CONTRIBUTIONS OF PREVIOUS PROJECTS TO THE DESIGN OF NEW RESEARCH REACTORS

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ABSTRACT

For the successful achievement of a new research reactor design, it is necessary to meet on one hand the project specifications and on the other hand Safety Authorities requirements.

Customer needs are usually centered on a common set of applications, however their balance is tailored to each specific project, hence resulting in a dedicated specification.

Safety Authorities have implemented in their own way the requirements of the international framework in the applicable national regulation. Currently, there is an increase in their expectations as regards the implementation of defense in depth, the robustness against internal and external hazards and qualification requirements of SSCs.

The common traits of customer’s and safety authorities’ expectations are to decrease the risk:

- as regards utilization and operation performances and the smooth project achievement
- as regards potential consequences for the operators, the public and the environment.

Both are expecting up to date and fitted to purpose practices while using a proven design, qualified SSCs as well as state-of-art qualified methodologies.

Both customer’s expectations and safety requirements are progressing and constantly pushing the designer to challenge his solutions while keeping the best level of proven design.

Meeting all these expectations at once is a big challenge for designers.

To address this issue, the paper presents and illustrates on the basis of TechnicAtome (formerly AREVA TA) practices how the past and ongoing project experience is implemented in the design of new research reactors.

The topics of concern are:

- the reactor overall architecture as regards utilization and operation performances
- the experimental devices ensuring experimental and production applications
- the SSCs ensuring utilization, operation or safety functions as regards their proven design characteristics and qualification requirements
- the methodologies, approaches and tools as regards their qualification.

The way to address these issues is discussed in the paper showing the cross-cutting contributions of past and current projects and are illustrated with some examples in the light of AREVA and TechnicAtome experience.

1 INTRODUCTION

For the successful achievement of a new research reactor project, it is necessary to meet:

- on one hand the Customer specification,
- on the other hand Safety Authorities requirements.

Customer needs are often centered on a common set of applications. However their balance is tailored to each specific project, thus resulting in dedicated specifications.

Safety authorities have flown down in their own way the requirements of the international IAEA framework in the applicable national regulation. Currently, there is an increase in their expectations as regards:

- the implementation of defense in depth: in particular, the importance of the 4th level of defense in depth in the design has increased following Fukushima Daichi accident. More unlikely events are considered in the safety analysis and engineered features independent from the ones of the 2nd and 3rd levels have to be introduced.
- the robustness demand against internal and external hazards: as a result of the consideration of design extension hazards.
- qualification requirements of System, Structures and Components (SSCs).

The common traits of customer's and safety authorities' expectations are to decrease the risk:

- as regards utilization and operation performances and the good project achievement
- as regards potential consequences for the operator, the public and the environment.

Both are expecting up to date and fit to purpose practices while using a proven design, qualified SSCs as well as state-of-art qualified methodologies.

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2 NEW PROJECT REQUIREMENTS

For each new project, the set of interactors shown on Figure 1 are driving the requirements.

