# DESIGN CONSIDERATIONS FOR HIGH-PERFORMANCE RESEARCH REACTORS

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Many decades ago, the international community coined the term Research Reactor (RR) to clearly indicate the intended purpose (i.e. research) for the facilities being built at that time, ranging from a few watts up to a few hundred megawatts. With the implementation of a variety of services to external users that were provided by RRs, the term Multipurpose Reactor (MPR) was developed but for facilities above the tens of megawatts.
More recently, the increasing demand for the supply of radioisotopes used in medical applications and the industry in general has shifted the design focus towards what are now identified as High-performance Reactors.
While safety remains as the overarching requirement, availability, reliability, flexibility, adaptability, and efficiency are important factors in the design of these facilities. This paper describes the focal areas that need to be addressed in the design of High-performance Reactors and some of the technical solutions available for each one.

## 1. Introduction

Several design aspects of these High-performance Reactors are to be revisited for addressing new requirements in different areas such as:

- Nuclear safety: frequent changes in reactivity and cooling conditions produced by irradiation targets and devices being loaded/unloaded with the reactor at power.
- Radiological safety: the large production rates and dispatching frequency are correlated with higher collective and individual doses on the staff.
- Availability, reliability, flexibility and adaptability for satisfying demanding customers' requirements and the development of new products.
- Efficiency: the characteristics of the products (i.e. its radioactive decay) and the cost of irradiation require an efficient use of the facility, both in terms of irradiation conditions as well as on the logistics associated with the dispatch.

As a consequence of these new requirements, solutions that have been proved fit for the design of RRs and MPRs need to be revisited for High-performance Reactors including the focal areas described hereafter. This paper shows the considerations taken to improve the design of critical systems to achieve the abovementioned updated requirements including:

- Core: variable configurations ensuring a variety of neutron fluxes and spectra.
- Irradiation facilities: accommodating variable volume and irradiation conditions with minimal modifications (i.e. not requiring re-licensing) in terms of cooling and shielding.
- Handling devices for radioactive materials including dose reduction features aimed at controlling the exposure of the staff.

## 2. Focal areas in the design of high-performance reactors

A high level of nuclear safety has been achieved in the design of modern RRs and the introduction of high-performance's related requirements must preserve this. This is also applicable to the radiological safety levels currently achieved as reflected in the optimized protection of public and workers provided in the latest designed facilities.

In addition to these two fundamental safety targets (i.e. nuclear and radiological), a high-performance design requires special attention to the so called "abilities" related with the additional features demanded by the final users of the items produced in the facility (mainly radioisotopes).

On the other hand, since the relationship between Operating Organizations (OO) and users is now being switched to a vendor-client model, production costs are a relevant factor demanding an efficient use of the facility including items such as fuel economy, staffing, and logistics.

## 2.1. Nuclear safety

Nuclear safety remains as the overarching aspect in the design but it may be affected by many factors which could be grouped into two main categories:

a) Addition of new postulated initiating events (PIEs) or its respective probabilities.
b) Reduction of the effectiveness of the limiting and protecting actions.

While for the PIEs associated to external events the set considered in High-performance Reactors is quite similar to the ones normally used for RRs (note that it is beyond the scope of this paper discussions on the security issues triggered by the increased flow of parcels and people), for internal PIEs two aspects are requiring special design attention:

- Frequent modifications of the core reactivity and cooling generated by the in-service loading and unloading of irradiation targets.
- Handling of heavy casks across the facility and in the pools with the consequent risk of dropping on sensitive SSCs or releasing its content.

In relation with safety actions effectiveness, a very demanding utilization/production scheme may affect maintenance and inspection activities aimed at ensuring their reliability. Increased revenues associated with the operation of high-performance facilities are generally allowing proper resources for running these activities thus ensuring that safety is not compromised but, the high availability and longer cycles required are affecting the time available for its execution.

## 2.2. Radiological safety

The exposure of the public and staff has been reduced thanks to the implementation of suitable protection but the large production rates expected in high-performance facilities produce that, even negligible dose rates associated to certain processes grow up to high collective annual doses when its frequency is increased.

A particular situation is related with the utilization of transportation shielded casks for dispatching the production. These casks are designed in accordance with the transport regulations but the storage of these casks while waiting for the transport vehicles generates accumulated doses in some cases so high that represent the major contributor to the staff exposure and much higher than the ones associated to the reactor itself.

In addition, controls over the packages (including clearances) require many maneuvers in the proximity of loaded casks increasing the exposure of the staff.

In summary, the design of High-performance Reactors from the radiation protection viewpoint remains equal to the process used for RRs but the increased number of maneuvers and the introduction of dispatching related ones require special design attention.

## 2.3. Abilities

High performance facilities shall be designed for providing some new features but also to tailor others normally considered in the case of research reactors such as reliability and availability.

