TOURR nuclear research reactors

Towards Optimized Use of Research Reactors in Europe
Project Number: 945 269

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Strategy for optimized use of research reactors in Europe

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EXECUTIVE SUMMARY

This report combines the major findings of the TOURR project in the first 2 years of its implementation.

After circulating a tailor-made questionnaire among Research Reactors (RR) in Europe - Figure 1 shows an overview of countries whose RR have responded to our questionnaire - which resulted in a response rate of 84%, three gaps analyses have been drafted – to interpret the collected data – assessing the gaps and opportunities along the 3 axes of the TOURR project:

1. Science and technology
2. Medical applications
3. Education and training

As a further step, a SWOT (strengths, weaknesses, opportunities, and threats) analysis has been drafted and used as a basis by the consortium to write this report in a more descriptive form and in a way that makes it accessible to the largest possible public.

In parallel with the whole process, two events have been organised:

- Match-making workshop (held online due to active COVID restrictions in April 2021)
- Mid-term workshop (held in person, as a side event to the European Radiation Protection Week 2022 in October 2022)

The first event was mainly intended to make the TOURR project known to relevant audiences.
The second workshop targeted a particular segment of end-users: medical physicists and more in general professionals close to the medical applications of RRs.
This decision was made, since it was apparent after analysing the questionnaire responses, that data related to medical applications are not only among the most sensitive but also the most complex to handle when it comes to a European-wide view of the RR fleet.
Useful feedback has been gathered from both events, which will be taken into consideration in this report in the relevant chapters.

To support the findings and in line with the TOURR project target namely "to secure access and availability of RRs as a vital part of the European Research Area and to support stable supply of medical radioisotopes" an online platform is planned to be deployed. That will allow RR to better communicate and interact among themselves. It will also allow better internal and external communication. One major goal is to provide a communication interface which facilitates easier contact between potential users and RR operators.

It is worth specifying as general comments that:

- Given the fact that this report public, and being the TOURR committed to guarantee the confidentiality of data shared with us, we will avoid making any references to specific facilities.
- All our considerations are based on the data collected which has been gathered on voluntary basis (no question was mandatory) and also they reflect the perspective of the facility given by the particular respondent to the questionnaire.

The TOURR project is indicated is one of the outcomes of SAMIRA (Strategic Agenda for Medical Ionising Radiation Applications[1]) adopted by the European Commission to seek the energy sector contribution in beating cancer.

[1] https://energy.ec.europa.eu/topics/nuclear-energy/radiological-and-nuclear-technology-health/samira-action-plan_en

At the same time, TOURR results, are being monitored and will be taken into consideration by ERVI (European Radioisotope Valley Initiative)[2]
The scope of this document is to provide the reader with some recommendations inferred from all the analysis tools which have been put in place by the consortium.

