Recent Achievements on Irradiation Facilities

REPORT OF A CONSULTANTS MEETING

IAEA Headquarters, Vienna, Austria

17 – 20 June 2019

Working Material Produced by the International Atomic Energy Agency

Vienna, Austria, 2019

1. INTRODUCTION

There are many applications and markets that have been well-served by radioisotope equipment for many years (see Annex I). These applications include:

- Medical applications (excluding therapy):
  - Blood irradiation
  - Tissue banks
- Food and agricultural applications
  - Sterile insect technique (SIT)
  - Food irradiation
- Industrial applications:
  - Sterilization
  - Cross-linking
  - Non-destructive testing (NDT)
- Research applications:
  - Biology (including plant breeding and small animal research)
  - Geology
  - Materials
  - Chemistry

However, lately users of radioisotope sources face many issues. One of the major challenges is restricted supply of Co-60 and Cs-137, the most commonly used radioisotopes. Increasing security concerns result in challenges in transportation and logistics as well as in overall radioisotope lifecycle management. All these factors lead to significant increase in cost of using radioisotope sources. At the same time, accelerators can provide an alternative that would address one or more of the challenges posed by radioisotopes. This report will discuss different uses of radioisotope sources and provide examples of ways that accelerators can substitute for them.

2. DISCUSSION

2.1. Overview

What has been done?

In many areas, radioisotope sources have been replaced or in the process of being replaced (completely or partially) by non-isotopic alternatives. For example, it was shown that cesium blood irradiators can be successfully substituted with 160-240kV x-ray systems. In some countries, for example Norway and France, all cesium blood irradiators were replaced. In others, such as the USA, the conversion is successfully ongoing, owing to DOE NNSA ORS programs. Another example is medical linacs, which have replaced Co-60 teletherapy in many countries. In case of NDT, the conversion is ongoing as in some cases gamma sources can be replaced by x-ray tubes, linacs, or betatrons. Finally, industrial accelerators are being installed worldwide to replace Co-60 sterilization facilities. Still, a lot of work remains to be done.

What is being done?

Numerous governments and international organizations including IAEA are concerned about source security and provide institutional support for the retirement of radioisotopes. Efforts are made to establish gamma/e-beam/x-ray equivalence for an array of polymers which should simplify licensing and regulations for the transition to alternative technologies. In many countries acceptance of food irradiation is growing, and food is increasingly being treated with e-beam. For example, in China more than 1M tons/year is currently processed with e-beam.

Accelerator manufacturers are expanding their offerings to cover various applications by providing a portfolio of machines ranging from 100's keV to 10 MeV. Dual mode machines (e-beam and x-ray) are offered much more often nowadays.

What still needs to be done?

To continue the conversion process, it is vital to provide even more viable industrial cobalt-60 replacement technologies, both more efficient and more cost-effective. One of the options for reducing the costs is to investigate the re-use, re-purposing, and re-cycling of existing facilities and equipment. It is also necessary to clarify the export restrictions on accelerators. Improved methods for specifying the shielding requirements for machines are also needed.

One of the major hurdles for transitioning to alternative technologies is a need to re-license or re-qualify every irradiated product before switching the irradiation modality. Better dialog between regulators and industry would significantly simplify this transition and help save time and money. In case of food irradiation rationale should be provided to increase x-ray limit for food from 5MeV to 7.5MeV.

Finally, we should continue educating all the players. We should provide public education about the benefits of radiation technology. We should also expand basic education about radiation applications and alternative technologies to radiation technology professionals as well as for decision makers.

2.2. Radioisotope sources and alternatives

To provide examples of ways that accelerators can substitute radioisotope sources, we broke them into several categories, depending on the application, radioisotope, and its typical activity. Below we will discuss each of the categories and possible alternatives in detail.