Reliability has been always considered in the design of safety and safety related SSCs but in high performance facilities, this concept shall be extended to critical SSCs on the flow of products in order to make the distribution of them reliable in terms of delivery-time. The date and time of delivery is really important for radiopharmaceuticals products waiting for being used in patients.

In a similar manner, the availability of the SSCs shall be extended to those that play a relevant role in the flow of products even requiring the inclusion of redundant routes for reception and dispatch of raw material and products.

Flexibility is another feature to be applied to the production associated processes which shall be capable of adapting the production levels to the market needs. In other words, the radioisotope market is shared among few facilities around the world which may experience downtimes due to failures or many other factors and high-performance facilities shall be ready for coping with this by adjusting its production rates. On the other way around some clients may stop the request of certain products or reduce the amount needed thus requiring the flexibility for continue with the production of other items without impacting its production cost or quality.

Adaptability is also a feature to be considered in the design aimed at ensuring the possibility of running other production processes in the future after reaching a sustainable maturity level. In other words, the experience is showing that new medical and industrial applications may be developed in the future requiring specific irradiation conditions or post-irradiation processes which can only be provided if a substantial part of the facility is modified accordingly.

## 2.4. Production costs

Many OOs are funded by national governments rendering the calculations of operating costs rather complicated (capital reimbursement, salaries, waste disposal, and others are covered by the public budget). In this context, the price of the isotopes produced are mainly based on international markets but, in order to have a viable operation scheme, the associated operational costs should at least be covered by the sales or by governmental support.

In any case, the design shall be ensuring that costs are minimized and this is achieved by minimizing the costs of every contributor such as:
- Fuel economy
- Logistics delays
- Additional human resources

## 3. Engineering solutions applicable to focal areas

The focal design areas listed in section 2 must be addressed by developing appropriate engineering solutions. The experience accumulated in the design of recent facilities is shown in this section.

### 3.1. Reactivity control related solutions

Targets not containing fissile material and not cadmium sheeted are generally not introducing relevant reactivities in the reactor core and, for the sake of simplicity are generally manually loaded and unloaded.

On the other hand, targets as the ones used for molybdenum production present an important reactivity worth making the loading and unloading maneuvers relevant when reactivity insertion accidents (RIA) are considered.

Design solutions are mainly based on ensuring a maximum displacement speed compatible with the reactivity insertion rates able to be compensated by the control systems. In implementing these devices, some advantages of the manual handling are lost such as the accuracy in the positioning and sensing the pulling force.

These features are to be compensated by positioning systems very accurate or allowing some manual manipulation of the lifting devices. The limitation of the pulling force is achieved by the use of load cells or similar devices preventing damages in the irradiation position or the rig itself.

It is also relevant in the design the introduction of features preventing a sudden release of the irradiation rigs while being handled which may be pulled/ejected by the coolant flow triggering a RIA.

### 3.2. Cooling related solutions

Many irradiation positions share the cooling flow with other core components thus requiring design solutions ensuring that the core remains properly cooled when targets are introduced or withdrawn.

In addition, the targets itself, especially those generating heat, shall be properly cooled until a defined time has elapsed from the moment in which they are withdrawn from the neutron flux.

An associated complexity to these two issues appears when multiple configurations of targets are to be considered requiring many times administrative procedures defining how many positions can be used or operated at the same time.

Complementing these administrative procedures, design solutions are to be implemented for ensuring minimum flows to both, irradiation positions and core components by flow restrictors of adequate size and shape placed in core structures or the rigs itself.

The cooling of irradiated targets is another element to be considered since many of them produce heat even after their removal from the irradiation position. The natural convection cooling available when the targets are underwater is an easy and cheap solution but requires devices ensuring targets are not exposed to air before certain cooling down time has elapsed.

Parking positions ensuring proper geometry for sustaining natural circulation cooling regimes and enough delay are a suitable design solution for ensuring safety.

## 3.3. Shielded transport casks handling

Products are packaged in shielded transport containers which are heavy objects introducing new internal events such as:
- Unexpected drop into core structures
- Drop or collision with vital SSCs or building elements.

Design solutions encompass the engineering of appropriate lifting devices featuring protective systems such as double breaks and cables up to the design of structures for limiting the zones where the casks may drop or distributing the impact forces in larger areas and absorbing the energy of the impact.

In addition to solutions aimed at limiting the SSCs and building areas potentially affected by the handling of cask, some protective reinforcement could be installed around sensitive areas and, some of them, may also provide additional radiation shielding over the staff.

In the design of high-performance facilities, including a dedicated area where these casks are loaded together with dedicated transport devices (smaller intermediate transfer casks, hot cells, pneumatic transport systems or conveyor belts) is an optimal solution contributing to both safety and efficient logistics.