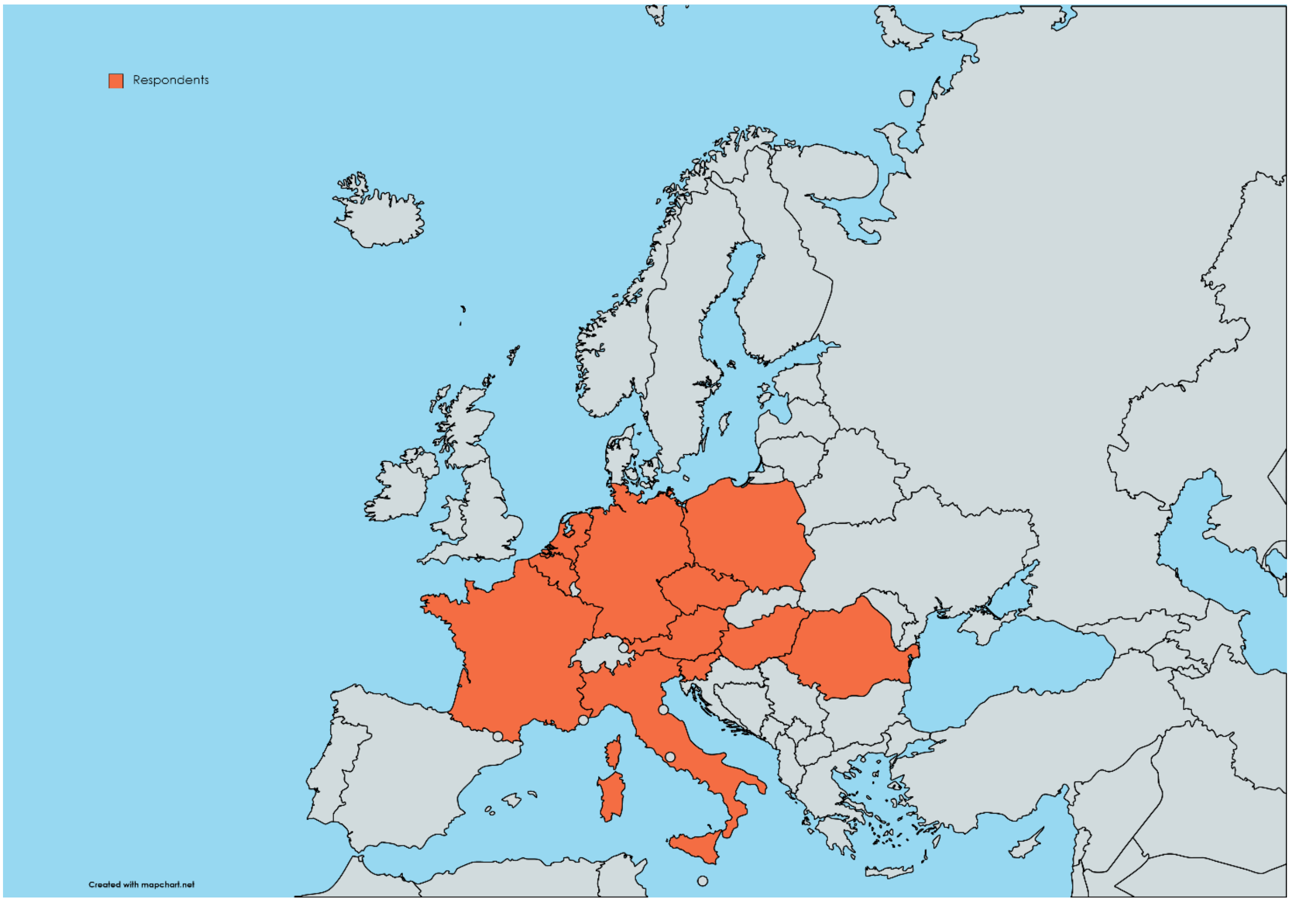

Figure 1 European countries represented in the analysis

[2] https://energy.ec.europa.eu/system/files/2023-01/Consultation%20results%20report%20Rev%20C.pdf

CONTENT

1 INTRODUCTION

This report summarizes the main findings of the TOURR Project after almost two years of analysis of the data received from RR across Europe.

The scope of this document is to provide the reader with some recommendations inferred from all the tools which have been put in place by the consortium:

- Data collection from RR
- Gap analysis on three different axis
    - Science and technology
    - Medical applications
    - Education and training
- SWOT analysis
- Workshops feedback

It will be articulated into ‘main findings’, declined over the three axes of the TOURR project and later ‘recommendations’ declined according to the time frame they apply to (immediate, near, and further future).

2 MAIN FINDINGS

2.1 Science and Technology

This section is the most diverse of the whole analysis, as it addresses all other science and technology applications besides medical and education. In a research reactor (RR), a number of different technological applications are possible, many of them at the same time. Based on the information collected and the data analysis, below, the traditional and future RR possible applications.

The degree of exploitation in different RR applications was determined using the questionnaire.
Initial data acquired from the questionnaire is available in D1.1 – "Database of the European RR fleet". This is a public report published on the webpage, under the ENEN website, devoted to the TOURR project: https://enen.eu/index.php/portfolio/tourr-project/ and on the TOURR website: https://www.tourr.eu/documents).
Gaps and opportunities have been identified via statistical analysis and interpretation of the data. The details of the statistical analysis and the interpretation of data are confidential and not publicly available. Only the main findings and conclusions are presented in this report.

Regarding the overall RR utilization in science and technology, the main findings were that the overall level of exploitation of the EU RR fleet is between low and medium for technological applications other than medical and educational. Furthermore, the analysis showed that the need for expansion is present, however, it is obstructed by obstacles, mainly the **lack of funding and manpower**, which are correlated.

The analysis further showed that in Europe there is definitely a high level of expertise in the nuclear sector and the available RRs in the EU RR fleet are quite diverse (TRIGA, SUR-100, tank in pool, critical assembly...) offering a variety of different possible applications. At the same time, the expertise is very focused meaning the personnel is very highly specialised and for this reason very hard to replace. For several applications, there is a real threat that the knowledge and competences will be lost once the current generation of experts will retire, for example in applications like **NAA (**Neutron Activation Analysis**) or PGNAA** (Prompt Gamma Neutron Activation Analysis) and more in general in **Nuclear data measurements** or general research connected to **Nuclear data**.