2.2.1. Cs-137 blood irradiators and research irradiators

Thousands of cesium blood irradiators are installed world-wide and used in a semi-production basis. However, users of cesuim sources are motivated to change to accelerators (x-ray tubes) by regulatory, financial, and operational considerations. For example, IAEA is no longer supplying cesium sources to developing Member States. As we mentioned before, several countries either completed, or are in the process of conversion to non-isotopic alternatives. Several machines from various vendors (Radsource, Hopewell Designs, Precision X-ray, etc) are currently available to replace cesium blood irradiators. Parameters of the typical accelerator replacing cesium blood irradiator are shown in Table 1. Several companies, for example RadiaBeam, are currently working on the next generation of low energy compact accelerators to replace cesium blood irradiators. Parameters of the next generation accelerators for this application are also shown in Table 1.

Cs-137 is also still widely used for R&D purposes. Over 2,000 Cs-137 research irradiators are installed world-wide and they are used intermittently for very diverse applications, including biology, geology, and material science. Many research institutes, universities, and government laboratories have begun the conversion from Cs-137 to x-ray devices, however this process has a number of challenges. Existing low energy x-ray machines might be a good substitute for blood irradiations, however, diverse uses of research irradiators require higher x-ray penetration with good dose uniformity and therefore higher energy. There is a need for 660 keV (or greater) average photon energy to substitute for Cs-137 research irradiators. New generation accelerators (see Table 1) can serve for both blood irradiation and R&D work.

Table 1. Existing and next generation accelerators to replace cesium blood irradiators and research irradiators.

Parameter	**Existing accelerators**	**Next generation accelerators, suitable for both blood irradiation and R&D**
Energy	140-240 kVp	2-4 MeV
Current	10-50 mA	100-200 μA
Dose rate	1-5 Gy/min	5-15 Gy/min
Size	1.2m x 1m x 2m	1.2m x 1m x 2m
Weight	1000-2000 kg	1000-3000 kg
Power requirements	220 V, 30 A	220 V, 20 A
Cost	$250-500K	$300K-1M
Lifetime (with annual maintenance)	>20 years	>20 years

2.2.2. Co-60 research irradiators

Co-60 has a significantly shorter half-life compared to cesium and therefore is less common for R&D applications. Nevertheless, ~500 self-shielded Co-60 installations (such as Gammacell 220 or similar) are estimated to be present worldwide in research institutes, universities, and government laboratories. Uses of Co-60 research irradiators are as diverse as uses of Cs-137 research irradiators. Good x-ray penetration and dose uniformity ratio (DUR) are usually a requirement for such applications. Therefore, substitutes for Co-60 irradiators must produce photons with at least 1.25 MeV average energy. Development of 4 MeV electron accelerators equipped with bremsstrahlung converter to produce ~1.25 MeV photons will solve the penetration problem and provide higher dose rates. Such energy accelerators are already available now (for example for radiation oncology), however the existing technology would not meet the expectations of the market in terms of price, complexity, and maintenance. We estimate such a machine to cost $1-2M. If the production volumes approached 50 units per year, then the market price could drop below $1M. A dedicated design, development, and packaging effort to meet this requirement could be accomplished in 1 to 3 years. Parameters of the accelerator suitable to replace research irradiator are summarized in Table 2.

Larger (few hundred kCi) Co-60 research irradiators are less common than self-shielded units, however, we estimate ~50-100 installations worldwide. Typical facility consists of a concrete bunker with a source pool (or source rack) in the middle. Products to irradiate are usually placed around the source, sometimes on turntables (see Figure 1). This setup can accommodate larger volumes of samples compared to self-shielded units.

It might be possible to retrofit the facility by replacing Co-60 source with a 4 MeV (or higher energy) accelerator. In this case, water needs to be removed (in case of wet source), and accelerator needs to be installed in the pit with the electron beam going upwards. Bending magnets can be used to bend the electron beam so that it's horizontal. Adding bremsstrahlung converter and rastering magnets will result in bremsstrahlung photon beam on the conveyor (see Figure 1).

This technology is already available today and the parameters of such accelerators are summarized in Table 2.