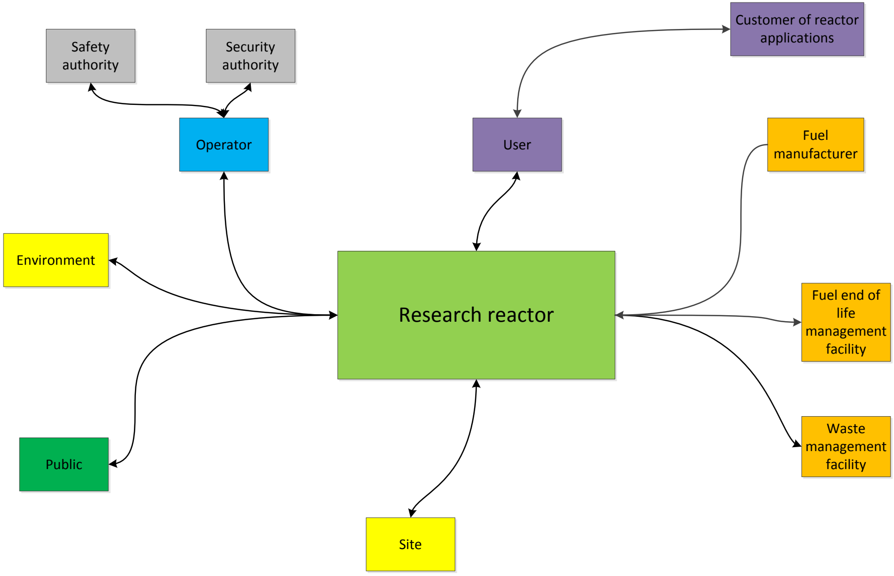

Figure 1 Reactor facility context

As regards reactor utilization, the most frequent applications for a new research reactor are training, radioisotope production, neutron activation analysis, neutron beam applications for science and industry, and neutron transmutation doping.
Material and fuel testing is an application implemented on 6% only of the research reactors currently in operation; nevertheless, it has been requested by several new research reactor projects planned or under construction.
Even if the set of applications is common to several projects, the level of performance of each application and the balance in terms of priority between the applications differ from one project to another, impacting the core and reflector designs as well as the reactor power.

A recent aspect of new research reactor projects is to consider that a subset of applications or sometimes all of them have to provide revenue. As a minimum, an asset management approach is considered by the project owner and, in some specific cases, a sustainable business case covering the whole lifecycle cost is a project requirement. This induces clearly a focus on the control of project good achievement within performances, CAPEX, OPEX, and schedule objectives.

It is clear that the site and environment context is unique. At least interface requirements would be specific, e.g.:

- meteorological conditions and the kind of the ultimate heat sink drive the design of cooling and conditioning systems ,
- local waste routes drive the design of waste management facilities integrated in the plant,
- the radioisotope processing interface drives the design of facilities dealing with wet and dry loading of shielded transport casks (i.e. hot cell and in pool cask loading station and associated handling facilities including truck hatch),
- the integration into a preexisting nuclear site leads to specify some constraints on equipment standardization for harmonization purpose ; at the opposite, a new site leads to embark within the research reactor scope some ancillary and support facilities required for its operation and utilization.

As regards safety, the evolution of IAEA Safety standards from 35-S1 to NS R 4 ref <1.> in 2005 and recently SSR-3 ref <2.> (in 2016) illustrates the increased stringency of safety requirements (some of them did not exist ten years ago). In particular, the following changes may significantly impact a research reactor design:

- more demanding requirements dealing with the 4th level of defense in depth leading to consider more unlikely events in Design Extension Conditions such as more severe accidents or combination of events. For example, a new research reactor design shall now address the combination of an extended station blackout with several weeks of autarchy as regards decay heat removal. In addition, Design Extension Hazards such as more stringent meteorological conditions, aircraft crash, earthquake or flooding shall also be considered.
- more stringent requirements in terms of independence regarding the safety groups acting at different levels of defense in depth,
- qualification of items important to safety (such as requirement 29 of SSR-3 ref <2.>) introduced in the very recently published SSR-3.

This evolution is also reflected within new national nuclear regulations which implement some additional requirements e.g. dealing with redundancy, independence, diversity. These requirements drive the SSC’s design especially those devoted to the 3b, or 4th level of defense in depth.

To summarize, it could be considered that a new research reactor implies that the reactor designer can cope with:

- Utilization requirements tailored to meet the strategic plan needs by definition unique,
- Safety and regulatory requirements among which some of them did not exist 10 years ago,
- Site specific requirements.

In addition, reactor designers have to live with this paradox consisting of meeting these new requirements with only proven design features in order to assure the customer of the good project achievement within budget, schedule and expected performances.

3 DESIGN OF THE REACTOR

Prior to the discussion about the possible different approaches to a new research reactor design, it is useful to share the following background information:

- Product Breakdown Structure (PBS) of a research reactor,
- What a breakdown structure items is made of,
- Impact of the different types of requirements on the reactor breakdown structure items.

Taking SSR-3 table of content as guidance, a typical reactor PBS can be established and is shown on the following Figure **2**.