A possible solution is represented by attracting new people to the field and investing in them over time with adequate training and opportunities to gain relevant experience. This approach will address the 'lack of personnel' issue but in the same time will allow for potential expansion of current domains of use.

In some other cases, **radiochemistry** for example, there are dedicated Euratom-funded actions to attract young people to the field. They are quite successful if we look at the manifestation of interest towards the proposed activities of the CINCH project series[3] for instance (website visits, number of applications to take part in Hands-on Training sessions…) but if the overall amount of RR around Europe is decreasing, as a direct consequence there will be fewer opportunities in this field as well.

Applications like **silicon transmutation doping or actinide transmutation studies** suffer from a lack of financing since they require quite a long time investment in terms of partnerships to establish and development of the activity at the RR. Furthermore, transmutation requires high power (and usually a fast neutron spectrum) so not all RR can develop this field. New installations like Myrrha may bring new strength and opportunities. It should be noted that with the increase of renewable energy and quickly expanding production of hybrid electric vehicles, the need for silicon doping will increase and a new RR with long time investment strategy will be needed in the future.

A similar situation applies to **material irradiation and testing** since not all RRs have a high enough neutron field to carry on this activity. On the bright side, this knowledge is transferrable among RR

[3] https://www.cinch-project.eu/

so, once more, this proofs that **better communication and interconnection** within the EU RR fleet can be beneficial.

A high neutron flux is required as well for **nuclear fuel irradiation and testing**, hence the same limitation applies. The demand for this service is increasing though, hence it can be seen as an opportunity for expansion and involvement of young new professionals. Such applications do not have the same level of threat of RR closures in the long run, as the Jules Horowitz material test reactor (JHR) is under construction, ensuring future capabilities.

Other, more uncommon applications like **geochronology** or **gemstone coloration** although appealing since being open to cross-disciplinary interactions (e.g. with the geology community), require shipping and handling of neutron-activated material. Such actions require extensive paperwork and so it is seen as a discouraging activity. Furthermore, it was determined that such applications suffer from a lack of customers/demand. The less activity is performed by the RR, the higher the risk of losing this competence over time.

The same 'threat' of losing customers applies to **gamma irradiation** because there is no specific need for a RR to perform it (the ultimate goal being radiation hardness test) but it is also possible to use other gamma-ray sources, like accelerators. The advantage of using RR for gamma irradiations is the higher gamma flux, from which an opportunity can be derived as RR's could increase its gamma field characterization, making the irradiations possible and with that attract the customers, since irradiation can be performed also when the reactor is shut down.

In the field of **neutron scattering** and **neutron radiography/tomography,** which are among the most common applications of RR, there is definitely room for expansion in its utilization. The main problem is that the installed equipment has to be renewed while at the same time, modernizing the installation (new digital imaging technique) could attract young specialists resulting in a good opportunity for bridging the generational gap in the EU RR fleet.

Instrument development, testing, and calibration is a field that all RR operators would like to further analyse, moreover with new RR designs (small modular reactors – SMR and Generation IV) it can definitely be seen as an opportunity to increase the field of RR utilisation. The diversity of facilities (intended as type of RR) present in the EU RR fleet is a strong point since it enables to testing of state-of-the-art equipment and the need to test and calibrate instrumentation is likely to increase in the future. However, a threat of not building the new RR designs is present, as the instrument development would stall if no future reactor systems are present for the equipment to be tested on.

Positron sources production and **boron neutron capture therapy** have a high potential for expansion but they require a specific core configuration and ad hoc operation of the RR which makes it a limited field.

Finally, when it comes to the **support of nuclear power reactors programs** the analysis showed that this requires intensive collaboration between the different departments in the same RR as well as **better communication among different RRs in the fleet.** As of today, RR are at full capacity having only some small margins and the aging of the fleet may lead to a loss of expertise.

An expansion of the fleet is advisable, not to lose this opportunity and to preserve the diversity among the facilities needed to enable to study and support of all future nuclear designs (SMR, Generation IV). It is important to mention that the type of RRs required for this purpose (zero-power mock-ups and prototypes, in particular with fast spectrum) is rather different (in design and utilization) form the kind of RRs (essentially pool type reactors) that are required for all the other applications discussed in this document.

