NATO Security through Science Series - B:
Physics and Biophysics

Countering Nuclear and Radiological Terrorism

Edited by
Samuel Apikyan
David Diamond

Springer

NATO
OTAN

This publication is supported by: The NATO Programme for Security through Science

Countering Nuclear and Radiological Terrorism

NATO Security through Science Series

This Series presents the results of scientific meetings supported under the NATO Programme for Security through Science (STS).

Meetings supported by the NATO STS Programme are in security-related priority areas of Defence Against Terrorism or Countering Other Threats to Security. The types of meeting supported are generally "Advanced Study Institutes" and "Advanced Research Workshops". The NATO STS Series collects together the results of these meetings. The meetings are co-organized by scientists from NATO countries and scientists from NATO's "Partner" or "Mediterranean Dialogue" countries. The observations and recommendations made at the meetings, as well as the contents of the volumes in the Series, reflect those of participants and contributors only; they should not necessarily be regarded as reflecting NATO views or policy.

Advanced Study Institutes (ASI) are high-level tutorial courses to convey the latest developments in a subject to an advanced-level audience

Advanced Research Workshops (ARW) are expert meetings where an intense but informal exchange of views at the frontiers of a subject aims at identifying directions for future action

Following a transformation of the programme in 2004 the Series has been re-named and re-organised. Recent volumes on topics not related to security, which result from meetings supported under the programme earlier, may be found in the NATO Science Series.

The Series is published by IOS Press, Amsterdam, and Springer, Dordrecht, in conjunction with the NATO Public Diplomacy Division.

Sub-Series

A. Chemistry and Biology	Springer
B. Physics and Biophysics	Springer
C. Environmental Security	Springer
D. Information and Communication Security	IOS Press
E. Human and Societal Dynamics	IOS Press

http://www.nato.int/science
http://www.springer.com
http://www.iospress.nl

Series B: Physics and Biophysics – Vol. 7

Countering Nuclear and Radiological Terrorism

edited by

Samuel Apikyan
Advanced Science & Technology Center (ASTEC),
Yerevan, Armenia

and

David Diamond
Brookhaven National Laboratory,
Upton, NY, U.S.A.

Springer

Published in cooperation with NATO Public Diplomacy Division

Proceedings of the NATO Advanced Research Workshop on
Countering Nuclear and Radiological Terrorism
Yerevan, Armenia
2–6 October 2005

A C.I.P. Catalogue record for this book is available from the Library of Congress.

ISBN-10 1-4020-4920-X (PB)
ISBN-13 978-1-4020-4920-0 (PB)
ISBN-10 1-4020-4897-1 (HB)
ISBN-13 978-1-4020-4897-5 (HB)
ISBN-10 1-4020-4921-8 (e-book)
ISBN-13 978-1-4020-4921-7 (e-book)

Published by Springer,
P.O. Box 17, 3300 AA Dordrecht, The Netherlands.

www.springer.com

Printed on acid-free paper

Printed in the Netherlands.

CONTENT

Chapter I PLANNING FOR COUNTERING NUCLEAR TERRORISM

Chapter II PROTECTING NUCLEAR POWER PLANTS

Chapter III RESPONDING TO NUCLEAR TERRORISM

Chapter IV RADIATION DETECTION

PREFACE

The objective of this workshop was to a) identify connections between technology needs and the underlying science and technology, and b) to establish research strategies that will advance our ability to counter this form of terrorism. The objectives were met by bringing together international experts familiar with the relevant technologies and policies at a four-day workshop that was held at the Regional Advanced Science & Technology Center "ASTEC", Yerevan, Armenia during October 2005. Indeed, the consensus of the attendees was that this was an extremely worthwhile endeavor and should lead to similar workshops in the future.

The workshop brought together representatives of 16 countries (and several international organizations) from North America, Western Europe, Israel, and the Commonwealth of Independent States (the former Soviet Union). The 40-60 attendees (depending on day) were primarily from governmental organizations and public and private research institutes. Financial and programmatic support was from NATO through their Public Diplomacy Division, Collaborative Programmes Section and the organizing committee is extremely appreciative of this support. Additional financial support was from the International Science and Technology Center (ISTC), headquartered in Moscow. The organizing committee is also grateful to the Regional Advanced Science & Technology Center "ASTEC" for the hospitality and logistic organization of the workshop.

The many topics covered included: radiation detector development, risk assessment and decision making, decontamination techniques, structural materials resistance to conventional explosives, vulnerability and physical protection of nuclear facilities, security of radiation sources, response to radiological dispersion devices, relevant international and national laws, and non-proliferation.

The most catastrophic terrorist threat involving radioactive materials would be a self-sustained fission chain reaction detonating in an urban area, which could result in a significant number of deaths, massive devastation and radioactive fallout. Such a device needs only to contain several kilograms or a few tens of kilograms of a fissile isotope, which could be transported in a small truck and would be difficult to detect because of the relatively small amount of external radiation that it would produce before being detonated.

Another scenario of great concern involves the use of a radiological dispersion device, or “dirty bomb,” made up of a combination of conventional explosives and radioactive material. The release of radionuclides may also occur from the sabotage of nuclear facilities, or from hospitals where they are used for diagnostic and therapy.

Protection against both the improvised nuclear weapon and the radiological dispersion device were discussed. As many of the current approaches rely upon the detection of radioactive materials, participants focused on the scientific and technological challenges related to different detectors. Participants also discussed the development of integrated response systems which would make use of radiation detectors.

In conclusion although the meeting was successful in achieving its objectives, it is clear that there is much to be done in the future to counter nuclear/radiological terrorism. The support of organizations such as the NATO Science Program will continue to be an important factor in developing the necessary technology.

SAMUEL APIKYAN
DAVID DIAMOND

CHAPTER I

PLANNING FOR COUNTERING NUCLEAR TERRORISM

MOTIVATION AND REDIRECTION: RATIONALE AND ACHIEVEMENTS IN THE RUSSIAN CLOSED NUCLEAR CITIES

GREG KASER
Project Director for Europe and the Middle East, HTSPE Ltd (UK)[1]

Abstract: The non-proliferation rationale and achievements of the collaboration between the UK and Russia for a personnel redirection programme in the Closed Nuclear Cities is described. A framework for the interaction between demand and supply dimensions of proliferation threats is developed to show how redirection programmes to enable WMD specialists move into civilian activities reduce these same threats. Early results from the UK-Russia Closed Nuclear Cities Partnership are presented and compared with the parallel US funded Nuclear Cities Initiative and similar local economic development measures.

Keywords: closed cities, nuclear proliferation, demand-side

1. Introduction

The threat posed by the proliferation of knowledge and materials required for weapons of mass destruction (WMD) has become a subject for intergovernmental collaboration. At the Kananaskis summit meeting of the

---

[1] HTSPE Ltd is the Programme Manager for the Closed Nuclear Cities Partnership under contract to the UK Department of Trade and Industry. HTSPE Ltd manages the programme in association with AEA Technology Plc. The content, findings, conclusions and interpretations expressed in this paper are those of the author alone and should not be taken as reflecting the position or policies of the UK Government or its contractor HTSPE Ltd. Mark Allington, Patrick Gray and Robin Solomon contributed to analysis on which this paper is based.

S. Apikyan and D. Diamond (eds.), Countering Nuclear and Radiological Terrorism, 1–29.

leaders of the Group of Eight countries in Canada in 2002, a Global Partnership against the spread of weapons and materials of mass destruction was launched. The G-8 states pledged to provide up to $US 20 billion over a ten-year period. While the main beneficiary is Russia, other countries from the former Soviet Union (FSU), such as Ukraine, have joined or are involved in parallel bilateral co-operation. The Global Partnership has made tangible progress in destroying chemical weapons, dismantling decommissioned nuclear submarines in north-west Russia, and in the disposal of some fissile material. The fourth priority of the Global Partnership involves providing alternative civilian employment for former weapons scientists, where international programmes have also started to make a significant contribution.

The UK Government has been active in supporting these initiatives. A budget of £GB 128 million (€ 183M) has been provided for the period 2001-2007, to contribute to the international effort to reduce the substantial environmental, safety and security implications of the nuclear legacy in the FSU. Prime Minister Tony Blair committed the UK to contribute up to $US 750 million to the Global Partnership over a ten-year period.[2] One of the programmes, the subject matter of this paper, is the Closed Nuclear Cities Partnership between the UK and the Russian Federation. The budget for this programme has been around £GB 4.5M a year (€ 6.4M). A Memorandum of Understanding between the UK's Department of Trade and Industry (DTI) and the Russian Federal Agency for Atomic Energy (RosAtom) was signed in November 2004 to establish the partnership.

Other international programmes have been initiated to tackle to the potential threat posed by weapons specialists who are no longer required as the defence establishment is rationalised following the end of the Cold War. In 1994, the International Science and Technology Centre was set up in Moscow, together with the Science and Technology Centre in Ukraine, to provide grants to weapons scientists for civilian research and development. A number of countries support the ISTC and the STCU, but the largest sponsor is the European Union. The International Atomic Energy Agency set up a Nuclear Security Fund in 2002, upon which member states can draw to fund to improve physical security systems, personnel training and combating illicit trafficking in nuclear and radioactive materials. The US Department of Energy (DoE) and the Ministry for Atomic Energy of the Russian Federation (MinAtom) agreed a co-operative programme of economic diversification for the Closed Nuclear Cities in 1998.

---

[2] Department of Trade and Industry (2004) *The G8 Global Partnership: Second Annual Report*, DTI/Pub7670/2k/12/04/NP, p.5; downloadable from www.dti.gov.uk/energy/nuclear/fsu/index.shtml

The initiative formed part of the work of the Gore-Chernomyrdin Bilateral Commission aimed at helping the Russian nuclear weapons complex to downsize and jointly improve the national security of both countries by reducing the potential threats from proliferation. Later, in 2004, the Global Threat Reduction Initiative was announced by the US to identify, secure, recover and/or facilitate the disposition of vulnerable, high-risk nuclear and other radioactive materials around the world. US programmes have been brought together within the Global Initiative for Proliferation Prevention, managed by the DoE.

Initially, international concern arose from the realisation that the transformation of the Soviet planned economy to a market-based system, had left thousands of weapons specialists without adequate incomes to support themselves. While many of these specialists were employed within closed towns, known by the Russian acronym as ZATO (see box), it was feared that they were vulnerable to offers from governments or organisations wishing to hire their services for illicit development of WMD.

1.1. RUSSIA'S CLOSED CITIES

When a new Constitution for the Russian Federation was adopted, towns and settlements that had previously been subjected to restrictions on the freedom of movement and of establishment were designated as ZATOs or Closed Administrative-Territorial Formations (*zakrytye administrativno-territorial'nye obrazovaniia*) in 1992. Originally there were 38 ZATOs but the list had lengthened to 47 by 2001.

Ten of them were the responsibility of the Ministry for Atomic Energy (MinAtom), reorganised in 2004 as an agency, RosAtom. These Closed Nuclear Cities were established in the period 1947-56. Their combined population grew from 690 800 in 1989 to 747 800 in 1998.

Other ministries with responsibility for ZATOs include the Ministry of Defence, while two are located in Kazakhstan, on territory leased back to Russia: the Baykonur Cosmodrome and the nuclear test site formerly known as Semipalatinsk-21. There are some 15 or so cities for which the names have never been published. These are thought to include towns like Zagorsk-7 and Sverdlovsk-17 (the biological weapons centre where at least 60 people died from anthrax poisoning in 1979). The inhabitants of the identified ZATOs number nearly 1.3 million.

ZATOs retain the right to local self-government but until 2005 received state funding for municipal services directly from the federal budget, rather than from the provincial administration. ZATOs were permitted to retain a greater proportion of local taxes and to offer a low tax regime for businesses but these regulations were tightened to clamp down on tax evasion, after companies were found to have registered their head offices in ZATOs without transferring any production or creating employment there.

Sources: Richard H Rowland (1996) Russia's secret cities, *Post-Soviet Geography and Economics*, 37, 7: pp 426-462; Anatoli S Diakov (2000) *Russia's closed nuclear cities: social and economic conditions*, Paper presented to Conference on Helping Russia Down-size its Nuclear Weapons Complex held at Princeton University 14-15 March 2000; Gabor Szabo and Vladimir Kitov (2001) Russia's closed cities are open and shut case, *The Russia Journal*, 16 November 2001: p. 5.

The ten Closed Nuclear Cities (CNCs) are all small to medium-sized towns located in a band across Russia, from Sarov, in the west, to Zheleznogorsk in eastern Siberia. Table 1 gives details of the towns and their main activities. The UK-Russia Closed Nuclear Cities Partnership (CNCP) is active in five of the ten towns, and may, in future, expand its activities to others. The US Nuclear Cities Initiative (US NCI) is active in three towns.

Hundreds of thousands of workers with varying levels of degrees, knowledge and skills remain today throughout the FSU. While the economic situation has stabilised from the days in the mid to late 1990s, when wages were very low and often paid in arrears, the fact remains that the nuclear defence sector and the communities it supports has, by in large, not benefited from the opening up of the economy.

> "The Russian economy is still unable to provide the necessary conditions for job creation to adequately employ [the] vast network of experts [in the Closed Nuclear Cities]. Although the [ISTC] and a variety of other unilateral and multilateral projects have made important progress towards employing ex-Soviet experts, the situation in the cities remains a serious concern and a threat to international peace and security. Without concerted and prolonged assistance to these locations, the situation is likely to get worse."[3]

Experts with sensitive knowledge were vulnerable to subversion.

> "Anecdotal reports persist of former Soviet scientists, especially those in Central Asia and the Caucasus, being approached by officials from proliferant states. Further, a 2003 survey of Russian scientists with weapons expertise found that 20 percent of respon-

---

[3] Valentin Tikhonov, Russia's Nuclear and Missile Complex: The Human Factor in Proliferation, Carnegie Endowment for International Peace, June 2001.

> dents would consider working in North Korea, Syria, Iran or Iraq for a year or more." (US Department of State website)[4]

The intersection of supply and demand for sensitive knowledge, technical know how and material is the point where the greatest threat lies. The UK programme addresses the supply side of the equation in order to reduce the possibility that the demand, if presented, would not be attractive enough to subvert the loyalty of personnel with sensitive expertise or access to materials.

TABLE 1. Closed Nuclear Cities of the Russian Federation

City Province Region	Population 1998	Nuclear Workforce (estimate)	Main Nuclear Activities	Risks for Proliferation	Potential for Diversification	Russian Partner Organisation	Other International Activity	UK-RF CNCP Activity
Sarov Nizhny Novogorod Volga-Vyatka Region	83 000	20 000	Nuclear warhead design and assembly; Plutonium storage	Design teams Technical know how Fissile materials	Significant	All-Russian Scientific Research Institute of Experimental Physics (VNIIEF)	US Nuclear Cities Initiative; ISTC.	Support to spin-off medical production; including export products; advice for TechnoPark.
Zarechny Penza Volga	63 800	10 000	Nuclear warhead assembly and disassembly	Technical know how Fissile materials	Limited	Production Association START		Opportunity for activity under review.
Ozersk Chelyabinsk Ural Region	89 000	18 000	Plutonium, MOX and Tritium production; radioisotope production; warhead component manufacture; reprocessing and waste management; weapon material stor-	Design teams Technical know how Fissile materials	Significant	Chemical Combine MAYAK PO	ISTC; UK and Norway (environmental clean up projects) EU Tacis	Support to SMEs. Provision of greater access to management education.

---

[4] Statement of the Bureau of Non-proliferation of the US Department of State viewed on 1 September 2004 on www.state.gov/t/np

			age; scientific research and environmental clean-up					
Snezhninsk Chelyabinsk Ural	48 100	15 000	Nuclear warhead design; Plutonium and Highly Enriched Uranium storage	Design teams Fissile materials	Significant	All-Russian Scientific Research Institute of Experimental Physics (VNIIEF)	US Nuclear Cities Initiative; ISTC.	Innovative start-up projects funded for spin-off companies and SMEs. Provision of greater access to management education.
Trekhgorny Chelyabinsk Ural Region	31 300	6 000	Nuclear warhead assembly and disassembly; Plutonium and Highly Enriched Uranium storage	Technical know how Fissile materials	Possible	Instrument Building Plant (PSZ)		No activity.
Lesnoy Sverdlovsk Ural Region	55 000	9 500	Nuclear warhead assembly and disassembly; Plutonium storage	Technical know how Fissile materials	Limited	Combine ElektroKhim-Pribor		No activity
Novouralsk Sverdlovsk Ural Region	96 600	15 000	Uranium enrichment; Highly Enriched Uranium storage and blend-down	Fissile materials	Limited	Ural Electro-Chemical Combine		Activities at planning stage.
Seversk Tomsk Western Siberia Region	118 400	15 000	Plutonium production; Uranium enrichment and reprocessing; processing of nuclear materials; warhead component manufacture; waste management;	Design teams Technical know how Fissile materials	Significant	Siberian Chemical Combine SibKhim-Kombinat (SKhK)	EU Tacis Scientific Cities Project. ISTC; US Elimination of Plutonium Production Programme planned.	Establishment of Business Development Agency. Support to technology development projects with

			weapon materials storage; civil nuclear power plants					commercial application and to SMEs.
Zheleznogorsk Krasnoyarsk Eastern Siberia Region	94 000	8 300	Plutonium production; reprocessing, waste management and weapon materials storage	Fissile materials	Limited	Mining and Chemical Combine (SibKhim-Stroy)	US Nuclear Cities Initiative; ISTC; US Elimination of Plutonium Production Programme planned.	Support to spin-off companies and SMEs.
Zelenogorsk Kransnoyarsk Eastern Siberia Region	68 100	10 000	Uranium enrichment; military fuel fabrication	Technical know how Fissile materials	Limited	Electro-Chemical Combine (EKhK)		Activities at planning stage.
All CNCs	747 300	126 800						

Sources: Anatoli S Diakov (2000) *Russia's closed nuclear cities: social and economic conditions*, Paper presented to Conference on Helping Russia Down-size its Nuclear Weapons Complex held at Princeton University 14-15 March 2000; US Nuclear Cities Initiative; UK-Russia Closed Nuclear Cities Partnership.

2. Rationale

The objective of the CNCP is to promote international security by reducing the risk of nuclear proliferation in the Closed Nuclear Cities of the Russian Federation. The programme is focused on the scientists and technicians who have the know how that is proliferation sensitive. CNCP works closely with the International Science and Technology Centre, where the DTI is a partner, and co-ordinates with the US NCI.

A detailed rationale lies behind the design of the CNCP programme. The United Kingdom's International Security Strategy states: "The use of weapons of mass destruction against us, and terrorist attacks on western targets around the world, now constitute the most potentially catastrophic threats to UK security".[5] The human, environmental and economic consequences of the misuse of a nuclear device would vary enormously according to a range of factors, most obviously the nature of the weapon itself

---

[5] UK International Priorities: A Strategy for the FCO, December 2003, Cm 6052

and of the target. Based on information from the Pugwash Group of scientists[6], the effects could include:

- explosion of a single stolen nuclear weapon or a weapon developed with access to sophisticated knowledge, equipment and materials: 50 000 - 10 million deaths;
- explosion of a single nuclear weapon produced with more rudimentary resources: up to 50 000 deaths;
- deployment of a dirty bomb combining conventional explosives with nuclear material: unknown but probably limited health consequences but enormous psychological, social and economic impacts.

Any of these events would have far-reaching and devastating ramifications. This is illustrated by the many thousands of deaths, the constraints on travel and the billions of extra security costs which followed the attacks on the World Trade Centre and the Pentagon in September 2001. In addition, an attack involving a nuclear device would have widespread health and environmental effects, and would greatly increase pressure on third countries to acquire weapons of mass destruction, leading to an arms race which could spiral out of control.

2.1. NUCLEAR PROLIFERATION

Historically, the spread of nuclear weapons has largely depended on transfer of knowledge and personnel from one country to another (see Figure 1). Following the Manhattan project, resources were passed from the United States to Britain and France. Information illicitly passed on by American and British scientists helped the USSR acquire nuclear weapons. The USSR then helped China to develop its own nuclear capacity in the 1950s.

Israel's acquisition of nuclear weapons in the 1960s depended on information and materials acquired, in part clandestinely, from the United States and France. It in turn, for a period, assisted South Africa with nuclear weapons development. Pakistan's programme depended on help from China, and it later passed knowledge and technology onto North Korea, Libya, Iraq, and possibly to Iran. Iraq in the 1970s and 1980s sought knowledge and components for its uranium enrichment programme from

---

[6] Robert Hinde and Joseph Rotblat (2003) War no more, British Pugwash Group

the Soviet Union and nuclear sub-contractors in Western Europe. Of all the current nuclear powers, only the United States and India have developed military nuclear programmes without substantial assistance from scientists and engineers in other nuclear weapons possessing countries.

While further arms reductions may take place as a result of the end of the Cold War, the international community is considered less safe, with several regional tensions festering and terrorist organisations evolving. UN Secretary General, Kofi Annan, at a press conference on 23 July 2004, in response to a question about whether the world has become a safer place, replied, “no”. There are new issues contributing to the current underlying atmosphere of insecurity.

Two new features of proliferation emerged in the 1990s. The first was the apparent breakdown of state control over nuclear weapons development in Pakistan. Dr Abdul Qadeer Khan, the Director of Pakistan's nuclear weapons programme, offered equipment and technology to a number of, mainly, Moslem countries in the 1980s in return for large sums of money. AQ Khan’s efforts were facilitated by the relative autonomy of the Pakistani military and security services from democratic accountability and by pervasive corruption in government. It is noteworthy that prime minister Benazir Bhutto promoted scientific and technical co-operation with North Korea in 1993/94 allegedly for missile production. She denies that Pakistan accepted payments of $US 100M each from Iran, Iraq and Libya for access to Pakistan’s nuclear know-how and claims to have tried to stop such sales. Indeed, there was a period (1992-95) when Libya suspended its nuclear-related development activities, but Ms Bhutto had not left power when deals to supply gas centrifuge were later made with both Libya and Iran.[7]

The second feature is the willingness of irregular armed groups to engage in terrorism involving mass casualties. The attacks of 11 September 2001 have only served to underline this trend. The drivers of proliferation remain stronger than ever in some respects, given the many unresolved conflicts besetting several regions and the generalisation of some of these struggles by Islamist *jihadi* extremists. Internationally prohibited weapons of mass destruction may offer so-called ‘rogue states’ and irregular forces the chance to inflict damage and destruction well above their conventional force capability.

A recent report from the US National Intelligence Council sums up many of the changes challenging global security. The NIC concluded that

---

[7] *Financial Times*, April 6, 2004. Benazir Bhutto and her husband were convicted on corruption charges in April 1999. She was twice prime minister in 1988-1990 and in 1993-96.

"weak governments, lagging economies, religious extremism, and youth bulges will align to create a perfect storm for internal conflict in certain regions. … The open demonstration of nuclear capabilities by any state would further discredit the current non-proliferation regime, cause a possible shift in the balance of power, and increase the risk of conflicts escalating into nuclear ones. Countries without nuclear weapons – especially in the Middle East and Northeast Asia – might decide to seek them as it becomes clear that their neighbours and regional rivals are doing so".[8]

We may characterise the proliferation problem today into threats driven by underlying factors on both the demand and supply sides. These threats should be matched systematically by appropriate solutions. This approach is illustrated in Figures 2, 3 and 4.

2.2. DEMAND-SIDE THREATS

There is a cycle of problems that drive proliferation. A number of underlying threat factors contribute to unstable international relations. The lack of progress in revitalising and revising the Treaty on Non-proliferation of Nuclear Weapons has hampered the development of enforceable international rules. The stalled 'Peace Process' in the Middle East has kept several governments in the region on a war footing and fed irregular militias with recruits, financial support and sympathy. The Middle East is only one of a number of regions where conflict exists. Internal instability appears to be linked to socio-economic problems, notably to unemployment among young men. The US 9/11 Commission's Report recognised a link between high birth rates and a high ratio of younger to older men to internal instability and the use of terrorist tactics.[9] These underlying factors may be manifested in ideological terms (secessionism, a moral order for government, nationalism, and such like).

Another powerful driver is economic insecurity. The UK Government suggests "global economic inequalities are likely to increase and, with them, political tensions" with Africa and the Middle East identified as "urgent regional priorities" for poverty reduction and the promotion of sustainable development. The paper goes on to note that:

---

[8] US National Intelligence Council, *Mapping the Global Future*, Report of the NIC's 2020 Project, NIC 2004-13, December 2004, Executive Summary

[9] National Commission on Terrorist Attacks upon the United States (2005) *Final Report*, Chapters 2 and 12, Washington: US Government Printing Office.

> “The growth of young populations in North Africa, the Middle East, Latin America and much of Asia will place strains on natural resources and social stability. Greater awareness of wealth disparities, and frustration at a lack of opportunities, may find expression in political or religious extremism as much as in campaigns for democracy and modernity. This risk is pronounced in the Middle East, North Africa and Central Asia.”[10]

We may also cite the testimony of George Tenet, the former Director of US Central Intelligence to the Senate in March 2004.

> “Many factors play into the struggle to … dry up the wellsprings of disaffection … More than half of the Middle East’s population is under the age of 22. ‘Youth bulges’, or excessive numbers of unemployed young people, are historical markers for increased risk of political violence and recruitment to radical causes.”[11]

Underpinning the common threats noted on both sides of the Atlantic are the social and economic tensions in regions where there are few job opportunities for young people. In turn, this means that young people are unable to start family life with hopes for their own futures, leading to social dislocation and a tendency towards violence among young men. Such “wellsprings of disaffection” are a foundation for radical responses and recruitment. Though the demographic situation in the FSU differs from that in the Middle East, there is widespread unemployment and under-employment and low incomes in much of the FSU, and many symptoms of social stress are apparent. We need to target the channels that permit the underlying threat factors to be realised as opportunities to:

- influence state policy through terrorism; or,
- profit from inadequate state controls, arising from the existence of ‘state within a state’ and/or from corruption within government.

The *jihadi* movement is believed to have sought materials and expertise for the development of weapons of mass destruction. This may include radioactive materials for a so-called ‘dirty bomb’. The informal network of as many as 111 “associated entities”, commonly known as al-Qaeda (‘the Base’), apparently investigated the use of nuclear materials.[12] However

---

[10] UK Government, “UK International Priorities: A Strategy for the FCO”, December 2003, Cm 6052, Chapter 2 “The World in the Next Ten Years”.

[11] Testimony of the Director of Central Intelligence, George J Tenet, before the Senate Armed Services Committee on 9 March 2004.from www.cia.gov/cia/public_affairs/speeches/2004/tenet_testimony

[12] Osama bin Laden funded and organised four training camps for men wishing to practice *jihad* in Afghanistan; these camps and others were referred to as the Base (*al-Qaeda*). It is estimated that between 70 to 100 000 young men had passed through these by late 2001, although not all received guer-

the evidence for *jihadi* interest in WMD is not conclusive. An American commentator has asserted that:

> "Bin Laden and his al-Qaeda terrorist network have made their desire for nuclear weapons for use against the United States and its allies explicit, by both word and deed. Bin Laden has called the acquisition of WMD a 'religious duty'."[13]

It should be noted that this citation is a selective amalgam of statements. On 11 May 1998, three days after India conducted its nuclear test, Osama bin Laden said "we call upon the Muslim nation and Pakistan – its army in particular – to prepare for the *jihad*. This should include a nuclear force". This statement goes no further than indicating that bin Laden advocated Pakistan's nuclear armament. However, searches in Afghanistan after the overthrow of the so-called Taliban government in late 2001, showed that irregular fighters had been instructed in the preparations for a 'dirty bomb', or radiological dispersal device. Pakistani intelligence told the *Washington Post* that Pakistani nuclear scientists held discussions with bin Laden and others in August 2001 in Kabul. Allegedly bin Laden claimed to have acquired radiological materials from the Islamic Movement of Uzbekistan. The *al-Watan al-Arabi* magazine reported in November 1998 that bin Laden offered Chechen bandits $30M in opium in exchange for nuclear warheads and had claimed that a team of five nuclear scientists had been assembled from Turkmenistan, led by an Arab who had worked on the Iraqi nuclear programme.[14]

---

rilla training. The International Institute for Strategic Studies estimates that "al-Qaeda and its affiliates are now 18 000 strong". See "Al-Qaeda outsmarts sanctions, says UN", Stephen Fidler, *Financial Times*, August 28, 2004; "The west is mired in a losing battle", Anthony Cordesman, *Financial Times*, July 22, 2004and Rohan Gunaratna, 2002, *Inside Al Qaeda: Global Network of Terror*, London: C Hurst & Co.

[13] "Securing the Bomb, An Agenda for Action," by Matthew Bunn and Anthony Wier,

Project on Managing the Atom, Belfer Centre, Harvard University, June 2004. The bin laden quotation is cited in Rohan Gunaratna, 2002, *Inside Al Qaeda: Global Network of Terror*, London: C Hurst & Co: p.49. Bin Laden repeated this in an interview with *Time Magazine* published December 24, 1998.

[14] "Al-Qaeda's quixotic quest to go nuclear", David Albright, *Asia Times*, November 22, 2002; "WMD Terrorism and Usama bin Laden", Kimberly McCloud and Matthew Osborne, CNS Reports, November 20, 2001.

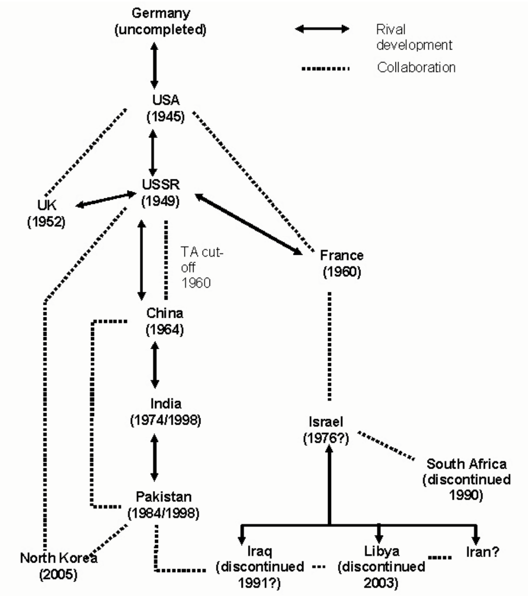


Figure 1. The chain of nuclear proliferation

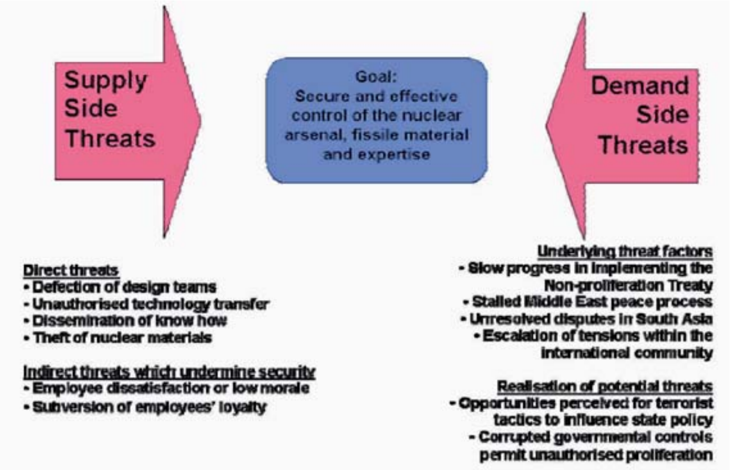


Figure 2. Factors Driving Proliferation Threats

Figure 3. Responses to Proliferation Threats

There is sufficient evidence of interest by irregular fighters in acquiring WMD-related devices, notwithstanding the difficulty in substantiating the assertions of intelligence services. Given that Russia faces an insurgency in parts of the North Caucasus, centred on Chechnya, which has involved *jihadi* fighters in acts of terrorism, the security of FSU nuclear installations and know how is a high priority.

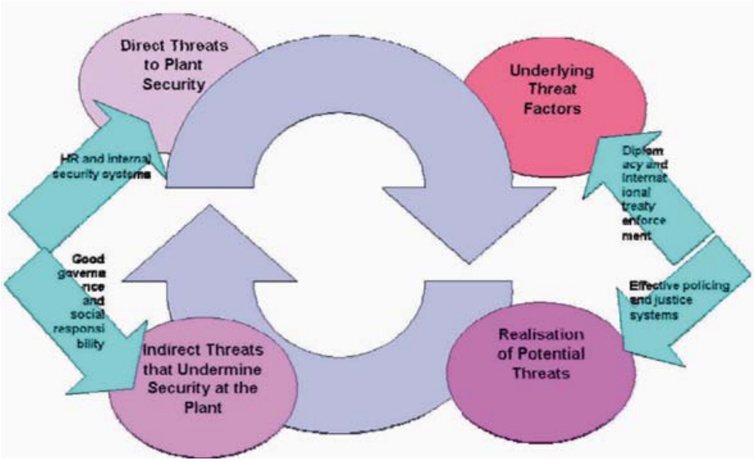


Figure 4. Responding to Threats Systematically

The complex inter-relation of threat factors calls for an integrated policy on the part of the member states of the Global Partnership and the international community. Responding to the threats will involve a mix of diplomacy and enforcement of international treaties, along with effective national and international policing and bringing criminals to justice. We have outlined the threats and appropriate responses into a logical framework matrix, in Table 2.

TABLE 2. Logical Framework for CNCP Programme Rationale

Wider Objectives (Goal)	Indicators of Achievement (Impact)	Objectively Verifiable Indicators	Assumptions and Risks
To reduce the threat to the UK from the proliferation of weapons of mass destruction, their associated technology and expertise.	Cessation and winding-up of new WMD development. Curbing of illicit exchanges of information and materials between WMD possessor states and other (proliferator) states and irregular forces, including intermediaries. International inspection regimes are in place and functioning in all states.	Impact assessment by HMG as reported in FCO Annual Reports.	Intelligence and open-source information is genuine and complete. Global Partnership against weapons and materials of mass destruction proves to be an effective structure. UN agencies, including IAEA, are effective. Top level political support for counter-proliferation continues.
Specific Objectives (Purpose)	Indicators of Achievement (Impact)	Objectively Verifiable Indicators	Assumptions
To undertake programmes of international co-operation to: address the proliferation of WMD and disarmament; counter terrorism; and, improve the safety and security of sites using sensitive technologies.	Knowledge and expertise is confined to authorised institutions and personnel within WMD possessor states and the responsible inspection agencies of the international community. Materials are accounted for and controlled at authorised sites and during transit. The provisions of the NPT and the CWC relating to disarmament are respected by all signatories.	Indicators of illicit trafficking and proliferation provided by UN agencies (e.g. IAEA, OPCW) and by national governments, including: the CIA and, FCO	Specific to the Programme The Global Partnership is adequately resourced by the G-8; UN agencies are adequately resourced by the member states; Wider International Context Regional conflicts are addressed, especially those involving Israel-Palestine and India-Pakistan. The Transatlantic

	No illegal use of WMD designs or materials occurs.		Partnership and the enhanced co-operation between the EU and Japan operate effectively and address security issues comprehensively; Strategic partnerships between the EU and Russia, India and China strengthen through dialogue and co-operation over common security concerns. International police co-operation is strengthened and enhanced. International development co-operation and assistance tackle “the wellsprings of disaffection” in developing countries.
Form of the Threat	Drivers	Response Measures	Risks
Supply Side of Proliferation			
Transfer of expertise and/or materials from a WMD possessor state:	Global or regional insecurity. Deep-rooted social conflicts remain unresolved.	Ensure that the UK obtains timely and accurate intelligence.	Intelligence assessments are distorted by uncertainty associated with its collection or through the application of ill-suited models to its analysis.
Authorised transfer	To secure or strengthen an alliance of states To counter a perceived threat from a third party To inflict deadly harm on a third party	Diplomacy to defuse and resolve inter-state conflicts. Terrorism is defined and outlawed internationally. The UN system enforces international law, universal principles of natural justice and treaty obligations with economic and cultural sanctions. Pre-emptive attack by a threatened state if the UN Security Council fails to resolve the matter.	Global inequalities in power and wealth undermine the search for inter-state consensus, so too little is done too late. ‘Rogue states’ manipulate the international system to their advantage. ‘Great Powers’ fail to observe international law and their treaty obligations (problem of ‘double

			standards’).
Unauthorised transfer	Breakdown of state administration and executive agencies into uncontrolled ‘baronies’. Subversion of state administration and executive agencies to unconstitutional ends.	Define internationally recognised standards of good governance (including respect for basic rights, democratic control and accountability of the executive and military, and judicial autonomy). Multilateral diplomacy with neighbouring states to patrol borders, smuggling, deal with cross-border insurgents, etc. Peer pressure from other states in the same regional association to encourage good governance and the rule of law. Promotion of national cohesion, human rights and democracy in trade and development co-operation. Sanction and interception of materials that might have a dual-use related to WMD development.	Entrenched regimes are not susceptible to external pressure because their resources are criminal in origin (e.g. drugs, diamonds, internal coercion by thugs, etc.). ‘Failed states’ are protected by the code of non-intervention in the internal affairs of other states.
Demand Side of Proliferation			
Acquisition of expertise and/or materials from a WMD possessor state by:	Global or regional insecurity. Deep-rooted social conflicts remain unresolved.	As above for the supplier side governments. Promotion of dialogue between communities, faiths and civilisations. Extending equality of opportunity to end discrimination. Promoting economic and social development through financial aid and technical assistance.	The parties to the conflicts are not ready to compromise. Timing problems may mean that development programmes, which bring benefits in the long-term, fail to improve the situation of the groups experiencing discrimination or economic marginalisation. Short-term subsidies may be needed to bridge this gap between immediate socio-economic problems and long-term market-based development.
A proliferator state; through:	As for the drivers on the supplier side (see		

	above).		
Espionage: By gaining access to the establishment By recruitment of staff By remote means (e.g. hacking into the IT system)	Lax internal security and corruption at a WMD establishment or facilities with associated risks turns the establishment into a magnet.	Physical security measures (fences, gates, CCTV, etc.) with well-motivated and disciplined guards. System of passes to regulate personnel and visitors to the establishment. Encourage a culture of loyalty and vigilance to the state. Carry out background checks on recruits and at specified stages in an employee's career. Discourage corruption. Counter-intelligence operations and surveillance of communications in/out of the establishment.	It is more difficult to vet temporary employees and sub-contracted personnel.
Theft: From the establishment While in transit Through electronic means	As above. Transport is a recognised weak link in an otherwise secure material processing cycle. IT developments permit the download of huge amounts of data.	Encourage a culture of loyalty and vigilance within each company that handles sensitive information and/or materials. Ensure that management systems provide for verification and delimit discretion.	It is more difficult to vet temporary employees and sub-contracted personnel.
Defection or subversion of a WMD specialist: For mercenary motives For ideological motives For personal motives (dissatisfaction, revenge) As a result of a personality disorder or mental illness From coercion (e.g. family is held hostage)	Employment insecurity or inadequate pay can undermine morale. Redundant employees can feel betrayed and under stress as a failed 'bread-winner' for their family. The breakdown of a community formerly dedicated to a single main employer weakens neighbourly ties and can isolate households, making it easier for an employee to be targeted by a gang.	Ensure that there is a well-understood career structure that rewards good performance and loyalty fairly and at market rates. Careful planning of personnel retrenchment that takes account of individual circumstances and career options. Careful planning of the restructuring of the establishment that will build up management capability to take advantage of a wider set of business opportunities. Mitigation measures are implemented to address the social consequences of restructuring at the company/establishment level and the local employment area level. Encourage reconversion	A bureaucratic organisation may be less able to seize market opportunities. But there is also a risk that the government attempts too large a transformation at the same time: retrench employment to rationalise the defence establishment and to reorient the organisation along market lines. Careful sequencing of the changes will reduce the unsettling impact on the personnel. Trust can be lost through a single

		partnerships between local actors to diversify the economic base.	incident and regaining this may be difficult. Good practice among companies recognises that the employees and community are key stakeholders in the business and consultation with employee representatives and local governments is important when major change is being considered.
Purchase from an intermediary/black market: By sale By subterfuge	Profit motive: a criminal organisation may find one-off trades in sensitive materials or designs lucrative. A sub-contractor to a related industry may circumvent dual-use rules for gain. An agent may manipulate a criminal gang to rob a vehicle or site where sensitive materials or designs are available.	Careful selection of subcontractors. Encourage fair business dealing and discourage corruption. Intelligence operations and surveillance of communications in/out of the establishment.	
An irregular force; through:	A group sees an armed liberation struggle as the only avenue to redress perceived discrimination from the state or dominant group. Attacks on the state and the people are seen as legitimate means to pressurise for political change (i.e. terrorism).	Tackle the “wellsprings of disaffection” through: Promotion of dialogue between communities, faiths and civilisations. Extending equality of opportunity to end discrimination. Promotion of economic and social development through financial aid and technical assistance.	The parties to the conflicts are not ready to compromise. Timing problems may mean that development programmes, which bring benefits in the long-term, fail to improve the situation of the groups experiencing discrimination or economic marginalisation. Short-term subsidies may be needed to bridge this gap between immediate socio-economic problems and long-

			term market-based development
As above; and,			
Infiltration of an establishment	The establishment is itself the target, perhaps because it is seen as a danger to the surrounding community.	Physical security measures (fences, gates, CCTV, etc.) with well-motivated and disciplined guards. System of passes to regulate personnel and visitors to the establishment.	The guards must be able to distinguish between protestors and terrorists at sensitive establishments.
Attack on an establishment	The establishment is itself the target, because once in control the irregular force can threaten to endanger the surrounding community or execute the staff.	As above. Armed guards and back-up police force with counter-terrorist training. A crisis management plan must be agreed and regularly updated and tested with the local authorities.	

2.3. SUPPLY-SIDE THREATS

On the ‘supply side’ of the proliferation problem we find the sources of WMD expertise and production capacity. Factors like employee dissatisfaction are indirect threats that can be exploited to undermine loyalty and security at a sensitive establishment. Corrupted government officials or subversive groups can take advantage of weaknesses in the bond between employer and employee. Low morale may undermine vigilance or encourage standards of work or reporting.

Such weaknesses may in turn manifest themselves as direct threats, including the:

- Defection of design teams;
- Unauthorised transfer of technology, perhaps using electronic means;
- Dissemination of know how to unauthorised recipients or researchers;
- Theft of nuclear and radiological materials from the site.

Russia’s Closed Nuclear Cities contain people with all of the skills needed to develop a nuclear weapons programme. About 40 000 hold certificates of higher education, and many are engaged in work such as storing and processing enriched nuclear power plant fuel, which could be experience potentially of service to a proliferator. The number of specialists with proliferation sensitive knowledge is not known, but the US-based Nuclear Threat Initiative think tank cites as credible estimates of up to 3 000 individuals from the FSU who could design a bomb or make a major contribution to doing so, and between 10 to 15 000 people who have at least some knowledge that could be critical for a weapons development programme.[15] Information is not necessarily available on the ultimate destination of scientists and engineers who go abroad, but it is known that:

- a group of scientists from a weapons design centre in the Urals were arrested before they boarded a plane to North Korea in 1992;[16]
- some 40 nuclear weapons specialists emigrated to Israel in the 1990s;[17]
- it is also possible that three nuclear weapons scientists who disappeared following a foiled attempt by Taliban representatives to recruit a Russian nuclear specialist in 2000 may have gone to Afghanistan.[18]

These examples relate to the 1990s. Nonetheless the overall internal threat profile amongst FSU scientists still remains a concern. The people of Russia's Closed Nuclear Cities and at the nuclear physics institutes within the FSU have adapted as best they can to their changing circumstances, seizing such opportunities as exist, but their financial circumstances are difficult. For the most part, scientists, and especially technicians, receive low wages *vis-à-vis* their Western counterparts. Some may not have much meaningful work because research contracts from the state have been reduced. Their pension prospects are poor, with many state pensions set at just above the poverty line in FSU countries. Their employing institutions often lack the capacity to support career development in the more competitive business environment.

Weapons establishments throughout Russia and the FSU are operating under difficult economic conditions, appear to have security weaknesses when measured against international standards, and remain vulnerable to a variety of proliferation threats. To be sure, not all is perfect in the UK, or US, either. For example, there was a serious discrepancy in the USA, where more than 100 kilos of enriched uranium was discovered to be missing some years ago (allegedly stolen by the Israelis for their secret weapons programme). Most recently it was reported that a group of scientists in South Korea had undertaken an experiment to enrich uranium, which had been reported to the IAEA.[19] But the FSU countries face a particular chal-

---

[15] Matthew Bunn and Anthony Weir (2005) *Securing the Bomb 2005: The new global imperatives*, Nuclear Threat Initiative, p. 50.

[16] *Jane's Defence Weekly*, quoted on www.uralpolit.ru

[17] Yevgeni Bovkun, *Izvestia*, 19 October 1992.

[18] See www.nti.org

[19] "South Koreans Way Secret Work Refined Uranium", David Sanger and William Board, *The New York Times*, September 3, 2004.

lenge in that whilst the Cold War military-industrial complex was a drain upon the planned economy, it is now an unsustainable burden upon the market economy. Restructuring the complex through rationalisation of the facilities and conversion of the redundant people and companies is in itself a major undertaking. According to the most recent estimates from RosAtom, about 12 000 job losses are anticipated inn the next few years. Neither Russia, nor the other FSU countries, which renounced nuclear weaponry on gaining independence, can afford to safely and securely decommission and convert the complex in this transition period without international assistance.

Rationalisation of the nuclear weapons complex is inevitable. During the Cold War it made sense to duplicate facilities to ensure that the complex could survive an attack. Such robustness no longer makes sense. Moreover, the conversion of research and production capacity to civilian uses will assist Russia’s goal to become a competitive knowledge-based economy. Thus, the conversion of defence-related facilities to civil market-oriented activities is the most appropriate response to the problem. There is a need to avoid a disruptive or unfair process of making personnel redundant. Affected personnel should have access to alternative means through which to secure their livelihood and career development. Loyalty cannot be bought – it must be earned – and is easily lost by failing to provide decent treatment during a period of change.

Another answer is to update the material control and accountancy system through the introduction of Western computerised systems. Although large strides have been made to modernise materials security in the CNCs much has still to be done. Only a quarter of Russia's nuclear materials stores had undergone comprehensive security upgrades by 2004. A decline in the number of reported thefts of uranium and plutonium (against a rising trend for thefts of radioactive medical and industrial materials) suggests that these steps are proving effective. However, the window of vulnerability for the most dangerous materials will remain open until the upgrade programme is complete in approximately ten years time. In any case such systems depend upon the capability of the operating personnel, which is affected by the morale and motivation issues already mentioned.

3. Methodology and instruments

Over the next few years, RosAtom plans large cutbacks in staff, while steps to up grade security systems in the Closed Nuclear Cities will be still incomplete. Funding research through the International Science and Technology Centre will no longer be an answer, as the people involved will have left the facilities. Creating the basis for on-going civil sector business development in the CNCs is the only available instrument for preventing a second crisis, with all that that could entail in terms of the threat of nuclear proliferation. The Russian Government has a conversion programme, but RosAtom and its associated institutions in the CNCs have found it difficult to attract sufficient investment. CNCP is thus playing an important role here.

The threat of expertise proliferation from within Russia's CNCs is potential, rather than imminent. High levels of integrity and loyalty among the personnel and the physical security barriers and restrictions on their movements have generally proved effective. But the evidence on both the supply and demand sides, summarised in this paper, indicates that international support to encourage diversification into peaceful technologies and civil employment will remain necessary over the coming years. A 2003 US study indicates that Russian scientists receiving a Western grant were half as likely as their non-funded counterparts to consider moving to North Korea, Syria, Iran or Iraq, but that overall 21 percent would consider accepting such an offer.[20]

The CNCP will, throughout the duration of the Global Partnership up to 2013, seek to make a real and measurable contribution to reducing the proliferation threat posed by the restructuring of Russia's closed nuclear cities and by relevant nuclear establishments in the FSU. It will do so by:

- creating a significant and material number of lasting, non-weapons jobs for those made redundant, or to be made redundant from the nuclear weapons complex and relevant nuclear establishments in the remaining FSU countries;
- creating a sustainable capacity and capability for diversification and commercialisation with the programme's partners.

Specifically, CNCP aims to:

- Generate lasting, non-weapons related employment for scientists, engineers and technicians with proliferation sensitive expertise;
- Develop opportunities to commercialise products and services from scientific institutions in the Closed Nuclear Cities in conjunction with UK and other international partners;

---

[20] Bureau of Non-proliferation of the US Department of State, 1 September 2004, on www.state.gov/t/np

- Develop market oriented business skills among the scientists, engineers and technicians.
- Promote local economic development in the Closed Nuclear Cities.

The programme started its activities in late 2002. The objectively verifiable indicators for CNCP are the numbers of new jobs coming into being, of which no less than 55 percent must be filled by former employees of the nuclear weapons complex. At the time of writing, CNCP is one-third of its way through its programme.

As an initial step in evaluating potential grant projects, CNCP undertook technology audits of organisations in Seversk, Snezhinsk, Ozersk, Novouralsk and Zheleznogorsk. These technology audits led to the identification of a number of grant projects that support job creation in the closed nuclear cities and promote development of new, commercially viable technologies. The grants are usually used to purchase machinery and equipment, often from Western suppliers, for personnel training, or to defray the cost of repaying commercial investment loans.

There is a two-phase process for project evaluation, selection and funding. Proposals are first made to the UK Steering Group to fund initial business plan development and market research. After the findings are reported to the Steering Group, second phase funding is considered. First stage requests are typically under £GB 30 000 and second stage requests can be up to approximately £GB 200 000. A balanced portfolio of projects that include both mainstream manufacturing and services and high technology businesses has been developed. A project supervisor, usually having experience in business and the relevant technology, is employed by the Programme Managers (HTSPE Ltd) oversees the development and implementation of projects. Projects and activities are tailored specifically to the needs of each Closed Nuclear City.

Some of the projects are proposed by the nuclear weapons establishments themselves to diversify their activities into civilian directions or by spin-off companies from the establishment. Other beneficiaries are small and medium-sized enterprises (SMEs) based in the CNC (but outside the nuclear weapons establishment) that are starting up production or investing for expansion.

4. Achievements to date

Thus far, CNCP has provided grants for 20 projects, representing a funding commitment of nearly three million pounds sterling (€ 4.5M), with up to

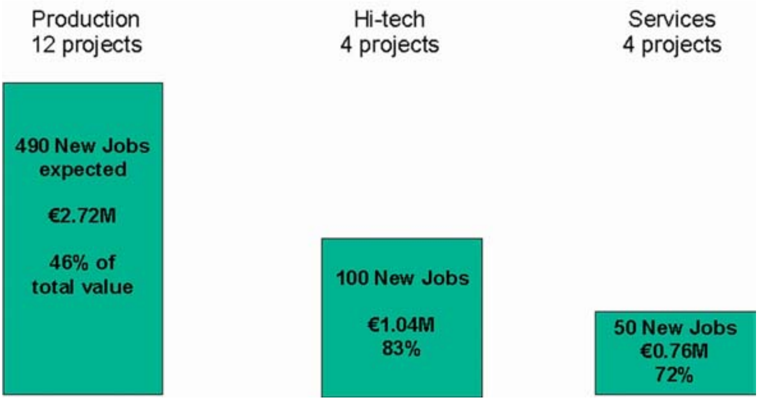


Figure 5. Analysis of UK-RF CNCP funded Investment Project

640 associated jobs anticipated in the business plans prepared by the recipients. Figure 5 shows the make-up of the projects and their contribution to job creation.

Investment co-funded by CNCP has generated over 140 actual new jobs, so far. By the end of financial year 2005-06, the Programme Managers will have implemented or completed 50 commercialisation and investment projects in five of the ten closed nuclear cities. Business training centres will be operating in three closed nuclear cities, providing courses based upon Open University programmes, and a new MBA programme aimed at technologists. A young entrepreneur scheme is planned. Determined efforts are being made to broker commercial partnerships or joint ventures between UK companies and Russian enterprises.

CNCP will also aim to consolidate local economic development activities, based around the new business development agency in Seversk.

The value of the CNCP programmes in Russia is about £GB 4.5 million a year in total, of which investment grants are approximately £GB 2.5 million a year. When compared to a government programme for economic development or industrial conversion these are relatively small expenditures. For example, the DTI spent £GB 2.6 billion in 2003/04 on enterprise and economic development.[21] Of this, over £GB 100 M went towards Regional Selective Assistance and £GB 50 M for Enterprise Grants from SMEs. The US Economic Development Administration spent about $US 100 M a year on defence adjustment grants between 1991 and 1997.[22]

---

[21] DTI, *Departmental Report 2005*, Annex A9, p. 179.

[22] US Department of Commerce (1999) *Economic Development Administration: Defense Adjustment Assistance Program is Well Focussed*, Audit Report No. DEN-9806-9-0001, p.2.

The Programme managers have benchmarked the results achieved by CNCP so far against comparable measures. CNCP has only one exact comparator, the US Nuclear Cities Initiative. US NCI undertakes similar projects in several of the same Closed Nuclear Cities in Russia. The Initiative has created jobs in Sarov and Zheleznogorsk at a cost of around $US 6 000/job. Figures for the last 5 years in Sarov indicate that 300 jobs were created from investments of $US 2.5 M, which is equivalent to $US 8 330/job, or 0.8 jobs per $US 10 000 invested. The US NCI operates a 'criterion' of $US 10 000 to $15 000/job in assessing projects.[23]

It is more problematic to compare economic development and conversion programmes across countries. A common feature of this type of programme is that they seek to provide incentives to firms and entrepreneurs to invest in a business that will absorb redundant employees. The key to success is to pitch the incentives at just the right level to entice the entrepreneur and his or her investors into locating and recruiting as desired, without 'over-paying', and thus wasting public funds. What may motivate an entrepreneur in the EU or USA may not be the same in Russia.

In practice, the level of incentive is tested through experience. Economic development professionals gain a feel for what is needed from successive negotiations with applicant companies. Their knowledge is reflected in the maximum permissible values for 'cost per job' specified in the conditions for making the grant. In the UK, the DTI has specified this at about £GB 4 000/job, though higher amounts, of up to £GB 17 000/job, may be warranted depending on the quality of the jobs.[24]

That said, the make-up of the schemes differs. The DTI recognise that its business support programmes are not the only source of subsidy for companies. For example, training grants are available and the local authorities or regional development agencies may provide infrastructure and premises. This is also reflected in the £GB 4 000/job figure, which would be larger if all the programmes were rolled up into a single grant.

Experience shows that the overall cost to the public purse of incentives to foreign direct investors was £GB 8 910/job in Scotland for the period 1991 to 1995.[25] It should be noted that only 74 percent of the jobs were 'new jobs', with the remainder being 'safeguarded jobs'. If these latter jobs

---

[23] Information given on 5 October 2004 at a US-Russian seminar held at Pacific Northwest National Laboratory, Hanford, Washington State, USA.

[24] For Regional Selective Assistance.

[25] Scottish Office (1998) Memorandum to the Select Committee on Scottish Affairs of the UK Parliament, Annex E (www.publications.parliament.uk/pa/cm199798/cmselect/cmscotaf/698-i/69814.htm).

are disregarded, then the overall cost rises to £GB 12 040/job. In Wales, the National Economic Development Strategy states that "based on empirical data, an average net cost per job created is approximately £GB 17 500".[26]

For the EU structural programmes, it has not been easy to find information. However, the European Commission told a conference on investment in 2001 that "the cost of creating one new job through … regional aid [is] some € 16 000".[27]

In the USA, Rutgers University evaluated the Department of Commerce's Economic Development Administration (EDA) Defence Adjustment Programme for the years 1992 to 1995. This study concluded that the construction projects cost the EDA $US 8 052/job, and $US 12 045/job if all sources of funding were included.[28] The main activity in response to military base closures and rationalisation involved to re-use of sites for industry, so construction projects were an important feature of defence conversion.

Lastly, we consider the Canadian Industrial Research Assistance Programme (IRAP). The National Research Council of Canada evaluated the performance of Technology and Advisory Services and the Non-Repayable Contributions to SMEs for R&D for the period 1996 to 2000. The study estimated that the contribution from IRAP amounted to $C 32 000/job (approximately $US 22 860/job).[29]

At this point, the investment grants from CNCP in Russia have achieved a cost/job ratio of £GB 4 940 (about € 7 060). This is equivalent to 0.7 jobs per € 10 000 invested. These results are therefore in line with good practice, suggesting that CNCP is a cost-effective programme.

The impact of CNCP is more difficult to estimate. Assuming a high side estimate of 20 000 personnel with sensitive expertise, representing about 15 percent of all CNC weapons complex employees, implies that around 3 000 new jobs for such proliferation sensitive staff must be created in order to cope with a possible 20 000 redundancies up to 2012. Only a proportion of the redundancies will involve personnel with proliferation sensitive knowledge, and some of these can be expected to retire in any

---

[26] National Assembly for Wales (2001) *A Winning Wales: the national Economic development Strategy of the Welsh Assembly Government*, Implementation (www.wales.gov.uk/themesbudgetandstrategic/contents/neds/consultation)

[27] Speech by Mr Heinz Zourek, Deputy Director-General for Enterprise, European Commission, to the EU-Japan Investment Symposium, Tokyo, on 11 December 2001 (http://jpn.cec.eu.int/PHP).

[28] Center for Urban Policy Research (http//policy.rutgers.edu/cupr/projectedaevaluation/defeseadjustment.htm)

[29] National Research Council website: www.nrc-cnrc.gc.ca/aboutUs/audit_irap_e.html.

case. If CNCP can stimulate around 1 000 posts for former weapons personnel, it will have made substantial inroads into reducing the problem. At current levels of UK Government funding, such an aspiration is quite feasible.

5. Exit strategy

The fundamental rationale for the UK Programme addressing the nuclear legacy in the FSU countries arises from the collapse of the Soviet economy on its adoption of the market mechanism. No one expected such a precipitate decline in industrial production and incomes, but the result was that the successor states were left with a legacy they could not afford to manage safely and securely. The FSU's nuclear legacy became an international problem because the FSU countries lacked the managerial and fiscal resources to:

- Initiate and manage a controlled rationalisation of the nuclear weapons complex;
- Undertake environmental clean up;
- Invest in improvements in the safety and security of nuclear installations.

Therefore, the rationale for the assistance offered by the UK, and its partners, expires once the Russian government is in a position to pay its own bills. This depends on making a success of the transition, and in translating economic development and growth into jobs, social security and environmental protection.

The CNCP will have achieved its mission when the inhabitants of the closed nuclear cities see that there are systematic measures in place to overcome the adverse social consequences of defence rationalisation through local economic development and business support for job creation in alternative civil activities. As such, measuring the general confidence of the inhabitants, decision-makers and investors in their future prospects will be a key indicator of CNCP's wider impact.

6. Conclusions

In a world characterised by complexity and decentralised power it has not been possible to fulfil the aims of the 1970 Non-proliferation Treaty of undertaking effective nuclear disarmament. Nor has it proved possible to resolve conflicts peaceably within the terms of the UN Charter. As a result, the proliferation of WMD technology and sensitive materials has emerged as one of the most worrisome threats facing the international community.

These issues emerged in the context of the transformation and break-up of the Soviet Union in the 1990s. Its nuclear legacy posed a considerable management and security challenge as national income in the FSU fell. The international community responded with technical and financial assistance to the FSU successor states. Moreover, Russia faced a number of secessionist movements, some of which resorted to terrorism. Recent events have demonstrated the readiness of some groups, including Chechen guerrillas with *jihadi* links, to inflict mass murder.

This paper has set out a framework for conceptualising the socio-economic and ideological factors that contribute to national and global insecurity. In turn, we may view certain state and non-state actors as opportunist agents of proliferation. If democratic and judicial structures for accountability are undermined by corruption or capture by a 'state within the state', we have seen nation states embark upon the development of internationally prohibited weapons of mass destruction. Non-state actors including irregular forces view the acquisition of WMD as an opportunity for terrorism to exert asymmetric power.

The schematics presented illustrate a cycle of threats and institutional weaknesses that need to be addressed systematically if nuclear or other sensitive facilities are to be rendered secure. Targeted measures must be adopted to ensure that organisational change or the rationalisation of activities does not undermine the relationship between employer and employee in sensitive establishments. Loyalty and vigilance are relatively easy to undermine where there is low morale and poor motivation. Redirection programmes, encompassing the facilitation of job creation in civilian activities and career development are targeted measures appropriate to the potential threat.

IMPLEMENTATION OF THE 8 JULY 2005 AMENDMENT TO THE CONVENTION ON THE PHYSICAL PROTECTION OF NUCLEAR MATERIAL

PATRICIA A. COMELLA[*]
U.S. Department of State, 2201 C Street, N.W., Room HST 3320,
Washington DC 20520, USA

Abstract: The purpose of this paper is twofold: firstly, to summarize objectives and provisions of the 8 July 2005 Amendment to the Convention on the Physical Protection of Nuclear Material; and, secondly, to discuss implementation of the physical protection provisions of the Amendment in terms of the kinds of institutions and organizations within a State that would be expected to have a role in ensuring the effectiveness of the State's regime for the physical protection of the nuclear material and nuclear facilities used for peaceful purposes within the territory of the State, coupled with how those institutions and organizations could be expected to fit together to form an integrated physical protection system.

Keywords: CPPNM; Convention; Amendment; physical protection; nuclear material; nuclear facility

1. Introduction

The Convention on the Physical Protection of Nuclear Material ("Convention" or "CPPNM") is one of the universal instruments related to the prevention and suppression of international terrorism. Drafted in the 1970s, adopted at Vienna, Austria, on 26 October 1979, and opened for signature on 3 March 1980, the CPPNM is of limited scope, with physical protection obligations covering only

---

[*] Correspondence should be addressed to: Patricia A. Comella, Office of Nuclear Energy, Safety and Security, Bureau of International Security and Nonproliferation, U.S. Department of State, 2201 C Street, N.W., Room HST 3320, Washington DC 20520, USA; e-mail: comellapa@state.gov. The views expressed in this paper are the author's own and not those of the U.S. Government.

S. Apikyan and D. Diamond (eds.), Countering Nuclear and Radiological Terrorism, 31–45.

nuclear material used for peaceful purposes while in international nuclear transport (and storage incidental to such transport).[1]

By the early 1990s, only a few years after the Convention's entry into force on 8 February 1987, international concerns began to rise over illicit trafficking in nuclear material, the potential for malevolent use of such material, and the adequacy of the CPPNM to effectively address those concerns. In 1998, the U.S. Government undertook an initiative to gain amendment of the Convention. In response, International Atomic Energy Agency ("IAEA") Director General ElBaradei convened a series of open-ended expert meetings that began in November 1999 to consider the question of whether the CPPNM should be amended. The expert meetings concluded in March 2003 with recommendations on a set of possible amendments to the Convention. The recommendations provided the basis for proposed amendments to the CPPNM that were considered at a diplomatic conference of CPPNM parties that met at the IAEA, 4-8 July 2005. Eighty-nine Parties to the CPPNM and twenty-one non-Party observers attended the Conference.[2] The conference reached consensus on July 8 and adopted an Amendment that, once it enters into force,[3]

---

[1] Physical protection obligations under the 1979 Convention apply to nuclear material used for peaceful purposes while in international nuclear transport (Article 2, paragraph 1) and while in storage incidental to such transport (Annex I). “International nuclear transport” is defined in Article 1 to mean “the carriage of a consignment of nuclear material by any means of transportation intended to go beyond the territory of the State where the shipment originates beginning with the departure from a facility of the shipper in that State and ending with the arrival at a facility of the receiver within the State of ultimate destination.” The physical protection obligations of Articles 3 and 4 and paragraph 3 of Article 5 that apply to nuclear material while in international nuclear transport do not apply to nuclear material used for peaceful purposes while in domestic use, storage and transport, with the exception of nuclear material during storage incidental to international nuclear transport (Paragraph 2 of Article 2 and Annex I). Paragraph 3 of Article 2 makes clear that the physical protection obligations applicable to nuclear material while in international nuclear transport do not otherwise apply or affect “the sovereign rights of a State regarding the domestic use, storage and transport of such material.”

[2] CPPNM PARTIES PARTICIPATING IN THE CONFERENCE: Albania, Algeria, Argentina, Armenia, Australia, Austria, Azerbaijan, Belarus, Belgium, Bolivia, Bosnia and Herzegovina, Brazil, Bulgaria, Burkina Faso, Cameroon, Canada, Chile, China, Colombia, Croatia, Cuba, Cyprus, Czech Republic, Denmark, Ecuador, Estonia, Finland, France, Germany, Greece, Guatemala, Honduras, Hungary, Iceland, India, Indonesia, Ireland, Israel, Italy, Japan, Kenya, Republic of Korea, Kuwait, Latvia, Lebanon, Libya Arab Jamahiriya, Liechtenstein, Lithuania, Luxembourg, Madagascar, Mali, Malta, Mexico, Monaco, Mongolia, Morocco, Mozambique, Namibia, Netherlands, New Zealand, Nicaragua, Norway, Oman, Pakistan, Paraguay, Peru, Philippines, Poland, Portugal, Republic of Moldova, Romania, Russian Federation, Senegal, Serbia and Montenegro, Slovakia, Slovenia, Spain, Sudan, Sweden, Switzerland, The Former Yugoslav Republic of Macedonia, Tunisia, Turkey, Turkmenistan, Ukraine, United Kingdom of Great Britain and Northern Ireland, United States of America, Uruguay and the European Atomic Energy Community (EURATOM).

NON-PARTY OBSERVERS AT THE CONFERENCE: Cambodia, Egypt, Ethiopia, Haiti, Iran, Iraq, Jordan, Kazakhstan, Malaysia, Myanmar, Nigeria, Saudi Arabia, South Africa, Syria, Venezuela, Yemen, Zambia, Zimbabwe, the United Nations, the IAEA and League of Arab States.

[3] The Amendment will enter into force for a State Party to the CPPNM that deposits its instrument of ratification, acceptance or approval of the Amendment on the thirtieth day after two-thirds of the States

will significantly strengthen the 1979 Convention and the international regime for the physical protection of nuclear material and nuclear facilities used for peaceful purposes.[4,5] Given the significance of the Amendment for global improvement of physical protection, implementation of the Amendment seemed an appropriate topic for this NATO Advanced Research Workshop on “Countering Nuclear/Radiological Terrorism.” The Amendment's significance can be understood by considering what constituted the international physical protection regime at the time the amendment initiative began.

Given the narrow scope of the 1979 Convention, the international physical protection regime, as a practical matter, has been grounded not so much in the

---

Parties deposit such instruments. Thereafter, the Amendment will enter into force for a State Party upon deposit of its instrument of ratification, acceptance or approval of the Amendment with the depositary.

[4] Text of the 1979 Convention and the 8 July 2005 Amendment to the 1979 Convention can be downloaded from the IAEA website, www.iaea.org. From the IAEA “Home Page” select the link to the "Publications” page. From the “Publications” page, select the link to the "IAEA Documents and Conventions" page. From the “IAEA Documents and Conventions” page, select the link to the “International Conventions and Legal Agreements" page. From that page, select the link to the "Convention on the Physical Protection of Nuclear Material" page. Texts of both documents can be downloaded from the “Related Resources” section of that webpage. In addition, the unofficial consolidated text of the Convention and Amendment can be obtained via e-mail as described on the webpage. The negotiating history is discussed in a series of six papers presented at the 2000 through 2005 Annual Meetings of the Institute of Nuclear Materials Management. See references 1-6.

