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The Chernobyl Forum's Evaluation of Health Consequences
Twenty Years after the Chernobyl Accident

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Abstract. The Chernobyl Forum was an initiative of the United Nations to review the health and environmental consequences of the Chernobyl accident as evident twenty years after the event and to advise governments and the population of affected areas on effective measures for addressing the lingering issues still surrounding the accident. The Forum completed its work during 2003-2005. Main points of the evaluation were that countermeasures and remedial work performed after the accident generally prevented high doses to the workers, evacuees and residents of contaminated areas. For the most part, the Chernobyl accident was a low-dose event. For this reason, marked increases in cancer incidence have not been observed. An exception is the large number of thyroid cancers incurred by children from high doses of radioactive iodine received during a short period immediately following the accident. The population affected by the accident lives under a burden of psychological stress that could best be alleviated by good information on the real risks from the accident and by nationally and internationally supported projects and self-help measures to improve the general public health and economic level of the region.

1. Introduction

The Chernobyl accident was an unprecedented disaster of very large scale. There was widespread radioactive contamination of the environment, harmful consequences to human health, and also substantial social and economic costs. It was the most devastating accident that could ever occur in a nuclear power plant, with total destruction of the reactor core and the release to the environment of enormous quantities of radioactive materials.

Surely this was a unique event that will never be allowed to occur again. This one accident has given indelible lessons on reactor safety and on how to manage the response to such a catastrophe with effective counter-measures, protective actions, and recovery strategies.

The accident was so serious and the consequences so diverse and complex that questions still remain on the actual effects caused by the accident and on what further measures of protection or surveillance might still be needed. Authoritative assessments of the many outstanding issues are needed to guide governments with useful and cost-effective measures to continue to deal with the accident and to advise and reassure the residents of the contaminated areas.

To contribute to better understanding of the outstanding issues and more effective management of the limited resources that can or must continue to be directed at the recovery process, the Chernobyl Forum was established in 2003 as an initiative of the International Atomic Energy Agency (IAEA) and sponsored by a number of inter-national organizations. Two expert groups were formed: one on environmental issues, with the IAEA serving as the secretariat, and one on health effects, with the World Health Organization (WHO) providing secretariat services. The United Nations Development Programme (UNDP) played a major role in evaluating the social and economic consequences of the accident. The report of the Forum was presented at an international meeting held in Vienna in September 2005. 3

The Chernobyl Forum involved from the start the active participation of representatives of the governments of the affected region, who have been dealing with the social and economic aspects of the accident. It was deemed important to have a broad consensus on the evaluation by government representatives and the many scientists from numerous countries who have experience in evaluating the health and environmental aspects of the accident and who prepared the expert reports for the Chernobyl Forum. 2, 3

2. Need for the Forum

The three countries most affected by the Chernobyl accident: Belarus, Russia and Ukraine, are severely burdened by the financial costs of dealing with numerous health, environmental, social and economic aspects of the accident. A clear need exists to provide accurate evaluation of the consequences of the accident and to reach consensus on useful and sensible ways for dealing with the issues of the accident that still remain and that require and demand continued attention. The Chernobyl Forum intended to take a close look back at the experience of the past two decades and then to recommend the continuation or establishment of positive and effective ways to improve the health and economic well being of the residents of the three countries.

At the beginning of the Forum’s activities, all could agree on the basic issues to be addressed. Everyone recognized the serious consequences of the Chernobyl accident, both in scope and duration of the distress and disruption that resulted, and appreciated the extensive efforts that have gone into the clean-up, remediation, monitoring, and, in general, dealing with the complex impacts on human health and on the environment.
Clearly, however, complex issues remain, and decisions must be made to ensure further recovery and well being of the affected population. Although radiation exposures are part of the problem, there are many other factors involved, including social disruptions, depressed economic development and psychological stress that detract from the well being of the populations of the affected regions.

The goal of the Chernobyl Forum was to provide a wider public understanding of the consequences of the accident and clear priorities for further research and to continue to effectively manage the recovery process. It was hoped that the Chernobyl Forum could contribute in a positive way to achieve consensus on disputed issues, to promote public understanding, and to make realistic suggestions to help alleviate the lingering consequences of the accident.

3. Method of work and basis for the assessment

Many scientists as well as representatives from UN organizations and governments of affected regions participated in the work of the Chernobyl Forum. Several meetings of the Forum were necessary to initiate the work and monitor the progress of the expert groups. Two expert groups formulated comprehensive reports – one on environmental issues, organized by the IAEA, and one on health issues, organized by the WHO. Experts from throughout the world were invited to contribute to these evaluations. The representatives of governments and the staff of international organizations then reviewed the results of these groups to be sure that the reviews were complete and the evaluations reasonable, so that they could serve as the basis for consensus agreements and effective recommendations for further dealing with the consequences of the accident.

The work of the Chernobyl Forum did not materialize from a clean slate of absent information and unknown facts. Of course, the Forum built on the work of other efforts to review and assess the consequences of the Chernobyl accident. It was a tribute to the Soviet scientists to have an assessment ready for international presentation by August of 1986, just a few months after the accident. This started an effort to be open and factual with information then available. The first assessment of the accident was published by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) in 1988. Good estimates could be made at that time of the amounts of radioactive materials released and their spread through-out the hemisphere from numerous measurements in countries throughout Eastern and Western Europe and in other countries of the northern hemisphere. The experience in treating the highly exposed workers could also be described in the 1988 UNSCEAR report.

In 1990 and 1991 the IAEA conducted the International Chernobyl Project, in which scientists from many countries, who were experts on environmental and health aspects of radiation, met with their counterparts in the Soviet Union to compare methods of evaluating radiation exposures and to conduct an extensive screening of health effects in the exposed population. This was an ambitious and highly successful project from the scientific point of view.

During the time of the International Chernobyl Project and for some years after, the Sasakawa Foundation of Japan provided substantial support for Chernobyl projects, especially the health projects of WHO. Other international and bi-national efforts began to conduct epidemiological studies to carefully evaluate the health consequences of the accident. A further evaluation of the exposures and effects of the Chernobyl accident was published by UNSCEAR in its 2000 report.

The Chernobyl Forum sought to review all relevant scientific publications for its update of the effects of the accident. The expert groups on environmental and health issues considered available information on the continuing environmental levels of radioactive contamination and the health consequences of radiation exposures received by workers, evacuated persons, and by those who continue to live in contaminated areas. The scientific evaluation by the Forum forms the basis for sensible, practical recommendations that could be adopted by governments to manage the public health problems that will be faced for still some time as a legacy of the accident. A careful review of social and economic issues was also prepared by UNDP to serve as a basis for new national and international initiatives to help the recovery process. 4)

4. Key points of the evaluation

The Chernobyl accident was a disaster that required massive response. The former Soviet Union and the successor countries reacted with heroic efforts to limit the contamination of the environment and exposures of the public. The protective measures were extremely effective. It can truly be said that except for the high exposures received by workers on the night of the accident and for many children who very unfortunately received high exposure to radioactive iodine released in the accident and who later incurred thyroid cancer, the accident was a low dose event.

The majority of workers who participated in the clean-up efforts, the many thousands of persons evacuated during the early days following the accident, and all those who continued to live in contaminated areas received radiation doses from Chernobyl-released radionuclides that were relatively low and unlikely to lead to wide-spread and serious health effects. The doses to these individuals are comparable to those caused by naturally occurring radionuclides that produce a background level of radiation to which everyone in the world is exposed. Some notable regions of high background radiation exist in several countries that are caused by higher concentrations of thorium or uranium radionuclides in the
beach sands or in soil or water. The Chernobyl exposures are not unlike these naturally occurring areas that are not asso-ciated with discernable radiation health effects.

Given that the radiation doses were for the most part relatively low, serious health consequences in the affected countries have not been observed. The main exception has been the numerous thyroid cancers that occurred in child-ren exposed to high doses of radioactive iodine shortly after the accident, when restrictions on consumption of contaminated milk were not yet in place. Nearly 5000 cases of thyroid cancer have been diagnosed in those who were children at the time of the accident. The incidence rate is higher and the onset is earlier than expected. One reason may be due to iodine deficiency in the region, allowing higher doses and earlier onset of the cancers. Thyroid cancer is treatable, and survival rates are high. Only 9 children have died from thyroid cancer.

Review of specific radiation effects studies of Chernobyl workers or affected population groups was made by the Chernobyl Forum. Comparisons of exposed and un-exposed workers or residents have not been conclusive of any increase in leukemia, solid cancer or non-cancer effects. Epidemiological studies based on individual dose estimates are underway to continue to evaluate carefully the health consequences of the accident.

Many of the health effects in the population of the Chernobyl-affected regions are caused by factors other than radiation. That is not to belittle the possible conse-quences of radiation exposures, but it is to recognize the harm done by smoking, excessive alcohol consumption, poor diet, or inadequate health care or advice. It may make sense to address these other issues at the same time or even instead of the radiation threats to achieve the best progress in improving public health and well being in the Chernobyl countries. It is essential to see things in wide perspective and to accept proper priorities to improve public health in the region.

There has been considerable interest in estimating the number of deaths caused by the Chernobyl accident. This was not a specific goal of the Forum. However, a publish-ed estimate was quoted to give some order of magnitude value.

Deaths of workers and fire fighters caused by injuries, burns, and radiation exposure in the night of the accident are accurately known. Two deaths of workers occurred immediately from physical injuries from the explosions. Among 134 workers who showed signs of acute radiation sickness, indicating very high doses, 28 died within the first weeks or months after the accident, and a further 19 deaths occurred between 1987 and 2004. Not all of the latter deaths were radiation related. Radiation doses to all other workers and also to evacuees and those who contin-ued to live in contaminated areas were low, and deaths from radiation causes among this group are completely indiscernible among the numerous deaths from all other causes in the large population.

Of course, a risk estimate obtained from epidemiology studies can be multiplied by the average dose and number of persons in the large population group, and a projection of a number of deaths can be obtained. Cardis et al. 53 made such a projection for the affected population of 600,000 persons more directly affected by the accident (200,000 workers, 135,000 evacuees, and 235,000 resi-dents of high contaminated areas). The average doses ranged from 100 mSv in workers, to 10 mSv in evacuees, and 50 mSv in residents. The total of projected deaths over the lifetimes of these persons was 4000. For the further population of 6,000,000 persons in less contamin-ated areas, the projected value was about 5000 deaths. However, the average dose of this large group was just 7 mSv, little different from natural radiation background levels.

These projections were made without adjustment of the risk estimate for the low, chronic exposures and the dif-ferent cancer background incidence rates and demograph-ics in the Chernobyl region. Such estimates are thus in-tended to be order-of-magnitude or rough scop-ing esti-mates used for public health planning rather than as an accurate projection of actual cases. These estimates were simply quoted by the Chernobyl Forum to counter earlier claims that tens or even hundreds of thousands deaths would be caused by the Chernobyl accident.

It was never fully understood by the media, following the presentation of the Forum’s report, that the projected deaths can never be directly attributed to radiation or dis-tinguished in any way in the population. The cautions and caveats surrounding the estimates were lost. It is generally recognized that projecting deaths in a large population group exposed to low doses of radiation or any other agent is basically an unreasonable and futile exercise.

An important contribution to the Chernobyl Forum’s work was a review by UNDP of the social and economic impact of the accident. 43 It has become clear that a psy-chological burden on the affected population conferring a victimization attitude has become a main lingering conse-quence of the accident. It is important that good informa-tion and clear presentation of real risks and dangers be provided. In addition, national and internationally sup-port ed projects and self-help measures are needed to improve the general public health and stimulate the econ-omy, leading to a better quality of life for the affected population.

The Chernobyl Forum made a number of specific recommendations to the governments of the affected region. It is hoped that by utilizing these and the consen-sus evaluation of the Forum, effective means could be realized for dispelling unfounded views on the conse-quences of the accident, redirecting the limited resources in the most effective ways, and restoring the trust of the public that is so essential to resolve the problems that are still faced as residual features of the accident.

The Chernobyl Forum concluded with great expecta-tions for progress and continued alleviation of the
consequences of the accident, for the economic development of the whole region and for the improvement in public health that all aspire and strive for.