Our research showed that besides the current RR applications, there are also opportunities in new and exciting fields in which a RR could be utilized. One of such is the **Nuclear-driven production and**

processing of chemicals[4], where renewable fuel additives can be produced from waste organics, indicating a promising research field with a circular economy and waste treatment where research reactors would play a major role. Possible new opportunities for research reactors, connected to **Fusion,** are water activation studies, radiation hardness studies with high energy gamma rays, gamma and neutron shielding studies, materials activation studies, etc.

In the light of European energy transition **Research in the field of fuel cells, hydrogen storage, and batteries** can be also depicted as an opportunity, as the hydrogen economy (e.g. fuel cells, hydrogen storage), electromobility (batteries, electromotors, efficient energy conversion) and circular economy are focal points of the EU policy on climate change. Neutron beamline techniques, including PGAA for element analysis, diffraction for structure analysis, and imaging for macroscale structure visualization, all offer non-destructive, contactless, and real-time measurement opportunities at RRs. This novel research field might bring fresh money to the neutron centers and allow them to demonstrate their usefulness towards the general public.

2.2 Medical Applications

The majority of facilities are quite reluctant to share data related to the medical applications that are in place at their RR. This is easily understandable since this type of data is deeply entangled with commercial interests and most of the time unique for the facility.

As a consequence, data collection for this section of the study has been more difficult. This is the main reason behind the decision to have the mid-term workshop targeting this specific end-user segment.

The population related to the medical applications of RR is composed of facilities operators but also end users of RR products. Reaching out to them allowed us to have a more rounded vision of the issue.

Since the implementation of medical applications is dependent on radioisotopes productions and dispatch of the radioisotopes to end-users, we will provide our main findings per each of the main elements.

TOURR will not, however, consider Molybdenum (Mo-99) since the primary goal of Nuclear Energy Agency (NEA) group of the Organisation for Economic Co-operation and Development (OECD) and their initiative of the High-level Group on the Security of Supply of Medical Radioisotopes (HLG-MR) as well as Nuclear Medicine Europe (former AIPES) is the sustainable supply chain of molybdenum-99 (Mo-99) and its daughter radionuclide technetium-99m (Tc-99m)2. For these reasons, the TOURR project in the analysis of the RR fleet capacities focuses on radionuclides other than molybdenum-99 (a parent radionuclide for technetium-99m).

Iodine (I-131 / I-125 / I-124)

There is a high demand for Iodine-131 (^{131}I) in Europe and globally. For decades it was and still remains the most widely used radionuclide and it has a very well-established role in the nuclear medicine field. Due to the affinity of iodine to the thyroid tissue, it's indicated for the imaging and therapy of thyroid disorders, including thyroid cancer. Iodine-131 is approved for medical use either as such (in the form of sodium iodide-^{131}I solution for injection or for oral administration) or in the form of gelatin capsules containing sodium iodide-^{131}I for oral administration, both for diagnostic and therapeutic use depending on the administered radioactivity dose. Another application of ^{131}I is for the radiolabeling of molecules, an example of that being radiopharmaceutical metaiodobenzylguanidine (^{131}I-MIBG) which localizes to adrenergic tissue and thus can be used to identify the location of tumors such as pheochromocytomas and neuroblastomas as well as for therapy of these tumors, especially in pediatric patients. More recent developments include ^{131}I

[4] Plant, A.G., Kos, B., Jazbec, A. *et al.* Nuclear-driven production of renewable fuel additives from waste organics. *Commun Chem* **4**, 132 (2021). https://doi.org/10.1038/s42004-021-00572-5

labelled prostate cancer inhibitor MIP-1095 for diagnostic imaging and therapy in patients with prostate cancer or ^{131}I IPA(I-iodo-phenylalanine) for therapy in recurrent glioblastoma multiforme.

Iodine-131 is produced in research reactors using two different production routes. One of them is the isolation from ^{235}U fission products in the process parallel to the separation of molybdenum-99, hence its production is very much dependent on the production of ^{99}Mo and is limited to the few nuclear reactors worldwide. This limitation does not apply to the production of ^{131}I via the neutron irradiation of tellurium targets, but due to the high number of irradiation positions needed to satisfy the high demand for ^{131}I, its production limits the access of these positions for the production of other radioisotopes. The use of ^{131}I for therapy generates liquid biological and radioactive waste, this is usually well taken care of in dedicated therapy wards in hospitals.