[5] The concept of " physical protection regime" is not defined in the Convention, the Amendment or in the internationally accepted recommendations on the physical protection of nuclear material and nuclear facilities that were published in the IAEA Information Circular ("INFCIRC") entitled, "The Physical Protection of Nuclear Material and Nuclear Facilities," and popularly referred to as INFCIRC/225/Rev.4 (corr.). However, what constitutes an appropriate physical protection regime can be inferred from consideration of the elements of physical protection identified in those documents. For example, from consideration of Article 6 of the Amendment, which adds new Article 2A to the Convention and which will be discussed below in greater detail, the “physical protection regime” of a State would include the legislative and regulatory framework governing the physical protection of the nuclear material and nuclear facilities used for peaceful purposes under the jurisdiction of that State and the institutions and organizations within the State responsible for developing, implementing and maintaining that framework, for taking other appropriate measures necessary for the physical protection of such material and facilities, and for applying insofar as reasonable and practicable twelve Fundamental Principles of Physical Protection. The institutional and organizational components would include the components of the Government responsible for developing the legislative and regulatory framework to govern physical protection, the State agencies responsible for carrying out the State’s evaluation of the threat and assessing the potential impact of the threat on nuclear material and nuclear facilities, the competent authorities designated to implement the legislative and regulatory framework governing physical protection, the operators and other license holders and employees or contractors thereof with physical protection responsibilities, and the components within the government, whether at the national or local levels with responsibilities for effectively combating threats to nuclear material or nuclear facilities or mitigating or minimizing the consequences thereof. The physical protection regime would also include the hardware, procedural and design features implemented by each holder of a license or other authorizing document regarding the physical protection of nuclear material and nuclear facilities under the jurisdiction of the State. As used here, the term "international physical protection regime" refers to the physical protection regimes of all States, taken collectively.

Convention itself as in the recommendations in INFCIRC/225/Rev.4 (corr.). Although widely followed, the recommendations are not legally binding. They can be applied selectively, which has led to significant, country-to-country variation in the measures taken to protect nuclear facilities and nuclear material with similar characteristics. In contrast, the Amendment embodies new, universally applicable international norms for the physical protection of nuclear material used for peaceful purposes while in domestic use, storage and transport and for the physical protection from sabotage of nuclear material and nuclear facilities used for peaceful purposes. The existing norms in the CPPNM for the physical protection of nuclear material used for peaceful purposes while in international nuclear transport and storage incidental to such transport are already in force for States Parties. Although the Amendment is not expected to enter into force for a number of years, it is expected that some States will decide to embrace the Amendment and the norms therein as a matter of policy, pending its entry into force.[6] Thus, the Amendment's effects with respect to strengthening the international physical protection regime are likely to be felt before the Amendment enters into force.

Given that expectation, the primary objective of this paper is to identify the essential institutional components of a State's physical protection regime and, for a State that contemplates embracing the Amendment's provisions, to discuss how those components individually and collectively would contribute to effectuating the purposes of the Amendment to the Convention as they relate to achieving and maintaining effective physical protection of nuclear material and nuclear facilities used for peaceful purposes. The paper continues with a brief overview of the Amendment and then launches into a partial dissection of the Amendment in the context of identifying the institutional components of effective physical protection and their inter-relationships. Throughout, the overarching theme of the paper is that effective physical protection of nuclear material and nuclear facilities used for peaceful purposes demands effective coordination among and integration of the institutional components of a State's physical protection regime.

---

[6] As of 2 September 2005, 115 States and EURATOM were Parties to the Convention. Reaching the point where a State is ready to deposit its instrument of ratification, acceptance or approval with the depositary can take several years and different States are likely to complete their internal processes at different times.

2. July 8, 2005 Amendment to the 1979 Convention

The Amendment to the 1979 Convention is intended to accomplish three purposes (set forth in Article 4 of the Amendment, which would add a new Article 1A to the Convention):

- to achieve and maintain worldwide effective physical protection of nuclear material used for peaceful purposes and of nuclear facilities used for peaceful purposes;
- to prevent and combat offences relating to such material and facilities worldwide; and
- to facilitate co-operation among States Parties to those ends.

To effectuate these purposes, the Amendment extends the scope of the 1979 Convention to cover the physical protection of nuclear material used for peaceful purposes while in domestic use, storage and transport and of nuclear facilities used for peaceful purposes and establishes, among other things:

- new international norms for the physical protection of nuclear material and nuclear facilities, including protection from sabotage of such material and facilities (Article 6 of the Amendment, which would add a new Article 2A to the Convention);
- strengthened obligations for cooperation among States Parties to the Amendment on matters of physical protection (Article 7 of the Amendment, which would replace the text of Article 5 of the Convention with new text), for protection of the confidentiality of physical protection information (Article 8 of the Amendment, which would replace the text of Article 6 of the Convention with new text), and for the prosecution and extradition of those committing offenses enumerated in the Amendment involving nuclear material and nuclear facilities used for peaceful purposes (Article 10 of the Amendment, which would add new Articles 11A and 11B to the Convention); and
- new criminal offenses that must be made punishable offenses by each State Party to the Amendment under the national law of that State Party (Article 9 of the Amendment, which would replace the text of paragraph 1 of Article 7 of the Convention with new text).

Accomplishing the Amendment’s purposes requires each State Party to the Amendment to take “responsibility for the establishment, implementation and maintenance of a physical protection regime within the State” (taken from new text for paragraph 2 of Article 2 of the Convention as set forth in Article 5 of the Amendment). In other words, in order to "achieve and maintain worldwide effective physical protection,” to “prevent and combat offences … worldwide” and to “facilitate co-operation among States Parties,” cooperation between and among States and cooperation between and among the institutional components of the physical protection regime within a State will be necessary.

The basic physical protection obligation set out in the Amendment is found in paragraph 1 of new Article 2A to the Convention:

> “Each State Party shall establish, implement and maintain an appropriate physical protection regime applicable to nuclear material and nuclear facilities under its jurisdiction, with the aim of: (a) protecting against theft and other unlawful taking of nuclear material in use, storage and transport; (b) ensuring the implementation of rapid and comprehensive measures to locate and, where appropriate, recover missing or stolen nuclear material; when the material is located outside its territory, that State Party shall act in accordance with article 5 [of the Convention as amended]; (c) protecting nuclear material and nuclear facilities against sabotage; and (d) mitigating or minimizing the radiological consequences of sabotage.”

The basic physical protection obligation set forth above requires that the threats specified in sub-paragraphs (a) and (c) be effectively combated and, in the event that the threats materialize, that effective response measures, specified in sub-paragraphs (b) and (d) be taken to prevent, mitigate or minimize consequences. Such threats could be internal or external to the State or a nuclear facility and could be directed against a nuclear facility or against nuclear material at a fixed site or in transport or storage incidental to such transport. As discussed in the next section, new Article 2A gives States some direction as to what a State Party must do carry out its basic physical protection obligation.

3. Identifying the threats against which nuclear material and nuclear facilities must be protected

Before threats can be combated, they must be identified, described and characterized. Fundamental Principle G of paragraph 3 of new Article 2A makes clear that “the State’s physical protection should be based on the State’s current evaluation of the threat.”[7] Paragraph 1 of new Article 2A provides

---

[7] Fundamental Principles of Physical Protection of Nuclear Material and Nuclear Facilities are set forth in paragraph 3 of new Article 2A. They were developed during the IAEA-sponsored expert meetings to consider the question of whether the CPPNM should be amended. Largely extracted from INFCIRC/225/Rev.4 (corr.), they are considered to be essential elements of an effective physical protection regime that all States having nuclear material and nuclear facilities used for peaceful purposes need to apply insofar as reasonable and practicable. The Fundamental Principles pertain to (A) Responsibility of the State; (B) Responsibilities during International Transport; (C) Legislative and Regulatory Framework; (D)

general direction to States Parties on the kinds of threats to be combated: theft and other unlawful taking of nuclear material in use, storage and transport (sub-paragraph 1(a)) and sabotage against nuclear material and nuclear facilities (sub-paragraph 1(c)).

Information relevant to evaluation of the threat likely will come from a number of sources, ranging from publicly available information to highly classified intelligence information; and, within the government of a State Party, the threat evaluation is likely to require the involvement of more than one governmental agency or ministry, none of which it would be reasonable to exclude from the evaluation process. For example, law enforcement agencies likely would possess information regarding criminal activities that, e.g., could pose threats from organized crime within the country. Such agencies also would have contacts with law enforcement authorities in other countries or in various international organizations concerning external criminal threats that might have a nexus to internal criminal activities. Military intelligence likely would come from intelligence services within the Ministry of Defense. Other agencies with similar roles to the U.S. Central Intelligence Agency likely would provide intelligence.[8]

Effectively combating threats also requires resources. Resources must be devoted to responding to threats that materialize in order to defeat them. In addition, resources must be devoted to addressing the consequences from threats that are not defeated. Paragraph 1 of new Article 2A also provides general direction to States Parties on the actions to be taken to address the consequences and potential consequences from the two major categories of threats identified in sub-paragraphs 1(a) and (c): rapid and comprehensive measures to locate and, where appropriate, recover missing or stolen nuclear material, including cooperation with other States Parties when nuclear material is located outside its territory (sub-paragraph 1(b)) and measures to mitigate or minimize the radiological consequences of sabotage (sub-paragraph 1(d)). To prevent threats from materializing and to limit the consequences of threats that

---

Competent Authority; (E) Responsibility of the License Holders; (F) Security Culture; (G) Threat; (H) Graded Approach; (I) Defence in Depth; (J) Quality Assurance; (K) Contingency Plans; and (L) Confidentiality.

[8] For example, in the United States, an assessment requires the collaboration of many agencies of the U.S. Government, including the Defense Intelligence Agency, the Department of the Navy, the Department of the Army, the Department of the Air Force, the Nuclear Regulatory Commission, the Federal Bureau of Investigation, the Central Intelligence Agency, and the Department of Energy. An asssessment details relevant threat information about postulated adversary team sizes, characteristics, capabilities and applicability to national security assets. It is based on intelligence information detailing actual terrorist attacks and the equipment and tactics utilized in the attacks, expert judgments regarding stated terrorist intentions, the ability of the terrorist to execute the stated objectives, and postulated capabilities based on the latest knowledge concerning terrorist activities.

do materialize require that the State's physical protection include maintenance of an adequate level of preparedness. As discussed in the next section, doing so requires the preparation and maintenance of contingency plans and periodic exercise of those plans by the agencies and organizations with roles in emergency response, not only individually, but also collectively to ensure an integrated and effective response. In other words, resources must be devoted to the contingency planning functions.

The inherently finite resources of any State Party cannot deal with all of the threats against nuclear material or nuclear facilities that could be hypothesized. As a practical matter, each State must make practical choices as to the threats against which the State will require that nuclear material and nuclear facilities be protected and as to the allocation of limited resources to do so. The formulation of the Article 2A obligations, as illustrated by the underscored text in the examples in the note below, makes clear an expectation that States are expected to apply a "rule of reason" in balancing competing considerations and making tough choices in the face of real resource constraints and limitations.[9]

As Fundamental Principle G makes clear, balancing the competing considerations and making the tough choices that are part of a State Party’s being responsible for the physical protection regime within that State must be done in the context of the State's current threat evaluation. Conduct of an ongoing evaluation of the perceived threat environment and assessment of how it might affect nuclear facilities and nuclear material are reasonable in light of the continuing occurrence of terrorist attacks in many parts of the world before and since September 11, 2001, including in Bali, Madrid and London. Taking into consideration the effect of the post-9/11 global threat environment on the

---

[9] For example,

In establishing, implementing and maintaining its physical protection regime,

“each State Party shall (a) establish and maintain a legislative and regulatory framework to govern physical protection; (b) establish or designate a competent authority or authorities responsible for the implementation of the legislative and regulatory framework; and (c) take other appropriate measures necessary for the physical protection of nuclear material and nuclear facilities” (Paragraph 2 of new Article 2A, emphasis added).

In doing so, “each State Party shall, without prejudice to any other provisions of this Convention, apply insofar as reasonable and practicable . . . the [twelve] Fundamental Principles of Physical Protection of Nuclear Material and Nuclear Facilities that are set forth in paragraph 3 of new Article 2A.

Sub-paragraph (a) of paragraph 4 of new Article 2A contemplates that a State may reasonably decide not to subject certain nuclear material to the physical protection regime mandated by the Article 2A. Specifically, the provisions of Article 2A "shall not apply to any nuclear material which the State Party reasonably decides does not need to be subject to the [established] physical protection regime . . . , taking into account the nature of the material, its quantity and relative attractiveness and the potential radiological and other consequences associated with any unauthorized act directed against it and the current evaluation of the threat against it." However, nuclear material that is not subject to sub-paragraph (a) "should be protected in accordance with prudent management practice.”

current threat evaluation, particularly after a major terrorist event, is also reasonable. And, in reflection of the resource constraints discussed above, it is also reasonable for a State, in implementing Fundamental Principle G, to base its physical protection on the most credible threats (i.e., most likely) to nuclear material and nuclear facilities.

In and of itself the State's national-level evaluation of the threat probably is not sufficient to identify the specific threats to be combated at the facility or operator level. Rather, threat evaluations need to be translated into assessments of the threat to nuclear material and nuclear facilities and coupled with relevant policy judgments about the risks from those threats to the public health and safety, the common defense and security, and the environment and about the appropriate means to combat those risks.[10] There is broad agreement in the international community, which is implicitly reflected in new Article 2A, that the designated competent authority or authorities responsible for implementation of the legislative and regulatory framework governing physical protection, with appropriate consultation as necessary, should carry out the threat assessments and make the relevant policy judgments.

For example, in the United States, the U.S. Nuclear Regulatory Commission ("NRC") and the U.S. Department of Energy ("DOE"), as the designated competent authorities, carry out those assessments and form those judgments, which form the bases for the policies of each agency governing the physical protection of nuclear material and nuclear facilities within their respective jurisdictions. The physical protection policies that are current at any point in time are derived from and associated with a current national intelligence threat evaluation, such as described in note 8, and reflect the most credible threats to nuclear facilities and nuclear material. Those policies provide an informed basis for developing and implementing the physical protection regime at both the State and operator levels.

To sum up, from an institutional perspective, the physical protection regime of a State Party includes those agencies and institutions of the State that have a role in conducting the State's evaluation of the threat, in translating those evaluations into assessments of the threats to nuclear material and nuclear facilities, and in formulating the policies of the State that will apply to the protection of nuclear material and nuclear facilities against the most credible

---

[10] Relevant to making the appropriate risk judgments and reflecting those in the policies that will govern facility-specific or activity-specific physical protection, is Fundamental Principle H, which concerns the graded approach to physical protection:

"Physical protection requirements should be based on a graded approach, taking into account the current evaluation of the threat, the relative attractiveness, the nature of the material and potential consequences associated with the unauthorized removal of nuclear material and with the sabotage against nuclear material or nuclear facilities."

threats. As indicated above, there is broad international agreement that the conduct of threat assessments and the making of risk judgments are within the purview of the designated competent authorities. Lastly, there is broad international agreement that the threats to be combated are those deemed to be the most credible threats.

4. Role of competent authorities in ensuring protection against the most credible threats to nuclear material and nuclear facilities

Under the Amendment, the designated competent authority or authorities have responsibility for implementation of the legislative and regulatory framework, which is an essential component of the physical protection regime each State Party must establish, implement and maintain to combat the threats identified in paragraph 1 of new Article 2A. As discussed above, paragraph 1 sets forth the basic physical protection obligation in the Amendment. Paragraph 2 of new Article 2A requires each State Party to establish that legislative and regulatory framework and designate the competent authority or authorities responsible for implementing that framework. Paragraph 3 of new Article 2A lays out further requirements for implementing the obligations in paragraphs 1 and 2 of Article 2A; namely, implementation of the twelve Fundamental Principles of Physical Protection insofar as reasonable and practicable.[11] Several of the Fundamental Principles (C, D, E and K) have important implications for the relationship of the competent authority or authorities to other governmental authorities that have a role in ensuring the adequacy of the State's physical protection regime, including effective implementation of the legislative and regulatory framework that governs physical protection.[12] None of these Fundamental Principles

---

[11] Paragraph 2 of new Article 2A requires that: "In implementing paragraph 1, each State Party shall: (a) establish and maintain a legislative and regulatory framework to govern physical protection; (b) establish or designate a competent authority or authorities responsible for the implementation of the legislative and regulatory framework; and (c) take other appropriate measures necessary for the physical protection of nuclear material and nuclear facilities." Article 2A, paragraph 3 requires that: "In implementing the obligations under paragraphs 1 and 2, each State Party shall, without prejudice to any other provisions of this Convention, apply insofar as reasonable and practicable the . . . [twelve] Fundamental Principles of Physical Protection of Nuclear Material and Nuclear Facilities [set forth in paragraph 3]."

[12] Fundamental Principle C identifies the functions that should be provided for in the legislative and regulatory framework and carried out by the designated competent authorities:

"This framework should provide for the establishment of applicable physical protection requirements and include a system of evaluation and licensing or other procedures to grant authorization. This framework should include a system of inspection of nuclear facilities and transport to verify compliance with applicable requirements and conditions of the license or other authorizing document, and to establish a means to enforce applicable requirements and conditions, including effective sanctions."

Fundamental Principle D specifies that:

"The State should establish or designate a competent authority [or authorities] which is[/are] responsible for the implementation of the legislative and regulatory framework, and is[/are] provided with adequate speaks to intra-governmental coordination at the national level and coordination between national and local authorities in achieving effective physical protection at a facility-specific or activity-specific level, but the need for effective coordination is essential and must be inferred.

In the preceding section, intra-governmental coordination was discussed in the context of the State's evaluation of the threat and the competent authority or authorities' role in assessing the threat to nuclear material and nuclear facilities and establishing physical protection policies to combat the most credible threats to nuclear material and nuclear facilities. In this section, intra-governmental and inter-governmental coordination is discussed in the context of ensuring adequate physical protection of nuclear material and nuclear facilities at the level of a specific facility or specific activity involving nuclear material. Contingency planning and the periodic exercise of contingency plans by all license holder and authorities concerned, both individually and collectively at the facility-specific or activity-specific level, will be a focus of the discussion, based on a firm belief that contingency (emergency) planning and preparedness are essential to meeting the basic physical protection obligation set forth in paragraph 1 of new Article 2A.

The physical protection regime of a State, including the legislative and regulatory framework, is embedded in a broader constitutional, legislative and regulatory framework that must be taken into account in interpreting the scope of the competent authority or authorities' responsibilities, in deciding what the competent authority or authorities can reasonably, practicably and legally require of the operator or other license holder, and in identifying the other governmental authorities that must be involved to combat the most credible threats to nuclear facilities and nuclear material at the facility-specific or

---

authority, competence and financial and human resources to fulfill its[/their] assigned responsibilities. The State should take steps to ensure an effective independence between the functions of the State’s competent authority [or authorities] and those of any other body in charge of the promotion or utilization of nuclear energy."

Fundamental Principle E primarily concerns the responsibility of license holders, but also underscores the need for a clear identification of responsibilities for implementing the various elements of physical protection within a State:

"The responsibilities for implementing the various elements of physical protection within a State should be clearly identified. The State should ensure that the prime responsibility for the implementation of physical protection of nuclear material or of nuclear facilities rests with the holders of the relevant licenses or of other authorizing documents (e.g., operators or shippers)."

Fundamental Principle K concerns the need for contingency planning and the conduct of periodic exercises to test the adequacy of contingency plans:

“Contingency (emergency) plans to respond to unauthorized removal of nuclear material or sabotage of nuclear facilities or nuclear material, or attempts thereof, should be prepared and appropriately exercised by all license holders <u>and</u> authorities concerned” (emphasis added).

activity-specific level, particularly in the area of contingency planning.[13] Contingency planning may require coordination and integration at higher levels of government than those at which the competent authority or authorities for physical protection are placed.

In carrying out their responsibilities to implement the legislative and regulatory framework for physical protection, in particular for establishing physical protection requirements, the designated competent authority or authorities must translate the applicable physical protection policies into requirements for facility-specific and activity-specific application. In formulating and applying those requirements, the designated competent authorities must take into account the actions that an operator or other license holder reasonably and practicably could undertake as a legal or practical matter. Those facility/activity-specific requirements must then be communicated to the appropriate licensees/operators.[14] They must also be communicated to the

---

[13] This would include other relevant laws, statutes, decrees, orders and high-level policy instruments that implement basic law involving national security and public safety and health as those pertain to effectively combating threats to nuclear material and nuclear facilities.

[14] The competent authorities of a number of States, including the United States, utilize the so-called "Design Basis Threat" ("DBT") as a regulatory tool to communicate to certain licensees or facility operators information about the threats (adversaries) that the facility's/activity's physical protection system must be designed to combat and to assess and improve the effectiveness of the physical protection systems as implemented at the facilities or for the activities to which the DBT (or portions thereof) apply. INFCIRC/225/Rev.4 (corr.) defines a "DBT" to mean "the attributes and characteristics of potential insider and/or external adversaries, who might attempt unauthorized removal of nuclear material or sabotage, against which a physical protection system is designed and evaluated." INFCIRC/225/Rev.4 (corr.) regards a DBT as "an essential element of a State's system of physical protection." In circumstances where a State does not used a DBT as a regulatory tool, the applicable regulatory requirements governing physical protection against what are judged to be the most credible threats must be communicated to licensees/operators and those requirements must be based on the State's current evaluation and assessment of the threat as discussed in the previous section.

In the United States, the NRC and the DOE both follow the same general process to develop DBTs and protection requirements. However, there are differences in the DBTs applied to NRC regulated facilities and those applied to DOE facilities. Those differences reflect differences in the types of facilities and materials for which they have responsibility and some differences in the governing law and modes of regulation. For example, Federal law empowers guards and response forces protecting DOE nuclear material and nuclear facilities to use deadly force when necessary to protect those assets in combating threats. In contrast, State law governs the actions that may lawfully be taken to protect nuclear material and nuclear facilities subject to regulation by the NRC. These differences have implications for what the competent authority can lawfully expect of the facility operator in combating threats to nuclear facilities or nuclear material and to the development and exercise of contingency plans to respond to threats involving unauthorized removal of nuclear material or sabotage of nuclear material or nuclear facilities.

Elements of the general process of DBT development and protection requirements employed by DOE and NRC include review of intelligence, the analysis of which considers such factors as frequency, motive, security conditions, target type, availability, portability, tactical utility, geographic location and a description of the group/adversary possessing the postulated characteristics; coordination with the intelligence community and national law enforcement agencies; and periodic meetings with facility operators and officials at the State and Local Levels that provide opportunities for feedback to improve the effectiveness and governmental authorities that also have roles in contingency planning and preparedness.

As examples of legal constraints that affect the scope of a licensee/operator's physical protection responsibilities, some States do not allow the use of onsite armed private guard or response forces to protect certain critical infrastructure and assets, such as nuclear facilities and nuclear material. Some States use special police forces or internal troops to provide armed response capability of nuclear assets. Such troops might be under a Minister of the Interior, whereas the designated competent authority for physical protection might be in another ministry, such as the Ministry of Energy, or in an independent agency that may or may not be of ministerial rank in the governmental hierarchy. Some States, including the United States, permit the use of onsite armed private guard and response forces, but in responding to some threats, offsite response may be needed. To ensure the effectiveness of facility-specific or activity-specific physical protection all three situations require contingency planning by the licensee/operator and others and coordinated exercise, as well as individual exercise, of those plans on a periodic basis. However, in each of the three situations, the competent authority or authorities can compel the licensee/operator to coordinate planning with the other involved authorities, but cannot compel the other involved authorities to coordinate with the licensee/operator. In each of the three situations the competent authority or authorities may be able to take an active role in facilitating the necessary coordination. In the coordinated exercise of contingency plans or in actual response to unauthorized removal of nuclear material from a facility or during an activity or sabotage of nuclear material or a nuclear facility or a threat thereof, management of the integrated exercise or response may require centralized command and control at a governmental level sufficient to exercise authority over all of the governmental agencies involved in the response. Of necessity, such a management function would have to be

---

integration of contingency planning and preparedness, including periodic and coordinated exercise of the plans.

The physical protection and DBT policies of the NRC and DOE also reflect a graded threat concept that considers and accounts for such factors as the consequences of a malevolent event affecting or involving a nuclear-related asset, the attractiveness as a target of a nuclear-related asset to an adversary, the ability of an adversary to accomplish a given objective involving a targeted asset, and the resources required by an adversary to accomplish the objective. Using this concept, graded threat levels can be established, which are proportional to the relative attractiveness of targeted assets and/or to the consequences from successful attack. Application of the graded threat concept allows different levels of physical protection to be established for different targets. For the highest threat level defined in the DBT, the adversary numbers in the DBT will be at their largest, and the equipment and tactics specified in the DBT will be more sophisticated and challenging. At the lowest defined threat level, specific protection requirements are likely to be prescribed, with a focus on compliance with these requirements. Although analyzed, the specific threat levels may not actually be described in a document labeled as the DBT.

carried out at a level of government higher than the competent authority or authorities.'

In summary, when considering implementation of the basic physical protection obligation, which is set forth in paragraph 1 of new Article 2A, with respect to implementing the contingency (emergency) planning functions of the State's physical protection regime, the designated competent authority or authorities would not be the only governmental institutions involved. Even though Article 2A of the Amendment contemplates that the designated competent authority or authorities governing physical protection would have "adequate authority, competence and financial and human resources" to carry out their responsibilities for implementation of the legislative and regulatory framework outlined in Fundamental Principle C, in fact (as well as most likely in law), effective application and implementation of Fundamental Principle K on contingency planning, is likely to involve additional competent authorities with responsibility for emergency planning for effective threat response. Where this situation prevails, as it does in many States, including the United States, then arrangements must be made for overall coordination of the emergency response functions, which includes establishment of clear lines of responsibility governing the relevant institutions with roles in times of such emergencies.

5. Conclusion

When viewed from the perspective of implementation of the physical protection obligations set forth in new Article 2A, in particular from the perspective of the institutional components that need to be involved in establishing, maintaining and implementing an appropriate physical protection regime applicable to nuclear material and nuclear facilities used for peaceful purposes within a State, inter-relationships among various governmental institutions must be taken into account. Among those are the institutions involved in the State's evaluation of the threat and assessment of its impact on nuclear material and nuclear facilities, as well as the institutions involved in carrying out the contingency (emergency) planning functions as they would apply to responding to unauthorized removal of nuclear material or an act of sabotage against nuclear material or nuclear facilities and in dealing with the consequences from such threats. In order to identify at least some of those institutions, the paper first considered the obligation to base the State’s physical protection on the State's current evaluation of the threat. The paper then considered the obligation to develop and exercise appropriately contingency (emergency) plans to respond to unauthorized removal of nuclear material or sabotage of nuclear facilities or nuclear material, or attempts thereof. The purpose in doing so was to move beyond the reasonably well understood relationship between the designated competent authority or authorities for physical protection within a State and the operators or other license holders with responsibility for facility-specific or activity-specific physical protection to a broader understanding of the institutional elements of an effective physical protection regime aimed at implementing the physical protection obligations defined in the 8 July 2005 Amendment to the CPPNM. The views expressed herein are the author's and not the views of the U.S. Government. (The presentation does not address the Fundamental Principles concerning Security Culture (I), Defense in Depth (G), Quality Assurance (J) or Confidentiality (L).)

References

1. Patricia A. Comella et al., *Convention on the Physical Protection of Nuclear Material,* 41st Annual Meeting of the INMM, July 16-20, 2000.
2. Patricia A. Comella et al., *Revising the Convention on the Physical Protection of Nuclear Material,* 42nd Annual Meeting of the INMM, July 15-19, 2001.
3. Patricia A. Comella, *Revising the Convention on the Physical Protection of Nuclear Material,* 43rd Annual Meeting of the INMM, June 23-27, 2002.
4. Patricia A. Comella, *Revising the Convention on the Physical Protection of Nuclear Material—Chapter IV,* 44th Annual Meeting of the INMM, July 13-17, 2003.
5. Patricia A. Comella, *Revising the Convention on the Physical Protection of Nuclear Material—Chapter V,* 45th Annual Meeting of the INMM, July 18-22, 2004.
6. Patricia A. Comella, Revising *the Convention on the Physical Protection of Nuclear Material—Chapter VI,* 46th Annual Meeting of the INMM, July 10-14, 2005.

NUCLEAR MATERIAL SECURITY NEEDS IN THE 21ST CENTURY

NERSES H. KRIKORIAN
Laboratory Fellow, Nonproliferation Division
LARRY R. AVENS
Project Leader, International Space and Response Division
LEROY E. LEONARD
Project Leader, Global Threat Reduction, Nonproliferation Division
Los Alamos National Laboratory,University Of California
PO Box 1663Los Alamos, New Mexico 87545 U.S.A.

Abstract: Since September 11, 2001 there has been a fundamental transition in the way we view radiological sources and devices in our environment. Ionizing Radiological Sources, (IRSs) which serve a multitude of important medical, industrial, and research needs in our modern society, were not so long ago viewed as common place in an industrialized society, only of concern to health and the environment if control is lost accidentally. But, 9/11 taught us that those bent on indiscriminant terror are capable of taking the most common place elements of our advanced technology and turning them into effective weapons of mass destruction. And radiological sources quickly became the object of concern as a potentially disruptive threat to our national security.

Keywords: power reactors, nuclear materials, safeguards, radiological dispersion device, ionizing radiation sources

1. INTRODUCTION

Although the term terrorism, and in particular the concerns of nuclear terrorism now receives front page attention by the media, at Los Alamos concerns, discussions and studies of this threat area have been ongoing for over 30 years. However, what has most recently galvanized the focus in the United States were the unprovoked, cruel, and cowardly acts of

S. Apikyan and D. Diamond (eds.), Countering Nuclear and Radiological Terrorism, 47–61.

September 11, 2001. The lives lost in these non-nuclear attacks has driven a need for renewed analysis and actions that should help prevent events of an even more serious and devastating consequences, such as nuclear and radiological catastrophes.

Indeed, the NATO Advanced Research Workshop, focusing on "Countering Nuclear/Radiological Terrorism" is a result of this international concern. It is gratifying to note that evolving international events now embraces such a conference, permitting the inclusion of participants and scientific colleagues who just as short as two decades ago would not have had the opportunity to share the podium to discuss the countering of nuclear/radiological terrorism.

Historically, in the 1940's, after the development of nuclear weapons, and after World War II, the then U.S. Secretary of State, General George C. Marshall, promulgated a plan that stimulated the economic recovery of both Japan and Germany and served the interests of all countries impacted by a devastating war. In the same spirit, President Dwight D. Eisenhower in the 1950's proposed sharing nuclear knowledge and technology for peaceful purposes aimed at raising the living standard of the world through the "Atoms for Peace" program. However, in the 1950's an international enthusiasm for the promise of atomic energy, and radiation science, coupled with a benign attitude concerning the impact that such initiatives might have resulted in nuclear technologies and radioactive sources broadly distributed by many nations without thought for the strict controls prevalent today.

What was at first seen as a benevolent and benign action was soon realized to be a double edged sword and led to the development and implementation of controls through treaties and other international agreements meant to minimize the threat of nuclear proliferation. As we look back, for the most part, nations have been responsible and established and created a legal basis and institutional infrastructures for the sharing and exchange of nuclear information, technology and key materials, as well as controlling both fissile and fissionable elements. But, our world is never static.

As the application of nuclear technologies multiplied environmental concerns evolved and a conscious effort was begun to clean up the radiological residue of nuclear origin. Society became keenly aware of possible harmful effects that paralleled the race for nuclear weaponry during the cold war years. While in the peaceful arena, the rush to develop atomic energy and beneficial radiological applications out-raced the measured pace of developing disposal facility to support cleanup of our spent nuclear fuel and radioactive materials. Dominated, early on by budget limitations, since in general it was determined that although cleanup was necessary it was not an immediate threat to health, the mission to complete the life cycle management of nuclear and radiological material lagged behind. This was the case in the U.S. and for essentially all nuclear and radiological enterprises world-wide.

Nuclear enterprises are, of course, not all the same. Power reactors, well financed by their customers, with large technical resources might well be able to safely and securely store spent fuel for many years while waiting for a disposal facility to be developed. The same, might be the case for Government supported research reactors, but there are few installations of this type world-wide compared to the tremendous number of enterprises which utilize radiological sources - 23,000 radiological materils licensees in the U.S. alone. When these smaller enterprises no longer need or want their ionizing sources, but there is no pathway to disposal the impact is proportionally much more severe.

2. Changing perspective

Los Alamos National Laboratory (LANL) has long studied the problems of nonproliferation and the potential of nuclear terrorism. However, it was not until the early 1980s at Los Alamos, that the U.S. Department of Energy formally organized an effort to clean up the residues of the research projects of the Manhattan Project. About that same time LANL was called upon to begin recovery of legacy Ionizing Radiation Sources" (IRSs) containing Pu-239[1] which had been distributed nationally and international under Atoms for Peace. But, this effort was intended to recover valuable Pu-239 not to clean up the environment.

By the early 1990s the recovery effort at LANL had expanded to include commercially manufactured IRSs containing Am-241 and Pu-238 on a case by case bases. The idea of this radiological material recovery remained, however, was still emerging and had not yet been connected to any adversarial threat. This was an environmentally focused effort. During this period incidents in the Republic of Georgia[2] with Strontium-90 and the

---

[1] Plutonium-239/Beryllium Neutron Sealed Sources: Origins, Inventory, and Suitability for Disposal at the Waste Isolation Pilot Plant, by Jeremy Boak, Lee Leonard, Frank Montoya, and Jessica Archuleta, Los Alamos National Laboratory, LA-UR-04-4289, June 1, 2004

[2] IAEA Searches for Discarded Radioactive Sources in Republic of Georgia: IAEA press release 19, May, 2000

memory of deaths in Goiania, Brazil[3] with Cesium-137 provided vivid examples of what impact discarded "orphaned" IRSs could have health and safety. Yet there was no formally organized procedure for proper disposition of "orphaned" IRSs as a legacy of earlier days. When small nuclear gauges containing IRSs began turning up in the scrap metal industry (84 accidental meltings[4] as of may 2004) this ever emerging problem began to quantify itself. The economic benchmark in the U.S. steel industry[5] for a plant to recover from an accidental melting of an IRS has cost 3 to 20 million U.S. dollars.

The listing below, Table 1 compiled by W. Robert Johnston[6] is a more detailed reference to sealed IRS incidents which resulted from a failed policy to have a disposition plan for radiological material at the end of their useful life.

TABLE 1 Sealed Source Incidents - Related To Failed Disposition

Site	Deaths, Injuries	Device
PRC, Sanlian orphaned source 1963	(2, 4)	Co-60 Seed Irradiator
Ciudad Juarez, Mexico orphaned source 1983	(1, 4)	Co-60 Teletherapy
Goiania, Brazil orphaned source dispersal 1987	(5, 20)	Cs-137 Teletherapy
Jilin, PRC orphaned source, 1992	(3, 5)	Co-60 Radiography
Tammiku, Estonia stolen source, 1994	(1, 4)	Cs-137 Teletherapy
Lilo, Georgia orphaned sources, 1996	(0, 11)	Assorted
Istanbul, Turkey orphaned sources, 1998-1999	(0, 10)	Co-60 Teletherapy
Kingisepp, Russia orphaned source, 1999	(3, 0)	Sr-90 RTG
Samut Prakarn, Thailand orphaned source, 2000	(3, 7)	Co-60 Teletherapy
Kandalaksha, Russia orphaned source, 2001	(0, 4)	Sr-90 RTG
Liya, Georgia orphaned sources, 2001-2002	(0, 3)	Sr-90 RTG
Kola Harbor, Russia orphaned sources, 2003	(0, 1)	Sr-90 RTG

By the year 2000 the environmental concern over excess and unwanted IRSs with no disposal path was becoming well understood in the U.S. and an organized recovery effort was established at Los Alamos. By the sum-

---

[3] IAEA: Dosimetric and medical aspects of the radiological accident in Goiania in 1987. IAEA-TECDOC-1009, 2998

[4] Communication between Shelby J. Leonard Los Alamos National and Ray Turner, Chairman of the Study Committee for the United Nations.

[5] Ibid.

[6] Selected entries from database prepared by Wm Robert Johnston and published on internet at: www.johnstonsarchive.net/nuclear/radevents/

mer of 2001 almost 3000 individual excess and unwanted IRSs had been recovered from U.S. licensees, packaged, and placed in secure storage at Los Alamos. But, everything was about to change again.

On September 11, 2001, a small group of terrorists demonstrated how common place elements of our high-tech society (in this case jet airliners) could be transformed into effective weapons of mass destruction, and by individuals with only modest skills and training. Although the idea of a radiological weapon, or radiological dispersion device, (RDD) was not new in 2001, the realization of how readily terrorists might create one with far less skill than that required to fly a jet liner was cause for reconsideration. Coupling this with the knowledge that large numbers of IRSs containing various dangerous isotopes were stockpiled all over the world with no disposal path was a sobering thought.

Following 9/11 the focus of control of IRSs, especially the growing stock pile of excess and unwanted IRSs changed, from health and safety concern to one of a radiological terrorism threat. By January 2002 the U.S. Nuclear Regulatory Commission (USNRC) requested[7] the U.S. Department of Energy Office of Environmental Management to accelerate the program at Los Alamos National Laboratory (LANL) for recovery of excess and unwanted IRSs in the U.S. which had no disposal path. Later that same year the U.S. Congress appropriated a supplemental budget to support LANL recovery program and accelerates the effort with the goal of recovering an additional 5,000 IRSs in 18 months.

In March of 2003 the International Conference on Safety and Security of Radioactive Sources held at the IAEA in Vienna focused high-level attention on the IRS problem with the Governor General of the IAEA and the U.S. Secretary of Energy making clear statements of the importance of world-wide security of nuclear material to include IRSs. Later that year, the IRS recovery effort at LANL was transferred from the DOE Office of Environmental Management to the National Nuclear Security Administration (NNSA) for future management under the newly formed Radiological Threat Reduction Taskforce. Source recovery in the U.S. was henceforth seen as a national security issue, not an environmental or waste management issue.

---

[7] U.S. Government Memorandum from Richard Meserve, Chairman, U.S. Nuclear Regulatory Commission to Robert G. Card, Under Secretary for Energy, Science, and Environment, U.S. Department of Energy, January 16, 2002.

3. The threat

The threat of nuclear terrorism presents the most urgent challenge. A nuclear detonation caused by either a fission or a thermonuclear weapon is the ultimate in terms of real weapons of mass destruction. Damage is massive and devastating with no analogue on the planet earth in which we live. The quick realization by scientists and politicians of the consequences of nuclear weapons and the potential of improvised nuclear weapons (INDs) has led statesmen to develop controls. Treaties, agreements and formal documents and rigorous procedures have been implemented to minimize the threat posed by nuclear materials. Organizations such as the International Atomic Energy Agency (IAEA) and export control organizations, national regimes and formal protocols have been established to expedite knowledge of possible transgressions and to establish strong nuclear material controls. This body of safeguard[8] has been rigorously researched, studied, debated and implemented over the recent decades and has a solid history which we can learn from and build upon as we go forward into the twenty-first century.

Radiological sabotage at nuclear facilities[9] is a second concern, especially because of possible released very large amounts radiation. Response would be a massive undertaking requiring trained and coordinated action of a large number of entities. In densely populated areas with nuclear power reactors cooperative efforts to detect, prevent and respond to radiological sabotage remains a necessity in the twenty-first century. But, the number of power and research reactors world-wide is a reasonably finite number. Methods to secure and harden such sites is a continually evolving, yet mature discipline. International cooperation on both nuclear and radiological events has become a necessity. In spite of language, cultural, and political differences new mechanisms must continually evolve encouraging us to work together.

But what about radiological materials? Cleanup after nuclear weapons tests and experiments have alerted us to the possibility of damage from RDD, the so-called "dirty bomb[10]." Knowledge about radioactive contamination and its effects is not new. Neither is the idea that someone might disperse radioactivity maliciously, which has been studied extensively when evaluating radiological sabotage. What is new is the need for a dis-

---

[8] See Pillars of Nuclear Cooperation IAEA Web Site: http://www.iaea.org/OurWork/SV/index.html

[9] See Nuclear Safety and Security IAEA Web Site: http://www-ns.iaea.org/

[10] The U.S. Nuclear Regulatory Commission Fact Sheet on Dirty Bombs: http://www.nrc.gov/reading-rm/doc-collections/fact-sheets/dirty-bombs.html

cipline that considers, with objective scientific rigor, the true risks that RDDs may present in the context of the world-wide abundance of radiological material and unwanted IRSs. In this world radiological material are widely distributed at tens of thousands of locations in two fundamental forms:

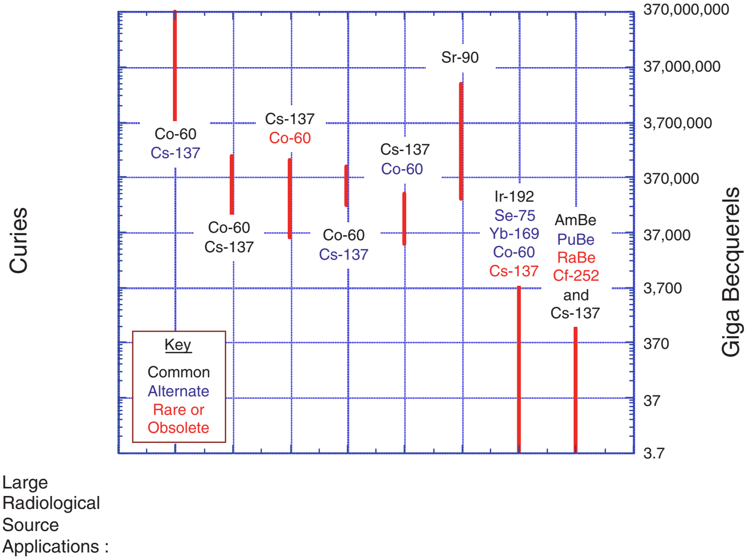
1. The legacy of excess, unwanted and unused IRSs from past decades which have no pathway to safe secure disposal.
2. The IRSs and devices which continue to be manufactured and used and have become indispensable to medicine, industry, and science.

What do we know about the potential of RDDs? We do know that RDDs do not have structurally destructive power as do nuclear weapons. The physical damage from an RDD is generally assumed to be limited to that of the explosive used to disperse the radioactive material. Neither are RDDs likely to be immediately life threatening to a larger number of people. Again, if an explosive is used to generate dispersal the initial explosion would tend to be greatest immediate hazard to life. But, cleanup of the dispersed radioactive material would be time consuming and costly. Denial of access to high-value property for days, weeks, months, or perhaps years could have enormous economic impacts. The response of the public both immediate and long-term could have immeasurable effects on the economy, the psychological health of the community, or the social and or political stability. Used as a weapon of mass destruction, RDDs would require cooperative action by local and federal government, fire and police departments, medical and hospital personnel, and trained staff for detection and cleanup in ways not yet well understood. While exercises simulating the expected situation and disruption would be helpful in analyzing major potential problems, we are in only in the beginning stages of thoroughly understanding the potential of RDDs.

We understand the basics of radioactive dispersal and resulting contamination, but the tremendous variety of IRSs available to fuel an RDD makes for a great number of forms that a finished weapon could take. When one then tries to consider the many ways and in the many environments in which an RDD might be deployed the challenge of parametrically analyzing and quantitatively evaluating the potential consequences of RDDS is rather daunting.

Consider the variety of IRSs. The radioactivity spans many levels of magnitude depending on the particular original intended use. Table 2 covers nine orders of magnitude for the various isotopes used and identifies their general usage.

TABLE 2[11].



Prioritizing the Risk

As already discussed unlike the mature study disciplines of nuclear terrorism and radiological sabotage, we are just beginning to understand the potential of radiological terrorism. A document that has begun to define the proper management of IRSs on an international basis is the *IAEA Code of Conduct for the Safety and Security of Radioactive Sources*[12] which has

---

[11] This Graphic is Taken from: Reducing RDD Concerns Related to Large Radiological Source Applications, Gregory J. Van Tuyle,
Tiffany L. Strub, Harold A. O'Brien, Caroline F.V. Mason, Steven J. Gitomer, LA-UR-03-6664, Los Alamos National Laboratory, September 2003

[12] See http://www-ns.iaea.org/tech-areas/radiation-safety/code-of-conduct.htm

now received support from 80 countries[13] as well as U.S. Nuclear Regulatory Commission (NRC) on behalf of the U.S. While the Code of Conduct addresses the elements of controlling radiological sources it focuses on large Category 1 and 2 IRSs from the health physics perspective only. The Code nor the technical documents on which it is based are not vehicles for assessing the potential quantitative risk presented by specific IRSs as they are used throughout the world. Risk is commonly understood as the product of a defined consequence of an event and the probability that the event will occur. In traditional *safeguards* of nuclear material we assume that the potential consequence is unacceptable (the detonation of a conventional or improvised nuclear device) and our conduct of material management provides for complete control through Detection, Delay, and Response measures to assure that the occurrence of an event is incredible. The Code of Conduct for sources does not provide this level of assurance nor does it permit, through a structured risk analysis, a method to prioritize risk from sources. The Code is therefore an excellent first step in development of a *safeguards* infrastructure for IRSs, but it is only a first step and much more needs to be done. A number of researchers have shown in the open literature[14], including presentations to the U. S. Congress that the use of an RDD made from even a single Am-241/Be neutron-emitting IRS (Category 3 source under the Code of Conduct) could have a major impact on the U.S., especially in an urban environment. This realization has stimulated extensive research in consequence analysis, attribution of IRSs, emergency response planning, etc. Yet at this time the method for comprehensive risk assessment from IRSs, to permit a quantitative method to prioritize and prevent an event does not yet exist. There are many parameters which would factor into the probability coefficients of a rigorously developed IRS risk equation which have yet to be thoroughly researched and defined.

An analysis by the Australian Radiation Protection and Nuclear Safety Agency has qualitatively categorized factors to consider when answering the threat of RDD's as shown in Table 3. The three categories of risk, although not quantitative introduces the necessary factors that are helpful in

---

[13] Ibid: See – States Expressing Support for the Code of Conduct and the Import/Export Guidance

[14] The Four Faces of Nuclear Terror And the Need for a Prioritized Response William C. Potter, Charles D. Ferguson, and Leonard S. Spector, From *Foreign Affairs*, May/June 2004

making real world judgments on which types of IRSs might require the most urgent attention.

The task of RDD Prevention:

While we wait for this emerging discipline concerning the threat of radiological terrorism to catch up in sophistication and depth of knowledge as other disciplines regarding nuclear and radiological sabotage we need to do what we can in a practical way to prevent the possibility of an RDD being fabricated and deployed. In general we can say that every IRS recovered from an unsecured environment and relocated to a secure environment lowers the radiological or RDD threat. In the U.S. decisions about source recovery by the LANL source recovery programs are prioritized as follows:

TABLE 3[15]Additional Factors to Consider When Assessing Threat of an IRS for potential use in an RDD

	Lowest Risk	**Medium Risk**	**Highest Risk**
Composition	Metal	Ceramic	Powder
Containment	Special Form	Sealed	Unsealed
Mode	Fixed	Transportable	Portable
Stage of Life	Acquiring	In Use	Store/Dispose
Construction	Integral w/Shield	Single	Multiple

- **Unwanted IRS** – with no security or physical control – Recover immediately
- **Unwanted IRS** – Physically controlled with limited security – Recovery advised
- **In-use IRS** - where the sustainability of control and security need to be carefully scrutinized by cognizant regulatory authority. – Recovery needs to be considered.

In the U.S. when excess and unwanted sources are recovered they are secured in a highly secure location such as LANL, or disposed by permanent isolation from the environment, at which time the potential threat is

---

[15] Austrailia's Experience of Implementing the Code of Conduct: Asia-Pacific Nuclear Safeguards and Security Conference November 8-9, 2004, Presented by Peter Colgan, Australian Government, Austrailian Radiation Protection and Nuclear Safety Agency.

reduced to zero. In some instances a recovered source may be recycled into reuse where re-establishment of security and safe physical control can be assured under an appropriate regulatory program.

TABLE 4 Primary Isotopes Distributed by U.S. Government Programs as IRSs or for the Manufacture of IRSs (1955 – Present)

**	Pu-239	Pu-238	Am-241	Cs-137	Sr-90
Total in (kg)	109.2	137	45	90	80
Recovered or Disposed to date (kg)	76.64	132	15	30	30
Amount remaining in Sources (kg)	32.56	5	30	60	50
Number of units to dispose Waste Package disposal form	190 55 Gal Drums as TRU waste	2,550 55 Gal Drums as TRU Waste	3,000 55 Gal Drums as TRU Waste	5,200 1 cubic meter Shielded Concrete Waste Container as LLW	60 Existing Package as LLW

**These quantities Should be considered preliminary estimates. Further research is needed to refine these data.

The task of preventing the potential of RDDs by removing the excess and unwanted (most vulnerable) IRSs from the environment is a significant task before the nations of the world, but should not be seen as an overwhelming task. The nations that have distributed isotopes in the form of manufactured IRSs and devices is relatively small[16]. While the sources themselves are numerous the total amount of radioactive material to be managed once recovered through storage or disposal is modest. A preliminary estimate of the total quantity of the primary long-lived isotopes contained in IRSs produced and distributed domestically and internationally by the U.S. government over the past 50 years is shown in Table 4[17] below. Also shown is the estimated amount removed from the environment by recovery, decay, and disposal. The total mass believed to remain in

---

[16] The Primary long-lived isotopes of concern have and continue to be distributed from states with established nuclear weapons programs through formal government-sponsored isotopes sales programs.

[17] These data are estimates compiled by the Off-site Source Recovery Program at Los Alamos National Laboratory 2004, See also: http://osrp.lanl.gov/

IRSs either in use or excess is shown in the third row. Finally, in the forth row we describe the unitized quantities which now, or sometime will require disposal. To acquire these numbers we assume all of the remaining isotopic mass shown in row three is recovered and packaged for disposal in a waste form typical of disposal methods used in the U.S. The only conclusion that can be reached by this table is that if all of the IRSs ever produced from U.S. distributed isotopes were recovered and then disposed; only a modest storage and/or waste management program would be required.

Global radiological threat reduction from potential RDDs will only be achieved when the nations responsible for IRS distribution take a leadership position in accepting and recovering the excess and unwanted IRS legacy currently growing in the world. The U.S. has begun this process at home, and is beginning to repatriate IRSs of U.S. manufacture on a case-by-case basis, but full international cooperation in this area has yet to be achieved. Policies to return IRSs to their developed nation of origin are urgently needed, especially as these legacies of IRSs effect developing countries. Only following a general global recovery of this legacy backlog can regulators, both in the U.S. and internationally, begin to effectively address the safety and security of IRSs currently in use and those that will be necessary in the future.

4. IRS recovery by LANL

We began with some discussion of the origins of the work at LANL to identify and recover excess IRSs in the U.S. and the program that evolved after 9/11. The current recovery strategy is a qualitative approach to threat reduction prioritization as mentioned above and will remain so until sophisticated quantitative risk analysis tools become available. The current method is based on the total activity of radioactive material at a site, the relative level of sustainable security at the site, and the potential economic stress on the source owner/custodian if applicable. The prioritization method is coordinated between the US NRC and NNSA. Under all the programs at LANL which began in 1979 over 13,000 IRSs of various types have been recovered and secured, with over 8,500 of these having been recovered and secured since 9/11/2001[18].

---

[18] Information compiled by the Off-Site Source Recovery Program, Los Alamos National Laboratory as of October 1, 2005

The history of the recovery program is displayed in Table 5[19]. The impact of 9/11 is clearly manifested in the number of sources recovered in 2001 and in the following year. The U.S. nuclear agencies reacted vigorously in reducing the nationwide stockpile of excess or unusual sources containing ionizing radiation.

Table 5 Sealed Radioactive Source Recovery History by LANL

RECOVERIES

U.S. Federal Fiscal Year	Number of Sources per year	Cumulative Number of Sources	Number of Sites from which sources were recovered by year	Cumulative Number of sites
1997	5	5	1	1
1998	11	16	6	7
1999	52	68	14	21
2000	38	106	17	38
2001	2874	2980	27	65
2002	1238	4218	77	142
2003	3122	7340	73	215
2004	2718	10058	145	360
2005	1634	11014	61	421

In total over 106,000 Curies of radioactivity have been recovered and secured. The source recovery program as initiated in 1979 through 1998 focused on collecting Pu-239/Be sources, but has since expanded to include the actinides, curium-244, americium-241, plutonium-238 and 239 and californium-252. The expansion also includes the following beta-gamma emitters of concern: cobalt-60, strontium-90, cesium-137, radium-226 and iridium-192.

---

[19] Ibid.

5. Organization and procedures

Under the threat reduction mission the approach at LANL has been to implement an infrastructure that combines all elements necessary to address the legacy of excess and unwanted IRSs in the U.S. and where necessary internationally through cooperation with the IAEA.

Team – A small group of train professionals at LANL works closely with the NNSA sponsor and regulators plan efficient cost-effective recovery operation. The team is supplemented by a small group of specialty subcontractors with historical expertise in IRSs.

Tools – An information management system has been especially developed to track the management of excess and unwanted IRSs from the time they are identified through recovery storage and disposal. Instrumentation to identify unknown IRSs is an important part of the infrastructure. Multifunction containers, for packaging, transportation, and safe storage have been developed and procured including a capsule system that supports creating U.S. DOT – compliant *special form* in the field when IRSs are found leaking or without appropriate documentation. LANL has been instrumental in opening a pathway for all Pu-239 IRSs of U.S. manufacture to find disposal at the Waste Isolation Pilot Project (WIPP) in Carlsbad, NM. LANL has also developed the technical basis which has ultimately supported disposal of large Sr-90 Radio Isotope Thermal-Electric Generators (RTGs) as Low Level Radioactive Waste (LLW) at the Nevada Test Site (NTS) and the Hanford disposal site in eastern Washington State. The project staff continues to explore and support efforts to implement disposal for IRSs which remain without disposal paths.

6. Current work scope and planning

In 2005 the recovery project at LANL expanded into the decommissioning of large gamma irradiator facilities recovering spent Co-60 IRSs for disposal as LLW and Cs-137 IRSs for secure storage and possible recycle. Two large Sr-90 RTGs were recovered and placed in secure storage at LANL At the end of FY-05 the project had a prioritized list of approximately 500 beta/gamma IRSs awaiting recovery in the U.S. and about 1500 IRSs containing Transuranic isotopes. The project has begun to support IAEA IRS recovery efforts in FY-2005. This work has included the repatriation of 68 Am-241 IRSs of U.S. origin which were recovered by IAEA teams in Africa. In conjunction with IAEA, LANL teams have traveled to South Africa, first to consult on the design and construction of an

IAEA portable hot cell for recovery and management, in remote regions of high-activity IRSs, and then to demonstrate the methods and equipment for handling field recoveries of Transuranic neutron-emitting IRSs. With IAEA LANL teams have packaged sources in Uruguay and over the next year will continue to expand support. The LANL project maintains a website at, http://osrp.lanl.gov which can provide additional information on the IRS recovery effort and offers a place to register excess and unwanted IRSs with the project.

7. Conclusion

The twenty-first century will place increased demands on the world for continued vigilance in combating nuclear terrorism and addressing the threat of radiological terrorism. Improved safeguard and security will be required and the mechanisms supporting international cooperation in these areas will need to need to be enhanced. But, the twenty first century has brought with it a sudden awareness of a threat, present, but not well considered before 9/11. The potential to turn common-place IRSs and devices into weapons of radiological terrorism is now clearly recognized, but not yet well understood. Much needs to be done to rigorously evaluate the nature and potential of radiological terrorism in quantitative terms. Much needs to be done to develop and implement an international safeguards and security infrastructure for IRSs as we have for nuclear materials. This is needed for IRSs which are in use, but also for the legacy fraction of IRSs long excess and unwanted but without a safe and secure disposal pathway.

There is much that needs doing in the twenty first century. While these tasks are underway LANL will continue to support the global effort where ever possible, while continuing the work of recovering IRSs and proportionally lowering the radiological threat.

MULTI-ATTRIBUTE ANALYSIS OF NUCLEAR FUEL CYCLE RESISTANCE TO NUCLEAR WEAPONS PROLIFERATION

ANATOLY ZRODNIKOV, VALERIY KOROBEYNIKOV,
ALEXANDER CHEBESKOV, BORIS TIKHOMIROV
State Scientific Center of Russian Federation - Institute of Physics and Power Engineering named after A.I. Leipunsky, Obninsk, Bondarenko Sq., 1,

Abstract: Calculation study has been carried out to analyze the proliferation resistance of different scenarios of nuclear fuel cycle organization. Scenarios of stable and developing nuclear power were considered with involvement of thermal and fast reactors. The attention was paid mainly to the cycles with extended plutonium breeding on the basis of fast reactor technology, and to the schemes of fuel cycle organization allowing to minimize the proliferation risk.

Keywords: proliferation resistance; multi-attribute utility method; fast reactor; nuclear fuel cycle; risk proliferation; once- through and closed fuel cycles; accumulated plutonium; minor actinides; plutonium breeding.

1. Introduction

Potential threat of non-authorized use of fissile materials circulating in nuclear fuel cycle for terrorist purposes or for creating nuclear weapons gives warrantable public concern. It is quite natural that development of nuclear fuel cycle (NFC) being maximally resistant to nuclear material theft or diversion is one of the most important directions for the specialists. Both existing and perspective nuclear power is considered mainly in view of realization of once- through and closed fuel cycles.

In once-through NFC which assumes disposal of spent nuclear fuel (SNF), irradiated fuel subassemblies are considered as a form of radioactive waste. At that, along with fission products, considerable amount of valuable materials is subject to final disposal: under-burned uranium, accumulated plutonium, minor actinides that could be reused as a fuel for power reactors. Long-term cooling erodes radiation barrier from the spent fuel, facilitating its possible reprocessing and plutonium separation. This results in

S. Apikyan and D. Diamond (eds.), Countering Nuclear and Radiological Terrorism, 63–84.

simplification of weapon application of such materials. A lot of other obstacles arise on the way of direct SNF disposal, which in fact have led to moratorium of this back-end NFC technology in the majority of countries, and consequently to a heavy disproportion between the quantity of plutonium accumulated in stored SNF and the quantity of plutonium being actually eliminated.

Alternative to SNF geological disposal is multiple recycling of plutonium and uranium. In principal, in this case the proliferation problem is solved, provided that nuclear waste is disposed. However, none of the countries in the world has implemented complete closed fuel cycle concept, promoting growth of plutonium inventories in both SNF and separated form.

Many countries still did not clarify for themselves the strategy of NFC back-ending, and follow the policy of postponement of solving this problem. Such policy envisages temporary, but long enough storing of SNF followed by its extraction from storage facilities for further reprocessing or final disposal.

The goal of this work is to assess potential plutonium proliferation risk in long-term nuclear fuel cycle strategies and to find the ways of its reduction.

To analyze proliferation resistance, calculation studies were performed for different options of nuclear fuel cycle organization schemes. Scenarios of steady-state and developing nuclear power with thermal and fast reactors were modeled. The main attention was paid to fuel cycles with plutonium breeding using fast neutron reactors, and to approaches of organizing NFC in such a way that would give the minimal proliferation risk value.

2. On some specific features of proliferation risk assessment task

The quantitative analysis of fissile nuclear material proliferation risk assessment is the field that in a literal sense comes into being before our eyes. In the methodological respect this task has some common features with the task of environmental risk assessment because in both cases we have the same risk source (nuclear fuel cycle), standard and non-standard conditions of its functioning are being studied (nuclear accidents or fissile materials losses) and finally, the probability of any impact on human health and environment with consequences of various severity is determined.

Based on this analogy it is quite natural to try and develop methods for fissile material resistance to proliferation in terms of the final impact risk. These methods should include the detailed description of NFC facilities, the analysis of possible channels for fissile material diversion and probability of these events, estimation of explosive devices' capacity and consequences of their use. However the implementation of this algorithm for the non- proliferation task is associated with a number of significant problems. One of the most serious problems consists in the lack of particular facts. Isolated cases of fissile material theft have only been registered and fortunately there were no actions of its unauthorized use for terrorist purposes. An extremely low probability of events related to violation of NMPC&A regime turns the task of direct proliferation risk assessment into the task that is very difficult to formalize and extremely complicated to describe mathematically. That is why in order to solve this problem consideration is given to the new sections of mathematical analysis being developed today, that is the theory of fuzzy sets or interval algebra.

Evidently the success of the methods of proliferation risk assessment in terms of the final impact risk is yet to come. But at the initial stage of their development it is quite reasonable to address the assessment of potential risk of fissile materials in the way it was done at the beginning stage of development of quantitative methods for environment risk assessment (calculation of potential radionuclide risk indices).

The given paper demonstrates the approaches to the analysis of nonproliferation problem in terms of potential risk of fissile materials for two tasks. The first task is related to the assessment of proliferation risk in the global long-term strategies of NFC development and is based on papers [1-3.] The second task is related to determination of the role of nonproliferation issues when the specific decision is made on the choice of effective strategy of weapons grade and civil Pu disposition in Russia. It is based on papers [4-6].

3. Methodology

Development of nuclear fuel cycle (NFC) being maximally resistant to nuclear material theft or diversion (inappropriate use) is one of the most important directions for the specialists.

The method of risk proliferation (P) assessment used in the study was proposed by R. Krakowski [1] and is based on calculation of so-called *«risk exposure»* E over the time with account for the factor of possible nuclear technologies improvement:

$$E_j = \int_0^t \frac{I_j \, dt / 10^6}{(1+r)^t} \tag{1}$$

$$P_j = w_j E_j \tag{2}$$

$$P = \sum_j P_j \tag{3}$$

where j – stage of nuclear fuel cycle (reactor, irradiated fuel in storage facility, reprocessing, storing of separated plutonium, etc.); I_j – streams (inventories) of plutonium at stage j; r – discount factor reflecting future technological improvements; w_j – weight factors.

Weight factors w_j define the level of plutonium attractiveness and accessibility at different stages of fuel cycle from the viewpoint of their possible use for NED creation. The choice of these weights is performed based on expert estimation and is a task of a great difficulty. Numerical values for w_j in [1] were determined by use of well-known method of Saaty's pairwise matrix [3]. Value of 1 was taken for plutonium residing in operating reactor. Value of separated civil plutonium was set equal to 8. The weight values calculated using Saaty's matrix then are normalized so that the sum of the weights for all NFC stages is equal to 1.

4. Initial variants used for the analysis

It is obvious that the primary task on the way of proliferation risk reduction is elimination of inventories of weapons materials and decrease of stored quantities of separated fissile materials used for fuel fabrication down to operating reserve volume.

In the work[6], efficiency of different approaches to elimination of weapons and civil plutonium inventories was evaluated. Particular activities were to be evaluated and specific decisions were to be made not only issuing from the "Non-proliferation" criterion, but also based on economics, technical readiness and safety of reactors used for separated fissile materials burning, and possible ecological damage. Application of such a system approach becomes widespread.

Within the framework of this very study we are interested in finding out the efficiency of the activities mainly from the viewpoint of non-proliferation and proliferation risk reduction in global strategies of nuclear power development when the excess weapons and civil plutonium is already consumed.

4.1. STABLE NUCLEAR POWER

Below the variants of nuclear fuel cycle for which the proliferation resistance was studied using risk exposure criterion are described. Every scenario considered simulated power system of the same installed capacity. Proliferation risk was calculated over the time interval of 80 years. "Stable nuclear power" was considered in 6 variants (Figure 1):

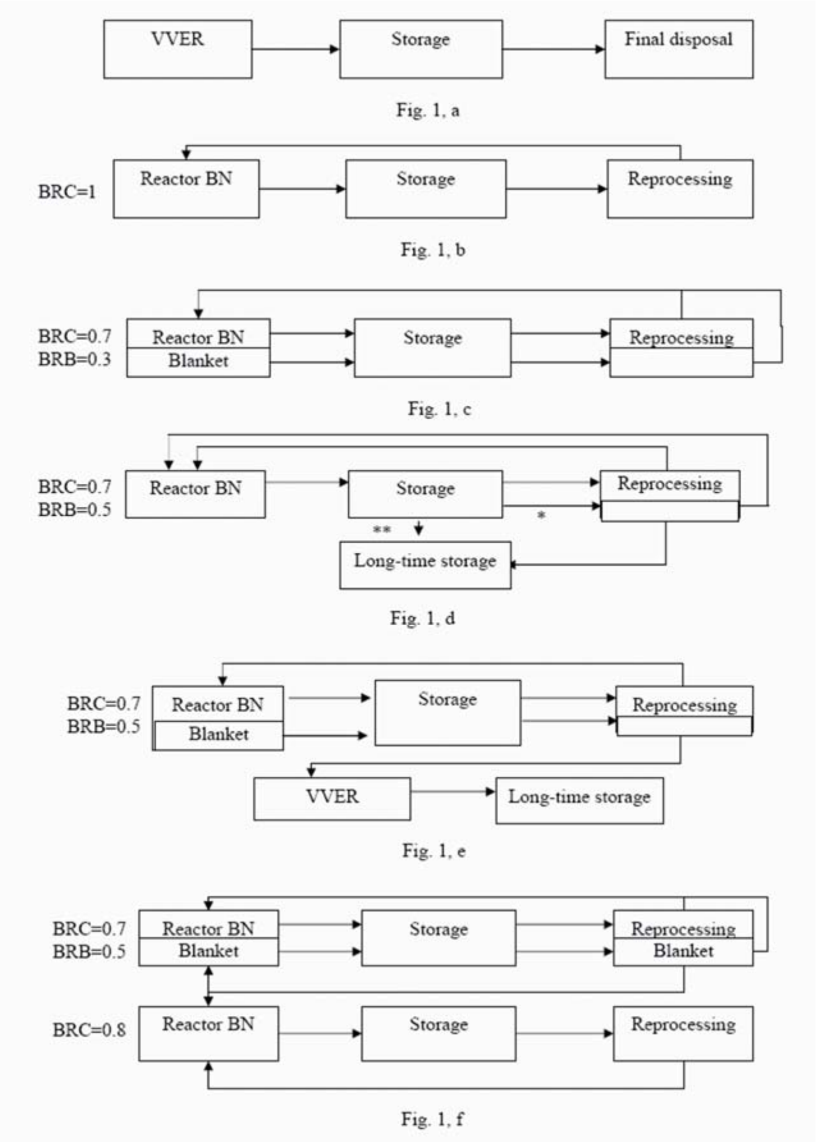


Fig. 1, a

Fig. 1, b

Fig. 1, c

Fig. 1, d

Fig. 1, e

Fig. 1, f

Figure 1. Flowchart of stable nuclear power fuel cycles scenarios

- The power system is comprised of VVER-1000 reactors operating on uranium fuel, with final disposal of spent fuel after in-reactor cooling. The flowchart is presented on Fig.1,a.
- The power system is comprised of fast neutron reactors operating on uranium-plutonium (MOX) fuel with BRC=1, BR=1. Plutonium being built up in such scheme is reused. The flowchart is presented on Fig. 1,b.
- The power system is comprised of fast neutron reactors with BRC<1, BR=1. Two types of plutonium are used for fuel fabrication: plutonium generated in core, and plutonium built up in blankets. The flowchart is presented on Fig. 1,c.
- The power system is comprised of fast neutron reactors with BR>1. Excess plutonium is cooled down in the in-reactor storage facility, then it is shipped either to the long-term storage or to the reprocessing and consequent storage. The flowchart is presented on Fig. 1,d.
- The power system is comprised of two types of reactors: BN-1000 and VVER-1000. Fast reactor operates in closed fuel cycle, excess plutonium is consumed by VVER-1000 reactors. The flowchart is presented on Fig. 1,e.
- The power system is comprised of two types of fast neutron reactors. The first type has BR>1, the second one has BR<1. Excess plutonium from the first type reactors is used to compensate the lack of plutonium for the second type reactors. The flowchart is presented on Figure 1,f.

4.2. DEVELOPING NUCLEAR POWER

In the model of developing nuclear power we considered three variants. All the scenarios considered had the same rate of installed capacity increase. Proliferation risk was calculated over the time interval of 80 years.

- Nuclear power grows exclusively at the expense of commissioning fast neutron reactors with BR>1.
- Nuclear power development is made exclusively by VVER-1000 reactors in once-through uranium fuel cycle.
- Both thermal and fast reactors are used for nuclear power development. Fast reactors have BR>1; for commissioning new fast reactors, plutonium from both fast and thermal reactors is used.