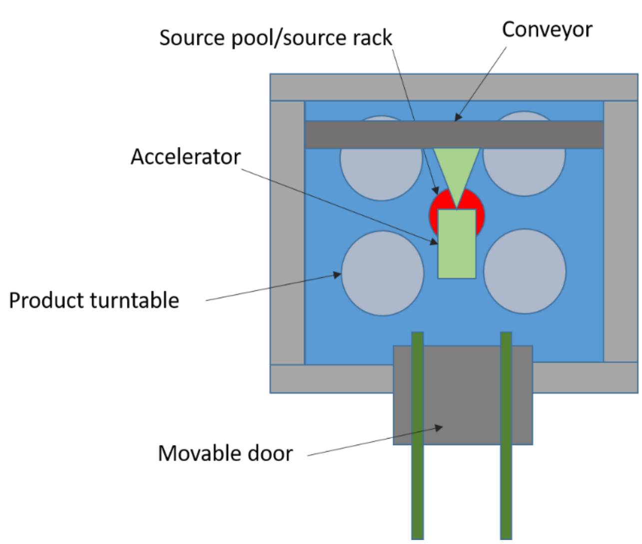

Figure 1. Schematic representation of the large research irradiator in a bunker. Co-60 source is shown in red, accelerator in green.

In many cases it might not be possible to retrofit the existing facility, so a new facility would need to be built. In this case any beam orientation is possible. Constriction of the new facility needs to be added to the overall cost of the project. We estimate the cost of new facility (including the accelerator) to be about $2-4M (see Table 3).

Table 2. Parameters of accelerators to replace Co-60 research irradiators.

Parameter	**To replace small (self-shielded) irradiators**	**To replace large (bunker) irradiators**
Energy	4 MeV	4 MeV
Current	100-200 μA	2-10 mA
Dose rate	5-15 Gy/min	1-10 kGy/min (at 1 m)
Size	1.5m x 1m x 2m	
Weight	2000-6000 kg	
Power requirements	220 V, 20 A	
Cost	$500K-1M	$1M-2M
Lifetime (with annual maintenance)	>20 years	>20 years

2.2.3. Co-60 industrial irradiators

Industrial irradiators are primarily used for phytosanitary applications and medical device sterilization. They operate in continuous or, less commonly, in large batch mode. Products come in pallets or tote boxes. Most of the small (~1 MCi) industrial irradiators are used for food irradiation as it typically requires less dose. They can also deliver sterilization doses, but at lower speed. Large (~5 MCi) industrial irradiators are usually used for medical device sterilization as they can deliver high doses at high speed. They can also be used for phytosanitary applications with split source rack.

Currently about 500 MCi of Co-60 is used for industrial sterilization (primarily medical devices) and the installed activity grows by ~3.5% annually. These production volumes can easily be treated with x-rays or e-beam. Depending on the application and the country, 5-7.5 MeV accelerators can be used in the x-ray mode. For some applications, 10 MeV e-beam mode can be used. To replace 1-5 MCi of Co-60, more than one accelerator should be installed in each facility. Parameters of these systems are given in Table 3.

Table 3. Parameters of accelerators to replace Co-60 industrial irradiators.

Parameter	**To replace 1 MCi**		**To replace 5 MCi**	
	X-ray	**E-beam**	**X-ray**	**E-beam**
Energy	5-7.5 MeV	10 MeV	5-7.5 MeV	10 MeV
Current (total for all accelerators)	15-30 mA	1.5-3 mA	140-160 mA (5 MeV) 80-100 mA (7.5 MeV)	8-20 mA
Cost (accelerators)	$2M-4M		$6M-15M	
Cost (full facility)	$5M-15M		$12M-25M	
Lifetime (with annual maintenance)	>20 years		>20 years	

2.3. Costs of ownership

The economics of conversion already makes sense with existing technologies and may be very attractive depending on the specific application. Table 4 and 5 show capital and operational expenses of the existing radioisotope sources, existing accelerator-based replacement, and future replacements. Operational expenses include radioisotope source decay, electricity, maintenance, and other expenses. Note that high quality, reliable electricity sources are mandatory for these solutions.

Table 4. Capital expenses.