There will certainly be challenges in the way forward. It will not be easy to transform the recommendations of the Chernobyl Forum into practical measures that can be enacted by governments to contribute to a better future of their countries. The contamination will not go away, even if we understand the transfers of radionuclides in the environment and realize the countermeasures that are most effective for dealing with this. The stress and worry of the public about radiation effects will only slowly dissipate, even with good information and clear presentation of the real risks and dangers. The economy will not respond quickly to new initiatives, even if these seem in the long term to be most sensible and effective for fostering economic development.

In spite of the difficulties, the challenges must be faced realistically and resolutely. There must be patience with the long recovery, while the resolve is kept to deal stead-fastly with the issues in a sincere and truthful way, so that the efforts of government, international organizations, and the public will be united and coordinated, and all will be satisfied that we are doing our utmost to recover from the serious consequences of the Chernobyl accident.

Especially for the persons directly affected by the accident, we must wish that the work of the Chernobyl Forum and further efforts to prepare informative materials and present these findings of the Forum will be translated into effective actions that will benefit them directly and improve their health and well being and their prospects for productive and fulfilling lives. They are the ones who deserve and expect the fruits of our efforts and the good that may come from our effective actions.

References
Abstract: The current recommendations of the International Commission on Radiological Protection (ICRP) were published in 1991. Since then, ICRP has published additional recommendations, and the system of protection has become increasingly complex. New scientific data have made it necessary to update the biological and physical assumptions underlying the recommendations. The Commission has decided to revise its recommendations while at the same time maintaining stability with the previous recommendations. The international consultation on the draft recommendations has involved health physics professionals all around the world. A revised draft was be put on ICRP’s website for consultation during the summer of 2006. When ICRP adopts its revised recommendations, 16 years would have passed since the 1990 recommendations were adopted.

INTRODUCTION

The primary aim of ICRP’s recommendations is to provide an appropriate standard of protection for people and the environment, without unduly limiting the beneficial actions giving rise to radiation exposure. This aim is achieved through the combined use of scientific concepts and value judgements about the balancing of risks and benefits, i.e. an approach similar to other fields concerned with the control of hazards.

The system of radiological protection, set out in Publication 60 (1), was developed over some 30 years. Since then, there have been additional recommendations regarding numerical restrictions on dose, based on different ideas and spanning several orders of magnitude (2-10). A framework for environmental protection has also been published (11). The system has thus become increasingly complex, and it has in some respects been difficult to explain or understand completely the variations between different applications. New scientific data have been published, and the biological and physical assumptions and concepts need updating. There have also been societal developments in that more openness or transparency is expected in developing new recommendations that could be accepted globally. Therefore, while recognising the need for stability in international and national regulations, the Commission has decided to issue these revised recommendations having three primary aims in mind:

- To take account of new biological and physical information and of trends in the setting of radiation safety standards;
- To improve and streamline the presentation of the recommendations; and
- To maintain as much stability in the recommendations as is consistent with the new scientific information.

In the new recommendations, much will remain as in the 1990 recommendations because they have been demonstrated to work and are generally clear. Further explanation is needed, however, in some areas and where omissions have been identified, these will be addressed. There has also been an improved understanding in some areas, for example of radiation effects, which will result in some changes in recommendations, but the overall radiation risks are essentially unchanged. A series of documents have been and are being developed to underpin the revised recommendations:

**Committee 1 (radiation effects):**
- Low-dose extrapolation of radiation-related cancer risk (12).
- Biological and epidemiological information on health risks attributable to ionising radiation: A summary of judgements for the purposes of radiological protection of humans (will appear as an annex to the recommendations).

**Committee 2 (dosimetry):**
- Basis for dosimetric quantities used in radiological protection and their application (annex to the recommendations).

**Committee 3 (protection in medicine):**
- Radiological Protection in Medicine.

**Committee 4 (application of ICRP’s recommendations):**
- Optimisation of radiological protection (13).
- Assessing dose to the representative individual (13).
Committee 5 (protection of the environment):
- The concept and use of reference animals and plants for the purposes of radiological protection.
Main Commission:
- The scope of radiological protection: exemption and exclusion.

The international consultation on the draft recommendations and of the above-mentioned documents was the culmination of several years of work and followed discussions with health physics professionals all around the world. The new recommendations should be seen as consolidating the 1990 recommendations and those published subsequently. The opportunity is also being taken to include a coherent philosophy for natural radiation exposures and to introduce an approach to radiological protection of the environment. The major features of the 2006 Recommendations are:

- Maintaining the three fundamental principles of radiological protection, and clarifying how they apply to radiation sources and to the individual, as well as establishing that the source-related principles apply to all controllable situations (planned, emergency and existing exposure situations);
- Updating the understanding of the biology and physics of radiation exposure;
- Updating the radiation and tissue weighting factors in the dosimetric quantity effective dose;
- Maintaining the Commission’s limits for effective dose and equivalent dose from all regulated sources that represent the most that will be accepted in planned situations by regulatory authorities;
- Using the same conceptual approach of constraints in the source-related protection to all situations, regardless of the type of source. The dose constraints quantify the most fundamental levels of protection for workers and the public from a source;
- Complementing the limits and constraints with the requirement to optimise protection from a source; and
- Including a policy approach for radiological protection of non-human species.

RADIATION DETRIMENT

There have been developments in biological and dosimetric knowledge that justify a re-appraisal of the radiation-weighting factors, \( w_R \) (14). Most values of the relative biological effectiveness have been obtained at high doses and must therefore be extrapolated to the low doses that are of interest for radiological protection. For practical purposes, ICRP recommends the use of the same \( w_R \) values for all organs and tissues. For photons and beta particles, a \( w_R \) of unity is retained for all low-LET radiations, and a \( w_R \) of 20 is retained for alpha particles. ICRP believes that a \( w_R \) of 5 for all protons of energy > 2 MeV is an overestimate of the biological effectiveness, and recommends a \( w_R \) of 2 for incident protons. For neutrons, ICRP recommends the use of \( w_R \) values that depend upon energy of incident neutrons, and that a continuous function be used. The \( w_R \) for neutrons should thus be decreased for energies below 1 MeV to take account of the absorbed dose contribution by low-LET gamma rays that are induced in the body by neutrons.

The fundamental role of radiation-induced DNA damage in the induction of mutations and chromosome aberrations provides a framework for the analysis of risks at low doses and low dose rates. For cancer and hereditary disease at low doses and dose rates, the evidence weights in favour of the use of a simple proportionate relationship between increments of dose and increased risk. A dose and dose-rate effectiveness factor (DDREF) of 2 is retained. While the existence of a low-dose threshold does not seem unlikely for radiation-related cancers of certain tissues, the evidence as a whole does not favour the existence of a universal threshold, and there seems to be no particular reason to factor the possibility of a threshold into risk calculations for purposes of radiological protection. The linear, no-threshold (LNT) hypothesis remains a good basis for protection at low doses and low dose rates.

A better understanding of the mechanisms for radiation-related adaptive response, genomic instability, and bystander effects is needed before they can be evaluated as factors to be included in the estimation of risk after exposure to low levels of radiation. The dose responses for in utero radiation-induced tissue reactions, malformations and neurological effects are judged to show dose thresholds above a few tens of mSv. Uncertainty remains on the induction of IQ deficits but at low doses the risk is thought to be insignificant. Risks of non-cancer disease at low doses remain uncertain and no specific judgement is possible.

ICRP has revised the tissue weighting factors, \( w_T \), and the most significant changes from Publication 60 (1) relate to breast, gonads and treatment of remainder tissues (Table 1). The new nominal probability coefficients for cancer and heritable effects are \( 6 \times 10^{-2} \) Sv\(^{-1}\) for the whole population and \( 4 \times 10^{-2} \) Sv\(^{-1}\) for adult workers (Table 2). The nominal detriment coefficients for both a workforce and the general public are thus consistent with, although numerically somewhat lower than, those given in Publication 60. While the nominal risk estimates are now slightly smaller, for practical purposes the risk is in the same order of magnitude as before. Thus, the approximate overall risk coefficient of about 0.00005 per mSv on which the current international radiation safety standards are based continues to be
appropriate for purposes of radiological protection.

Table 1. ICRP’s revised tissue weighting factors, $w_T$

<table>
<thead>
<tr>
<th>Tissue</th>
<th>$w_T$</th>
<th>$\sum w_T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bone-marrow, Colon, Lung, Stomach, Breast,</td>
<td>0.12</td>
<td>0.72</td>
</tr>
<tr>
<td>Remainder Tissues*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gonads</td>
<td>0.08</td>
<td>0.08</td>
</tr>
<tr>
<td>Bladder, Oesophagus, Liver, Thyroid</td>
<td>0.04</td>
<td>0.16</td>
</tr>
<tr>
<td>Bone surface, Brain, Salivary glands, Skin</td>
<td>0.01</td>
<td>0.04</td>
</tr>
<tr>
<td>Bladder, Oesophagus, Liver, Thyroid</td>
<td>0.08</td>
<td></td>
</tr>
<tr>
<td>Remainder Tissues*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bone-marrow, Colon, Lung, Stomach, Breast,</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spleen, Liver</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pancreas, Prostate, Small intestine, Spleen</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thymus, Uterus/cervix</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Remainder Tissues: Adrenals, Extrathoracic (ET) region, Gall bladder, Heart, Kidneys, Lymphatic nodes, Muscle, Oral mucosa, Pancreas, Prostate, Small intestine, Spleen, Thymus, Uterus/cervix.

Table 2. Detriment-adjusted nominal coefficients for cancer and hereditary effects ($10^2$ Sv$^{-1}$)

<table>
<thead>
<tr>
<th>Exposed population</th>
<th>Cancer Present</th>
<th>Publ. 60</th>
<th>Heritable effects Present</th>
<th>Publ. 60</th>
<th>Total Present</th>
<th>Publ. 60</th>
</tr>
</thead>
<tbody>
<tr>
<td>Whole</td>
<td>5.5</td>
<td>6.0</td>
<td>0.2</td>
<td>1.3</td>
<td>6</td>
<td>7.3</td>
</tr>
<tr>
<td>Adult</td>
<td>4.1</td>
<td>4.8</td>
<td>0.1</td>
<td>0.8</td>
<td>4</td>
<td>5.6</td>
</tr>
</tbody>
</table>

CONSTRAINTS

The most fundamental level of protection is the source-related restrictions to the dose that individuals may incur, namely the dose constraint. This term was introduced by ICRP in 1990 as part of the principle of optimisation of protection:

‘This procedure should be constrained by restrictions on the doses to individuals (dose constraints), or the risks to individuals in the case of potential exposures (risk constraints), so as to limit the inequity likely to result from the inherent economic and social judgements’ (Paragraph 112, ICRP 60).

The constraint is used to provide a level of protection for the most exposed individuals from a source within a type of exposure. Compliance with the relevant constraint is not in itself a sufficient condition to satisfy ICRP’s recommendations; radiological protection must also always be optimised. ICRP continues to emphasize that optimisation of protection is the most important concept to achieve a satisfactory protection against radiation.

ICRP now uses the same conceptual approach in the source-related protection, regardless of the type of source. This means that optimisation of protection is always constrained by a level of dose where action is almost always warranted. This level of dose, constraint, is aimed at excluding from the process of optimisation any protection options that would involve individual doses above the selected constraint. In the case of planned situations (practices), the regulator or the operator establishes the constraint and it is a continuous part of the optimisation process. In other situations, the constraint may be established once, and then not used more, e.g., in the case of the design of a source or in the selection of emergency constraints. In the case of exposure from diagnostic medical procedures, the diagnostic reference level serves as a kind of constraint for a specified examination or procedure, but it does not relate to individual patients. The important message from ICRP is that a similar approach is used in optimisation, regardless of the type of source or the terminology used.

The dose constraint is not a form of retrospective limit - this function is provided by dose limits. In planned situations, the constraint is less than the dose limits, and in emergency or existing exposure situations, it represents the level of dose or risk where action is almost always warranted. The chosen value will depend upon the circumstances of the exposure and will be established by the national regulator or by the operator.