5. Calculation results of proliferation risk evaluation

5.1. STABLE NUCLEAR POWER

Calculations were performed using relations (1)-(3).

Figure 2 shows the calculation results of cumulative proliferation risk for the above described scenarios. The OT-TR cycle with final SNF disposal after a very short time period (3 years) looks the most advantageously (curve 2). Already after 20 years, MR-FR cycle takes the second position (curve 1), leaving behind the OT-TR cycle with long-term storage of SNF (curve3).

However if one takes a non-zero value for the final disposal stage, the picture will change, and with time the accumulated proliferation risk of open fuel cycle with even very short intermediate SNF cooling can turn to be higher than that of NFC with fast reactors having a short external cycle time.

Closed fuel cycle in scenario 2 also was modified. Figure 3 demonstrates proliferation risk estimates for two technologies of fast neutron reactors: existing (BN with sodium coolant) and potentially perspective (BREST with lead coolant) [8]. Improvements of fuel cycle for the perspective fast reactor were concluded in increase of refueling intervals and use of spent fuel reprocessing technology without separation of plutonium from uranium. Analysis of the results has shown that proliferation risk decreases by increasing refueling intervals (curves 2,4 and 1,3) and decreasing external cycle time (curves 2,1 and 4,3). Spent fuel reprocessing technology without separation of plutonium from uranium also makes an additional contribution to proliferation risk reduction.

As one can see from Figure 3, the studies on “risk exposure” model in general have confirmed some advantage of BREST lead-cooled fast reactor fuel cycle with respect to fissile materials proliferation resistance in comparison with fuel cycle realized by sodium-cooled fast reactors of BN type.

Previous studies dealt with fuel cycles with no excess plutonium generation, and all the plutonium built up has the reactor quality. The quality of plutonium generated in blankets is very high in view of nonproliferation. Therefore, further we focus on how the value of proliferation risk is changed by involving blanket plutonium in the nuclear fuel cycle. Let us consider variants 3 - 6.

In scenario 3 BRC<1, BR=1 and blanket plutonium is reprocessed and used to feed the core. In scenario 4 BRC<1, but BR>1 and not all the plutonium generated in blankets goes to fuel fabrication. Some part of plutonium is shipped for long-term storage with two alternatives: plutonium is extracted in a form of dioxide and then is shipped to storage facility (a), no extraction, plutonium rests in irradiated blanket assemblies (b).

Figure 4 shows comparison of calculation results for the above described scenarios. The lowest risk (as was expected) is calculated in the variant which envisaged reuse of all the built plutonium. Among the variants with storing the excess plutonium, the variant of plutonium dioxide storage has the lowest scores.

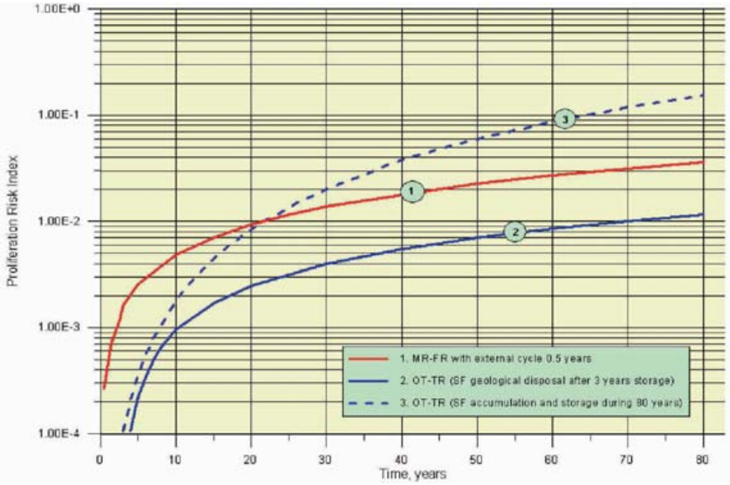


Figure 2. Comparison of plutonium proliferation risk estimates

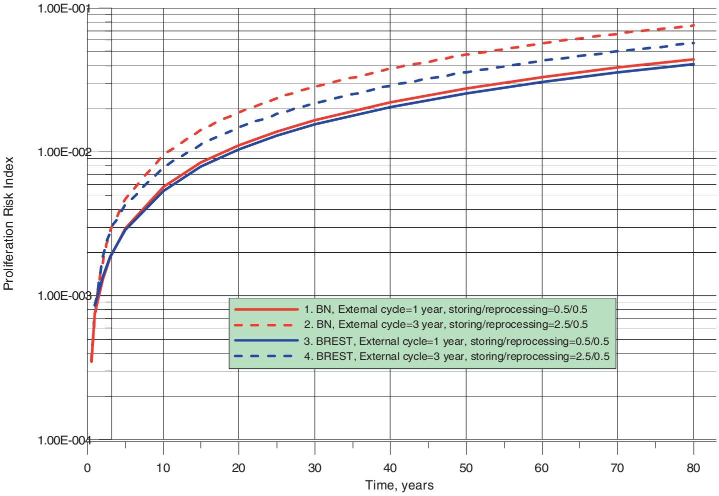
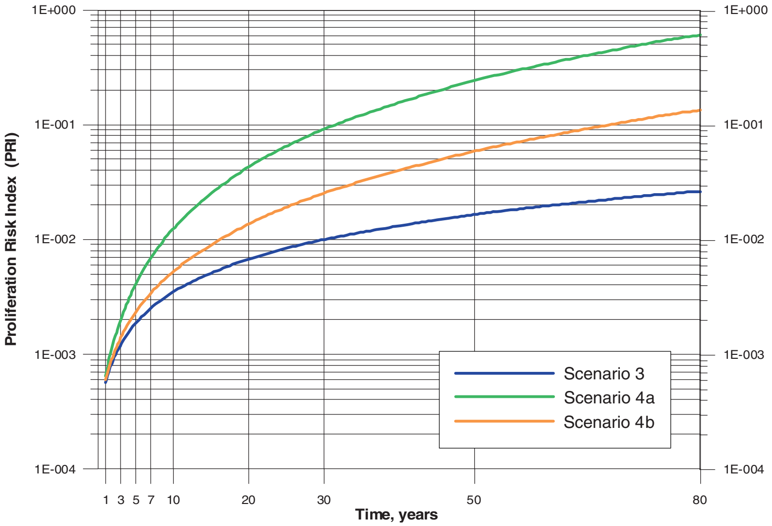


Figure 3. Plutonium proliferation risk index for different fast reactor technologies



Fiure 4. Comparison of proliferation risk estimates for blanket plutonium recycling (scenario 3) or storing (scenario 4) strategies

Figure 5 demonstrates comparison of scenarios 4 and 5. Both scenarios envisaged plutonium accumulation in storage facilities. Let us take a more detailed look at scenario 5, in which the system of fast and thermal reactors is being modeled. Fast reactors operate in extended breeding mode providing a part of plutonium for VVER-1000 MOX fuel fabrication. MOX fuel is used in VVER-1000 once, and then irradiated fuel is shipped to storage facility. Calculation results allow to see that the risk curve for scenario 5 lies below than those of both sub-variants of scenario 4, meaning that scenario 5 is better from the nonproliferation point of view. The reason of this fact is that the quality of plutonium originated from VVER-1000 spent fuel is much worse than that of plutonium built up in breeding blankets of fast reactor.

Figure 6 demonstrates comparison of scenarios 5 and 6. Both scenarios have reactors that build up excess plutonium, however in scenario 5 this excess plutonium goes for once-through use in VVER, in scenario 6 this plutonium is used to feed fast reactors with BR<1. Risk curve for scenario 6 lies considerably lower that that for scenario 5, because plutonium in scenario 6 always returns into the fuel cycle.

Now let us consider closed fuel cycles with circulation of plutonium having different quality from the viewpoint of non-proliferation problem. Figure 7 shows risk curves for scenario 2 in which only the plutonium from reactor core circulates, and for scenario 6 which envisages usage of both core and blanket plutonium. Risk curve for scenario 6 lies just slightly above the risk curve for scenario 2.

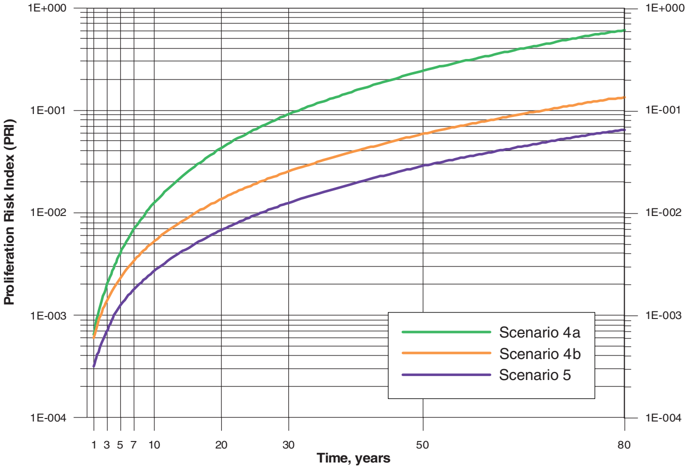


Figure 5. Comparison of proliferation risk estimates for storing blanket (scenario 4) or civil(scenario 5) plutonium

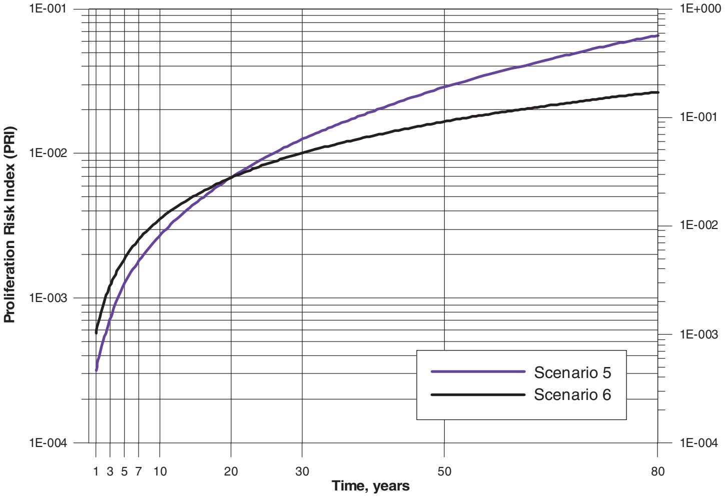


Figure 6. Comparison of proliferation risk estimates for use of excess blanket plutonium in thermal (scenario 5) or fast (scenario 6) reactors

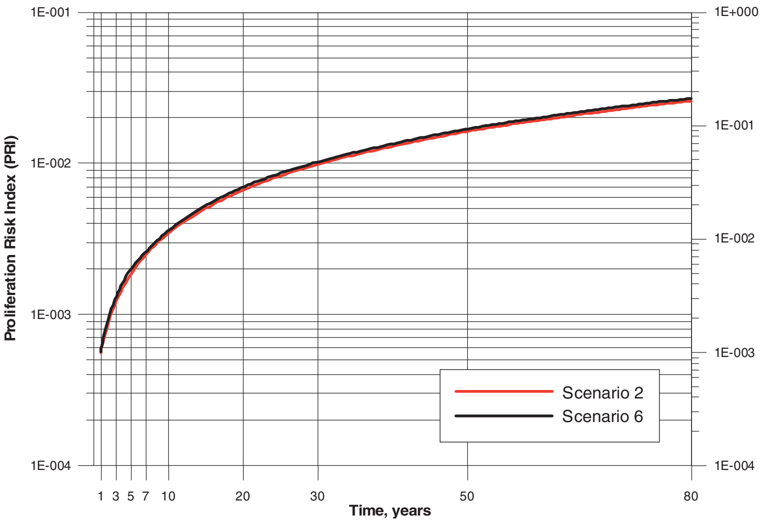


Figure 7. Comparison of proliferation risk estimates for recycling of civil (scenario 2) or civil and excess blanket (scenario 6) plutonium in closed fuel cycle

Thus, the results of calculations demonstrate that if excess plutonium built up in blankets goes back to the reactors in a form of fuel, no considerable increase of proliferation risk with time occurs. Observance of plutonium generation and consumption balance, lengthening of refueling interval, reduction of external cycle time – all these measures turned out to be substantially more efficient than refusal of extended breeding.

5.2. DEVELOPING NUCLEAR POWER

Results of calculation studies carried out for the variants of developing nuclear power are presented on Fig. 8

All the calculations were carried out for the same rate of installed capacity increase. It can be seen from the calculation results that the highest risk arises in the scenario of nuclear power development using thermal reactors (O-TH) with delayed disposal of spent nuclear fuel. The risk is considerably decreased if SNF after a short cooling down in an intermediate storage goes to the final disposal (O-TH_FD). Three remaining scenarios represent closed fuel cycle. Developing nuclear power with fast reactors (CC-FR) has practically the same risk as the scenario of once-through fuel cycle with deep geological (inaccessible) SNF disposal.

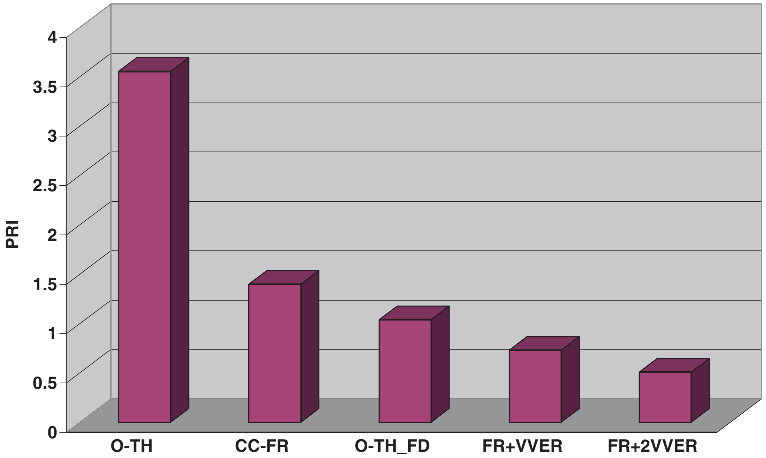


Figure 8. Proliferation risk in nuclear power development scenarios. Calculation period - 80 years

In case when a developing nuclear power, along with closed fuel cycle based on fast reactors, involves thermal reactors, the proliferation risk decreases, the decrease is proportional to share of thermal reactors. This latter result is connected with overall reduction of quantity of plutonium circulating in the system.

5.3. SENSITIVITY OF MODEL TO INPUT PARAMETERS

Weight factors used in risk assessment methodology are the parameters of ultimate importance. They condition the sensitivity of proliferation risk of the same quantity of plutonium at different stages of nuclear fuel cycle. Figure 9 demonstrates the values of weight factors w_j, used in scenario analysis.

For comparison, attractiveness of separated weapons plutonium is given. It follows from the results of comparison that fuel cycle should be optimized in such a way that the duration of fissile materials presence at SNF reprocessing and fuel assembly fabrication stages is minimized. The most dangerous stages of the fuel cycle are inventories of separated weapons and civil plutonium.

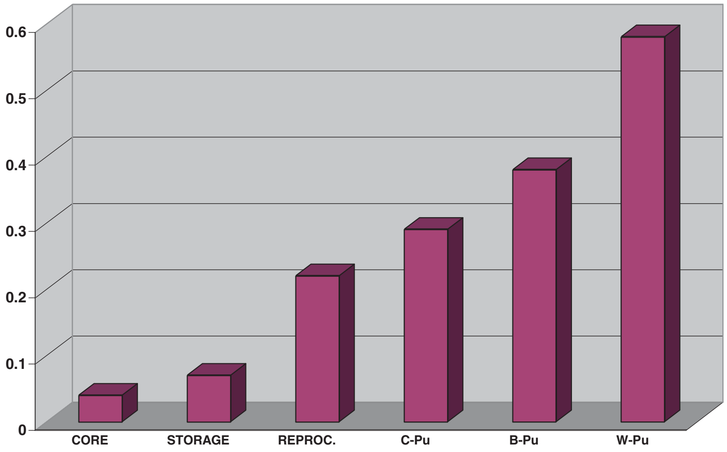


Figure 9. Relative attractiveness of plutonium at different stages of nuclear fuel cycle

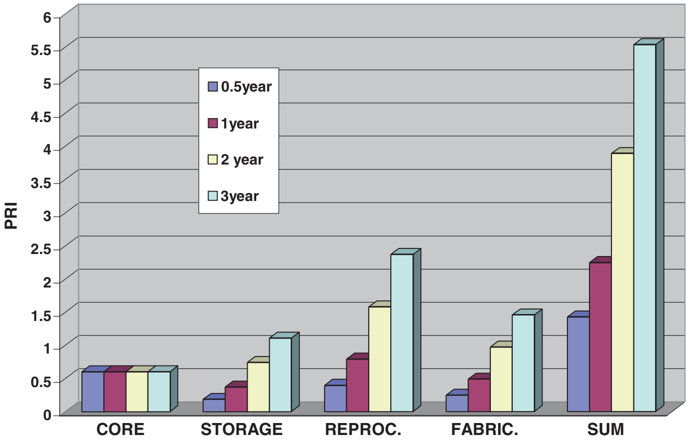


Figure 10. Proliferation risk at fuel cycle stages versus external cycle duration (Calculation period 80 years)

Figure 10 demonstrates proliferation risk versus duration of external fuel cycle under condition that duration of its individual stages is proportional to the whole external fuel cycle duration. The results show that increase of external fuel cycle time leads to considerable increase of contribution of some stages. Overall change of proliferation risk value is also substantial. Especially large contribution is made by the reprocessing and fuel fabrication stages; in-reactor storage facility makes less essential contribution. It is worth noting once more that the largest contribution to proliferation risk is made by the stages of plutonium separation and long-term storing of separated plutonium.

The same dependence, but under condition that durations of spent fuel reprocessing and fuel fabrication remain unchanged is presented on Figure 11. It can be seen from the calculation results that proliferation risk increases with increase of external cycle duration due to the stage of storing, and overall risk is decreased as compared to that of the previous case.

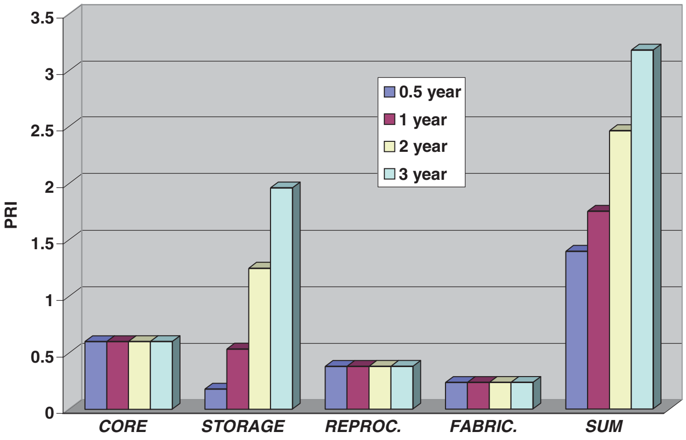


Figure 11. Proliferation risk at fuel cycle stages versus external cycle duration. Duration of reprocessing and fuel fabrication stages in unchanged

6. Analysis of nonproliferation aspects for Pu disposition alternatives in Russia

The real evolution of nuclear complex in many countries of the world went in the absolute contradiction with the requirement to minimize "the Pu risk exposure" that follows from the model considered. As a result, a big amount of Pu has been accumulated primarily in the non- reprocessed spent fuel of thermal reactors. Besides, the stockpiles of separated civil Pu are still growing in France, Great Britain and Russia. The USA and Russia declared the amounts of weapons-grade Pu as surplus for the defense purposes. So the potential proliferation risk has not demonstrated the tendency towards its decrease yet.

The Russian Federation seems to have the broadest spectrum of various types of Pu, including the surplus weapons – grade Pu, civil Pu separated from spent fuel, Pu in spent fuel of thermal and fast reactors, Pu accumulated in fast reactor blankets. It is well-known that the principal position of the Russian Federation consists in declaration of Pu as valuable fuel material which should not be subjected to final disposal in geological formation. From this standpoint sooner or later the transfer to the strategy of Pu use as a reactor fuel will be inevitable. In view of that the fact that in the US-Russian Agreement on disposition of 34 tons of surplus weapons – grade Pu the reactor disposition technology was chosen as the main technology, could be considered as a great success in Russian policy.

Preparation of the program on weapons-grade Pu disposition and development of a long- term strategy of Pu involvement into the NFC of Russia required comprehensive consideration of all the available reactor alternatives in terms of political, economic and social criteria and the criterion of nonproliferation. The principal estimation of the strategies of once-through and closed cycle in terms of nonproliferation mentioned above is certainly one of the key issues of this analysis. At the same time in practice a wide spectrum of political, technical and organizational questions appear, the questions, which characterize the peculiarities of the task and not the general features important for the comparison of global strategies. For example, the specific time periods for disposition of surplus weapons-grade Pu, account for various degrees of attractiveness of weapons-grade and civil Pu for theft and diversion, international collaboration which includes coordination of different options of weapons-grade Pu disposition with the USA, specific features of NMC&A system at various sites, transportation routes and amounts of fissile materials being transported, reliability of storage, etc.

The multi-attribute utility method has been chosen as a methodology that in our opinion complements and specifies, to the required extent, the method of “risk exposure” when the alternatives of Pu disposition are studied [5]. This model is widely used for preparation of decisions in power industry, including the nuclear power. An additional argument in favor of this choice was the fact that it has already been used in the USA for the analysis of alternatives of ex- weapons-grade Pu management [6].

The multi-attribute utility method is based on calculation of the function of relative efficiency (utility) $U(x_1, x_2, x_3 \ldots x_n)$ of the alternative that depends on a great number of parameters. The additive estimation of the function has the form:

$$U(x_1, x_2 ... x_n) = \sum_{i=1}^{n} w_i v_i (x_i) \qquad (4)$$

where $v_i(x_i)$ – is a single-attribute value function in terms of i, whose value varies from 0 to 1;

w_i – is a weight factor of the single-attribute value function $v_i(x_i)$, with $\sum_{i=1} w_i = 1$.

The general algorithm of this method implementation as applied to the task of Pu disposition in nuclear reactors consists in the following:

- to determine the main goal (disposition efficiency) and to choose the alternatives for its achievement (reactor scenarios of Pu disposition);
- to distinguish objectives and tasks for the next hierarchic levels and to determine the value (weight) of each of them (to form a task tree);
- to construct one-valued efficiency functions for each single attribute in the range of a single-attribute change definition domain;
- to estimate the values of single-attribute efficiency functions for specific values of variables in the given option;
- to sum up single-attribute efficient function values with equation (2) and to determine the utility function $U(x_1, x_2, x_3, ..., x_n)$;
- to analyze sensitivity.

Based on this algorithm in paper [5] the total "plutonium disposition efficiency" was determined quantitatively. This value consisted of three components: economic efficiency, ecological safety and proliferation resistance. The nonproliferation factor was considered by the US specialists as the most important one as compared to two others (the nonproliferation factor "weight" was equal to 0.5072). In our study we focused on a part of the "goal tree" related to the issue of nonproliferation only (Figure 12).

The goal of "Nonproliferation", as it is shown in fig.12, is achieved by solving five rather independent tasks. The first task, theft resistance, consists in the analysis of fissile material stealing by terrorist groups. The main barrier for proliferators in this case is physical protection of nuclear materials during their use and secure sites where fissile materials are located. The state is responsible for all these measures.

The second task, "Diversion Resistance", reflects the option protection against the possible diversion of civil fissile material into the military sphere of its use by the state as the owner of nuclear materials, the possibility of international control and acceptability of the option from the point of view of the world community. The barrier for fissile material diversion at the state level is the international control (including the IAEA safeguards). Then comes the task of "Irreversibility" (it reflects difficulties in material recovery to the form usable for weapons production) and the task of "International Cooperation" (it encourages the cooperation in the field of disarmament and nonproliferation).

The last of the five tasks, "Timeliness", reflects the level of option orientation towards the reduction of accumulated plutonium risk. The big tasks of "criteria tree", in their turn, are subdivided into smaller ones, up to the elementary level of single-attribute function (Figure 12).

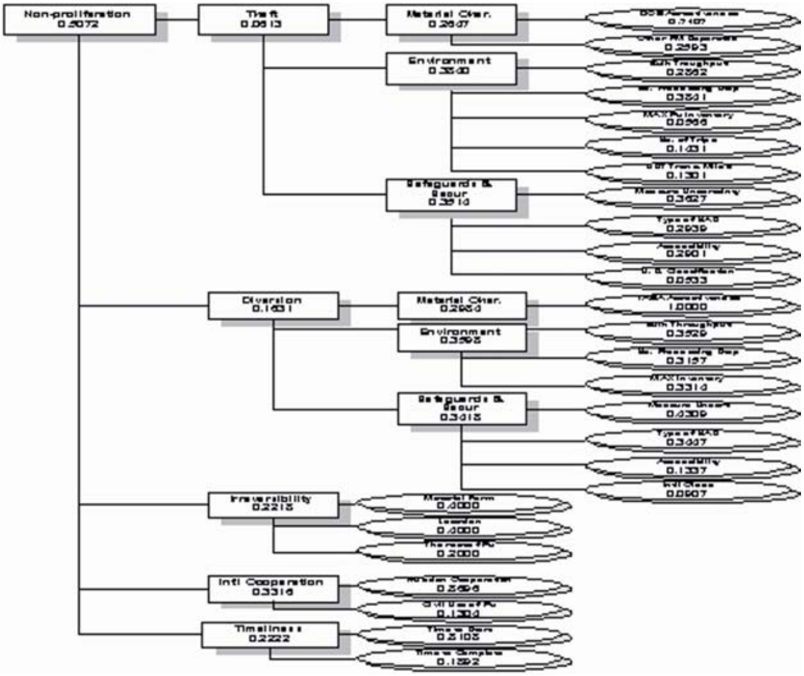


Figure 12. Criteria tree in terms of nonproliferation

For surplus weapons grade plutonium the model developers interpreted the notion of timeliness as a reduction of time required to begin and complete the mission of full Pu disposition. In the period of the model development the US administration rejected the possibility to recycle civil Pu. Maybe because of that the authors gave so narrow interpretation of the "timeliness" notion. In order to extend the multi-attribute approach to the task with civil Pu disposition included we had to update the initial diagram (figure 12) and broadened the notion of "timeliness" and included the proliferation risk criterion from various links of comparable fuel cycles (weapons and civil Pu storage facility, SFA storage facility, etc.).

The diagram shown in figure 12 reflects two different sides of nonproliferation problem. Three target functions in the bottom serve as indices of efficiency in solving the global task of reducing the risk of accumulated Pu inventories, first of all weapons grade Pu (a wide interpretation of nonproliferation issue). At the same time the technical questions of ruling out its unauthorized use (a narrow interpretation of nonproliferation issue) are characterized by the two top target functions.

The multi-attribute model whose set of criteria and their weights at various levels of criteria tree are given in figure 12 was used by the authors of the given work to compare the efficiency of reactor options of Pu disposition in terms of nonproliferation criterion. In the disposition scenarios chosen for comparison the consideration was given to the possibility to use both currently existing Russian power reactors and the reactors whose construction is planned in the program of Russian nuclear power development. Figure 13 shows the calculated results of efficiency (rating) in terms of "nonproliferation" criterion for several scenarios out of the big number of scenarios considered. Let us point out some general tendencies illustrated in figure 13.

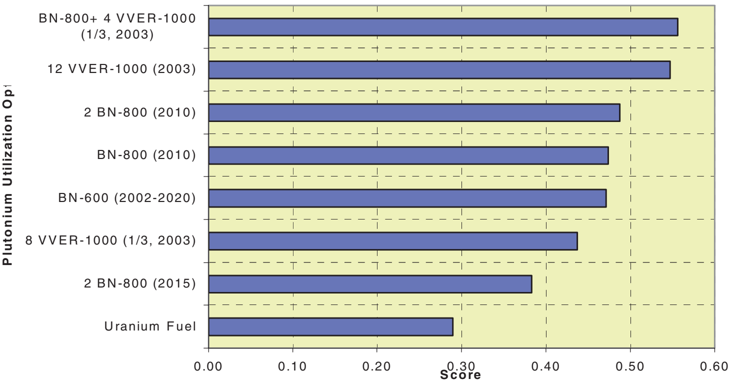


Figure 13. Rating of various options of Pu disposition in terms of nonproliferation. In brackets there is an indication of VVER reactor core loading fraction for MOX-fuel and the year of Pu disposition in reactors, respectively

The nonproliferation policy that considers the aspects of nuclear disarmament encourages the transfer to MOX U-Pu fuel both in thermal and fast reactors. The scenarios which presuppose an early disposition mission and fast elimination of the most dangerous ex-weapons Pu inventories have the highest rating. It is a mixed option with BN – 800 and 4 VVER – 1000 reactors (with 1/3 MOX fuel core loading) and the option with 12 VVER – 1000 reactors with 1/3 MOX core.

Figure 13 shows that due to a high demand of BN – reactors for Pu and due to a number of other circumstances the disposition efficiency in one reactor of this type build in 2010 will exceed the efficiency of all the operating VVER – 1000 reactors transferred to 1/3 MOX core in 2003. The scenario of reactor operation with U fuel that is being currently implemented and that results in Pu accumulation in various forms has the lowest rating (i.e. a long-term Pu storage is considered the most dangerous in this model as compared to its reprocessing).

The indicated model shows rather definite limits of adequacy for the scales of MOX fuel technology implementation into fast and thermal reactors and determines the time frames within which the transfer to this fuel is consistent with the signed agreements. So it follows from fig.13 that it will be in- efficient to involve the second BN – reactor into disposition of surplus weapons grade Pu (< 50 tons) declared by Russia. The delay in transferring VVER – 1000 units into MOX fuel significantly lowers the rating of scenarios into which they are involved. But the delay in commissioning a fast reactor, if it is the only one in this scenario, has especially negative impact on the scenarios rating.

Besides that some interesting results have also been obtained but they haven’t been reflected in figure 13. The multi-attribute model showed that the use of MOX fuel in the BN – 600 reactor gives the possibility to provide the same efficiency of ex-weapons Pu disposition both in the Russian Federation and in the USA, even if the pace of transferring to MOX fuel in thermal reactors of Russia within the near 10 – 15 years lags behind the pace of that in thermal reactors of the United States. Currently this fact is realized and accepted at all the levels and is considered in specific plans of disposition.

In the model the statement about the expediency of concentrating the reactors and NFC facilities involved in the process of disposition, on one territory (“nuclear island”) finds its quantitative confirmation. The options in which the reactors are located at the same site with weapons grade conversion facilities and MOX fuel fabrication facilities have substantial advantages over the option where reactors are dispersed on a large territory. That is due to a much higher level of physical protection that can be achieved on the “island” and no need for external fuel movement. The BN –

800 constructions at the Mayak site fits this concept ideally. Moreover the BN–800 location at the Beloyarsk site will make it possible to drastically reduce the number and the length of U–Pu fuel transportation as compared to the option of Pu disposition in thermal reactors

On the whole this method gave quite reasonable and explainable results in terms of "Nonproliferation". However the final estimation of Pu disposition efficiency calculated in view of ecological and especially economic factors shifted the rating of results towards the use of U – Pu fuel in the currently operating BN–600 and VVER–1000 reactors.

7. Conclusion

Comparison of once-through and closed NFC on the criterion of potential plutonium proliferation risk ("risk exposure") allows to conclude that well organized closed fuel cycle has lower proliferation risk than once-through fuel cycle. The most important safety requirement in respect with plutonium – the balance of plutonium build-up and its irreversible consumption

("burning" up to fission products) – can be strongly met only in closed NFC. From this point of view, closed fuel cycle has fundamental advantages over the open fuel cycle. Good NFC proliferation resistance can be assured only under condition that risk exposure for the stage of SNF final disposal is reduced to zero. The possibility of meeting this requirement for a long-term time intervals is extremely difficult and disputable question.

Fuel cycles with extended plutonium breeding were studied along with fuel cycles without excess generation of plutonium, in which all the plutonium built up has reactor core quality. The quality of plutonium generated in blankets is very high from the non-proliferation point of view.

The results of study have demonstrated that if excess plutonium built up in blankets goes back to the reactors in a form of fuel, no considerable increase of proliferation risk with time occurs. Observance of plutonium generation and consumption balance, lengthening of refueling interval, reduction of external cycle time – all these measures turned out to be substantially more efficient than refusal of extended breeding.

Within the fuel cycles of nuclear power, the stages of SNF reprocessing and MOX fuel fabrication are the most dangerous ones from the viewpoint of proliferation of fissile materials having definite attractiveness in view of nuclear weapons creation.

Contribution of operative resource of plutonium required for MOX fuel fabrication into the proliferation risk turned out to be rather essential. Under certain circumstances (high grade of plutonium purification, size of operating resource), this contribution can become the governing one, and exceed the risk from all the remaining stages in closed or once-through fuel cycle.

In the models of developing nuclear power, substantial decrease of proliferation risk occurs when thermal and fast reactors are used co-jointly, plutonium from thermal reactors is used in fast reactors.

The scope of present study was limited mainly with assessment of proliferation risk of different kinds of plutonium. Another very important task is to take into account contribution of natural and enriched uranium at different stages of fuel cycles.

It is quite illustrative that for the practical implementation of the policy of nuclear disarmament, in order to reduce the potential risk of surplus weapons grade Pu accumulated in the RF and USA, one of the key parts of the closed NFC – reactor disposition of Pu – had to be addressed. The nuclear reactors available in Russia make it possible to consider two ways in the near future to solve the task of elimination of the declared surplus weapons grade Pu: the strategy of Pu disposition in water reactors, “symmetrical” to the US strategy, and “asymmetrical” strategy of its disposition in fast reactors that provides the same disposition efficiency.

The methods of quantitative proliferation risk analysis considered in the paper have found a wide application in the system studies and form a good basis for further improvement. Along with the transfer from the relative proliferation risk assessment at various stages of fuel cycle to the direct proliferation risk assessment at these stages it seems reasonable to move towards the estimation of proliferation risk cost in money terms. It is quite obvious that the method of quantitative proliferation risk analysis agreed upon at the national and international level could be widely used by scientists and technical specialists in the nuclear industry.

References

1. Krakowski R.A., Bathke C.G. Reduction of Worldwide plutonium inventories Using Conventional Reactors and Advance Fuels: A Systems Study. LA-UR-97-2809, 1997.
2. Krakowski R.A. Review of Approaches for Quantitative Assessment of the Risks of and Resistance to Nuclear Proliferation from the Civilian Nuclear Fuel Cycle. LA-UR-01-0169, 2001.
3. Saaty T. A scaling method for priorities in hierarchical structures. J. Mathematical Psychology, 1977, v.15, p.234.
4. R. L. Keeney, H. Raiffa. Multi-criteria Decisions with Multiple Objectives, Translation from English, M. Radio and communication, 1981.

5. James S. Dyer, T. Edmunds, J.S. Butler, J. Jia. Evaluation of alternatives for the Disposition of Surplus Weapons-Usable Plutonium. Amarillo National Resource Center For Plutonium, ANRCP-1997-1 (1997).
6. Poplavsky V.M., Oussanov V.I., Chebeskov A.N. Korobeynikov V.V., Tikhomirov B.B., Iougai S.V. Estimation of efficiency of measures on fissile material proliferation risk reduction based on system analysis models. – Atomnaya Energija, 2001, vol.91, issue 5, pp.353-362.
7. Nikipelov B.V. Nuclear materials non-proliferation in XXI century. Nuclear proliferation, 2000, issue 35, pp. 52-57.
8. Adamov E.O. Realization of Russian initiative will allow to solve safety problems and decrease the threat of proliferation. Nuclear control, 2001, №1, pp. 4-10.
9. Orlov V.V. Initiative of the President and strategy of Minatom, Nuclear Society of Russia, №5, November 2001, pp. 27-34.

KEY ASPECTS ON THE NON-PROLIFERATION MEASURES

GUILLERMO VELARDE*
(President) Institute of Nuclear Fusion – Polytechnic University of Madrid José Gutiérrez Abascal nº 2 – Madrid 28006 – Spain.

NATIVIDAD CARPINTERO SANTAMARÍA
Institute of Nuclear Fusion – Polytechnic University of Madrid – José Gutiérrez Abascal nº 2 – Madrid 28006 – Spain.

Abstract: The purpose of this paper is both to present a reflection on the international policy evolution after the end of Cold War, with the emergence of islamic terrorism and also what we consider main aspects to take into account when dealing with terrorist possibility of having improvised nuclear devices (IND's).

Keywords: Non-proliferation; Al-Qaida; gun-type weapons; implosion-type weapons; terrorist use - predetonation probabilities; plutonium production; developing countries.

1. Introduction

This year 2005 we commemorate the 60th anniversary of World War II. 60 years have passed after Hiroshima that have not been an easy path for the welfare of mankind. After the disaster of the war with 50 million killed, people thought that a new era of peace and good coexistence was not only possible but necessary.

The missile crisis in Cuba in 1962 was very useful to show that both nuclear powers and the rest of the world were on the edge of the abyss and

---

* To whom correspondence should be addressed. Guillermo Velarde, President of the Institute of Nuclear Fusion – Polytechnic University of Madrid – José Gutiérrez Abascal nº 2 – Madrid 28006 – Spain. E-mail: gvelarde@denim.upm.es

S. Apikyan and D. Diamond (eds.), Countering Nuclear and Radiological Terrorism, 85–94.

that something should be done to avoid the step to the extinction. This dangerous situation led to different agreements between the East and the West for the reduction of both strategic and nuclear weapons, being the most important one the Treaty on the Non-Proliferation of Nuclear Weapons, which was signed in Washington, London and Moscow and entered into force on March 5, 1970.

The way to eliminate totally nuclear weapons is still hard and long. On 10 September 1996 the United Nations adopted for this aim the Comprehensive Nuclear Test Ban Treaty Organization and, although 175 countries have adhered the Treaty, it has not entered into force yet.

However, the first year of the 21st century announced the world that a new sort of political tactic was born: blackmail under international terror. 11 September 2001 opened a new chapter in our history. Al-Qa'ida, a political phenomenon theoretically linked to the islamic world with living human weapons through suicidal younsters linked not to an entity, as many people think, but to an ideology with very well trained elements.

When Nasir Ahmad Nasir al-Bahri, known by the nickname of “Abu Jandal”, member of al-Qa'ida since 1996, former personal bodyguard of Usama Bin Ladin and leading al-Qa'ida element in Yemen was arrested in Yemen after the operation to destroy the US destroyer “Cole” in the Port of Aden, the American FBI officers asked him whether Al-Qa'ida had chemical plants and nuclear weapons. He said literally following the Koranic verse “I recall that my answer to them was that Usama Bin Ladin has a weapon that is far superior to all the US weapons. What is this weapon, they asked? I told them “Among the believers are men, who have been true to their covenant to God: of them some have completed their vow (to the extreme) and some (still) wait. But they have not never changed (their determination) in the least”. The US arsenal is full of weapons but it does not have the men”. And when talking about the future of Al-Qa'ida he said “As to the future of Al-Qa'ida, I believe that it has found what it wanted. It can now melt into a new caldron, and a new giant would be reborn, of which Al-Qa'ida would be a part. Many of the Islamic World leaders would join it and the confrontation with the United States would be inevitable. And, Al-Qa'ida would not be the leader but a vanguard army”. His testimony is an important piece in this complex puzzle of Al-Qa'ida.

Taking into account the actions executed up to now in the United States, Spain, Saudi Arabia, Bali, Kenya, the United Kingdom, etc and considering also that the Islamic World consists of 71 states, these words are rather frightening and although the defeat of the Taliban in the

Afghanistan government weakened the movement, Bin Ladin continues being its ideological leader.

The cells and commanders hide a very complex reality: Bin Ladin movements have actually evolved so as to adapt them to the firm international efforts to fight them. Following Abu Jandal "Al-Qa'ida members are fully qualified and equipped to carry out any operation at any time... and the assignement of persons depends on capabilities".

On November 17, 2004 Abu Salma Al-Hijazi, one of the leaders of Al-Qa'ida, in an interview held in Faluja, 50 km to the West of Bagdad and one of the main focus of the Iraqi resistance, said that he expected by those days a terror attack in the United States which would cause about 100,000 casualties. Fortunately it was a bluff that put into account that we are not only subjected to physical attacks but to another way of terror more machiavelic and pervasive: psychological harrassment.

Probably the biggest danger to all this lies in the nuclear weapons nations that have big nucleus of population with the same ideology than these terrorist groups. It is rather likely that in the nuclear facilities of these nations we can find engineers and scientists linked to Al-Qa'ida ideology that could transfer to the terrorist groups nuclear weapons components which, in turn, can be easily introduced in countries such as the United States or the European Union, where more specialized groups could assemble these weapons to be used in the precise moment and place.

2. Technical problems in the development of nuclear weapons of fissile material in developing countries

Some developing countries may be tempted to fabricate nuclear fission weapons, avoiding the Non Proliferation Treaty. In this second part of the paper, main technical problems in the fabrication of a nuclear fission weapon in developing countries will be analyzed: the enrichment of uranium and plutonium that can be used in crude weapons; the predetonation probabilities, the conditions to obtain plutonium from the irradiated fuel elements, etc.

2.1. GENERAL DESCRIPTION OF THE TECHNICAL PROBLEMS

2.1.1. *Gun-type weapon*

- Fabrication: affordable by low technology countries.

- Weapon-grade uranium: it requires complex facilities with high technology (gas centrifuge cascade). Tune-up requires highly specialized engineers.
- Utilisation: it can be dismantled into easily transported components. This weapon is the most appropriate for terrorism purposes because its components can be introduced in the countries following, for instance, the route of illegal inmigrants, private ports and airports, etc.
- Detection: the gas centrifuge cascade plant is difficult to detect.

2.1.2. *Implosion-type weapon*

- Fabrication: complex**.** Detonators must have a standard deviation inferior to nanosecond. The chemical explosive lenses and the hollow sphere of plutonium must be obtained by melting in void chambers so as to avoid cavities that distort the sphericity of the implosion wave. High precision mechanisation of the weapon components is required.
- Weapon-grade plutonium: it is obtained from the fuel elements of the nuclear reactor after irradiating them about 3% to 10% of the time they would be irradiated in a commercial reactor. Since the irradiated fuel elements are very radioactive, they should be handled in hot cells. This technology is affordable by medium technology countries.
- Utilisation: its dismantling into components is complex.
- Detection: nuclear reactors in surface (not underground) are easy to detect by satellites.

3. Enriched uranium used in the gun-type weapons

Following table 1, the separation work units (SWU) per kg for a 50% enriched uranium is a 63% of the one required to achieve a 94% enrichment, but the bare critical mass is about three times. This implies that the SWU is duplicated as the enrichment of 94% to 50% is reduced.

TABLE 1. Separation work units for Uranium metal of several enrichments

enrichment %	SWU/kg	bare critical		10 cm reflector of Unat	
		mass kg	SWU	mass kg	SWU
94	200	53	10600	19	**3800**
50	125	160	20000	35	**4375**

3.1. COMMENTS

3.1.1. If 50% enriched uranium were used instead of the weapon grade uranium (WGU), the cost of the used uranium in the weapon would duplicate and the amount of the required uranium would triplicate (in the case of bare critical), thus making a very large weapon.

3.1.2. Developing countries that have got a gas centrifuge cascade to obtain reactor grade uranium (about 3% enriched) could distribute the cascade of thousand of centrifuges in such a way that they would obtain 50% enriched uranium or, in the last case, WGU (94% enriched).

3.1.3. As a rule of thumb, about 1500 centrifuges adequately distributed would produce 15 to 20 kg of WGU per year, enough to make a nuclear weapon.

4. Neutron emission from spontaneous fission in the weapon and reactor grade plutonium and its influence in the predetonation probability

In table 2 it is indicated the neutron emission from spontaneous fission of the different plutonium isotopes and that of the weapon and reactor-grade plutonium.

The isotopic concentration of the reactor grade-plutonium depends on the type of reactor and its burnup, the enrichment in Pu239 and Pu241 is about 70% for the different types of reactors.

Taking into account the critical mass and the assembly time of the weapon, it is obtained in table 3 the probabilities to get the nominal and fizzle yield for WGP and RGP. It is observed that when using RPG there is a 24% probability to obtain the nominal yield and a 21% probability to get a fizzle yield.

TABLE 2. Weapon grade plutonium and reactor grade plutonium concentration at fuel discharge and neutron emission from spontaneous fission

Isotope	SF $n \cdot g^{-1} \cdot s^{-1}$	WGP (94% Pu239) isotopic concentration %	RGP isotopic concentration %		
			PWR	HWR	GGR
Pu 238	2600	0.01	1.3	--	--
Pu 239	0.030	93.80	56.6	66.6	68.5
Pu 240	1020	5.80	23.2	26.2	25.0
Pu 241	--	0.35	13.9	5.3	5.3
Pu 242	1670	0.02	4.7	1.5	1.2
SF, $n \cdot g^{-1} \cdot s^{-1}$	--	66	366	302	295

TABLE 3. Probability to obtain nominal and fizzle yield for WGP and RGP

Probability %	WGP (94% Pu239)	RGP (60% Pu239)
100 (nominal yield)	90	24
<5 (fizzle yield)	2	21

4.1. COMMENTS

4.1.1. Developing countries can be tempted to use the plutonium obtained in the fuel discharged by the reactor after operating the maximum burnup commercially available. But in this case, there is a small probability to get nominal yield (about 24%) and a big probability to get fizzle yield (about 21%) comparing these values with those of WGP.

4.1.2. If the developing countries want to ensure a nuclear explosive of nominal yield (with a probability bigger than 90%) they should use highly enriched plutonium (94% in Pu239).

5. Plutonium production for commercial reactors and for weapon grade plutonium operation

In table 4 it is analyzed plutonium production for the PWR, HWR and GGR. To get plutonium 94% enriched in Pu239, it is necessary that the burnup or the stay time of the fuel elements in the reactor should be reduced considerably, so as to prevent that the Pu239 obtained from U238 becomes Pu240 per neutron capture.

TABLE 4. Plutonium production for commercial reactor operation and for weapon grade plutonium

reactor type	net thermal efficiency	commercial reactor operation		WGP operation			
		burnup MWd/T	annual production kg/MW_e	burnup		annual production	
				MWd/T	%	kg/MW_t	kg/MW_e
PWR	0.32	30000	0.33	1000	**3.3**	**0.18**	0.56
HWR	0.29	7500	0.63	1000	**13.3**	**0.33**	1.14
GGR	0.28	4000	0.82	200	**5.0**	**0.35**	1.25

100% capacity factor

$$\%\ \text{burnup} = \frac{\text{MWd/T for WGP operation} \quad \text{x}\,100}{\text{MWd/T for commertial reactor operation}}$$

WGP = 94% Pu 239

The necessary burnup to obtain WGP should be 3.3%, 13.3% or 5.0% of the one used during the commercial operation of the power reactor, whether we consider PWR, HWR or GGR.

5.1. COMMENTS

Developing countries can follow two different ways to obtain plutonium:

5.1.1. One way would be to build a low power experimental heavy water or graphite moderated reactor (about 20MWt) which would produce 0.33 kg of plutonium 94% enriched in Pu239 per thermal megawatt (for a 20MWt reactor, 6.6 kg would be obtained, enough to build a crude weapon per year).

5.1.2. The other way would consist to irradiate some of their fuel elements in one of their power reactors until they reach a burnup of 1000 MWd/T for PWR and HWR, or 200 MWd/T for GGR. For instance, to obtain 6.6 kg of enriched plutonium at 94% in Pu239 in an HWR of 1000 MWe, it would be enough to irradiate only 0.6% of their fuel elements to a burnup of 1000 MWd/T.

6. Conclusions

Developing countries that want to have nuclear weapons in their arsenals, have taken or will take the following steps:

6.1. To sign and ratify the Non Proliferation Treaty in order to achieve collaboration and minimize possible suspicions.

6.2. To send hundreds of scientists and engineers to developed countries that are equipped with research centers, laboratories and facilities of high precision mechanisation, high chemical explosives, nuclear fission science and technology, uranium metallurgy, uranium enrichment, fuel elements fabrication, hot cells and reprocessing of plutonium, production of heavy water or graphite with nuclear purity, etc.

6.3. To establish dual-technology projects that allow to import components which can be applied to the development of nuclear weapons.

6.4. To project and fabricate a research low power graphite or heavy water moderated reactor with its corresponding facilities, to obtain the moderator, fuel elements and hot cells.

6.5. To establish a program of nuclear power plants for energy supply and afterwards to achieve international agreements to provide them with uranium and components for these nuclear power plants.

6.6. To sign international agreements in order to install a factory of fuel elements, a plutonium reprocessing plant and a gas centrifuge facility to produce slightly enriched uranium.
However in the case that pressures exerted by certain nations could prevent these agreements to be signed, these developing countries would try to obtain these facilities illegally from countries that have got this technology, and either have with them analogous ideology or economical interests.

6.7. To design a policy of confusion in order to hinder, disturb and obstruct the mission of the inspectors of the International Atomic Energy Agency.

References

1. G. Velarde. Neutronic of laser-fission-fusion systems : NEACRP-L-166 (ISBN 84-500-1578-2). (1976).
2. G. Velarde, C. Ahnert, J.M. Aragonés, M. Gómez-Alonso, G. Leira, R. Luque, J.M. Martínez-Val, J.M. Perlado. Analysis of laser-fission-fusion systems : Time dependent coupled nuclear-thermohydrodynamic analysis and applications. *Atomkernergie.* Vol. 35. Nº 1. (1978) pp. 58-72.
3. G. Velarde, C. Ahnert, J.M. Aragonés, M. Gómez-Alonso, G. Leira, R. Luque, J.M. Martínez-Val, J.M. Perlado. Analysis of laser-fission-fusion systems : Deve-

lopment of methods for nuclear and thermohydrodynamic calculations. *Atomkernergie.* Vol. 35. Nº 1. (1980) pp.40-53.

4. G. Velarde, C. Ahnert, J.M. Aragonés, M. Gómez-Alonso, G. Leira, R. Luque, J.M. Martínez-Val, J.M. Perlado. Coupled nuclear-thermohydrodynamic analysis of laser-fusion-fission microspheres. *Atomkernergie.* Vol. 36. Nº 3 (1980) pp. 213-217.
5. G. Velarde, C. Ahnert, J.M. Aragonés, M. Gómez-Alonso, G. Leira, J.M. Martínez-Val, J.M. Perlado. ICF of DT solid micropellets with tampers of Pu, U and Pb. *Trans. Am. Nucl. Soc.* 38. 208 (1981).
6. J.C. Mark, T.Taylor, E. Eyster, W. Maraman, J. Wechsler. Nuclear Control Institute, www.nci.org/k-m/makeab.htm (1986).
7. J. Carson Mark. Reactor-Grade Plutonium's Explosive Properties. Nuclear Control Institute, NPT/95 (1990).
8. C. Sublette. Nuclear Weapons: The High Energy Weapons Archive- A Guide to Nuclear Weapons. www.envirolink.org/issues (1996).
9. B.B. Fischer. *At Cold War's End : US Intelligence on Soviet Union and Eastern Europe, 1989-1991.* History Staff. Center for the Study of Intelligence. Central Intelligence Agency. (1999).
10. F.A. Gerges. *The Far Enemy. Why Jihad Went Global.* C.U.P. (2005).

SECURITY OF RADIOACTIVE MATERIALS FOR MEDICAL USE

ALEX ELLIOTT
University of Glasgow, Western Infirmary, Glasgow G11 6NT, UK

Abstract: Both sealed and unsealed radioactive sources are used in hospitals throughout the world for diagnostic and therapeutic purposes. High activity single sealed sources are used in teletherapy units, although these are becoming less common as they are replaced by linear accelerators, and in blood irradiator units, which are in widespread use. Lower activity sealed sources are used in brachytherapy. High activity unsealed sources are used typically for the treatment of thyroid cancer and neuroblastoma in inpatients while diagnostic doses of unsealed radioactive materials have much lower activities. In the case of a central radiopharmacy producing patient doses of radiopharmaceutical for several Nuclear Medicine departments, however, quite large amounts of radioactive materials may be held. Hospitals are, by their nature, less secure than other licensed nuclear sites and the ever-changing patient/visitor (and staff) population is a further complicating factor. Hitherto, security of radioactive materials in hospitals has tended to be considered from the perspective only of radiation safety but this approach is no longer sufficient.

Keywords: hospitals, teletherapy, nuclear medicine, radiopharmacy

1. Introduction

Over the last few years, there have been several incidents related to radioactive materials originating from medical use. Probably the best known of these is the Goiania incident(1) in which a telecobalt source was cut open in a scrap yard. The potential for such incidents was increased by the well-intentioned efforts of medical physicists in the developed world who replaced their teletherapy units with linear accelerators in the 1970s and 1980s. There were several cases of the replaced teletherapy units being

S. Apikyan and D. Diamond (eds.), Countering Nuclear and Radiological Terrorism, 95–104.

donated to centres in the developing world which either did not have the necessary funds to obtain a linear accelerator or, indeed, did not have a guaranteed supply of electricity to enable operation of an accelerator. While all of the necessary regulations in the country of origin were observed, there were cases where the recipient organisation was not subject to a well-defined regulatory system. The IAEA categorisation(2) places teletherapy sources in category 1, blood irradiators in category 2, brachytherapy sources in to category 3 and other sources in category 4. This categorisation is driven primarily by consideration of orphan sources. In categorising the top ten radiation risks, the USAEC(3) places transportation of cobalt 60 sources first, teletherapy sources in second place, blood irradiators in fifth place, sales/resales of cobalt 60 sources in sixth place and sales/resales of blood irradiators in ninth place. Medical sources thus occupy four of the top 10 places. The advent of the so-called "dirty bomb" renders such sources in particular potential targets for terrorist groups.

Within the European community, the Directive 2003/122/Euratom, control of high-activity sealed radioactive sources and orphan sources (HASS Directive)(4) has been enacted. Compliance with this directive is equivalent to compliance with the IAEA Code of Conduct(5). The HASS limits, which are of particular concern to hospitals, are:

- Cobalt-60 4GBq
- Cesium-137 20GBq
- Irridium-192 10GBq

The first two of these relate to teletherapy units with cobalt 60 being most common in Europe in blood irradiators while Irridium-192 is a brachytherapy source. The directive appears to be designed for industry but it should again be emphasised that hospitals are not industrial sites.

While the regulations apply to sealed sources, the principles can (and should) be extended to unsealed sources: within healthcare, there is much more widespread use of the latter.

2. Terrorism

The aims of terrorist groups can be simplified to:

a) Publicity – to broadcast the objectives of the group

b) Destabilise society – this may involve inflicting economic damage by destroying or putting out of use (for example) buildings, energy sources, etc., by threatening a course of action which causes mass panic or by killing/injuring members of the target population.

c) Recognition – in gaining sufficient influence that society either yields to their demands or, at least, is forced to negotiate.

Seen in this context, the amounts of radioactive materials stored in larger hospitals could certainly help to fulfil the first two of these aims. News of the mere seizure of radioactive materials would almost certainly cause a high level of concern in a population, even where the actual hazard associated with the materials was low.

In the case of a blood irradiator source, this could be used in a dirty bomb but it is unlikely that it would be capable of causing high casualty levels – a weapon of mass disruption rather than mass destruction.(6) Nevertheless, as shown by the Goiania incident, deaths could ensue. The quantities of radioactivity in brachytherapy sources or as unsealed sources available in larger hospitals would certainly be sufficient to cause economic damage by arranging for (e.g.) the contamination of a small area.

Any of the above scenarios would certainly generate a great deal of publicity for any terrorist group.

3. Healthcare sites

A major healthcare facility will have a radiotherapy department with several linear accelerators, at least one brachytherapy system and several sealed sources for specialist treatments (e.g. eye plaques). As a major transfusion centre, there may well be an associated blood irradiator. Either as a separate department or as part of the imaging department, there is likely to be a nuclear medicine department and possibly a separate nuclear cardiology section. Radioactive materials will be utilised within diagnostic laboratories, albeit in much smaller quantities. A typical inventory of a large UK hospital in its radiotherapy (no teletherapy machines) and radiopharmacy units is shown in Tables 1 and 2.

TABLE 1. Typical Radiotherapy Department Inventory

Cs-137	800GBq
I-131	25GBq
I-125	20GBq
Am-241	10GBq
I-123	10GBq
Ir-192	10GBq
Blood irradiator Cs-137	70TBq

TABLE 2. Typical Centralised Radiopharmacy Inventory

Mo-99	1TBq
Tc-99m	1TBq
H-3	100GBq
Xe-133	35GBq
I-131	25GBq
T1-201	15GBq
I-123	4GBq
Re-186	4GBq
Sm-153	4GBq
At-211	4GBq
Y-90	3GBq
P-32	2.5GBq
I-125	2GBq
Xe-127	2GBq
Rb-81	2GBq
Kr-81m	2GBq

In addition to the above, some high-activity technetium generators utilise depleted uranium shielding rather than lead.

4. Public perception

As noted above, the public's perceptive of the dangers of radioactive materials can be out of proportion to the actual hazard involved. It is necessary for the scientific community to make a greater effort to educate the public and to place the risk into context. The Goiania incident was responsible for five deaths and 28 cases of radiation burns with 49 people being admitted to hospital. Whilst this is clearly unacceptable, the scale of casualties was not as great as either the Madrid or London bombings, neither of which involved radioactive materials. In terms of assessing the impact of terrorist use of materials available from healthcare facilities, perhaps the most interesting feature of the Goiania incident is that 112,000 people presented themselves for monitoring, the vast majority simply for reassurance. A terrorist mediated small-scale release (or even the threat of such) could lead to a similar response. This would achieve the short-term aims of destabilisation and publicity.

It is suggested that, while most concern has been concentrated on scenarios with the potential for fatal and/or near fatal outcomes, increased consideration should be given to those consequent upon theft from healthcare facilities. From a terrorist perspective, the latter are not defended with potentially lethal force but could yield sufficient material to achieve their aims.

There is undoubtedly need to increase security of radioactive materials held on healthcare premises but this has to be done without increasing the radiation exposure to staff or compromising patient care. Once again, it is a question of balancing risk.

5. Counter measures

The main means of denying access to radioactive materials to unauthorised persons is to control the distribution. This has the facets of production, transport, accumulation and disposal. The maintenance of records, preferably by electronic means, is clearly key to each of these and affords a linkage between them.

There is a debate over whether inventories of radioactive materials should be held at a local or national level. If a detailed national inventory is kept, it would be necessary only to hack into a single system to obtain details of the holdings in an entire country. A series of local inventories would be more secure in this regard and could probably hold a greater level of detail. The update frequency requires to be decided and the levels of security assessed carefully; would user sites be able to access the master database directly or would they simply be able to e-mail corrections for input by regulatory staff.

Public education can also be regarded as a counter measure in that the degree of alarm would then be minimised. Increased efforts are required in this regard, particularly in relating the risks associated with radiation to those of other activities where the public either completely disregard risk or consider the risk acceptable.

The HASS directive requires vetting for “staff and others with access to sources”. This is an area in which healthcare premises are particularly vulnerable. Unlike most licensed nuclear sites, a relatively large number of staff may have access and the level of staff turnover is probably higher. There is also the question of agency staff who are drafted in (often at extremely short notice) to cover for absent permanent members of staff. By definition, numbers of patients pass through both diagnostic and therapeutic facilities sometimes with almost no advance notice and, for inpatients, there are the associated visitors.

6. Vulnerability

At least, while in use, teletherapy systems are sited in restricted radiation areas (figure 1). Physical access will be restricted also, although there is a need to permit rapid emergency access to patients which restricts options during working hours. Since the weight of the overall treatment head would render transport extremely difficult, it is assumed that a terrorist group would attempt to remove the source from its housing in situ. This requires specialist tools and would be time consuming.

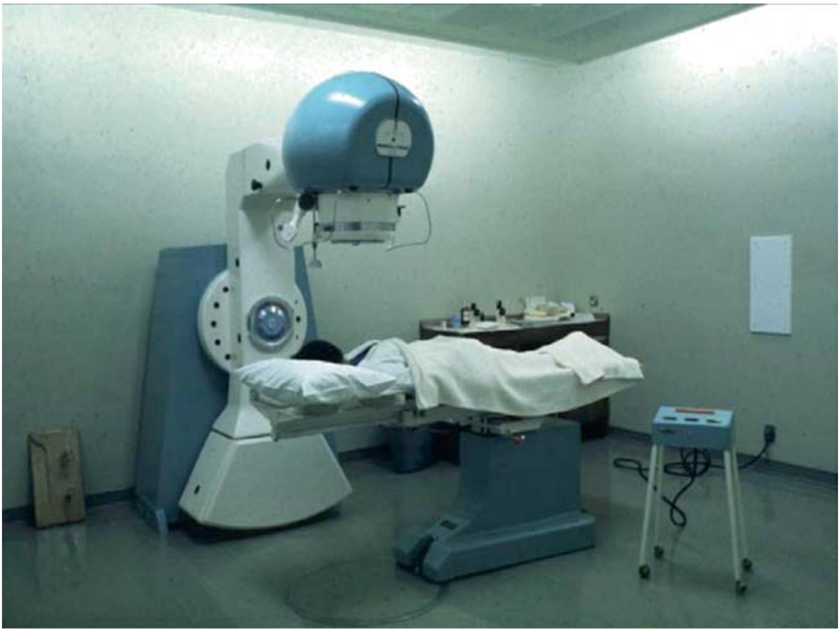


Figure 1.

Brachytherapy sources, on the other hand, are often stored in wheeled trolleys (figure 2) and are kept in relatively accessible areas of a healthcare site often in a special side room at the end of an inpatient ward. Albeit farfetched, it is conceivable that a patient could be kidnapped to obtain the radioactive materials.

Figure 2.

Other sealed sources are generally kept in a sealed sources handling bench which is sited in a less accessible area and usually has two or more security barriers to prevent unauthorised access.

Unsealed sources are usually contained in volumes of 1-30ml and so are readily transportable even: a 500GBq molybdenum technetium generator is contained within a shield weighing only 25 kilos.

As noted above, healthcare sites are intrinsically more vulnerable than conventional licensed nuclear sites. Security is still predicated, however, upon the 3D system – D Deter, Detect (as quickly as possible) and Delay (for as long as possible). These facets are implemented by design considerations, the adoption of appropriate standard operating procedures and careful monitoring.

In terms of design, a physically remote part of a site can minimise the risk of opportunistic attack, although the drawback is that it may be quieter. The surrounding area should be well lit and, where practicable, subject to surveillance. While international regulations lay down strict controls on notices at the entry to controlled radiation areas, a lack of signposting of any radiation facility is also to be commended. This can be achieved by the use of double doors with the external door bearing no labelling and the internal door bearing the statutory signage.

In terms of layout, the areas where sources are stored should be internalised as far as possible and measures taken to delay access/egress, although this must be balanced with the need for operational efficiency. Lastly, adequate alarm systems should be designed in; these will be a combination of intruder and radiation detectors.

Doors giving access to source storage areas should be designed carefully with concealed hinges and secured mountings into the surrounding wall to offer maximum security. The use of windows should be minimised and, where necessary, these should be fitted with shatterproof glass.

The standard operating procedures for any such facility should lay out clearly the responsibilities of each member of staff with regard to the maintenance of security. There should be strict procedures for ordering materials, checking deliveries, storage/usage records, the maintenance of the records themselves and IT security.

One of the least secure aspects of the medical use of radioactive materials lies in the transport and delivery system. Once again, appropriate training must be provided and the responsibility of delivery staff and those taking receipt of radioactive materials set out carefully(7). There can be particular problems with deliveries to healthcare institutions out-of-hours and, even where this is a rare occurrence, there must be a rigorous procedure(8). It is wholly unacceptable for such materials to be received into (for example) the Accident and Emergency reception desk and left there to await uplift. The vehicles themselves should be fitted with radio contact to their base (this may be by mobile telephone provided that coverage the area of operation is adequate).

The security level attached to each storage area will be dependent upon the category of source being stored. It is good practice to minimise the quantities held in any case but this becomes increasingly important when viewed from a security aspect.

Good record-keeping is an essential part of the system and each site should update its inventory appropriately, ensuring that the necessary paperwork stays with each source. Transfers/removal should be noted at the time when this occurs and, if necessary, regulatory authorities notified. Random audits should be carried out to ensure that the system is working properly.

When designing new facilities, advice should be sought from a counter-terrorism security expert.

7. Monitoring

For sites storing higher levels of activity, automatic access control systems should be employed. The complexity of these will be determined by the security risk but there are, once again, features of a healthcare site which may make this more difficult. Keypad locks are not recommended; there may be large numbers of these on a particular site which leads either to the same code being used for several different locations or the likelihood of the number being written on the adjacent walls. The need for emergency access to patients may also mean that there is the need for an emergency override to be sited somewhere in the vicinity, often in the form of a break-glass box. As noted above, an intruder alarm system will be required. Dependent again on the category of source being stored, the alarm may transmit a signal to the hospital switchboard or directly to the local police. There requires to be a set procedure detailing how any alarm will be dealt with, emphasising the need for the response time to be inversely proportional to the activity stored.

Closed circuit televisions are widely used within hospitals but it should be remembered that these are efficacious only insofar as the image is monitored diligently.

Automatic radiation alarm systems can be utilised also.

8. Conclusion

Given the present public perception of the hazards associated with radiation, categorisation by activity alone may be inappropriate. More consideration should be given to unsealed sources. The threat of release of a small amount of a low-hazard radionuclide would probably still be enough to cause a degree of panic. In order to ameliorate this, public education should be a priority. In this regard, a careful balance will have to be struck between acknowledging the risks involved but placing them into the wider context.

Legislation/regulation must account for clinical practice. Too often in the past, regulations which were intended for industrial sites have been applied to hospitals without recognising the lower levels of risks involved and the associated logistic problems. There is a need also to recognise the direct benefit to patients of the use of radioactive materials, to facilitate diagnosis/treatment and to minimise the risk to staff handling the sources.

At the same time, the medical sector must pay more attention to the security aspects of its work utilising radioactive material.

References

1. International Atomic Energy Agency 1988. The radiological accident in Goiania. IAEA, Vienna.
2. International Atomic Energy Agency 2003. Categorisation of radioactive sources : IAEA-TECDOC – 1344, IAEA, Vienna.
3. Lin C, 2003. Perspectives of Managing Radiation Protection in United States.
4. European Union 2003. Council Directive 2003/122/Euratom. On the control of high activity sealed sources and orphan sources, OJEU, L346, 57-63.
5. International Atomic Energy Agency 2003. Code of conduct on the safety and security of radioactive sources IAEA/CODEOC/2004. IAEA, Vienna
6. Edwards R, 2005. Millions of dirty bomb sources, http://www.newscientist.com/articles.ns?id=dn2455
7. Lawson RS, Davies G, Hesslewood SR, Hinton PJ and Maxwell A., 2004. Delivery and collection of radioactive packages to and from hospital nuclear medicine departments, Nucl Med Commun, 25, 1161 – 1167
8. Elliott AT, 2004. Delivering security, Nucl Med Commun, 25, 1159

CHAPTER II

PROTECTING NUCLEAR POWER PLANTS

ON THE IMPORTANCE OF THE SECURITY AND SAFETY OF THE REACTOR PRESSURE VESSEL TO EXTERNAL THREATS

A. BALLESTEROS, J. GONZÁLEZ,
Tecnatom, Madrid, ES

L. DEBARBERIS
Joint Research Center of the EC, Institute for Energy, Petten, NL

Abstract: Nuclear power plants have long been recognized as potential targets of terrorist attacks, and critics have long questioned the adequacy of the existing measures to defend against such attacks. The 11-S 2001, 11-M 2004 and 7-J 2005 attacks in USA, Spain and UK illustrated the deadly intentions and abilities of modern terrorist groups. These attacks also brought to surface long standing concerns about the vulnerability of nuclear installations to possible terrorist attacks. Commercial nuclear reactors contain large inventory of radioactive fission products which, if dispersed, could pose a direct radiation hazard on the population. The reactor pressure vessel (RPV), which contains the nuclear fuel, is the most critical component of the plant. This paper shows that small amount of explosive material can produce irreversible damage in the RPV and the release of radioactive material. Therefore, access of working personal to the vicinity of the RPV during the refuelling outage should be strictly limited. It should be considered a high priority security issue.

