlesex TW11 0LW, United Kingdom	0044 20 8943 6425 0044 20 8943 6161 michael.woods@npl.co.uk	Subcontractor

Annex 2 – Publications and reports arising from Network activities

Table 6 – Internal publications arising from network activities

Type	*Title*	*Reference*
Intercomparison reports	Report on the 1st Intercomparison (January 2000)	HSL/IEAS/00/01
	Report on the 2nd Intercomparison (December 2000)	HSL/IEAS/00/09
	Report on the 3rd Intercomparison (March 2002)	HSL/IEAS/01/01†
Progress reports (for period)	October 1998 – September 1999	HSL/IEAS/00/02
	October 1998 – March 2000	HSL/IEAS/00/11
	October 1998 – September 2000	HSL/IEAS/00/12
	Final report (March 2002)	HSL/IEAS/02/01
	Synthesis report (March 2002)	HSL/IEAS/02/02
Management reports (for period)	October 1998 – March 1999	Management report 1
	April 1999 – September 1999	Management report 2
	October 1999 – March 2000	Management report 3
	April 2000 – September 2000	Management report 4
Research report	*Current research activities and future research needs*	HSL/IEAS/99/07
	Reference materials available for total uranium and isotopic thorium analysis	JRC/GE/R/ACH/16/99

† the report on the 3rd Intercomparison was ascribed this identification number in 2001 but was not finalised until March 2002 due to extensive consultation/review process

Table 7 – External publications by Network partners arising from the workshop

Title	Reference	Pages
Analysis of Thorium in Workplace Materials (editorial) O.T. Butler and A.M. Howe	Radiation Protection Dosimetry Vol. 97 No.2 (2001)	85 - 87
The EC Thematic Network on the Analysis of Thorium and its Isotopes in Workplace Materials A.M.Howe *et al.*		95 - 100
Current Research Activities in the Measurement of Thorium and its Isotopes in Workplace Materials M.A.White *et al.*		101-104
Experiences in the Determination of Activity in Thorium Contaminated Materials in Working Areas using Gamma Spectrometer Measurements from the Viewpoint of Practical Radiation Protection R. Kreh and J. Stainer		105 –108
Thorium Isotopic Analysis by Alpha Spectrometry T. Gingell		109 - 116
Determination of Thorium by ICP-MS and ICP-OES L .Holmes		117 -122
Determination of ^{232}Th by Neutron Activation Analysis using Isotope-related k_I Factors G Küppers		123 - 126
Nuclear Data Used in the Analysis of Thorium in the Workplace S.A.Woods et al.		133 - 136
Thorium in the Workplace: The Preparation and Validation of Comparison Samples for a European-based Measurement Comparison Project A.V. Harms *et al.*		137 - 140
Thorium in the Workplace: Results from a European-based Measurement ComparisonPproject D.K Tyler *et al.*		141 - 152
Standard Reference Materials for Thorium Analysis L Holmes		199 - 202

Table 8 – Other external publications by Network partners

Title	Reference
Determination of Thorium in environmental and workplace materials by ICP-MS L. Holmes and R. Pilvio	Appl. Radiat. Isot. 53 63-68 (2000)
Thorium in the workplace measurement intercomparison D. Modna et al.	Appl. Radiat. Isot. 53 265 – 271 (2000)

Table 9 – External publications produced by workshop delegates

Title	*Reference*	*Pages*
Dosimetric Models for Thorium and Practical Problems in Assessing Intakes N. Stradling *et al.*	Radiation Protection Dosimetry Vol. 97 No.2 (2001)	89 - 94
Separation and Measurement Techniques for the Determination of ^{228}Th, ^{230}Th and ^{232}Th in Various Matrices J. Eikenberg *et al.*		127 - 132
Distribution of Natural Thorium in theTtissues of a Whole Body S.E. Glover *et al.*		153 - 160
In Vitro Dissolution Characteristics of Aged and Recrystallised High-fired $^{232}ThO_2$ S.P.LaMont *et al.*		161 - 168
Ultra Low-level Gamma Ray Spectrometry of Thorium in Human Bone Samples M.J.Martinez Canet *et al.*		169 - 172
The In Vivo Assessment of Thorium Body Burden by Gamma Ray Spectrometry J.L.Genicot and M. Bruggeman		173 - 176
Thorium in Mineral Products D.E. Collier *et al.*		177- 180
Analysis of Thorium and its Progeny by Gamma Ray Spectrometry and Alpha Track Methods L. Dinescu *et al.*		181 - 186
Thorium Determination in Intercomparison Samples and in some Romanian Building Materials A. Pantelica *et al.*		187 - 192
Analytical Methods for Thorium Determination: A Journey from Conventional Methods to Novel Applications K. Mayer *et al.*		193 - 198