DESIGN OF A PALLAS-REACTOR

MARISA VAN DER WALT, ENGINEERING MANAGER
Design and Licensing Project, Pallas
Comeniusstraat 8 Alkmaar,
PO Box 1092, 1810 kb Alkmaar, the Netherlands

ABSTRACT

The future PALLAS-reactor is to be a privately financed safe and reliable multi-functional facility based on proven technology and designed in accordance to engineering best practices. The main functions of the PALLAS- reactor are to irradiate Mo-99 targets and other medical and industrial isotopes, irradiate fuel and material samples, and have the reservation to perform complex fuel testing or the capacity to irradiate more Mo-99 targets/other isotopes as market demand changes.

To ensure the desired outcome, Stichting Voorbereiding PALLAS-reactor (PALLAS) prepared a set of technical describing the needs and functions of the future reactor. Underlying concepts of the PALLAS-reactor technical requirements are a set technical drivers that are required to be implemented by the designer within the design process. The goal of these drivers are to strengthen the safety and economic performance of the PALLAS-reactor.

An optimal balance of technical drivers need to be implemented at an affordable cost. This will be determined in the design by taking in consideration safety, cost control and value management mechanisms.

1 Introduction to PALLAS

1.1 PALLAS Objectives

The design philosophy of the PALLAS-reactor, that will replace the High Flux Reactor (HFR) in Petten the Netherlands, is defined as a safe and reliable multi-functional facility based on proven technology and designed in accordance to engineering best practices. The basis of the safe PALLAS-reactor design is the Dutch Safety Requirements [3] and IAEA standards and guidelines.

The main technical functions of the PALLAS-reactor is to:
- irradiate Mo-99 targets and other isotopes used for medical or industrial purposes;
- irradiate fuel and material samples;
- have the reservation to perform complex fuel testing or the capacity to irradiate more Mo-99 targets/other isotopes as market demand changes;

The financial objectives of PALLAS is to have an affordable reactor and limit the operational cost.

1.2 Project Overview

The PALLAS project, as presented in Figure 1, has two phases comprising of procurement, design, licensing, raising funds, putting in place the necessary nuclear organisation, construction and commissioning activities. Once successfully commissioned, the PALLAS-reactor will be ramped up to full production in a defined period to support the achievement of the PALLAS Business Case.

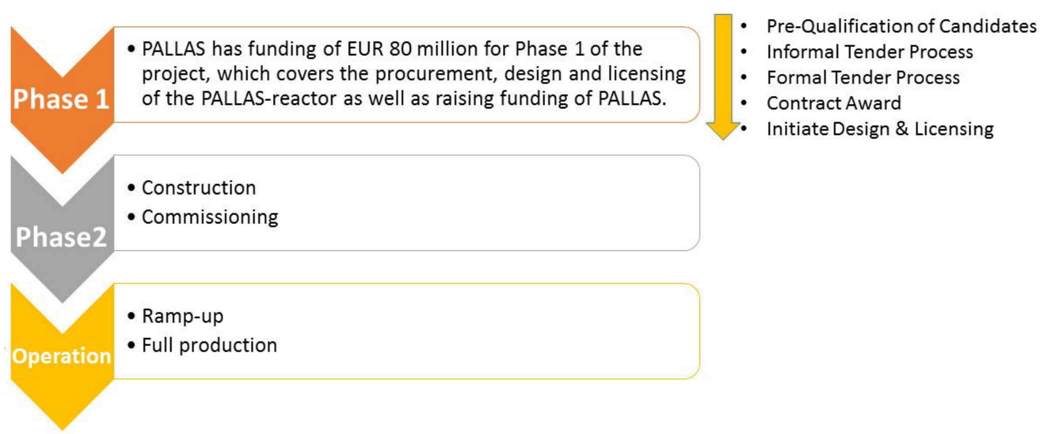

Figure 1: PALLAS-reactor Project Phases

PALLAS is following an EU Negotiated Procedure to procure Engineering, Procurement , Construction Management and Commissioning services. As part of the Tender Phase, PALLAS engaged in approximately one year of dialogue with the pre-qualified candidates. The dialogue process included various technical discussions with candidates and visits to facilities designed, constructed and commissioned by the candidates. The site visits were mainly done to learn from the experiences of the current owners. Information gained during this period was used to direct and enhance the development of the technical requirements along with input from other Stakeholders.