## 3.4. Maintenance features

The stress in maintenance and inspection activities posed by the high availability demanded justify the inclusion in the design of SSCs of features facilitating these processes such as:
- Modular system design for easy replacement in case of failure or for preventive maintenance.
- Additional instrumentation for predictive maintenance.
- Increased replacement scheme of SSCs before reaching its mean time between failure.
- Shielding design ensuring the in-service access to maintainable SSCs.
- Optimization of refueling downtime by proper staffing (e.g. outsourcing some maintenance tasks thus coping with the high manning level required during refueling without increasing the facility staff).

## 3.5. Radiological aspects on logistic chain

Several activities are required for dispatching the radioisotopes produced in a High-performance Reactor including:
- Packaging the production in proper transport containers.
- Radiological clearance in terms of confinement and shielding.
- Appropriate labeling.
- Storage until delivery.
- Security clearance.

These activities require features designed for reducing the exposure of the staff as well as facilitating the maneuvers considering the large number of operations foreseen.

Automation and remote operations are the two most suitable solutions for many activities such as the ones related with the dispatching of the loaded transport containers, for example:
- Bolting the shielding lids
- Testing airtightness and external contamination
- Final packaging (shock absorbers, overpackaging, etc.) and labeling

Many industrial solutions are currently available in the markets including several robotics applications.

In addition to these engineering solutions, the layout of High-performance Reactors should contribute to the reduction of the staff exposure by providing proper separation between production streams thus preventing the doses from one line to operators in another. Nevertheless, this concept is challenging since dispatching points are commonly reduced in number due to security requirements.

## 3.6. Considerations on flexibility

Flexibility for attending changing production volumes require design features in several areas being the core design the most relevant. Some targets, depending on the mass, physicochemical and geometrical shape, influence the whole core behavior by affecting the flux profile or redistribution of cooling flows.

Irradiation rigs, designed in such a way that variable number of targets can be loaded maintaining the neutronic and thermohydraulic characteristics is the simple way for coping with this but it may require the introduction of flux flatteners which translates into longer irradiation times.

Once the targets are irradiated, the flexibility also extent to the logistic chain including the possibility of using transport containers of different sizes with the consequent impact on docking ports and lifting devices.

## 3.7. Considerations on adaptability

Adaptability is a twofold consideration in the design of High-performance Reactors:
- Possibility to provide neutron fluxes suitable for producing new types of radioisotopes or running new experiments, and
- Facilities for handling the processes associated to these new isotopes or experiments.

For tackling the first bullet, reconfigurable irradiation positions are to be incorporated in the design. These positions shall be able to modify the neutron spectra and also the gamma contamination for triggering different production reactions and preventing phenomena at organic molecular levels.

Solutions for these issues are available for many years but the challenge is now to ensure during the design stage the feasibility of implementing them once the facility has been in operation for many years, especially for in-core positions where the pitch and dimensions of fuel assemblies are limiting the design options.

For out-of-core positions, configurable reflector positions are the preferable solution allowing some decoupling from the core but limiting the fluxes available.

On the other hand, adaptability of SSCs dedicated to the post irradiation handling of targets are quite difficult to managed due to the large variety of processes and interfaces. Therefore, the considerations in the design shall be focused in the feasibility for replacing those SSCs by completely new ones designed specifically to the new requirements.

A special situation is related with the hot cells which shall be able to couple with transfer shielded casks introduced by customers in the future as well as the possibility of housing some radiochemical processes. In this regard, the design of High-performance Reactors must ensure a layout and a building structure allowing the removal of the whole hot cell and the installation of new ones without affecting slabs, beams and structural columns.

### 3.8. Considerations on costs

Fuel consumption is one contributor to the operation costs of the facility and it is considered in the design of High-performance Reactors by maximizing the fuel economy achieved by appropriate operating cycle length and discharge burnup.

These two parameters may be handled by modifying the uranium load or using burnable poisons in the nuclear fuel but this may require the manufacturing of a unique fuel design thus reducing the availability of alternative suppliers and losing the changes of obtaining competitive prices in the future.

Human resources are also important, in particular if staff is to be hired just for managing the production and/or performing actions requiring accreditation or training such as in the case of hot cells' operations.

Automation is therefor to be studied as an alternative to manual operations but everything depends on how mature are the processes and technologies involved.

Finally, the fact that radioisotopes are naturally decaying requires that dispatching of products shall be done as expeditive as possible. Solutions commonly used in logistics are therefore considered in the processes following the irradiation of targets including storage, and transport and lifting devices.

## 4. Conclusions

The concept of High-performance Reactors is reflected in projects currently being tendered and under design where a business case has been developed for establishing the technical specifications in a notional manner rather than fixing relevant parameters.

From the designer's viewpoint these flexible technical specifications provide an excellent opportunity for engineering solutions such as the ones depicted in this paper but also require the demonstration that the facility will cope with them across its lifetime.

Both, value engineering techniques and logistics considerations, are now to be also applied to the design of SSCs related with the processing of the production after its irradiation for ensuring the clients' satisfaction (and associated revenues) as well as maintaining the nuclear and radiological safety levels currently achieved by RRs and MPRs.