Application	Radioisotope source	Accelerator (full facility)	Accelerator only	Accelerator Capex (future)
Cs-137 blood irradiator	$100K – 300K	$250K – 500K	N/A	----
Cs-137 research irradiator	$200K – 400K	$1M – 4M	N/A	$300K – 1M
Co-60 self-shielded research irradiator	$400K – 700K	$1 – 4M	N/A	$300K – 1M
Co-60 research irradiator compact bunker	$2M – 4M	$2 – 4M	$1M – 2M	---
Small industrial irradiator (1MCi)	$5 – 15M	$5M – 15M	$2M – 6M	---
Large Industrial irradiator (5MCi)	$15 – 30M	$12M – 25M	$6M – 10M	---

Table 5. Operational expenses including decay, electricity, maintenance, and other.

Application	Isotope source (Opex/Year)	Accelerator (Opex/Year)
Cs-137 blood irradiator	$0K – 20K	$10K – 30K
Cs-137 research irradiator	$0K – 20K	$10K – 40K
Co-60 self-shielded research irradiator	$10K – 40K	$20K – 60K
Co-60 research irradiator compact bunker	$0.2M – 0.5M	$0.2M – 0.5M
Small industrial irradiator (1MCi)	$0.5 – 1M	$0.2M – 1M
Large Industrial irradiator (5MCi)	$2.5M – 4M	$1M – 5M

Using these numbers, we estimated the cost of ownership assuming cost of Co-60 to be $4 /Ci, and electrical cost to be $0.10/kW-hr. We did not include costs of building and conveyor system, assuming they are comparable. Instead we considered only the "irradiator" (Co-60 acquisition in one case and accelerator + electricity in the other case). It can be seen from Figure 2 that 1 MCi (and greater) equivalent accelerator-based facilities are economically competitive with Co-60 irradiators.

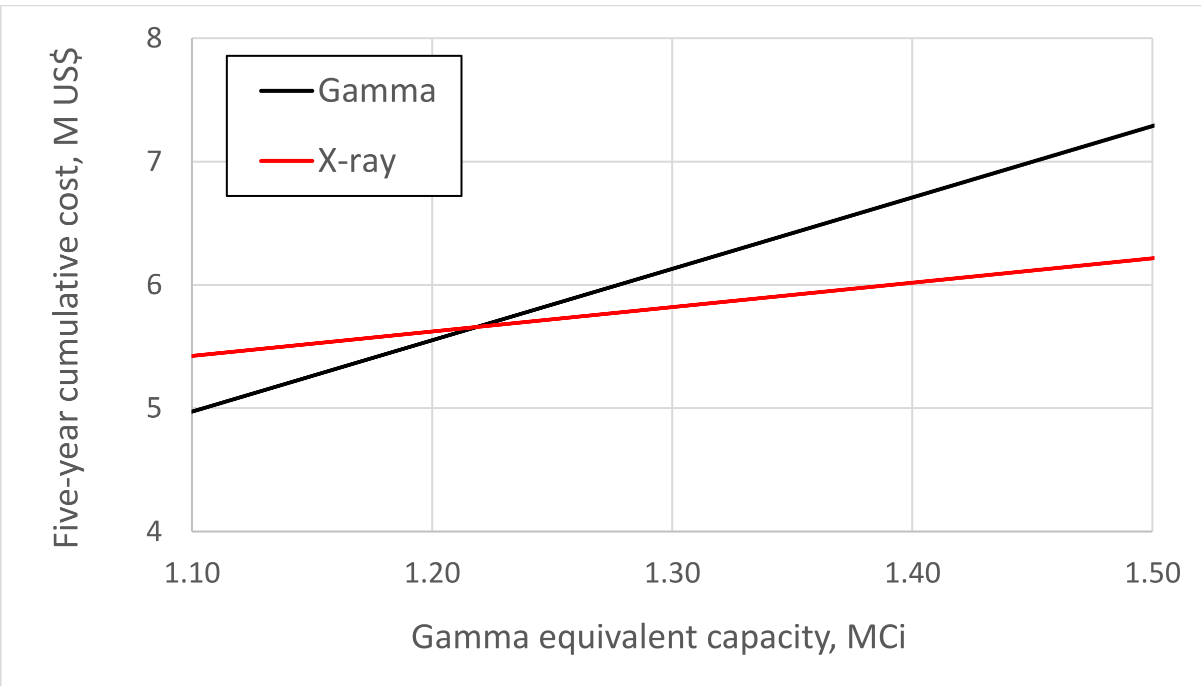

Figure 2. Five-year cost of ownership (acquisition and electricity).