1.3 PALLAS-Reactor Technical Overview

The technical overview of the PALLAS-reactor is given in Table 1.

Table 1: PALLAS-reactor Technical Overview

No.	Parameter	Description
1	Reactor type	Light water moderated, open pool type reactor
2	Reactor Power (MW_{th})	As low as possible (expected) < 30 MW_{th} (expected)
	Thermal Flux (n/cm ^{2}/s)	• Low flux zone - 1.0 X 10^{14} • Moderate flux zone- 2.0 X 10^{14} • High flux zone - 3.0 X 10^{14}
3	Fast flux	Not a driver for the reactor design
4	Reflector type	Beryllium Elements and/or Heavy Water
5	Reactor Fuel	• Low-enriched Uranium Silicide-Aluminium dispersion • The density of the total Uranium mass in the fuel meat shall not be higher than 4.8 g / cm^3. • The cladding of the fuel plate shall be Aluminium or Aluminium alloy based. • Fuel burn-up more than 55%.
6	Cooling philosophy	Cooling category 2 as per the Dutch Safety Requirements – passive cooling in case of loss of off-site power
7	Coolant flow direction	Upwards flow
8	Risk Category	Risk Category 3 as per the Dutch Safety Requirements
9	Reactor availability	>300 Full Power Days
10	Number of Hot Cells	Minimum of two
11	Loading scheme	Redundant dry loading streams and wet loading as a divers method
12	Production envelope	Mo-99, other isotopes for industrial and medical purposes
13	Research envelope	• Support research in medical isotopes • Irradiation of fuel specimens in capsules • Irradiation of materials samples
14	Reservation for adaptation	Extra space and infrastructure for either: • introducing one complex fuel irradiation solution in the future (for instance irradiation of fuel in steady state or accident or ramp-up conditions) • or increasing irradiation of medical (such as Mo-99 etc.) or industrial isotopes

2 Holistic View

Figure 2, presents a holistic view of the interrelation between the selected design drivers, value engineering and design-to-cost that are required to be taken into account during the PALLAS-reactor project life cycle.

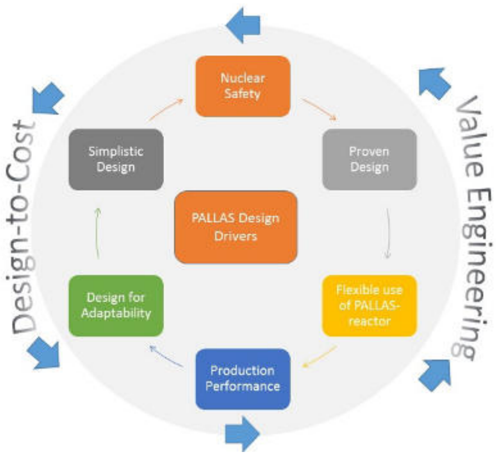

Figure 2: Integrated Approach to Design Drivers, Value Engineering and Design-to-Cost

This paper focusses on four goals PALLAS wants achieve during the design phase:

- To realise the preferred functionalities selected to drive value proposition/ possibility for generating revenue for PALLAS by implementing and managing the design drivers within the design,
- To manage the 'value' of PALLAS within the project lifecycle by means of value engineering (what is currently important to PALLAS),
- To enable the increase of 'value' to the customers and future owner during the PALLAS-reactor lifecycle by means of design for adaptability (enable what is important in the future),
- To manage the cost of the preferred functionalities and 'value' through design-to-cost methods.

2.1 Implementation Stage

An example of a typical breakdown of incurred project cost for new built Research Reactors is presented in Figure 3.