ICRP regards dose limits as being close to the point where the doses from the sources to which its limits apply result in a level of risk that, if continued, could be described as unacceptable for those sources in normal circumstances. A dose limit is not a measure of the degree of rigour implied by the recommendations. That should be judged by the overall impact of the system of protection, of which the optimisation of protection is the most onerous and effective component.

DISCUSSION

The Commission recognises the need for stability in regulatory systems at a time when there is no major problem
identified with the practical use of the present system of protection in normal situations. The use of the optimisation principle, together with the use of source-related constraints and the individual-related dose limits, has resulted in a general overall reduction in both worker and public doses over the past decade.

The philosophy of radiological protection is based on the LNT hypothesis. Because we do not know the level of risk associated with very low radiation doses, ICRP considers it to be the best approach to manage radiological protection. The LNT hypothesis also has characteristics that make it a useful tool and facilitates radiological protection. For example, it allows consideration of each source and exposure separately from other sources and exposures. It makes it possible to average dose within an organ or tissue over that organ or tissue, doses received at different times can be added, and doses received from one source can be considered independently of the doses received from other sources. The probabilistic nature of stochastic effects makes it impossible to make a clear distinction between ‘safe’ and ‘dangerous’, and the major policy implication of the non-threshold relationship is that some finite risk must be accepted at any level of protection. This has led to the system of protection with its principles of justification, optimisation and individual dose limitation. These principles continue to be the cornerstones of ICRP’s recommendations. A revised draft of the recommendations was be put on ICRP’s website for a second round of international consultation during the summer of 2006. When ICRP adopts its revised recommendations, 16 years would have passed since the 1990 recommendations were adopted.

REFERENCES

Radiation Protection – Philosophy and Practices in Indian Nuclear Power Programme and Fuel Cycle Facilities

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Radiation Protection is an integral component of the development of atomic energy related programme in India including nuclear fuel cycle facilities. The radiation protection standards are basically derived from ICRP recommendations and IAEA’s Basic Safety Standards. A well structured regulatory organization exists in the country. The radiation protection standards in nuclear fuel cycle facilities and NPPs are implemented through the Health Physics Unit (HPU) and Environmental Survey Laboratories (ESL) established at these plants. The HPUs and ESLs are independent of the plant management and they report to Health Safety & Environment Group, BARC. Adequate personnel monitoring programme has been established at all the sites. Training of personnel is an important aspect of the radiation protection programme. With the importance given to the implementation of protection standards generally the dose received by occupational workers is well below the regulatory limits. Cases of exposure above the limits are negligible. Dose to public from radioactive effluents are only a small fraction of the limit.


1. Introduction

Atomic Energy programme in India was initiated 50 years back and nuclear power was the mainstay of this programme as it would provide an impetus to the nation building through infrastructure facilities. Full fledged nuclear fuel cycle technology has been developed to support this programme. India has embarked now on an ambitious programme of achieving 40000 MW electrical installed capacity from Nuclear Power Plants. At present, nuclear power contributes only 3.3% of the total electrical power requirement of the country. The programme envisages to raise this percentage to 10 by the year 2020 AD by indigenous development of more 220 MWe and 540 MWe units of Pressurised Heavy Water Reactors (PHWR), importing Light Water Reactors and by the introduction of Fast Breeder Reactors. India has only limited resources of natural uranium. Therefore, the Nuclear Power Programme envisages plutonium recycle in thermal as well as fast reactors. Since the country possesses vast resources of thorium, its utilization in breeder reactors in the long run also, is planned. Therefore, India’s nuclear fuel cycle, operations are diverse and wide ranging. The operations include mining and milling of uranium and thorium, production of nuclear grade uranium and thorium oxides, fabrication of fuel elements, fuel reprocessing and radioactive waste management. Fig 1 gives a representation of Nuclear Fuel Cycle Operations.

2. Radiation Protection Status in India

Radiation Protection, both occupational and public, and the related research and development activities are an integral component of the nuclear fuel cycle operations. In the early stages of the programme itself, a firm foundation was laid for effective self reliance in the radiation protection programme in the country, especially in the field of nuclear power generation related activities. Therefore, simultaneous with power generating activities an ongoing programme for the assessment of radiological impact of the programme, both in occupational and public environment, has been continuously undertaken, successfully backed up by a strong and reliable R&D programme.

2.1 Radiation Protection Standards in India, like in any other country, are basically derived from recommendations of the International Commission on Radiological Protection (ICRP) and their transformation into more practicable form by the IAEA, in its Basic Safety Standards. Though international standard and guidelines are basically respected and accepted for radiation protection, the Atomic Energy Act of 1962 formulated to provide the development for control and use of atomic energy, forms the legal basis for implementation of the standards and guidelines related to radiation safety in the country. Rules pertaining to radiation safety were framed from time to time based on the Atomic Energy Act of 1962.
2.2 A suitable regulatory mechanism, backed up by an appropriate organizational structure, is existing in India for the proper implementation of the radiation safety programme. The Atomic Energy Regulatory Board (AERB), an independent body, is the apex regulatory body for the nuclear and radiation safety in India. The Bhabha Atomic Research Centre (BARC) is governed by a separate regulatory agency called BARC Safety Council (BSC). The organizational structure of the regulatory body is so evolved as to take care of the radiation protection aspects during various stages, such as siting, design construction, commissioning, operation and decommissioning of all types of nuclear facilities. For effective surveillance of the radiation safety in such installation, Health Physics Units are established in each facility/plant which are independent of the facility/plant management and report to Health Safety and Environment Group of BARC which is a scientific support organization to the regulatory body on radiation safety related activities. The primary responsibility for maintaining radiation safety and ensuring radiation protection standards in the plant rests squarely with the management of the concerned plants and HPUs provide advisory support to the plant management. This is a very unique feature of the radiation protection organization in India.

3 Personnel Monitoring Programme

Personnel Monitoring is the most important aspect in radiation protection programme. The programme ensures that exposure of workers to radiation is effectively controlled to comply with regulatory limits. The personnel monitoring programme for external radiation was initiated in the country many decades ago and has evolved along with the atomic energy programme. Presently it covers around 3700 institutions and about 65000 radiation workers, out of which 25000 are from DAE institutions. Indigenously developed TLD badges based on CaSO$_4$:Dy are used for external monitoring.

In addition to the external dose internal dose received, if any, also needs to be assessed. Internal dose due to radioactive materials by inhalation, ingestion or skin contamination is measured indirectly by routine bio-assay programme using special instruments and techniques. Internal dose due to radioactivity inside the body is directly measured by screening the workers using whole body or organ counters which are capable of detecting very low levels of internal contaminations. In this context, it is important to state that in the PHWR, which is the mainstay of India’s nuclear programme, internal dose of workers due to tritium constitutes about 25 percentage of the total dose. Internal dose is an important component in the front-end of the fuel cycle where radon and thoron are present in the working environment. In addition to TLDs, the external dose is also measured by SSNTD based personal monitors to evaluate doses for mine workers.

The results of whole body/organ counting and bioassay measurements are used to obtain estimates of intakes and Committed Effective Doses for demonstrating compliance with regulatory dose limits (30mSv/y as prescribed by AERB).

4 Environmental Radiological Surveillance

Since its very inception, the Indian nuclear power programme has laid a strong emphasis on radiation surveillance in the environment. Systematic measurements of radiation levels in the environment and related investigations have been undertaken by the Department of Atomic Energy (DAE). The Indian nuclear programme recognizes the importance of this aspect and established a chain of Environmental Surveillance Laboratories (ESL) at all major nuclear sites long...
before any statutory regulations were established by government agencies.

The primary aim of the environmental monitoring programme is to demonstrate compliance with the radiation exposure limits set for members of the public (1 mSv/yr). In pre-operational phase, ESLs generate baseline data on the levels of external radiation dose and concentration of natural radioactivity and also carry out epidemiological and dietary survey. This requires a detailed measurement of the radionuclides in different environmental matrices covering 30 km radial distance around the plant. In the operational phase the ESL continuously monitors the external radiation exposure levels in the environment, measures meteorological parameters and analyzes the distribution and concentration of plant related radionuclides in samples of different environmental matrices to assess the contribution, if any, from the plant releases. The samples are selected on the basis of potential pathways of exposure. The number and type of samples and sampling frequency can be site specific depending on the nature of operations, aspects related to utilization of the local environment, existence of population clusters etc. The programme also undergoes modification based on experience. Generally, more samples are taken close to the plant premises or wherever population clusters exist and sampling frequency gets reduced with distance. Instrumentation and techniques have also undergone changes over the years. A Quality Assurance Programme in which results of selected measurements are compared with international standards such as those of the World Health Organisation (WHO), the International Reference Centre (IRC), France, and the International Atomic Energy Agency (IAEA), Vienna, ensure the quality of measurements and the data. Although the primary emphasis is on samples that are relevant directly to the estimation of dose such as drinking water, edible food items, air etc. a number of other samples are also assayed for radioactivity and used as trend indicators and sensitive detectors or markers. Examples of the former are sea water, sediment and the latter, goat’s thyroid which concentrates the radionuclide $^{131}I$, if present in the environment, to a large extent. Contribution from plant related radiation is small when compared with the radiation exposure received in the public domain from naturally occurring sources as well as its wide variation from region to region in the country. This has been amply demonstrated by the voluminous data generated by the Environmental Survey Laboratories.

ESLs also study the meteorological characteristics of the environment like wind speed, wind directions, air temperature, relative humidity etc. which are continuously monitored and recorded. Meteorological towers with mounted instruments are available at all important nuclear sites. At complex terrains, sophisticated instruments such as SODAR are used. These measurements provide vital input parameters for assessing the atmospheric diffusion properties, external dose from radioactive plumes and for undertaking effective counter measures in public domain in case of accidental release of radioactivity into the environment.

4.1 Concept of Dose Apportionment

The concept of dose apportionment, known as ‘dose constraints’ in international parlor was introduced in India for a judicious utilization of the public dose limit. In this concept, the principal limit of 1 mSv/year for a member of the public is apportioned among the various facilities operating and planned at the site and further among the atmospheric, aquatic and terrestrial routes and also among specific radio-nuclides depending on the specific characteristics of the installation. The extreme value analysis of the operating experience data of the facilities or similar facilities elsewhere is used as the prime basis for the dose apportionment. At multifacility sites (Tarapur, Kalpakkam and Rawathbhata) only about 85% of the public dose limit is apportioned leaving the balance for future facilities. Fig 2 shows the concept of dose apportionment as applied to Tarapur site.

Based on these concepts a three-tier system of regulatory control and compliance is employed for radiological surveillance of effluents and the resulting exposure in the public domain arising from nuclear operations: (i) discharge criteria are specified for each plant in the form of Technical Specifications for plant operations (ii) all effluents before they are discharged from the plant are sampled and monitored at the source to ensure that discharge criteria are being met; any deviation to be reviewed for corrective action and (iii) an independent means of monitoring the environment by organizing and conducting a detailed environmental monitoring programme is established. These detailed measurements are carried out by the Environmental Survey Laboratory located at each of the main nuclear sites in the country and operated by HSE&G, BARC.

5. Radiological Characteristics of Nuclear Fuel Cycle Operations

The radiological characteristics of nuclear fuel cycle operations are widely different at each stages of the fuel cycle. The front-end operations of nuclear cycle facilities, especially in mining and milling and in thorium extraction, the naturally occurring radioactive materials are present in an already highly dispersible or mobile form, in the form of solutions, slurries and powders often associated with a wide variety of reactive and corrosive chemicals. The front-end is characterized by the presence of large quantities of low specific activity naturally occurring radioactive materials. Internal exposure of occupational workers is due to the naturally occurring short-lived radon and thoron daughters as well as due to the long-lived uranium, radium and thorium. The tailing pond filled with fine fraction of the waste rocks from mining operation to extract uranium is important from the point of view of public exposure. In the fuel fabrication plants the main hazards arise from potential inhalation exposure to uranium oxide dust and chemical
pollutants. In the mixed oxide/mixed carbide fuel fabrication plants, the problem is one of handling large quantities of highly toxic and pyrophoric powders containing mixtures of oxides and carbides of uranium and plutonium.