Another reactor-produced radioisotope of iodine interesting for medical community is iodine-125, which is used in the form of sealed sources in radiation therapy (brachytherapy) to treat a number of conditions, including prostate cancer, ocular cancers, or brain tumors. Its half-life is 59.49 days and decays by gamma decay with a maximum energy of 35 keV. Hence, it is an excellent isotope to administer low-dose rate (LDR) brachytherapy.

Iodine has also a positron-emitting radioisotope, ^{124}I, which is produced in cyclotrons and allows diagnostic imaging using the positron emission tomography (PET) technique. Some new applications are under investigation, for instance, the use of ^{124}I for prostate-specific membrane antigen (PSMA) PET imaging.

In the last decades and at present, there is **high demand for ^{131}I** globally. In the long history of medical applications, ^{131}I had played an important role in the managements of patients and the demand for ^{131}I and other matching iodine radioisotopes is on the rise. In the fall of 2022, when the BR2 reactor in Belgium was out of operation and could not contribute to the irradiations of ^{131}I, the issue of sustainable supply chain of ^{131}I became critical.

Lutetium (Lu-177)When looking at the number of published papers, lutetium-177 (^{177} Lu) became the most effective and demanded radioisotope for therapeutic use in patients with neuroendocrine tumours. ^{177}Lu belongs to the radiolanthanides and is ideally suited for therapeutic use due to its attractive physical characteristics. It decays by β^- emission with energies of 177 and 498 keV. Furthermore, the emitted γ photons of 113 and 208 keV can be used for imaging the in-vivo localization of the administered ^{177}Lu targeting agent using SPECT scanners. The emitted photons facilitate dosimetry calculations.

The benefit of using ^{177}Lu in the therapy of neuroendocrine tumours has been demonstrated in a number of clinical trials which lead to the first ^{177}Lu-labelled radiopharmaceutical with marketing authorisation – ^{177}Lu-DOTATATE (Lutathera). **In the last decade, the demand for ^{177}Lu increased dramatically** after the success in the therapy of disseminated metastases of prostate cancer using ^{177}Lu labelled PSMA inhibitors.

One major limitation in the production of ^{177}Lu is the access to highly enriched target materials. It can be produced in research reactors using two different nuclear reactions, one of them leading to the carrier-added ^{177}Lu and the other one leading to the non-carrier-added ^{177}Lu. In both cases, highly enriched target materials are needed (either in ^{176}Lu or in ^{176}Yb). In Europe there is a number of facilities capable to process ^{177}Lu and they would be able to cover larger needs. However, at present the shortages in the supply of enriched target materials seems to be the bottle neck in the access to ^{177}Lu. New methods for separation of stable isotopes ^{176}Lu and/or ^{176}Yb as well as new facilities for their production are needed in order to satisfy the growing demand for ^{177}Lu.

Terbium (Tb-161)

After the success of ^{177}Lu in therapy of various cancers nowadays the focus of investigators is on terbium-161 (^{161}Tb) which decays by β^- emission with a half-life of 6.89 d. It is a low-energy β^- emitter. These physical properties make it similar to ^{177}Lu, but ^{161}Tb emits also a significant amount of conversion and Auger electrons, which are expected to provide a better therapeutic effect compared to ^{177}Lu. This radionuclide is particularly interesting due to the fact that together with other terbium isotopes such as ^{149}Tb (alpha emitter), ^{152}Tb (positron emitter), and ^{155}Tb (gamma emitter) it can form a series of theranostic pairs. Compared to ^{177}Lu the use of ^{161}Tb in therapy of neuroendocrine tumors and in prostate cancer patients is expected to results in better therapeutic effect. Currently, the first promising pre-clinical and clinical results have been published and there is a number of ongoing clinical trials. The demand for ^{161}Tb is growing rapidly. This was also reflected by the high demand for target material – enriched ^{160}Gd.

Terbium-161 can be produced in a nuclear reactor by irradiation of ^{160}Gd with thermal neutrons. Needless to say that i**n the last few years, the potential of ^{161}Tb for therapy dominated the research and the debate** on new medical radioisotopes.

Radium (Ra-223)

Ra-223 has an 11.4-day half-life. Radium-223 dichloride is an alpha particle-emitting radiotherapy drug that mimics calcium and forms complexes with hydroxyapatite at areas of increased bone turnover. The principal use of radium-223, as a radiopharmaceutical to treat metastatic cancers in bone, takes advantage of its chemical similarity to calcium, and the short range of the alpha radiation it emits. Notably, radium-223 (Xofigo) was the first radiopharmaceutical with alpha-emitting radionuclide that has been granted marketing authorization. That paved the way for the use of other alpha emitters in medical applications, such as ^{225}Ac.