3. CONCLUSIONS

- Accelerators are desirable because of lower risk profile. Accelerators provide an alternative that can address one or more of the challenges posed by radioisotopes.
- Technologies are already available to provide accelerator-based solutions for some applications of Cs-137 and Co-60 irradiators.
- The commercial irradiation equipment market can be satisfied with current technologies.
- The research irradiation equipment market has expectations that cannot be met at this time (price, operating costs, simplicity)
- Continuous improvement of accelerators and sub-systems will make these solutions even more attractive.
- Customer expectations about reliability for isotope sources cannot be matched with accelerators. Continuous improvement of reliability and electrical efficiency must be pursued.

4. RECOMMENDATIONS

- IAEA should support the development of accelerator solutions to satisfy all isotope-based research irradiator applications.

- IAEA should provide financial assistance to developing member states for attending conferences such as ICARST and/or AccApp.

- IAEA should send representatives to industry meetings and conferences to gain understanding of global commercial/technical needs.

- IAEA should support meetings for the development of a harmonized position on the global growth or reduction of radioisotopes.

- IAEA should support educational programs for students, technologists, and professionals regarding accelerator sources.

Meeting participants on day one of the Consultants Meeting:

From left to right: Kenneth Hsiao, Christophe Malice, David Brown, Aleksandr Bryazgin, Dinara Abbasova, Salime Bucher, Anne-Laure Lamure, Valeriia Starovoitova, Joao Osso Jr, Bum Soo Han.

ANNEX I

TABLE OF EXISTING RADIOISOTOPE DEVICES

Attribute	Cs-Cl Blood Irradiator	Cs-Cl Research Irradiation	Co-60 research irradiator – low dose rate	Co-60 research irradiator – high dose rate	Large Co-60 Research Irradiator	Small Industrial Co-60 Irradiator	Large Industrial Co-60 irradiator
Reference number	1	2	3	4	5	6	7
Approximate number of units	500 - 1000	1500 - 3000	300 - 500	50 - 100	30 - 50	200 - 300	80 - 120
Applications	Blood irradiation	Small animal research	Low dose Blood Tissue	High dose Blood Tissue	General research Pilot production Small-scale commercial	Pallet, tote, or off-carrier Food Medical device Bioburden reduction	Pallet or tote irradiator Food Medical device Bioburden reduction
Type	Category 1	Category 1	Category 1	Category 1	Category 4	Category 4	Category 4
Photon energy	660 kV	660 kV	1.1 and 1.3 MeV	1.1 and 1.3 MeV	1.1 and 1.3 MeV	1.1 and 1.3 MeV	1.1 and 1.3 MeV
Activity	3 – 7 kCi	1 – 10 kCi	5 kCi	30 kCi	100 – 300 kCi	0.5 – 1 MCi	1 – 6 MCi
Dose rate	5Gy/min	1 – 10 Gy/min	Up to 50 Gy/min	Up to 300Gy/min	Up to 1 kGy/min		
Treatment type	Batch	Chamber	Cylinder	Cylinder	Batch	Continuous	Continuous
Chamber/product size	0.8 – 3.9 litres	4 – 10 litres	15cm dia x 18cm high	15cm dia x 18cm high	4m x 4m room		
Dose and dose accuracy	25 Gy	0 – several kGy	0 – 1 kGy +/-10%	0 – 35 kGy +/-10%		0.4 kGy – 100 kGy +/- 5%	0.4 kGy – 100 kGy +/-5%
Type of shield	Self-Shielded	Self-Shielded	Self-Shielded	Self-Shielded		Concrete bunker	Concrete bunker
Mass	1000 kg	1000 – 4000 kg	4000kg	4000-6000kg			
Footprint	1m x 1m	1.5m x 2m	1.8m x 0.9m	1.8m x 0.9m		300 – 500 m^2	400 – 700 m^2
Floor loading	1000-2000 kg/m^2	1000 – 3000 kg/m^2					
Height	2m	2m				5-8m	6-8m
Power input	Normal wall-plug	Normal wall-plug				5 – 10 kW	10 – 30 kW
Cooling requirement	None	None				5 – 15kW	10 – 80 kW
Lifetime	Over 30 years	Over 30 years					
Capital cost	$270K - 400K USD	$250K – 500K USD	$400K – 600K	$500 – 700K		$3 – 15M USD	$15 – 30M USD
Operating cost						1% decay per month 0.5% per month gamma-related overheads	1% decay per month 0.25% per month gamma-related overheads
Operating hours per year							