The Reactor operations and back-end of the fuel cycle are characterized by high specific activities of fission products, activation products and actinides. During the normal operation of the reactors most of the radioactivity is well contained within the fuel element and the radiation hazard is mainly due to activation products and the small amount of fission products that leak from the fuel elements into the primary coolant. The internal exposure at the reactor operation stage is mainly due to tritium in PHWRs. In the fuel reprocessing plant, fission products are present in very high concentrations along with actinides often in the presence of highly corrosive and reactive chemicals. Although the large inventory of the short-lived fission product noble gases and volatile species, are absent due to long period of cooling, other long lived species such as $^3$H, $^{14}$C, $^{85}$Kr, $^{90}$Sr, $^{129}$I, $^{137}$Cs and the actinides appear at the reprocessing stage. Internal exposure due to long lived actinides is also a characteristic feature at reprocessing stage. The radioactive waste generated at different stages of fuel cycle operations are also of different characteristic. In the waste vitrification plants, the concentrated fission product solutions are again subjected to high temperature process and converted to a solid form suitable for ultimate disposal. The presence of non-radiological hazard, especially chemicals is a special characteristic in the front-end and back-end of the fuel cycle.

In the following part of the paper, the operating experience with respect to radiation protection in nuclear fuel cycle facilities and NPPs in India are detailed both in the occupational and public domain.

6. Front End of the Nuclear Fuel Cycle

6.1 Uranium Mining & Milling

The Uranium mines at Jaduguda, Bhatin and Narwarpa in Singhbhum district of Bihar was set up by Uranium Corporation of India Limited (UCIL). The ore body containing natural U is the source of external exposure due to beta and gamma radiation. Radon-222 ($^{222}$Rn) emanating from the ore body and broken ore in the mine drips through rock strata which may be slightly porous or fissured due to mining operations and disintegrate to form atoms of short lived radon progeny ($^{218}$Po, $^{214}$Pb, $^{214}$Bi and $^{214}$Po). These daughter products which are positively charged at the time of formation get readily attached to the fine aerosols abundantly present in the mine air, cause inhalation dose to the workers. The low active U ore dust also causes internal dose to the lung. Since the abundance of $^{233}$U and $^{234}$U is low in natural uranium their contribution towards occupational hazard in mining operation is considered to be insignificant most of the contribution coming from $^{238}$U.

The only practical method of control of internal exposure is by providing good and adequate underground ventilation to dilute and minimize the radon concentration to less than the prescribed limits (1000 Bq/m$^3$ for radon and 0.3 working level for radon decay products). It is seen that a well planned ventilation system which is adequate to take care of the conventional underground pollutants like blasting and diesel vehicle flumes, is more than sufficient for
controlling radon and its decay products concentration in low grade U mines.

The radiological protection programme in the mine and mill has ensured that occupational exposure of mine and mill workers have remained within the regulatory limits. Table 1 gives the occupational dose data for facilities in the front-end of the fuel cycle, averaged over the period 2001 to 2005. Steady decline in collective dose and average dose over the years have been observed and this bears testimony of the effects of radiological protection programme at uranium mines and mill in India.

Table 1 Occupational Dose Data in the Front-End of the Nuclear Fuel Cycle (2001-2005)

<table>
<thead>
<tr>
<th>Facility</th>
<th>Average Collective Dose, P. Sv/y</th>
<th>Average Individual Dose mSv/y</th>
<th>No of Cases &gt;20 mSv/yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>U mining</td>
<td>7.47</td>
<td>7.06</td>
<td>0</td>
</tr>
<tr>
<td>U milling</td>
<td>1.17</td>
<td>2.10</td>
<td>0</td>
</tr>
<tr>
<td>Mineral processing IRE plants, Kerala</td>
<td>2.44</td>
<td>6.14</td>
<td>1</td>
</tr>
<tr>
<td>Fuel Fabrication Plant, Hyderabad</td>
<td>1.56</td>
<td>1.43</td>
<td>0</td>
</tr>
</tbody>
</table>

Environmental Surveillance programme at Uranium Mine Complex has been extended to the surrounding environment since liquid and gaseous effluents from the plant ultimately reach the public domain. In order to assess the enhanced radiation levels resulting from such releases, the base-line natural background radiation levels in these areas due to the presence of radioactivity in the earth’s crust, radon/thoron and their decay products in air and traces of radioactivity in water and food are established. Because of active ore deposits in Jaduguda area, the natural background radiation is slightly elevated compared to other places. The gamma radiation background in Jaduguda is about 0.75 – 1.8 mGy/year while the radon background is about 4-20 Bq/m³ which is an order of magnitude higher than the background levels else where. The environmental releases of radon from U mines and the concentration of U(nat.), ²²⁶Ra and Manganese in the near by rivers are below the AERB limits.

6.2 Monazite & Thorium Extraction

Indian Rare Earths Limited operates the monazite separation and thorium extraction plants at Manavalakurichi (Tamil Nadu), Chavara and Udyogmandal (Kerala) and OSCOM (Orissa). From the mineral deposits, monazite, ilmenite, rutile, zircon, etc. are recovered. The monazite is further chemically processed to extract thorium and rare-earths. Thorium and its decay products in monazite pose radiological safety problem during operation of the plant while they are processed. Substantial reduction in occupational radiation dose was achieved in recent years due to technological upgradation of the operation at these plants along with effective radiation protection measures (refer Table 1). Some of these measures are shifting from manual to mechanical operation; reduction in dust level by usage of wet concentration methods; Mechanized drying which reduced the contact time of the workers with the materials; containerization of monazites reduced the exposure of the workers and spillage and improvement in house keeping.

Chemical processing of monazite generates liquid effluents, containing low levels of ²²⁸Ra, phosphates and fluorides. Treatment of the effluents with lime and calcium chloride has resulted in very low concentration of the above nuclides in the receiving water body.

It is observed that there is no enhancement in radiation exposure of the public due to the operation of the IRE plants, on the contrary, the background exposure in mined areas is found to have reduced because of mining operations.

6.3 Fuel Fabrication

Nuclear fuel fabrication facilities are located at the Nuclear Fuel Complex at Hyderabad. The main hazards in these operations arise from potential inhalation exposure to Uranium oxide dust and chemical pollutants. These are, however controlled by ventilation and use of protective equipment. Occupational dose statistics are given in Table 1.

Comparatively speaking, fuel fabrication gives rise to very few atmospheric and aquatic discharges. Solid wastes of rattanite cake containing U are sent to the U mill for recovery of U. Chemical effluents containing mainly ammonium nitrates and sodium nitrates are solar evaporated at site in specially constructed and polythene lined ponds for recovery of salt. Washing from the plants are directed to settling tanks adjusted for pH and are used for horticulture purposes within the premises. Public exposure has been found to be negligible.

6.4 Nuclear Power Plants

Details of the 8 operating Nuclear Power Plants in India are given in Table 2.
Table 2  Operating Nuclear Power Plants in India

<table>
<thead>
<tr>
<th>Name of the NPP</th>
<th>Type</th>
<th>Capacity (MWe)</th>
<th>Location (State)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TAPS 1&amp;2</td>
<td>BWR</td>
<td>160 x 2</td>
<td>Tarapur (Maharashtra)</td>
</tr>
<tr>
<td>TAPS 3&amp;4</td>
<td>PHWR</td>
<td>540 x 2</td>
<td>Tarapur (Maharashtra)</td>
</tr>
<tr>
<td>RAPS 1&amp;2</td>
<td>PHWR</td>
<td>200 x 2</td>
<td>Rawatbhata (Rajasthan)</td>
</tr>
<tr>
<td>RAPS 3&amp;4</td>
<td>PHWR</td>
<td>220 x 2</td>
<td>Rawatbhata (Rajasthan)</td>
</tr>
<tr>
<td>MAPS 1&amp;2</td>
<td>PHWR</td>
<td>220 x 2</td>
<td>Kalpakkam (Tamil Nadu)</td>
</tr>
<tr>
<td>NAPS 1&amp;2</td>
<td>PHWR</td>
<td>220 x 2</td>
<td>Narora (Uttar Pradesh)</td>
</tr>
<tr>
<td>KAPS 1&amp;2</td>
<td>PHWR</td>
<td>220 x 2</td>
<td>Kakrapar (Gujarat)</td>
</tr>
<tr>
<td>KGS 1&amp;2</td>
<td>PHWR</td>
<td>220 x 2</td>
<td>Kaiga (Karnataka)</td>
</tr>
</tbody>
</table>

Major fraction of the occupational collective dose and the number of radiation workers in the nuclear fuel cycle operations belong to the operating Nuclear Power Plants (NPPs) in the country. Therefore, radiological aspects of NPPs have to be dealt with in detail. The “critical group” of workers whose individual dose was exceeding 20mSv/yr were identified and more attention was paid on this group of people. Their work areas, nature of work and the radiation protection procedures followed by them, etc. were scrutinized. The successful implementation of ALARA committees recommendations, strict adherence to radiation protection procedures etc. has resulted in reducing the collective dose. Table 3 gives the occupational dose data of NPPs in India, averaged over the period 2001-2005.

Table 3  Occupational Doses at NPPs in India (2001-2005)

<table>
<thead>
<tr>
<th>Plant</th>
<th>Collective Dose (P-Sv)</th>
<th>Avg. Individual Dose mSv/yr</th>
<th>Cases &gt; 20mSv/yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>TAPS1,2</td>
<td>7.87</td>
<td>3.09</td>
<td>2</td>
</tr>
<tr>
<td>RAPS1,2</td>
<td>6.99</td>
<td>3.07</td>
<td>37</td>
</tr>
<tr>
<td>MAPS1,2</td>
<td>14.54</td>
<td>4.53</td>
<td>29</td>
</tr>
<tr>
<td>NAPS1,2</td>
<td>6.86</td>
<td>3.39</td>
<td>26</td>
</tr>
<tr>
<td>KAPS1,2</td>
<td>3.78</td>
<td>2.04</td>
<td>4</td>
</tr>
<tr>
<td>KGS1,2</td>
<td>1.76</td>
<td>1.05</td>
<td>0</td>
</tr>
<tr>
<td>RAPS3,4</td>
<td>2.52</td>
<td>1.27</td>
<td>0</td>
</tr>
<tr>
<td>TAPS4</td>
<td>0.081</td>
<td>0.04</td>
<td>0</td>
</tr>
</tbody>
</table>

A decreasing trend of collective dose has been observed in spite of undertaking many unique radioactive jobs in high radiation dose rate areas, such as:
- Replacement of recirculation system equalizing line and bypass line at TAPS 1&2
- Replacement of cleanup system heat exchanges and pipings at TAPS 1&2
- Replacement of core spray and cleanup system check valves and piping at TAPS
- Replacement of feed water heaters at TAPS
- En-mass coolant channel removal work in RAPS-2
- Repair work of over pressure relief device (OPRD) of RAPS-1
- Stuck-fuel incident at MAPS
- Channel removal for Post Irradiation Examination works at MAPS
- Moderator pump seal replacement at NAPS
- Adjustor rod replacement at NAPS

These works in high radiation field areas were completed successfully, sometimes consuming lesser collective dose than budgeted for such works.

Better fuel performance and chemical decontamination of the system at MAPS-1&2 and RAPS-1&2 have also resulted in decreased radiation levels around the working areas. The reduction due to system decontamination was effective only for a limited period. The internal dose due to tritium, which contributes about 25 to 30% of the station collective dose, is another important feature of radiation protection programme at PHWR.

India was among the first few countries, which had adopted the revised public limit and had translated the limit into technical specification for the nuclear facilities at Kalpakkam site, and later on applied to other plants. For more details on environmental surveillance refer to section 4. Table 4 gives the annual average release rate of radionuclides from the operating NPPs in the country. A declining trend of releases from older Plants at TAPS-1&2, RAPS-1&2 and MAPS-1&2 is observed mainly due to better fuel behavior and leak tightness of the systems.