Keywords: Reactor pressure vessel, vulnerability, terrorism, blast

1. Introduction

Nuclear power plants have long been recognized as potential targets of terrorist attacks, and critics have long questioned the adequacy of the existing measures to defend against such attacks. The 11-S 2001, 11-M 2004 and 7-J 2005 attacks in USA, Spain and UK illustrated the deadly intentions and abilities of modern

S. Apikyan and D. Diamond (eds.), Countering Nuclear and Radiological Terrorism, 105–110.

terrorist groups. These attacks also brought to surface long standing concerns about the vulnerability of nuclear installations to possible terrorist attacks.

Commercial nuclear reactors contain large inventory of radioactive fission products which, if dispersed, could pose a direct radiation hazard, contaminate soil and vegetation, and be ingested by humans and animals. Human exposure at high enough levels can cause both short-term illness and death, and longer-term deaths by cancer and other diseases. To prevent dispersal of radioactive material, a series of "containments" are designed (in-depth defence philosophy with 3 containments). Nuclear fuel and its fission products are encased in metal cladding within a steel reactor pressure vessel (RPV), which is inside a concrete containment structure.

The RPV, which contains the nuclear fuel, is the most critical component of the plant. Access by terrorists to the RPV vicinity during reactor operation is extremely improbable, and the plant operators should have enough time to shutdown the reactor. A more factible situation, as shown in Figure 1, is to put some explosive material near the RPV wall by an insider during a routinely outage. In this period, the plant performs the maintenance and refuelling activities, and personal of external organizations can access to different parts of the plant.

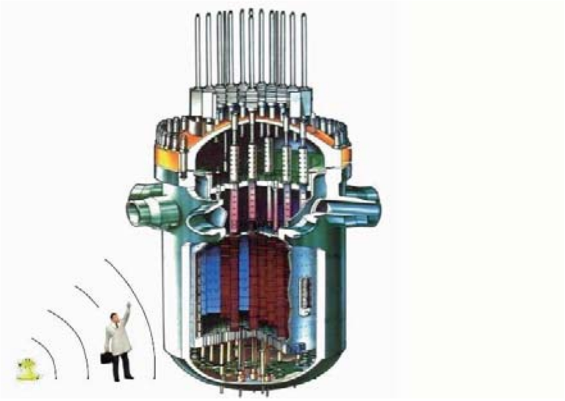


Figure 1. Explosion in the vicinity of the RPV wall

2. Methodology. RPV Failure Criteria

In order to determine the minimum amount of explosive material to damage the RPV, a simple method is proposed in this research work. The first step is to model the RPV as a cylinder of thin wall, as shown in Figure 2. For this case, and when R/r ≥ 10, the principal stresses σ_I, σ_{II}, σ_{III}, adopt a simple form as a function of the external pressure P and, the radii (R) and thickness (r) of the pressure vessel.

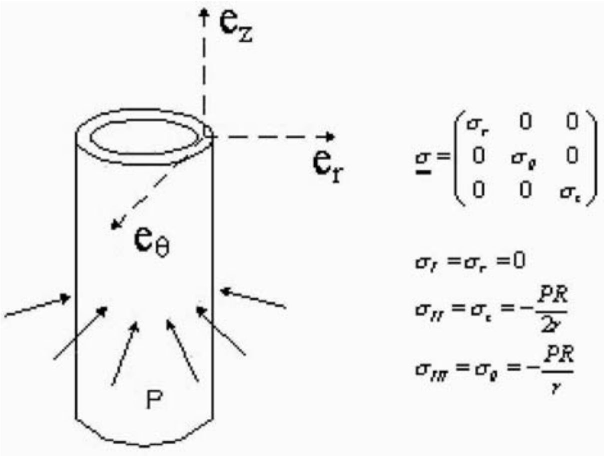


Figure 2. Principal stresses in a cylinder of thin wall under external pressure

It is assumed we have a uniform external pressure P around the RPV during the explosion. This assumption is reasonable since we are determining the minimum amount of explosive material needed to damage the RPV.

The second step is to define the failure criteria. Here we have several possibilities [1]. The elastic failure criteria is chosen and represented by the following equation,

$$\sigma_r = \sqrt{\frac{1}{2}\left[(\sigma_I - \sigma_{II})^2 + (\sigma_{II} - \sigma_{III})^2 + (\sigma_I - \sigma_{III})^2\right]} \qquad (1)$$

Using Equation (1) and the expressions for the principal stresses, we can obtain the pressure needed to start the plastic deformation of the RPV steel,

$$P = \frac{2}{\sqrt{3}}\frac{r}{R}\sigma_Y \qquad (2)$$

3. Results. Amount of explosive material

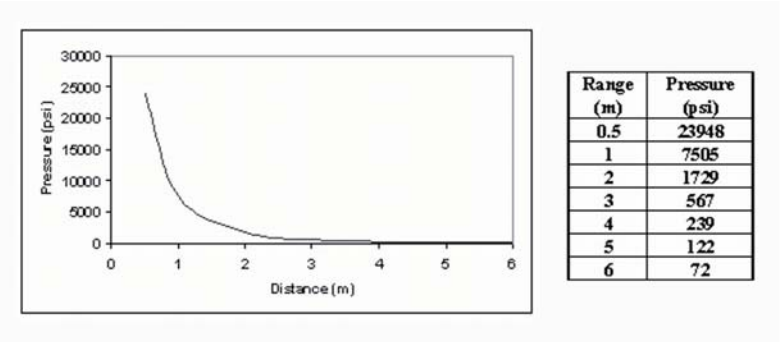
A blast wave striking an object will generate a pressure on the face of the object which is greater than the peak static pressure of the wave. This occurs because the forward moving air molecules are brought to rest and further compressed by the collision. The peak static overpressure is the pressure that would be felt by a particle moving with the wave-front. When a stationary object is struck by the blast wave, however, the object will face this pressure and will also be hit by the particles being carried with the stream- the blast wind. This leads to the concept of dynamic pressure, q, which is defined as

$$q = \tfrac{1}{2}\cdot\rho u^2 \qquad (3)$$

Here u is the particle velocity and ρ is the air density immediately behind the wave front.

The total pressure experienced by the object face, in our case the outside surface of the RPV wall, is the peak reflected pressure, P, a combination of static and dynamic pressure.

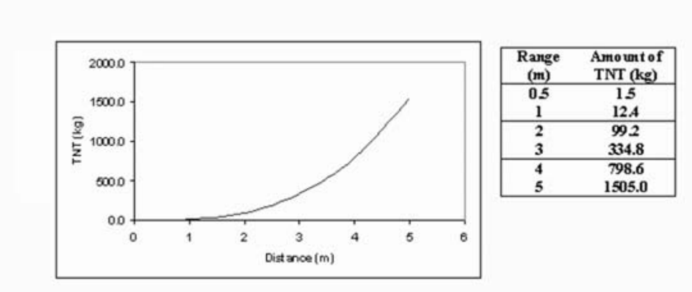
According to Equation (2) and for a selected RPV, for instance with R = 2 m, r = 0.2 m and $\sigma_Y = 65{,}000$ psi, the minimum reflected pressure, P, needed to start the plastic deformation is 7505 psi (51,7 MPa). Figure 3 shows the peak reflected pressure of 12,4 kg TNT for different distances calculated with the computer program ATBLAST [2]. The blast pressures are reduced significantly as distance increases. For distances lower than 1 m this amount of TNT can damage the RPV.



Range (m)	Pressure (psi)
0.5	23948
1	7505
2	1729
3	567
4	239
5	122
6	72

Figure 3. Reflected pressure for 12.4 kg TNT

Figure 4 shows the amount of TNT needed to generate a reflected pressure of 7505 psi at different distances. Just for reference, person-carried explosive devices are generally considered to be less than 50 kg, and are usually assumed to be approximately 20 kg.



Range (m)	Amount of TNT (kg)
0.5	1.5
1	12.4
2	99.2
3	334.8
4	798.6
5	1505.0

Figure 4. Amount of TNT needed to damage the RPV at different distances

A given explosive can be converted to an equivalent amount of TNT by multiplying its mass by the TNT equivalence factor. Conversion factors can be based either on the impulse delivered by the explosive or the energy per unit mass of the explosive. The two factors will be slightly different [3]. Table 1 gives conversion factors for a few explosives based on the energy per unit mass (a partial list from [3]). Using these conversion factors and the ATBLAST program we are able to determine the minimum amount of different explosive materials needed to damage the RPV (for $R = 2m$, $r = 0.2m$, $\sigma_Y = 65{,}000$ psi). The calculated values are given in Table 1.

TABLE 1. Minimum amount of explosive materials to damage a selected RPV

Explosive	TNT Equivalent Factor	Amount of Explosive (kg) at 0.5 m distance	Amount of Explosive (kg) at 1 m distance
TNT	1.000	1.5	12.4
AMATOL 80/20 (80% ammonium nitrate 20% TNT)	0.586	2.6	21.2
Compound B (60% RDX, 40 TNT)	1.148	1.4	10.8
RDX (Cyclonite)	1.185	1.3	10.5
HMX	1.256	1.2	9.9
Mercury fulminate	0.395	3.9	31.4
Nitroglycerin (liquid)	1.481	1.0	8.4
PETN	1.282	1.2	9.7
Pentolite 50/50 (50% PETN, 50% TNT)	1.129	1.4	11.0
Torpex (42% RDX, 40% TNT, 18% Aluminum)	1.667	0.9	7.4

4. Conclusions

Experts consider the nuclear reactors to be potential “high-value targets” for terrorists aiming to maximise public panic as well as inflicting large-scale destruction and death. The most critical component of a commercial nuclear power plant is the RPV which contains the reactor core. Small amount of explosive material can produce irreversible damage in the RPV and the release of radioactive material. Therefore, access of working personal to the vicinity of the RPV during the refuelling outage should be strictly limited. It should be considered a high priority security issue.

References

1. R. J. Roark and W. C. Young, Formulas for Stress and Strain, Fifth Edition, McGraw-Hill International Book Company, ISNB 0-07-085983-3. 1983.
2. A. T. Blast vers. 2.1 (Anti-Terrorism Blast) is a software program developed and distributed by Applied Research Associates, Inc. July 2004. http://www.araseas.com/
3. P. D. Smith and J. G. Hetherington, Blast and Ballistic Loading of Structures, Butterworth and Heinemann Ltd., Oxford, 1994.

PROLIFERATION RESISTANCE FEATURES IN NUCLEAR REACTOR DESIGNS

B.A. GABARAEV, YU.S. CHEREPNIN N.A. DOLLEZHAL
A. Dollezhal Research and Development Institute of Power Engineering (NIKIET) Russia, 101000 Moscow, P.O.B. 788

Abstract: The paper presents a review of the main principles for technologies and materials protection from unauthorized proliferation and application to be considered in nuclear reactors designing. Nuclear power features certain operations sensitive to nuclear weapons proliferation (such as separation of uranium isotopes (enrichment), long storage of spent fuel, processing of spent fuel, plutonium and/or uranium recovery from spent fuel, storage of recovered fissile materials). Proliferation resistance is defined as a nuclear energy system characteristic that impedes the diversion or undeclared production of nuclear material, or misuse of technology with the purpose of acquiring nuclear weapons or other nuclear explosive devices. The basic principles of non-proliferation established in the INPRO international project sponsored by IAEA have been discussed as implemented for designing of the innovative nuclear energy systems based on fast lead-cooled nuclear reactors.

Keywords: Non-proliferation of nuclear weapons, reactor design, separation of uranium isotopes, plutonium recovery, safeguards, INPRO project, innovative reactors, fuel cycles, BREST fast reactor.

1. Introduction

An important issue in the design of modern nuclear plants is safeguarding of reactor technologies and materials against diversion and unauthorised application. Nuclear weapons proliferation came on the agenda in the polemics on nuclear power long ago. This was only natural, considering that nuclear technology started with production of fissile materials intended for weapons fabrication – i.e. plutonium production in nuclear reactors and production of highly enriched uranium by way of isotopic separation.

S. Apikyan and D. Diamond (eds.), Countering Nuclear and Radiological Terrorism, 111–120.

Nuclear power features certain processes and operations sensitive to nuclear weapons proliferation [1]:

- separation of uranium isotopes (enrichment);
- long storage of spent fuel;
- plutonium and/or uranium recovery from spent fuel;
- storage of recovered plutonium.

The current goal consists in minimising the proliferation risks associated with the nuclear fuel cycle. To achieve this goal, it is necessary to prevent material diversion for potential application in nuclear weapons – either as a result of sabotage or by misuse of fuel cycle facilities. It is also essential to keep a close watch over the know-how in the area of production and reprocessing of highly enriched uranium (i.e. enrichment techniques) and plutonium.

Proliferation resistance is defined as a nuclear energy system characteristic that impedes the diversion or undeclared production of nuclear material, or misuse of technology with the purpose of acquiring nuclear weapons or other nuclear explosive devices [2].

The degree of proliferation resistance results from a combination of technical design features, operational modalities, institutional arrangements and safeguards measures. These can be classified into intrinsic proliferation resistance features and extrinsic measures.

Intrinsic proliferation resistance features are those features that result from the technical design of nuclear energy systems, including those that facilitate the implementation of extrinsic measures. This presentation discusses implementation of intrinsic proliferation resistance features in nuclear reactor designs developed in NIKIET.

Early in their design activities, designers choose technical features that would reduce nuclear system attractiveness for nuclear weapons programmes. In particular, these are material characteristics such as isotopic composition, chemical form, mass and bulk, and radiation properties.

The second type of intrinsic proliferation resistance features comprises the technical features of a nuclear system that prevent or inhibit the diversion of nuclear material. These include design features that confine nuclear material to locations with limited points of access and make material difficult to move without being detected due to such characteristics as size, weight, or radiation.

The third type of intrinsic proliferation resistance features consists of the technical features of a nuclear system that prevent or inhibit the undeclared production of direct-use material. Thus, reactors are designed so as to preclude undeclared irradiation of target materials in or near the core. Reactor cores have small reactivity margins that would prevent reactor operation with undeclared targets. Fuel cycle facilities and processes are difficult to modify for undeclared production of nuclear materials. Processes have intrinsic limitations that would preclude their use for production of direct-use materials.

The fourth type of intrinsic proliferation resistance features consists of the technical features of a nuclear energy system that facilitate verification, including continuity of knowledge. This includes designs that facilitate design information verification throughout their life cycles, and design features that provide for facility surveillance and monitoring.

There is currently a need in the methods of assessment of the degree and effectiveness of the proliferation resistance of system’s design. Such assessments could be used by system developers to study the impact of intrinsic design features on the overall proliferation resistance of the system. This would help the designers to make an intelligent choice of the features and increase the robustness of proliferation resistance. The lack of a generally recognized methods and a system for assessment of proliferation resistance characteristics, along with the immature regulatory framework, impede nuclear power development across the world.

TABLE 1. The basic proliferation resistance principles established by INPRO [2]

1	Proliferation resistant features and measures should be implemented in a nuclear power system to minimise the possibilities of undeclared use of nuclear materials for weapons production.
2	Both intrinsic features and extrinsic measures are essential, and neither should be considered sufficient by itself.
3	Extrinsic proliferation resistance measures, such as control and verification measures, will remain essential, whatever the level of effectiveness of intrinsic features.
4	From a proliferation resistance point of view, the development and implementation of intrinsic features should be encouraged.
5	A clear, documented and transparent methodology is required for comparison and assessment of proliferation resistance.

Following Russia’s President initiative supported by Director General of IAEA, an international project has been in progress since 2001 on innovative reactors and fuel cycles – INPRO [2]. NIKIET was actively involved in formulating objectives for the studies to be performed in the framework of this project. In the first phase of INPRO, the key principles and requirements for modern nuclear power were identified in the following principal areas: economics and competitiveness, safety, environmental impact (waste management) and proliferation resistance.

These principles could serves as a groundwork for a system of requirements for a nuclear reactor design. Developers of nuclear systems should be encouraged to use intrinsic features to support proliferation resistance in their designs, and governments should be encouraged to consider extrinsic measures to supplement the intrinsic features. All this will improve the level of proliferation resistance provided by today's nuclear power systems.

Proliferation resistance is achieved through the use of optimal combinations of intrinsic features and extrinsic measures. Complete reliance on extrinsic measures results in high verification expenses. On the other hand, there may be a point at which the cost of intrinsic proliferation resistance features exceeds the benefit. This means that there are tradeoffs between different intrinsic features and extrinsic measures, as well as tradeoffs between intrinsic features for proliferation resistance and other design considerations such as safety, maintainability and cost.

Proliferation resistance should be taken into account as early as possible in the design and development of nuclear energy systems. This requirement encourages designers to consider proliferation resistance from the early stages of their design activities and provides the greatest opportunity to incorporate intrinsic design features at a minimum additional cost. For example, consideration of proliferation resistance could result in small changes in nuclear system configuration with minimum additional cost.

It is important to understand that though these features can significantly contribute to proliferation resistance of a nuclear energy system, they will not make it fully proliferation resistant by themselves.

Assessment of the robustness of the proliferation resistance of a design is a difficult and complex task, therefore, it is essential to start an effort to develop appropriate methods of assessment. The initial versions may be debatable and complicated, but they will give an impetus to this work. It is critical that any methodological limitations be clearly identified to avoid misinterpretation or misapplication. The mechanism for coordinating such R&D remains to be established. Materials prepared within the INPRO Project could be of use.

All projections predict the nuclear power growth in the 21st century. The existing nuclear capacity amounts to ~360 GWe. If it increases to thousands of GWe, it will be difficult to take an accurate account (at least to hundreds of kilograms) of the thousands of tonnes of ^{235}U and Pu circulating in the system. If deployed to a large scale based on existing reactor designs, nuclear power will compromise the prospects for banning the nuclear weapons.

NIKIET has been advocating nuclear power development based on reactors of a new generation with a maximum level of proliferation resistance. The new energy technology should rely on fast neutron reactors operating in uranium-plutonium fuel cycle, which will help gradually reduce the proliferation risk. The basis for such an approach is the huge amount of plutonium accumulated in the spent fuel of thermal reactors, and more efficient neutron utilisation in fast reactors as compared to thermal facilities. With the considerable plutonium stockpiles, the high breeding rate and ratio are no longer on the agenda, which allows using excess neutrons for the benefit of safety and economics [1].

These principles were used to develop a concept of the BREST-type plants, with a fast reactor *(Fig. 1)* and a “naturally safe” closed fuel cycle (CFC) using uranium-plutonium fuel *(Fig. 2)*.

The key features of the BREST technology are:

- high-density heat-conducting fuel with equilibrium composition UN-PuN-MA;
- chemically inert lead coolant;
- no blanket;
- closed fuel cycle without enrichment and separation of fissile isotopes.

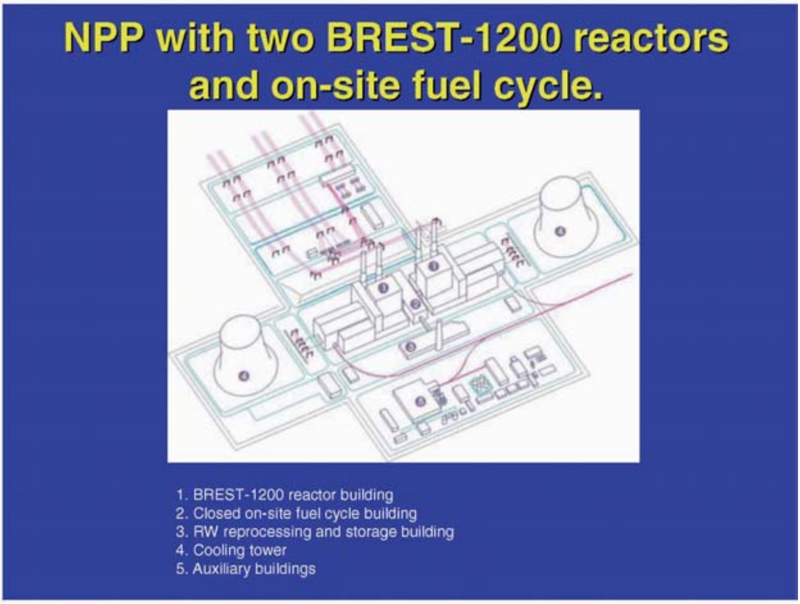
The use of mononitride uranium-plutonium fuel featuring high density (~ 13 g\cm³) and heat-conductivity (10-15 times greater than that of oxides) allows fundamental modification of fast reactor parameters and design, the most important of which is the elimination of the uranium blanket. The absence of uranium blanket in fast reactors with full Pu reproduction in the core (CBR~1) sets the stage for the technological support of the nonproliferation regime. Uranium blanket is replaced with lead reflector, which, as shown by calculations and experiments, significantly improves the core neutronics and the reactor safety in general.

The first charge is made of natural or depleted uranium mixed with plutonium recovered the spent fuel of light-water reactors (VVER). Plutonium stockpiles, kept in storage facilities, will gradually diminish, and all spent fuel stored in the cooling ponds at modern NPPs will be reprocessed to recover plutonium to fabricate the first cores of fast reactors. Initial recovery of Pu and fabrication of the first charges for fast reactors should be done at existing facilities in the nuclear countries, or in the international nuclear technology centres under the IAEA safeguards. This will be the major step towards reduction of Pu stockpiles on the planet and, hence, consolidation of the nonproliferation regime.

One of the key aspects of plutonium application in the fast reactors of a new generation is the use of equilibrium fuel. In this case, the mass and isotopic composition of plutonium and minor actinides loaded into the core and retrieved on the end of the life cycle, remain practically unchanged. The fuel removed from the core, contains less uranium-238 than the initial charge, which should be compensated in the course of reprocessing. In this case, there is no need to recover or add plutonium when fabricating new fuel.

The BREST fuel cycle includes the following stages which match the stages of a closed fuel cycle of traditional fast reactors, except for the blanket subcycle [3]:

- fuel irradiation in reactor;
- post-irradiation cooling of spent fuel assemblies and their transportation to a reprocessing shop;



NPP with two BREST-1200 reactors and on-site fuel cycle.

1. BREST-1200 reactor building
2. Closed on-site fuel cycle building
3. RW reprocessing and storage building
4. Cooling tower
5. Auxiliary buildings

Figure 1. Layout of NPP with BREST-1200 reactor

- SFA cutting to retrieve fuel and detach steel components of fuel assembly;

- reprocessing;
- adjustment of fuel mixture composition;
- fabrication of nitride pellets;
- fabrication of fuel rods and fuel assemblies;
- temporary storage;
- delivery to reactor.

Figure 2 shows configuration of a closed cycle with nitride fuel. In this cycle, the nonproliferation principle is translated into the requirement that the reprocessing technique should be incapable of separating uranium and plutonium at any stage of the process. The fast reactor physics allows rough cleaning of fuel from fission products in the course of reprocessing (with 1-5% of FP remaining in fuel). Moreover, americium, neptunium and curium remain in the fuel to be transmuted. Together, these impurities account for the high activity of fuel (about 50 Ci/kg with 1% of FP remaining in fuel), and act as an intrinsic physical (radiation) barrier to fuel theft. Reprocessing without plutonium recovery is limited practically to the cleaning of fuel from fission products. Furthermore, fuel recycling is confined to the reactor building and the adjacent fuel cycle facility, which is crucial for the improvement of material safeguarding against unauthorised application

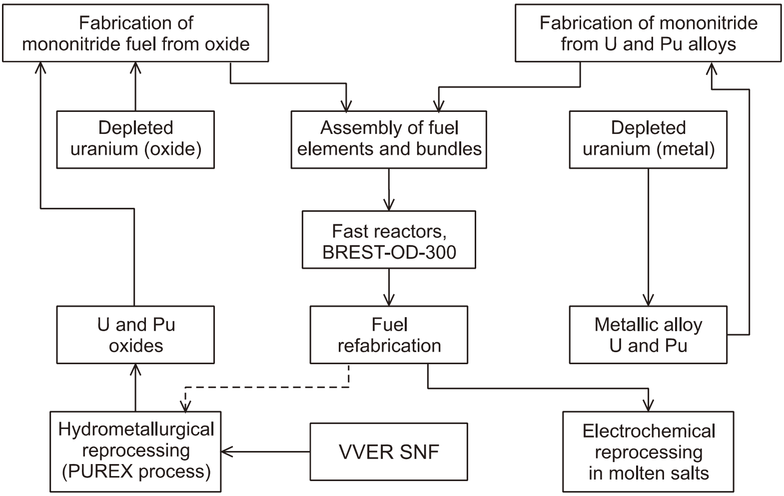


Figure 2. Closed fuel cycle of BREST NPPs

A specific feature of an on-site fuel cycle is that it is based on an unmanned technology, i.e. the process itself, adjustment and maintenance of equipment are managed remotely. The fuel cycle of the BREST-type reactors does not require shipment of spent fuel assemblies to a reprocessing plant. After a one-year cooling in an in-pile storage facility, SFAs are transferred to an on-site fuel cycle facility via transfer corridor connecting reactor compartment with the facility. This eliminates all risks and expenditures associated with SFA transportation for reprocessing. Moreover, no transportation and handling equipment associated with shipment is needed.

A formidable barrier to the illicit use of the BREST-type reactors for production of pure Pu suitable for weapons manufacture, is the absence of Pu recovery facilities and technologies in the on-site fuel cycle. BREST fuel – delivered for reprocessing and reprocessed – is unsuitable for fabrication of nuclear charges. A fundamental requirement for the reprocessing technique is that it should keep uranium and plutonium inseparable, in the same proportion as in the spent fuel delivered for reprocessing. Reprocessed fuel contains up to 1% of fission products, which simplifies its safeguarding (this feature of the BREST fuel is sometimes referred to as "self-safeguarding").

An important task facing now developers of the on-site fuel cycle is fuel protection against theft and misuse. The process is being reviewed to identify its vulnerabilities in terms of unauthorised fuel extraction or equipment modification for the purpose of Pu recovery.

This technique has been under development in Russia for more than 15 years, in parallel with the relevant R&D to support it. The work relies on more than 40 years of experience in civil fast reactors and submarine facilities with heavy-metal coolant (Pb-Bi). The cost estimates performed for a nuclear power plant with two BREST-1200 reactors and on-site fuel cycle facilities capable of handling 24 t of spent fuel a year, have shown that the fuel costs will not exceed 15% of the cost of the entire energy complex.

It is worth mentioning that the BREST fuel cycle will afford practically unlimited expansion of resources available to nuclear power, owing to the recycling of the equilibrium U-Pu fuel, with only a small amount of depleted or natural uranium added to it.

Surely, BREST is not the only one feasible technology; nor is it ideal. However, it is the first and most advanced concept of an innovative nuclear plant, which meets all requirements for large-scale nuclear power in terms of the fuel balance, safety, cost, waste management, and proliferation resistance. This technology has been developed to a level when it can be used to design and construct a demonstration plant, which can be done within the time and to the cost usual for such undertakings.

BREST facilities possess many physical properties that make them proliferation-resistant:

- in a fast reactor with full Pu reproduction in the core (CBR~1.05), the amount of fissible plutonium loaded into the core practically equals the amount of Pu retrieved on the end of the life cycle, so that there is no need to recover Pu for the fabrication of fresh fuel;
- reactor does not need and should contain no uranium blanket capable of producing weapons-grade plutonium;
- transmuted actinides present in the fuel, and rough fuel cleaning from FPs, facilitate fuel protection against thievery at all stages of the fuel cycle;
- all fuel cycle facilities will be placed on the NPP site to exclude large interim storages and avoid long-distance shipments, and hence reduce the risk of fuel theft or loss;
- reprocessing technique is not required to include Pu recovery, therefore, it is possible to develop technology that will be incapable of this operation;
- stockpiled plutonium will be used for fabrication of the first cores of new reactors, as part of the uranium-plutonium mixture.

Simple analysis shows that plutonium accumulated in the spent fuel of Russian NPPs can be completely utilised by the end of the 21st century in the fast reactors of a new generation (assuming that one BREST-1200 or 1.5 - 3 BN-800 reactors are put in operation each year). To provide plutonium for the first cores, it is necessary to construct reprocessing plants with the total capacity of 1000 – 1000 t SNF/year. When all plutonium present in the spent fuel of thermal reactors comes to end, further deployment of fast reactors will be based on surplus plutonium produced in the fast reactors with CBR~1.05. The task is quite realistic for Russian economy. Moreover, this solution will not only give cheap electricity to Russia but will also significantly reduce the proliferation risks.

References

1. Prof. E.O. Adamov (ed.) “White Book of Nuclear Power”, Moscow, 2001.
2. IEAE - TECDOC – 1362. Guidance for the Evaluation of Innovative Nuclear Reactors and Fuel Cycles. 2003.

3. V.V. Orlov, A.V. Lopatkin et al. Fuel Cycle of BREST Reactors. Addressing the Problems of Radioactive Waste and Proliferation. ICONE-11. Report 36405. 2003.

THE ROLE OF STRUCTURAL MATERIALS IN THE VULNERABILITY OF NUCLEAR POWER PLANTS

LUIGI DEBARBERIS, KAISA SIMOLA
EC-JRC-IE, Institute for Energy, Petten, The Netherlands

ANTONIO BALLESTEROS
Tecnatom, Madrid, Spain

ALEXANDER KRYUKOV
ASE, ATOMSTROYEXPORT, Moscow, Russia

MILAN BRUMOVSKY
NRI, Rez, Czech Republic

Abstract: The nuclear power plants (NPPs) world-wide are generally very robustly designed and constructed, capable to stand very extreme conditions. Small design differences from this point of view can be found among the various reactor types of the same generation; PWR, WWER, etc. The NPP structures are thus designed to accommodate all originally thinkable unwanted conditions, to cope with various extreme scenarios and respond safely to the various considered initiating events. In addition to the robust design, a series of complex redundant and diverse safety barriers, following a defence in depth concept, have been developed to avoid negative consequences, or at least mitigate the consequences of the events. Recently, questions and debates are appearing with regard to the vulnerability of the NPPs and their possible exposure to external threats; like for example terrorist attacks involving few individuals able to by-pass security and introducing small charges of explosive inside or near-by such containments. The role of the structural materials is in these situations very important for the safety of the NPP. The worst consequences of an event can contemplate of course huge environmental damage, like release of radio-activity combined with possible human losses and considerable direct costs, and financial and logistic indirect consequences. Such negative consequences are especially impacting the nuclear industry; in fact, it can be foreseen that a single accident or serious incident may put in danger the complete NPP fleet operation simply due to public opinion justified pressure. The response of the structures subjected to non-design impacts is discussed and reviewed in this paper. Although the main focus is on structural integrity, the paper also discusses the overall risk assessment of terrorist attacks presenting the link between structural analyses and plant risk analysis.

S. Apikyan and D. Diamond (eds.), Countering Nuclear and Radiological Terrorism, 121–133.

Keywords: Vulnerability, Structural Materials, Nuclear Power Plants

1. Background

In the world there are several hundreds of civil nuclear reactors producing a large fraction of the total world energy needed. Such NPPs are located in large geographical areas mainly concentrating in the most developed countries and slowly appearing in developing countries as well. A distribution map is given as example in Figure 1 for the enlarged EU and neighbouring countries.

A significant effort to assure safe operation of such power plants which are progressively ageing is done the Institute for Energy of the Joint Research Centre of the European Commission (Sevini et al., 2004), in particular within the frame of the SAFELIFE Action (Debarberis et al., 2004).

The existing NPPs were designed in the years 60'. Their potential dangers were taken into account, and a unique safety approach was developed for the nuclear reactors. Of course the first generation of reactors built was still suffering a few design shortcomings, but rapidly the new safety approach led to world-wide generally robustly designed and constructed NPPs structures and systems, capable to stand any thinkable conditions including very extreme ones. In fact all thinkable unwanted conditions were considered including all possible initiating events.

For each initiator a series of complex been developed to avoid negative consequences or at least mitigate the consequences of the events. A philosophy of redundant systems and diversified systems has been applied as well since the very beginning.

Intrinsic barriers over-dimensioned and large safety margins have been considered as well for materials and structures. The result is that the NPP structures can actually accommodate and are able to cope with extreme scenarios, and can respond safely to the various considered initiating events.

Natural catastrophic events like tornados and earthquakes as well as accidental aircraft or other object impact, have been considered since the early days of nuclear power and in connection of modernization projects. The European Union is home to 155 nuclear power plants units located in 25 Member States, generating about 30% of the EU electricity. Some of these plants are located near large urban population centres. Experts consider the EU nuclear reactors to be "high-value targets" for terrorist determined to attract public concern besides inflicting large-scale destruction and death.

Figure 1. NPPs distribution in the enlarged EU and neighbouring countries

Nowadays, nuclear power plants and nuclear installations in general are recognized as potential targets of terrorist attacks, and critics have long questioned the adequacy of the existing measures to defend against such attacks. The September 11, 2001 and March 11, 2004 attacks in USA and Spain illustrated the deadly intentions and abilities of modern terrorist groups. These attacks also brought to surface long standing concerns about the vulnerability of European nuclear installations to possible terrorist attacks. It is not a surprise that the EU citizens consider the international terrorism amongst few other items as the major fear (Sondage nº 58.1, Eurobarometre, Oct/Nov 2002).

The worst consequences of an event can contemplate of course huge environmental damage like release of radioactivity combined with possible human losses and huge direct costs and financial and logistic indirect consequences. Such negative consequences are especially impacting the nuclear industry; in fact, it can be foreseen that a single serious accident/incident may put in danger the complete NPP fleet operation simply due to public opinion justified pressure.

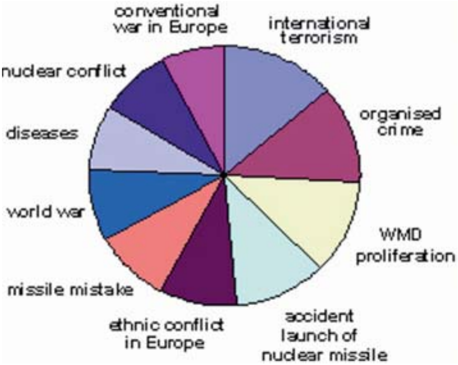


Figure 2. Sondage nº 58.1, Eurobarometre, Oct/Nov 2002

Consequently, the directions of the various financial programmes of the EU are targeted to find solutions to the issues which are indicated by the citizens, see Table 1.

TABLE 1. Priorities in the preparatory actions 2004-2005 for Security Research in the EU

EU priorities
Optimizing security and protection of networked systems
Protecting against terrorism (including bio-terrorism and incidents with biological, chemical and other substances)
Enhancing crisis management (including evacuation, search and rescue operations, control and remediation)
Achieving interoperability and integration of systems for information and communication
Improving situation awareness (e.g. in crisis management, anti-terrorism activities, or border control).

It is understandable that a major effort is required to reinforce and protect the energy sector critical infrastructure; including: production, distribution, storage, etc., as indicated in Figure 3. In particular, it is also clear that most of the listed priorities are also involving implicitly nuclear installations and related infrastructures and networks.

In fact, the production of electricity is for a large fraction assured by nuclear installations, which need to be safeguarded.

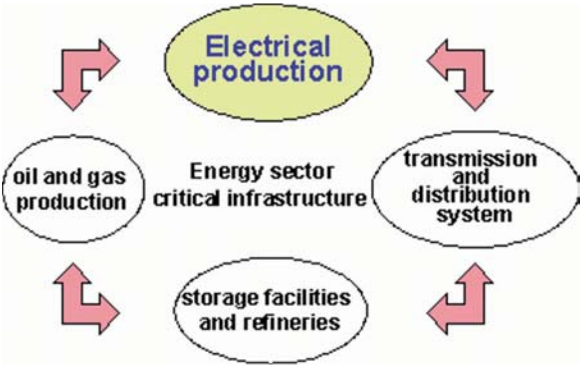


Figure 3. Energy sector critical infrastructures

2. NPP structures vulnerability

As it was already considered before, the NPP structures are designed to accommodate and to cope with extreme scenarios, natural catastrophic events, accidental aircraft or other object impact, etc. To avoid any catastrophic release of radioactivity, a series of safety barriers, following a defense in depth concept, have been provided. Probably the only events not explicitly considered were those of malicious and terrorist nature; including intentional airplane impacts or terrorist attacks involving both large charges (truck bombs) to the case of few individuals introducing small charges of explosive inside or near-by such containments. It is then of course a challenge to answer the recently rising questions regarding the vulnerability of the NPPs and their possible exposure to external threats. Small design differences from this point of view can be found among the various reactor types of the same generation; PWR, WWER, etc.

Recent works have been dedicated to study the blast of large car/truck bombs located near the outer containment. Such cases involve from several hundreds to up to 6000 Kg of TNT equivalent (Gaukler et al., 2002; Peplow et al., 2004, Schmidt 2003); typical of recent terrorist attacks on non-nuclear targets. Less attention has been paid to the security by-passing with smaller amounts of explosives. Of course we must assume that a clamorous failure of the security occurred in such a case. Anyhow such scenario is considered generally plausible and it is today believed that up to few kilograms of explosives can bypass security in certain conditions.

The structural analyses combined with risk analysis methods form a comprehensive approach to analyse NPP structural vulnerability. Such an approach enables the identification of weakest points related to safety and security issues – whether of technical/structural or organisational nature – and prioritisation of countermeasures.

The analysis of terrorist attack scenarios can be split in following phases:

- Analysis of the probability that the terrorists manage to enter the plant
- Analysis of the damage caused by the blast
- Consequences of the attack

The main focus of this paper is on the second phase, i.e. the structural response. Before discussing the structural analyses we present the modelling approach that can be used in the first phase, and discuss the consequence analysis and its relation to existing PSA analyses.

In the evaluation of consequences, we need to distinguish between local damage and the consequence at the plant level. If we think of the final consequences of an attack they could be classified in several groups taking into account the economical consequences, immediate injuries or fatalities, and radioactive releases. For simplicity, we are concentrating in the following in nuclear safety, and do not take the possible fatalities in consideration.

An illustration of the approach is presented in the following. In this example we analyse a scenario of a terrorist attack where few individuals attempt to by-pass security and introduce explosive material inside the power plant.

3. Event tree approach to analyse the accessibility of the installation

In the modeling of the by-passing of plant security, we have adopted the event tree modeling technique commonly used in risk assessments. An event tree is a representation of the logical order of events leading to some condition of interest for a considered system. The event tree initiates with a basic initiating event and develops from there in time until all possible states with adverse consequences have been reached. For the model, we need to identify information of basically three different types (in addition to the definition of the initiating event):

- the gates of the event tree
- probabilities assigned to the gates
- consequences assigned to event tree outputs

In our case, the gates in the event tree represent different physical and human barriers, which are aimed at stopping the attack. We have here adopted a simplified version of an event tree exercise presented by McCormick (1981). However, we have extended the example to include also access to the containment building, since we need to analyse separately attacks directly targeted against the reactor pressure vessel.

Further, the containment building is assumed to represent an additional physical barrier. The barriers defined in our example are:

- The gate as a physical barrier
- The fence as a physical barrier
- Gate guards
- An alarm system, that notifies mobile guards at the plant if the gate or fence has been attacked
- The mobile guards
- The containment (as physical and psychological barrier)

The event tree is aimed at analysing the probability that the terrorists manage to enter the plant. Thus we start by defining following three consequences to be used as input in further steps of the analysis:

- Terrorists are stopped
- Terrorists manage to enter the plant, but not the containment building
- Terrorists manage to enter the containment

It is of interest to analyse two different initiating events: an "open attack", where the terrorists enter the installation by force, and a smuggling of a smaller amount of explosives. It would be reasonable to assume, that the amount of explosives in the second case is smaller than in the first case. Since the amount of explosive material is very important in the structural analyses, we split the two last consequence categories to account for the size of the charge.

Finally one needs to assign probabilities to the success of different barriers, i.e. the event tree gates. In our illustration we use similar probabilities as McCormick (1981). In the case of smuggling the explosive, the physical barriers of the gate and the fence are not considered. It is also assumed that in this case the terrorists are not armed. For the access to the containment we use the probability 0.05 (this probability should reflect not only the difficulty to enter but also the terrorists' expected interest to get inside the containment).

Sensitivity analyses of the model can be made by varying the success probabilities of various events.

The event trees for the two different initiating events are presented in Figure 4. The end state of each path in the tree is indicated at the right side of the tree, with corresponding probabilities. The total probabilities of each end state are indicated at the bottom.

		Fence	Gate	Gate guards	Alarm	Mobile Guards	Access reactor	END STATE	
	Attack Fence								
	0.5	0.9						OK	0.45
		0.1			0.99	0.7		OK	0.0346
						0.3	0.05	RPV	0.000742
							0.95	PLANT	0.01410
Attack									
					0.01		0.05	RPV	0.000025
							0.95	PLANT	0.000475
	Attack Gate								
	0.5		0.1					OK	0.05
			0.9	0.8				OK	0.36
				0.2	0.99	0.7		OK	0.0623
						0.3	0.05	RPV	0.00133
							0.95	PLANT	0.0254
					0.01		0.05	RPV	0.000045
							0.95	PLANT	0.000855
Smuggling			0.9				OK	0.9	
				0.1			0.005	RPV-S	0.0005
							0.995	PLANT-S	0.0995

Figure 4. Event tree analysis

The probability of stopping the terrorists ("OK") is ~96%. There is a few %s probability that the terrorists succeed to attack the plant outside the containment. The probability for an attack inside the containment is an order of magnitude lower. The above simple calculation is just an example of the use of the event tree methodology.

4. Nuclear power plants structural materials

In this paper we concentrate to the case of very small charges that can be taken near primary structures like RPV or primary piping. Studies on structural response of a selected typical nuclear power plant under several terrorist and internal sabotage scenarios are planned at JRC. Such studies will contribute significantly to decrease the vulnerability of nuclear power plants by improving situation awareness on the structural integrity of key nuclear components and allowing for development of security strategies needed for the re-enforcement of available defenses as well as the establishment of new systems, lay-outs and plant procedures.

The behavior of nuclear power plant structures subjected to impact or explosion conditions can be determined by using complex finite element tools which allow performing a detailed analysis of the non-linear dynamic of the fluid-structure systems subjected to fast transient dynamic loading (explosions in enclosures, study of shocks and impacts of projectiles on structures, etc.).

One of the key points is the demonstration of the capability of the structures to respond to such new non-design loads. The materials which are used in NPP structures can be summarised as given in Table 2.

TABLE 2. Primary loop and materials matrix

Structures/components/ Systems	Materials	Remarks
Pressure vessel base and welds	Ferritic steels	- Component subjected to radiation damage - DMW TO JOIN FERRITIC TO AUSTENITIC STEELS - Small differences in western types and Russian design types
Primary piping	Austenitic steels	DMW
Pressurizer	Ferritic steel	DMW
Steam generator/heat exchanger	Alloy	
Active components	Different alloys,	- pumps - valves

(*) anticorrosive layer facing primary water

In the following, the pressure vessel is considered in more details as an example to quantify the scale of the energies involved.

The proposed simple way to estimate the minimum theoretical energy required to allow complete fracture of the vessel, $E_{fracture}$, is as follows:

$$E_{fracture} \approx 3{,}14 * D * s * USE_{CV} * \Psi \quad \textbf{(1)}$$

Where:

D	is the vessel diameter (m)
s	is the vessel thickness at the critical zone (m)
USE_{CV}	is the upper shelf energy measured on standard CV impact test (converted to J/m^2)
Ψ	is the global factor (>1) taking into account for the different fracture rate (CV normally obtained at 5 m/s impact velocity), sample size extrapolation, dissipations, etc.

For the scope of this paper, only considerations on the minimum theoretical energy to fracture will be done for simplicity.

Typically USE_{CV} of about 150-200 J are measured on standard CV notched specimens (full cross section 10x10 mm; ~80% breaking surface) (Davies, 1999). A minimum USE is even required by the ASME (ASME code Appendix G).

We have also to consider that the materials properties are degraded at end-of-life (EOL) when compared to beginning of life (BOL) conditions.

The estimated minimum calculated energy, Eq. 1, for different vessel types and specific materials is in the range of ~10 MJ. An example of the estimation, on a small thickness vessel, considering ageing, is done for example in Figure 5. Both base metal and welds are considered at the beginning of life (BOL) and degraded at end-of-life (EOL). As it can be seen the ageing of materials plays also a significant role.

Similar estimations can be found for primary piping and other primary components. In terms of explosives, these amounts are equivalent to approx a few Kg of TNT or dynamite. Such quantities could easily pass security unobserved.

Fortunately, in reality much larger charges would be required due to several factors, including: the efficiency of the energy transfer to the component critical section which cannot be really optimized due to different boundary and environmental conditions, the distance, the minimum peak overpressure created, etc. Empirical formulas based on available test data or complex simulations are normally developed to estimate the peak overpressure, Eq. 2, and to account for the standoff distance of the charge, Eq. 3.

$$P_{overpressure} = A * \left(\frac{d}{W^m}\right)^{-n} \quad \textbf{(2)}$$

$$t = W^m / (B\frac{d}{W^m} + C) \qquad \textbf{(3)}$$

Where:

W	is the weight of the charge
d	is the standoff distance
$P_{overpressure}$	is the in induced peak overpressure
t	is the maximum wall thickness which can be breached
A, n, m, B, C	are constant factors (obtained from fitting of test data)

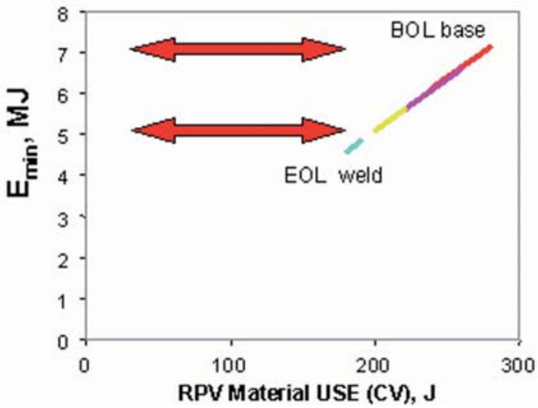


Figure 5. Estimated minimum energy to fracture versus USE of materials

If we account for the various factors, the required explosive charge amount could be one order of magnitude larger that the amount determined by the proposed minimum required energy (Eq. 1). Such amount would not easily pass unobserved through the security service.

It is anyhow clear that materials are key barriers and need to be further carefully studied with respect to their function beyond design to stand malicious events.

Further studies are required and the development and benchmarking of simulation tools need to be finalised as well. Such work is necessary to assure the safety of NPPs and prove the performance of the available defenses of the plant. In addition, re-enforcement of existing defenses or design of new defenses can be developed and optimised when required.

5. Consequence analyses

In addition to breaking structural components, the explosion may damage other safety-significant items, such as cabling. It is important from the consequence analysis point of view, whether the explosion, besides causing e.g. a LOCA initiating event by breaking a certain pipe, damages other important equipment in the vicinity causing unavailability of safety systems. The results of a fire PSA analysis could be very useful for these evaluations, since they include detailed walk-through of different compartments.

For the consequence analysis, it would be convenient to classify the consequences as they are classified in the PSA. Level 1 PSA defines different damage states of the reactor core, and different release categories are defined in level 2 PSA.

If the explosive charge is assumed to be placed inside containment, close to the RPV, and the charge is enough to damage the RPV, the probability of core damage can be assumed to be 1.

In cases when the core damage is not evident, the plant PSA model could be used to analyse the case further. In such cases, the blast analysis should be detailed enough to realistically identify the damages. In the PSA calculations, the damaged components should be set unavailable to obtain the probability of core damage. Peplow et al. (2004) claim that standard approximations used in probabilistic safety assessment calculations are not applicable for analysing such attacks. However, there is variability in PSA models and the applicability of the model should not be condemned before closer investigations.

6. Conclusions

The NPPs are generally very robustly designed and constructed, and are capable to stand very extreme conditions. From this point of view only small design differences can be found among the various reactor types of the same generation; PWR, WWER, etc. A major effort is required to answer recent questions with regards to the vulnerability of the NPPs and their possible exposure to external threats and malicious acts.

A comprehensive approach is required in order to evaluate NPP vulnerability, involving the use of probabilistic methodologies, event tree analysis, etc. In this way the probabilities of different scenarios can be compared.

From the point of view of structural response, simple methods can be developed based on the knowledge of the various materials impact properties.

A simple method to evaluate the theoretical minimum energy required to fracture large primary component is here proposed. The obtained results are relatively low compared to the explosive specific energy. The real energy required is much higher than the estimated minimum, and the relative explosive amounts are probably too large to pass unobserved through security. The role of the structural materials is fundamental and important also if we need to develop new defenses.

Ageing of materials is also an important factor to be considered, in fact the impact properties of materials are decreasing with time and usage. Using more complex simulation tools more precise responses can be calculated. More knowledge of nuclear primary loop materials behaviour during explosion is required, as well as the development and benchmarking of simulation tools.

This is in particularly necessary to assure safety on NPPs and prove the efficiency of the available defenses of the plant. In addition, re-enforcement of existing defenses or design of new defenses can be developed and optimised when required.

References

1. ASME Code, American Society of Mechanical Engineers Boiler and Pressure Vessel Code, Appendix G to Part 50-Fracture Toughness Requirements
2. Sevini, F., Debarberis, L., Taylor, N., Gerard, R. and Brumovsky, M., 2004, Study of aging mechanisms for structural materials within SAFELIFE project. *Strength of Materials*, 36, No. **1**:37-41
3. Davies, L.M., 1999. A comparison of western and eastern nuclear reactor pressure vessel steels. *Int. J. Pressure Vessels and Piping* **79**:163-208
4. Debarberis, L., Sevini, F., Acosta, B., Pirfo, S., Bieth, M., Weisshaeupl, H., Törrönen, K., Kryukov, A. and Valo, M., 2004, Radiation embrittlement understanding for PLIM Activities at EC-JRC-IE. *International Journal Strength of Materials*, 36, No. **1**:14-18
5. Schmidt, J.A., 2003, Structural Design for External Terrorist Bomb Attacks. In: *Structure* March 2003: 14-15
6. Sondage nº 58.1, Eurobarometre, 2002
7. Gaukler, P.D., Barnett, S. and Rosinski, D.J., 2002, *Nuclear Energy and Terrorism*, NR&E, 165-207
8. McCormick, N.J., 1981, *Reliability and Risk Analysis*, Academic Press, New York, New York
9. Peplow, D., E., Sulfredge, C.D., Sanders, R.L., Morris, R.H. and Hann, T.A., 2004, Calculating nuclear power plant vulnerability using integrated geometry and event/fault-tree models, *Nuclear Science and Engineering* **146**:71-87

CHAPTER III

RESPONDING TO NUCLEAR TERRORISM

COMBATING RADIOLOGICAL TERRORISM – A MULTI-FACETED CHALLENGE

ALEX WOLF, ILAN YAAR
Nuclear Research Center Negev (NRCN), P.O. Box 9001,
Beer-Sheva 84190, Israel

Abstract: In the twentieth century, radioactive sources have become extensively used in everyday life. These sources, in the hands of terror organizations, can become a threat to the security of civilized nations, causing severe disruption to normal life. One of the main challenges of the civilized world is to keep ahead of the terrorist organizations and take appropriate preventive measures in order to prevent and reduce to minimum the impact of their actions. In order to succeed, a joint and comprehensive effort has to be undertaken to address the scientific, technological, organizational, sociological, psychological and educational aspects of the radiological terrorism threat. In this paper, some of the main activities required for preventing radiological terror events, and the way in which a modular response plan can be prepared are discussed.

Keywords: radiation sources, radiological terrorism.

1. Introduction

In the last decade, terrorism has become a global threat. Terrorist organizations have succeeded to achieve a high level of organization, and with relatively simple devices have managed to induce severe damage to the security of civilized nations, causing severe disruption to normal life in many countries. Many governments responded to the new threat by responding appropriately. Special institutions were established, security measures

S. Apikyan and D. Diamond (eds.), Countering Nuclear and Radiological Terrorism, 135–142.

were taken and enforced, and funds were invested in the development of advanced technologies for preventing and combating terror.

Three main features are characteristic of the new threat: the fact that relatively simple devices are used, the extensive use of panic as a way to disrupt the course of normal life in densely populated areas, and the surprise factor. Many terrorist organizations have ingeniously used these features to their advantage. Therefore, one of the main challenges of the civilized world is to keep ahead of the terrorist organizations and take appropriate preventive measures in order to reduce to minimum the impact of their actions. The question of radiological terrorism has to be addressed in this context, namely, by taking appropriate measures in order to prevent the psychological and material damage that can be produced in case that a group of terrorist will try to use radioactive materials in conjunction with a terror event, or will attempt to attack a nuclear facility.

In this paper we briefly describe the main activities required in order to prevent radiological terror events, stress the importance of adequately dealing with the different challenges involved, and discuss the way in which a modular response plan can be prepared.

2. Radiological terrorism – the problem

In the twentieth century, radioactive sources have become extensively used in civil life. Radioactivity has many applications in completely different fields of everyday life: from determining the strength of concrete at construction sites, to sophisticated medical tests and therapeutic activities. Due to these activities, radioactive sources are quite common and relatively easy to obtain. Moreover, in many cases the security measures for protecting the sources are quite loose, or at least were so until recently. Thus, it is quite possible that terrorist organizations are already in possession of various types of radioactive sources. The fact that many borders, especially in Europe, are now open or loosely controlled makes the task of transporting these sources to the centers of main cities relatively easy. When we combine these facts and deductions with the psychological impact that the concepts “radioactivity” and “nuclear” have on the public, we conclude that radiological terrorism is a potential threat that has to be considered very seriously.

3. Main steps in combating radiological terrorism

The first and probably most important step is prevention. Since the use of radioactive sources has become so widespread, measures at the state level have to be taken for the accounting and physical protection of these sources. Such measures have already been taken by many states, and they can and should be enhanced by international cooperation. In addition to protecting the sources, in recent years more and more states are focusing their attention on preventing the smuggling of radioactive or nuclear materials. Special radiation detectors at border control points have been deployed to this purpose. The results of these activities are interesting: many smuggling attempts have been detected and investigated, thus proving that, indeed, it is very possible that radiological terrorism is a real threat.

Another important step is the development of the technology and methodology for dealing with the problem. As we will briefly discuss later, in this respect considerable progress has been made. The scientific and technological community has promptly responded to the challenge, and many new technical developments, many of them based on previous work, have been achieved. The training of qualified personnel for prevention and response, another important task, has not been given, to our opinion, enough attention. Another area, which seems not to have been given enough attention, has to do with public education, i.e., specific actions to be taken in order to explain to the public the dangers of radioactivity and diminish the psychological impact of the problem. An important conclusion from this short discussion is that radiological terrorism poses many challenges to the civilized world, some of which are not yet adequately addressed. In the following section, we will briefly discuss these issues.

4. The multi-faceted aspects of combating radiological terrorism

The multi-faceted aspects of the fight against terror are shown schematically in figure 1. In order to be prepared, a country has to invest resources in each aspect, as discussed in the following sections.

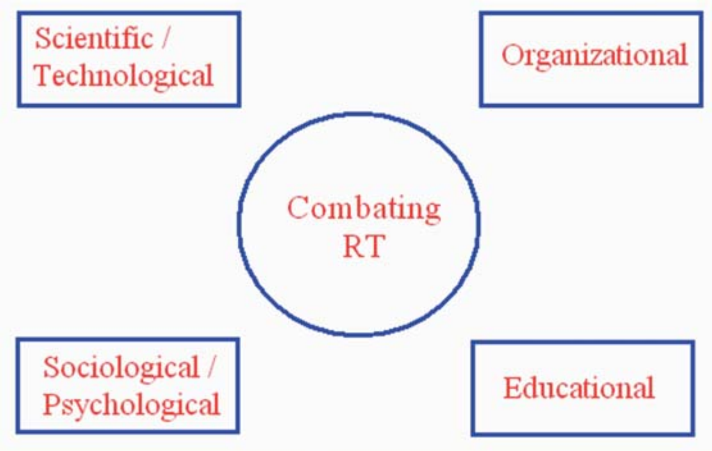


Figure 1. The multi-faceted aspects of the fight against radiological terrorism

4.1. THE SCIENTIFIC/TECHNOLOGICAL CHALLENGE

Since radioactive sources are relatively easy to detect, it is only natural that the first thing that comes to mind when we consider detection and prevention, is to develop sophisticated and sensitive radiation detectors. According to the use, several types of detectors were developed:

- Small and inexpensive for police use
- High resolution and high sensitivity for qualified personnel
- Compact detectors for securing sources
- Portals for use at inspection points

The specifications of the detectors developed vary according to their use. A general request is to detect as low intensity radioactive sources from as far as possible, and as fast as possible. Detailed required characteristics were defined by various organizations, such as, for example, the IAEA and the Austrian government, which performed a study known as ITRAP (Illicit Trafficking Radiation Detection Assessment Program). This study defined the alarm levels, detection probabilities, false alarm rates, background levels and environmental tests required of the detector systems. Many such systems are now in use in many countries. The detectors used in Israel are discussed in a paper presented by Ilan Yaar at this conference.

Another scientific challenge is the development of what has become to be known today as the field of nuclear forensics. The main idea here is to be able to perform trace analysis of nuclear materials, in order to detect smuggling attempts and to attribute specific materials to their source countries or organizations. While for radiation detection, we need to detect as fast as possible and from as far as possible, nuclear forensics require techniques capable to detect as few atoms as possible, usually present in smear samples taken at various inspection points. Techniques such as mass spectrometry combined with chemical analysis have been developed, making possible the detection minute amounts of the order of nanograms or even picograms of nuclear materials. The remarkable progress achieved in nuclear forensics requires now the preparation of adequate procedures for the interface between conventional and nuclear forensics. This is important because most, if not all conventional forensics laboratories do not have the facilities to work with radioactive materials. Here we note that while science and technology have achieved considerable progress in the field of trace analysis, the interface between the various authorities that are supposed to use the results of this progress, does not seem to have been given enough attention.

Besides detector development and nuclear forensics, another important scientific field relevant to radiological terrorism is the evaluation of material dispersion pattern caused by an explosion in which radioactive sources or nuclear materials are involved, and the relevant risk assessment in urban areas. Considerable progress has been achieved in this field, and many papers were presented at this conference, including organizational aspects such as international collaborations on meteorological conditions, which are important to the dispersion of radioactive materials and risk assessment.

4.2. THE ORGANIZATIONAL CHALLENGE

Since the problem has many completely different aspects, the coordination between the various authorities involved (i.e., police, radiation workers, hospitals, etc.) is crucial. First, one has to prepare a comprehensive response plan. This plan has to be modular, in order to cover all possible scenarios. We will discuss this later. Here we only mention that such a plan has to be prepared and approved at the state level, and afterwards qualified personnel has to be designated and trained. Finally, special drills need to be carried out to test the response plan and make adjustments if necessary. The organizational aspect of radiological terrorism has been given attention lately, as we can see from several papers presented at this conference.

4.3. THE SOCIOLOGICAL, PSYCHOLOGICAL AND EDUCATIONAL CHALLENGE

A radiological terrorism event has a large number of implications that need to be addressed promptly, such as: panic of the public due to lack of information and uncertainty, trauma due to the combined effect of a conventional bomb and fear of radiation, evacuation of urban areas possibly for a considerable amount of time in order to decontaminate, and so on. These effects need to be studied and evaluated in advance, and appropriate steps have to be taken in order to be able to deal with them if necessary. To our knowledge, these problems have not been addressed as well as the other aspects of radiological terrorism. An important area in which one has to devote considerable efforts is education. It is our opinion that comprehensive education plans need to be established and carried out through schools and the media. The public has to be given information on hazardous substances, radioactive materials and their effects, and ways in which to protect itself. Public education is probably the most neglected issue related to radiological terrorism, and therefore preparation and implementation of appropriate plans of action should be considered with high priority.

5. Response to a radiological event – design of a modular response plan

In case of a radiological terror attack, the response should include:

- Detection of "dirty bomb"
- Deployment of qualified personnel
- Identification of the radioactive material in the device
- Containment of contamination
- Medical treatment of exposed persons
- Fast, on-site risk assessment
- Evacuation of contaminated area
- Communiqué to the public

DecontaminationEach of the above steps has to be well prepared in advance, and the needed actions at each step depend on the specific scenario. Since many scenarios are possible, a modular response plan should be considered, and in order to achieve this it is important to make a list of the possible generic scenarios. One can classify the scenarios according to two criteria: type of source and method of dispersion. The possible types of sources are alpha, beta, gamma and neutron. As for the methods of dispersion, the first one that comes to mind is of course a combination of conventional explosion with radioactive materials (dirty bomb). Other possibilities are the placement of a strong source in a public place in order to cause panic and the danger of high exposure doses to the public, as well as use of a rocket to carry a “dirty bomb”. The contamination of food or water, although completely different from other methods of dispersion, should also be considered. Since we used two classification criteria, we can define a matrix for the possible scenarios. This matrix is shown in Table 1. The numbers indicate the various scenarios as defined by the two criteria. For developing the response plan, some scenarios are similar (1 and 1a, 2 and 2a, 3 and 3a), or even identical, in which case they are marked with the same number in Table 1. From the table we see that within this simple model, we do not have a large number of scenarios. The response plan should be built with modules for each step of the response activities mentioned above, and each module should be designed to fit the various scenarios in Table 1.

TABLE 1. The matrix of possible scenarios for a radiological terror attack

Type of source	Type of radiation		
	Alpha	Beta, gamma	Neutron
Method of dispersion			
Conventional explosive	1	2	3
Placement in public location	-	4	4
Rocket	1a	2a	3a
Water/food contamination	5	5	-

6. Summary

In this paper we have briefly considered the various aspects of radiological terrorism. While some of them, especially the scientific and technological aspects, are being extensively treated, others have been given much less attention. The main challenge of the civilized world is to go ahead and develop a comprehensive plan that will properly deal with all aspects of the problem. In this respect, international collaboration is very important. Through such collaboration, one should achieve better protection of radioactive sources, exchange information on technological topics and plans of response, and perform coordinated drills. In this way, we will make progress towards strengthening the security of the world, and prevent terrorist organizations from disrupting the normal course of life.

References

1. IAEA Draft Specification "Technical/Functional Specifications for Border Radiation Monitoring Equipment", IAEA, December 2003
2. P. Beck**,** ITRAP, Illicit Trafficking Radiation Detection Assessment Program, Final Report, OEFZS-G --0005, October 2000.

ESTIMATION OF INHALATION RADIATION DOSES ASSOCIATED WITH A ^{90}SR DIRTY BOMB EVENT

VLADIMIR P. RESHETIN
Joint Institute for Power and Nuclear Research, National Academy of Sciences of Belarus, Sosny-Minsk, 220109, Belarus; http://reshetin.net

Abstarct: The initial stage of dispersion of ^{90}Sr radiological dispersion device (dirty bomb) in a terrorist event was investigated on the basis of a numerical solution of the full system of Navier-Stoks equations. Maximum inhalation doses at the level of ≥1, ≥5, ≥10, ≥50 mSv are used as evaluative criteria to assess probable consequences. The intentional release of a relatively small amount of ^{90}Sr using a conventional explosive has the potential to cause internal exposure to beta-radiation with relatively high maximum inhalation doses achieving hundreds of mSv, but the spatial extent of the area within which high exposures might occur is very small with most of the population receiving maximum inhalation doses between 1-10 mSv. The extent of radiation contamination (area and activity) is dependent on ^{90}Sr particle size, the height of release, and local weather conditions.

Keywords: dirty bomb, radioactivity, dispersion, atmosphere, dose, inhalation exposure, Strontium-90

1. Introduction

Numerical modelling of dispersion of suspended radioactive particles in the atmosphere is a base for assessments of the consequences of a dirty bomb event. An accent in modelling is made on the estimations of radiation contamination of the city and the doses of external and internal irradiation to which the population is exposed. Non-uniformity of contamination, an origin of separate spots with a relatively high contamination level, essentially influence the evaluation of the danger scale. So, contaminated spots arising in different parts of the city might be interpreted by the population as a large-scale and dangerous radiation contamination.

The other important issue that should be solved under modelling is an assessment of the initial dimensions of the radioactive cloud. Both underestimation and overestimation result in mistakes in computation of

S. Apikyan and D. Diamond (eds.), Countering Nuclear and Radiological Terrorism, 143–150.

concentrations and, as a consequence, the doses of external and internal radiation. In this connection, the distribution of radioactive substances in the next-to-the-blast zone would be especially interesting as it is here that heavy contamination could be expected.

Modern development of physics and technique of blasts allows the design and creation of a simply-constructed explosive device that would be capable of delivering and dispersing radioactive materials at arbitrary heights within 10-200 m of the ground. Special note should be taken that a radiological dispersion device (RDD), or dirty bomb, can be created on the basis of the pyrotechnical resources such as salute rockets, petards and fireworks. Technology for manufacturing RDDs based on them is not much more complicated than all other dirty bomb creation technologies taking into account possible risks of irradiation. It is not totally possible to exclude the fact that RDDs can be made without keeping strictly to radiation safety regulations.

In scientific literature the main attention paid is to the scenarios where the powdered radioactive materials are attached directly to the explosive in such a way that they can be dispersed and start propagating in the atmosphere. Though such a scenario seems to be plausible, nevertheless initial dispersal of radioactive materials can take place without explosive matter. For example, small quantities of powder can be dispersed by lifting particles from a turntable using a venturi aspirator. The turntable can rotate at variable speeds, controlling aerosol concentrations in a wide range. Shear forces created in such aerosol generator are sufficient to de-agglomerate most dry particles in the size range from 0.5 to 50 micrometers. Liquid radioactive materials could be dispersed by the generators of liquid aerosols, where the dispersal occurs when passing through a special nozzle, so at the exit highly-concentrated, stable and reproducible aerosols form. RDDs created on the basis of a generator of liquid aerosols allow prompt dispersal of a solution of radioactive isotopes including strontium salts, many of which have high specific activity.

In contrast to the RDD, where detonation is applied for the dispersion, the spreading of radioactive aerosols by the generators could go on unnoticed for a long time, not attracting the attention of people. A relatively small mass, the possibility of prompt dispersal of radioactive materials and the small size of aerosol particles allow us to draw a conclusion about the dangerous potential of RDDs based on generators of solid and liquid aerosols.

For investigation of the dispersion of radioactive substances in the atmosphere, a number of models were developed, amongst which LASAIR

(*Walter H.*, 2001) and HOTSPOT (*Homman S.G.,* 1994), created in the Lawrence Livermore National Laboratory, USA, are the most famous. Some results of numerical modelling of radioactive aerosols dispersion in the atmosphere after a detonation are described in the works (*Reshetin V.P.,* 2005; *Bolshov L.A., R.V. Aryutyunyan, O.A. Pavlovsky,* 2002).

2. Initial phase of dispersion

After the explosive detonation, a so-called 'thermal' containing radioactive isotopes forms in the atmosphere. It has initial momentum and thermal energy (see. Fig. 1a). Due to the initial momentum and buoyancy the initial rise occurs. While increasing in dimensions approximately 4 times, the store of its thermal energy and momentum decrease. Cold air penetrates the body of the thermal and its rise slows down. It is interesting to note that in literature the self-similar solution of the boundary layer equations describing the thermal's motion was found. So, its height over the ground can be described by the power-like dependence on the time elapsed after the detonation (*Gostintsev Yu.A., L.A. Sukhanov, A.F. Solodovnik,*1980; *Turner J.S.,*1973):

$$H(t) \approx \zeta \Theta^{1/4} t^{1/2}, \tag{1}$$

where Θ is THT equivalent in kg, t is time interval elapsed after detonation, s. Self-similar motion arises in 1-1.5 sec after explosion. When the thermal is moving, typical geometry proportions conserve, including the ratio of its height to diameter. The wind transfers the cloud in a horizontal direction, not disturbing its motion upwards. The height of the thermal's rise and consequently, due to similarity, its diameter and vertical dimension depend also on a mass of explosive powered in 0.25, which is consistent with results of experiments on determining the initial dimensions of a cloud performed at a test place in Munster (*Thielen H., E. Schrodl,* 2004). In accordance with the data presented in the work (*Thielen H., E. Schrodl,* 2004), the height of a thermal is proportional to the mass of explosive powered in 0.25, which exactly coincides with the theoretical dependence, and its diameter, to the mass powered in 0.22.