ANNEX II

TABLE OF REQUIRMENTS TO ALTERNATIVE ACCELERATOR BASED RADIATION GENERATORS

Attribute	Low energy x-ray Blood Irradiator substitute	Cs-137 Research irradiator substitute	Cs-137 + Co-60 Research irradiator substitute	Small commercial irradiator (e-beam and/or x-ray)	Large Industrial x-ray irradiator
Machine type	X-ray tube	Linac	Linac	DC accelerators RF accelerators	DC accelerators RF accelerators
Replaces	Cs + Co blood irradiator Cs small animal Cs cell research	Cs blood irradiator Cs small animal Cs cell research	Cs + Co blood irradiator Cs + Co small animal Cs + Co cell research Co low dose rate Co high dose rate	Gamma plants	Gamma plants
Projection for number of installations	1000 +	2000 +	1000 +	200 +	200 +
Applications	Blood irradiation	Blood irradiator with high penetration and high throughput	Blood irradiator with high penetration and high throughput	Box-by-box Tote or pallet	Pallet or tote irradiator Food Medical device Bioburden reduction
Electron energy	160-240 kV	2 MeV	4 MeV	5 – 10 MeV	5 – 7.5 MeV
Average beam current	45 mA	100 – 200 µA	100 – 200 µA	2 – 15 mA @ 10 MeV 10 – 30 mA @ 5-7.5 MeV	15 – 80 mA
Average photon energy	50 kV	660 kV – 1.25 MeV	1.25 MeV	E-beam mode X-ray mode	1.66 – 2.5 MeV
Export restrictions	No	Yes	Yes	Yes	Yes
				15 kW/MCi in e-beam 100 kW/MCi @ 7MeV	140 kW/MCi @ 5 MeV 100 kW/MCi @ 7 MeV
Dose rate	14 Gy/min	1 - 25 Gy/min	1 - 25 Gy/min		
Treatment type	Batch	Chamber	Chamber	Continuous 2 conveyor paths	Continuous
Chamber/product size	6 x 900mL	4 – 10 litres	4 – 10 litres		
Dose and dose accuracy	25 Gy	0 – several kGy	0 – several kGy	0.4 kGy – 100 kGy +/-5%	0.4 kGy – 100 kGy +/-5%
Type of shield	Self-Shielded	Self-Shielded	Self-Shielded	Concrete bunker	Concrete
Mass	1200 kg	2000 – 4000 kg	2000 – 4000 kg		
Footprint	1.2m x 1m	1.8m x 1.3m	1.8m x 1.3m	400 – 700 m^2	400 – 700 m^2
Floor loading	1000-2000 kg/m^2	1000 – 3000 kg/m^2	1000 – 3000 kg/m^2		
Height	2 m	2 m	2 m	4-8 m	6-8 m
Power input	220V, 30A, single phase	220V, 20A, single phase	220V, 20A, single phase	150 kW – 800 kW	300 kW – 1.5 MW