The results of environmental monitoring programmes carried out at the NPP sites in terms of annual average dose to public at exclusion distance of 1.6 km is given in Table 5. The Table also indicates dose resulting from natural sources at these sites. The dose resulting from NPP operation is only a small fraction of the natural background radiation at these sites and in case of older plants (TAPS, RAPS and MAPS) have always been less than 10% of the ICRP dose limit. The doses at farther distances are still less. For Tarapur and Kalpakkam site the dose is inclusive of
small fraction resulting from fuel reprocessing and other facilities operating at these two sites. In the cases of later versions of PHWRs (NAPS, KAPS, KGS and RAPS-3&4) the doses are lower by an order of magnitude. The reduction is primarily due to changes in system design, such as absence of air cooling in the reactor structures which has eliminated the production of Ar-41. The impact due to long lived radionuclides like radio cesium and radiostrontium are negligible and are at global fall-out levels.

Table 4 Environmental Discharges from NPPs - Percentage of Technical Specification (Avg. for 2001-05)

<table>
<thead>
<tr>
<th>Plant</th>
<th>Atmospheric Discharges</th>
<th>Aquatic Discharges</th>
<th>Gross Beta</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$^3$H</td>
<td>$^{40}$Ar</td>
<td>FPNG</td>
</tr>
<tr>
<td>TAPS1,2</td>
<td>-</td>
<td>-</td>
<td>5.93</td>
</tr>
<tr>
<td>RAPS1,2</td>
<td>35.11</td>
<td>20.42</td>
<td>2.09</td>
</tr>
<tr>
<td>MAPS1,2</td>
<td>8.86</td>
<td>12.82</td>
<td>0.64</td>
</tr>
<tr>
<td>NAPS1,2</td>
<td>25.17</td>
<td>3.35</td>
<td>0.44</td>
</tr>
<tr>
<td>KAPS1,2</td>
<td>14.25</td>
<td>1.54</td>
<td>0.09</td>
</tr>
<tr>
<td>KGS1,2</td>
<td>2.26</td>
<td>1.88</td>
<td>5.96</td>
</tr>
<tr>
<td>RAPS3,4</td>
<td>8.47</td>
<td>9.35</td>
<td>3.04</td>
</tr>
<tr>
<td>TAPS4</td>
<td>0.01</td>
<td>0.4</td>
<td>0.02</td>
</tr>
</tbody>
</table>

* combined limit for inert gases
+ No direct discharges to sea from MAPS

6.5 Fuel Reprocessing

The Power Reactor Fuel Reprocessing (PREFRE) plant at Tarapur has a design throughput of 100 Te/yr of spent Uranium fuels discharged from PHWRs after irradiation to about 6000 MWD/Te and cooling time of 3 to 5 years. This cooling period directly helps in circumventing some of the radiological safety problems such as:
- dry transportation of spent fuel without forced cooling
- minimizing the activity due to hazardous fission products such as $^{95}$Zr – $^{95}$Nb and $^{106}$Ru
- reduced cooling requirement of high active liquid waste
- lower dose to occupational workers and members of the public.

Co-locating of reprocessing and associated waste management plants, including recycled fuel fabrication plants, at the same site as that of a nuclear power station considerably reduces the transportation problem and associated risk to public.

Operating experience of PREFRE indicates that occupational exposure and environmental releases have been very satisfactory. The collective dose and average dose of occupational workers at PREFRE Plant at Tarapur is given in Table 6.

The present public dose apportionment for PREFRE plant is 0.03mSv/year. Present experience indicates that radioactive releases in to the environment can easily be controlled to meet the above stringent criteria without any difficulty. Table 7 gives the annual release value of gross alpha and gross beta activities into air and water from PREFRE. It was possible to achieve a decreasing trend of discharges over the years because of the efforts put up by the plant management and health physics unit in executing the necessary system modifications and changes in procedures vis-à-vis stringent regulatory requirements. Some of the activities directly connected in improving the radiological conditions at PREFRE plant are as follows:
- Segregation of liquid effluents
- Dedicated treatment plants, such as evaporator condensates
- Treatment of spent fuel storage bay water with non-regenerable resins
- Reduction in generation of effluents, such as disposable cation exchange beds

Some of the globally dispersed long lived radionuclides (Tritium, $^{129}$I and $^{14}$C) originate from the fuel reprocessing plants. About 25 – 30% of the tritium inventory of PREFRE is released to the environment, out of which 20 – 30% is in liquid effluents, mainly in the final condensate from evaporators; the remainder is estimated to be present in zircalloy cladding. About 10% of $^{129}$I is released, out of which 8% through stack and 2% in liquid effluents. About 10% of $^{14}$C inventory is released mostly in gaseous effluents.
Table 5: Effective dose to members of the public at NPP sites at 1.6 km (Average for 2001-2005 \( \mu \text{Sv/yr} \))

<table>
<thead>
<tr>
<th></th>
<th>Doses</th>
<th>External</th>
<th>Internal</th>
<th>Total</th>
<th>Natural Bkg.</th>
</tr>
</thead>
<tbody>
<tr>
<td>TAPS</td>
<td>16.78</td>
<td>1.32</td>
<td>18.1</td>
<td>1960</td>
<td></td>
</tr>
<tr>
<td>RAPS</td>
<td>36.28</td>
<td>4.08</td>
<td>40.36</td>
<td>2120</td>
<td></td>
</tr>
<tr>
<td>MAPS</td>
<td>12.25</td>
<td>0.49</td>
<td>12.74</td>
<td>2400</td>
<td></td>
</tr>
<tr>
<td>NAPS</td>
<td>1.03</td>
<td>0.82</td>
<td>1.85</td>
<td>3220</td>
<td></td>
</tr>
<tr>
<td>KAPS</td>
<td>0.96</td>
<td>0.4</td>
<td>1.36</td>
<td>2220</td>
<td></td>
</tr>
<tr>
<td>KGS</td>
<td>1.39</td>
<td>1.17</td>
<td>2.56</td>
<td>1870</td>
<td></td>
</tr>
</tbody>
</table>

6.6 Waste Management

Facilities are existing at all sites, where nuclear fuel cycle installations are operating, for processing, conditioning, handling and disposal of radioactive waste that arise in different phases of the fuel cycle operation. For solid wastes the disposal facilities are divided in to earth trenches, R.C.C. trenches and tile-holes based on the surface dose rate on these waste packages (less than 2 mGy per hr in earth trenches, 2 to 20 mGy per hr in R.C.C. trenches and more than 20 mGy per hr in tile holes). The results of analysis of water samples collected from bore-holes surrounding these disposal facilities have demonstrated that there was no migration of radionuclides from these facilities in to underground water.

Low level liquid effluents are treated and diluted at the facility itself and discharged in to the recipient water body ensuring that the discharge concentration is within the regulatory limits. High level liquid wastes, which generally originate at fuel reprocessing plant, are further processed in separate plants. Medium level alkaline wastes are processed at Waste Immobilisation Plant (WIP) to contain the waste by bituminization/cementation/ion-exchange process. High level acid waste (raffinate) is also treated at WIP for vitrification.

Nuclear waste management can be sequentially depicted as collection, interim storage, treatment packaging, interim storage and final disposal. The treatment steps may also give rise to some effluents, which are to be suitable disposed off. Operating experiences of waste management plants at Tarapur indicate that all these techniques of radioactive waste management can be handled fully adhering to the regulatory dose limits to occupational workers and members of the public. Table 6 shows the occupational dose statistics at the Waste Management Plants at Tarapur, viz: 1) Radwaste Management Plants consisting of Low Level Liquid Waste Treatment Plant, 2) Solid Waste Management Facility and 3) Waste Immobilisation Plant (WIP).

Table 6 Occupational Doses at Reprocessing Plant and Waste Management Plants at Tarapur (Average for 2001-05)

<table>
<thead>
<tr>
<th></th>
<th>PFREFRE</th>
<th>WIP</th>
<th>Rad. Waste Mng. Plant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collective Dose person ( \text{Sv/yr} )</td>
<td>9.4</td>
<td>0.37</td>
<td>0.15</td>
</tr>
<tr>
<td>Individual dose ( \text{mSv/yr} )</td>
<td>2.05</td>
<td>1.08</td>
<td>1.10</td>
</tr>
<tr>
<td>Cases ( &gt; 20 \text{ mSv/yr} )</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

The environmental discharges from Waste Management Plants at Tarapur are shown in Table 7. The major components in the gross beta activity are the long lived isotopes of Sr, Ru and Cs. The gross alpha activity release from the WIP into air is insignificant (1/100 of gross beta). Gross beta discharges from WIP exhibit a steady downward trend.

Table 7 Environmental Releases from Reprocessing and Waste Management Plants (Percentage of Tech. Spec. (Average for 2001-05))

<table>
<thead>
<tr>
<th></th>
<th>PFREFRE</th>
<th>WIP</th>
<th>Rad. Waste Mng. Plant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gross alpha</td>
<td>0.014</td>
<td>0.34</td>
<td></td>
</tr>
<tr>
<td>Gross beta</td>
<td>0.013</td>
<td>7.47</td>
<td></td>
</tr>
<tr>
<td>Water</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gross alpha</td>
<td>51.92</td>
<td>0.34</td>
<td>6.66</td>
</tr>
<tr>
<td>Gross beta</td>
<td>0.95</td>
<td>9.34</td>
<td>15.42</td>
</tr>
</tbody>
</table>

* No stack discharges

7. Training of Personnel

For effective implementation of radiation protection standards, it is important to have comprehensive educational training programme not only for the radiation safety professionals but also the plant personnel. This forms a
regulatory requirement at all nuclear facilities in India. To meet the growing demand for radiation safety professional, a full-fledged training programme for creating a reserve of trained manpower in the country is in place. Radiation workers in varying categories and grades require good awareness of radiation safety and proper appreciation of the hazards associated with radiation. To inculcate this, all plant workers are trained and retrained periodically in various aspects of radiation protection.

8. Conclusion
Radiation Protection Programme both in occupational and public domain has been an integral component of the nuclear energy programme in India right from the initial stage itself. Internationally accepted radiation protection standards such as ICRP Recommendations, IAEA’s Basic Safety Standards are applied in the country with the endorsement by the national regulatory body. The success of the programme has been clearly indicated in the downward trend of radiation dose for occupational workers. Cases of exposure above the regulatory limits are very few. The environmental releases are only fraction of the regulatory limits and the resulting dose to members of the public is negligible. The downward revision of radiation protection standards by ICRP in 1990 and their endorsement by AERB with added restrictions and conditions have thrown a challenge to radiation protection professionals engaged in nuclear fuel cycle operations. But these challenges have been effectively met by demonstrating the compliance with the revised standards without resorting to major modifications or retrofitting in the operating plants. Design modifications improvements in monitoring techniques, better training of personnel will ensure minimum radiological impact in the occupational and public domain with future nuclear facilities coming up.

General Reference
The Development of Radiation Protection in Korea

S. H. NA
Korea Institute of Nuclear Safety
Chairman of Foreign Affairs of KARP

1. Introduction
Korea has twenty nuclear power plants (NPPs) in commercial operation, and an additional four NPPs are now under construction. They provide more than 40% of electric needs of Koreans. According to the long-term power development plan, eight more NPPs consisting of four OPR 1000s (Optimized Power Reactor 1000) and four APR 1400s (1400MW class Advanced Power Reactor) will be constructed by 2015.

Moreover, in terms of radiation applications as of December, 2005, 2,733 facilities are using radioactive isotopes/radiation generators in the fields, such as industries, hospitals and research institutes. Currently, around 30,000 workers are registered as occupational radiation workers.

In line with this expansion, the safety and security of radiation source, and the health effects of radiation exposure from ionizing radiation have been paid to the widespread attention from the public and government. In this regard, the government reaffirms that the radiation safety and security takes a top priority in the development of nuclear energy and the application of radioisotopes in various fields. Thereafter, the subjects on radiation effect of low dose, safety and security of radiation source, emergency preparedness and radioactive waste management are the priorities for the perspective researches in the current decade.

In this paper, the summaries of the current status and strategies of development on the radiation protection in Korea, and a new protection concept to include on-call alert system against the terror or illicit traffic as well as an integrated system of emergency called AtomCARE are described.