For each of the PBS items, to facilitate the discussion, it could be considered that its design includes:

- A concept driving the system or assembly architecture,
- The functional sizing of the system,
- Some components to be specifically sized and manufactured, such as heat exchangers,
- Some components selected from catalogue: components procured on the open market (COTS - Commercial Off-The-Shelf) or, when they are subject to qualification requirement (for example an environmental qualification e.g. earthquake), from the reactor designer catalogue (to benefit from previous projects qualifications),
- Some physical links between the components (cables or pipelines) possibly subject to safety-related hazards (e.g. internal fire, earthquake),
- Some fittings required for the system integration within the plant: penetrations and supports (those may be subject to specific qualification requirements such as fire, earthquake, flooding, etc.)
- The structural sizing of the components and fittings.

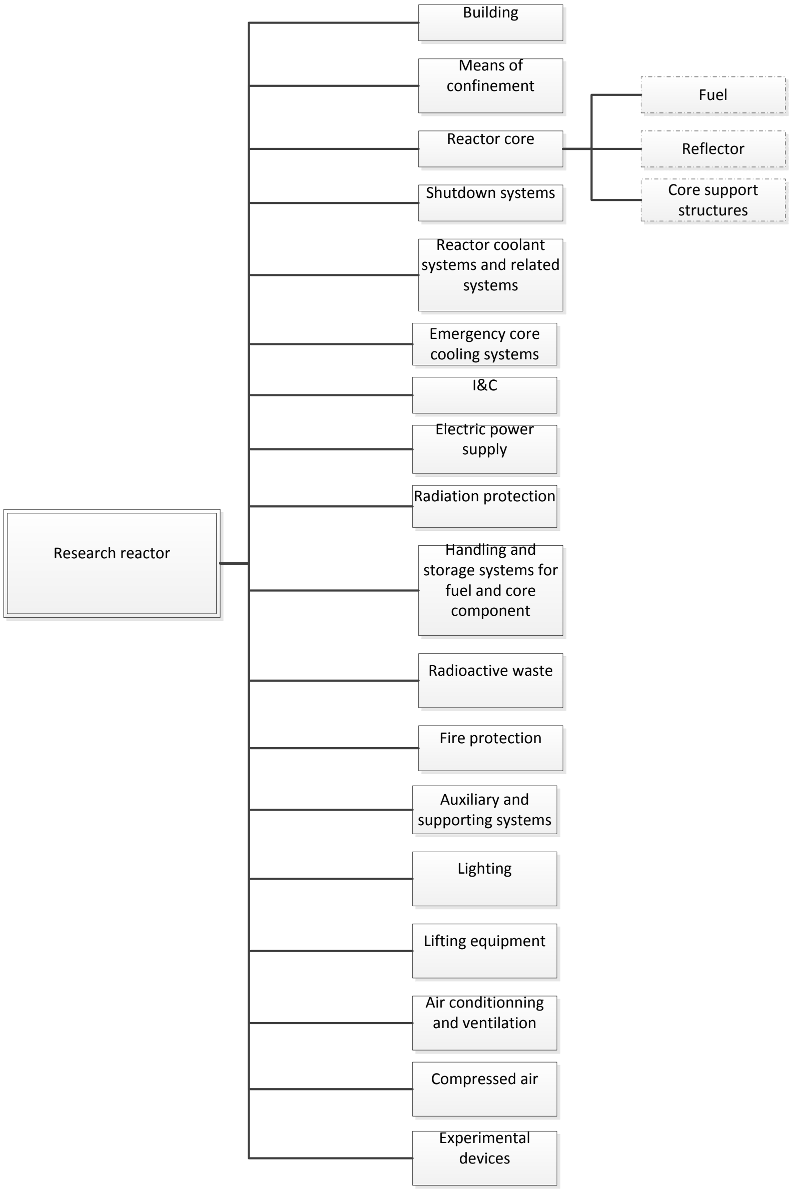

Figure 2 - example of research reactor Product Breakdown Structure

Looking at this breakdown structure and at Table **1**: Main impacts on PBS items (in appendix), the following comments can be made:

- The reactor core, shutdown systems and I&C designs are driven by both utilization and safety and regulatory requirements.
  - These requirements impact the selection of:
    - ∗ the fuel element (flat or curved plates, plate size),
    - ∗ the fuel assembly (shape, dimensions),
    - ∗ the reflector material (water, heavy water, graphite or beryllium),
    - ∗ the core and reflector layout,
    - ∗ the reactor architecture (see ref <3.>) and the reactor power.
  - Qualification is especially important for:
    - ∗ the reactor fuel (fuel element and fuel assembly - ref <11.> and <12.>),
    - ∗ shutdown systems (as illustrated on the JHR project in ref <7.>),
    - ∗ and I&C systems (as illustrated in ref <10.> and <8.>).