Cooling requirement	None	None	None	150 kW – 800 kW	300 kW – 1.5 MW
Lifetime	Over 20 years	Over 20 years	Over 20 years		
Capital cost	$250 - 600K USD	$300K – 1M USD	$300K – 1M USD	$15 – 30M USD	$15 – 30M USD
Operating cost		$2 – 5 per hour for electricity $10 – 100 per hour	$2 – 5 per hour for electricity $10 – 100 per hour	$15 - $80 per hour for electricity $5 - $25 per hour for machine related overheads	$30 - $250 per hour for electricity $10 - $40 per hour for machine related overheads
Reliability requirement	High for blood banks Lower for intermittent users	High for blood banks Lower for research applications	High for blood banks Lower for research applications	Very high for perishable products	Very high for perishable products
Operating hours per year				Up to 8000	Up to 8000

ANNEX III

LIST OF EXPERTS AND IAEA REPRESENTATIVES

Belgium	Mr Christophe MALICE IBA Chemin du Cyclotron 3 Ottignies 1348 LOUVAIN-LA-NEUVE BELGIUM Email: Christophe.Malice@iba-group.com
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ANNEX IV

MEETING AGENDA

Monday, 19 August 2019

9:00 - 9:30	Registration at the Gate 1, IAEA headquarters, VIC
Session I:	**Introductory Session**
10.00 - 10.30	Opening of the meeting by: - Ms Melissa Denecke, Director NAPC (IAEA) - Mr Joao Alberto Osso Junior, Section Head of RPRT (IAEA) - Mr Bumsoo Han, Scientific Secretary, RPRT (IAEA) - Ms Valeriia Starovoitova, RPRT (IAEA) - Ms Dinara Abbasova, RPRT (IAEA) Scope and Objectives of the Meeting, Adoption of the agenda Election of the chairperson of the meeting, introduction of participant
Session II:	**Participants' Presentations**
10:30 – 11:00	Coffee Break
11:00 – 11:45	Presentation by Mr Christophe Malice **(IBA, Belgium)**
11:45 – 12:30	Presentation by Mr Dave Brown **(MEVEX, Canada)**
12:30 – 14:00	Lunch break
14:00 – 14:45	Presentation by Mr Kenneth Hsiao **(CGN Dasheng, China)**
14:45 – 15:30	Presentation by Mr Aleksandr Bryazgin **(BINP, Russia)**
15:30 – 16:00	Coffee Break

16:00 – 16:45	Presentation by Mr Salime Max Boucher **(RadiaBeam, U.S.A.)**
17:30 – 20:00	Welcome Drinks (sponsored by the IAEA)

Tuesday, 18 June 2019

Session III & IV:	**Recent Achievements on Irradiation Facilities**
09:00 – 10:30	Discussion on Current Status and Recent Issues on Irradiation Facilities
10:30 – 11:00	Coffee Break
11:00 – 12:30	Discussion on Current Status and Recent Issues on Irradiation Facilities
12:40 – 14:00	Lunch Break
14:00 – 15:30	Discussions on How to Move from RI Sources to Machine Sources in Irradiation Facilities (Both for Research and Industries)
15:30 – 16:00	Coffee Break
16:00 – 17:30	Discussions on How to Move from RI Sources to Machine Sources in Irradiation Facilities (Both for Research and Industries)
17:30 – 18:00	*Finalize and document the discussion*

Wednesday, 19 June 2019

Session V & VI:	**The Advanced Approaches in Irradiation Facilities and the Role of the IAEA**
09:00 – 10:30	Discussion on the role of the IAEA on Irradiation Facilities

10:30 – 11:00	Coffee Break
11:00 – 12:30	Discussion on the role of the IAEA on Irradiation Facilities
12:40 – 14:00	Lunch Break
14:00 – 15:30	Recommendations on the Directions and Guidelines for Irradiation Facilities to IAEA Member States
15:30 – 16:00	Coffee Break
16:00 – 17:30	Drafting of the Meeting Report
17:30 – 18:00	*Finalize and document the discussion*

Thursday, 20 June 2019

Session VII:	**Final Review and Acceptance of Meeting Report**
09:00 – 10:30	Finalizing meeting report (scope/contents/structure/conclusions/recommendations)
10:30 – 11:00	Coffee Break
11:00 – 12:30	Review and acceptance of the meeting report
12:40 – 14:00	Lunch Break
14:00 – 16:00	*Closing of the Meeting*