2. Evolution of Radiation-related Industries
Since the first NPP, Kori Unit 1, started its commercial operation in 1978, the nuclear power generation programme in Korea has developed rapidly. As of October 2006, 20 NPPs are in operation and 4 additional NPPs are under construction. In addition, seven units are planned to be completed between 2010 and 2015 as shown in Table 1.

<table>
<thead>
<tr>
<th>Number of operating units</th>
<th>2005</th>
<th>2010</th>
<th>2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generating capacity in MWe (%)</td>
<td>17,720(28.0)</td>
<td>18,720 (31.4)</td>
<td>27,320(34.2)</td>
</tr>
<tr>
<td>Power generation in GWh (%)</td>
<td>123,091(37.4)</td>
<td>155,983(41.3)</td>
<td>199,041(46.3)</td>
</tr>
</tbody>
</table>

The thermal power output of the first NPP was 587 MWe, but the newly designed 1,000 MW class Korean standard nuclear power reactor began its commercial operation since 1998. Thereafter, the new design and construction technologies have been the basis to enhance the operational efficiency and safety of domestic nuclear power plants.

All of the NPPs are Pressurized Water Reactors (PWR), except for 4 NPPs at the Wolsung site, which are Pressurized Heavy Water Reactors (PHWR). These NPPs are owned and operated by the Korea Hydro and Nuclear Corporation (KHNP).

In the field of radiation application, the first permit for utilizing radioactive isotopes was issued in 1963 to a medical facility and an educational research institute. As of December 2005, the number of licensed facilities for radioisotopes and radiation generators was 2,723, which demonstrates a rapid increase of about 15% annually. The radioactive sources and radiation generators have become a general use in a various fields, such as medical application for diagnosis and treatment, food sterilization, radiographic nondestructive testing, and industrial fields as shown in Table 2.

In view of this rapid increase in nuclear and radiation-related industries during the past 30 years, the proactive involvement of Korean government has been an effective tool for the radiation protection system. It should also be noted that the policies on radiation protection are being constantly changed and updated.

3. Status of the Infrastructure of Radiation Protection
A. Radiation Protection Legislation
The Korean regulatory system for radiation protection is based on the Atomic Energy Act Law, which provides the basic mandate and the fundamental guidelines concerning the development and utilization of atomic energy and radiation. This Act is supported by three lower supporting tiers, which consist of the Enforcement Decree of the Act (Presidential Decree), Enforcement, Regulation of the Act (Ministerial Ordinance), and the Notice of the Minister of Science and Technology (MOST).
### Table 2. Over 2,700 Facilities using Radiation Sources in Korea (as of December, 2005)

<table>
<thead>
<tr>
<th>No. of facilities</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Industrial Firms</td>
<td>1,490</td>
</tr>
<tr>
<td>Non destroyed test firms</td>
<td>36</td>
</tr>
<tr>
<td>Hospitals</td>
<td>140</td>
</tr>
<tr>
<td>Research Institutions</td>
<td>261</td>
</tr>
<tr>
<td>Sales firms</td>
<td>96</td>
</tr>
<tr>
<td>Public organizations</td>
<td>424</td>
</tr>
<tr>
<td>Educational organizations</td>
<td>215</td>
</tr>
</tbody>
</table>

Fig. 1 presents a schematic of the legal system pertaining to radiation protection in Korea. The Act provides the basic mandate and fundamental guidelines concerning the utilization and regulation of atomic energy and radiation. The Decree provides the technical standards and particulars entrusted by the Act and necessary for the enforcement of the Act. The Regulations provide the particulars entrusted by the Act and the Decree such as detailed procedures and format of documents.

The Notice provides detailed particulars for the technical standards and guidelines.

The purpose of the Act is "to promote the development academically within industry, to prevent the harms due to radiation and to secure the public safety for the enhancement of public life and welfare by stipulating the research, development, production, utilization and the safe management of nuclear energy.” This should be interpreted as an intention to maintain a balance between the promotion of the peaceful uses of atomic energy and of the safe use of radioactive products.

The detailed regulations and prescriptions for radiation protection are described in the presidential decree promulgated in 1982 and recently revised in June of 2006. The Ministerial Ordinance is divided into 3 parts: the Enforcement Regulation concerning the Technical Standards on the Nuclear Facilities and Technical Standards on Radiation Safety Management.

The Ministerial Notice consists of 83 different Notices covering administrative procedures as well as technical guidelines and standards. Among these, 19 Notices are directly concerning radiation protection and 20 for the management of radioactive wastes including nuclear fuels. The recent main Ministerial Notices on radiation protection were amended in 2004 as the issues on emergency preparedness, physical protection, and in 2005 as the notices for the radioactive waste control.

During the earlier initial stage, radiation protection legislation was largely stipulated by referring to legislation enacted by the United States, Japan and by other advanced nations. However, current laws and regulations in Korea are the reflection of recommendations of the International Commission on Radiological Protection (ICRP) and the standards of the International Atomic Energy Agency (IAEA), which are fundamentally consistent with and based on internationally accepted norms and practices.

**B. Framework of Regulation and Management**

The Ministry of Science and Technology (MOST) is a governmental organization and the competent authority in terms of radiation protection regulations related to the peaceful use of nuclear energy and radioactive materials, and the therapeutic use of radiation in hospitals. It issues many types of licenses to nuclear and radiological industries, such as construction permits or operational licensing with respect to nuclear power plants. The Nuclear Safety Commission under the jurisdiction of the Minister of MOST and its sub-committee for radiation protection were established in order to deliberate and decide on important matters concerning nuclear safety and radiation protection, pursuant to the Atomic Energy Act.

Meanwhile, the diagnostic use of X-ray radiation is regulated by the Ministry of Health and Welfare and the Korea Food and Drug Administration (KFDA).

To support governmental activities, a regulatory expert organization, Korea Institute of Nuclear Safety (KINS) was established in 1990 by special act. This organization performs safety assessments and regulatory inspections pertaining to the use of radioactive materials.
Licensed radiation sources should not be dumped, released, or disposed without legal permission from the Ministry in Korea, even if they have substantially decayed. All licensed sealed sources and solid radioactive wastes from medical centers must be transported to an authorized disposal site in Daejon, called the Nuclear Environment Technology Center (NETEC) for disposal.

C. Man-power Development

It should be noted that the curricula of the relevant departments at universities are mainly focused on the manpower requirements for nuclear energy in terms of the implementation of the national development program for nuclear power plants. The areas of health physics and radiation protection have been overlooked. Therefore, we are facing shortage of
the qualified experts in the field of radiation protection in Korea.

Fortunately, the effort for development on radiation protection is being strengthened at universities, especially in the graduate schools, reflecting the rapid growths of radiation-related industries, according to Mid-to-Long range nuclear research program conducted by government.

D. Current Policy

The fundamental objective of radiation protection policy is not only to ensure the occupational and public health but also to keep the balance between the promotion of the nuclear industry and the requirement for safety regulations that limit or prevent radiation hazards.

The recent issues in the field of nuclear safety regulation are the periodic safety review (PSR) and the risk-informed regulation (RIR) implementation as well as power updates. The PSR has been carried out since 2001 in order to ensure that the operating plants are maintaining safety levels with respect to the current licensing bases.

The RIR was prepared by the KINS research team and tested by a task inspection group through pilot applications to the model of nuclear power plants for three years. The ORP type NPPs have been the current models since March 2006.

4. Current trends of Radiation Protection in Korea

The recent trends of radiation exposure of radiation workers in various radiation-related facilities, is shown in Fig. 3. The average individual dose was 1.21 mSv/year in 2005.

![Fig. 3 Annual Average Exposed Radiation](image)

In the early 1980’s, the average individual dose was about 6 mSv/year. From the middle of 1980’s, in line with the world trends, Korean government made the continuous efforts to achieve the objective of ALARA by devising appropriate measures for protecting radiation workers from radiation exposure. Korea has accomplished the reduction of radiation exposure doses by applying new reduction methods and technologies, which were acquired through the exchange of information from the IAEA and OECD/NEA ISOE.

There are 28,888 radiation workers in the various radiation-related facilities, and their average individual dose was 0.29 - 3.28 mSv/year (Fig. 1). The trends of average doses have gradually decreased, but the average dose is still high in some facilities especially in the area of non-destructing testing according to ALARA.

In order to enhance the functions of safety of workers, Korea establish two systems: one for the national record keeping and the other for the professional analysis of individual lifetime dose so called Korea Information system on Occupational Exposure as shown in Fig.4.

Although the use of radioisotopes and radiation generators in Korea has sharply increased with the development of industry and life style improvements, the infrastructure and the personnel required to ensure that safety regulations are met, have not kept pace. As a result, the theft and loss of radiation sources still occurs and concerns have been expressed by the mass media and the public.

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Therefore, it has become necessary to effectively improve the safety and security provided by the safety regulations in order to accommodate the increased need for radioactive products and our need to enhance safety level, taking into account the social, economical, and technical circumstances.

For this reason, a Korean web based information system has been developed, called Radiation Safety Information System (RASIS) as shown in Fig.5. This system is designed to effectively monitor and trace down the life cycle of radioactive materials and its inventory. And it is note that all import/export radioactive materials are confirmed by the Custom Clearance at Korean ports through on-line connection with RASIS.

Moreover, the safety of nondestructive test source (so called the moving source) has been a public attention especially in the case of lost or misplacement of a radioactive source. Thereafter, the source tracking system has been established after attaching the mobile station on most all NDT instruments (about 900). It is named as Radiation-sources Location Tracking System (RADLOT) and presented in the AOCRP-2.

5. Enhancement of Radiation Protection Regulations

Korea imports about 97% of all domestically required energy sources. Taking into account the far-reaching effect of the nuclear industry and the position of nuclear energy as an essential energy source for the continuous development of the economy and the considerations of the Convention on Climate Change, nuclear energy should be the favored option despite of its potential radiation hazards. Therefore, it seems to be essential that the Korean nuclear energy community builds and fosters a sound environment and restore public awareness and confidence in nuclear energy especially under the current oil price.

Under these circumstances, the future direction of radiation protection policy should focus on balancing the increasing needs of the general public to assure the health and environmental safety, and to outreach the general understanding on the true nature of radiation risk.

A. Implementation of ICRP 60 and IAEA/BSS-96

Korea takes about seven years to reflect the ICRP Publication 60 recommendations and the IAEA/BSS-96 into legal system. And follow up researches and projects are being carried out in Korea. Lessons learned during the course of the project emphasize on the time to be sufficient for reviewing and testing the legal system and to provide enough opportunity for national consensus to adopt the recommendations. In addition, the issue of cost benefit on the dose reduction has always been a major subject of discussion occurred during the past implementation period even more in the current practice time.

We are looking forward to having the new ICRP recommendation after prudential review of the concerns and comments from all over the world. It is our hope to have sufficient time to ensure that the current practices are not satisfied to comply with the requirement of optimized safety level.
B. AtomCARE: Computerized Technical Advisory System for a Radiological Emergency

The purpose of the AtomCARE system is to provide the technical support and advisory services to the national radiological emergency response system in the case of a radiological emergency from a radiation accident at a nuclear facility such as an identification of the accident status, dispersion of the radioactive materials into the environment, estimation of the following accident doses to the public and so on.

The AtomCARE system conducts the following major functions during a radiological emergency as well as the normal operations of the nuclear power reactors:

1) Collects the safety parameter values and analyzes the nuclear safety functions and meteorological information on a real time basis,
2) Automatically notifies the relevant organizations of any abnormalities on a real time basis when the collected safety parameter values and functions exceed the limit values and criteria defined by the design based analyses,
3) Calculates the amounts of radioactive materials released and assesses the pathways and dispersion of the radioactive materials into the atmosphere,
4) Recommends and provides the technical support for the resident publics protection actions with an estimation and assessment of the affected area by the released radiation,
5) Builds the geographical information system (GIS) by employing an electronic map of 1:5,000 scale with the radius of 40 km from the center of a nuclear power plant site,
6) Analyzes the information obtained from a monitoring of the environment radioactivity levels across the country by an online system,
7) Operates a system for fast information exchanges in the case of radiological accidents,
8) Operates a video conference system for the communications among the radiological preparedness organizations and
9) Provides the technical support for the emergency preparedness and response to the central and local autonomous governments.