    - Among the various shutdown systems concepts, control rod drives mechanisms allowing neutron absorbers dropping, reflector vessel draining in the event of low power reactor or heavy water use as reflector material, or poisoning systems are the most frequently used. These SSCs are of utmost importance as regards the performances and the good achievement of the project.
    - A fit to purpose core design, especially the core and reflector arrangement and reactor power definition, requires extensive and accurate calculations by the means of computer codes from the early stages of the design (see ref <4.>, <5.>, <6.> and <9.>).
- Confinement means design is driven by safety and nuclear regulations only, dealing with redundancy, confinement strategy (static or dynamic), protection against overpressure, reactor containment isolation. The impact of the utilization on this design driver is almost limited to the source term to be considered through the reactor power, while sample and target radiological inventory is in general of a lower impact.
- The building design is driven by both safety and utilization requirements:
  - The building layout is driven on one hand by the applications driving the building layout backbone and on the other hand by the external hazards driving the building shape and the withstanding structure, especially in the event of challenging earthquake or aircraft crash (military aircraft or large commercial aircraft). It is also influenced by the segregation requirements that ensure the independence between safety systems.
  - The building size is defined by the applications, ancillary systems and support systems not provided by the site, the power of the reactor to be housed as regards the pools and rooms space allocation and by the number of trains of safety-classified systems acting at the different levels of defense in depth (e.g. existence or not of systems devoted to Design Extension Conditions management).
  - The penetrations and equipment supports design is mainly driven by internal and external hazards. Their qualification has been recently required in IAEA safety standard ref <2.>. In some countries, in particular in France, qualification of safety items has already been requested for several years. As regards the French experience, there are important differences in terms of design, sizing, justification (and subsequently in terms of cost and schedule) between penetrations and support technologies in use in nuclear compared to other industrial projects.
- The emergency core cooling systems, reactor coolant systems, experimental devices and electric power supply systems designs are also driven by all requirements:
  - Their functional specification is a mix of safety requirements and application requirements,
  - The concept selection or system architecture is also driven by a mix of application and safety requirements,
  - The system functional sizing is eventually defined by the applications and associated performances,
  - There are some COTS but most of the components are subject to qualification requirements.
- The fire protection and auxiliary supporting systems design is driven by safety and site requirements: the main drivers are the on-site pre-existing facilities and the country standards
- The radioactive waste, air conditioning and ventilation, compressed air systems designs are driven by site requirements as regards:
  - the scope of supply,
  - the sizing parameter being the meteorological conditions for air conditioning and ventilation systems, and the applicable standards.

- The lighting, lifting equipment, radiation protection, handling and storage systems design is not strongly impacted by project-specific requirements.

It could be noticed that these requirements impact the design of a reactor at 2 levels:

- At reactor level, with impacts on building layout, reactor architecture (open core/tank-in-pool, primary flow direction), core design, reactor power, pool sizing to provide the requested cooling autarchy, safety features acting at different levels of defense in depth. Regarding these items, the selection of the right design options and right overall sizing seems to be the most important success factor to address key issues dealing with performances and safety. New requirements impacting this level jeopardize the reutilization of previous reactor design.
- At PBS items level (i.e. SSC level), the proven design character of each SSC (i.e. maturity of the SSCs design) and capability to properly implement them appear to be of utmost importance. The increasing expectations regarding qualification constitute a major challenge as regards reutilization of previous designs.