Taking into account constant ζ changes in the range of values of 5-10 m/(kg$^{1/4}$sec$^{1/2}$), the time of the thermal's rise is about 20–30 sec (*Gostintsev Yu.A., L.A.Sukhanov, A.F.Solodovnik,*1980), and TNT equivalent of explosive of 10-20 kg, the height of the thermal's rise is 20–25 m depending on the mass of explosive. (1 kg of burnt TNT generates 4.2 MJ of heat). In Fig.1b is presented the graph of dependencies of the cloud's dimensions computed on the basis of self-similar solution and empirical data of the test place at Munster (*Thielen H., E. Schrodl,* 2004). The value of ζ was adjusted in accordance with empirical data only for one point. Though checking the dependence $H(t) \sim t^{1/2}$ for the data of work [6] was difficult because of possible errors when measuring thermal height in the presented graph, nevertheless our calculations for instants of time 2 sec, 5 sec, 10 sec, 15 sec and 20 sec demonstrated satisfactory compliance with this theoretical dependence.

The variations in the cloud width normally were smaller than in the cloud height. Under stable conditions the reproducibility was larger than under unstable conditions. The variations of the experiments with the explosive mass were within a range around a maximum factor of 2 concerning cloud width and height. The variations due to changes of the experimental parameters (kind of explosive, meteorological conditions, underground and charge mounting) were hence covered by a factor of 2.

It is interesting to note that in most cases a clearly reduced concentration in the lower third of the cloud was noticed by the evaluators. An exact quantitative evaluation due to brightness difference was not possible on the basis of video material. An estimation of the concentrations in the upper and lower parts of the cloud suggests a concentration in the lower part reduced by a factor of three to the upper part. A more realistic modelling of the source configuration would be the assumption that the lower part of the cloud contains less aerosol than the upper part.

For assessment of the height and diameter of radioactive cloud after a detonation of explosive, a formula from model HOTSPOT was adopted in LASAIR. Blast experiments carried out at Munster as well as former blasting experiments in connection with the retention capability of a foam-filled containment indicate the formation of a cloud under experimental conditions which is clearly smaller than calculated by HOTSPOT. The deviation of volumes is approximately 1-2 orders of magnitude. An over-estimation of the volume to the same degree means under-estimation of the concentration and doses of irradiation at the next-to-the-blast zone.

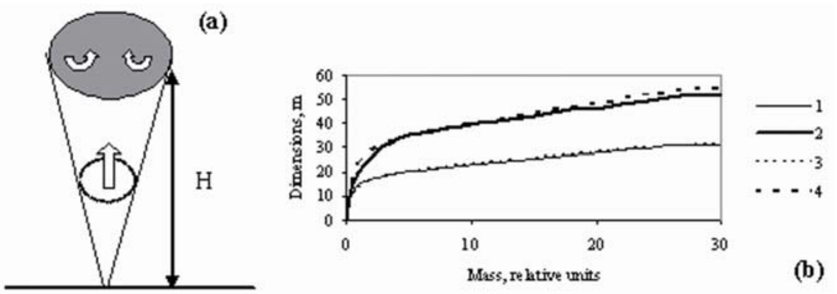


Figure 1. Diagram of air circulation in the thermal moving upwards (a). Dependence of height (1,3) and diameter (2, 4) of a cloud against a mass of explosive (1, 2) is empirical dependence (Thiele H., E. Schrodl, 2004), 3,4 is estimation based on self-similar solution (b)

3. Numerical modelling

The initial stage of dispersion was investigated on the basis of a numerical solution of the full system of Navier-Stoks equations. With this aim the well-known program STAR-CD (*Star-CD ver.3.10a,* 1999), that allows the modelling of the gas motion under a wide variety of different conditions, was applied. An example of dispersion of radioactive cloud containing Sr -90 after a dirty bomb explosion is presented in Fig. 2. The case of detonation of the explosive corresponding to 1 kg of TNT that results in a release of isotopes of Sr-90 with total activity of 10 Ci in the atmosphere was elaborately considered. The location and geometry of all the objects near the place of blast correspond to the real location of buildings, trees, etc in one of the streets in Minsk. The trees and other vegetation were modelled as objects with some transparency.

By the time when the explosive matter burns out, a typical dimension of thermal achieves about one meter and the density of gases released after the blast equals 1 kg/m^3, that is about 20% less than the density of the surrounding atmosphere. The shock waves reflected from the ground and the buildings change the configuration of the thermal, increasing its diameter and decreasing its height. For the case when the place of blast is close to the buildings, the shock waves can deform the geometry of the thermal and its initial dimension and configuration will sufficiently depend not only on the mass of explosive but the place of blast, particulars of building location and their geometry.

4. Big particles

Sr-90 in RDD can be presented in the form of a powder with a wide range of particle sizes including the case where the main mass contains big particles exceeding 50-400 μm. The height where initial dispersal of radioactive substances occurs influences the scale of contamination evaluated by the area and the density. The blasts near the ground contaminate first of all the territory adjacent to the place of the explosion. As a rule, a considerable portion of the radioactive materials contained in the RDD falls out during a short time period after explosion. The particulars of dispersal of big particles are not only high speed of deposition but also a slower rate of convective diffusion. Big particles have significantly more time of aerodynamic relaxation, and as a consequence they are incorporated into the gas motion with some delay. For the speed of carrying phase of U ~ 1-10 m/sec and the particle size on the level of ~ 100 μm, Reynolds number Re << 1, and

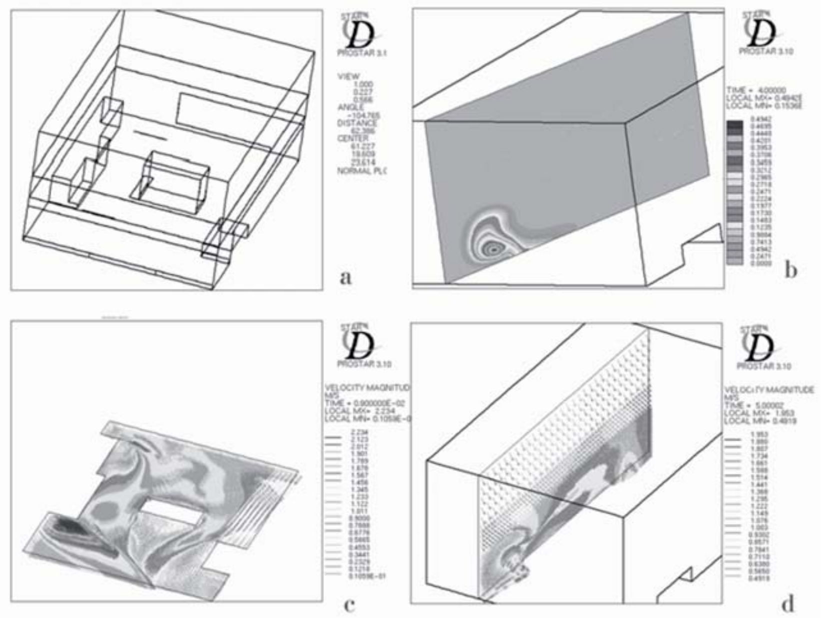


Figure 2. An example of numerical computation of initial phase of Sr-90 dispersion after an explosive of a RDD. (a) – calculating domain; (b) – Sr-90 concentration,Ci/m^3, *4 sec after explosion; (c ,d) – velocity magnitudes for two moments of time.*

the formula for the aerodynamic drag force transfers to the well-known expression for the force in the Stocks approach. In this case the time of aerodynamic relaxation coincides with the time during which the particle gains constant speed in the gravitational field:

$$\tau_A = \frac{2}{9}\frac{\rho_s}{\rho_g}\frac{r^2}{\nu},$$

where ρ_s and ρ_{gas} are correspondingly solid and gas density, ν is viscosity. For typical values $\rho_s / \rho_g \approx 10^3$, ν~0.1 cm^2/sec, r ~100 μm, the time of aerodynamic relaxation is τ_A~0.1 sec, but at the same time fine inhalation particles with size of r ~1 μm have relaxation time τ_A~10^{-5} sec and they almost immediately incorporate into the motion of carrying phase.

It should be taken into account that as distinct from the Munster data (*Thielen H., E. Schrodl,* 2004) where fine powder was used for modelling, after near ground detonation of an RDD, big particles are closer to the ground surface than fine ones. When modelling atmospheric dispersion, the initial big and small particle distribution over height can be presented as a superposition of two Gaussian functions reflecting a difference in their space distributions after the explosion. The results of modelling testify that the monotonic reduction of contamination density with distance is observed for ground level blasts. The contamination density that can be high next to the place of explosive is then scaled down with increasing distance from the place of the blast. When the effective height of a blast h_0 increases, the distribution of contamination density against distance has two maxima. The first of them is next to the explosion and arises due to high ground level concentration of big particles immediately after the blast; the second arises at the distance where the cloud dimension achieves the value of $\Delta z \approx h_0$. Finally, when the blast occurs at relatively large heights the maximal contamination density arises at the distance approximately equal to several effective heights h_0.

5. Conclusions

Estimation of radioactivity levels associated with a ^{90}Sr dirty bomb reveals that a terrorist event involving an RDD containing a relatively small amount of ^{90}Sr (i.e., approximately 0.07g) might result in a relatively small area within the overall contaminated zone in which the theoretically possible maximum inhalation doses might equal several mSv. The majority of the population along a centre line of the cloud might receive maximum inhalation doses varying between 0.01 and 0.1 mSv. The potential consequences of a terrorist incident can be further minimized by developing effective emergency response and decontamination capabilities. In fact, investment in such preparedness combined with active measures to secure orphan sources of non-fissile materials and interdict illicit materials are likely to reduce significantly the threat posed if terrorists use a dirty bomb to release radioisotopes in an urban area.

References

1. *Walter H.*, 2001: Ein Programm zur Berechnung der Strahlenexosition nach der Umsetzung einerUSBV mit beigefugten radioaktiven Stoffen, 6. Informationssveranstaltung zur Nuklearspezifischhen Gefahrenabwehr, Salzgitter-Bad.
2. *Homman S.G.,* 1994: HOTSPOT Health Physics Codes for the PC, Lawrence Livermore National Laboratory, UCRL-MA-106315.
3. *Reshetin V.P.,* 2005: Estimation of radioactivity levels associated with a ^{90}Sr dirty bomb event. Atmospheric Environment (in press).
4. *Bolshov L.A., R.V. Aryutyunyan, O.A. Pavlovsky,* 2002: Radiological terrorism. High impact terrorism. Proceeding of a Russian-American Workshop, National Academy of Sciences, 143-144.
5. *Gostintsev Yu.A., L.A. Sukhanov, A.F. Solodovnik,*1980: Limit laws of non-stationary turbulent uprising convective movements in the atmosphere. Reports of Academy of Sciences of USSR, **252**, 2, 311-314.
6. *Turner J.S.,*1973: Buoyancy effects in fluids. Cambridge. At the University Press.
7. *Thielen H., E. Schrodl,* 2004: Blast experiments for derivations of initial cloud dimensions after a “dirty bomb” event. EUROSAFE, Internet publication.
8. *Star-CD ver.3.10a,* 1999: Computational Dynamics Ltd.

STATUS OF THE RODOS SYSTEM FOR OFF-SITE EMERGENCY MANAGEMENT AFTER NUCLEAR AND RADIOLOGICAL ACCIDENTS

WOLFGANG RASKOB, J. EHRHARDT, C. LANDMAN, J. PÄSLER-SAUER
Forschungszentrum Karlsruhe GmbH, Institut für Kern- und Energietechnik, Hermann-von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen, Germany

Abstract: Under the auspices of its Euratom Research Framework Programmes, the European Commission (EC) has supported the development of the comprehensive decision support system RODOS (Real-time On-line DecisiOn Support) for off-site emergency management after nuclear accidents for more than a decade. Many national research programmes, research institutes and industrial collaborators contributed to the project, in particular the German Ministry of Environment, Nature Conservation and Reactor Safety (BMU). The RODOS system can be applied to accidental releases into the atmosphere and various aquatic environments within and across Europe. It provides coherent support before, during and after such a release to assist the analysis of the situation and decision making about short and long-term countermeasures for mitigating the consequences with respect to health, the environment, and the economy. Appropriate interfaces exist with local and national radiological monitoring data systems, meteorological measurements and forecasts, and for the adaptation to local, regional and national conditions in Europe. Within the European Integrated Project EURANOS of the 6th Framework Programme, the RODOS system is being enhanced, among others, for radiological emergencies such as dirty bombs attacks, transport accidents and satellite crashes by extensions of the nuclide list, the source term characteristics and the atmospheric dispersion model.

Keywords: RODOS, EURANOS decision support, emergency management, radiological emergencies

S. Apikyan and D. Diamond (eds.), Countering Nuclear and Radiological Terrorism, 151–166.

1. Introduction

The Chernobyl accident had a profound effect on emergency preparedness and post-accident management worldwide and, in particular, in Europe. Deficiencies in arrangements dealing with an accident of this magnitude, at both national and international levels (e.g., in world food trade), led to many problems of practical and political nature. Many lessons have been learnt, and considerable resources have since been committed, to improve emergency preparedness and post-accident management in order to avoid similar problems in future. Improvements have been made at national, regional and international levels and have been diverse in nature. However, more needs to be done to ensure a timely and effective response to any future accident.

Emergency management, more generally, has received increased attention following the tragic events in the U.S. in September 2001. Attacks with radiological dispersal devices (RDD), which spread radioactive material by aerosolising or dissolution in water reservoirs are currently under intense discussion.

A number of requirements emerge from these considerations; they include

- the need for a more coherent and harmonized response in Europe and during different stages of an accident (in particular, to limit the loss of public confidence in the measures taken by the authorities for their protection);
- exchanges of information and data in an emergency so as to enable neighbouring countries to take more timely and effective action; and
- the necessity to make better use of limited technical resources and avoid duplication.

The RODOS project was established to respond to these needs. It was launched in 1989 and increased in size through the European Commission's 3rd, 4th and 5th Framework Programs. Many national R&D programs, research institutions and industrial collaborators have provided significant additional funds. In particular, the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) contributed to the project financially with a special focus on early emergency response. Up to 40 institutes from some 20 countries in the Western and Central Europe (CEE), as well as in the former Soviet Union (FSU) were actively involved in the project [1] (http://www.rodos.fzk.de).

These collaborative actions resulted in the development of the comprehensive decision support system RODOS for general application to accidental releases into the atmosphere and various aquatic environments within and across Europe [2, 3] e.g. in national or regional nuclear emergency centres. RODOS provides coherent information at all stages of an accident (i.e., before, during and after a release) to assist the analysis of the situation and decision making about a wide range of potentially useful countermeasures (e.g., sheltering and evacuation of people, distribution of iodine tablets, food restrictions, agricultural countermeasures, relocation, decontamination, restoration, etc.) to mitigate the health, economical and environmental consequences of an accident with respect. Appropriate interfaces exist with local and national radiological monitoring data, meteorological measurements and forecasts, and for adaptation to local, regional and national conditions in Europe.

The current version of the system (RODOS version PV 6.0) has been, or is being, installed in national emergency centres in several European countries for (pre-operational) use (Germany, Finland, Spain, Portugal, Austria, the Netherlands, Poland, Hungary, Slovakia, Ukraine, Slovenia, and the Czech Republic). Installation is foreseen or under consideration in Switzerland, Greece, Romania, Bulgaria, and Russia within the next few years. Installation in the CEE and FSU has been achieved with support from the European Commission's ECHO, PHARE and TACIS programs, respectively.

Installation is most advanced in Germany [4]. A RODOS Centre has been established at BfS/ZdB, Neuherberg, and has been coupled to the nuclear reactor remote monitoring systems (KFÜ), the German Integrated Measurement and Information System (IMIS), and the German Weather Service (DWD).

Installation of the system for (pre-operational) use in many national emergency centres is indicative of the success of the system and its potential for achieving more coherent and effective responses to future accidents which may affect Europe.

2. The RODOS system: technical performance

2.1. THE RODOS CONCEPT OF DECISION SUPPORT, DATA ASSIMILATION, AND UNCERTAINTY HANDLING

The RODOS system provides coherent decision support at all levels, ranging from largely descriptive reports, such as maps of the predicted, possible and, later, actual contamination patterns and dose distributions, to a detailed evaluation of the benefits and disadvantages of various countermeasure strategies and their ranking according to the societal preferences as perceived by the decisionmakers (see Fig. 1). It is also able to perform ‘what-if’ calculations, allowing investigations of how a situation could develop in different scenarios. Its modern decision analysis techniques (MAV/UT - multi-attribute value and utility models) support emergency managers in evaluating the overall efficacy of possible countermeasure strategies. Data assimilation techniques combine model predictions and monitoring data for smooth transition from pure model predictions (in the pre-release phase) to a real situation (in the post-release phases). The Bayesian decision analysis approach addresses all issues of uncertainty and data assimilation in a manner coherent with the decision analysis techniques used in evaluation. No decision support system on this scale has ever achieved this broad functionality in other contexts, much less so in an area as demanding as a nuclear emergency.

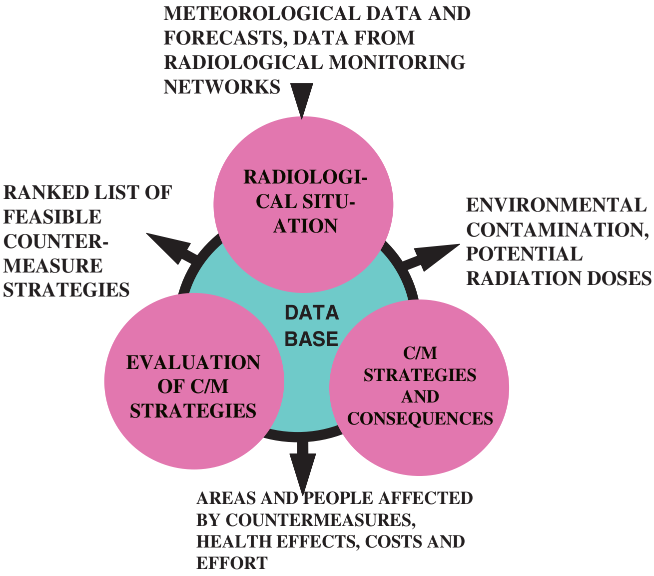


Figure 1. Information processing in RODOS

2.2. INTERFACES WITH PLANT SAFETY AND ENVIRONMENTAL MONITORING

The RODOS system provides appropriate interfaces to meteorological and radiological monitoring data and numerical weather prognoses from national weather services broadly used in Europe (see Fig. 2). Customisation guidelines help the user adapt the system to regional and national conditions.

Prototype software tools have been developed within the STEPS/ASTRID and STERPS projects[1] which, in the event of an emergency situation in a light water reactor, allow monitoring of the progression of an accident from the moment it is detected to forecasting the future behaviour of the reactor and estimating ongoing and potential releases as a function of time. The source term, thus evaluated faster than in real time, can be used to predict and/or assess the potential and/or real radiological consequences. A uniform interface exists which allows direct transfer of source term data to the RODOS system. On the basis of the results of its prognostic calculations, decisions about precautionary emergency action can be initiated in a timely manner.

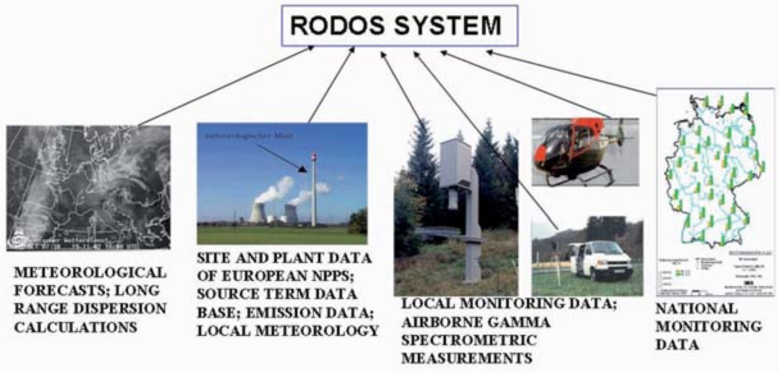


Figure 2. Coupling RODOS to meteorological and radiological monitoring data

3. User interfaces

Three user interfaces are adapted to the needs of different users. The first one is based on X-Windows for UNIX and is intended for qualified operators and systems developers (User Category A). This interface offers full access to all systems functions, model parameters and stored data. The second interface (User Category B) is based on the design of Internet sites using well-established WWW technology. It is intended for users (User Category B) not needing permanent access to the system (e.g., only during an emergency or in drills), such as radiological advisers, decision makers, etc. The third user interface for User Category C is identical with Category B, but is limited to receiving results of RODOS calculations only (see Figure 3).

In the current configuration of the RODOS Centre at BfS/ZdB, Neuherberg (see Fig. 4), ten main users actively access the RODOS Centre as A- and B-users; seven of these are responsible for emergency management in their respective federal states, and three of them act at a national level. Five federal states are passive C-users.

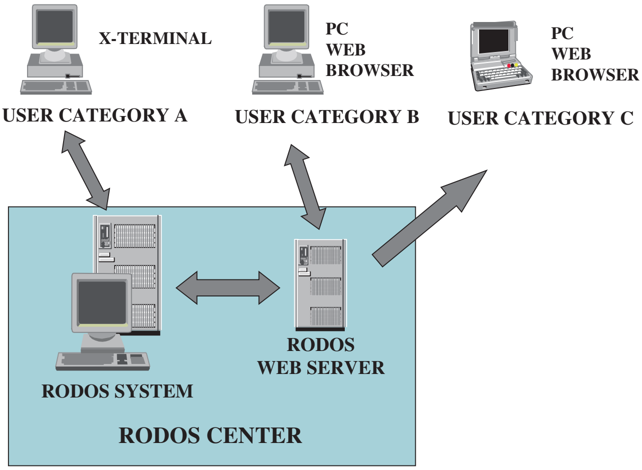


Figure 3. User categories of the RODOS system

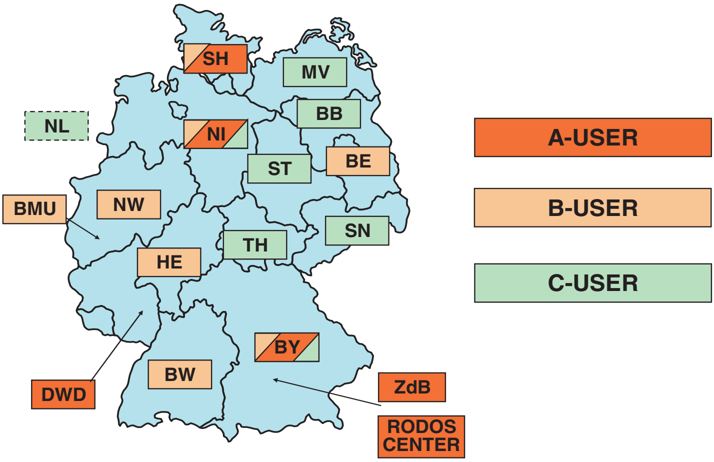


Figure 4. RODOS users in Germany

With increasing power of personal computers and the extended functions of their operating systems it is now possible to migrate the RODOS system to one of the most advanced operating systems running on personal computers, the LINUX operating system. The possibility to use powerful PCs and LINUX servers will greatly reduce installation and maintenance costs. In that way, dependence on one hardware provider (Hewlett Packard) will cease to exist, and platform-independent installations of RODOS will become possible. The first LINUX-based RODOS version will be available in summer 2006.

3.1. DATA EXCHANGE BETWEEN NEIGHBOURING COUNTRIES

As past experience clearly demonstrates, the consequences of nuclear emergencies do not stop at national borders. It is essential in good emergency management that dose assessments and decisions be co-ordinated and harmonized among the countries affected. Countermeasures, recommendations, and information of the public and the media must be consistent. Discrepancies in assessments by different emergency centres and decisionmakers in different countries must be avoided or, at least, must be well understood. Consequently, there is great need for thorough, rapid, reliable exchanges of all kinds of information.

Given the fact that computer-based decision support systems for nuclear emergencies have become a reality in Europe, the most effective way of achieving this goal is by ensuring timely and direct data and information exchanges among those systems. Accomplishing this objective will guarantee that, regardless of the operating system and hardware platform, decision support systems will be able not only to run and serve their purpose, but also to communicate with each other and share all necessary information and data associated with an accidental release of radioactivity, thus ensuring prompt and adequate emergency management.

With the MODEM Project[1, 5], a Web server technology based data exchange tool using the XML format has been developed which allows for direct communication among decision support systems, such as RODOS (push-pull concept). The tools have already been tested successfully in a number of European-wide emergency drills. Their application in international data exchange between the U.S. and Japan is currently under investigation.

4. Future steps

4.1. GENERAL IMPROVEMENTS

Despite the considerable resources devoted to improving the management of consequences of nuclear emergencies and, in particular, the progress achieved in the RODOS project, the situation in Europe continues to be characterized by national solutions in the technical as well as the administrative/political areas. The EURANOS Project, which integrates 17 national emergency management organizations with 33 research institutions, combines best practice, knowledge and technology to further preparedness for Europe’s response to any nuclear or radiological emergency (see Fig. 5). The five-year multinational project, which started in April 2004, combines all EC-funded activities in nuclear and radiological emergency management and rehabilitation strategies in one integrated project (http://www.euranos.fzk.de).

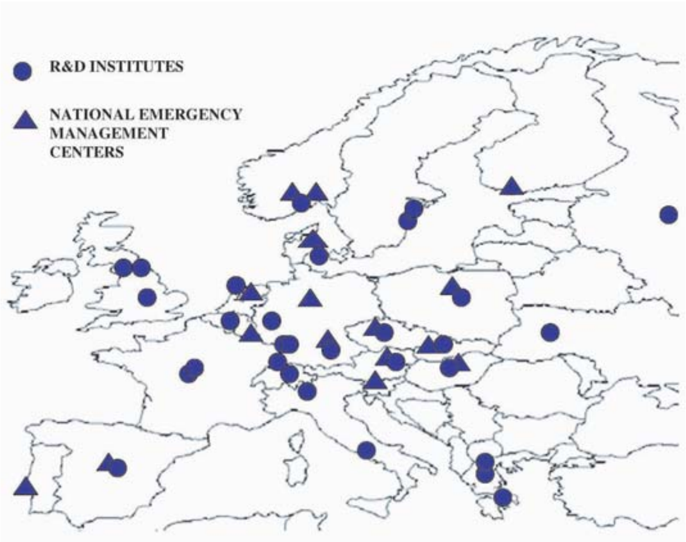


Figure 5. European extension of the EURANOS project

One of the key objectives of the EURANOS project is to ensure that RODOS is operational with state of the art IT-technology and tailored to the request of all possible end-users which are applying the system at the moment or can be attracted to use it in future. To this purpose the RODOS Users Group (RUG) was established in the beginning of the project. Activities will be carried on with an enhanced interaction with the RUG but also complemented with new activities aiming at engaging other end-users and stakeholders in the process of further developing of the RODOS DSS. The RUG will be integrated into the RTD development from the beginning of a work package and it is expected from the RUG that priorities on further RTD work is provided. The key elements of the R&D work can be summarised as follows:

- Extension of the portability and operability of the RODOS system (e.g. migration from the UNIX to the LINUX operating systems).
- Development and integration of models for estimating activity concentrations in inhabited areas together with adequate countermeasure strategies for reducing radiation doses, including the acquisition of monitoring data to improve model predictions.
- Enhancement of all models with respect to radiological accidents (terrorist attacks, dirty bombs, etc.).

- Development of flexible modules supporting the preparation of emergency drills.
- Enhancement of methods and tools for evaluating and ranking countermeasure strategies within the decision-making process.
- Improvement, for practical applicability, of models of the hydrosphere (rivers, lakes, sea) and agricultural countermeasures.

One of the very new aspects of the future developments of RODOS relates to the enhancements for radiological emergencies which were first considered in this working programme.

4.2. ENHANCEMENT FOR RADIOLOGICAL EMERGENCIES

In order to extend the application of RODOS to events, accidents, or attacks, involving radioactive material ("radiological emergencies"), a literature study [6] has been carried out as a part of the EURANOS Project, with the aim to surveys the different radiological emergency types, to investigate the principle applicability of RODOS for them, and to define the necessary or desirable model modifications or model or database extensions. The following chapter summarises the main findings.

4.3. CHARACTERISTICS OF RADIOLOGICAL EMERGENCIES

Radiological emergencies can result from deliberate attacks or from an involuntary incident, for instance a transport accident or a satellite re-entry. As RODOS is primarily a decision-aiding tool for radiological off-site emergency management, the enhancement focuses on three types of radiological emergencies with the potential for a contamination of larger areas or a radiation exposure of a larger number of people significant enough to consider decontamination or protective measures, namely

- attacks with radiological dispersal devices;
- accidents during the transport of radioactive material;
- re-entry of a satellite or other spacecraft containing radioactive material.

The enhancement will not encompass localised incidents involving the radiation exposure of one or a few individuals caused by the handling, industrial or medical use of dangerous radioactive sources or radiation devices, or by criminally induced or accidental contact with radiological sources abandoned, lost, or stolen ("orphan sources"). Events where orphan sources unknowingly get dispersed in air, e.g. during scrap metal processing, show similar features than attacks with radiological dispersal devices and are therefore included in that category.

Radiological dispersal devices - commonly referred to as "RDDs" - are devices that spread radioactive materials by aerosolising or dissolving in water reservoirs. RDD attacks using the air as a carrier could occur by explosion of a device combining radioactive materials with conventional explosives ("dirty bombs"), a release of radioactive gas from a container, spraying of radioactive material with an aerosol generator, or manual dispersion of a fine powder into the environment.

In principle, all kind of radioactive materials could be used in a RDD. Because there has been long-standing concern about both nuclear weapons and materials that could be used in making nuclear weapons, there is generally good security in the handling of these materials, which makes them hard to acquire. In contrast, the world of industrial, medical, scientific or public applications of radiological sources developed prior to recent concerns about terrorism, and many of the sources are either unsecured or provided, at best, with an industrial level of security, which makes them less hard to acquire. Therefore, is thought far more likely that material from radiological source applications will be employed rather than fissile material, fresh or spent nuclear fuel, or radioactive waste. Some panic and hysteria is a likely initial public response to an RDD attack, regardless of the amount and type of radioactive material dispersed. Concerning attacks with RDDs using minimal amounts of radioactive materials, it must reasonably be assumed that it is practically impossible to completely prevent them. The most viable response in such a case would be to provide reassurance that the radiation hazard is of no real consequence, and to counter claims by others to the contrary, insofar as this is possible. On the other hand, properly regulating and securing large and hazardous radiological sources could contribute significantly to reduce illegal access and thus the probability of larger and more consequential RDD attacks.

A radiological transport accident can occur during the transport of radiological sources for industrial, medicinal, scientific or public purposes, of radioactive waste, of fissile materials for the nuclear fuel cycle, or of nuclear weapons. The transport container of the radioactive material depends on the type of vehicle being utilised and on the kinds and amounts of nuclides involved. The release of the radioactive material from its containment to the environs can only happen if a transport container cracks during the accident. This can be caused by mechanical forces, by heat (if there is a fire), by an explosion (conventional explosive in a nuclear weapon), or by a mixture of these. The majority of authorised transport movements involves relatively innocuous materials in containers designed to withstand moderately rough handling conditions (called "Type A" containers). On the other hand, fissionable material or high radioactive waste, for example, is transported in containers designed to withstand rigorous stresses such as the German "Castor-Behälter" (called "Type B" containers). Such transports are infrequent but account for most of the transported activity.

The focus of the RODOS extension lies on accidents during authorised transport by rail, road, or air. Accidents during transport by sea, lake, or river are not considered.

In case of re-entry into the atmosphere, reactor systems currently in orbit have been designed with the aim that the heat during re-entry would result in total dispersion of the fuel in fine particulate form in the atmosphere, and this is still the philosophy in Russia. Future U.S. design considers fuel confinement. All but the earliest Radioisotope Thermoelectric Generators and Lightweight radioisotope heater units are designed to withstand major launch accidents and re-entry intact. Intended re-entries of satellites in the park orbits will not occur for hundreds of years. Accidental re-entries resulting e.g. from a collision of a satellite in a park orbit with space debris, however, cannot be excluded.

4.4. ENHANCEMENTS OF THE RODOS SYSTEM

Radiological dispersal devices and Transport Accidents. If a radioactive release into the atmosphere from a RDD or during a transport of radioactive material takes place at a known location, local meteorological data can be used to run a dispersion model calculation with an assessed or estimated source term. The results can be used to define an area in which preparations for measurements and countermeasures can be taken. First measurements will be carried out detecting for gamma and beta radiation and/or alpha and beta activity in the air and on ground surface. Evaluation of measured data should determine the nuclide(s) in the release and their quantities. With this information the dispersion and deposition calculations can be repeated and potential inhalation and gamma doses can be assessed.

If the RDD is not an explosive device the situation is much more unclear. Then the release may be produced silently and invisible by some hidden vaporiser and location and time of release will not be detected easily if at all. Only routine measurements of the airborne radioactivity in national and private surveillance systems could detect the existence of unusual increase of activity of some nuclide. On the other hand it is very probable that soon there would be a message from a confessor if the release of radioactive material was from an RDD with terrorist or criminal background - otherwise nobody would notice that a terrorist attack was going on. So also in case of a silent release there could be some information about time and location of the event.

Even if all the necessary data are available there are cases where usual atmospheric dispersion calculations might not be a useful tool. This is true for releases in buildings (commercial, public, and governmental buildings) or in underground systems, where air drafts driven by ventilation systems cause the transport of the hazardous material. If the release takes place in a deep street canyon (like in Manhattan) a micrometeorological flow model combined with a Lagrangian particle dispersion model may be needed to predict the contamination. If the release takes place in an open area or in a town without pronounced canalisation effects, or if information of such effects is not available, local meteorological data may be used as input for calculations with a Gaussian puff dispersion model.

Having discussed this, the question emerges directly whether it is useful to implement a complex micrometeorological flow model combined with a Lagrangian particle dispersion model into a DSS. The advantage would be to have a physical model which is capable to simulate flows around buildings and the dispersion inside street canyons. But does the decision making team requires this information? What seems to be most important is the information on the general wind direction and the source term. Given the uncertainties of a good prognosis of a wind field in a large urban area in a very short term, a decision maker cannot base his/her decision on this information alone. Therefore, decisions will be always announced for a wider area to take this uncertainty into account. Further more, as soon as the radioactive cloud evolves from the street canyon, it behaves like a Gaussian cloud as has been demonstrated by wind tunnel experiments [7]. A further drawback of the complex model is the need for a very detailed database covering all urban areas of the country. Without such a detailed database of a resolution of 10m, no useful simulation can be carried out. In particular for the RODOS project which aims to provide decision support for Europe, it is very doubtful if such a database could even become available. Therefore, the Gaussian dispersion model was solely enhanced by an explosion module which describes the initial widening of the cloud due to the explosive. As RODOS is also used in the later stages, the data assimilation features of the system will be further enhanced to combine measurements and model simulations in urban areas. Only this will assure that both measurements and simulation information are used in a consistent way not contradicting each other.

Satellite re-entry

Under the assumption that the fuel of a Radioisotope Thermoelectric Generator (RTG), a Lightweight radioisotope heater unit (LWRHU), or a reactor, after re-entry is either perfectly contained or fully dispersed in the upper atmosphere, atmospheric dispersion does not play a role and only detection and measuring of the non volatile radioactive fragments is important. Therefore only improvements of RODOS for processing the monitoring information with data assimilation features seem to be of importance.

Radionuclide related data bases

Provided that RDDs employing material from large radiological sources, there seems to be broad agreement on the prime importance of the following seven reactor-produced radioisotopes: Plutonium-238, Americium-241, Californium-252, Strontium-90, Iridium-192, Caesium-137, and Cobalt-60 [6]. Also the α-emitter Radium-226 and the β-emitters Selenium-75 and Ytterbium-169 might be among those nuclides from radiological sources of concern in connection with RDDs.

For accidents involving the transport of larger radiological sources, larger sources, and excluding accidents involving the transport of smaller radiological sources, all isotopes identified for RDDs are relevant, plus Molybdenum-99/Technetium-99m from the "Molybdenum cows" used in hospitals.

Fission bombs employ either highly enriched Uranium, or bomb-grade Plutonium. Fusion bombs consist of a small fission bomb core, and a shell of fusion material containing Tritium. Very big fusion bombs additionally have a shell of Uranium 238 for making use of the U-238 fission reaction with fast neutrons. Concerning atomic bombs, it is highly doubtful whether any nuclear weapon involved in a transportation accident would, or could, detonate in a nuclear fashion. However, most nuclear weapons will contain conventional high explosives in varying amounts up to many hundreds of pounds that constitute the major hazard associated with accidents involving nuclear weapons. If a nuclear weapon is enveloped in the flame of a gasoline fire, the high explosive may ignite, burn, and, in some cases, detonate in one large or several small explosions. Regardless of the nature of fires or detonations of high explosives in nuclear weapons, the major radiological threat will be the release of plutonium.

With respect to the transport of fissile material, we assume that all authorised transport of fissile material is done with "Type B" containers, and do not take into account the possibility that a Type B container leaks during an accident. We also do not consider accidents during unauthorised transport of fissile material.

With respect to satellites, there are two reported RTGs basing on Polonium-210 still in orbit. Po-210 undergoes alpha decay to stable lead with a radioactive half-life of 138 days. It can reasonably be assumed that the remaining Po-210 activity will pose no substantial radiological problem on re-entry. All other RTGs and the LWRHUs employ basically Plutonium-238, with contributions of other Plutonium-isotopes. Many or most of the nuclear reactors still in space operate with highly enriched ^{235}Uranium-fuel.

As RODOS was designed to assess the radiological consequences of severe accidental airborne releases from nuclear power plants, many of the nuclides potentially relevant for radiological emergencies were already contained in the RODOS PV6.0 list of nuclides. Based on study [6], that nuclide list was extended by Se-75, Yb-169, Ir-192, Ra-226, Cf-252, U-234, U-235, and U-238, to provide the capability to consider the most common nuclides which may appear in a radiological dispersal device, a transport accident, or a satellite re-entry event.

5. Conclusions

An explicit aim of the work programme described in this report is the improvement of RODOS to an extent that it could be used by national emergency management organisations in a fully operational emergency mode. To achieve that goal, the interaction with the end-user has been strengthened and continuous exercising and demonstrating of the newly developed features will assure that the end products will be fully operational. This interaction will also ensure that new features will be only implemented in case the end-user asks for this as it is essential to improve emergency management for nuclear or radiological emergencies. This might result also in further modifications related to the features implemented for radiological emergencies. However, with the current knowledge available, decision making should never rely solely on computerised tools as long as uncertainty bounds are not represented appropriate. Therefore, it seems to be more realistic to use simpler model approaches not to dupe accuracy which can never achieved in reality.

Acknowledgment

The work described in this publication has been carried out with the support, inter alia, of the European Commission under the EURATOM Research and Training Programme on Nuclear Energy (2002-2006), EURANOS Project, contract No. FI6R-CT-2004-508843. The views expressed in this paper are those of the authors and do not necessarily reflect those of the EURANOS Project.

References

1. E.-H. Schulte, G. N. Kelly, C. A. Jackson, Decision Support for Emergency Management and Environmental Restoration, European Commission, Luxemburg, Report EUR 19793, 2002
2. J. Ehrhardt, A. Weis (eds), RODOS: Decision Support System for Off-site Nuclear Emergency Management in Europe. European Commission, Brussels, Report EUR 19144, 2000
3. J. Ehrhardt, (ed.), Migration of RODOS to Practical Applicability, Forschungszentrum Karlsruhe, Report FZKA-7015, 2004
4. J. Ehrhardt, M. Rafat, W. Raskob, Errichtung und Betrieb des RODOS Systems an zentraler Stelle (RODOS Zentrale), Forschungszentrum Karlsruhe, Report FZKA-6765, 2002
5. T. J. Sullivan, M. Chino, J. Ehrhardt, V. Shershakov, International Exchange of Emergency Phase Information and Assessments: an Aid to National/International Decisionmakers. Rad., Prot. Dos. vol. 109, No 1-2, p. 133, 2004
6. C. Landman, J. Päsler-Sauer, Enhancement of RODOS for radiological emergencies, Forschungszentrum Karlsruhe, Report FZKA-7195, to be published
7. W. Theuer, Ausbreitung bodennaher Emissionen in komplexen Bebauungen, Inst. Für Hydrologie und Wasserwirtschaft, Heft 45, 1993

DECISION MAKING AFTER THE USE OF RADIOLOGICAL DISPERSION DEVICES

FRANK HARDEMAN*
SCK•CEN, The Belgian Nuclear Research Centre, Foundation of Public Utility, Boeretang 200, B-2400 MOL, Belgium

Abstract: In the present situation, it is to be expected that an attack using a radiological dispersion device is possible, if not probable. Where or when it will happen remains of course very uncertain, but preparedness is primordial, if an adequate response is to be given. This paper will not include aspects of protection of highly active encapsulated sources; aspects of transport security; prevention and response in a context of improvised nuclear devices; proliferation issues at the level of states; risks and consequences of attacks upon nuclear facilities or clean-up and remediation strategies. It focuses on a few remaining issues: an adequate response after an attack with a radiological dispersion device (RDD), with focus upon public health, reassurance and limitation of public disruption, and secondly on a comparison between an adequate response in case of an RDD as compared to a 'normal' radiological or nuclear accident related to a facility.

Keywords: radiological dispersion device; RDD; response; emergency; orphan source; accident; modeling; assessment; protective actions

1. Attacks using radiological dispersion devices (RDD): context

1.1. MYTH OR REAL THREAT?

Recent events in the modern history seam to indicate that terrorism - whatever terrorism may mean in the mind of members of various countries, societies, religions, political ideas - is playing a more and more important role at the international level. And terrorists have used almost all types of imaginable weapons to disrupt societies: biological threats (anthrax cases in the USA), chemical weapons (nerve gases in the underground in Japan), explosions throughout the world (Indonesia, Spain, Iraq), and of course the use of civil airplanes (USA). Virtually the only arms not used today are the radiological and nuclear ones.

S. Apikyan and D. Diamond (eds.), Countering Nuclear and Radiological Terrorism, 167–177.

This paper will deal only with radiological dispersion devices, and therefore nuclear materials and proliferation issues will not be included. We will focus on radiological dispersion devices making use of radioactive sources. IAEA has provided guidance for the classification of radioactive sources, and has published extensive information about orphan sources and cases of smuggling (IAEA 2003, IAEA 2004). This information shows that:

- several severe accidents related to orphan sources have led to serious accidents with lethal consequences and/or huge economic impact (IAEA 1988, IAEA 1998);
- hundreds, if not thousands of radioactive sources are reported missing each year; some missing sources are rather related to changes in political and military systems, e.g. in the former Soviet Union (Makarovska, 2005; Atoyan et al., 2005);
- the number of cases of smuggling of radioactive material reported every year seems to increase. However, it is not easy to know whether this is due to an increase in smuggling or to a more efficient control and detection, or a combination of both.

Anyway, as a conclusion, one must conclude that there is 'sufficient' radioactive material available for the preparation of a radiological dispersion device. And societal concern about terrorism is high in many parts of the world, including Belgium (Carlé and Hardeman, 2004). Furthermore, there is a lot of public information available on the web as regards the preparation of 'dirty bombs', so the technological threshold is very low. Therefore, we conclude that an attack with a RDD may take place, and therefore, it is necessary to be well prepared.

1.2. SOME POSSIBLE RDD SCENARIOS

Many scenarios are possible. The most 'famous' one is the so-called 'dirty bomb': the combination of an explosive material with a radioactive source, combined with electronics for timing, detonation etc. But many other alternatives are possible.

The contamination of water bodies is technically relatively easy to do, and water supply systems can not be secured till the ultimate tap. However, dilution would be very strong, and a terrorist would have to choose between creating either a contamination over a large area with low activity levels in the water, or high levels of activity in a limited area (a few buildings). Therefore, such an event would presumably lead to consequences that are minor from a radiological point of view. But of course the psychological impact and societal disruption may be important, and cleaning a contaminated water pipe system takes quite some time.

A contamination of the food chain seems feasible as well, but also here a terrorist would have to choose large volumes of contaminated products (with relatively low contamination levels) or a more limited number of products being seriously contaminated and probably causing harm to consumers. Although the sanitary impact would presumably be limited, the societal disruption could be very high. Moreover, the economic consequences could be very important as well.

It is obvious that many other scenarios are possible: contamination of air conditioning systems (Reshetin 2005), of the underground or other public transportation etc. It is not possible and presumably not wise to discuss them all in public in this paper. In the remainder of this paper, we will restrict ourselves to 'dirty bomb' style scenarios.

1.3. SOURCES AND RADIONUCLIDES

Typical radionuclides suitable for RDD could be ^{60}Co, ^{137}Cs, ^{192}Ir and similar nuclides used frequently in industry and medicine. IAEA (IAEA 2003; IAEA 2004) gives a good overview of sources, their normal use, typical radionuclides and activity levels. Other possibilities may be products originating from the nuclear industry, e.g. wastes. In the former Soviet Union, ^{90}Sr orphan sources seem to be a problem (Reshetin 2005). Or historic sources: radium needles or radium ores; technologically enhanced concentrates of naturally occurring radioactive materials (NORM). The control of all these materials is variable (from very strict and severe for the nuclear industry, to virtually not existing for 'historic' materials) and differs over the countries as well. Furthermore, control depends also on activity levels. For terrorists, mobile sources are presumably easier to obtain as compared to the very active sources in facilities such as irradiators. For terrorists, the selection of radionuclide and activity level will therefore presumably be based on a mixture of general availability, control mechanisms, and easiness to manipulate.

2. Consequence assessment of RDD attacks using modeling: some comments

The usefulness of modeling the consequences of RDD attacks is limited, if an event occurs. Indeed, since such an attack can occur anywhere - with all types of explosives, radionuclides, physicochemical features, surroundings - it is very difficult to get sufficient and reliable information in order to make the assessments. There are also very large uncertainties in what regards local wind fields, the influence of buildings in urban areas etc. But in a stage of preparation, performing model calculations is very useful. At least such calculations allow getting some insight over the areas involved and the main exposure pathways.

In the public domain, the Hotspot code (Homann 2002) provides a very useful tool; at European level some further developments are also on their way (Euranos 2006). These models are relatively simple in use, but as stated above, this is sufficient for preparedness purposes.

Other models do exist to assess e.g., the spread of radioactivity or other pollutants in buildings. These are also important for preparedness purposes.

But the main issues, such as psychological impact or socioeconomic consequences are very hard to model, and to our knowledge no adequate models are easily available. Lessons learnt from past accidents with orphan sources showed that the economic impact may be considerable, as proven by the Goiania accident (IAEA 1988).

3. Response after a radiological/nuclear accident or after a terrorist attack

3.1. LOCATION

Terrorist attacks with RDD can occur anywhere, including non-nuclear countries, which are potentially less prepared than countries with a nuclear industry. But also in nuclear countries, preparedness to RDD attacks poses some problems related to location. First of all, the number of potential targets is huge: public buildings, main transport infrastructure, industrial estates, city centers etc, whereas the number of nuclear sites within a country is much more limited. It is obvious that emergency staff and decision makers are much better trained and made familiar with radioactivity in the surroundings of a facility. Therefore, many decision makers and emergency workers involved in the response to a RDD attack might not be experienced. Other differences in circumstances can also be mentioned: monitoring provisions are better in place close to facilities; emergency plans are better elaborated; staff is better trained.

In many countries, nuclear facilities are built in rather remote areas, while RDD attacks may target large publics (urban areas, stadiums, etc.). The social impact and disruption may be thus much larger.

3.2. START-UP OF EMERGENCY RESPONSE

In case of an accident with a nuclear facility, there will usually be an immediate warning, either by the operator of the facility, or via some automatic monitoring systems. Due to the technical arrangements in nuclear power stations, certainly if they have a containment building, there may be considerable delays between an initiating event and a potential release. This allows to bring together expertise and monitoring capacity and to decide on protective actions, if needed prior to the release.

In case of an attack with a RDD, there will presumably be no warning at all, and the contamination may exist for a long time before it is identified as such. Probability is real that the situation is identified as a radiological problem either just by coincidence, or, in the most unfortunate case, by the medical staff identifying deterministic effects with some victims. Therefore, the decision makers may be put in a situation of chasing after the facts.

3.3. ACTORS AND CONFIDENTIALITY

Many actors involved in civil emergency response will intervene in the case of a terrorist attack. But there may be other actors involved as well, not necessarily used to collaborate with the civil nuclear experts and support teams. There will probably be a mixture of military and civil staff brought into action. Even foreign staff may pop in, certainly if the main target might be an embassy or some headquarters of an international organization or a multinational.

Moreover, some of the objectives may be contradictory: quick clean-up of debris versus forensic requirements to get a complete picture; evacuation of people versus screening of people present. It is obvious that openness and transparency would be useful to reassure the people, but for reasons of intelligence this may be difficult. Another illustration: many forensic laboratories may not be equipped to handle radioactively contaminated samples to trace and identify explosives. Therefore, the collaboration between all those people and the achievement of objectives is not guaranteed.

4. Lessons learnt from past accidents with orphan sources

The accident related to dispersed[1] orphan sources that has been studied the most up to now is the Goîania accident in Brazil (IAEA 1988), but other accidents have occurred as well (IAEA 2002, Estevan 2003). Some of the main findings are:

---

[1] The IAEA has reported also a number of accidents related to orphan sources that have not bee dispersed; these of course are very relevant for policy making, and from a social point of view, but less relevant for the sake of this paper.

- The accident may lead to lethal effects if it is not dispersed entirely; this may happen as well if an RDD is not well dispersed. On the other hand, if the source is dispersed completely, as was the case in the Ageciras accident (Estevan 2003), no health consequences at short term are to be expected, and the off-site concentrations of radioactivity are very low.
- Many accidents with lost sources are identified via doctors after symptoms of deterministic effects (vomiting, skin burns), although the radiological nature of these symptoms is very often not identified as such immediately. There clearly could be an important role for the medical staff in an affected area, if an attack with a RDD occurs without claim by some terrorist association and if the emergency workers do not recognize the presence of radioactivity.
- Simulations show that on short term the inhalation pathway may be very important, certainly if alpha emitting nuclides are involved; on longer terms, there may be a considerable extra dose due to ingestion of contaminated food. External contamination may also lead to skin problems.
- The cost of clean-up and the value of lost products may be considerable and the process may be lengthy. In the Goîania case, the gross product of the region went down for several years; in the case of a molten source in a plant in Algeciras, the value of the shares of the company went down as well for several months.
- The psychological effects of the victims and the societal impact in the region may be substantial, certainly if very important targets would be hit. This may mean not only importance from an economic or military point of view, but also one of a symbolic nature.

5. Main concerns after an attack with a Radiological Dispersion Device

The concerns will evolve over time (Sohier and Hardeman, 2006); we discuss them from a radiation protection point of view, but there may be other approaches (such as finding the offenders, preventing a subsequent attack on short term etc.). The first concern will be to evaluate whether there are any victims, and if so, to make sure that they are treated well. A second need showing up quickly is to verify whether there is any radiological component (and presumably also a check of chemical and biological threats). Another immediate concern will be to make sure that the intervening staff is adequately protected. In a context of RDD, this includes the availability of dosimeters and some possibilities to check for contamination. An issue coming up soon as well is to identify the affected area, and to limit the presence of public in that area. A next step is to decide whether the people should be sheltering, or be evacuated, if this seams necessary and feasible (not trivial in large cities!). In Belgium, automatic sheltering measures are foreseen as soon as the presence of radioactivity is confirmed after an explosion.

The nature of the contamination is another important factor. This information will most likely not be immediately available, depending of the nature of the contamination (type of radiation emitted by the nuclides), and the presence or absence of advanced detection equipment and staff with expertise. Ordinary dose rate measurements will not be sufficient, but in case of gamma emitters, there is sufficient portable equipment with sufficient energy resolution. On longer terms, one may consider relocation of some population, closing public places, interventions in the food chain and elaboration of control programs. All of these actions would have to be supported by an adequate program of information, in order to reassure the population. Also here, there may be contradictory requirements of openness in order to reassure the population, and the confidentiality of forensic actions and juridical procedures.

The final stage is to determine whether special clean-up actions are needed, and if so, to follow up the effectiveness of the techniques employed.

6. Consequences for actions, with focus on monitoring and measurement strategies

It is impossible to tackle in detail the monitoring requirements after an attack with an RDD in the scope of this paper. We refer to a forthcoming publication (Hardeman et al., 2006). The main concern in the beginning of the crisis is to save as many lives as possible, and this should get the highest priority. This includes the deployment of emergency teams. It is obvious that the safety of these teams is of utmost concern. The people going into action should preferably have a dosimeter and protective clothing; in many countries, protective clothes and respiratory protection as well, which is sufficient for first interveners. Preferably specialized monitoring teams should be brought in (which may not be trivial at all depending on the location and the provisions available in the target area). Their first task is to confirm the presence or absence of radioactive substances.

Specialized teams should also start delimiting the affected area, and look for hot spots in easily accessible parts. Depending on the nature of emitted radiation, this can be based on dose-rate easements, but it may also include contamination measurements, if there is little or no gamma-emission. The outcome of this campaign is ideally quickly available and yields a contamination map as valuable input to the decision makers that should now tackle whether sheltering or evacuation are needed, which information to spread to the media and the public, and to delimit a zone where the protective actions are needed.

Many people may have evacuated spontaneously after the attack and prior to an official guidance is available. If there is a risk that vast numbers of the population may be contaminated, guidance will have to be given to the people to change clothes, how to decontaminate themselves, what to do with their contaminated clothes etc. But there will also be a need for control measurements for people that are worried; a need to have monitoring teams in hospitals where injured people have been sent to; a check for internal contamination; adequate information to medical doctors (treatment of injuries; clarification of potential consequences; reassurance; psychological support). Therefore, a large variety of measurements needs to be set-up quickly and in large amount.

In a later stage, there will also be a need of a profound radiological assessment, including controls in the environment, food chain, water collectors, etc. Clean-up actions also will require follow-up: control of supporting staff (contamination, dosimetry), effectiveness of decontamination actions; control measurements in streets, houses, offices, in order to reassure people. It is obvious that waste streams will also have to be checked, both for safety and economical reasons.

7. Organizational issues

To deal adequately with the tasks described very briefly in the above paragraph, a considerable effort of preparedness has to be made. First of all, there is a need of adequate monitoring equipment. This should be available in the main emergency divisions that would probably have to intervene given an attack with a RDD. The identification of these teams depends on the identification of strategic points within a country that could be potential targets for terrorist actions.

An investment in monitoring equipment is one step. This also implies the set-up of an adapted training program for the staff; information to authorities; a maintenance program for the equipment; availability of supporting material (calibration sources; material to replace windows of detectors; tools to register dose data after interventions etc.). There is also a need for advanced techniques and well equipped laboratories.

All of these actions should be part of a Quality Assurance program. Reliability of results is essential in maintaining trust of all stakeholders (public, interveners, and political authorities).

For many countries and regions in the world, these requirements are very hard to fulfill. And often, they are not an absolute priority, if these countries or regions face huge problems of social, medical, environmental nature. Therefore, international collaboration is essential in many parts of the world, especially for expertise and advanced equipment or analyses.

At local level, in any part of the world, there should be access to reliable dosimeters (preferably also electronic ones with alarm functions). Dose rate monitoring and beta-contamination monitors are not too expensive and too difficult to use either, and therefore should be made available in the main emergency services. Sample taking procedures and equipment is also essential and should be in place.

Each country should have access to a gamma spectrometry laboratory; to alpha contamination monitoring equipment; some basic competence for modeling; gross alpha and beta measurements; low level measurements of alpha contamination in food products etc.; whole body monitoring; bioassay. If it is impossible for an individual country to organize all of this independently, a regional solution could be envisaged, or at least collaboration agreements could be made with countries having a better infrastructure or more important nuclear activities.

The very specialized and expensive techniques (advanced modeling, aerial gamma survey possibilities, and large laboratories) should be arranged internationally. International organizations such as the IAEA, the NATO and the European Union are important actors that give support to many researchers and countries, efforts that are to be encouraged.

8. Case study: Belgium

The responsibility for all legislation, licenses and controls of nuclear facilities, radioactive sources, medical and industrial use of radioactivity has been attributed to the Federal Agency for Nuclear Control (FANC); radioactive waste related issues are the responsibility of NIRAS/ONDRAF. These actors play an important role in the prevention of loss of sources.

In response, the Belgian authorities have updated the radiological and nuclear emergency plan in 2003 to include terrorist actions (Royal Decree 2003). After a terrorist attack involving radioactivity, an automatic sheltering measure is taken by the governor of the province where the incident happens (a province is approximately one tenth of the territory), and the Belgian authorities are alerted. These authorities take over the responsibility as soon as they are operational. The structure put in place is identical to the structure for nuclear or radiological accidents, but is adapted of course as there is no identifiable operator, while the location may be different from a nuclear site. This includes bringing in radiological expertise and the set-up of a measurement cell composed of representatives of the main Belgian institutions working in the field of radioactivity and disposing of relatively large and mostly accredited laboratories. There also is an automatic monitoring network for radioactivity, but one should recognize it has been optimized for nuclear facilities, and therefore may not be very useful if a terrorist attack would occur elsewhere in the country. The plan also foresees to bring in extra specialists when needed, including representatives from the Defense. This would certainly be useful if 'suspect packages' would be involved, or to assess the explosive charge that was used during an attack. The main infrastructure missing at this moment is the capability to perform aerial gamma surveys, but it is hoped to have it available shortly.

Whereas the general structure would presumably be sufficiently adequate to quickly assess the situation, there may in practice remain quite a lot of problems. Especially if the target would be remote from a nuclear site, there may be insufficient expertise with the local staff and authorities that would have to intervene. Furthermore, monitoring equipment and decontamination means may be insufficient, if large groups of the population would be targeted. And the information strategies in place for nuclear accidents may be perturbed in case of terrorism because of huge media pressure and the difficult relation between confidentiality and transparency, both needed after terrorist actions.

9. Conclusion

The recent history has obliged many countries to prepare not only for accidents involving radioactivity, but also against malevolent acts with dispersion of radioactivity. Although the emergency plans put into place for accidents can be adapted relatively easily to include terrorism, there may be some problems related to availability of equipment and expertise in non nuclear (parts of) countries and a lack of means to provide these in short notice. Therefore, international support and exchange is very important and should be stimulated as much as possible by the large international organizations working in the field.

References

1. Atoyan, A., Pyuskyulyan, K. and Apikyan S., Search and Neutralization of the orphan radioactive sources in Republic of Armenia, NATO Workshop 'Countering Nuclear/Radiological Terrorism', Yerevan, Armenia, October 02 - 06, 2005
2. Carlé, B. and Hardeman, F., 2003, Veiligheid en risicoperceptie – resultaten van de opiniepeiling in november 2002 in België, *Rapport BLG 938* SCK•CEN, (in Dutch) and

"Perceptions des risques et de la sécurité – résultats du sondage de novembre 2002 en Belgique" *Rapport BLG 939* SCK•CEN (in French) www.sckcen.be/pisa

3. Estevan, M.T., 2003, Consequences of the Algeciras accident and the Spanish system for the radiological surveillance and control of scrap and the products of its processing, Proceedings of the IAEA conference on the Security of Radioactive Sources IAEA 2003 pp. 347-355.
4. Euranos, 2006: www.euranos.fzk.de
5. Hardeman, F., Rojas-Palma, C., Sohier, A., van der Meer, K., Bendam, K., Monitoring in case of emergency situations related to orphan sources, Accepted for publication in the International Journal of Risk Assessment and Management
6. Homann, St. G., 2002, Hotspot V2.06 Lawrence Livermore National Laboratory 7/11/2002, http://www.llnl.gov/nai/technologies/hotspot.
7. IAEA 1988, *The Radiological Accident in Goiânia*, STI/PUB/815, ISBN 92-0-129088-8, International Atomic Energy Agency, Vienna, 1988
8. IAEA 1998, *Dosimetric and Medical Aspects of the Radiological Accident in Goiânia in 1987,* IAEA TECDOC 1009, IISN 1011 - 4289, International Atomic Energy Agency, Vienna, 1998
9. IAEA 2002, *The Radiological Accident in Samut Prakarn,* STI/PUB/1124, ISBN 92-0-110902-4, International Atomic Energy Agency, Vienna, 2002
10. IAEA 2003, *Code of Conduct on the Safety and Security of Radioactive Sources*, GOV/2003/49-GC(47)/9 Annex 1, International Atomic Energy Agency, Vienna, 2003
11. IAEA 2004, *Strengthening control over radioactive sources in authorized use and regaining control over orphan sources – National strategies*, IAEA-TECDOC-1388, International Atomic Energy Agency, Vienna, 2004
12. Makarovska O., 2005, Radiation Sources Safety and Security Regulation in Ukraine, NATO Workshop 'Countering Nuclear/Radiological Terrorism', Yerevan, Armenia, October 02-06, 2005
13. Reshetin, V. P., Inhalation exposure associated with a Sr-90 dirty bomb event, NATO Workshop 'Countering Nuclear/Radiological Terrorism', Yerevan, Armenia, October 02 - 06, 2005
14. Royal Decree, 2003, Royal Decree fixing the nuclear and radiological emergency plan for the Belgian territory, Royal Decree of 17/10/2003, Belgian Official Journal of 20/11/2003
15. Sohier, A. and Hardeman, F., Radiological Dispersion Devices: Are we prepared?, *Journal of Environmental Radioactivity 85 (2006) 171-181*

USE OF THE DECISION SUPPORT SYSTEM RECASS NT FOR ANTITERRORISM ACTIONS

V.G. BULGAKOV
SPA "Typhoon", Federal Environmental Emergency Center of Roshydromet
A.M. GARIYANTS, V.S. KOSYKH, V.M. SHERSHAKOV

Abstract: Decision support system RECASS NT was developed and is still enhancing in Federal Service Roshydromet for providing on-line estimates and prognoses of radiation and chemical situation in the event of an emergency, including acts of terrorism, as well as to estimate transboundary pollutants transport. RECASS NT has been installed at all ten NPPs of the Russian Federation, in Crisis Centres of Roshydromet, concern Rosenergoatom and Minatom, at plants for destroying chemical weapon. The paper will describe the structure of RECASS NT system and discuss its possible application in case of an emergency on examples of using the system during radiation emergency response exercises at NPPs. RECASS NT can be used for developing recommendations regarding time when antiterrorism operations are better to be started with a view to minimize damage.

Keywords: Decision support system, on-line and prognostic information, emergency, contamination, environment, hazardous chemicals or radioactive materials, meteorological information, monitoring network, dispersion model, dosecal culations, countermeasures, prevention of the public, exercises, decision-makers, consequences, damage, antiterrorist operations.

1. Introduction

The Uniform State System of Emergency Prevention and Response was created in the Russian Federation and is currently being developed. In the framework of the system Federal Environmental Emergency Response Centre (FFERC) is responsible for providing on-line and prognostic information on emergencies that may cause contamination of the environment on the territory of the Russian Federation from either hazardous chemicals or radioactive materials. FEERC

S. Apikyan and D. Diamond (eds.), Countering Nuclear and Radiological Terrorism, 179–189.

forms part of Scientific Production Association "Typhoon" of Federal Service on Hydrometeorology and Environmental Monitoring (Roshydromet).

FEERC is also a designated Regional Specialized Meteorological Centre of World Meteorological Organization (WMO) and CIS Intergovernmental Council for Hydrometeorology (CIS-ICH) with the specialization to provide atmospheric transport model products for environmental emergency response for WMO Region II (Asia) and CIS.

To fulfil tasks which FEERC is responsible for within the framework of the Uniform State System of Emergency Prevention and Response and as a Regional Specialized Meteorological Centre of WMO (WMO RSMC) Radio Ecological Analysis Support System (RECASS NT system) was developed and is still enhancing in FEERC of Roshydromet.

RECASS NT system has been installed in FEERC of Roshydromet, at all ten NPPs of the Russian Federation, in Crisis Centres of concern Rosenergoatom and Minatom. It is used to provide on-line estimates and prognoses of radiation situation around NPPs in the event of an emergency, including acts of terrorism, as well as to estimate transboundary pollutants transport.

Installation of the system at all chemical weapon disposal and storage facilities is planned. (RECASS NT system has already been installed at two of such facilities which is in operation now.) The purpose of the paper is introducing the decision support system RECASS NT and discussing its possible application in case of an emergency.

2. Structure of RECASS NT system

Figure 1 shows schematically calculations and presentation of results in the system. The system is based on the client-server philosophy. The Server is designed for database management and calculations, whereas the client provides interaction with user, information presentation and calculation data.

RECASS NT system includes:

- \- integrated database;
- \- functional subsystems – control subsystem, prognosis and analysis subsystem, and assessment subsystem;
- \- telecommunication subsystem;
- \- client part of the system.

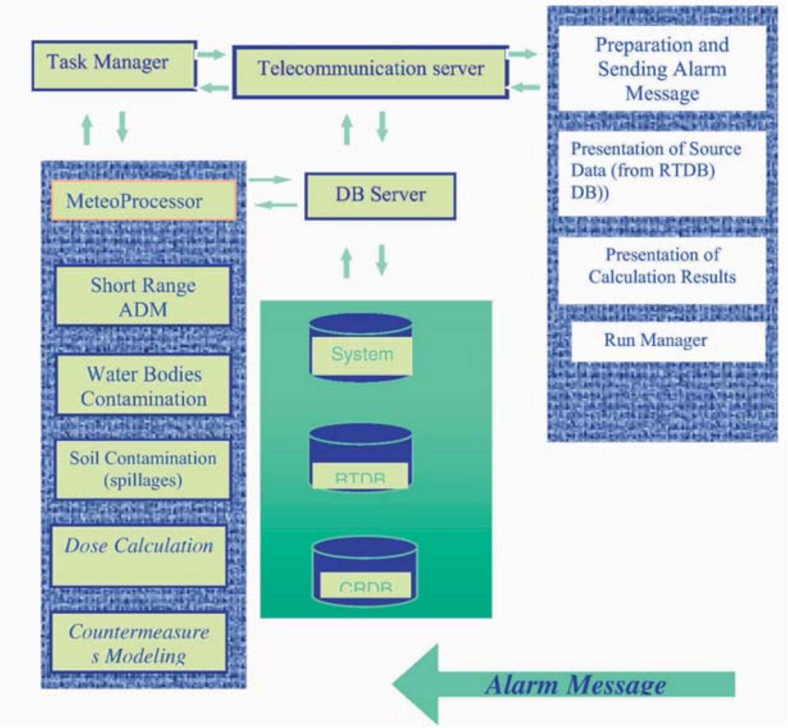


Figure 1. Structure of calculations of RECASS NT system

2.1. INTEGRATED DATABASE

Information part of the system (integrated DB) includes system database (cartographic information, relief data, demographic data, accident scenarios, etc.), database of calculation results, and operational database using for storage of source data needed for calculations.

Operational DB contains meteorological information, including prognoses, and data on the actual radiation (or chemical) situation in the area of NPP location or at the accident site .