The AtomCARE system also manages and stores the following information:

1) Manages the information system so that it smoothly exchanges the information,
2) Manages and controls the information on the accident status and emergency preparedness actions,
3) Manages and controls the emergency hotlines and contacts,
4) Manages and controls the information database on the emergency preparedness and response,
5) Provides public information on the accident status to the general public through the internet,
6) Effectively manages and controls the information on the emergency preparedness,
7) Manages and controls the CARE system users and
8) Manages and controls the IAEA’s Early Notification Network (ENAC) in the case of a nuclear or radiological emergency.


Future Plan is to grade up the AtomCARE System and to expand the functions as the following:
1) Installs the additional Safety Information Display System (SIDS) for the new reactors to be joined in the Korean nuclear power fleet,
2) Develops a new dose assessment system for the anti radiological terror (ATDAS: Anti-radiological Terror Dose Assessment System),
3) Reinforces the wind field models such as a long-range atmosphere diffusion assessment system (LADAS: Long-range Atmospheric Diffusion Assessment System), which can cover the atmospheric diffusion with the range of a radius of more than 40 km from a reactor center,
4) Extends the development of the Emergency Response Information eXchange (ERIX) system,
5) Reinforces the Geographical Information System (GIS) with displaying the radiation monitoring measurement data and
6) Extends the applications of the Automatic Information Notification System (AINS) for a radiological emergency as well as nuclear emergency. These include the Global Positioning System for Radioactive Source Tracking (GPS-RST) and Vital Area Identification Package (VIP). The upgrade VIP will enhance assessment capability and the compatibility with the AtomCARE (Computer aided Radiological Emergency) Response System.

C. On-call Experts Network
In the course of strengthening the safety and security an infrastructure of voluntary expert on-call in each province has been established and all members are connected through an internet system and individual cellular phone. The scopes of tasks are classified into three categories against radiological terrorism: prevention, detection, and response. Prevention includes measures to protect nuclear and other radioactive materials against theft or other form of loss of control in conjunction with the system of RASIS and RADLOT as described in the above.

If prevention fails, second line defence on detection should be in place. All national detection system will be on alert including the preliminary airport monitoring system. The project is on going to extend functions and to detect interdict unauthorized movement of nuclear and other radioactive materials.

In an supplementary system of emergency responding, the ‘On-Call Expert Network’ is constructed to enhance the first responding capability. The network is composed of modules to communicate with the voluntary local experts who has knowledge and experience in radiation protection and to excercise emergency response scenarios for training.

D. Biological Effects of Low Dose Radiation (LowRad) in Korea
The Radiation Health Research Institute (RHRI) leads the researches on biological effects of the low dose radiation in a rational level. The ultimate goal of the research on LowRad is to present a new paradigm for the LNT model, which is the current mainstream in risk paradigm. It is our hope to overcome the radio-phobia and can contribute to the peaceful use of radiation.

Recognizing the radiation caused cancer, the earlier phase of LowRad project was based that the threshold in the biological effects is existed. It is well known fact that the detriment is proportional to the radiation dose over 200 mSv; however, controversial events have occurred in the low dose radiation field. Thereafter, the biological effects of LowRad have been evaluated in wide spectrum, which might cause the hypersensitivity to the bio-positive effects. Likewise human beings have lived along with radiation, the radio-phobia has caused many problems in our daily lives. Some research results from Italy and Denmark, show that the occurrence of artificial abortion has increased temporarily after the Chernobyl accident, although the exposed radiation level was scientifically too low to cause hereditary effect. This is a good example of how the radio-phobia causes harmful effects.

In this regards, the LowRad projects have been carried out in both of the epidemiology and biology fields in Korea. In the epidemiology field, researches for the nuclear power plants workers and nearby residents have been done since 1990. In the biology field, individual researches focused on adaptive responses to radiation have been done. In 2000,
LowRad projects were started by Korea Institute of Radiological & Medical Sciences through the long-term atomic energy development study.

For the researches, a low dose radiation facility was built in April of 2005 for the first time in Korea and a biological material bank for workers at nuclear power plants and a genomic identification system that enables detection of the LowRad specific genes were constructed. Recently, this institute is working on the 10-year LowRad project funded by the Ministry of Commerce, Industry and Energy in Korea. The purposes of the project are to improve the scientific and technical knowledge about the health effects of LowRad and to provide adequate tools for protection of workers. Since this project is collaborative network with the institute, university, and industry, it is expected to be a basis to expand scopes of researches on low dose radiation.

E. Advanced Radiation Research Institute(ARTI)

In a course of promotion of radiation technology the ARTI was established in 2005 and gamma-irradiator, electron beam accelerator, ion implantor, gamma cell irradiator and gamma-phytotron are installed including a 30 MeV cyclotron which is under construction. Recent researches include the issues on hardening of high-polymer, surface grafting, gel production in industrial field, and treatment of pollutants in the air and the water by using radiation for clean environment. The studies on the irradiation of food and the improvement of plants are also active.

F. Repository Site of LILW

After establishment of the legal basis of project promotion by the amendment of the Atomic Energy Act (AEA) in 1986, the Korean government has striven to secure a site for the low and intermediate level radioactive waste (LILW) repository. Since 1986, the Korean government has elaborated seven times to select a candidate site for the LILW repository, but all efforts were in vain. Thereafter, the government promulgated a Special Act titled "Supporting the Local County Around the LILW Repository" in March 2005, and announced a Public Notice titled "Site Selection for LILW Repository" in June 2005. After conforming the compliance with the site selection procedure in November 2005, Gyeonju City, near by Wolsung NPPs site, was officially designated as the candidate site for the national LILW Repository. Site characterization studies at the candidate site have been performed since February 2006 and the first phase of construction will be completed until December 2009. The total disposal capacity of the site is going to be 800,000 drums, however, a rock-cavern type repository of 100,000-drum capacity is to be constructed in the first phase.

6. Conclusion

Korea made continuous effort to sustain the current development of radiation protection and to enhance the functions of radiation protection infrastructure. The rapid expansion of radiation use and the issue of repository site of radioactive waste ignite the sensitivity of public response against the radiation and it becomes much burden to outreach the risk of low radiation dose. Being influenced by the global movement to strengthen the safety and security of radiation sources, various researches and projects have been carried out in Korea and significant improvements have been achieved in Korea.

Among these results, the establishments of AtomCARE, RASIS, KISOE, on-call expert network, RADLOT are highlighted as the integrated computer systems and the researches of LowRad projects and those issues leaded by a new facility of ARTI are also described.

The concept of ALARA is an appropriate measure for protecting radiation workers. The average individual dose in radiation workers in Korea was 1.21 mSv/year and 3.26 mSv/year in the area of NDT as of December 2005. The trends of average doses have gradually decreased, but the average dose is still high in non-destructing testing fields according to ALARA. The future directions of radiation protection policy in Korea should focused on meeting the increasing needs of the general public for assuring health and environmental safety and for improving general understanding on the true nature of radiation risk.
Radiological Protection Standards: Dose VS. Risk Limits

Dade W. Moeller* and Lin-Shen C. Sun†

Abstract – Standards for the protection of population groups exposed to radiation from radionuclides released from nuclear facilities have historically been expressed in terms of a dose rate. Although this is appropriate for conditions in which the radionuclides have relatively short half-lives, or the duration of their releases is expected to be limited to a few decades, it will be neither adequate nor appropriate for facilities, such as high-level radioactive waste repositories, that represent prolonged sources of potential releases of long-lived radionuclides. The reason is that it is impossible to predict the health impacts (i.e., excess cancers) of radiation exposures, for a specified dose rate, more than five to ten decades into the future. The origin of this dilemma is three fold: (a) the primary source of data on the biological effects of exposures to ionizing radiation, namely, the survivors of the World War II atomic bombings in Japan, involved high doses received at high dose rates from external sources; (b) the process of transferring quantitatively the health-effects observed among the exposed Japanese population to those of other countries of the world is complicated; and (c) it is impossible to estimate the baseline rates of cancers in various body tissues and organs of a population group for hundreds to thousands of years into the future. This being the case, it would undoubtedly be easier to estimate future doses, than it would be to predict future risks. Nonetheless, it is the risk that is the primary factor of concern. While the inability to predict the risk represents a major problem, there is one consolation. That is the relatively rapid progress being made in developing vaccines for preventing, and medical therapies for curing, some of the more common cancers affecting population groups today. As a result, the health risks (excess cancers and associated deaths) per unit of radiation dose are expected to be reduced dramatically during the next 50 to 100 years, with similar progress continuing thereafter. If this proves to be true, it could well be that, should a large nuclear facility undergo a major failure 100 or 200 years from now, and its associated radionuclide releases increase by several orders of magnitude, the health risk may be of minimal health concern. In fact, it could be that, for nuclear facilities, such as the proposed Yucca Mountain repository, the projected time of maximum dose may represent a time of minimum risk. This does not mean, however, that radionuclide releases can be ignored. To the contrary, regulatory agencies should continue the time-honored practice of requiring that all nuclear facilities be designed to maintain anticipated radionuclide releases As Low As Reasonably Achievable (ALARA).

INTRODUCTION

Standards for the protection of population groups exposed to radiation due to radionuclides released from nuclear facilities (for example, commercial nuclear power plants, spent fuel reprocessing plants, and institutions in which radionuclides are used in research, medicine, and industry) have historically been expressed in terms of dose rates. While this is appropriate for conditions in which the radionuclides have relatively short half-lives, or the quantities involved are relatively small, it may be inadequate for conditions in which the exposures to the public will involve prolonged releases of long-lived radionuclides, one example being a high-level radioactive waste repository. In a situation of this nature, it is almost mandatory that the limits be expressed in terms of risk (for example, excess cancers), the reason being that the relationship between a dose rate, and the associated risk to health, can vary significantly within time periods as short as five to ten decades. The purpose of this paper is to review and evaluate dose versus risk relationships, and to identify and discuss some of the primary factors that influence them.

SUPPORT FOR RISK LIMITS

The United States has relatively large quantities of high-level radioactive wastes that were generated through the production of nuclear weapons during World War II, plus comparable amounts of spent fuel produced through the operation of nuclear power plants to generate electricity. It has been a longstanding U.S. policy that these wastes should be disposed in deep underground geologic repositories. Recognizing this fact, the U.S. Congress (1992) requested that the National Research Council (NRC) review and evaluate the bases for the establishment of standards for protection of the public from potential radionuclide releases from such a facility. In their report, the NRC (1995, pages 64-65) recommended that the limits be expressed in terms of the accompanying risk, one of the reasons being that:

“A risk-based standard would not have to be revised ... if advances in scientific knowledge reveal that the dose-response relationship is different than envisaged today. Such changes have occurred frequently in the past, and can be expected to occur in the future.”

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Another advantage, as cited by the NRC, was that a risk-based limit would enable:

Risks to human health from different sources, such as nuclear power plants, waste repositories, or toxic chemicals, to “be compared in reasonably understandable terms,” and limits on the releases of radionuclides from repositories or other sources of long term radiation exposures would not “have to be stated in radiation units, such as “Sieverts or Becquerels that are not easily understood by the general public.”

While these statements strongly support the adoption of risk as a measure of the impact of prolonged radionuclide releases, the implementation of such an approach involves the understanding and proper interpretation of a variety of factors. These are discussed in the sections that follow.