TOURR consortium recommends further research in the field of alpha-emitters. The SECURE[5] project (detailed in the following pages) has among its objectives to push research on alpha emitters and it is very beneficial that some of TOURR partners are involved in SECURE as well.

Actinium (Ac-225)

The decay properties of actinium-225 are favorable for usage in targeted alpha therapy (TAT); clinical trials have demonstrated the applicability of radiopharmaceuticals containing ^{225}Ac to treat various types of cancer. Its efficiency in clinical treatment still needs to be proved by further tests. However, the scarcity of this isotope resulting from its necessary synthesis in nuclear reactors or cyclotrons limits its potential applications. **For this reason, at present, there are several initiatives aiming at the increased availability of ^{225}Ac.** One should remember, that either for the nuclear reactor or cyclotron route the starting material for the production of ^{225}Ac is radium-226, and access to this target material is a challenge. In both routes, there is a **need for specialized processing facilities.**

Copper (Cu-67)

Copper-67 (^{67}Cu) is a β^- emitter useful for therapeutic treatments. Its half-life of 2.7 days is long enough to match the pharmacokinetics of slowly circulating large molecules, such as monoclonal antibodies. ^{67}Cu can also be paired with the cyclotron produced β^+emitters ^{64}Cu, ^{61}Cu, and ^{60}Cu to perform pretherapy biodistribution determinations and dosimetry using positron emission tomography (PET). ^{67}Cu can be produced in a nuclear reactor, however, requires a high flux of fast neutrons exceeding 10^{14} n cm^{-2}s^{-1}. Alternatively, it can be produced in cyclotrons. While the production of ^{67}Cu in nuclear RR is currently limited, there are several reports on the feasibility of ^{67}Cu production in cyclotrons, giving a promise of its wider availability. .Currently, the use of high specific activity ^{64}Cu in medical applications is very well established, and there are medicinal products with marketing authorisation on the market. It can be produced in a cyclotron using expensive nickel (Ni-64) targets which need to be recycled. Although ^{64}Cu can be used for both diagnostics and therapy, It is expected that the combination of ^{64}Cu for diagnostic imaging and ^{67}Cu for therapy is more effective. In US the DOE provides 67Cu for research and early clinical trials. Such services are bot available in Europe, hence, reliable sources of ^{67}Cu are needed.

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[5] https://enen.eu/index.php/portfolio/secure-project/

Cobalt (Co-60)

Its long half-life (more than 5 years) makes it highly suitable for brachytherapy. On the downside, **it can be produced only by a very limited amount of RR** and it requires strong shielding and hot cells to be handled. An opportunity is represented by producing ‘gamma knives’. It’s worth mentioning that ^{60}Co is broadly used in industry for industrial process control, in non-destructive testing and also in sterilization by gamma radiation, which is employed in medicine. These applications are using large volumes of RR produced ^{60}Co in the form of sealed sources.

Iridium (Ir -192)

The production of this isotope **production is a standardized procedure**, which constitutes a great advantage. Ir-192 is used industrially for non-destructive tests (NDT). It can also be used in patient brachytherapy but in that case, **hospitals are required to have a dedicated ward** for patients treated with this isotope, because the dose received is quite high. This also implied that the personnel needs to observe strict radiation protection measures. Due to the short half-life of the source (74 days), it needs to be replaced four (4) times a year.
Only in Poland there are 23 medical centers performing brachytherapy using ^{192}Ir sources. Globally, he demand for brachytherapy shows an upward trend.

The few examples discussed above clearly demonstrate that RR produced radioisotopes play a very important role in the healthcare system in Europe. A number of new developments were recently translated into the clinics, the forecasted demands for RR produced isotopes are much larger than in the last years. Actions towards upgrading and expanding the existing RR fleet are mandatory.

2.3 Education and Training

This section gathered quite complete feedback from the surveyed facilities since the need for E&T is well recognized and acknowledged.

The use of RR by researchers, students and fellow partners from other facilities is a great contributor to the increase in highly skilled human capacity. This highly skilled human resource is needed both by facilities themselves but also by the users of the RRs products.

In general, there is a strong will (80 % positive answers) across the RRs community to expand E&T activities.
Nevertheless since in some cases, “lack of manpower” was mentioned, it can be seen as an opportunity to look for more personnel.