Operational DB includes:

- data of objective analysis and prognosis from Hydrometeorological Centre (HMC) of Roshydromet;
- meteorological data from observation network of Roshydromet:
- synoptic data (are refreshed every 3 hours);
- aerological data (are refreshed every 12 hours);
- meteorological data from territorial (in-situ) observation network;
- data of radiation or chemical measurements from state monitoring network and from local (in-situ) observation networks (there were created networks of measurements of gamma dose rate located around NPPs, data of measurements are refreshed with 10 minutes interval in the normal mode).

2.2. FUNCTIONAL SUBSYSTEM

Functional subsystem consists of the following main modules:

- Atmospheric dispersion model for up to 100 km range including deposition calculations and airborne concentration calculations for given radionuclide (or other pollutant);
- Model of transboundary atmospheric pollutants transport;
- Model of wash-off of hazardous chemicals or radioactive materials from surface into water bodies;
- Model of transport of hazardous chemicals or radioactive substances in water bodies;
- Dose calculations;
- Block of elaboration of recommendations on countermeasures for prevention of the public.

2.3. CLIENT PART OF THE SYSTEM

Client part of RECASS NT system is designed for presentation both source data and calculation results. It can work both with local servers and remote servers. Cartographic subsystem which is designed for displaying data was developed using MapX component of GIS MapInfo. Cartographic DB of the subsystem currently includes maps of three scales:

- 1: 500 000 (Regional map of Russia)
- 1: 200 000 (control area of NPP)

- 1: 10 000 (NPP site)

The RECASS NT system permits in operative mode

- - to provide prognosis of meteorological situation in the area of an accident;
- - to provide data on the actual environmental contamination received from state environmental monitoring system and from local observation networks which are created around potentially dangerous facilities;
- - to provide assessments and prediction of consequences of accidental releases into the environment presented as spatial and temporal distributions of levels of contamination of ambient air, water, soil as well as doses to the public and personnel;
- - to work out recommendations for decision makers on prevention of the personnel and the public in accordance with legislation of the Russian Federation.

3. Use of RECASS NT system during radiation emergency response exercises at NPPs

Every year radiation emergency response exercises of different scales are conducted at NPPs of the Russian Federation including exercises on response to acts of terrorism at NPPs. Estimation and prediction of radiation situation are generated by RECASS NT system, calculation results are provided to decision-makers either on maps on which data of estimation and prediction are presented or in tables and in text documents. Wind fields and other meteorological parameters, data of radiation measurements, areas of different levels of concentration of radionuclides for different natural media, areas of different doses for the public, and areas where countermeasures on prevention of the public are required are presented on maps.

In September 2005 an exercise on response to acts of terrorism at NPPs was conducted. According to exercise scenario terrorist acts caused destroying spend fuel pool at Beloyarsk NPP. It caused discharge of radioactive water into basin-cooler, later into Pyshma river.

Results of prediction of contamination of water bodies by Cs-137 caused by given act of terrorism presented on the map of the territory are shown in Figure 2. Different levels of Cs-137 concentration in surface water in 78 hours after beginning of the accident are presented in the figure by different colors.

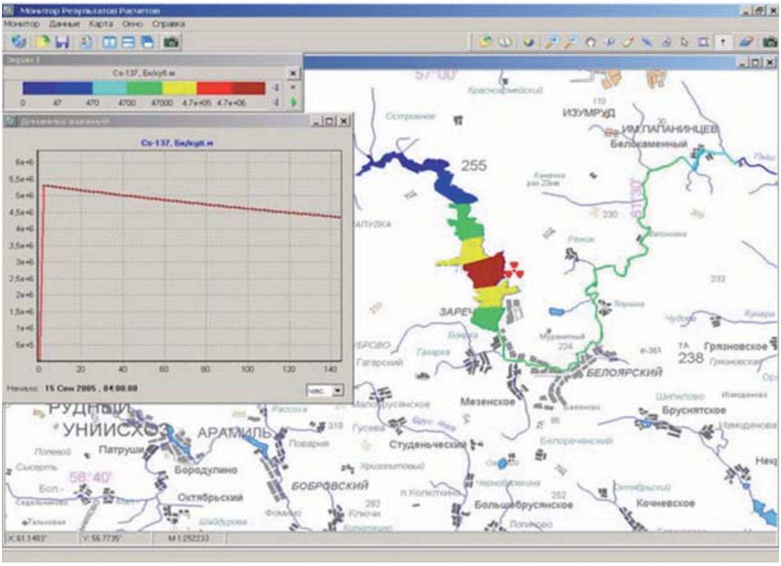


Figure 2. Concentration of Cs-137 in water bodies in 78 hours after the simulated act of terrorism at Beloyarsk NPP and curve of Cs-137 concentration in water of basin–cooler.

Curve of concentration of Cs-137 in basin-cooler of Beloyarsk NPP is presented in the left upper corner of the map. This information was used to work out recommendations on water use limitation for some settlements.

On 6-8 September 2005 comprehensive emergency response test was conducted at Kola NPP. According to the scenario of the exercise an accident relevant to 5 CLASS of International Nuclear Event Scale (INES) occurred. Inert gases, isotopes of radioactive iodine and cesium were released into the atmosphere as a result of the accident.

Figure 5 presents prediction of radioactive cloud transport during three day period which allows coming to a conclusion that no transboundary transport of radioactivity should be expected. A map showing results of prediction of public health effects from doses is presented in Figure 6. Areas with different thyroid doses for children of 1-2 year old in case when they are in the open air during radioactive cloud movement are shown in the figure. Dose scale in mSv is in the top of the figure. For example, green area is equivalent to doses of 200 - 500 mSv.

Figures 3-6 are the examples of presentation of data on the map of the territory during the exercise at Kola NPP.

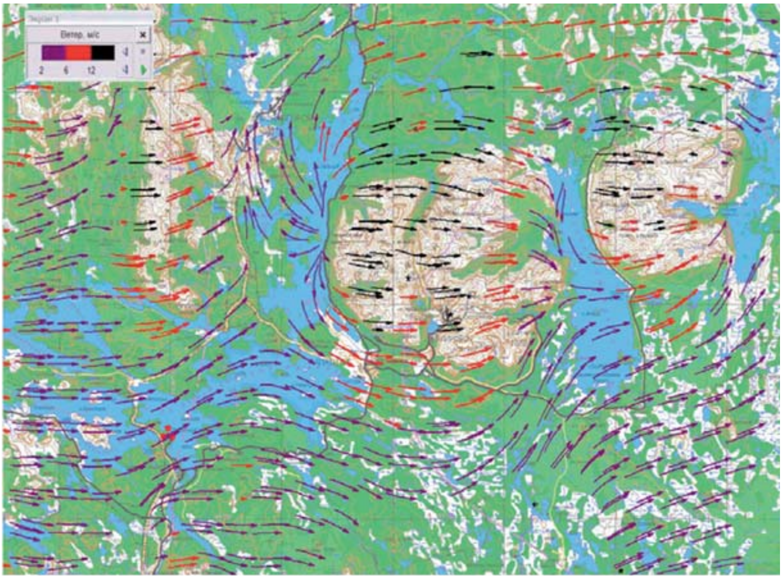


Figure 3. Wind field at a height of 10 m above ground surface, 06.09.2005 10:00

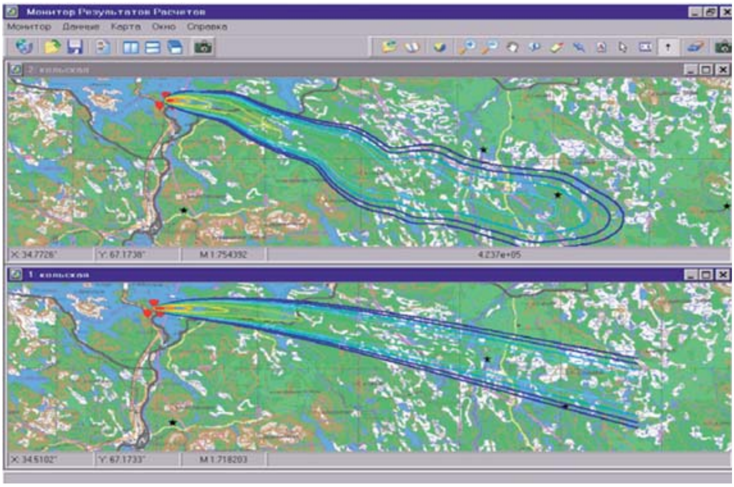


Figure 4. Traces of radioactive cloud with and without topographic effect

Wind field at a height of 10 m above ground surface is presented in figure 3, speed and direction of wind are presented for different spatial points. Wind field was calculated taking into account topographic effect on inleaking flow. When modeling atmospheric dispersion in the area of Kola NPP it is important to take into account topographic effect as area around Kola NPP has ridges and undulating ground. Traces of radioactive cloud calculated taking into consideration topographic effect and without it are shown in figure 4.

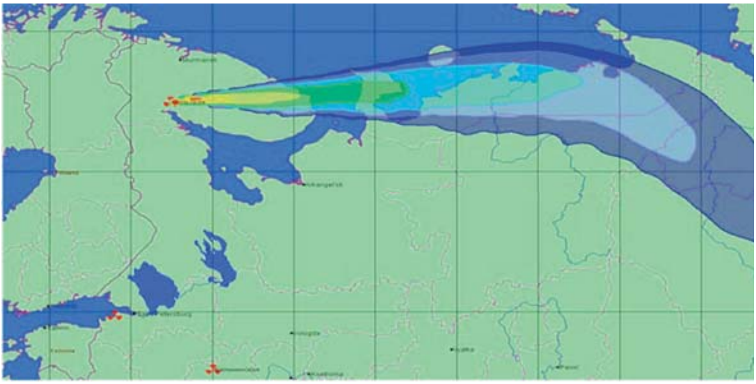


Figure 5. Prediction of radioactive cloud transport

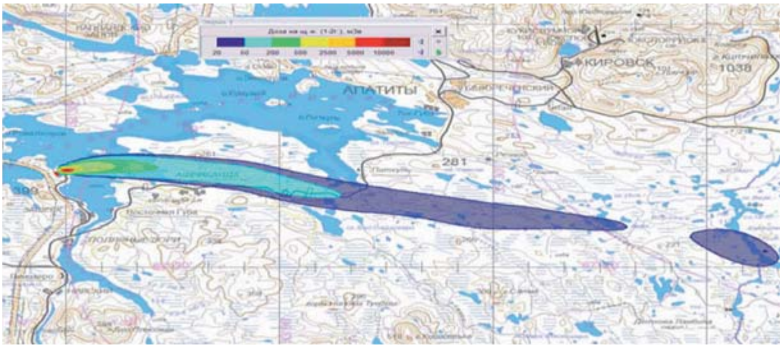


Figure 6. Thyroid dose for children of 1-2 year old

Data on the meteorological situation such as speed and direction of wind, atmospheric stability, etc. as well as radiation doses for different distances from the source of radioactive material release are also presented in table (or tabular) form. Besides, recommendations on countermeasures for prevention of the public of different settlements are prepared and provided.

A form containing recommendations is presented in Figure 7. The form contains a table with maximum distances from the accident site on which doses exceed the criteria when the countermeasures should be undertaken. Another table of this form contains list of settlements where relevant countermeasures (sheltering, intake of iodine tablets, evacuation) should be undertaken.

During the exercises possible consequences of emergencies are considered both under real meteorological conditions occurring during the exercises and the scenario ones. The scenario meteorological conditions (wind direction and speed, atmosphere stability etc) do not change in the course of the accident and release dispersion is taken to be such that protective measures are needed in the selected population points.

During the exercise at Kola NPP under the scenario meteorological conditions there are population points that have to be evacuated immediately because of the risk of exposure at levels leading to deterministic radiation effects and in the major population points sheltering and iodine prophylaxis are required

Under real meteorological conditions no evacuation was needed and sheltering and iodine prophylaxis would have to be conducted only in two small population points. The collective dose under real meteorological conditions is tens of thousands times lower then under the scenario.

Form 5

3.1. RECOMMENDATIONS ON COUNTERMEASURES FOR PREVENTION OF PERSONNEL AND THE PUBLIC

3.2. EMERGENCY RESPONSE EXERCISE SITE **KOLA NPP**

Table 1**. Distances in which the countermeasures on prevention of adults and children should be undertaken, km**

Countermeasure	*Adults*	*Children*
Sheltering	42	
Intake of iodine tablets	12	48
Evacuation	7.5	

Table 2. **List of settlements where relevant countermeasures are recommended in the beginning of the accident**

№№	Settlement	Distance, km	Sheltering	Intake of iodine tablets		Evacuation
				Adults	Children	
1.	Zasheeek	6	+	+	+	+
2.	Niva-1	8	+	+	+	
3.	Niva-2	18	+		+	
4.	Polyarnye Zori	11	+	+	+	
5.	Pinozero	16	+		+	
6.	Afrikanda	13				
7.	Kandalaksha	30	+		+	
8.	Apatity	40				
9.	Monchegorsk	60				

3.3. RECOMMENDATIONS ARE BASED ON COMPARISON OF ESTIMATES WITH LEVEL ☒ A ☐ B.

Class of event (INES scale): ☐ 0, ☐ 1, ☐ 2, ☐ 3, ☐ 4, ☐ 5, ☐ 6, ☐ 7.

Person on duty (name, signature)____

Time and data of form sending (MSK) _______________
«_____»__________2005.

Figure 7. Recommendations on countermeasures for prevention of personnel and the public

This fact makes it clear that the damage due to the accident is dependent on the meteorological conditions during an accident. This should be taken into account during antiterrorist operations. For example, in case of an act of terrorism at NPP, given the risk that radioactive materials are released to the environment, the actions against terrorists should be taken under such meteorological conditions when the damage from emissions of radioactive materials to the environment would be the lowest. To determine the optimum moment of actions RECASS NT can be used.

4. Conclusion

The most important application of RECASS NT is quick assessment and prediction of the radiation situation in case of emergency at facilities of potential hazard and development of recommendations for decision makers.

It should also be emphasized that RECASS NT can be used for developing recommendations regarding time when antiterrorism operations are better to be started with a view to minimize damage from an act of terrorism.

- Emergency assessment and prediction of the radiation situation should be based on using:
- methods of computer modeling the processes of dispersion of radioactive materials in the air and surface waters;
- actual information (observational data, geographical, demographic and other data) expert knowledge primarily about evolution of emergency;
- expert knowledge mainly on crisis situation development about.

The uncertainty in results is directly dependent on availability of sites of meteorological observations in the affected or adjacent areas, detailed maps and characteristics of the areas and river systems. These issues are dealt with at the stage of RECASS installation.

MOBILE MEASUREMENT FACILITIES FOR THE REAL-TIME INTERACTION WITH THE RECASS NT SYSTEM IN ANTITERRORISM ACTIONS

A.M. GARIYANTS, V.G. BULGAKOV, V.M. SHERSHAKOV,
G.P. ZHUKOV
SPA "Typhoon", Federal Environmental Emergency Center of Roshydromet

Abstract: The presentation outlines a mobile radiological facility, designed for determining of the source term parameters and atmospheric transport and dispersion parameters in the near zone during an accident. Those parameters serve as input to the RECASS NT system for forecasting atmospheric dispersion of pollutants. Information is generated by means of field simulation of contaminant transport and dispersion through creating a cloud of superlight tracers (chaff) at the simulated release height and tracking its transport and dispersion with the radar. Results of field experiments using the mobile radiological facility carried out in the vicinity of the Kola NPP and Kursk NPP are described.

Keywords: Mobile radiological facility, source term parameters, atmospheric transport and dispersion parameters, radar-tracer subsystem, spectrometric subsystem, dosimetric and spectrometric route survey, cloud of superlight tracers, radar tracking, data collection and processing center

The RECASS NT system provides information support to decision making based on analysis and prognosis of the radiation situation in emergency associated with radioactivity release to the environment.

The accuracy of such predictions can be rather low, provided complicated topography and meteorological conditions, which is primarily explained by uncertainty in estimating and predicting atmosphere characteristics governing radioactivity dispersion and in determining source term (release height, nuclide composition, etc.).

During the recent years a mobile measuring system has been under development in SPA "Typhoon" to be used for obtaining required information and sending it to data collection and processing centers. This serves as input to

S. Apikyan and D. Diamond (eds.), Countering Nuclear and Radiological Terrorism, 191–198.

the RECASS NT system for forecasting atmospheric dispersion of pollutants in the near zone during an accident.

The data include:

- \- source term parameters (release height, emission rate, nuclide composition, etc.),
- \- atmospheric transport and dispersion parameters (wind speed and direction at the release height, diffusion parameters).

Presented mobile radiological facility (MRF) makes possible to minimize the uncertainty in parameter estimates by measurements in the area affected as the emergency evolves.

This facility commissioned by Rosenergoatom and developed and manufactured by SPA "Typhoon".

Figure 1. The mobile radiological facility during the Rosenergoatom exercises at the Kola NPP

The facility comprises two interconnected systems:

- \- a radar-tracer subsystem (placed on trailer);
- \- a spectrometric subsystem (mounted on a vehicle);

The spectrometric subsystem is designed for (the functions relevant to the discussed issue):

- \- determining spatial characteristics of a radioactive cloud (plume transport direction and release height);

- - estimating the release composition and emission rate for specific radionuclides;
- – measuring the absorbed dose rate by dosimetric and spectrometric route survey as the vehicle moves along;
- – determining surface contamination levels for gamma-emitters.

The spectrometric subsystem includes a gamma-ray spectrometer with a collimated semiconductor detector GEM20P4 (High-Purity Germanium) and a portable multi-channel analyzer DigiDART ORTEC.

There are three possible positions for the detector and collimator, given different kinds of measurements:

- - First position: upward detector crystal, no collimator. This position is used for more accurate determining of the aerosol cloud axis and for route radiometric measurements;
- - Second position: upward detector crystal with collimator. This position is used for determining the radionuclide composition and release rate, as well as the effective release height.

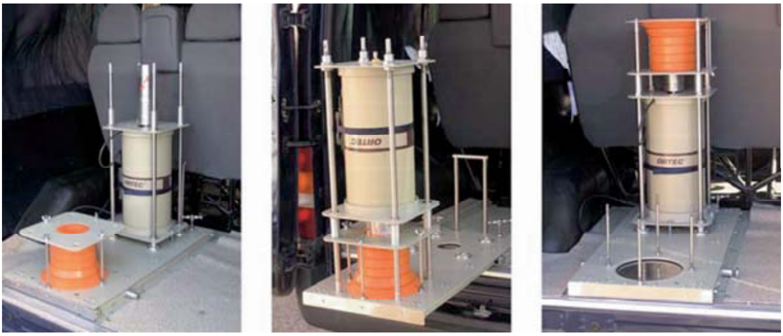


Figure 2. Detector positions

- -Third position: downward detector crystal with collimator. This position is used for measurements of surface gamma contamination. In this case the detector with collimator is pulled out on the platform through the vehicle tailgate.

The radar-tracer subsystem (RTS) is designed for:

- - obtaining more accurate data about the meteorological conditions in the emergency area (determining direction and speed of radioactivity transport at the release height);

- - determining main parameters of contaminant dispersion in the air at the release height (distribution of contaminant concentration in a cloud, wind speed fluctuations, integral time scale of turbulence, wind shift parameters).

Main components of RTS are:

- - the radar, (placed in a radio-transparent, see Figure 1);
- - the launching and dispersion unit (LDU).

Figure 3. The pneumatic launching and dispersing unit for launching a container with chaff (tracers)

MRF accommodated with computers, a satellite navigation system, a stand-alone power supply unit and telecommunication equipment for exchanging measurement data with Data Collection and processing Centers (DCC).

Using RTS, information is generated by means of field simulation of contaminant transport and dispersion through creating a cloud of superlight tracers (chaff) at the simulated release height and tracking its transport and dispersion with the radar.

The superlight radar tracers are dipole reflectors made of carbon fiber of high conductivity. Parameters of the superlight radar tracers are following:

Figure 4. A generated cloud, container descending on a parachute and cloud image on the monitor

Length of dipoles - 10 mm;

- Diameter of dipoles - 10 microns;
- Density of dipoles - 2 g/cm^3;
- Speed of gravitational subsidence - $\leq$ 3 cm/s;
- Weight of dipoles in a charge - about 200 g;
- Number of dipoles in a cloud - about 10^8;

The specific effective area of dispersion of dipoles of 0,4-0,5 m^2/g.

Let us dwell on the RTS functioning. The scheme of RTS functioning is following

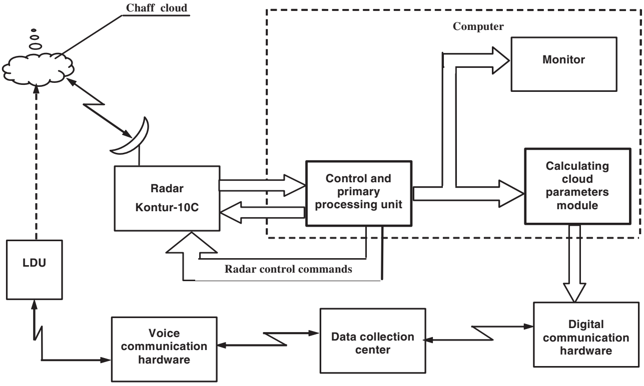


Figure 5. Overall scheme of RTS functioning

The LDU operator on receiving a command from the radar operator launches the container with chaff to the given height (The operators of the radar and LDU communicate using walkie-talkies). The cloud is tracked with the radar by radio beam scanning in a given sector through the area of maximum radio reflectance. The chaff cloud image is shown on the monitor on small and large scales. The operator, watching the cloud image on the monitor, adjusts the azimuth position of the centroid, scanning angle and tilt angle as a function of the cloud size and its distance to the radar.

Information from the radar is processed by the onboard computer and transmitted by radio channel to the DCC. These data include the direction and velocity of the cloud centroid, its current coordinates and characteristic spatial scales. This permits estimating in real time the trajectory of a radioactive cloud and its direction and speed. Besides, radar data are used to determine the cloud configuration and size at different distances from the source. The available hardware and developed software makes possible map-based presentation of information coming from the radar, i.e. trajectories and configuration of the chaff cloud are displayed at the DCC, as data are received from RTS (Figure 7).

Then the data obtained are used for calculations in RECASS NT system (Calculations results are shown in the Figure 7).

During the last three years several field experiments were conducted in different regions with differing climatic conditions, namely Kaluga region, Udmurtia, and the Kursk, Smolensk, Beloyarsk, and Kola NPPs.

Let us briefly describe the operations of the mobile radiological facility during the Rosenergoatom exercises on 6-8 September 2005 at the Kola NPP.

The facility was moved towards the NPP site and dosimetric survey was started in the area assumed to be affected. The route was taken to coincide with the wind direction under the scenario and shown by colored points in the figure. Thus the plume axis was determined to decide on the radar position.

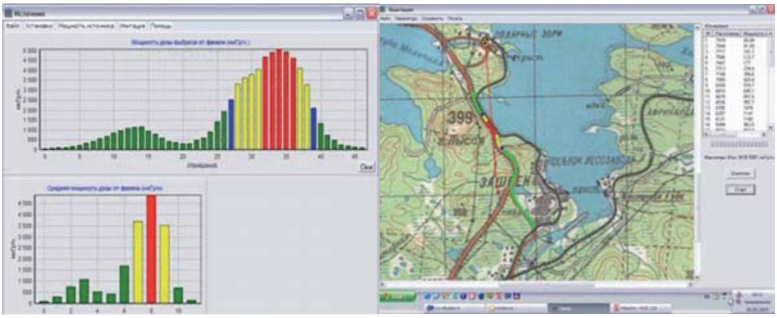


Figure 6. Results of the route survey

During the survey gamma spectrometric probing of the plume was performed to determine more accurately the effective release height and isotopic composition. After data on the effective release height were obtained, a container with chaff was launched by a pneumatic unit to a specified height, the generated cloud was depicted on the monitor and the cloud was tracked by the radar.

It is necessary to stress that while the operations of the spectrometric subsystem were virtual, rather than actual, since there was no real release, more accurate determination of atmospheric parameters was really carried out, and data were sent promptly to the data collection centers in the Rosenergoatom crisis center, local emergency center and FEERC of Roshydromet (SPA “Typhoon”).

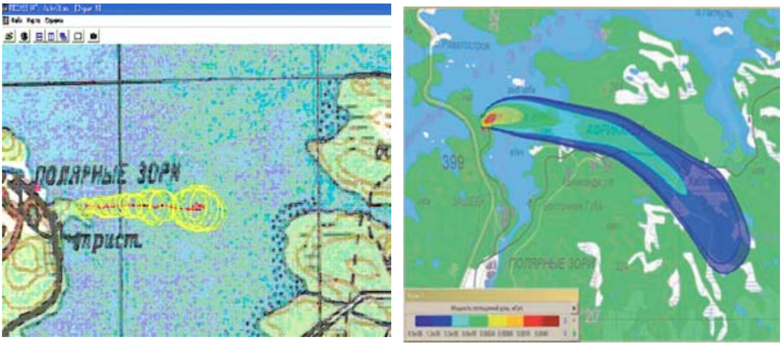


Figure 7. Chaff cloud trajectories and calculations results example (in given case - Gamma Dose Rate (mGry/s) 6 hours after release)

The extent of difference in atmospheric parameters governing contaminant transport and dispersion is illustrated by results of radar tracking during the preparations for the Rosenergoatom exercises at the Kursk NPP in 2002.

The picture shows the trajectories and outlines of the tracer cloud for two experiments conducted from the same point. The pattern of cloud dispersion can be seen to be different.

What was the reason? The wind direction changed only by 20 degrees.

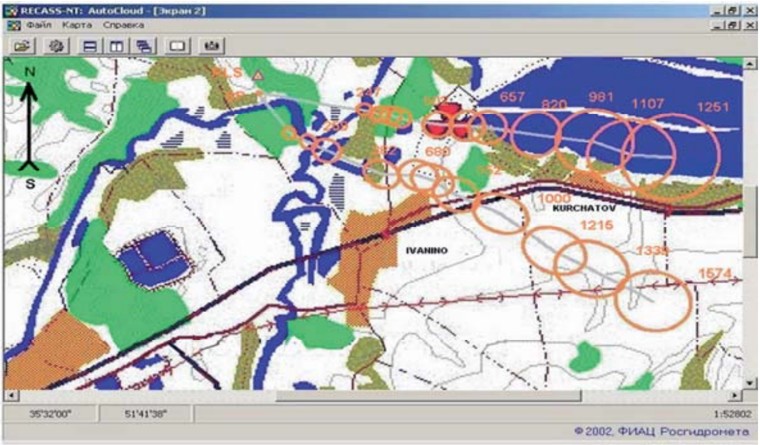


Figure 8. Chaff cloud trajectories and outlines derived in the data collection center during experiments № 1-2 in the area of the Kursk NPP

During the first experiments the chaff was moving south-east over the land. In the second experiment just an hour later the cloud was first moving over the land and then passed over the warm water surface of the cooling pond.

The heat exchange between the southern and northern parts of the reservoir is possible only by air and therefore there is a temperature contrast which resulted in occurrence of a temperature internal boundary layer above the water surface and complex air circulations. As a result, a complex pattern of wind, temperature and turbulence field was formed different from the one in the flow incoming from the land. This fact led to a change in the dispersion pattern in the second experiment.

Hence the prognostic calculations of possible contamination based on such data will also be different.

Thus the real-time use of data and information from the mobile radiological facility by the RECASS NT system improves significantly the reliability of calculation results for the vicinity of the release source.

CHAPTER IV

RADIATION DETECTION

EFFECTS OF TELLURIUM PRECIPITATES ON CHARGE COLLECTION IN CZT NUCLEAR RADIATION DETECTORS

G. S. CAMARDA*, A. E. BOLOTNIKOV, G. A. CARINI,
R. B. JAMES
Brookhaven National Laboratory, Upton, NY 11973

L. LI
Yinnel Tech, Inc., West Sample Street, South Bend, IN 46619

Abstract: It has been recently demonstrated that individual Tellurium (Te) precipitates identified with infrared (IR) transmission microscopes in radiation detector-grade CdZnTe (CZT) crystals correlate precisely with poor charge collection. This indicates that Te precipitates adversely affect the electron charge collection efficiency and thus the performance of nuclear radiation detectors produced from the crystals. By employing different techniques we investigated how Te precipitates affect different CZT devices. Our measurements indicate that Te precipitates put limits on the sizes, electrode configurations and spectral performance of CZT detectors. These limits can be relaxed by lowering the size and density of Te precipitates in the detectors.

Keywords: CdZnTe, nuclear detectors, room-temperature semiconductor detectors

1. Introduction

Large-area/volume CdZnTe (CZT) crystals are desired for efficient ambient temperature nuclear radiation detectors.[1,2] These types of room-temperature detectors are required for the detection of smuggled special nuclear materials, medical imaging, astrophysics, and industrial applications. Large-scale crystal

---

* To whom correspondence should be addressed. G. S. Camarda, Brookhaven National Laboratory, Upton, NY 11973; e-mail: camarda@bnl.gov

S. Apikyan and D. Diamond (eds.), Countering Nuclear and Radiological Terrorism, 199–207.

defects such as grain boundaries, twins, voids, etc. are well known to significantly impair device characteristics, and only single-crystal CZT can potentially provide the high level of performance achieved with small-size CZT detectors. In the past, significant efforts have been undertaken to increase the size of single-crystal CZT. Today, large-volume CZT single crystals, up to hundreds of cubic centimeters, are commercially available; however, the sizes of the actual CZT detectors produced from these crystals are much smaller, and they are limited by other smaller non-uniformities existing within the material. This study elucidates the role of the small-scale non-uniformities present in single-crystal CZT devices and explains why CZT detector volumes have thus far been limited to a size of only a few cubic centimeters or less.

Most of the non-uniformities in single crystals are related to the presence of Te precipitates, which can be easily seen with infrared transmission microscopes. It has been known for a long time that large Te inclusions, > 100-μm diameter, (and aggregations of smaller precipitates) degrade CZT device performances[3,4], but small isolated Te precipitates (1-20 micron diameter) were thought to be relatively benign. It was just recently demonstrated that individual precipitates correlate with poor charge collection areas, as identified by high spatial-resolution X-ray scans.[5,6,7] This strongly suggests that even randomly distributed small-size precipitates can significantly affect device performance.[8]

As background, Te inclusions are thought to originate at the growth interface as consequences of morphological instability, while Te precipitates are created in the solid phase during the ingot cool-down. The typical size range for Te precipitates is between 1-20 μm, while Te inclusions can be much larger.[9,10,11] Twins and grain boundaries are preferential nucleation sites for Te precipitates, because precipitates are found all along these extended macroscopic defects. They are also distributed in patterns or simply dispersed somewhat randomly in the crystals. The Te precipitates, which have different properties from the optical and electrical properties of bulk CZT, are also sources of extended areas of high dislocation densities in CZT material.[10]

The goal of this work is to demonstrate the effects caused by Te precipitates in different types of CZT devices by using a highly collimated X-ray source and pulse shape analysis techniques.

2. Experimental setup

The planar, coplanar-grid (CPG), and Frisch-ring CZT detectors were used to investigate the effects of Te precipitates on device performance. Commercial 15x15x7.5 mm^3 CPG detectors with contact patterns comprised of 350-μm-wide strips located at a 700-μm pitch, were acquired from eV Products. The CPG detectors were mounted inside a custom-made test box containing the readout electronics. The 5x5x1 mm^3 planar detectors and 6x6x11 mm^3 Frisch-ring detectors were fabricated by using CZT crystals acquired from Yinnel Tech, Inc. as previously described.[10] As-cut crystals were hand polished and etched briefly with a 2% bromine/methanol solution. After depositing gold contacts the side surfaces were polished further to reduce surface leakage currents. The detectors were mounted inside an eV Products device holder. The shielding electrode of the Frisch-ring device was connected to the cathode and kept at zero potential, while the positive voltage was applied to the anode. The data acquisition system included a spectroscopy shaping amplifier, MCA card, digital oscilloscope (LeCroy 6050 Waverunner) to store waveforms, and standard NIM electronics.

Uncollimated ^{137}Cs, ^{60}Co and ^{68}Ge sources were used to generate interaction events inside the devices. For the rise-time (depth sensing) measurements, a small, ~3 cm^3, BaF_2 detector and ^{68}Ge source emitting two back-to-back 511-keV annihilation photons were employed. The fast coincidence signals read out from the BaF_2 detector provided triggers to indicate the interaction events (arrival times) in the Frisch-ring devices. Our previous studies showed that, in the case of CPG and pixel devices, the leading edge of the cathode signal for each event can be used to identify the event's arrival time with an accuracy of <20 ns, which is sufficient for accurate rise-time measurements[12].

We employed highly-collimated, high-intensity X-ray beams available at BNL's National Synchrotron Light Source (NSLS) to study the non-uniform responses of CZT detectors caused by the presence of Te precipitates. Depending on the type of measurements, either a 10- or 25-μm diameter beam was used. Also data were generated using either a high-energy, quasi-monochromatic beam with photon energies centered at ~85 keV with a 10-keV spread or a low-energy ~30-keV monochromatic beam. For each position of the beam, we collected a pulse-height spectrum and evaluated a photopeak position and its full-width-at-half-maximum (FWHM).[5]

3. Results and Discussion

Figure 1 shows the maps that illustrate correlations between the Te precipitates identified with an IR transmission microscope inside thin, ~1 mm, CZT samples and the poor-response regions (dark spots) measured with collimated beam X-ray scans. The thin detectors were chosen to minimize the effects of overlapping precipitates and possible distortions in the X-ray images due to electric field non-uniformities. The spatial resolution of the X-ray maps (in these measurements, the beam size was always equal to the size of the steps in both x and y directions) and cathode biases are indicated on the maps. As is seen, the precipitates observed in the IR maps are 100% correlated with the degraded zones seen in the X-ray scans. Using the distances between two selected precipitates, it was possible to scale the X-ray map, which gives us an opportunity to evaluate the apparent sizes of the degraded zones located with the X-ray beam. As a ruler, the X-ray footprints of precipitates were found to be larger than their actual physical sizes measured with the IR, which cannot be simply explained by a beam's size or electron diffusion.

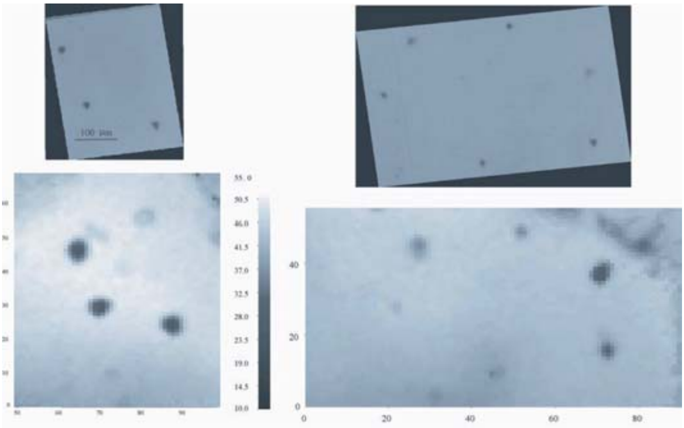


Figure 1. Correlations between IR images (top) of Te precipitates and the poor-response regions measured with an X-ray beam (bottom)

The large apparent size of precipitates could be attributed to the areas of dislocations with high trap concentration, which are believed to be present due to the crystal strain around precipitates.[5]

Figure 2 shows the evolution of pulse-height spectra as the beam was scanned over a Te precipitate. As seen, the peak position changes with the beam position, indicating a reduction in the collected charge by more than 50%. At the same time, the width of the peak roughly remains unchanged. The tails on the right side of the peaks are due to the beam splitting over the precipitate boundaries. These facts point out that the fluctuations in the charge loss associated with an individual precipitate are small, while the amount of charge loss can be large and strongly dependent on the precise location of an electron cloud with respect to the precipitate. These geometry governed variations were previously discussed by Amman *et al.*[3]

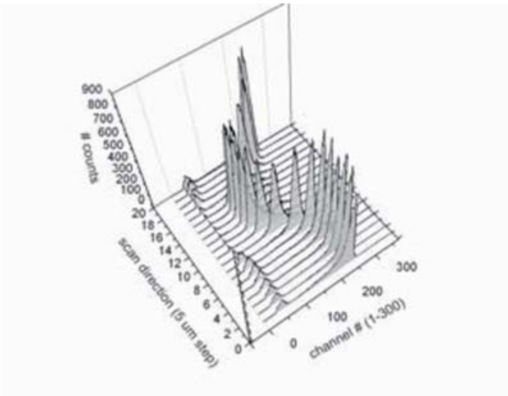


Figure 2. This figure shows the pulse height spectra at different points for a one-dimensional X-ray scan with a 5-um step size. The line scan was passed directly over a Te precipitate

Double peaks are often seen in the pulse-height spectra when the X-ray beam in pointed above a precipitate. Such behavior could be explained as if the precipitate under test has very sharp boundaries, i.e., the transition between the precipitate and a clear region is within a size of the x-ray beam, ~10 um.[5] Another possible explanation is the overlapping of two precipitates located at different depth. More detailed measurements are required to better understand the dynamics of how an electron cloud “interacts” with precipitates and the charge losses accompanied this process.

Figure 3 shows the pulse-height spectrum from an uncollimated ^{60}Co source and the rise-time distribution of output signals generated by the ^{68}Ge source. The data were taken with a 16-mm long Frisch-ring CZT detector, which had a high concentration of randomly distributed Te precipitates with a typical size of less than 20 µm as measured using the IR microscope. By fitting the curve representing the charge loss vs. drift distance, we estimate the electron lifetimes to be ~5 µs, which corresponds to high spectroscopic quality CZT material. Despite this, the measured FWHM of the peak is quite broad, ~5% at 662 keV, compared to the desired FWHM of 1-2%. Such peak broadening could be attributed to fluctuations in the charge loss caused by Te precipitates. Since the pulse-height spectra demonstrate the cumulative effect of carrier trapping, the device length becomes a critical factor that magnifies the effect of trapping by distributed Te precipitates. The broadening of the correlation curve (which reflects fluctuations in the collected charge) with the electron drift time can be clearly seen in the bi-parametric distribution.

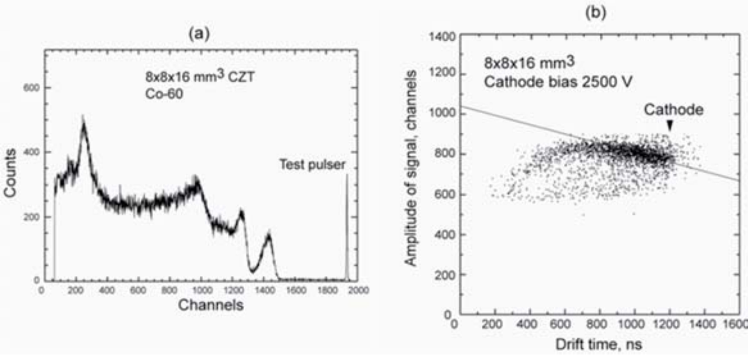


Figure 3. The pulse height spectrum (a) and correlation curve (b) measured for an 8x8x16 mm^3 Frisch-ring detector with a high concentration of Te precipitates

Te precipitates are likely to have surrounding areas with high concentration of dislocations, which may extend far beyond the actual physical boundaries of the precipitates. These areas containing many types of defect levels can potentially accumulate space charge causing local variations in the electric-field distribution and thus influencing the charge trapping. The charge carrier traps associated with Te precipitates are different from single-level traps normally present in CZT material. The later are uniformly distributed over a device volume and continuously trap electrons and holes as carriers drift from the point of interaction toward their collecting electrodes. In this case, the process of the charge loss is governed by Poisson statistics and the fluctuations in the charge loss are negligible, e.g., in the case of a 10% charge loss, a broadening of ~0.1% would be expected for 662-keV radiation.[8] Nevertheless, carrier trapping by point defects still results in some peak broadening, because the carrier drift time varies as a function of the location of each interaction point. However, this type of broadening can be easily reduced by applying depth or rise-time correction techniques.

In contrast, Te precipitates introduce local fluctuations in the uniform distribution of single-level traps. When the electron cloud passes across an individual precipitate, the amount of charge loss depends on the spatial distribution of the electrons inside the cloud relative to the trap distribution in the vicinity of the precipitate.[8] Dynamical effects, such as the filling and de-trapping of defects within or nearby Te precipitates and changing of the electric field, can also affect this process. As a result, the process of the charge loss can be treated as a chain of electron cloud interactions with individual precipitates, some of which are likely dependent on the incident flux, especially for high count-rate applications. Using a simple analysis[7] one can show that the fluctuations of the charge loss are proportional to the total number of precipitates encountered by the electron cloud. In other words, the fluctuations increase with an electron cloud drift path, which is reflected in Fig. 3(b).

Isolated Te precipitates become visible in the X-ray maps taken with a high spatial resolution on the scale of 50 μm or less. For lower resolution X-ray beam maps, their footprint images disappear entirely, which creates an impression that they do not produce any deleterious effects on device response and explains why dispersed small Te precipitates were assumed in the past to have little or no effect on detector performance. Their cumulative effects on both the energy resolution and collected charge (μτ-product) become notable for long drift-length (> than about 1 cm) devices. As an example, Fig. 4 shows a 2-D distribution of the electron μτ-products measured for ~1-mm thick CZT sample. The clear areas correspond to electron μτ products as high as 2×10^{-2} cm^2/V. In the areas with Te precipitates, the electron μτ products reduce to as low as 10^{-5} cm^2/V. The μτ products averaged over the entire area of the sample, i.e. when the spectra measured for each beam location are added together, which corresponds to a normal μτ-products measurements with uncollimated X-rays, is 1.1×10^{-3} cm^2/V.[5] In thicker devices, the apparent μτ-product value is also notably less than those measured for precipitate-free areas.

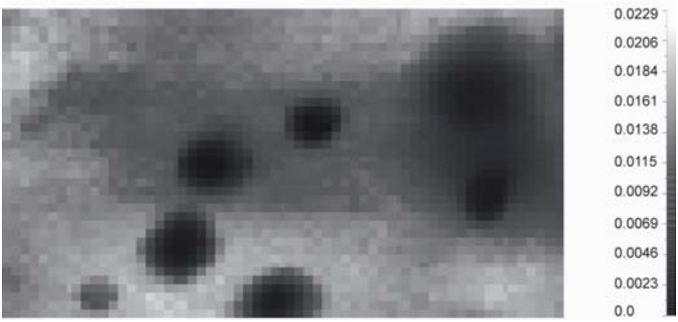


Figure 4. 2-D distribution of the electron μτ-products measured for ~1-mm thick CZT sample. The numbers indicated on the right are in cm^2/V

4. Conclusion

The effects of Te precipitates on charge collection in single-crystal CZT material have been demonstrated with planar and Frisch-ring CZT detectors. On a micron scale, Te precipitates correlate with small areas of poor charge collection as identified with X-ray scans. On a large scale, Te precipitates seem to be responsible for most of the material non-uniformities observed in single-crystal CZT. These could potentially explain many of the previously unexplained effects observed in single-crystal CZT material: the degradation of energy resolution in long-drift (> 1 cm) devices, local variations in the electric field seen in multi-electrode detectors such as CPG and pixilated arrays, "missing" counts, etc. However, more precise measurements and new experimental methods are required to better understand the effects of Te precipitates on CZT device performances and to determine steps to mitigate their adverse consequences.

Acknowledgements

The authors acknowledge the support of the technical and scientific staff of NSLS. Particular thanks go to Peter Siddons, Zhinjian Yin, and Claudio Arnone.

This manuscript has been authored by Brookhaven Science Associates, LLC under Contract No. DE-AC02-98CH1-886 with the U.S. Department of Energy. The United States Government retains, and the publisher, by accepting the article for publication, acknowledges, a world-wide license to publish or reproduce the published form of this manuscript, or allow others to do so, for the United States Government purposes.

References

1. R. B. James, T. E. Schlesinger, J. C. Lund and M. Schieber, Cadmium Zinc Telluride Spectrometers for Gamma and X-Ray Applications, in: *Semiconductors for Room Temperature Nuclear Detector Applications*, Vol. 43, edited by R. B. James and T. E. Schlesinger (Academic Press, New York, 1995), p. 334.
2. C. Szeles and E. E. Eissler, Current issues of High-pressure Bridgman growth of semi-insulating CdZnTe, in *Semiconductors for Room Temperature Radiation Detector Applications II*, Vol. 487, edited by R. B. James, T. E. Schlesinger, P. Siffert, W. Dusi, M. R. Squillante, M. O'Connell and M. Cuzin (Materials Research Society, Pittsburgh, PA, 1998), pp. 3-12.
3. M. Amman, J. S. Lee, and P. N. Luke, Electron trapping nonuniformity in high-pressure-Bridgman-grown CdZnTe, *J. Appl. Phys.* 92, 3198-3206 (2002).
4. V. Ivanov, L. Alekseeva, P. Dorogov, and A. Loutchanski, Correlation between quality of CZT crystals and spectrometric performance of hemispherical radiation detectors, *Proc. IEEE-RTSD* (Rome, 2004).
5. G. A. Carini, Development of CdZnTe radiation detectors, *PhD Thesis* (2005).
6. G. S. Camarda, A. E. Bolotnikov, G. A. Carini, L. Li, G. W. Wright, and R. B. James, "The Effects of Precipitates on CdZnTe Device Performance", in Proceedings of SPIE Hard X-Ray and Gamma-Ray Detector Physics VII, edited by R. B. James, L. A. Franks, and A. Burger (SPIE, Bellingham, WA, 2005), 592004-1 – 592004-7.
7. G. A. Carini, A. E. Bolotnikov, G. S. Camarda, G. W. Wright, and R. B. James, Effect of Te-precipitates on performance of CdZnTe detectors, (unpublished).

8. A. E. Bolotnikov, G. S. Camarda, G. A. Carini, M. Fiederle, K. T. Kohman, L. Li, G. W. Wright, and R. B. James, Non-uniform response of CdZnTe material seen with planar, coplanar-grid, and pixel detectors, (unpublished).
9. J. R. Heffelfinger, D. L. Medlin, and R. B. James, Analysis of Grain Boundaries, Twin Boundaries and Te Precipitates in Cadmium Zinc Telluride Grown by High-Pressure Bridgman Method, in: *Semiconductors for Room Temperature Radiation Detector Applications II*, Vol. 487, edited by R. B. James, T. E. Schlesinger, P. Siffert, W. Dusi, M. R. Squillante, M. O'Connell and M. Cuzin (Materials Research Society, Pittsburgh, PA, 1998), p. 33.
10. C. Szeles, S. E. Cameron, J.-O. Ndap, and W. C. Chalmers, Advances in the crystal growth of semi-insulating CdZnTe for radiation detector applications, *IEEE Trans. Nucl. Sci. NS* 49(5), 2535-2540 (2002).
11. A. E. Bolotnikov, G. S. Camarda, G. A. Carini, M. Fiederle, L. Li, D. S. McGregor, W. McNeil, G. W. Wright, and R. B. James, Performance Characteristics of Frisch-Grid CdZnTe Detectors, *IEEE Trans. Nucl. Sci.* (in press, 2005).
12. A. E. Bolotnikov, G. S. Camarda, G. A. Carini, M. Fiederle, L. Li, G. W. Wright, and R. B. James, "Performance Studies of CdZnTe Detector by Using a Pulse-Shape Analysis", Invited Paper, in Proceedings of SPIE Hard X-Ray and Gamma-Ray Detector Physics VII, edited by R. B. James, L. A. Franks, and A. Burger (SPIE, Bellingham, WA, 2005), 59200K-1 – 59200K-12.

COMBINED SENSORS FOR THE DETECTION, IDENTIFICATION AND MONITORING OF RADIATION SOURCES

ILAN YAAR[*]

Nuclear Research Center Negev (NRCN), P.O. Box 9001, Beer-Sheva 84190, Israel.

Abstract: Radiation sources widely used in industry, medicine, agriculture, research and education are most dangerous from the viewpoint of their widespread and easy access. The probability that these sources will be stolen and used to assemble a radiological dispersive (RDD) is not negligible. Such a device can be used by terrorist groups for the purpose of contamination of industrial centers, airports, seaports and residential areas, which can affect a large sector of the economy of a country. Detonation of a RDD can lead to death and exposure of the population to radiation, but, as a whole, the use of the bomb is aimed at creating panic among population, causing economic damage and social shock to the society. In this work, ways to reduce the threat of radiation sources obtained outside and within a country will be discussed.

Keywords: radiological dispersive device (RDD); radiation detectors; radiation sources.

1. Introduction

In a series of international conferences held in the last five years by the International Atomic Energy Agency (IAEA) [1], it was decided that the safe and secure management of radioactive sources is essential for ensuring the long-term security and control of them. In order to promote the establishment and maintenance of infrastructures for this purpose, states should make a concerted effort to follow the principles of the Code of Conduct on the Safety and Security of Radioactive Sources.[1] In this context, the identification of roles and responsibilities of governments, licensees and international organizations is vital.[1] The activities referred to above are primarily related to the prevention of loss of control over radioactive sources and contribute to enhancing security and safety of them.[2]

While most of the countries in the west are trying to close the borders against unauthorized radiation sources by installing radiation detectors, X-ray

S. Apikyan and D. Diamond (eds.), Countering Nuclear and Radiological Terrorism, 209–222.

and neutron scanning systems, thousands of radiation sources are already present inside any country in factories, research facilities, hospitals and private and government laboratories. Although most of these sources are kept under a controlled regulatory system, there is still a possibility that some could become a high radiological risk to the population[1], by being mistakenly misplaced or deliberately stolen. A radioactive, gamma, beta or alpha source, combined with conventional explosives, can also form a Radiological Dispersive Device (RDD), which may be used in an attempt to contaminate a large area[1]. The radioactive materials needed to build a RDD can be found in almost any country in the world, and some of these countries may have inadequate control and monitoring programs necessary to prevent or even detect the theft of these materials.

Some of the most common civilian used radiation sources that can be used by terrorists to make an RDD are listed in table 1. These sources were identified by the IAEA as the most hazardous ones based on considerations like, the source activity, the potential of the sources to cause deterministic effects, the nature of the work with the source, the mobility of the source, experience from reported accidents and typical verses unique activities within an application.

TABLE 1. The properties of the most common civilian used radiation sources that can be used by terrorists to make an RDD[1]

Isotope	$t_{1/2}$ (y)	Typical compound	Decay type	E (MeV)	Specific power	
					(Watt/g)	(Watt/TBq)
^{60}Co	5.27	Metal	γ , β^*	2.505, 0.318	16.35	0.39
^{192}Ir	0.2023	Metal	γ	1.457	79.51	0.23
^{137}Cs	30	CsCl	γ , β^*	0.661, 0.547	0.42	0.13
^{90}Sr	29.12	$SrTiO_3$	β^*	0.55 / 2.28	0.96	0.19
^{241}Am	432.71	Oxide	α	5.64	0.11	0.87
^{238}Pu	87.4	Oxide	α (n)	5.59	0.56	0.88
^{252}Cf	2.65	Metal	α (96.9%) s.f. (3.1%)	6.217 193.9	38.19	32.04

* - The energy listed in the table for beta sources is the maximum energy of the emitted beta particle.

Lost or illegally obtained radiation sources, similar to those listed in table 1, can be used by terrorists to assemble a Radiological Dispersive Device (RDD). A terror organization can easily buy or steal sufficient radioactive materials needed to produce an RDD. The radioactive material can be obtained abroad or inside a country. In the latter case, no border crossing is needed, and the chance that the source will be detected is minimal.

2. Ways to reduce the RDD threat

A terror organization that intend to use a radiation source obtained **outside** country borders to assemble a RDD, have to pass through a point of entry like, seaport, airport or a border control station. At any of these entry points, the source can be detected by radiation portals or personal radiation detectors (PDS) wear by custom officers. Radiation sources can be also obtained **within** country borders from sources held in hospitals, factories, scientific laboratories or irradiation facilities. Ones a source obtained outside country borders is successfully smuggled in, via a legal or a non-legal entry point, the source should in practice be consider as one obtained within country borders.

2.1. REDUCING THE THREAT OF RADIATION SOURCES OBTAINED OUTSIDE COUNTRY BORDERS

The most effective way to reduce the threat of radiation sources obtained outside country borders is by the implementation of international regulations aimed at minimizing the number of orphan sources and enhancing the safekeeping and monitoring of radiation sources and radioactive materials around the world, as embedded in the radiation sources code of conduct published by the IAEA. Political and technological cooperation among countries is needed to accomplish the above tasks. However, the preparedness to an incidence in which a terror organization will try to smuggle a radiation source into a country, obligating the installation of radiation portals and radiation detectors at points of entry. While the detection of a gamma or neutron source is relatively easy, due to the penetration nature of the emitted radiation, the detection of a concealed beta or alpha sources is a more challenging task, due to the short range of alpha particles in matter and to the small amount of high-energy photons and neutrons emitted from these sources[4]. Therefore, a radiation system planed to detect alpha or beta emitters will easily detect most of the gamma and neutron sources.

2.1.1. *Detection of concealed ^{241}Am alpha source*

A typical alpha emitter like ^{241}Am also emits some low energy (60keV) gamma rays that can be easily shielded by several millimeters of lead, a small amount of high energy gamma rays and neutrons generated via (α,n) reaction with light elements. The gamma spectrum of a 11.1 GBq ^{241}Am source shielded with 5 mm of lead is depicted in figure 1, and compared to simulation results obtained using the Monte-Carlo code MCNP-4C[6].

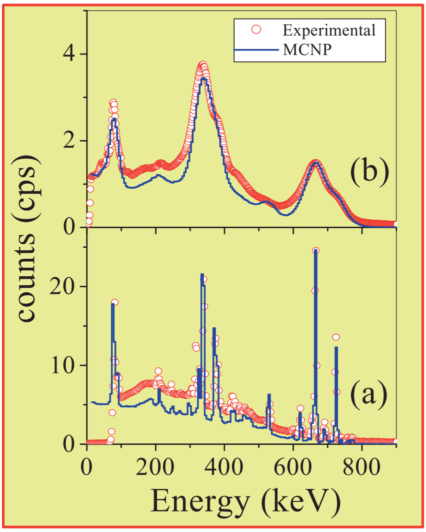


Figure 1. Experimental (o) and calculated gamma (—) spectra of 11.1 GBq ^{241}Am source encapsulated in 5 mm of lead shielding, taken with: (a) HPGe and (b) NaI(Tl) detectors[7]

The neutron emission rate (n/s/100 GBq) for a metallic, an oxide and a ceramic ^{241}Am source, calculated using the code SOURCES 4A[8] is listed in table 2. In view of the fact that most of the neutrons emitted from this source are generated via (α,n) reaction with light elements, the total number of emitted neutron is directly connected to the source type, as shown in table 2.

TABLE 2. Calculated neutron emission rate (n/s) for a metallic, an oxide and a ceramic[*] 100 GBq ^{241}Am source[**]

Source type	Spontaneous fission	^{17}O	^{18}O	^{25}Mg	^{26}Mg	^{27}Al	^{29}Si	^{30}Si	Total
Metallic	1	---	---	---	---	---	---	---	1
Oxide	1	180	1800	---	---	---	---	---	1981
Ceramic[*]	1	270	3240	7380	10440	5860	1620	765	29576

[*] - The ceramic enamel composition was taken as a mixture of 5% AmO_2 with 45% SiO_2, 15% AlO_2, 10% CaO_2 and 25% MgO (weight %)[9].

[**] ^{241}AmBe source with the same activity will emit $6.75x10^6$ n/s

Based on the measured and calculated given in figure 1 and in table 2, the minimum time required for the detection of a concealed metallic, oxide or ceramic ^{241}Am source can be calculated using the total background rate, *b*, and the net counts rate, *a*, in each detector. Let *N*(*r*,*t*) be the total number of counts obtained in a given detector, at a distance *r* from the source, where *t* is the counting time, then,

$$N(r,t) = \frac{at}{r^2}\exp(-\mu r) + bt \tag{1}$$

where *a* is the net count rate in a given detector placed 1 m from the source, μ is the absorption coefficient of the radiation in air and *b* is the background intensity rate. For a false alarm rate of 1 in 10,000, the instrument alarm rate (assuming normal Poisson counting statistics) must be set to at least 4σ higher than the average background[10], given a minimum detection time of:

$$\begin{aligned} N(r,t) &= \frac{at}{r^2}\exp(-\mu r) + bt \geq bt + 4\sqrt{bt} \\ \frac{at}{r^2}\exp(-\mu r) &\geq 4\sqrt{bt} \\ t_{\min}(r) &= \frac{16\,br^4}{a^2}\exp(2\mu r) \end{aligned} \tag{2}$$

The minimum time needed to detect a metallic, an oxide or a ceramic ^{241}Am source, using conventional 75x75 mm^2 NaI(Tl) gamma and 50x200 mm 3He neutron detectors, according to equation 2, is listed in table 3. The results are calculated for a detector-to-source-distance of 1 m, with a neutron background of 2.215±0.018 cps and a gamma background of 15.69±0.28 cps. The absorption coefficient of the gamma radiation in air[11] was taken as 0.012 m^{-1}, and no attenuation in air was assumed for the neutron radiation.

TABLE 3. The minimum time (in sec) needed to detect a 100 GBq ^{241}Am source from a distance of 1 m, using a 75 mm NaI(Tl) gamma and 50 mm by 200 mm ^{3}He neutron detectors.

Source shielding (mm)			75 mm NaI(Tl) gamma detector	50 mm by 200 mm ^{3}He neutrons detector	
lead	paraffin wax	cadmium		Oxide source	Ceramic source
5	---	---	0.03	2.07	0.01
30	---	---	1.35	3.94	0.02
30	168	2	2.00	9.15	4.40

2.1.2. *Detection of concealed ^{90}Sr beta source*

The continuous bremsstrahlung spectrum emitted form a 0.6 GBq ^{90}Sr beta source, taken with a 75x75 mm^2 mm NaI(Tl) detector and a 500x500x5 mm^3 BC-408 plastic scintillator is depicted in figure 2(a) and figure 2(b) respectively.

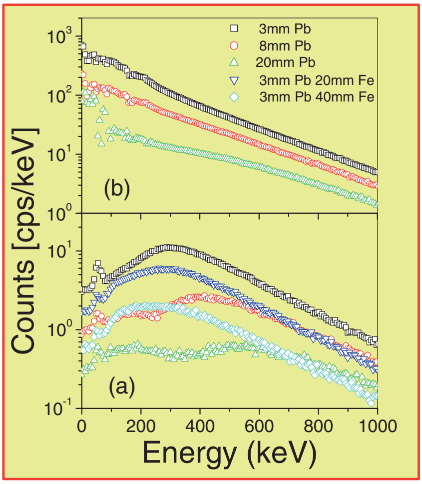


Figure 2. Gamma spectra of a 0.6 GBq ^{90}Sr source, taken with (a) 75x75 mm^2 NaI(Tl) inorganic scintillator, and (b) 500x500x50 mm^3 BC-408 plastic scintillator

Based on the measured results depicted in figure 2, and on MCNP calculations results,[3] the minimum time needed to detect a concealed 330 GBq ^{90}Sr RTG using the above detectors, are listed in table 4 as a function of tungsten shield. The results are calculated for a detector-to-source-distance of 1 m, with a gamma background level of 15 μR/hr and absorption coefficient of the gamma radiation in air taken from ref.[12.]

TABLE 4. The minimum time needed for the detection of a concealed 330 TBq ^{90}Sr RTG from a distance of 1 m, using 75x75 mm^2 NaI(Tl) inorganic and 500x500x50 mm^3 BC-408 plastic scintillator

Tungsten shield thickness (mm)	Minimum detection time (s)	
	NaI(Tl)	BC-408 plastic
160	0.9	0.02
180	60.2	5.2
200	4015.7	350

2.1.3. *Detection of a concealed radiation sources using thermal screening*

The amount of energy associated with the decay of the most common civilian used radiation sources is listed in table 1. This heat can also provide a supportive indication of the presence of such sources, particularly if the sources are well shielded or when their direct radiation emission is difficult to monitor because of its poor penetrability, as in the case of alpha and beta sources. In essence, heat leakage from a container is a natural way for screening radiation sources, since the presence of any other internal source of heat within a cargo container, or for that matter a suitcase, is quite unlikely. This heat leakage can be measured with conventional thermal (infrared) cameras. However, the surface temperature has to be sufficiently different from that of the ambient to be detectable. Moreover, one would expect a “hotspot" at the surface of the container in areas close to the source location[13].

Based on the data listed in table 1, the local and wider energy distributions were evaluated for a source concealed inside a homogenous medium. From the results of these calculations, the temperature gradient and the outer temperature were calculated using the computational 3D fluid dynamics (CFD) code FLUENT[14]. Because most of the energy emitted from alpha and beta sources is absorbed in the active volume of the source and in its shield, all of the heat distribution calculations were conducted assuming that all of the energy is absorbed inside this volume. This assumption eases the calculations with almost no effect on the results. The general physical problem that was selected relates to heat transfer dissipation from a central heat source to a free airflow (heat sink). The heat generation is conducted through the medium toward the surfaces, by heat conduction mechanism. The conductive heat flow is conveyed away from the surfaces by the free airflow according to natural convection mechanism. In natural convection, air motion is induced by density differences resulting from temperature gradients in the air. Various convective heat transfer coefficients (between the outer surface and the free air) were obtained experimentally due to surfaces orientation (vertical, horizontal upwards, horizontal downwards).

The solution of the 3D model for each case was carried out according to iterative procedure, involving the following steps:

1. Obtain a solution to the 3D heat conduction equation including heat generation term by using C.F.D commercial code Fluent.
2. Calculate the free convection heat transfer coefficients, using the temperature distribution obtained from the first step, and a user program developed for the heat transfer coefficients computations.
3. Use the free convection heat transfer coefficients calculated in step 2, to specify a new set of temperature field.
4. Continue the process of iteration until equilibrium is attained between the solutions of the temperature fields.

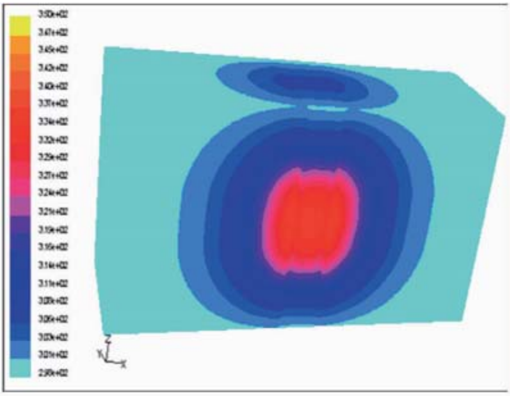


Figure 3. Temperature distribution (K) on the outer surface of a suitcase, for heat source of 10 Watt and typical effective thermal conductivities of 0.03 W/m°C

Typical calculations result of the temperature distribution on the outer surfaces of a suitcase with the dimensions of 300x500x1000 mm^3, obtained for heat source of 10 Watt and effective thermal conductivities of 0.03 W/m°C, is depicted in figure 3.

2.1.4. *Detection concept*

As demonstrated in sections 2.1.1 to 2.1.3, a shielded radiation source emits three types of detectable radiation: gamma, neutrons and Infra-Red (IR). A detection system (personal, portable or portal) should therefore include the capability of detecting several of the above radiation types. A combination of several detection techniques will achieve:

- Minimization of the detection time and false alarm rate.
- Maximization of the detection probability.

In this section, some of the detectors recently developed in Israel for this propos will be demonstrated.

(a) Personal radiation detectors (PRD)

A PRD is a small and mobile detector, having the size of cellophane. The detector can be attached to the belt of a police officer, a first-responder or a costume-officer. The detector combines gamma and neutrons detectors, and design according to the American ANSI N42.32-2003 standard[15].

The properties of the detector, shown in figure 4, are,

- Gamma (CsI-Tl) and neutron (^{6}Li) separated channels.
- Energy range of 0.03 to 1.8 MeV for gamma and 0.025 to 15 MeV for neutrons.
- Fast response time of less than 2 s.
- Measurement range of 1μSv/h to 100μSv/h.
- Dimensions of 120 x 65 x 33 mm (l x w x h).
- Weight: 240 gr with battery.
- Wireless communication interface.

Figure 4. The personal radiation detectors (PRD) developed in Israel

(b) Portable detectors

Gamma and neutrons detectors were design according to the American ANSI N42.34-2003 Standard[16]. The properties of the gamma detector, shown in figure 5, are,

- Radiation Detected Gamma above 50 keV.
- Scintillator NaI(Tl) 2" diameter, 2" thick.
- Sensitivity (^{137}Cs) 20,000 cps/mR/h.
- Energy Calibration Software calibrated single channel analyzer (SCA).
- Count Rate Range0 to 50,000 cps.
- Output Signals RS-232 or RS- 485 and TTL pulses.
- Temperature Range-30oC to +60oC (-22oF to +140oF).
- Humidity Range10% to 95% RH (non condensing).
- Dimensions340mm (13.4") length, 70mm (2.75") Diam.
- Weight1.75kg (3.9lbs).
- Casing Aluminum, splash proof, IP-65.
- Max. Cable Length TTL pulse - 100 m, RS-232 - 12 m, RS-485 - 1.2 km.

Figure 5. Gamma detector RP-11 model 4-0037-50[18]

The neutron portable detector consists of two ^{3}He detectors fixed inside a Polypropylene box with the electronics package attached on top. The detector, shown in figure 6, is only a prototype design to evaluate the ANSI[21] detection demands.

Figure 6. Neutron portable detector

2.2. REDUCING THE THREAT OF RADIATION SOURCES OBTAINED WITHIN ISRAELI BORDERS

All of the radiation sources in Israel are kept under the regulations and supervision of the Ministry of the Environment. Some of the sources are stationary and some are mobile. The mobile sources are usually less secure than the fix ones. A system for real-time Monitoring of Mobile Radiation Sources (MMRS), for the Ministry of the Environment, is now under development. The system under develop will facilitate real time monitoring capability of the location of fixed and mobile radiation sources. The system will also give an indication on the radiation level in the source vicinity. All the information regarding sources location and condition will be transmitted to a control room where an operator could coordinate a fast response on detection of an attempt to tamper with the source.

As written in section 1 of this work, continuous control of the location of radiation sources is a major step needed in enhancing the security of these sources, decreasing the possibility that they will be lost or stolen and minimizing their recovery time. The proposed work is aimed toward the development of an integrated radiation detection and transmission unit, connected to the radiation source shield. This unit will continuously transmit the location of the source and the radiation level around it to a control room, were a dedicated computer program will monitor the readings from all of the sources in a given area.

The result of the project will be a unique system capable of real time monitoring of radiation sources. The system will provide continuous real-time indication for the source location, for the radiation level around the source and for any attempt to tamper with the source shielding. A block diagram of the MMRS system is given in figure 7.

- The system will include:

  GPS or cellular based locating device.

  A simple gamma detector.

  Reliable and radiation resistant RFID tag and reader.

  Communication system.

  Central control system operated by the Ministry of the Environment.

- The system will provide:

  Accurate, real-time location monitoring, of mobile radiation sources, including during field deployment.

  Alerts on stealing attempts.

  Real-time monitoring of the radiation levels in the vicinity of the source.

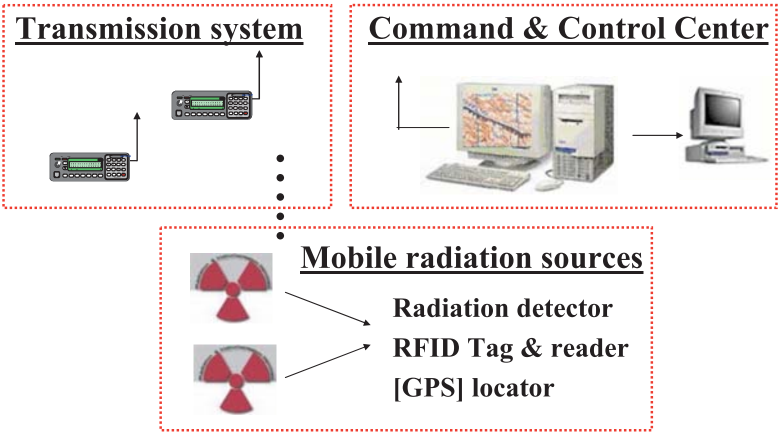


Figure 7. A block diagram of the MMRS system

3. Conclusions and future R&D directions

- Reduction of the RDD threat can be achieved by a combination of two systems:

  Radiation detection system installed at all points of entry.