In terms of cost breakdown, besides the building being several times bigger than the average cost items, all other cost items are from the same order of magnitude (once the auxiliary and ancillary systems have been grouped into 2 cost items).
As a consequence, cost impacts at overall reactor design level are generally important. At SSCs level, the qualification becomes also an important cost impact.

Achieving an acceptable design meeting all requirements is a real challenge for reactor designers. Each research reactor project being a specific case, there is no pre-existing recipe to address this issue.

However, 4 design strategies could be considered:

- Propose an <u>existing design without any significant change</u> or a drastic limitation of the design changes
- Start from an existing design and tailor it to fit the project requirements: so-called <u>Existing design adaptation</u>,
- Perform a fit to purpose design through:
  - a selection of a reference reactor type,
  - a tailored system architecture and building layout to match project requirements
  - a reactor architecture definition integrating a maximal number of SSCs with a proven design

    so-called <u>Built from proven design architectures and SSCs</u>
- Starting from scratch: totally <u>new design</u>.

A synthesis of the main advantages and drawbacks of these 4 design strategies is shown on Table **2** in appendix.

The main outcomes of this comparison are as follows:

- <u>Existing design without any significant change</u>

  Successfully implementing this approach is quite rare: despite TechnicAtome long and rich history in research and test reactor design, this extremely unlikely conjunction of adequate conditions for success was never encountered. Some rare cases could be observed: it seems that they result from an upfront agreement between projects, similar safety requirements and common site requirements. Today, as a consequence of the evolution in the regulatory and safety requirements, the conditions for the successful implementation of this strategy are drastically limited; the reference reactor has to be up-to-date. This approach seems almost impossible without a specific agreement and the same timeframe of the reference and new project.

– Existing design adaptation

This approach consists of a slight adaptation of an existing reactor overall design with a new core design.

To be realistic, it would require:

- very limited adaptations as regards systems architecture and building design to meet up-to-date safety requirements,
- existing SSCs qualifications compatible with the current requirements,
- site requirements not significantly challenging the systems to be housed in the nuclear island.

To be suitable, this approach is to be limited to projects having similar application requirements and no divergent challenging ones regarding external hazards that would jeopardize the layout and the integration of the reactor. Considering the very recent evolution of safety requirements, especially as regards defense in depth and external hazards, only very lucky projects can successfully implement this approach.

– Built from proven design SSCs and architectures

This approach consists in selecting a reactor architecture compatible with applications and associated performances, new core design, plant architecture fitting with up to date defense in depth and integrating as far as possible already proven design SSCs, nuclear island building designed to cope with challenging hazards.

It could always been implemented and combines the benefits of all the experience of past (through the SSCs technological bricks) and most recent and ongoing projects (trough the architecture, building design and qualified safety related items). It is fully compliant as regards performances and safety at efficient cost and schedule.

It has TechnicAtome’s preference since:

- Overall design and reactor architecture combine cross-cutting benefits not only from the JHR project, meeting up-to-date safety requirements including Post-Fukushima’s (see ref <1.>) but also all previous reactors’ design even the older ones, since only the concepts are reused within an up-to-date overall architecture as regards defense in depth,
- Core and experimental devices design benefits from:
    - the lessons learned from material testing, multipurpose and neutron beam reactors (e.g. OSIRIS, SILOE and ORPHEE),
    - the LEU silicide fuel qualification at fuel element level (OSIRIS, JHR) and fuel assembly (OSIRIS design remaining one of the fuel assemblies with the most remarkable operating records - 23 years of operation without any fuel failure at average fuel assembly power over 1.6 MW/fuel assembly),
    - the up-to-date design approaches and computer codes (cf ref <3.><9.><13.>),
- Reactor systems are designed based on a combination of proven concepts from past projects, up-to-date sizing using up-to-date tools, and already qualified component from component database of the TechnicAtome PLM (see ref <2.>). As regards component qualification, once addressed, the very stringent Cadarache site environmental conditions (in particular seismic hazard) become an asset for future projects.

– Totally tailored design

Lessons learnt from projects integrating wide range of innovative technologies lead to the conclusion that this approach cannot realistically be implemented since cost and schedule would exceed a reasonable target.