TRANSLATING RISK ESTIMATES TO OTHER POPULATION GROUPS

Although there have been many attempts to quantify the relationship between ionizing radiation and its health effects, experts world-wide agree that the single most important source of human data on this topic are those generated through the long-term epidemiological studies of the survivors of the World War II atomic bombings in Japan (NRC, 2006, page 141). While detailed and comprehensive information has been obtained on the effects of these exposures on the Japanese population, the application of these observations to populations in other countries of the world (for example, the People’s Republic of China, or the United States) is a very complicated process. The risk per unit dose, observed within the Japanese population, cannot be applied to any other population without significant modifications. Even more importantly, it is impossible to estimate the risks of exposures that occur far in the future. This is due to three primary factors:

- The exposures to the Japanese atomic bomb survivors involved relatively high doses received at high dose rates from external sources of gamma and neutron radiation. In contrast, the health impacts of radionuclide releases from a radioactive waste repository, or a spent fuel reprocessing plant, will involve low-level doses received at low dose rates due to the chronic intake of alpha, beta and gamma emitting radionuclides that have been released into the environment and internally deposited in the bodies of nearby residents. This is important because the health effects (risk), per unit dose, received at low dose rates from internally deposited radionuclides are substantially less than those received at high dose rates from external sources (Bair,1997). This difference is partially taken into account through the application of quality factors (radiation weighting factors) for different types of radiation and the Dose and Dose Rate Effectiveness Factor (DDREF) (NCRP, 1997, page 63).

- Due to differences in dietary preferences and lifestyles, the risks for cancers in various body organs within the Japanese population are not the same as those for populations in the U.S. or the People’s Republic of China. This is important because the baseline rates play a dominant role in the magnitude of the projected excess cancer risk in individual organs per unit dose of radiation. Our current state of knowledge leads us to believe that, for most cancers, the higher the baseline rate, the more susceptible a given population is to additional cancers due to radiation exposures. As a result, there are country-to-country, or spatial, differences in the risk of radiation-induced cancers for the populations residing in each of these countries.

- At the same time, the cancer-risk characteristics of all population groups (i.e., the baseline rates of cancers in various body organs) are undergoing continuous change. This leads to what might be described as temporal alterations in the risk of cancer in different body organs, per unit of dose. Since the primary contributors to these changes are the rapid advances in the development of preventive measures and cures for cancer, the general trend in these changes will be a reduction in the baseline rates.

Absent an unanticipated event, the potential exposures due to prolonged radionuclide releases from a properly designed nuclear facility are expected to be low. In general, therefore, the associated health impacts will be limited to those of a stochastic nature, that is, mutagenic and carcinogenic effects. Because “at low or chronic doses of low-LET irradiation, the genetic risks are very small compared to the baseline risk in the population” (NRC, 2006, page 252), the discussion that follows will be limited to the carcinogenic effects of ionizing radiation.

ACCOMPANYING CHALLENGES

The challenges represented by the need to address each of the above three factors are discussed below. For purposes of this review and evaluation, the challenges in estimating the cancer risks to the U.S. population will be used as an example, but the same principles apply in estimating the risk for any non-Japanese population.

Challenge #1: Converting Health Effects (Risks) due to Exposures at High Doses and Dose Rates to Those at Low Doses and Dose Rates

Based on extensive reviews and evaluations, the International Commission on Radiological Protection (ICRP, 1991, ¶ B62, pages 111 - 112), and the National Council on Radiation Protection and Measurements (NCRP, 1997, page 64), have recommended that, for the evaluation of the health effects (per unit dose) from low-dose and low-dose rate
exposures, the estimated risks (excess cancers) observed among the Japanese atomic bomb survivors should be reduced by a factor of 2. As noted above, this is known as the dose and dose rate effectiveness factor (DDREF).

Challenge #2: Transfer of Risk Estimates to the U.S. Population

Once the health risks to the Japanese population have been modified, taking into account the radiation weighting factors \( w_d \) and the DDREF, these risks must be transferred to the people living in the U.S. To accomplish this task, it is necessary to account for the differences in key characteristics of the populations in the two countries (NRC, 2006). Epidemiologists use the term, *risk*, to describe the excess health effects (e.g., cancer incidence and mortality) observed in populations that have been exposed to radiation. One approach being applied for assessing the accompanying health impacts is the *Excess Relative Risk* (ERR), which is defined as “the rate of disease in an exposed population divided by the rate of disease in an unexposed population minus 1.0.” (NRC, 2006, footnote 3, page 143). The basis for this definition is that the increased incidence of a specific cancer, per unit dose to a specific organ, is assumed to be proportional to its baseline rate.

Data show that the baseline risks for cancers of the colon, lung, female breast, and male prostate are higher in the U.S. population than in the Japanese population. This implies that the U.S. population is more susceptible to the development of cancers in these organs. In contrast, the baseline rates for cancers of the stomach and liver are higher in the Japanese population (NRC, 2006, page 241). In applying the concept of proportionality, it is assumed that if a given radiation exposure/dose increases the baseline risk of a specific cancer in the Japanese population by a certain percentage, it will yield the same relative increase in the baseline rate for the U.S. population. The importance of this relationship can be illustrated as follows.

**Estimated Increase in Colon Cancers**

*Japanese Population.* Assume that a dose of 1.0 Sv to the colons of the Japanese population yielded an Excess Relative Risk of 0.7, that is, it increased the baseline rate of colon cancer by 70% (NRC, 2006, page 149). Assume also that the lifetime baseline rate for colon cancer among 10,000 members of the Japanese population was 500. Under these conditions, a dose of 1.0 Sv would increase their baseline rate for colon cancer to:

\[
(500) (1.7) = 850.
\]

This represents an estimated increase of 350 (i.e., 850 - 500) in the number of colon cancers in the exposed population.

*U.S. Population.* Assume that, for 10,000 members of the U.S. population (which, as indicated above, is known to have a higher rate of colon cancer), the lifetime rate for colon cancer is double that for the Japanese population. This would mean that, over the same period of time, the baseline rate would be 1,000. Under these conditions, a dose of 1.0 Sv would increase their estimated baseline rate for colon cancer to:

\[
(1,000) (1.7) = 1,700.
\]

In this case, the increase in the number of excess colon cancers would be 700. This, as would be anticipated, is double the estimated increase in colon cancers for a similar sized population group in Japan.

**Challenge #3: Extrapolation of Risk Estimates to Future U.S. Populations**

Further complicating the transfer of data from one population to another is that the lifestyles and baseline cancer rates in the populations in various countries do not remain constant with time. This was exemplified by the increases that occurred in the baseline rates for cancers of the stomach, colon, lung, and female breast, among the Japanese population during the period from 1950 to 1998. This was attributed to the fact they were becoming more “westernized.” (NRC, 2006, page 268). Due to the dynamic sharing of cultures through modern communication tools, i.e., the Internet and the cell phone, it is anticipated that, in some cases, country-to-country differences could be dramatically reduced in the future.

Under these conditions, the only way that a dose rate limit, regardless of its magnitude, has any relevance is if the risk of cancers in the specific body organs, anticipated to occur due to continuing radiation exposures at that dose rate limit, can be quantified. If the nuclear facility in question (for example a high-level waste repository) is anticipated to continue to release radionuclides over prolonged periods of time, any meaningful interpretation of the associated risks depends on accurate quantitative projection of the host of factors that will affect baseline cancer rates at that time. Since such a projection is impossible, a dose rate limit designed to be applied far into the future is meaningless in terms of its associated risk. Recognizing this fact, the ICRP (1998, ¶41, page 13) has acknowledged that:

“Doses and risks, as measures of health detriment, cannot be forecast with any certainty for periods beyond around several hundred years into the future.”

In fact, based on the previously discussed Japanese experience during the last half of the 20th century, and the current pace of technological and medical advances, it would be extremely difficult to predict the changes that may occur within as short a time as five to ten decades from now. Witness the remarkable progress being made in developing
preventive measures (vaccines), and cures (gene therapy), for some of the more common cancers affecting populations today.

INFORMATION REQUIRED FOR LONG-TERM RISK ESTIMATES

Epidemiological studies have documented that there are multiple factors that determine the risks of cancer among members of a specific population group. These include the lifestyles, personal habits, and medical practices; as well as the type of cancer, the sex and age of the persons being exposed; and the biological, chemical, physical, and radiological characteristics of the radionuclides involved (NRC, 2006, page 267). In every case, these factors must be those known, and/or anticipated, to exist within the affected population at the time the exposures occur.

For purposes of discussion, these factors will be divided into three categories:

- Lifestyles and Dietary Habits

  Studies have confirmed that lifestyles and diets play a significant role in the incidence of cancer in population groups. The age at which a woman has her first child, her total number of children, and the duration of breast-feeding, for example, affect her probability of developing breast cancer – the younger the age, the larger number of children, and the longer the time of breast-feeding, the less the risk. Also of note is that people, who are obese, have a higher incidence of cancer. Another lifestyle habit of critical importance, in terms of lung cancer, is the prevalence of cigarette smoking. The anticipated exposure of a population group to chemical carcinogens, which is influenced to the types of occupations in which they are employed, must also be factored into the estimates of future risk.

  Advances in public health also play a role. As the average life span of an exposed population increases, their risks of developing cancer increases.

- Preventive Medicine and Cancer Research

  A primary example in this category is the status of programs for developing vaccines for the prevention of cancer. The U.S. Food and Drug Administration, for example, has recently approved a vaccine for preventing cervical cancer in women (Bridges, 2006). Similar developments relative to cancers in other human organs and tissues are anticipated. Also important is the status of programs for vaccinating children for chronic hepatitis B. This reduces the incidence of liver cancer. In contrast, the increasing rate of hepatitis C, for which no vaccine is currently available, may lead to a future increase in liver cancer.

  Still another influencing factor is the development of procedures (such as gene therapy) that may dramatically increase the rate of cures for certain cancers, once they develop. Although these procedures will not reduce the incidence of cancer, they will certainly reduce the risk of people dying as a result of developing certain cancers.

- Racial Composition of the Population

  Data show that African-American men have higher rates of prostate cancer. At the same time, they have significantly lower rates of malignant melanomas. This is thought to be due to the presence of melanin in their skin, a pigment that absorbs UV radiation and protects them from harm. The genetic susceptibility to cancer is also different for various races. As a result, it would be necessary to know, or project, the racial composition of future populations.

  Recognizing the significance of these factors, the NCRP has stated that:

  “At some future time, it is possible that a greater proportion of somatic diseases caused by radiation will be treated successfully. If, in fact, an increased proportion of the adverse health effects of radiation prove to be either preventable or curable by advances in medical science, the estimate of long-term detriments may need to be revised as the consequences (risks) of doses to future populations could be very different.” (NCRP, 1995, Section 4.2.2.3, page 51).

COMMENTARY AND RECOMMENDATIONS

This review documents that it is impossible to predict the health impacts of ionizing radiation exposures, for a specified dose rate, more than five to ten decades into the future. This being the case, it would undoubtedly be easier (assuming a nuclear facility that can potentially serve as a prolonged source of radionuclide releases) to estimate future doses, than it would be to predict future risks. Nonetheless, it is the risk that is the primary factor of concern. While the inability to predict the risk represents a major problem, there is one consolation. That is the relatively rapid progress being made in developing vaccines for preventing, and medical therapies for curing, some of the more common cancers affecting population groups today. As a result, the health risk (cancer deaths) per unit radiation dose is expected to be reduced dramatically during the next 50 to 100 years. If this proves to be true, it could well be that, should a large nuclear facility undergo a major failure 100 or 200 years from now, and its associated radionuclide releases increase by several orders of magnitude, the risk may be of minimal health concern. In fact, it could be that, for nuclear facilities (a primary example being a high-level radioactive waste repository) that represent potential sources of prolonged radionuclide releases, the projected time of maximum dose may represent a time of minimal risk. This does not mean, however, that radionuclide releases can be ignored. To the contrary, regulatory agencies should continue to require that nuclear facilities, such as the proposed Yucca Mountain repositories, be designed and operated to maintain anticipated radionuclide releases As Low As Reasonably Achievable (ALARA).
The efforts of the nuclear facility operator, however, need not stop there. Opportunities are available for doing even more to reduce the doses to people living in the neighboring communities. One possible approach is for the nuclear facility operator to support the installation of radon removal systems in public schools and residences in the adjoining communities. Based on U.S. data, analyses show that, on average, the remediation of about five homes will reduce the population collective dose from indoor-radon by an amount equal to that of the radionuclide releases from an average commercial nuclear electric generating station. The remediation of several hundred homes will reduce the collective dose to the neighboring population by an amount equal to that to the workers at a nuclear power plant. Beyond that point in time, the annual collective dose to people living in the neighboring communities will be less than it was prior to the construction and operation of the nuclear power plant.

REFERENCES