Training represents one fundamental pillar activity. The level of delivered training is very high thanks to the wide expertise. However, advanced training which goes beyond basic reactor physics is reactor technology specific. For example, each NPP has its own “certified” training centre and is normally not dependent on the training offers of RRs, which quite often do not have their teaching certified e.g. by regulators (country dependent). Therefore, a lack of customers prevents the RRs to expand their training activities. Regarding other aspects, the scenario is similar to teaching, e.g. the lack of manpower may become critical, especially in the future.

Another important aspect of educational activities is represented by **teaching**: radiation protection, nuclear engineering, biological science, etc. This aspect is already implemented on a medium or high level in two-thirds of the RRs and there is a strong will to further expand it. In this field, teachers are very experienced professionals because they deliver a very high level of knowledge. Most of the time teaching often provides an extra workload for the RR employee. With the nuclear phase-out and the ageing of the EU RR fleet, it is harder to keep competent teachers. An approach to overcome a possible future lack of facilities and scientific personnel is to foster the interlinkage of as many as possible EU RR facilities (communicate intensively – on the same platform). Moreover, the ageing and the decreasing number of EU RRs reduces the attractivity for a new generation of nuclear workforce. Especially in the field of radiation protection and radiology, also a lack of customers was observed. This may be related to the fact that these topics are already covered by the nuclear engineering programs of the RRs or depending on the specific content, these topics may rather be taught in other set-ups.

Activities like **public tours and visits** are very useful to raise public awareness around nuclear installations and debunk fake beliefs about dangers related to the nuclear field. They are a way to open the dialogue with participants to the visits and maybe to attract some of them to the field. The weak point is represented by the fact that sometimes allowing visits to nuclear facilities requires extensive paperwork and personnel acting as ‘guides’ will need to make time for this extra workload for which normally there are no structural fundings. The strong point on the other hand is provided by the unique character of the visit experience: each facility is one-of-a-kind in some sense and given that the guides are also technical professionals they can answer not only general but also technical-scientific questions. Altogether, most RRs are able to handle the extra workload to offer tours and visits and mostly there are no obstacles to expanding these activities. Thus, there is no real gap between the current scenario and the ideal one in this case.

Although access to RRs especially for researchers and for educational purposes is open, a good coordination in terms of time and use of isotopes is required. It has been identified that sharing this type of information between providers (RRs) and end users (researchers ,educators, etc.) would be in the benefit of all involved parties and it will help to better plan the use of the facilities.

3 RECOMMENDATIONS

Based on the collected data, the TOURR consortium recommends the following set of actions:

3.1 Actions to implement in the immediate future

There is a clear need to attract more workforce to the nuclear sector.

There is definitely the need to attract new talents to the nuclear field, to educate more engineers, scientists, technical staff etc. to cope with the lack of personnel or lack of time for the existing personnel. Opportunities can be found in higher education programs or training for professionals. In order to be able to offer access to these opportunities, close collaboration with other networks, projects, is encouraged.

In many cases, facilities indicated 'lack of personnel' or 'lack of time' as the main obstacle to expand their applications. This latter can be interpreted as: given the actual workforce in the facility, they cannot devote their time to specific applications. (Regardless of the 'type' of application).

To proceed in this direction, the consortium recommends fostering collaboration with and across other projects. The more this issue is manifested in the 'outer word' the higher the chances to find interested talents to be attracted to the field.

A strong connection is provided already with the ENEN2plus project[6], whose aim is exactly to build European nuclear competencies.

Having a pool of nuclear-educated people larger than today will represent a resource for the RRs community, in need of a larger workforce to expand their activities in all the sectors (and in particular in education and training - E&T).

If there was an a system that allows planning among all RR connecting all facilities, it would allow a broad view of the opportunities offered by the existing technology for students, PhDs, or general research collaborators. This may lead to producing scientific results (publications and articles are just an example). If RR E&T activities were centralized, it would be easier to keep track of them and tackle possible problems.

A centralised platform, where RRs could inventorize their activities, look for a target audience and cooperate with other RRs to offer a better program of activities would be highly beneficial for the RR community. The response of the TOURR project is providing a website to ease the path towards reaching this goal.

One of the aims of the TOURR project is indeed to build a platform and put it online for beta testing among the partners first and, for a wider community afterwards. This can represent the first step towards a centralised online reference for all EU RR facilities.

There are already actions in place as follow up of TOURR, for instance: the SECURE[7] project that has just recently (October 2022) kicked-off and has a lot of RR in its consortium. SECURE will investigate advanced techniques to produce and insure the long-term production for radio-isotopes, and the RR involved could represent a valid pool of users of the TOURR platform.