4 CONCLUDING REMARKS

Contributions of previous projects are key to the design of new research reactors.
The recent evolution of safety requirements together with the specific utilization features required to meet the needs of the customers' strategic programs raise challenges for the reutilization as a whole of pre-existing designs (especially those meeting previous safety requirements).
Pragmatism remains the general rule. Once the approach consisting of a totally tailored design has been wiped out because unrealistic in terms of cost and schedule, the selection among the 3 other possible strategies will be driven by the minimization of the design effort and risk.
In most cases, it is unlikely that a previous design can be tailored without in-depth modifications to fit new project requirements. Nevertheless, whenever possible, benefiting from this opportunity is the best way for the project. The most universal and best compromise is to build a customized design using preexisting concepts, technological and methodological bricks from previous or ongoing projects.

The relevant contributions of past projects to design of new research reactor come from:

- research reactor projects, for the reactor core, the fuel, the core support structures and the experimental devices,
- nuclear reactors projects in general from recent designs meeting up-to-date safety requirement, for other key safety SSCs such as shutdown systems, decay heat removal means, means of confinement, and building providing protection against external hazards,
- all recent and ongoing nuclear projects, for all other safety classified SSCs for which a qualification is required, the driving factor being preexisting qualification records.

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6 APPENDIX

PBS Item	Utilization	Safety and nuclear regulation	Site	Main drivers
Building	The layout is driven by the applications to be considered in the design especially when neutron guides, isotope production or fuel and material testing structuring shipping into shielded casks and its preparation acts as backbone for the building layout throughout the transfer routes : pools and hot cells	The design extension hazards (stringent aircraft crash, flooding, earthquake) strongly impact the building design	Soils characteristics impact the building foundation design. Magnitude of the external hazards but seems to be from a second order as regards design extension hazard	All the 3 are driving the design of the building
Means of confinement	The source term to be considered is defined by the reactor utilization throughout reactor power and the samples or targets to be irradiated.	Constraint are frequently expressed at 3 levels: – Requirement dealing with levels 3b and 4 of defense in depth especially long station black out impacts the confinement strategy – Doses constraints for the public in different conditions, – Specific requirements dealing with single failure criterion may apply	Proximity of public	The safety and nuclear regulation are the most important drivers
Reactor core	Core design (fuel assembly, size of the core, reactivity control, reflector material, core and reflector layout, the reactor architecture (coolant direction, pressurization or open core, cf ref <3.>) and the reactor power and power density are fully driven by utilization requirement	Safety and regulatory may impact the core design with a second order of magnitude except for the containment barriers (cf ref <3.>)	No significant interaction	Utilization mainly
Shutdown systems	The efficiency of the shutdowns system is driven by reactivity loss along the cycle due to core design and reactor power	The second system requirements such as redundancy, independence and diversity seems to be the most defined by the regulation	Little influence as regards external hazards magnitude e.g. earthquake	Application and Safety and regulation
Reactor coolant and related systems	Utilization drives the reactor power being a major input for the design as sizing input	May interact throughout the postulated initiating events to be considered	influence as regards the ultimate heat sink and ultimate heat sink temperature	All the 3 are driving the design of the building
Emergency core cooling systems	The power density required to meet the irradiation performances drives the need for a forced cooling at shutdown and during transient from full power to shutdown	Requirements may impact the number of systems and the pools volume because of the grace delay (SBO)	influence as regards the ultimate heat sink and ultimate heat sink temperature	All the 3 are driving the design of the building
I&C	I&C system architecture importance of the MTR applications, number and priorities in the preventive and mitigative functions such as reactor shutdown, power decrease,..	Impact from the regulatory requirements dealing with the shutdown systems	No significant impact	Utilization and safety
Electric power supply	Sizing of the cooling circuit supply and number and sizing of experimental devices to be supplied	Requirements impacting the design of safety systems support systems: redundancy, autonomy, independence,…	Nature and quality of external power supply	All the 3 are driving the design