  Monitoring system of Mobile Radiation Sources (MMRS).

- Despite the technology progress displayed in this conference and elsewhere, most of the radiation detection systems around the world are based on the well-known inorganic scintillators, ^{3}He and plastic detectors.
- Future R&D directions should be focused on

  Detection systems that combine several of today detection capabilities (explosives, gamma, neutrons, metals, IR), with the option to include future detectors.

  Inexpensive, sensitive and room temperature operated gamma detectors, with superior energy resolution.

  Real time monitoring systems for mobile radiation sources.

References

1. International Atomic Energy Agency (IAEA), Action Plan for the Safety of Radiation Sources and the Security of Radioactive Materials, GOV/1999/46-GC(43)/10, Vienna (1999) and GOV/2001/29-GC(45)/12, Vienna (2001).
2. International Atomic Energy Agency (IAEA), The code of Conduct on the Safety and Security of Radiation Sources, IAEA/CODEOC/2001, IAEA, Vienna (2001) and IAEA/CODEOC/2003, IAEA, Vienna (2003).
3. International Atomic Energy Agency (IAEA), Security of Radiation Sources: Interim Guidance for Comment, IAEA-TECDOC-1355, IAEA, Vienna (2003).
4. International Atomic Energy Agency (IAEA), Measures to Strengthen International Co-operation in Nuclear, Radiation and Transport Safety and Waste Management, GOV/2003/47-GC(47)/7, Vienna (2003).
5. International Atomic Energy Agency (IAEA), Strengthening control over radioactive sources in authorized use and regaining control over orphan sources, national strategies IAEA-TECDOC-1388, IAEA, Vienna (2004).
6. Committee on Science and Technology for Countering Terrorism, MAKING THE NATION SAFER, The national academies press, Washington, D.C., USA (2002) 48-49.
7. International Atomic Energy Agency, Categorization of radioactive sources, IAEA-TECDOC-1344, Vienna (2003).
8. JEF-2.2, Radiactive Decay data library, ver. 01 (1994).

9. Y. S. Touloukian, R. W. Powell, C. Y. Ho and P. G. Klemens, Thermophysical properties of matter the TPRC data series, Prude Research Foundation USA (1978).
10. Yaar I. and Hussein E.M.A, Passive detection of concealed ^{90}Sr radioisotope thermoelectric generators in transport, Packaging, Transport, Storage and Security of Radioactive Material, 15 (2004) 149-154.
11. Alvarez J.L., Defining, Explaining, and Detecting Dirty Bombs, Auxier & Associates. Inc., Knoxville, TN 37932, Health Physics Society Midyear Meeting, San Antonio, Texas, January 2003.
12. Briesmeister J.F. editor, MCNP- A General Monte Carlo N-Particle Transport Code, version 4c, Technical report LA-13709-M, Los Alamos National Laboratory, Los-Alamos, NM, USA (2000).
13. Yaar I and E.M.A. Hussein, PASSIVE DETECTION AND IDENTIFICATION OF A CONCEALED ^{241}Am SOURCE, Report submitted to: Canada Customs and Revenue Agency, Laboratory and Scientific Services, 79 Bentely Avenue, Ottawa, Ontario, K1A 0l5 (2003).
14. Wilson W.B, Perry R.T., Charlton W.S., Parish T.A., Estes G.P., Brown T.H., Arthur E.D., Bozoian M., England T.R., Madland D.G., Stewart J.E., SOURCES 4A: A Code for Calculating (α,n), Spontaneous Fission, and Delayed Neutron Sources and Spectra. Technical report LA-13639-MS, Los Alamos National Laboratory, Los-Alamos, NM, USA (1999).
15. Gorokhovskii A.V., Gorokhovskii V.A., Meshecheryakov D.V., Kopchekehi A.A. Production of glass ceramics as a method for comprehensive utilization of chemical industry waste. Glass and Ceramics 59 (2002) 353-355.
16. International Atomic Energy Agency, Detection of radioactive materials at borders, IAEA-TECDOC-1312, Vienna (2002).
17. Berger M.J., Hubbell J.H., Seltzer S.M., Coursey J.S., and Zucker D.S., XCOM: Photon Cross Sections Database, NIST Standard Reference Database 8 (1998).
18. Berger M.J., Hubbell J.H., Seltzer S.M., Coursey J.S., and Zucker D.S., XCOM: Photon Cross Sections Database, NIST Standard Reference Database 8 (1998).
19. I Yaar, M. Haim and E.M.A. Hussein, Feasibility of Detecting Heat Emission from Concealed Radioisotopic Sources using Thermal Screening, Report submitted to: Canada Customs and Revenue Agency, Laboratory and Scientific Services, 79 Bentely Avenue, Ottawa, Ontario, K1A 0l5 (2005).
20. Fluent CFD software, version 6.1.22, Fluent Inc., Lebannon, USA.
21. ANSI N42.32-2003, American National Standard Performance Criteria for Alarming Personal Radiation Detectors for Homeland Security, Published by The Institute of Electrical and Electronics Engineers, Inc. 3 Park Avenue, New York, NY 10016-5997, USA, 30 January 2004.
22. ANSI N42.34-2003, American National Standard Performance Criteria for Alarming Personal Radiation Detectors for Homeland Security, Published by The Institute of Electrical and Electronics Engineers, Inc. 3 Park Avenue, New York, NY 10016-5997, USA, 30 January 2004.
23. ROTEM Industries, http://www.rotemi.co.il/product_page.asp?catid=617&pgid=926&tmpltID=1 (last accessed 1/2006).

EXPERIMENTAL MODEL OF THE DEVICE FOR DETECTION OF NUCLEAR CYCLE MATERIALS BY PHOTONEUTRON TECHNOLOGY

A.M. BAKALYAROV
Russian Research Center “Kurchatov Institute”, Moscow, Russia

M.D. KARETNIKOV, K.N. KOZLOV, V.I. LEBEDEV,
E.A. MELESHKO, B.A. OBINYAKOV, I.E. OSTASHEV,
N.A. TUPIKIN, G.V. YAKOVLEV

Abstract: The threat of possible nuclear and radioactive terror causes the necessity of stringent control of trafficking of nuclear materials. The detecting abilities of currently used «passive» detection systems (radiation monitors) had practically reached their limits, especially in case of masked or shielded radioactive and fissile materials. These systems cannot detect non-radioactive materials such as lithium or heavy water since these materials do not emit the ionizing radiation.

Keywords: nuclear and radioactive terror, nuclear materials, passive detection, ionizing radiation.

1. Introduction

In general, the neutron technologies are capable to reveal the hidden fissile materials. However, the detectable mass of fissile material concealed in the large-size container is too big (more than 1 kg). Neutron technologies are unable to detect some other nuclear materials (e.g., heavy water). Moreover, a sufficient activation of controlled object after its irradiation by fast or thermal neutrons is possible. Assessments show that the photoneutron technology provides the better sensitivity, range of detectable materials, accuracy of localization, responsiveness compared to the existing methods of passive and neutron control technologies. It provides the better ecological compatibility compared to the neutron technologies.

Currently, the experimental model of the device for detection of nuclear materials by photoneutron technology is been developing based on the electron accelerator U-28. The results of preliminary choice of the main units of the device (converter, filter, collimator, diagnostic equipment) are reported.

S. Apikyan and D. Diamond (eds.), Countering Nuclear and Radiological Terrorism, 223–235.

1.1. ACTUALITY OF THE PROBLEM

Currently, more than 2000 ton of uranium and plutonium available for weapon application are stored all over the world, and their control is often not adequate to their significance. Experts believe that a number of non-nuclear countries can be well informed on the matter of nuclear weapon manufacturing, and their nuclear weapon programs are restricted only by the absence of required materials of nuclear cycle (MNC) (fissile materials (FM) and special non-nuclear materials (SNNM) (heavy water, tritium, litium-6) which can be used for nuclear bomb manufacturing.

Each object containing MNC should be secured by the complex system of protection, control, and account of MNC. The minimal quantity of MNC as from which they are subject to the Russian State System of account and control are given in Table 1 [1].

Most MNC are radioactive, some of them strongly absorb neutrons or gamma-rays, and their excited nuclei can emit penetrating radiation. Therefore, there are three technologies for MNC detection:

- "Passive" recording of radioactive decay products;
- Radiography for material identification by their absorption properties;
- "Active" irradiation of the object by gamma-rays or neutrons and recording the products of nuclear reactions.

Currently, the passive technology for MNC detection is generally used in the systems for physical protection of nuclear objects. The sensors installed at the control gate basically respond to gamma-ray emission of MNC, and, in much less degree, to their neutron emission.

The possible way of illegal trafficking of MNC through the control gates equipped with passive means of MNC detection may be the shielding of MNC. In this case, the passive gamma-detector cannot respond to the attenuated radiation.

The problems of MNC detection by passive technology were studied in [2-3]. The following shortcomings were revealed:

- Attenuation of radiation by shileding down to the undetectable limit;
- Problems of identification of FM hidden in legally shipped radioactive materials (e.g., industrial or medical isotopes);
- Impossibility to control SNNM which do not emit ionizing radiation, such as heavy water or lithium-6.

TABLE 1. Minimal quantity of MNC according to the State System of account and control

Nuclear material	Minimal quantity of nuclear material
Plutonium-239	15 g
Uranium-233	15 g
Uranium enriched with Uranium-235 by 10% or more	15 g by Uranium-235
Uranium enriched with Uranium-235 by less than 10% but more than natural uranium	15 g by Uranium-235
Uranium with Uranium-235 concentration less than 0.7%	500 kg
Thorium	500 kg
Lithium-6	1 kg
Heavy water	200 kg

High-energy gamma-rays can be used for effective selection of FM on the background of light materials (carbon, aluminium); however, they are unpractical for FM discrimination against heavy elements (lead, tungsten), or discrimination of light MNC (e.g., heavy water) or composite FM (e.g., fuel ball elements).

The active technologies of FM detection are based on additional fission of FM induced by some types of penetrating radiation (neutron, gamma-rays). The Table 2 outlines the most promising active technologies for FM detection. All of them can be in a great demand or are used already for some practical applications.

Currently, the most urgent task of prevention the illicit trafficking is the control of the sea cargo containers. The total number of containers processed in various ports of South Pacific is about 130 million TEU containers. The growth tendency for shipments is expected to continue into the future. By 2011 the number of processed containers in the South Pacific countries is expected to d reach 216 million TEU containers.

The inherent complexity of sea container control makes them potentially dangerous for smuggling illicit materials and items in them, including nuclear materials. A number of experts believe that the sea containers are the most probable way of shipping nuclear materials to the U.S. for the purposes of committing the global terrorist acts [4].

TABLE 2. Technologies for FM detection

Designation	Sounding radiation	Recording radiation	Physical principle	Adaptability for control of highly loaded sea cargo container	Restrictions	Status	Ref.
Passive inspection	No	Gamma-rays and neutrons	Spontaneous fission	As ancillary control	camouflaging through passive shielding or inside the legally shipped radioactive source	Used in control points	2
Thermal Neutron Radiography	Thermal neutrons	Thermal neutrons	Neutron capture	No	Possibility of camouflaging through shielding from thermal neutrons, low signal/noise ratio.	Experiments	2
High Energy X-ray radiography	Bremsstrahlung	Bremsstrahlung	Gamma-ray interaction with matter	As auxiliary control	Problems: 1) Compound FM, 2) Discrimination of FM in metal form against heavy metals	Used in control points	2
Differential attenuation technology	Thermal neutrons	Prompt neutrons	Neutron multiplication at induced fission	No	Insensitivity to U-238 and Th-232. Strong attenuation of sounding radiation in some cases	Experiments	5
NMIS-	Fast	Prompt fast	Neutron	Yes	Restricted	Experim	6

Nuclear Material Identification System, $n^X\alpha$ and $\gamma^X\alpha$ Neutron Analysis	neutrons	neutrons and/or gamma-rays	or gamma-ray multiplication at induced fission		intensity of sounding radiation to avoid events overlapping.	ents	
Delayed Neutron Technology	Fast or thermal neutrons	Delayed neutrons	Emission of delayed neutrons by fission fragments	No	Low intensity of recording radiation. The energy of sounding neutrons is restricted by 10 MeV	Experiments	2
Delayed Gamma-Ray Technology	Fast or thermal neutrons	Delayed gamma-rays	Emission of delayed gamma-rays by fission fragments	Yes	The energy of sounding neutrons is restricted by 10 MeV.	Experiments	7
Photonuclear Technology	Bremsstrahlung	Photoneutrons, delayed gamma-rays and neutrons	Photonuclear and photofission reactions	Yes	In case of photoneutron recording, neutron background from ^{57}Fe and ^{13}C isotopes inside constructional materials	Experiments	8

1.2. ADVANTAGES OF PHOTONUCLEAR TECHNOLOGY FOR CONTROL OF TEU CONTAINERS

The analysis of technologies for remote detection of MNC (Table 2) shows that only few of them are applicable for control of loaded TEU containers. The majority of containers at the checkpoints are half- or fully-filled, and their loading is close to 10–20 tons. The attenuation and scattering of probe (incoming) and informational (outcoming) radiation in the content of the container can affect the sensitivity of the control devices well above the detection limit.

The comparison of passive means, neutron and photoneutron technologies are given in Table 2. Concerning the sensitivity, the rate of photofission of ^{235}U by bremsstrahlung produced by the electron beam with the typical parameters (energy: 10 MeV, average current 10 μA) is close to (all other factors being equal):

- Rate of fission by fast neutrons with intensity of $5 \cdot 10^{11}$ 1/sec;
- 30 million times higher than the rate of spontaneous fission of ^{235}U;
- 500 thousand times higher than the rate of spontaneous fission of ^{239}Pu.

TABLE 3. Comparison of passive means, neutron and photoneutron technologies

Technology	Range of detectable materials	Activation	Detection of FM against RS	Technical problems
Passive	FM	No	Restricted	No
$n^X\alpha$ and $\gamma^X\alpha$ Nanosecond Neutron Analysis	FM	May be essential for some cases	Yes	Low lifetime of neutron generator with built-in alpha-detector
Delayed gamma-ray	FM		Yes	High intensity neutron generators with the neutron energy<10 MeV
Photoneutron	FM, SMNC	Low	Yes	No. The "off-shelf" equipment can be used.

The photoneutron technology can be implemented in the following way (Figure 1). The pulsed electron beam with the energy W= 8-10 MeV is scanned stepwise in vertical direction and incident on the vertical metal converter. At each moment, the electron beam produces a very narrow-angle bremsstrahlung of the same maximum energy (W) as the electron beam energy W. Due to the vertical scanning of electron beam, the averaged (through the scanning period) directional diagram of bremsstrahlung has the "knife"-type shape extended in the vertical direction along the beam- line. The object moves (optionally, stepwise) along the device in horizontal direction so all zones of the object are irradiated during the process of control. In case of presence of concealed sensitive materials, the photoneutrons are emitted and can be effectively recorded. As far as at each moment the electron beam produces a very narrow-angle bremsstrahlung, and photo-neutrons are emitted instantly (compared to the rate of electron beam scanning), this technology provides the possibility to define the location of concealed sensitive material. The part of bremsstrahlung passed through the object is recorded by the gamma-detector array. This "transmitted" image of the controlled object can be used for advancing the revealing capabilities of the method.

The FM can be also detected and selected against the radioactive materials by recording the delayed fission neutrons and gamma-rays.

1.3. DESIGN OF EXPERIMENTAL MODEL OF THE DEVICE

The experimental model of the device utilizing photoneutron technology is based on the U-28 linear electron accelerator [9]. The average beam energy at the output of the accelerator can be varied from 6 to 11 MeV by adjusting the parameters of the injector, phaser, RF power supply. Fig.2 displays the electron beam energy distribution in various modes of operation taken by magnetic spectrometer.

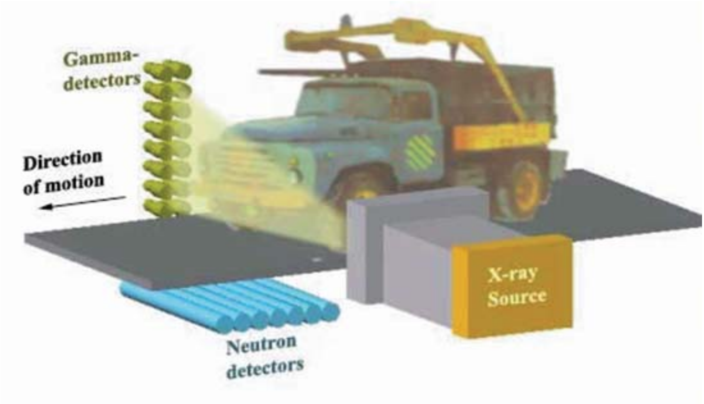


Figure 1. The principle of photoneutron technology

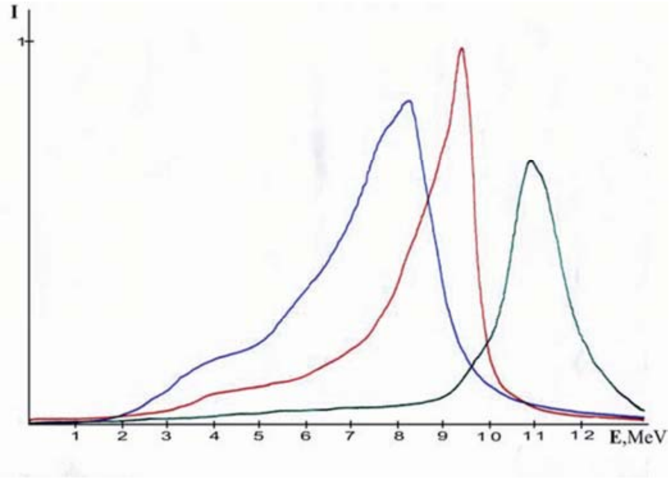


Figure 2. Electron beam energy distribution in various modes of operation

The basic components of the experimental module are given in Figure 3. The bremsstrahlung is produced at the converted and shaped by the collimator to the narrow beam. The rest of electron beam is absorbed by the filter.

For the preliminary choice of parameters of components of the experimental module and assessment of sensitivity of photoneutron technology, the numerical simulation of gamma-neutron transfer and recording was carried out. The real apparatus and items of experimental setup were simulated by parallelepipeds, cylinders, rings. In total, 92 modeling primitives were considered. The **GEANT3.21** [10] program package has been used.

Traditionally, the converter is made of heavy metal (gold, tungsten, their combinations [8]). However, at the beam energy of about 10 MeV, such converter is a high intensity source of prompt neutrons due to the low threshold and high cross-section of photoneutron (γ,n) reactions. We believe that at this beam energy it is more reasonable to use copper (the (γ,n) reaction threshold is 9.9 MeV). The comparison of counting rate of background neutrons in cases of tungsten and copper converters at the average beam energy of 9.5 MeV are given in Fig. 4. The very high background in case of tungsten is obvious. The maximum rate of photofission of ^{235}U at the tungsten converter is only 1.4 times higher then is case of copper one (Fig. 5). Thus, the copper converter was chosen as far as it provides much better effect/background ratio.

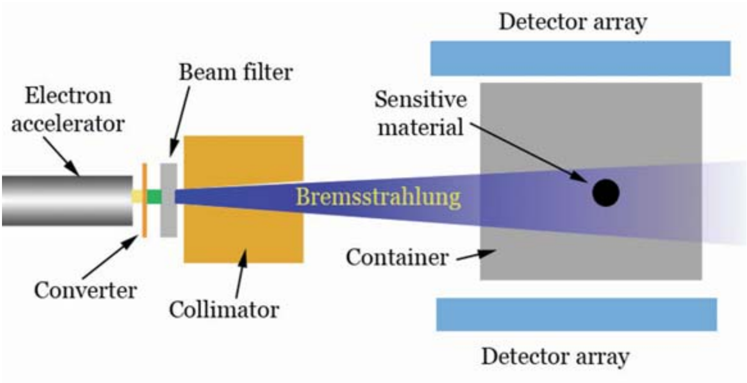


Figure 3. Components of the experimental module

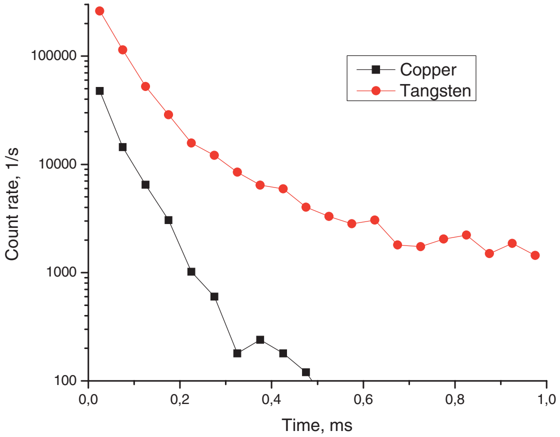


Figure 4. Counting rate of background neutrons in case of tungsten converter (upper curve) and copper converter (lower curve)

It may be seen from Figure 5, the dependence of fission rate on the converter thickness is comparatively flat with the slight maximum in the range of 0.5- 1 mm. Another important matter is the growth of radiation dose (in the container) with the converter thickness (Figure 6). Thus, the converter thickness of 0.5 mm is a reasonable compromise between efficiency of the converter and low radiation dose.

The filter is used for absorption of the rest of electron beam after passing the converter. Aluminium was chosen as filter material as far as it simultaneously meets the following requirements:

- low atomic number to minimize the additional dose of bremsstrahlung produced in the filter;
- good heat conductivity for filter cooling;
- high threshold of photonuclear reaction (to avoid generation of prompt photoneutrons in the filter).

The optimal filter width was assessed by the ratio of exposure doses from bremsstrahlung and electrons (Figure 7). This ratio grows with the filter thickness as far as electrons transform their energy to the radiation and ionization. At the chosen filter width of 2 cm the electron beam is almost entirely absorbed.

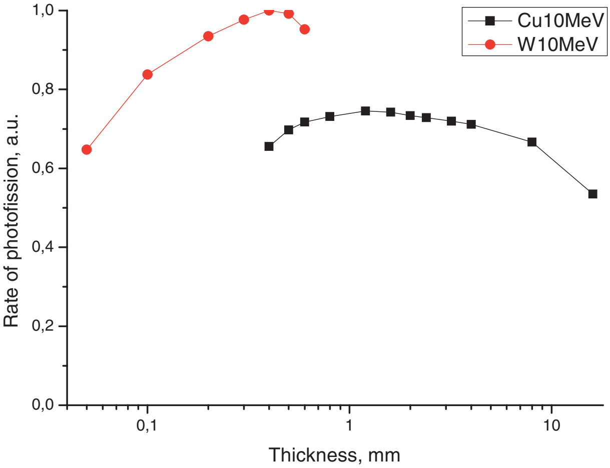


Figure 5. The relative rate of photofission of ^{235}U in case of tungsten (upper curve) and copper (lower curve) converters

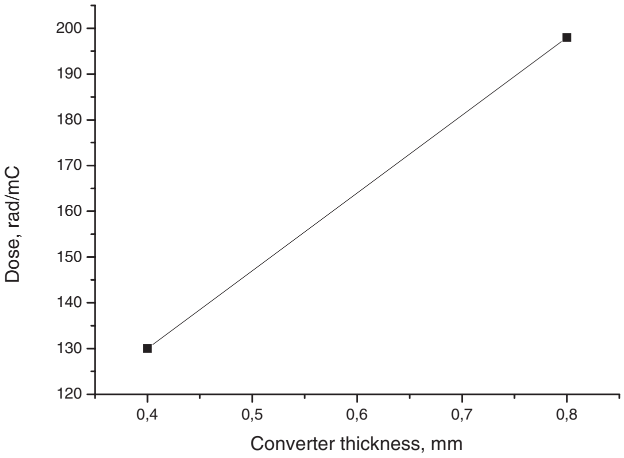


Figure 6. Exposure dose vs. converter thickness

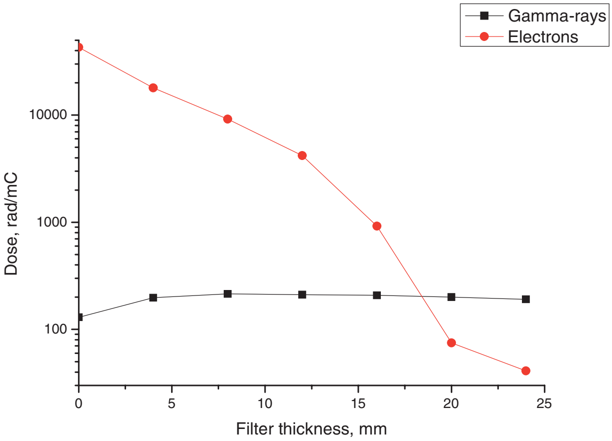


Figure 7. Exposure doses from bremsstrahlung and electrons vs. filter width

The collimator is used for shaping the bremsstrahlung to the "radiant beam" with the certain divergence angle. By the set of parameters (manufacturability, high cross-section of gamma-ray absorption, low neutron background), copper was chosen as the collimator material. The numerical experiments on assessment of quality of collimation at various widths of collimator were carried out. We determined the rate of fission of uranium ball (10 g) shifted from the collimator axis. The results given in Fig. 8 shows that the quality of collimation is sufficient at the width of 15- 20 cm.

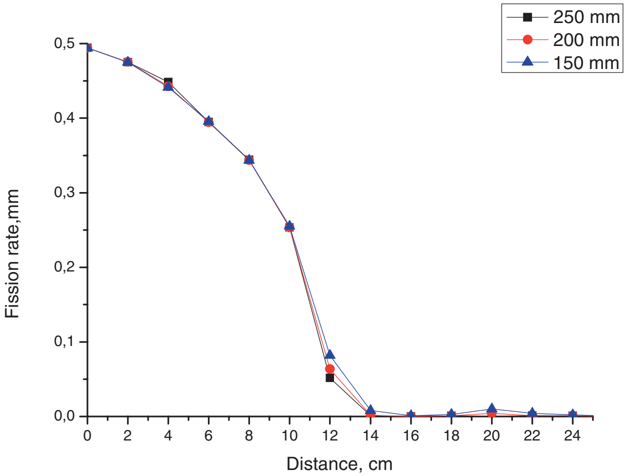


Figure 8. Rate of fission of uranium vs. distance from the collimator axis

For recording the prompt and delayed neutrons at the experimental module, the neutron detector array is used. It is based on the helium-filled counters (320 mm in length, 32 mm in diameter) located in low-density polyethylene moderator. The gamma-rays are recorded by NaI scintillators that were chosen due to low activation (compared to other heavy non-organic scintillators) of NaI by high-energy bremsstrahlung. The scintillator size is 78 x 78 mm.

The multichannel data control and acquisition system includes preamplifier units (located near detectors), shaper unit (located near PC) and FPGA board built-in PC. Each event transmitted to PC is represented by 48 bytes containing codes of number of electron beam pulse, number of detector, pulse amplitude, time of pulse registration (measured from the electron beam pulse). The programmable interlock during 0- 20 msec (3 μsec step) after the electron beam pulse can be set to avoid overload of control system just after beam pulse.

The experimental model of the device for detection of nuclear cycle materials was debugged and tested in 2005. The full-scale experiments with SNM are targeted at the beginning of 2006.

The authors are grateful to the specialists of Moscow Engineering Physics Institute V.V.Kadilin, V.M.Lubkov, A.A.Makarov A.A.Suharev for fruitful discussions and technical support.

References

1. Main Regulations of Account and Control of Nuclear Materials. ISA-LNPP0-RD-1579-R, 2001.
2. Fetter S. Science and Global Security, v.1, n.3, 1990, p. 225.
3. Dytlewski, N., Reinhard, M.I. and Alexiev, D., Investigate different scenarios that can be used to mask nuclear material with other gamma emitters, PART I, II: HEU,” ANSTO, February 2003- 2004.
4. PNL, "Nuclear and radiological threat detection for vehicle cargo ", Pacific Northwest National Laboratory, PIET-43741-QR-005, February 28, 2002,
5. Development of Technology of Non-destructive Identification of Fissile Materials in Control Stations, ISTC Project 0596. http://tech-db.istc.ru/ISTC/sc.nsf/html/projects.htm?open&id=0596.
6. Valentine T. E., L. G. Chiang, J. T. Mihalczo. Preliminary Evaluation of NMIS for Interrogation of Pu and HEU in AT400-R Containers at Mayak. ORNL/M-6648 R4, 2000.
7. Danilov M.M., Petrenko V.V. et al. Atomnaya Energiya, v.77, n. 6, 1994, p. 424.
8. J.L.Jones et al. Pulsed Photoneutron Interrogation: The GNT Demonstration System. WINCO-1225, Idaho, Idaho Falls, 1994.
9. Valdner O.A. et al. The Linear Electron Accelerator U-28. Debugging and Putting into Operation. In “All-Union Seminar on Linear Accelerators”. Kharkov, KhPhTI, 1976.
10. GEANT3.21 Detector Description and Simulation Tool , Manual, CERN Program Library, CERN Geneva, Switzerland, 1993.

INSTRUMENTATION MEASUREMENT AND TESTING COMPLEX FOR DETECTION AND IDENTIFICATION OF RADIOACTIVE MATERIALS USING THE EMITTED RADIATION

V.T. SAMOSSADNY
MEPhI.

V.V. DMITRENKO, V.V. KADILIN, S.V. KOLESNIKOV,
S.E. ULIN, V.M. GRACHEV, K.F. VLASIK, G.L. DEDENKO
D.V. NOVIKOV, Z.M. UTESHEV

Abstract: Simultaneous measurement of neutron and gamma radiation is a very useful method for effective nuclear materials identification and control. The gamma-ray-neutron complex described in the paper is based on two multi-layer ^{3}He neutrons detectors and two High Pressure Xenon gamma-ray spectrometers assembled in one unit. All these detectors were callibrated on neutron and gamma-ray sources. The main characteristics of the instrumentation, its testing results and gamma-and neutron radiation parameters, which have been measured are represented in the paper**.** The gamma-neutron sources and fissile materials reliable detection and identification capability was demonstrated.

Keywords: neutron and gamma radiation, neutron and gamma-ray sources, fissile materials, xenon gamma- spectrometer, multilayer neutron detector, absorptive screens

1. Introduction

The development of modern detection instrumentation is directed to creation of complex systems intended for detection of radioactive fissile materials using their gamma- and neutron radiation.

Besides determining their radiation fields the problem of measuring the spectrometric characteristics of this radiation is very actual, since that gives the possibility not only to detect, but to identify the objects under testing with high reliability.

S. Apikyan and D. Diamond (eds.), Countering Nuclear and Radiological Terrorism, 237–254.

The measuring complex intended for detection and identification of radioactive fissile materials in closed containers using the method of analysis of gamma radiation and neutron spectra has been developed and created in MEPhI.

The feature of this instrumentation is that gamma-radiation spectra and neutron flux in different energetic regions are detected simultaneously and with high resolution for gamma- radiation.

The use of a multi- layer neutron detector and a gamma- spectrometer as a detector of fissile materials stored in closed containers allows to exclude the change of a fissile material to a source simulating the material or withdrawal a part of the fissile material, since the neutron testing is sensitive to the weight of the source. Since the testing is non-sensitive to content and construction of the object under testing, this method is non-intrusive.

The main characteristics of the instrumentation, the results of its testing and the parameters of gamma-and neutron radiation, which have been measured, are represented in the paper.

The basis of the technology demonstration of identification of FM is the passive method of determination of specific characteristics of ionizing radiation emitted by these materials. Spectral characteristics of several groups of gamma-radiation emitted by fissile materials (uranium, plutonium, americium californium, etc.) may be obtained in the real time mode using the xenon gamma- spectrometer. Neutron multi-layer detectors with different sensitivity to neutrons of fixed energy groups allow to obtain information on the integral neutron flux and on ratios of different groups partial intensities under practically pilot conditions in the real time mode, these characteristics being inherent to the sources of the fixed sort.

The information obtained is usually sufficient for identification of fissile materials not protected by any intermediate screen. Information from gamma and neutron detectors is compare after appropriate processing in order to reduce probability of false detection and to improve trustworthiness. Results of comparison of neutron and gamma-detectors indications allow to supplement each other and to make a more correct and substantiated decision on FM identification.

Joint use of neutron and gamma detectors is especially necessary if there are protective and/or absorptive screens, since it is possible to reduce or avoid missing of the undetected FM only under these conditions.

Processing of information foresees use of personnel computer with appropriate software and database of response functions of the EMCC detectors. Response functions for FM behind different absorptive and protective screens are included into the database.

It is desirable to achieve optimum between universality, self-descriptiveness, costs, operation parameters of the method and its instrumentation when choosing means of radiation monitoring for rigging systems of control and account of fissile materials. Threshold, qualitative and half-quantitative and quantitative methods of detection and identification of nuclear materials are distinguished.

Threshold methods allow to fix the excess of the gamma- and neutron background in comparison of the natural one as rapidly as possible. Neither determination of the material amount nor determination of its content are included into the range of problems solved by these techniques. Main requirements to these methods are: high sensitivity, operative control, operation easiness, clear visual representation of the result (sonic and light signals for example).

Qualitative and half- quantitative methods are used for identification of the material type or confirmation of conservation of content of the object under testing using totality of several immediately measured radiation characteristics such as apparatus spectrum of gamma-radiation, integral yield or spectral content of neutrons. These methods do not give quantitative straight information, but they may be an objective measure of confirmation of the content conservation of the objects of any complexity, the probability of accidental coincidence or purposeful imitation of several radiation parameters being negligible. It is possible to make up a special radiation certificate of the object, which may be kept together with other characteristics in the account base.

Quantitative methods of determination of the isotope content and FM weight require carrying out precision spectrometric measurements and additional measurements with use of destructive methods. The main field of their application is independent determination of quantitative characteristics of fissile materials at carrying out independent inspections and forming the account data. Use of such methods is connected with limitations to samples‘ parameters: the isotope content must be homogeneous, other types of FM must be absent as well as great amounts of attending construction materials and so on. There is a wide class of narrowly specialized quantitative methods of determination of isotope, chemical and mass content of FM used for samples of a known type or under rigidly fixed conditions.

The instrumentation complex being developed in the project corresponds to requirements to qualitative and half quantitative methods and may be used for certification of account units of FM, output and input testing of materials containing FM.

2. Device description

A schematic diagram of the gamma-neutron complex is presented in Figure 1. The device consists of two MNDs [1], two HPXe spectrometric gamma-ray detectors [2], multi-voltage power unit "Power" [4] and a PC [3] containing two boards used for gathering spectrometric information.

The outputs of the MNDs are connected to a controller based on the MSC-51 processor, that transfers processed data into the PC via serial interface. This architecture allows connecting the controller to any computer via external interfaces without tampering with the internal buses. Furthermore, this allows freeing up system resources of the PC.

The HPXe gamma-ray detectors are connected to the inputs of two multichannel SBS-55m (Green Star) analyzers [2]. These represent two ISA-compliant boards. Each board includes a shaping-time amplifier and an 8192-channel ADC.

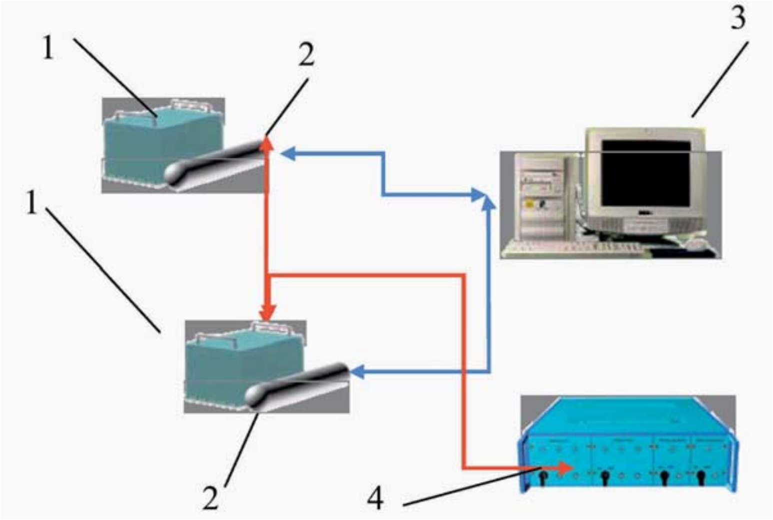


Figure 1. Gamma-neutron complex 1- multilayer neutron detector, 2- gamma-ray detectors, 3- PC, 4- multi-voltage power unit

All units of the measurement complex are connected with cables as described in Figure 1. Application-specific software controls data readout, storage, and analysis. The result of this analysis is detection and identification of radioactive sources.

3. Multilayer neutron detector

MND (fig. 2) consists of multilayer detecting unit based on ^{3}He slow neutron counter and fast neutron moderator (polyethylene); detecting layer signal sharpener amplifiers, multichannel capacity amplifier; counter supply high-voltage transformer unit; data acquisition, preprocessing and transmission to PC electronic unit.

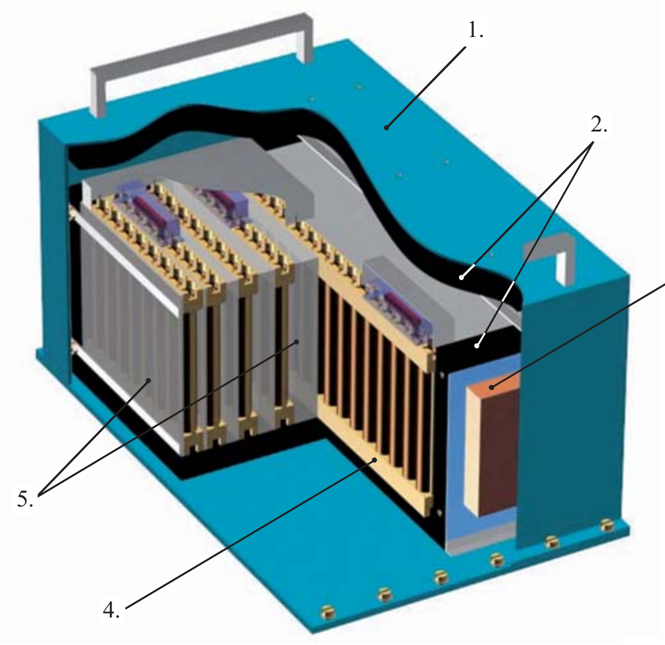


Figure 2. Multilayer neutron detector. 1 – MDN case; 2 – borated polyethylene safeguard; 3 – electronic unit; 4 – polyethylene cassette with helium counters; 5 – polyethylene moderators

Thermal neutrons counters are placed across descending neutron flux with different moderator depths.

Each MND consists of five detecting layers. Each layer contains 16 ^{3}He neutron counters. Polyethylene moderators separate these layers. There is an extra moderator layer next to last detecting layer. Each side of MND except the front one has a borated polyethylene blanket (2,5cm wide). Electronic signal takeout block, voltage transformer, capacity amplifier and system for data acquisition, preprocessing and transmission to PC are placed on the rear and on the side of MND.

Each detecting layer has it's own response function Q_i (i – detecting layer number), characterizing the dependence of detection sensitivity on neutron energy, $S_i(E)$:

$$Q_i = \int_0^\infty S_i(E)\varphi(E)dE\,,$$

$\varphi(E)$ - front descending neutron flux density. Directed divergence iteration method helps in neutron flux energy distribution reconstruction.

Simultaneous registration of every detecting layer response allows to perform control with high total sensitivity in a wide range of energies, from thermal to 14,5 MeV. Obtained data analysis allows real time neutron flux evaluation in some selected energy ranges [4]. Detected neutron flux energy distribution information thus enables studied sources physical characteristics comparison.

Neutron radiation is detected both integrally within 0,025eV-14,5 MeV energy range and separately in 5 energy groups. This approach makes radioactive materials hiding and falsification difficult and allows direct detected radioactive material identification during control.

Radioactive material identification is performed by spectrometry information obtained processing and its comparison with information stored in database.

Information acquisition and processing system is performed as a remote device which may be easily connected to any PC via standard input-output port.

Total sensitivity of different MND configurations is 80 to 150 cm^2 relative to the fission spectrum. The main technical specifications of multilayer neutron detectors are presented in Table 1.

TABLE 1. Main technical specifications of the multilayer neutron detector.

	MDN 1-01	MDN 1-02	MDN 2
Neutron energy groups number	5	5	5
Detecting layers number	5	5	5
Detectors in a layer number	16	16	10
Helium detector type	SI-14N	SI-14N	Helium -4-1
Fission spectrum sensitivity, cm^2	100	80	150
Power supply voltage, V	12	12	6
Mass, kg	40	40	35
Voltage transformation block power supply voltage, V	220	220	220
Autonomous regime	No	No	24 h
Data acquisition system	No	No	+
Data transfer interface	+	+	RS-232
1st energy group width, eV	0	0	0
	1	$1,0\cdot10^4$	$1,0\cdot10^5$
2nd energy group width, eV	1	$1,0\cdot10^4$	$1,0\cdot10^5$
	100	$6,0\cdot10^5$	$1,0\cdot10^6$
3rdt energy group width, eV	100	$6,0\cdot10^5$	$1,0\cdot10^6$
	$4,0\cdot10^5$	$2,0\cdot10^6$	$2,5\cdot10^6$
4th energy group width, eV	$4,0\cdot10^5$	$2,0\cdot10^6$	$2,5\cdot10^6$
	$1,6\cdot10^6$	$8,0\cdot10^6$	$6,0\cdot10^6$
5th energy group width, eV	$1,6\cdot10^6$	$8,0\cdot10^6$	$6,0\cdot10^6$
	$14,5\cdot10^6$	$14,5\cdot10^6$	$14,5\cdot10^6$

4. Xenon gamma-spectrometer

Pressurized xenon gamma-spectrometer (XGS) is used in IMTC for radioactive and fissile materials (RFM) detection. The base of the detector is a cylindrical ionization chamber with screening grid. Detectors main technical and physical characteristics are presented in Table 2. XGS main scheme is presented in Fig. 3.

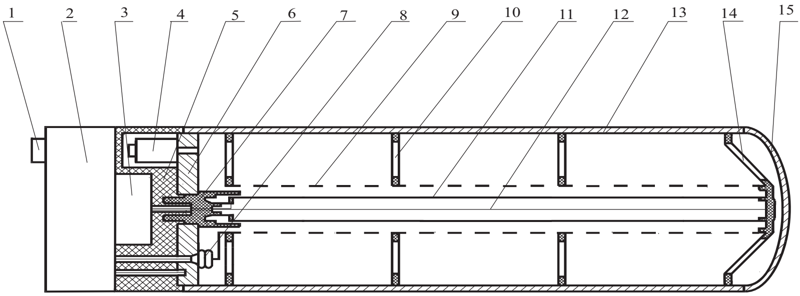


Figure 3. Cylinder configuration XGS with screening grid main scheme 1 - connector, 2 – high voltage power supply source, 3 –charge-sensitive amplifier, 4 - valve, 5 - teflon insulator, 6 - flange, 7 – metal-ceramic hermetic inlet, 8 – screening grid high voltage input, 9 – screening grid, 10 – vibration protected ceramic insulators, 11 - anode, 12 – zero-potential metal hair, 13 - case, 14 – figured ceramic insulator, 15 – ellipsoidal cover

TABLE 2. XGS main characteristics

Detectable gamma quantum energy range (MeV)	(0,05-5)
Gamma-quantum energy resolution (%): E_γ = 662 keV E_γ= 1330 keV	2,1 ±0,5; 1,4 ±0,5
Full absorption peak detection efficiency, in front and normal directions, with energy 662 keV (%):	15; 5
Front and side sensitive surface square (cm^3)	100; 500
Sensitive volume (cm^3)	5000
Xe mass (kg)	2,5
Time resolution (mks)	5-10
Power supply voltage (V)	24
Consumed capacity (Wt)	20
Operating temperature range (°C): with and without heating	10-100; -40-100
External dimensions (mm^3)	Ø120x800
Mass (kg)	9,5

5. XGS experimental studies

Standard gamma-sources set including ^{137}Cs, ^{60}Co, ^{22}Na, etc. were used for XGS main spectrometric characteristics definition. Uranium isotopes, plutonium and Pu-α-Be source gamma-radiation was also measured. Some gamma spectra of different gamma sources, measured with XGS are presented in Fig. 4.

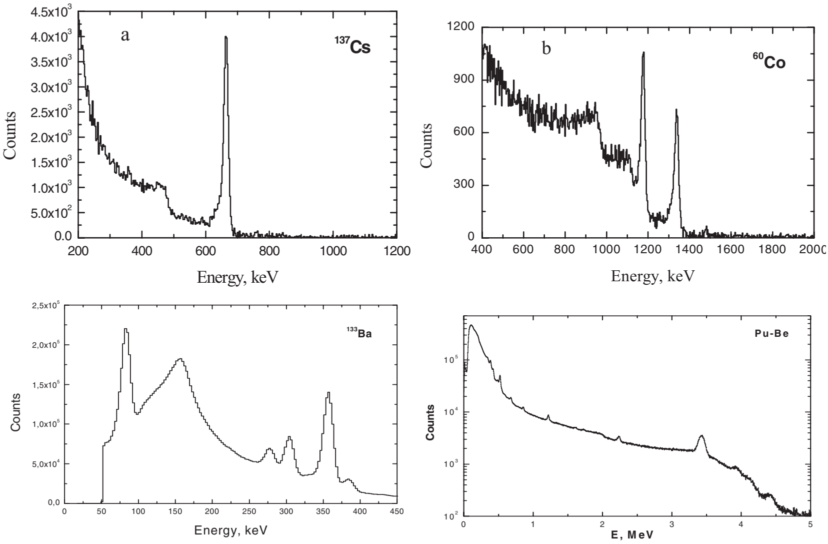


Figure 4. Gamma-spectra from different gamma-sources

Different modifications of MND were used for different radionuclide neutron sources response study. Detecting layers relative responses obtained with MND1, using different standard radionuclide sources: ^{238}Pu-α-Be, ^{239}Pu-α-Be, ^{252}Cf, and ^{252}Cf with moderator (polyethylene sphere, d=12cm) are presented in Fig 5. Results presented in Fig 6 show significant difference in relative responses for ^{252}Cf and Pu-Be sources, and practically exact agreement in responses for ^{238}Pu-Be and ^{239}Pu-Be sources, which have similar neutron spectra, that indicates MND's usability in sources identification.

Measurement results obtained with use of ^{252}Cf and ^{239}Pu-α-Be neutron sources are presented in Fig. 6 to demonstrate MND2 capabilities. Significant difference in neutron flux distributions is shown. This indicates that MND2 just like MND1 is capable to discriminate fission spectra neutron sources and radioisotope neutron sources based on (α, n) reaction.

Relative distributions showed in Fig. 5 allow fission spectra neutron sources and radioisotope neutron sources distinguishing, but energy distribution difference evaluation becomes possible after special mathematical processing only. This operation is performed by directed divergence method, which allows almost real-time presentation of front descending neutron flux energy distribution.

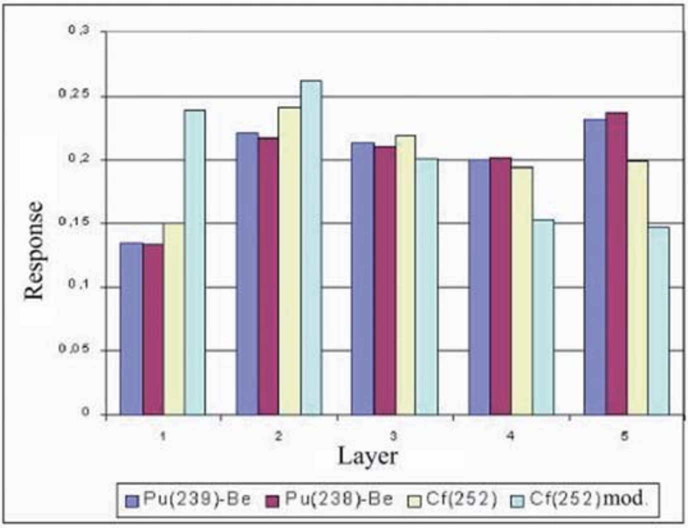


Figure 5. MDN1-01 detecting layers relative responses

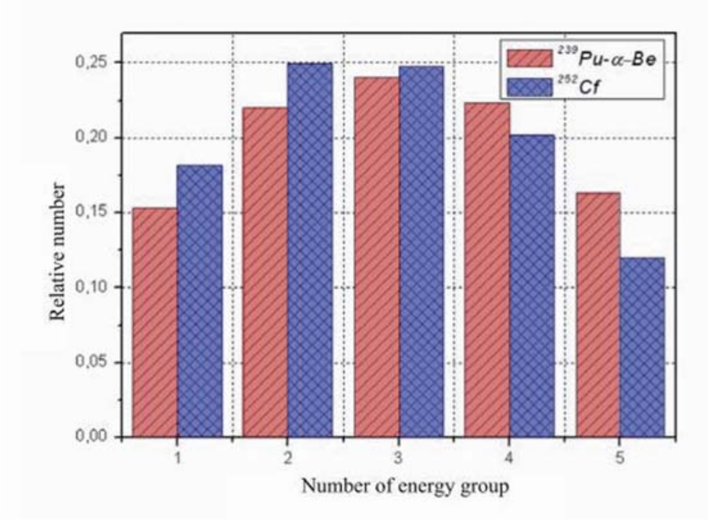
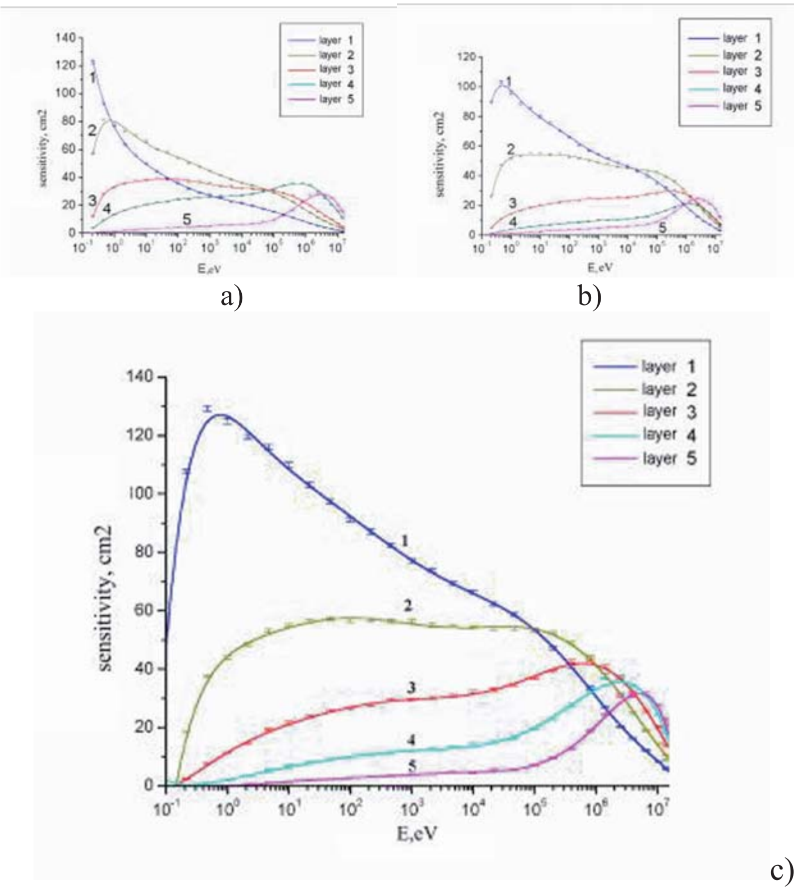


Figure 6. MDN2 detecting layers relative responses

A charged particles electrostatic accelerator was used for MND detecting layers sensitivity dependence on neutron energy definition. Monoenergy neutron beams were obtained on the accelerator in 7 keV – 17 MeV energy range. The results for lower energies were calculated. Fast neutrons (fission spectra) and thermal neutrons detection sensitivity were also defined during the experiment. Presented in Fig. 6, 7, the results obtained allowed to create neutron detection sensitivity matrix for MND five energy groups and to perform some experiments on neutron flux energy distribution reconstruction.



a) b)

c)

Figure 7. Detecting layers sensitivity dependence on neutron energy a)- MND1-01, b)- MND1-02, c)- MND2

Energy distribution reconstruction results after mathematical processing are presented in Fig. 8. Fluxes distributions of neutrons emitted by ^{252}Cf and ^{239}Pu-Be sources are additionally presented in the picture.

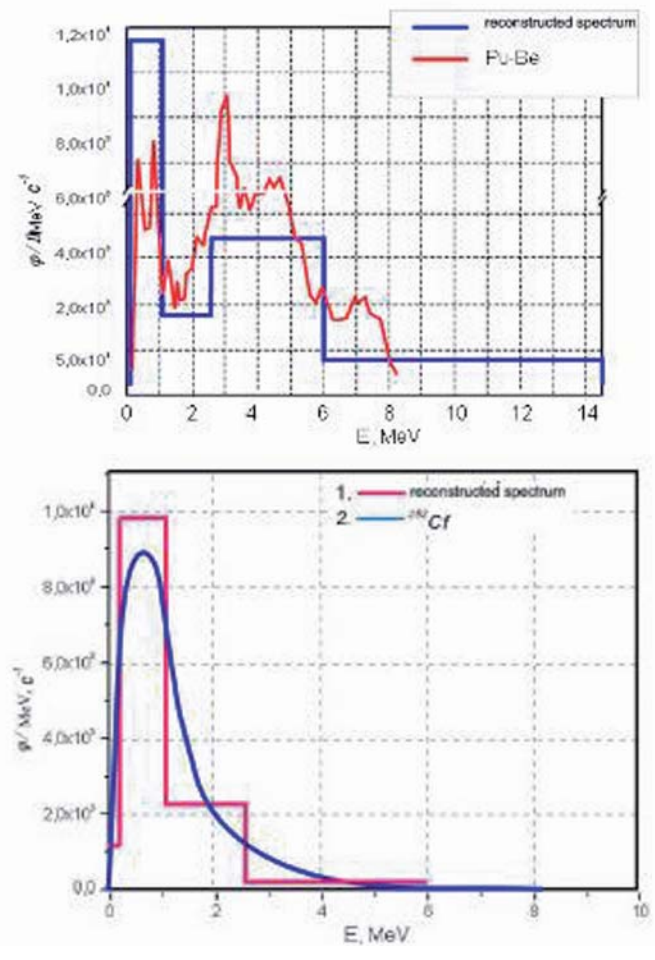


Figure 8. Neutron fluxes energy distribution reconstruction results

The results presented show the match of theoretical and experimental flux distributions of neutrons emitted by radioactive sources (divergence do not exceed 10%) and qualitative difference between two studied neutron spectra.

In case neutron source is placed inside a hydric container, a surface neutron flux will be much softer than a source neutron flux. An experiment was carried out in order to display MND2 abilities to distinguish safeguarded sources. ^{239}Pu-α-Be neutron source was placed inside industrial safeguards: AT316.004 (Russia) and 50240 (USA), with different guarding layer width. Distance between detector and container was about 1m.The results obtained and processed are presented in the Pic 9. The reconstructed neutron flux energy distribution from the same source without container is also presented in the picture for visualization.

The measurement results indicate that neutron spectrum of a ^{239}Pu-α-Be source placed inside containers has changed significantly. There were almost no neutrons of energies in 0,1 to 6,0 MeV range, but neutrons of higher energies have almost lossless overpassed the safeguard.

Multimodule neutron detector allows reliable distinction of neutron spectra from different isotope sources; it indicates it's possible to use the detector for spectral controlling of containers with different neutron sources inside. This maybe realized with data acquisition and processing system, which provides neutron spectra components reconstruction in five energy groups within considered energy range (thermal to 14,5 MeV). The proposed detector optimization seems possible to increase selectivity to neutron spectra of any source type due to moderator layers width selection in detecting layers.

Demonstration measurements were carried out in order to test IMTC efficiency in real-life environment. The experiments with fissile materials samples placed inside the guarding containers were taken at the RFNC ARRITP industrial area #20. The results obtained at XGS are represented in Figs. 10-12.

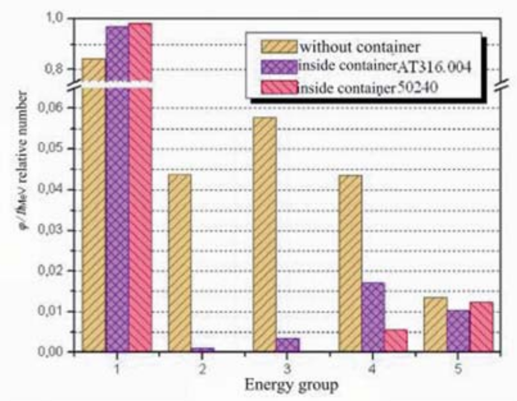


Figure 9. The results of neutron spectrum reconstruction by MND2 responses for 239Pu -Be source placed inside the AT316.004 (Russia) and 50240 (USA) containers. (Energy groups ranges according Table 1)

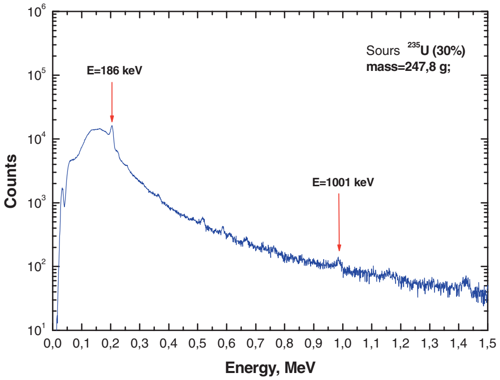


Figure 10. ^{235}U- source spectrum. Source to detector distance is 20cm

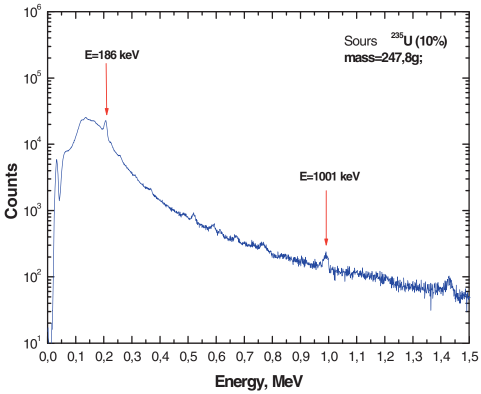


Figure 11. ^{238}U (10%)-source spectrum. Source to detector distance is 16cm

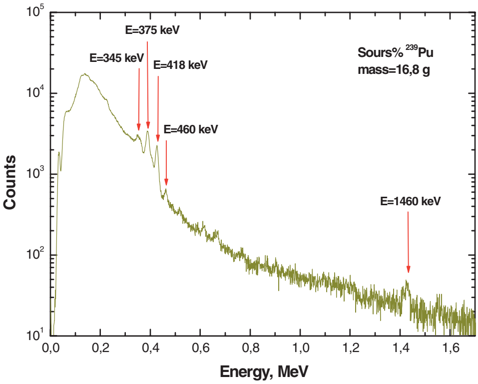


Figure 12. ^{239}Pu-source spectrum. Source to detector distance is 60cm

In spectra presented gamma-lines corresponding to specific gamma-sources may be distinctly seen. Gamma-lines measured with good resolution provide presented fissile materials detection and identification capability.

Some results obtained with MND2 are presented in Figs. 13-15. Similar measurements were taken with MND1-01 and MND1-02. Detectors responses with background (marked green) taken in consideration are presented in the diagram.

MND2 responses in detection of neutrons from calibration sources (^{252}Cf (76-001) with yield $6.72 \cdot 10^6$ n/s ($3.58 \cdot 10^6$ n/s at the measurement date) and ^{238}Pu-Be (FNS-8-556) with yield $6.73 \cdot 10^6$ n/s) out of containers are presented in Fig. 13.

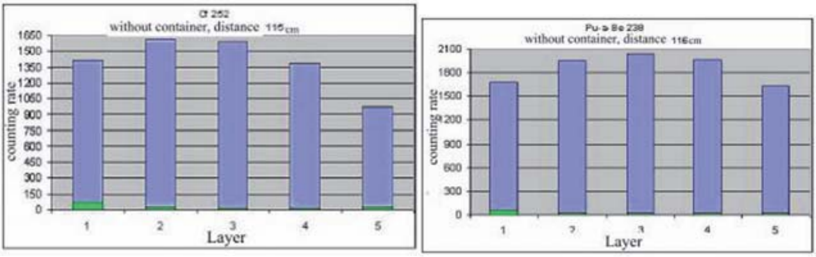


Figure 13. MND2 responses in detection of neutrons from calibration sources out of containers

Both total detectors sensitivities and each particular layer sensitivity were defined using the results of experiments with calibration sources described above. The results are presented in Table 3.

TABLE 3. Detectors sensitivities [cm^2] in measurements with calibration sources (^{252}Cf with yield 3.58··10^6 n/c (distance is 115cm) and ^{238}Pu-α-Be with yield 6.73·10^6 n/c (distance is 116cm)) out of containers

Detector	Source	Layer					
		1	2	3	4	5	Sum
MND-1.01	^{252}Cf	17.00	25.55	23.26	42.30	40.69	*148.80*
	^{238}Pu-α-Be	11.51	16.76	15.19	28.88	31.35	*103.69*
MND-1.02	^{252}Cf	30.19	33.42	28.18	26.74	29.41	*147.94*
	^{238}Pu-α-Be	19.41	21.36	18.54	18.71	22.57	*100.59*
MND-2	^{252}Cf	62.39	73.51	72.84	63.27	44.42	*316.43*
	^{238}Pu-α-Be	40.41	48.15	50.54	48.85	40.10	*228.06*

The results presented show larger values of sensitivities than those presented in Table 1, because the measurements were carried out without screening cone, so both direct source radiation and scattered radiation were detected. Comparison with the results obtained before using a screening cone placed between the source and the detectors (MND1-01 and MND1-02) show that sensitivity values measured have increased almost twice as much. The circumstance mentioned must be necessarily kept in mind in neutron flux spectral components reconstruction using the results of measurements taken without scattered radiation subtraction.

MND2 responses in registration of neutrons from the same sources placed inside the container are presented in Fig. 14. MND responses changing due to detected neutrons spectra changing is observed, ^{252}Cf source and ^{238}Pu-Be source distinction is still possible in that case.

MND responses in detection of neutrons from sources placed inside the sealed guarding containers are presented in Fig. 15. The right diagram presents the detector responses in registration of radiation of a Pu sample with mass 16,8g, placed inside the sealed AT-316.004 container at the distance of 15cm, the left one shows the detector responses in registration of radiation of a U sample with mass 247,8g, enriched till 36% of 235 isotope, placed inside the sealed AT-316.005 container.

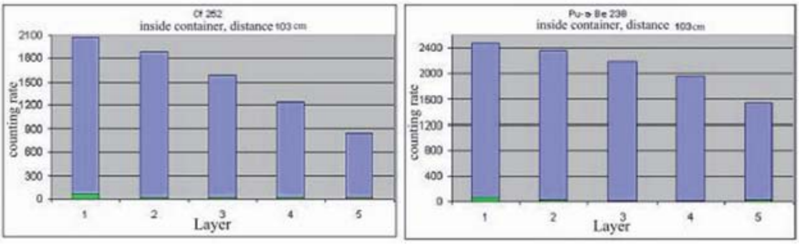


Figure 14. MND2 responses in registration of neutrons from calibration sources inside the container

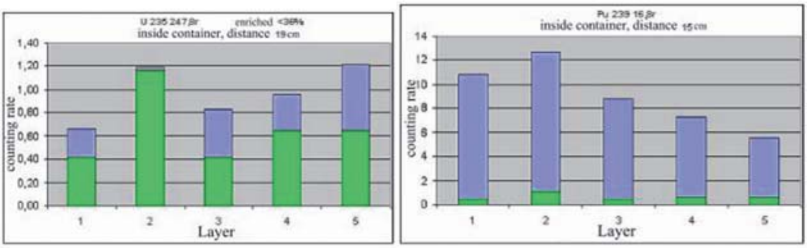


Figure 15. MND2 responses in registration of neutrons from fissile materials samples placed inside the sealed guarding containers

The results presented in Figs. 14 and 15 comparison shows that MND responses with ^{252}Cf neutron source, plutonium and uranium samples exceed background a little. The layers 3, 4 and 5 give the greatest background excesses. This phenomenon is caused by low neutron yield in uranium isotopes, besides, the greater part of neutrons may be caused not by spontaneous fission, but by the (α,n) reaction on light additives, which produces neutrons of more hard spectrum than the fissile neutrons.

6. Conclusions

The gamma-ray-neutron complex is based on two multi-layer ^{3}He neutrons detectors and two High Pressure Xenon gamma-ray spectrometers assembled in one unit. All these detectors were callibrated on neutron and gamma-ray sources.

As the γ-n radiation spectra presented show, the measurements taken using IMTC, allowed detection and identification of uranium and plutonium samples placed inside the special containers by their gamma- and neutron radiation.

The gamma-neutron sources and fissile materials reliable detection and identification capability was demonstrated during the experiments. IMTC detectors' high sensitivity and obtained results' reliability allow to conclude the commercial usage availability of the created measurement complex in different branches of radiation control.

Acknowledgements

The authors would like to express their gratitude to RFNC ARRITP members: Startsev A.N., Zhabunin V.M., Morozov A.N. for their assistance in measurement complex testing.

The work was supported by ISTC grants № 348 and № 1644.

References

1. L. Neymotin, V. Sviridova, Material Control and Accounting Instrumentation Catalog. 1998, BNL & VNIIA.
2. Seldyakov YU.P., Kondrashov M.V., Dorin A.B. et. al. "Current generation for nuclear radiation spectrometers and their application in science and technique", Proc., SNIP, 1997, p.35.
3. Ulin S.E., Grachev V.M., Dmitrenko V.V., et. al. Proc of SPIE Hard X-ray, Gamma-Ray, and Neutron Detectors Physics conf., Denver 1999, vol. 37-68, p.271.
4. G.L. Dedenko, V.V. Kadilin, A.A. Kaplan, S.V. Kolesnikov, A.V. Samossadny,
5. V.T. Samossadny, Multilevel detector for operative estimation of spectral content fields of neutrons. Equipment and Techniques, №3, 2002, p. 14-23.
6. M.Z. Tarasenko, Mothods of minimum of divergence in the tasks searching distributions. Preprint FEI N 1446, Obninsk 19832, p16.

USING ASSOCIATED PARTICLE TECHNIQUE FOR DETECTION OF SHIELDED NUCLEAR MATERIALS (NM) DETECTION OF HEAVILY SHIELDED NM

A.V. KUZNETSOV[1], D.N. VAKHTIN, I. YU. GORSHKOV,
A.V. EVSENIN, O.I. OSETROV
V. G. Khlopin Radium Institute, 194021, 28, 2nd Murinsky pr.,
Saint-Petersburg, Russia

Abstract: A novel method of simultaneous detection of concealed explosive substances and heavily shielded nuclear materials is described. Experimental setup based on a portable DT neutron generator and detectors of neutrons and γ-rays has been created and tested. Results of tests with real fissioning materials are presented.

Keywords: neutrons, gamma rays, neutron generator, correlation analysis.

1. Introduction

One of the weak points of most existing instruments used to detect and characterize radioactive materials, including fixed automated portals, is their inability to detect fissioning materials that are shielded by substances that absorb their spontaneous gamma radiation. "Passive" methods (like gamma-spectroscopy) are unable to detect fissioning materials shielded by >5 cm of lead. Detection of any shielded fissioning material can be done by measuring fission neutrons induced by external neutron radiation – "active" methods.