A common "place" to discuss E&T opportunities available all across EU RRs would be of great interest also for:

- Students looking for practical experience (e.g. in their thesis work or internship)
- Students and/or professionals who need reactor time for the validation of their work
- Specialized and/or general public who wish to visit a nuclear facility.

[6] https://enen.eu/index.php/portfolio/enen2plus-project/
[7] https://enen.eu/index.php/portfolio/secure-project/

This latter point may also help in the way of “public perception” of nuclear technology and applications. If people are shown how a RR works and what a RR can do for society, this insight will foster the development of their own critical mindset and opinions on nuclear applications.

In order for the EU RR fleet to be attractive for the young generations it is advisable to take into account the option of building new RRs, more modern and more accessible, focusing on cutting-edge research and being an E&T opportunity in the same research fields.

The TOURR consortium recommends that new Research Reactor projects should be started under coordination of the European Union level, where all EU states will have access to a vast number of RR applications. We recommend the design and construction of several reactors to cover a large number of applications mentioned and discussed in this report. A good example is a medium-power research reactor flexible for almost all domestic applications of Science and Technology (S&T)(e.g. NAA, Nuclear data measurements, neutron, and gamma irradiation,) and education & training (E&T) by being capable of performing unique experiments for future European nuclear engineers. Another is a zero-power RR, dedicated mainly to the research of reactor physics and benchmark experiments.

Finally, a new reactor to test new technologies for future electricity generation using nuclear energy, together with a higher percentage of renewables. Such type is a micro-reactor (or SMR) in development by several companies around the world, the concepts of which have not yet been tested in real experiments (e.g. being built and operated). All of the above-mentioned reactors will also benefit the public perception and attract new people to the field. Such a recommendation is applicable to both the near and long-term future as with new designs and increased need for isotopes, research, etc., more RR will be needed in the future.

3.2 Actions to implement in the near future

It is advisable to train the personnel to make them ready to be good mentors and or teachers on top of being good technical experts.

In general, not all research reactors in Europe are primarily designed for both education and training. This is related to the history of their origin and the subsequent focus on nuclear energy (development of new types of reactors) and materials research or production of radiopharmaceuticals.

This is usually related to the expertise of the personnel, mostly lacking a specific pedagogical education and without experience with E&T. Experience shows that in some countries it is often difficult for students of nuclear disciplines (at all levels) to find "suitable" tutors who, in addition to their work or projects, are able to lead and pedagogically guide those interested in the field.

Besides special pedagogical programmes of research reactor personnel, setting up cooperation with technical universities or academic institutions plays an important role. In particular, ensuring the "non-competitive" position of both parties (RR and universities) and creating communication platforms for mutually beneficial sharing of research experience and results, and building a healthy competitive environment for science and research.

3.3 Actions to implement in the long term

One of the conclusions of our analysis is that: it can be inferred that RRs are a great resource in terms of 'teaching' and allowing students and young professionals to get first-hand experience. This is in contrast with the fact that the number of RRs in the EU is decreasing.

Having fewer RRs means losing opportunities for the E&T sector including a high risk for human capacity in terms of qualified RR operators and/or employees. The RR fleet should be kept numerous and equipped with state-of-art installations to be attractive for the new generation of nuclear workforce.

This leads to the conclusion that having a larger pool of nuclear-educated people will represent a resource for the RRs community in need of a larger workforce to expand their E&T activities.

The following actions are encouraged to fill the gap between the current scenario and the ideal one:

- Promotion of nuclear education
- Retention of nuclear-educated people in the nuclear field
- Retention and attraction of nuclear-educated people in Europe and to EU RRs.
- Continuous exchange of the TOURR consortium with other nuclear networks and nuclear projects.

4 CONCLUSIONS

This report summarizes the main finding of the TOURR consortium about how to optimize the use of research reactors in Europe.

The TOURR project is articulated on three axes and the analysis has followed the same structure:

1. Science and technology
2. Medical applications
3. Education and training

A synthesis of the implemented analytical process has been presented and recommendations have been issued. Recommendations are suggested according to different time frames:

- To apply in the immediate future
- To apply in the near future
- To apply in the long run

The consortium recommends taking action to attract new people to the nuclear field, to train the personnel of the RR to be pedagogically prepared on top of their technical knowledge, and to keep strong connections with academia and other project networks.

A digital platform will soon be put in place within the TOURR project to facilitate achieving these goals.