PBS Item	Utilization	Safety and nuclear regulation	Site	Main drivers
Radiation protection	Implement Application and reactor power drive the potential radiological hazards	Dose limits and zoning requirements	No significant impact	Utilization and safety
Handling and storage system for fuel and core component	The frequency of handling operations and the sizing of storages are linked to the utilization throughout the reactor power	Regulatory requirement are not necessarily strong design drivers	Cask interfaces already more less generic (limited number of transport casks)	Not very sensitive
Radioactive waste	Applications generates specific wastes and reactor power drives the generated waste inventory	No significant impact (actually already considered in the waste routes to comply with)	Defines the waste routes to be compliant with and the system to be integrated in the facility to manage the waste	Site throughout waste route
Fire protection	Very limited impact: rooms with specific hazard	Fire hazard analysis requirement	Site response and standards to be applied	Site and safety
Auxiliary and support systems	No significant impact	When acting as safety system support systems, the support systems may be subject to requirements from the regulation. However, the main safety systems support systems have been already addressed in other PBS items	Unavailability of existing on site facility drives the systems to be integrated in the scope of supply	Not very sensitive
Lighting	No significant impact	No significant impact	No significant impact	Not very sensitive
Lifting equipment	No significant impact	No significant impact	No significant impact	Not very sensitive
Air conditioning and ventilation	Some need for ambient conditions	No significant impact	Meteorological conditions is driver for sizing	site
Compressed air	No significant impact – distribution of the consumers	When used as safety system support system	Interface with site drives the need for systems to be embedded in the design	site
Experimental devices	Fully driven by utilization : applications requirements	Safety requirements impact also experimental devices	Interface with upstream and downstream facilities eg processing facilities for isotopes Depending on the casks and their way of docking for loading, and also the combination of casks to cover the requested applications, it may have an important impact on the layout of truck hatch, hot cell as regards the auxiliary pool and handling facilities	All the 3 are driving the design

Table 1: Main impacts on PBS items

Design approach	Main design features	Advantage	Drawback	Comment
Existing design without any significant change	Existing reactor overall design Unchanged reactor architecture Existing SSCs Core and reflector layout have to be tailored	Control of construction cost and schedule once the design has been accepted Actual applications performances are known from early stage of the project	Risk of unbalanced design as regards application/CAPEX and OPEX Poor compliance against safety requirements: defense in depth implementation, specific safety requirement resulting in an higher licensing risk	To be suitable for the project, this approach can be implemented when the reference reactor has been design for the same applications, is a cutting edge state of art as regards safety, built on a challenging site as regards external hazards. The customer has to accept compromises This is very unlikely without specific agreement between 2 projects.
Existing design adaptation	Existing reactor overall design Reactor architecture slightly affected by adaptations With very limited adaptations as regards reactor systems architecture to meet safety requirements New core design Existing SSCs	Almost full control of construction cost and schedule once the design has been accepted Utilization performances under control and not so bad balanced as regards CAPEX and OPEX	Poor compliance against safety requirements: defense in depth implementation, specific safety requirement resulting in a higher licensing risk. In particular, the qualification of safety related SSCs would be an issue. Poor integration of applications outside the core	To be efficient, this approach would imply to limit the design changes to applications with limited impacts outside the core. Site and safety requirements do not affect significantly the scope of supply housed within the nuclear island and the building layout and design This approach to be suitable is to be limited to projects having similar application requirements and no challenging regarding external hazards jeopardizing the layout and the integration of the reactor
Built from proven design SSCs and architectures	Selecting a reactor architecture compatible with applications and associated performances, new core design, plant architecture fitting with up to date defense in depth and integrating as far as possible proven design SSCs, nuclear island building designed to cope with challenging hazards	Compliance against safety requirements: defense in depth implementation, specific safety requirement, qualification of safety related SSCs Good integration of the applications at core level and plant level as well Control of construction cost and schedule	Schedule and cost a little behind those of existing designs adaptation or without any change	This approach is always possible and especially efficient within stringent project environment. The more research reactors and nuclear facilities past projects you have the more this approach efficient is. Determinant contribution of reactor projects subject to up to date safety requirements.
Totally tailored design	Designed for compliance	Fit to purpose as regards utilization, safety and site requirements	High risk of cost and schedule beyond target	Not really realistic in true life because of the risk level as regards cost and schedule.

Table 2: Overview of possible design approaches