Application of the associated particles technique (APT) to detection of shielded fissioning materials offers a unique possibility to build an all-in-one portable system for detection of both neutron- and γ-ray emitters and materials with no significant spontaneous radiation. The most efficient approach is to use a portable DT neutron generator with built-in position-sensitive detector of

---

[1] E-mail: APL@ATOM.NW.RU

S. Apikyan and D. Diamond (eds.), Countering Nuclear and Radiological Terrorism, 255–269.

associated α-particles (Associated Particle Technique - APT) coupled with a Nanosecond Neutron Analysis – NNA [1-5].

Combination of APT/NNA offers the following advantages/possibilities:

- Detects presence of a source of secondary neutrons in the inspected volume.
- Identifies the found fissioning material.
- Drastically improves the signal-to-noise ratio, and thus reduces the detection time by about 100 times compared to non-APT "active" methods.
- Determines the exact position of the fissioning material in the inspected volume, using position sensitivity of the associated particle detector.

2. Experimental method

The proposed device will be based on the Nanosecond Neutron Analysis (NNA) method, which relies on measurement of correlations between 14 MeV neutrons produced by a portable neutron generator, and secondary radiation (neutrons and energetic γ-rays), that is produced by these neutrons in the material of the investigated object. The secondary radiation will be detected in very narrow (few nanoseconds) time intervals counted from the time of emission of each neutron from the neutron generator. This time, in turn, will be determined by detecting α-particles, that accompany neutron emission in the reaction $d+t \rightarrow n+\alpha$, by a position-sensitive or segmented semiconductor detector built into the sealed vacuum of the neutron generator. By detecting secondary radiation in coincidence with a-particles, one would be able to select the region of space, in which this secondary radiation has been produces by the primary neutron, thus achieving substantial suppression of the background arising from reactions of the primary neutrons on surrounding materials. NNA is a further development of the Associated Particle Technique (APT).

If the fissioning material is shielded by some neutron absorber (water, polyethylene), such absorber will be immediately visible by a huge number of secondary γ-rays, which it will produce in response to the probing 14 MeV neutrons. In a similar way, the proposed device will detect any explosive material by presence of carbon, nitrogen and oxygen.

2.1. DESIGN OF THE SYSTEM

The present design of the device for detection of "dirty bombs" based on Nanosecond Neutron Analysis is presented in Figure 1.

Numbers on the figure indicate: 1– detection module; 2 – neutron generator with built-in α-particle detector; 3 – γ-ray detectors based on $\varnothing 7.5 \times 7.5$ cm^3

BGO crystals; 4 – three neutron detectors based on 7×7×21 cm^3 plastic scintillator; 5 – inspected volume; 6 – remote control PC; 7 – data acquisition electronics.

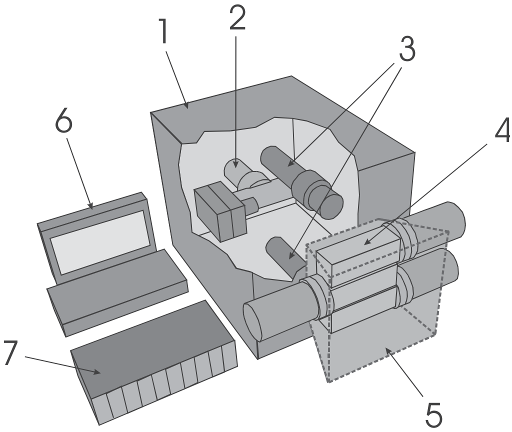


Figure 1. Preliminary design of the device for detection of "dirty bombs" based on Nanosecond Neutron Analysis (NNA)

2.2. RESULTS OF MATHEMATICAL MODELING OF FISSIONING MATERIALS DETECTION WITH MCNP CODE

Mathematic modeling with MNCP5 code for fissioning material detection was carried out. Three neutron detectors with dimensions 7×7×21 cm^3 each were placed at 40 cm from target of neutron generator as shown on Figure 2.

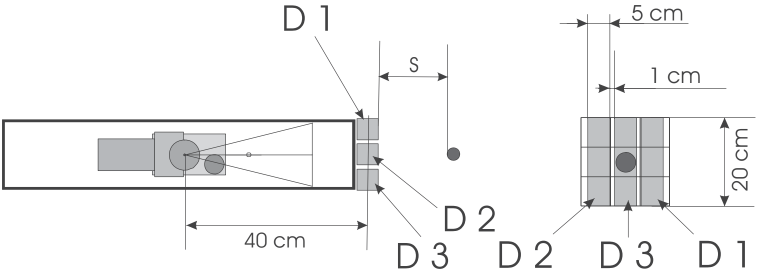


Figure 2. Sketch of the simulation geometry with three neutron detectors based on 7×7×21 cm3 plastic scintillator (D1, D2, D3). left –top view, right – front view; S – distance between the front plane of neutrons detectors and the investigated sample

The distance between the target of the neutron generator and the central plane of the neutron detectors was fixed at 40 cm. In the simulations, the detection threshold for neutrons was set at 1 MeV, and for γ-rays at – 0.1 MeV. The intensity of the neutron generator was assumed to be 2×10^7 neutrons per second into 4π (this value is close to the value that is routinely used in experiments).

The associated particle detector (α-particle detector) consisted of 9 segments with dimensions of $1\times1\text{cm}^2$ each, and covered the total solid angle of 0.25 srad. The average counting rate from one segment of the associated particle detector was estimated to be $4.4\times10^4\text{s}^{-1}$. The width of the coincidence window for neutron detection was 30 ns (relative to the signal from the α-particle detector). The main results of MCNP calculations are presented in Table 1.

TABLE 1. Results of MCNP simulations of the device for detection of fissioning materials. *=Coincidence rate between neutron detectors D1 and D2

Effect from 1kg WP sample	Distance to sample	n+n*	n+γ	γ+γ
	S = 5 cm	$27.9\ \text{s}^{-1}$	$12.3\ \text{s}^{-1}$	$1.7\ \text{s}^{-1}$
	S = 10 cm	$9.3\ \text{s}^{-1}$		
	S = 15 cm	$3.1\ \text{s}^{-1}$		
	S = 20 cm	$1.9\ \text{s}^{-1}$		
Counting rate in D1		$2.84\times10^4\ \text{s}^{-1}$		
Background				
cross-talk	without NNA	$271\ \text{s}^{-1}$		
	with NNA	$0.36\ \text{s}^{-1}$		
accidental coincidences	without NNA	$24.2\ \text{s}^{-1}$		
	with NNA	$0.032\ \text{s}^{-1}$		
total background	without NNA	$295\ \text{s}^{-1}$		
	with NNA	$0.39\ \text{s}^{-1}$		

Thus, the effect from a 1 kg WP (weapon grade plutonium) sample (coincidence between neutrons) is about $28\ \text{s}^{-1}$ in close geometry (distance between neutron detectors and the sample S = 5 cm), and drops to $3\ \text{s}^{-1}$ for S = 15 cm. This effect must be separated from the background, which has the following sources:

- Cross-talk in neutron detectors from primary 14 MeV neutrons;
- Accidental coincidences in neighboring neutron detectors due to high counting rate from primary 14 MeV neutrons;

- γ+γ coincidences in neutron detectors; and
- n+γ coincidences in neutron detectors.

By using Nanosecond Neutron Analysis (NNA) – i.e., including an α-particle as third components of the coincidence analysis (triple α-n-n coincidences), the background from the first two sources can be reduced from a total of 295 s^{-1} down to 0.39 s^{-1}.

The last two sources of the background (γ+γ and n+γ coincidences) can be suppressed by using time-of-flight spectra. Calculated TOF spectra for various distances between neutron detectors and the sample are shown in Figure 3.

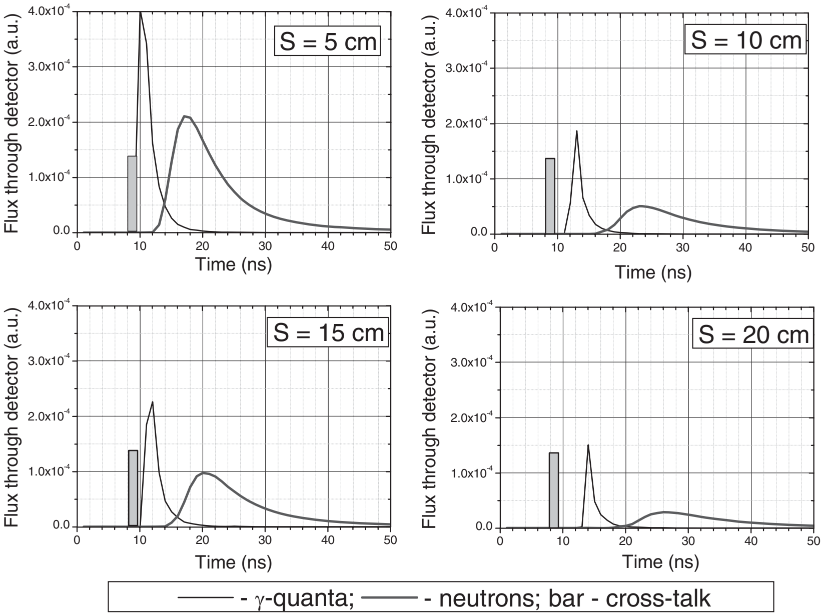


Figure 3. Calculated neutron and gamma time-of-flight spectra for different distances between neutron detectors and the sample. Cross-talk from 14 MeV neutrons is shown by gray bar

Calculations show that in all cases, 1 kg of WP can be detected in a few seconds time by using NNA – triple coincidences between "tagging" α-particle and two fission neutrons. The same calculations have been carried out with heavily shielded (by 5 cm of lead) samples.

2.3. SAFETY ISSUES OF THE PROTOTYPE PRODUCT

Dose load at different distances from the working neutron generator were calculated using MCNP code. The safe distance for the operator during the working cycle of the device was estimated to be about 6 meters at NG intensity 5×10^7 n/s.

3. Experimental results

3.1. NEUTRON DETECTORS

Based on results of mathematical modeling, a new concept of neutron detection for the proposed device for detection of shielded nuclear materials has been explored.

The main difficulty associated with extraction of coincidences from fission neutrons is connected with very high background in neutron detectors due to detection of primary 14 MeV neutrons from the neutron generator. If neutron detectors are placed outside the “pseudo beam” of tagged neutrons (i.e. those neutrons, for which the moment of their production in the neutron generator and flight directions are known from the detected associated α–particle), time of arrival of these background primary neutrons is uncorrelated with the detection time of α–particles. On the contrary, if neutron detectors are placed within the “pseudo beam” of tagged neutrons, then each detected primary 14 MeV neutron must have its tagging α–particle detected by the associated particle detector located inside the neutron generator. Moreover, the time of arrival of such background primary neutrons to the neutron detector is fixed by the distance from that detector to the target of the neutron generator. Thus, the background becomes correlated in time with the detection of the associated particles, and can be suppressed by performing time-of-flight analysis of the detected neutrons relative to tagging α–particles.

Three neutron detectors based on plastic scintillator with dimensions $7\times7\times21$ cm^3 were produced (see photo on *Figure 4*). Detectors can be stacked together to form a square with external dimensions about 25×25 cm^2 and 8 cm thick, which fits into the “pseudo beam” of tagged 14 MeV neutron at distance about 55 cm from the target of the neutron generator. Thus, any primary neutron detected by this assembly should in principle have a counterpart α–particle detected at one of the nine segments of the associated particle detector. Thus, for each such “background” neutron its time-of-flight is known: they all should arrive to neutron detectors about 11 ns after being emitted from the NG target (they all have ~5 cm/ns velocity; 5cm/ns × 11ns=55cm flight path).

It was estimated, that about 90% of primary neutrons pass through the assembly of neutron detectors unaffected, so such detector placement does not significantly reduce the intensity of neutrons incident on the inspected object, which can be located very close to (e.g. right behind) neutron detectors.

Figure 4. Neutron detector based on plastic scintillator and a photo multiplier

3.2. EXPERIMENTS WITH URANIUM SAMPLES

3.2.1. *Geometry*

First experiments were carried out using four aluminum-coated cylinders (∅2×7 cm^3) of metallic depleted uranium. These samples were placed at different locations relative to one neutron detector, as shown on *Figure 5* and *Figure 6*.

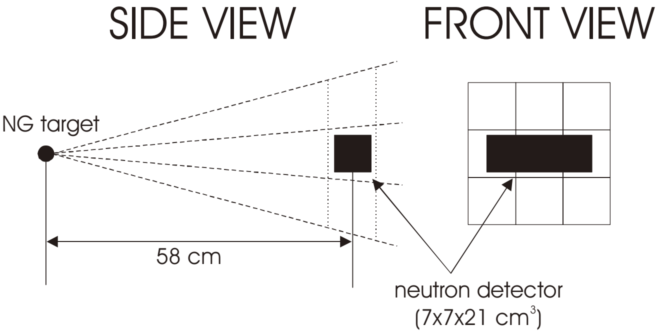


Figure 5. Measurement geometry. Rectangular neutron detector was placed at 58 cm from the target of the neutron generator (NG) so, that if fit within the “voxels” corresponding to three segments of the associated particle detector (“pseudo beam” of tagged neutrons)

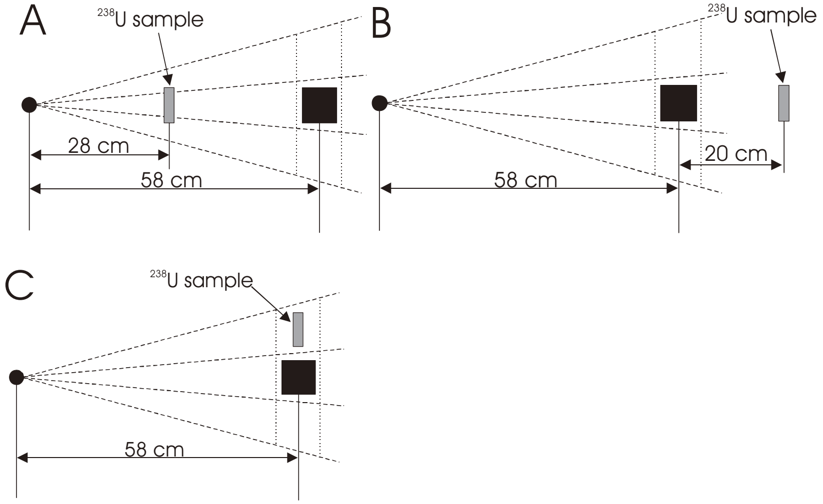


Figure 6. Three geometries, in which measurements with the U sample were carried out: A – sample between the NG target and the neutron detector; B – sample behind neutron detector; C – sample above neutron detector. The neutron detector was inside the "pseudo beam" of tagged neutrons (see *Figure 5*)

3.2.2. *Results*

One of the most important problems in detection of a weak flux of the secondary neutrons emitted in the induced fission of hidden fissile materials is reduction of the neutron and gamma backgrounds. Considerable part of this background comes from primary 14 MeV neutrons that are directly detected by the neutron detector.

In order to investigate this problem the background measurements for two locations of the neutron detector with respect to the "pseudo beam" of neutrons tagged by α–particles detected in different segments of the associated α–particle detector have been performed.

In the first series of experiments a neutron detector was placed outside the "pseudo beam" of tagged neutrons, so that α–particles, which accompanied 14 MeV neutrons hitting this detector, were not detected in the associated α–particle detector. In this case all the accidental coincidences between events in the neutron detector and α–particles were uncorrelated in time.

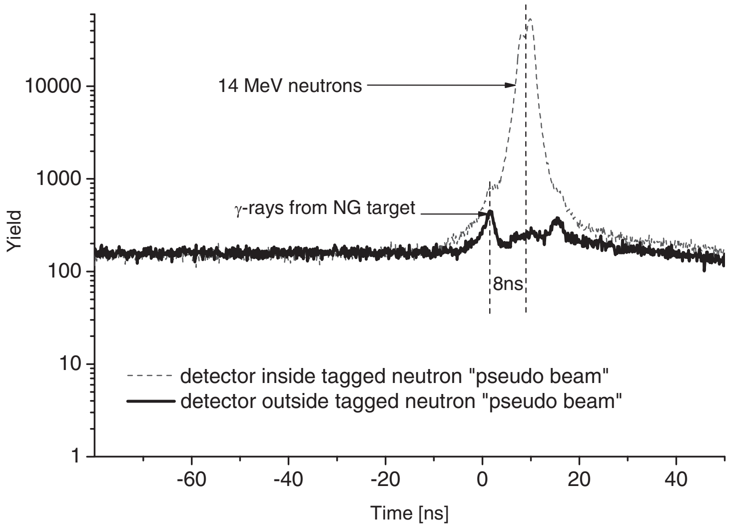


Figure 7. Background time distribution measured by means of neutron detector situated inside (dashed line) and outside (solid line) the "pseudo beam" of tagged neutron

In the second series of experiments the neutron detector was placed inside the "pseudo beam" of tagged neutrons (see examples of these geometries at *Figure 6*). In this case most of the primary 14 MeV neutrons hitting the neutron detector had their accompanying α–particle detected in one of the segments of the associated α–particle detector, so they produced a sharp peak in time-of-flight distribution. If the time resolution of the whole system allows one to separate between the peak of primary 14 MeV neutrons from the γ–rays and neutrons from induced fission, this geometry is preferable. In this case the neutron detectors are located at the closest possible point to the inspected object, and this may overweight the reduction of the 14 MeV neutron beam on the inspected object by about 10% due to reactions in the neutron detector.

Figure 7 demonstrates the difference in the time spectrum for different locations of the neutron detector. The background level estimated over the part of the spectrum corresponding to pure accidental coincidences (to the left from the "0" time – moment of emission of the 14 MeV neutron from the NG) and normalized to the total number of detected associated α–particles is approximately 10% higher in the case of the detector located outside the "pseudo beam" of tagged neutrons. This is due to the fact, that primary 14 MeV neutrons, that would have otherwise contributed to this uniformly-distributed background, have their accompanying α-particle detected in the associated particle detector inside the neutron generator, and are "collected" within a narrow peak corresponding to their time-of-flight from the NG target to the neutron detector. On the other hand, the background level at the right side of the spectrum (to the right from the 14 MeV neutron peak) is higher in the case of neutron detector inside the "pseudo beam" due to a "tail" of scattered neutrons. Thus, the optimal choice of the detector geometry depends on the relative positions of the NG target, neutron detector and the inspected object. This question will be addressed in further studies.

The goal of the next set of experiments was to determine time resolution of the α–detector – neutron-detector pair, and to measure time-of-flight spectra of different spectral components. Results are summarized on *Figure 8*.

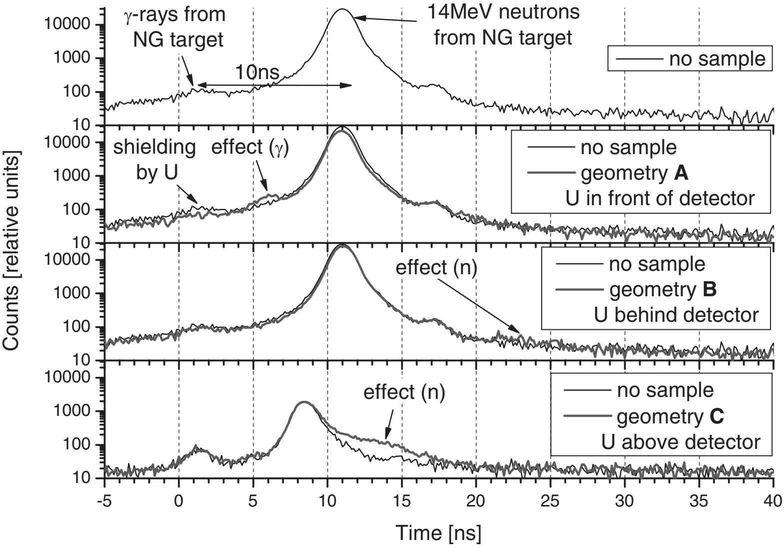


Figure 8. Time-of-flight spectra of events recorded in the neutron detector relative to associated α–particles detected in the built-in α–detector. Spectra obtained without sample for each case are shown with thin lines

The top time-of-flight spectrum corresponds to measurement without sample. Only events with α–particle detected in the central segment of the nine-segment α–detector were selected. No neutron/gamma discrimination was used. The main contribution to the spectrum comes from primary 14 MeV neutrons hitting the neutron detector (its central part corresponds to the central segment of the α–detector, see *Figure 5*). The width of this peak is FWHM = 1.55 ns, which includes time resolution of the α-n detector pair, as well as contribution from final dimensions of the α–detector segment neutron detector (width 7 cm). Thus, intrinsic time resolution of the α-n detector pair (plus electronics) is about 1 ns, which is enough for time-of-flight analysis.

Another feature of the top spectrum is a small peak coming from γ–rays produced in the material of the target of neutron generator. These γ–rays reach the neutron detector in about 2 ns, compared to ~11 ns needed for that for a 14 MeV primary neutron. So, the peak corresponding to these γ–rays is located about 10 ns left from the main 14 MeV neutron peak.

Another small peak ~8 ns after the 14 MeV peak comes from γ–rays produced by fast neutrons in the construction materials of the experimental setup.

U sample in front of neutron detector (geometry A).

When four U cylinders were placed between the NG target and the neutron detector (second spectrum from top on *Figure 8*), the following effects can be seen:

1. A small peak of γ–rays produced in NG target is reduced compared to the case without U sample due to shielding of the central part of the neutron detector by U cylinders.
2. A peak of prompt fission γ–rays appears ~5 ns after the γ–rays from the NG target and ~5 ns before the main 14 MeV neutron peak. These 5 ns represent extra time needed for 14 MeV neutrons to reach the U sample (flight path 28 cm).
3. Fission neutron are not visible, since they fall right in the huge main peak of 14 MeV neutrons.

U sample behind neutron detector (geometry B).

In geometry B effect from fission neutron can be seen as a wide distribution around TOF = 25 ns. Out of this time, ~16 ns are needed by 14 MeV neutrons to reach the U sample (a total flight path of ~80 cm), and the remaining 9 ns are needed by slower fission neutrons (which have average velocity about 2 cm/ns) to fly back to the neutron detector (flight path ~20 cm). γ–rays from fission in this case are not visible, since they fall right into the huge peak of 14 MeV primary neutrons. Though the time distribution of fission neutrons is rather broad, the integral number of events in it is consistent with the geometry of the experiment.

U sample above neutron detector (geometry C).

This experiment was carried out in order to demonstrate the use of position sensitivity of the associated-particle detector built into the neutron generator. The uranium sample was located in the area above the neutron detector corresponding to segment #6 of the associated-particle detector. So, any effect from this sample was expected in coincidence with segment #6, not with the central segment #9, as in the previous experiments. Time-of-flight spectrum from neutron detector relative to α–particles detected in segment #6 of the associated particle detector is shown on the bottom panel of *Figure 8*. The spectrum was not corrected for the time shift, which is due to the geometry of the associated particle detector, and the effect of scattering of α–particles on the NG target, so the "zero" time on the time axis in this case does not coincide with the "0" label of the axis.

The main peak of primary 14 MeV neutrons in this experiment is a factor of ten lower than in the previous cases. This reflects the fact, that only a small part of the neutron detector falls into the "tail" of the area corresponding to segment #6 of the tagging α–detector. The peak of γ–rays from the NG target is well pronounced, since neutrons coinciding with α–particles detected in segment #6 have to pass through thicker layer of the target holder than those coinciding with α–particles from segment #9.

A rather broad and well-pronounced peak about 5 ns after the main peak from 14 MeV neutrons corresponds to fission neutrons from the U sample. These extra 5 ns are needed by neutrons to travel ~10 cm gap separating the U sample and the neutron detector. Fission γ–rays coincide in time with the maximum of the main peak from primary 14 MeV neutrons.

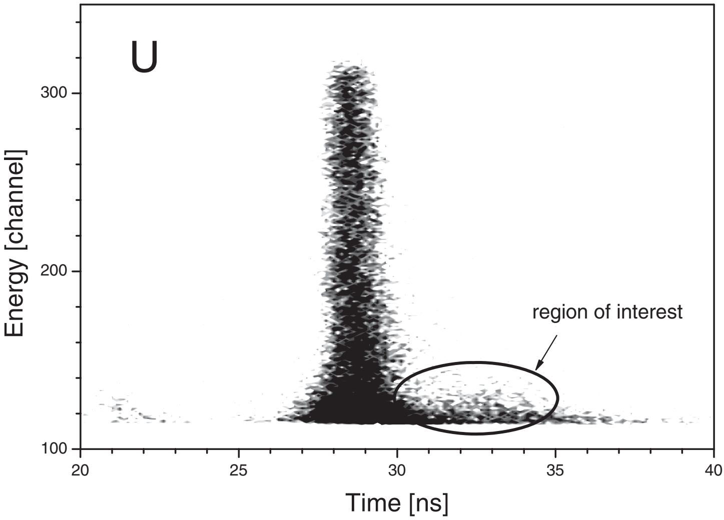


Figure 9. Two-dimensional amplitude-time distribution measured with U sample in the geometry shown in *Figure 6*C

Role of amplitude distribution.

Another task was to investigate the role of amplitude distribution measured by the neutron detector for better discrimination of fission neutrons. Over 80% of fission neutrons have energies below 5 MeV, while most of the detected 14 MeV neutrons leave more than 5 MeV in the detector. In *Figure 9* an example of a two-dimensional plot measured in the geometry shown in *Figure 6*C is presented. It can be seen that at amplitudes above the region, where fission neutrons are expected, there are some background events (most probably scattered incident neutrons), which can be removed by introducing of an upper amplitude threshold.

In *Figure 10* a time-axis projection of the distribution shown at *Figure 9* is given with and without pulse-height discrimination in the amplitude channel (events with energies over 145 ch were rejected). The spectra were normalized to the maximum of the peak at –15 ns corresponding to simultaneous arrival of prompt γ-rays created by 14 MeV neutrons in the NG target. One can note, that the fission neutron distribution in the vicinity of –4ns is more pronounced in the discriminated case, and the peak corresponding to the incident 14 MeV neutrons is somewhat suppressed.

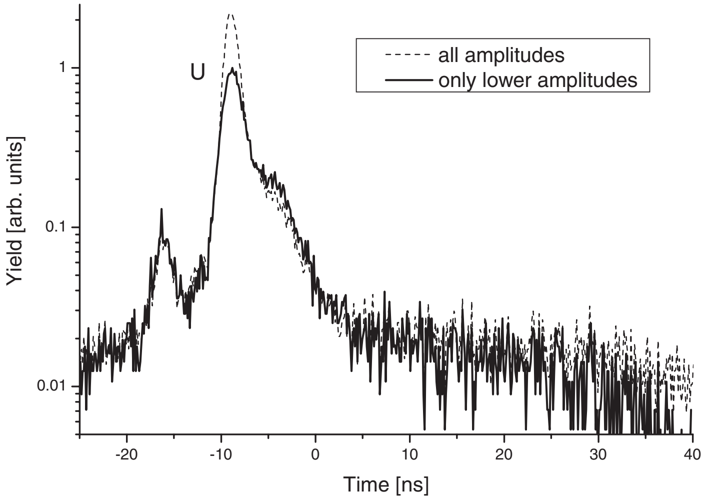


Figure 10. Time distribution corresponding to two-dimensional distribution shown in *Figure 9*. Black line – spectrum with the pulse height discriminated below channel 145 (see *Figure 9*)

4. Conclusions

Application of the associated particles technique (APT) to detection of shielded fissioning materials offers a unique possibility to build an all-in-one portable system for detection of both neutron- and γ–ray emitters and materials with no significant spontaneous radiation.

Results of the advanced Monte-Carlo calculations and first experiments show, that introduction of the APT technique into the traditional method of detection triple neutron-neutron-alpha coincidences allows one to:

4. detect ~1 kg of fissioning materials (FM) shielded with 5 cm of lead in less than one second;
5. identify the detected FM by spontaneous-to-induced fission ratio and other fission characteristics;
6. significantly improve the effect-to-background ratio and the detection time, relative to the traditional method without APT;
7. localize the detected object with precision determined by the geometry of the device and type of the associated particle detector.

When the 5 cm-thick lead shielding is complimented with a massive shielding against neutrons (e.g., polyethylene or water), the neutron coincidence count rate will drop. However, presence of such additional shielding can be determined by using an additional detector of γ–rays to detect secondary γ–radiation from inelastic scattering of primary (14 MeV) neutrons. Presence of most light chemical elements (carbon, oxygen, etc.) can be detected by characteristic peaks in the spectrum of this γ–radiation, measured using APT technique.

First experiments with one neutron detector and real uranium samples have shown, that observable effect from fission neutrons can be obtained even without use of neutron-neutron coincidences. The possible role of energy discrimination on time-of-flight spectra has been investigated. Introduction of additional neutron detectors and measurement of triple n-n-α and quadruple n-n-n-α coincidences within the time windows determined in the first experiments would allow one to account for different sources of the background in neutron detectors.

Experimental work using three neutrons detectors for detection of triple (n-n-α) and quadruple (n-n-n-α) coincidences between neutrons from induced fission of shielded fissioning materials will be continued during the year.

Acknowledgements

This work was supported in part by the NATO SfP grant #981003 “Detection of ‘dirty bombs’ using Nanosecond Neutron Analysis technique”, and in part by IAEA grant #12600 “Using associated particle technique for detection of shielded nuclear materials”.

References

1. Kuznetsov A.V., Using of the associated particle technique for the detection of shielded nuclear material. Proc. of Research Coordination and Technical Meeting (M2-RC-927), December 1 – 5, 2003 IAEA Headquarters, Vienna
2. A.V. Kuznetsov et al. “Portable multi-sensor for detection and identification of explosive substances”. // Proc. of the International Conference EUDEM2-SCOT: “Requirements and Technologies for Demining and the Removal/ Neutralization of Unexploded Ordnance”, 15-18 September, 2003, Vrije Universiteit Brussel, Bruxelles, Belgium. H.Sahli, A.M. Bottoms, J.Cornelis (Eds.), pp.633-637
3. A.V. Kuznetsov, et al., Detection of buried explosives using portable neutron sources with nanosecond timing. Applied Radiation and Isotopes, Vol. 61, Issue 1, p. 51, (2004)
4. A.V. Evsenin et al., “Detection of hidden explosives by nanosecond neutron analysis technique”// H.Schubert, A.Kuznetsov (eds.), Proc. of the NATO ARW #979920 “Detection of bulk explosives: advanced techniques against terrorism”, St.-Petersburg, Russia, 16 – 21 June 2003. Kluwer Academic Publishers, p. 89, (2004)
5. D.N. Vakhtin et al., “SENNA – portable sensor for explosives detection based on nanosecond neutron analysis”, Proc. of the NATO ARW “Detection and Disposal of Improvised Explosives”, 6 – 11 September, 2005, Saint-Petersburg, Russia, in print.

USE OF NEUTRON BASED TECHNIQUES IN THE CONTROL OF ILLICIT TRAFFICKING OF FISSILE AND EXPLOSIVE MATERIAL

G. NEBBIA
I.N.F.N. and Dipartimento di Fisica dell'Universita' di Padova, Italy

S. PESENTE, M. LUNARDON, S. MORETTO, G. VIESTI

Abstract: A prototype of portable sealed neutron generator has been recently built to deliver 14 MeV neutron beams tagged by a YAP:Ce α-particle detector in order to produce simultaneously multiple neutron beams to irradiate complex samples. Preliminary tests performed at the Institute Ruder Boskovic, Zagreb (Croatia) on the detection of explosives and fissile materials in maririme containers are presented.

Key words: Tagged neutron production, security non- invasive inspections

1. Introduction

The threat of terrorist use of explosive devices, chemical, biological and radioactive agents has become realistic since the SARIN attack in the Tokyo subway system on March 20, 1995 and after the tragic events of September 11, 2001. The possibility of further attacks against civil populations is one of the most important issues on the international political agenda. A scenario often evocated implies the use of the so called "dirty bombs": a sizeable quantity of radioactive material detonated by conventional explosive and dispersed in the environment. Illicit trafficking of explosives and fissile material through the conventional commercial networks (air, maritime and terrestrial) therefore represents a real challenge to security for the future.

In today's society acts of terrorism must involve in some stages the illicit trafficking either of explosives, chemical agents and nuclear materials. Therefore society must rely on an anti-trafficking infrastructure which en-

S. Apikyan and D. Diamond (eds.), Countering Nuclear and Radiological Terrorism, 271–290.

compasses responsible authorities, field personnel and adequate instrumental networks. Manual and visual inspection of large commercial payloads at terrestrial borders (trucks), airports and seaports (containers, see fig. 1) would not be a viable solution both from efficiency considerations and for legal reasons.

Figure 1.

From informations by the French Customs DDGGI the average cost of a manual inspection of a sea container can take a full day or more and has a cost ranging from 900 to 1500 Euros/container.

The standoff inspection of cargo by means of imaging and analytical methods in an integrated system based on a sound technology to identify threat materials is then needed.

The key to distinguishing explosives from benign materials is the use of elemental analysis [1,2]. While x-ray or γ-ray based systems (in particular Computerized Tomography) can give good precision density measurements with high-resolution three-dimensional images (fig. 2), these systems provide at best only gross information about the elemental content of the inspected item (low Z vs. high Z).

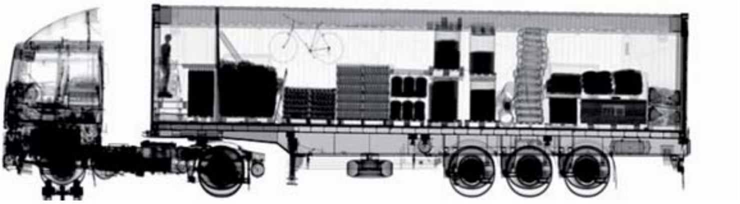


Figure 2.

Neutron interrogation, however, offers the possibility of measuring the elemental density of most elements in materials. Fast neutrons can be produced efficiently and economically by natural radioactive sources, small accelerators or compact electronic neutron generators, making possible the use of neutron based techniques in field applications. Gamma-rays produced by irradiating the sample with neutrons gives the elemental composition of the material, moreover, knowing the nuclear cross-sections and estimating the absorption factors in the different materials, it is possible to perform a quantitative analysis of elements in the sample even in depth; this is the most suitable technique for detecting hidden explosives. Furthermore with the use of "tagged" neutrons it is possible to determine the local distribution of elements inside the sample volume, or to inspect a precise element of volume (voxel) that has been identified as suspect [3,4]. Secondary neutrons and γ-rays produced by the irradiation of the sample can be used, by means of multiplicity measurements and/or spectral analysis, to identify the presence of fissile materials in the inspected volume. The list of materials which are subject to inspection with the aim of reducing the acts of terrorism includes explosives and radioactive materials.

There is a real risk that sub-national groups will in the future acquire fissile material – particularly Highly Enriched Uranium (HEU) – and construct a crude design nuclear weapon. Equally disturbing, and perhaps more likely, is the possibility that plutonium may be acquired by a group who will threaten to disperse it, by an explosion, and radioactively contaminate a large urban area. Nevertheless the detonation of a rudimentary nuclear device in an urban area represents by far the most destructive event that a terrorist attack could produce. As an example in fig. 3 is shown the predicted effect of a 2-3 kiloton device detonated in the Boston urban area.

The design of a “first generation” nuclear weapon, such as the bomb that destroyed Nagasaki in 1945, is no longer a secret; a competent nuclear physicist can find the relevant information in the open literature. Several types of these devices are possible: (i) Gun type and (ii) Implosive types. Implosion seems to be a favourite “first try”. For example Iraq’s importation of explosives and electronics suggested development of an implosion-type bomb. For this last type high-explosive charges are required. The amount of high explosive used in a fission weapon has decreased considerably since 1945 – from about 500 kg to about 15 kg or less. Explosive lenses and detonators adequate for an implosion-type atomic bomb are commercially available.

Figure 3.

In fig. 4 below is shown a sketch of a crude design implosion-type nuclear weapon using either HEU or Pu.

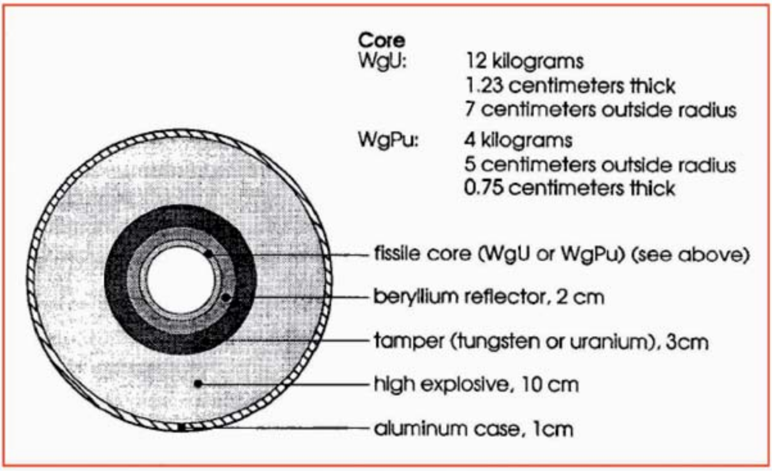


Figure 4.

2. Detection of explosives by the “Associated Particle Technique”

Of particular interest in the detection of conventional explosives are the densities of nitrogen, oxygen, carbon and hydrogen and their ratios.

In particular the use of Fast Neutron Analysis (FNA) can lead to identification of peculiar signatures of threat materials (in particular explosives) compared to benign materials from the gamma ray specctra following irradiation by fast neutrons. In fig. 5 is an example of such spectra for a number of different materials.

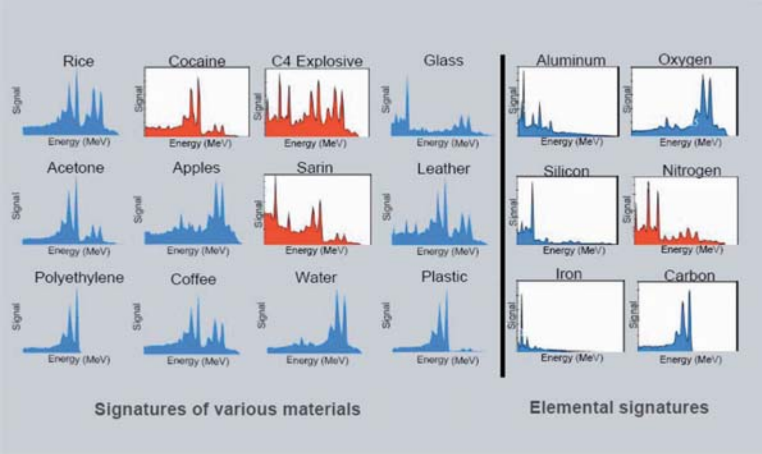


Figure 5.

In the fusion reaction of deuteron with tritium at energies of around 100 KeV the main decay channel produces an α-particle of about 3.5 MeV and a neutron of 14.1 MeV that are emitted nearly back-to-back . These reactions are easily produced in laboratory electrostatic accelerators and are the basis of compact neutron generator systems. The possibility of detecting the α-particle with a fast position sensitive counter of a given small area defines a tagged beam of neutrons emitted in the opposite direction and thus defines a corresponding specific area irradiated by the neutron beam and identified in X-Y coordinates by simple geometric projection. The tagged neutrons of energy 14.1 MeV travel at a fixed speed of about 5 cm/ns, therefore the γ-rays emitted by the elements in the irradiated area can be recorded in time coincidence with the tagged neutron thus defining the third dimension (Z-coordinate) of the irradiated volume.

In this way the region from which the recorded γ radiation originates can be accurately chosen by an "electronic" definition of the volume element (voxel) allowing a significant reduction of the background signals produced in the entire surrounding environment.

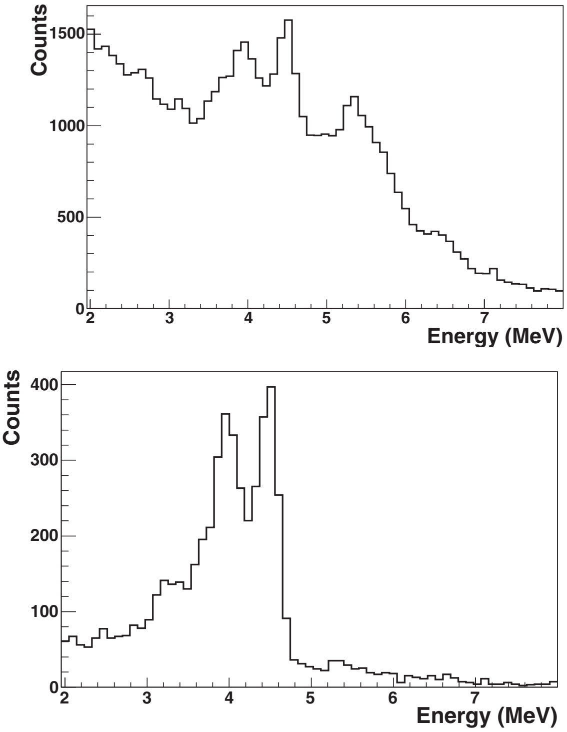


Figure 6.

In fig. 6 is an example of the background reduction for the irradiation of a small block of graphite by 14.1 MeV neutrons. In the left panel is shown the γ-ray spectrum recorded by an NaI(Tl) detector as seen without α-particle tagging of the incident neutron. One can see the 4.4 MeV gamma line (and first escape peak) standing on a high level background.

On the right panel is the same spectrum but with the α-particle tagging "swithced on".

The quality of the spectrum has remarkably improved, the signal/noise ratio is better by about a factor 50, it is expected that it could improve by two orders of magnitude.

The definition of the voxel to be inspected is then a crucial parameter in the choice of the appropriate equipment since the lower limit in its size is determined by the characteristic of the "tagging" detectors and of the γ-ray counters.

Similarly in fig. 7 is shown the difference of γ-ray spectrum recorded irradiating a normal suitcase filled with cloths and a device containing about 5 kg of TNT. Again in the left panel is shown the untagged spectrum and on the right the tagged one.

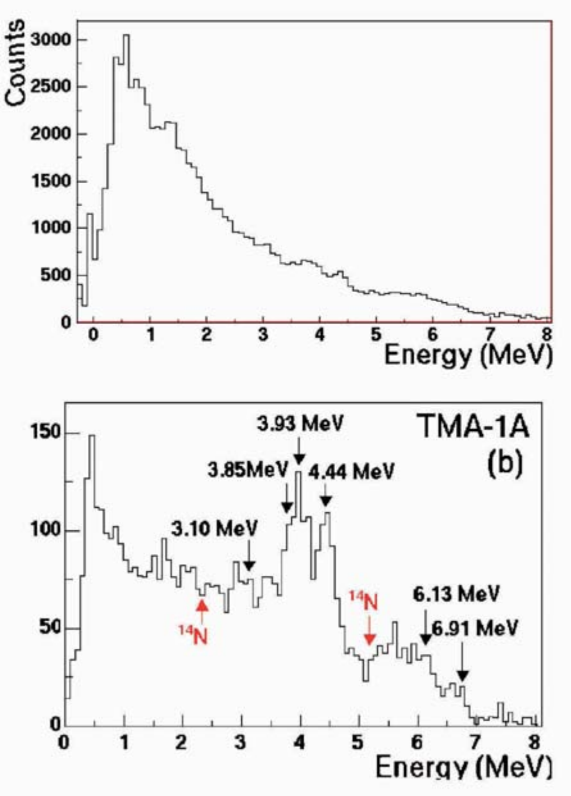


Figure 7.

3. First measurement on Depleted Uranium (DU) samples

Radioactive materials can be detected by measuring their decay products by "passive" radiation measurements; however the large volume of a standard container and the shielding of the load to the low energy γ radiation might make their identification very difficult when hidden in containers. Neutron induced β-delayed fission-neutron emission is also a possible way of detection for most fissile material, but the typical long time delay between the primary neutron and the delayed ones makes this technique unreliable for as large inspection volume such as a standard container. The loss of time correlation between neutron-in and neutrons-out could “disperse” the true signal among the background generated by neutron scattering inside the container. The test described here consists of irradiating a small portion of the inspected volume by means of a tagged neutron beam of 14.1 MeV and measuring the amount of α–γ–γ coincidence using a block of depleted uranium (DU) and an equivalent volume of clutter material (Fe and Pb).

The site for the tests has been setup at the Neutron Laboratory of the Rudjer Boskovic Institute in Zagreb (Croatia) where a 300 kV VdG accelerator delivers deuteron beams on a tritiated Ti target in order to produce 14.1 MeV neutrons.

The tagging system consists of a YAP(Ce) scintillating crystal equipped with a position sensitive photomultiplier tube that allows to determine the position where the associated alpha particle hits the crystal with a precision of about 1-2 mm.

Figure 8.

In a first test a block of about 10 kg of DU has been placed inside a maritime container in the direction of a neutron beam defined by the tagging of our α particle detector. Four 3”x 3” NaI(Tl) detectors have been placed around the DU sample at a distance of 75 cm as shown in the picture of figure 8.

A time-of-flight (TOF) measurement between the α particle and any two of the NaI counters is shown for the three samples in fig. 9.

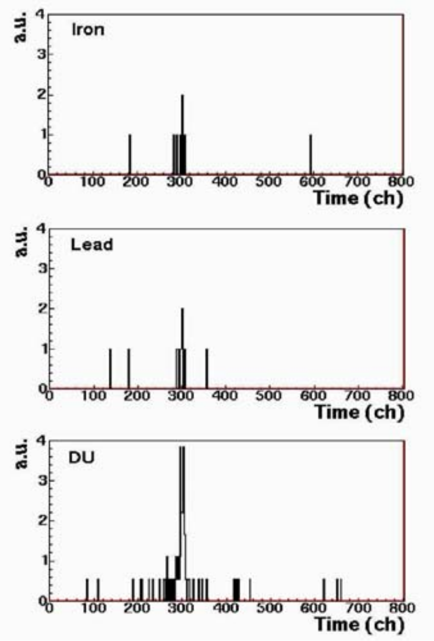


Figure 9.

A sizeable increase in the γ-ray coincidence yield due to the fission events is evident for the DU irradiation compared to the iron and lead irradiations. In fact the average γ-ray multiplicity per fission in DU is about 7.2 , therefore the probability of detecting two signals is very high compared to the probability of detecting two accidental coincidences in the clutter material irradiation.

More experimental work is foreseen using larger area detectors (probably plastic scintillators) positioned in a more realistic geometry around the outer walls of the container in order to verify the possibility of detecting fissile materials by simultaneous measurements of γ-ray and neutron multiplicities.

4. Simple statistical considerations on the effectiveness of a detection system

When using a detection system based on the response of an apparatus to the measurement of a given parameter, the decision on the quality of the information is determined by the fact that the measured value of such parameter is larger or smaller of a given threshold value.

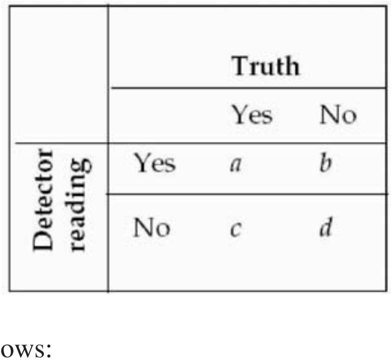
In case of the detection of a threat (explosives or SNM) inside a container or a suitcase, the measurement of one or more characteristics of the threat yields results that are then evaluated to determine wether the threat is real or not.

Often during tests the some procedures are applied as follows:

a) a detector with binary output ("yes" or "no") yields a binary measure of "truth" reflecting the actual ***presence*** or ***no presence*** of a threat in the volume inspected by the detector.

b) a number of tests are run, recording for each test the true status of the investigated volume and the detector response.

c) results are recorded in a 2 x 2 table (as shown below) called "table of truth", where a, b, c, d reflect the number of times that a particular combination of detector reading and true presence or absence of a threat occurs (out af a total of N = a+b+c+d total tests)



		Truth	
		Yes	No
Detector reading	Yes	*a*	*b*
	No	*c*	*d*

The table reads as follows:

a+c = number of tests with threat present
b+d = number of tests without threat present

If the detector response is considered a random variable one can the write the following conditional probabilities where D = yes means that the detector response indicates that there is a threat and T = yes means that the threat was really present during the test:

P(D = yes / T = yes) = a/(a + c) True Positive Fraction TPF
P(D = yes / T = no) = b/(b + d) False Positive Fraction FPF
P(D = no / T = no) = d/(b + d) True Negative Fraction TNF
P(D = no / T = yes) = c/(a + c) False Negative Fraction FNF
TPF is often called "*sensitivity*", while TNF is called "*specificity*".

It is interesting to notice that the "*sensitivity*" reflects the ability of the detector to identify a threat if the threat is present (i.e. the detector gives an "alarm" when it should).

The "*specificity*" reflects the ability of the detector to identify a threat only if the threat is present (i.e. the detector does not give an "alarm" when it should not).

Typically a detection system is based on measurements of some parameter that has a range of values expected in absence of a threat and a different range of values expected in presence of a threat (e.g. in the case of neutron inelastic scattering the parameter could be the χ^2 value obtained comparing the measured γ-ray spectrum with that of explosives and with that of benign materials).

The ranges of measured values of such parameter in presence or absence of a threat can be expressed as probability densities as shown in fig. 10

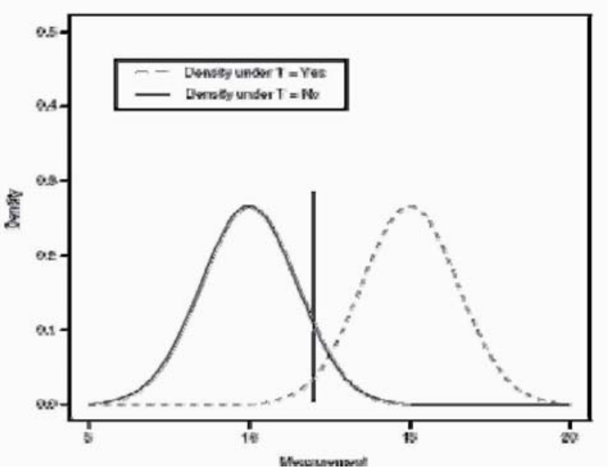


Figure 10.

The dashed line represents the values of the parameter corresponding to a true threat, while the solid line corresponds to the values where there is absence of a true threat. The overlap region of the two curves represents the values for which the parameter cannot give a definite answer. The vertical line corresponds to the "threshold" value established for the response to be recorded on the "table of truth".

We will see in the following how, for a given detection system, setting the threshold will change the "table of truth".

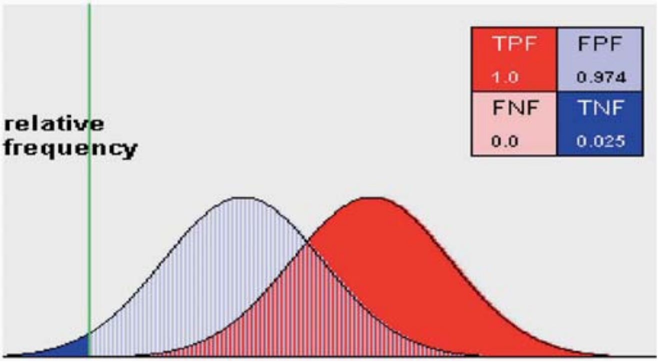


Figure 11.

In fig. 11 the cutoff threshold has been set "low", as a consequence the system shows a high TPF (*sensitivity*) meaning that all the tests where there is a real threat are correctly recorded by the detector, however one registers also a very high FPF therefore a very low TNF (*specificity*) consequently the detector gives a large number of "alarms" when there is no real threat.

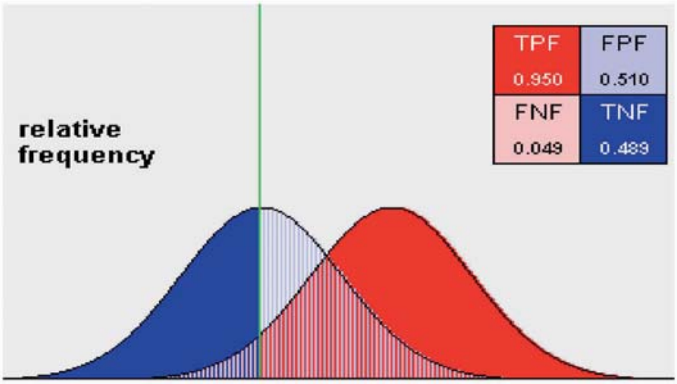


Figure 12.

In fig. 12 the cutoff threshold has been set "medium", as a consequence the system shows a good TPF (*sensitivity*) meaning that most of the test where there is a real threat are correctly recorded by the detector, but too high FPF therefore too low TNF (*specificity*) with the consequence that the detector still gives a large fraction of "alarms" (about 50% of the total) when there is no real threat.

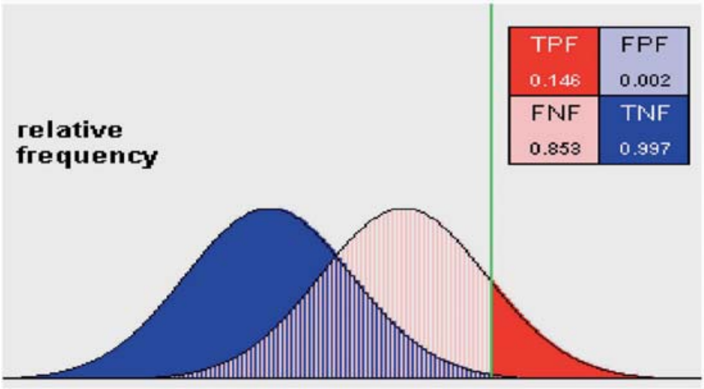


Figure 13.

In fig. 13 the cutoff threshold has been set "high", the result is that the system shows a high TNF (*specificity*) therefore a low FPF thus the detector does not give an "alarm" unless there is a real threat, but on the other hand the very low TPF (*sensitivity*) makes the detector not able to give an "alarm" in many cases when there is a real threat.

In fig. 13 are shown the effects of the change in threshold on a particular representation of the performances of a detection systema called ROC (Receiver Operating Characteristic curve).

Used originally to evaluate the performances of a radio receiver as a function of signal/noise ratio, the ROC curve is used as a 2-D representation of the performances of a test (in our case of a detection system) representing the correlation between FPF (1-*specificity*) vs TPF (*sensitivity*) as a function of the cutoff threshold set on the detector itself.

On the left panel of fig. 14 are shown three different values of the threshold set on a given parameter of a detection system, on the right panel is shown the position of the threshold as it results on the ROC curve representing the detection system.

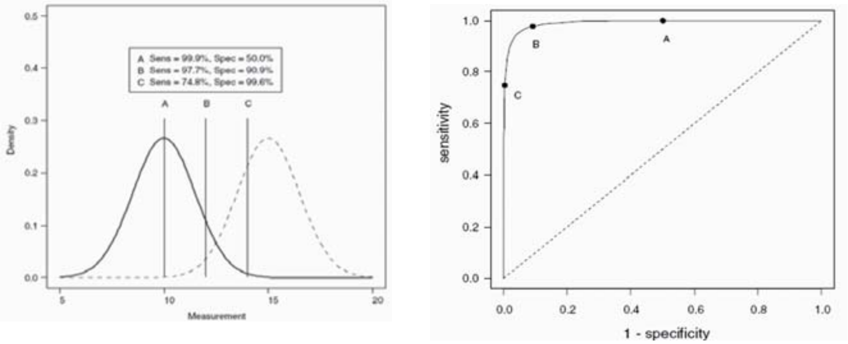


Figure 14.

It is interesting to recall the following characteristics of a ROC curve :

a) the AUC (Area Under the Curve) is a characteristic of any given detector and its integral defines the quality of the overall performances of the detector
b) the values of the threshold set during the tests are reflected on a point that runs along the ROC curve thus defining different “modes” of operation of the system
c) the dashed diagonal is the line where TPF = FPF meaning that the test has no diagnostic value (the detector responds like flipping a coin...).

Often during the assessement of the performances of a detection system the attention is concentrated on improving the ROC shape (maximize the AUC) to be able to work with a threshold defining a point as close as possible to the upper left corner of the ROC curve , therfore maximizing both specificity and sensitivity.

Nevertheless when dealing with rare events, this might not be the correct approach.

For this purposes let’s define two new conditional probabilities as follows:

P(T = yes / D = yes) is the “probability of true presence of a threat when an alarm occurs”

P(T = no / D = yes) = 1 - P(T = yes / D = yes) is the “probability that no threat is present when an alarm occurs”.These two probabilities reverse the conditioning order as compared to the previous definitions in fact they do not correspond to TPF and FPF respectively. The difference being the following :

TPF is "the probability of having an alarm out of all the tests where there is a real threat"
P(T = yes / D = yes) is "the probability that an alarm is true out of all the detector alarms"

FPF is "the probability of having an alarm out of all the tests where there is not a real threat"
P(T = no / D = yes) is "the probability that an alarm is false out of all the detector alarms"

The probability P(T = yes / D = yes) that an observed alarm is true depends on the sensitivity and specificity of the test and moreover on the frequency of background and real threats via the Bayes' Theorem :

$$P(T=yes\ /\ D=yes) = \{P(D=yes\ /\ T=yes)P(T=yes)\}/P(D=yes)$$

Where P(D=yes) is the probability that a detector sets an alarm during use with or without a real threat during the tests. It is possible to express this probability in terms of known values through the Law of Total Probability by:

$$P(D=yes) = P(D=yes\ /\ T=yes)P(T=yes) + P(D=yes\ /\ T=yes)P(T=no)$$

that is:

$$P(D=yes) = (\textit{sensitivity})P(T=yes) + \{1- \textit{specifici}\text{ty}\}\{1- P(T=yes)\}$$

The important point is that the probability P(D=yes) depends on the technical characteristics of the detector and on the "threshold position" along the ROC curve during the tests (*sensitivity* and *specificity*) but in particular it depends also on P(T=yes) which is the unconditional probability of having a true threat among the total number of tests and therefore represents the "*frequency of true threats*". Such frequency depends of course on the particular scenario and in the specific case of the application of new detection techniques to security is (fortunately !) an extremely small number.

This is an issue of paramount importance for the determination of the so called "*field effectiveness*" of a detection system, in fact in case of extremely low frequency of true threat (bomb in check-in luggage or SNM in a sea container) even a system with very high sensitivity and specificity can have an unacceptably high probability that any observed alarm is false.

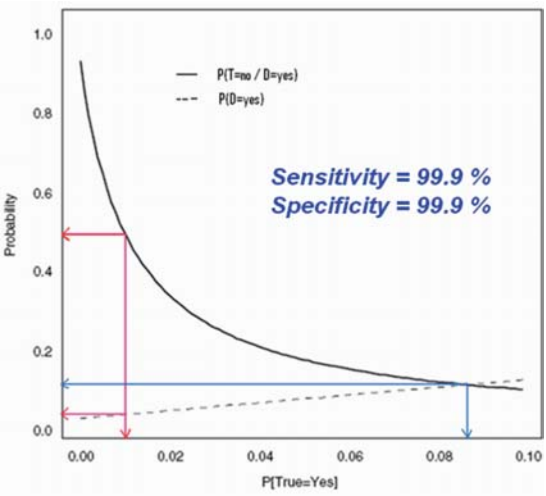


Figure 15.

In fig. 15 we can see two curves related to the likelihood that a certain kind of events be recorded by a detector with sensitivity = 99.9% and specificity = 99.9%. The probability that the detector sets an alarm P(D=yes) decreases linearly as the frequency of the real threats P(T=yes) decreases (dashed line), on the other hand the probability that no threat is present when an alarm occurs : P(T = no / D = yes) increases nonlinearly as the frequency of the real threat P(T=yes) decreases (solid line). In other words when the frequency of real threats is very low the probability that any alarm provided by the detector is a fals alarm is near 100%.

Let's consider again fig. 15 referring to an example related to aviation security.

The blue line shows that assuming about 8-9 real threat out of 100 tests (which is an abnormally high probability of a real threat meaning about 20 bombs for each commercial passenger flight !) the system under scrutiny will yield about 10 alarms of which 10% (about 1 alarm) are false.

The red line shows that assuming about 1 real threat out of 100 tests (still unreasonably high probability of a real threat meaning about 2 bombs for each commercial passenger flight) the system under test will yield about 2 alarms of which 50% (about 1 alarm) are false.

If one goes to even larger numbers one sees that for a rate of 1 threat every 1,000,000 (i.e. suitcases checked-in commercial flights) such a system will yield one alarm every 5 aircrafts and the probability that such alarm is false will be about 99.9%.

In the case of multiple systems where one uses different detectors it is important to verify the field performances of the combined response of the sytem under different conditions.

As an example let's consider a system made by two detectors used in an "OR" configuration as shown in fig. 16.

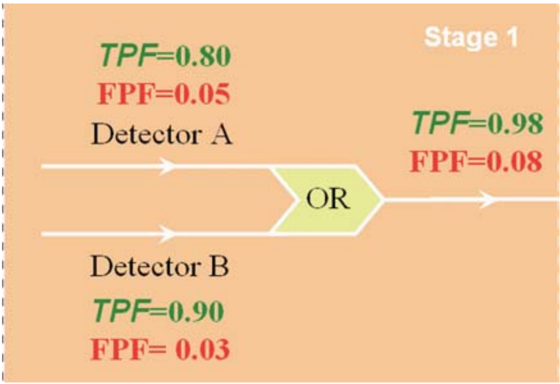


Figure 16.

In this case the sensitivities of detector A and B are 80% and 90% respectively, while the resulting sensitivity of the combined system has significantly increased to 98 %.

Nevertheless if one looks at the field performance of the combined system compared to that of one single detector the results are somewhat surprising.

In fig. 17a below are shown the same probability distributions as described in fig. 15 relative to detector B. One can see that again the probability to have an alarm decreases as the frequency of real threats decreases, while the probability that such alarms are false increases remarkably.

In fig. 17b are shown the same quantities but now for the combined response of detectors A and B used in "OR".

One sees that while the probability that the combined system gives an alarm is still reasonable, the probability that such alarm is false is larger than 90% over a wide range of values of P(T = yes) and is remarkably worse than the response of a single detector at low frequencies.

We can conclude that although the sensitivity of the response of a combined system of two detectors operated in "OR" mode is sensibly higher than the sensitivity of either one of the single detectors, the field effectiveness of the combined system for rare events is remarkably worse than that of a single detector.

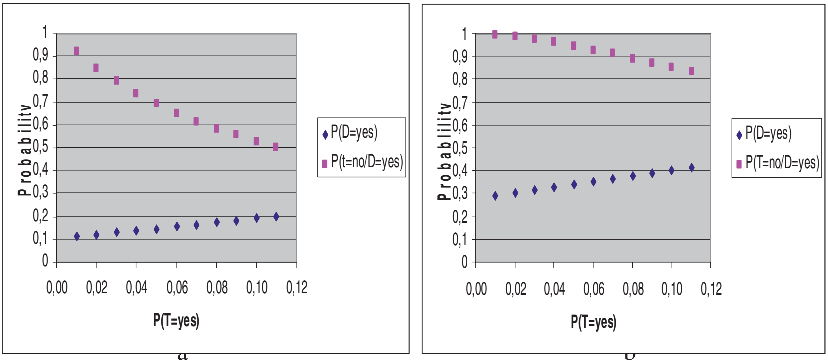


Figure 17.

Let's now consider the result of the "OR" operation of detectors A and B as the output of a single detector to be combined this time in "AND" mode with the output of a third detector (C) as shown in fig. 18.

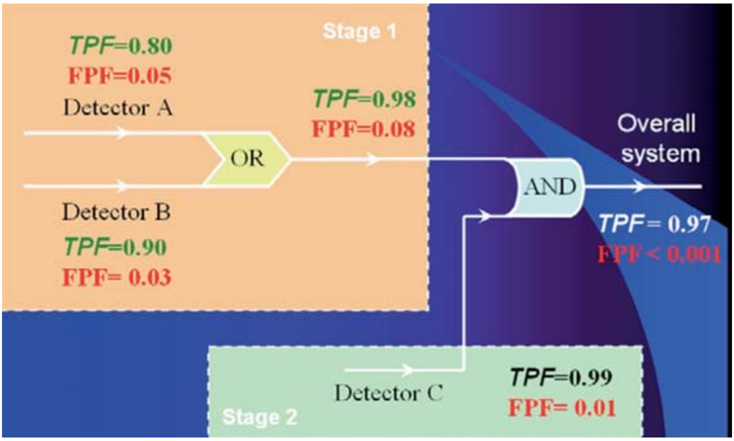
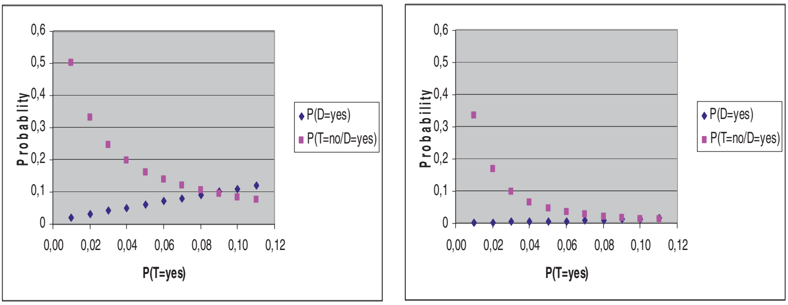


Figure 18.

In this case the resulting sensitivity of the combined system is 97 % to be compared with 98% for the output of detectors A and B, or with the sensitivity of 99% of detector C.

Therefore one is led to conclude that the combined operation in "AND" mode yields a slightly worse response of the overall system.

Let's now look in fig. 19 at two plots equivalent to those in fig. 17 but for the combined operation of detectors A B and C as described above.



a b

Figure 19.

In fig. 18a are shown the probabilities as described earlier for detector C alone, in fig. 18b the same functions are shown for the combination of detectors A and B combined in “AND” mode with detector C. In this case one notices that, despite a small decrease of the sensitivity of the overall system, the field performances for the system operated in “AND” mode are, for rare events, sensibly better than those of the single detector and far better than a combination of detectors used in “OR” mode.

5. Conclusions

In the first part of this paper we demonstrated that:

- The use of the “associated particle technique” to tag 14 MeV neutrons for inspection of cargo improves the quality of the g-ray spectra largely reducing the background (up to a factor 50)
- Inspection of large items with miscellaneous loads (like a maritime container) requires the identification of a suitable size “voxel” (unit element of volume) to be irradiated
- It is possible to reach a “voxel” size of about 30x30x30 cm3 in any location inside a container using a suitable alpha particle detector that will allow to do “3D chemical imaging” of a large inspected volume
- Once defined the position of a suspect object it should be possible to identify the presence of <u>both</u> explosives and SNM

In the second part of this paper from simple statistical considerations we have shown that:

- Evaluation of the performances of any detection system for security screening purposes <u>must</u> take carefully into account the threat scenario
- *Sensitivity* and *specificity* of a detection system are not necessarily the relevant quantities to be considered
- In applications aimed at detecting very rare events the results based on the above parameters could be misleading
- The use of multiple sensors in "OR" mode generally increases the *sensitivity* but not necessarily the "field performances" of the combined system
- The use of multiple sensors in "AND" mode while decreasing the overall sensitivity of the system results in a remarkable improvement of the "field performances" of the combined system when dealing with the detection of very rare events (like in most security applications).
- This work has been performed with the financial support of the NATO Science for Peace programme under grant N. SfP-980526.

References

1. G. Vourvopoulos and P.C. Womble, P.C., Talanta 54 (2001) 459
2. P. Bach et al., Nucl. Instr. and Meth. B 79 (1993) 605
3. A. Beyerle el al., Nucl. Instr. and Meth. A 299 (1990) 458
4. S. Mitra et al., Appl. Radiat. Isot. 49 (1998) 537

INDEX