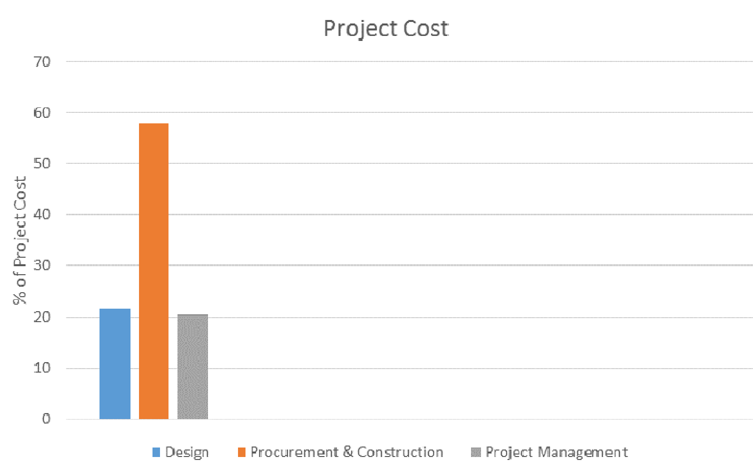

Figure 3: Example of Incurred Project Cost

As presented in the figure above, the percentage project cost expended during design and especially conceptual design is considerably lower than that expended during procurement and construction. As described in [4], the selected concept design will determine the majority of the life cycle cost of the PALLAS-reactor. If the concept design is performed poorly it may cause the following downstream issues:

- Cost overruns,
- Need for design changes,
- Schedule delays,
- Delays caused by licensing,
- Contract variations and deviations,
- Challenges in training of operating team.

For this reason, the integrated holistic approach as presented in this paper is to be implemented in the conceptual design stage of the PALLAS-reactor project.

3 PALLAS-reactor Design Drivers

To strengthen the safety and economic performance of the PALLAS-reactor an optimal balance of important technical drivers need to be assured within the design. The technical drivers comprise of concepts underlying the development of the technical requirements and guidelines for designers to support the development of the PALLAS-reactor design. The design drivers describes the overall functionality of the PALLAS-reactor.

The objective is to define a model to quantify the drivers and numerically describe the optimal balance as an input to value and cost steered design decisions. The description in the following paragraphs forms a basis of future development of this model.

3.1 System Design Driver Factor

The objective during the design stages is to determine an optimal System Design Driver Factor (**SDF**) for investment, as per [1]. In other words, the largest functionality in terms of design drivers at the most affordable total costs over the life of the PALLAS reactor.

The seven metrics to quantify the system design driver factor selected for PALLAS are:

- Nuclear Safety (**S**), driving the main objective to protect members of public, workers and the environment from harmful effects of ionizing radiation during the full lifecycle of the PALLAS-reactor.
- Production performance ($\mathbf{P_P}$) with the focus on a reliable and continuous operation of the reactor and work streams including the receipt, irradiation, handling and dispatch of products.
- Proven design (**P**) with the focus of using commercial off-the -shelf (COTS) items and SSCs with a high technology readiness level to reduce licensing and operational risks.
- Flexible (**F**) design that refers to the multi-functional use of the PALLAS-reactor where the capacity can be adjusted within a defined operating envelop according to the market need.
- Design for adaptability (**A**) is taken into account in the PALLAS-reactor so that it will provide an increased value over its life time to customers.
- Non-complex design (**C**) with the emphasis on number of SSCs, plant layout, system design, and handling.

Each metric is measured on [0,1] scale. The weight factors must meet the following criterion:

$$\sum_{i=\{S,P,F,A,C,P_P\}} W_i = 1$$

System Design Driver Factor (**SDF**) is expressed as the weighted average of the seven metrics:

$$SDF = \frac{w_S S + w_{P_P} P_P + w_P P + w_F F + w_A A + w_C C}{Cost}$$

Since each metric is within the range [0,1] and weights sum to one, SDF ∈[0,1]. Optimisation methods are to be applied to determine the optimal set of parameters.

More detailed information on the description of the various PALLAS design drivers are given in the paragraphs below. As future work the specific drivers need to be express mathematically.

3.2 Nuclear Safety

Considering, nuclear safety the main objective is to protect members of public, workers and the environment from harmful effects of ionizing radiation during the full lifecycle of the PALLAS-reactor.

Nuclear safety within the PALLAS-reactor is to be accomplished by implementation of a safety concept to ensure:

- Maintaining the main safety function in all operational modes and states,
- Implementing and maintaining of Defences (DiD levels and barriers)
- Implementing and maintaining a safety culture. This includes for instance a safety culture enhancement programme and working in a disciplined manner by implementing configuration management.

3.3 Proven Design

In support of safety, availability, reliability and cost savings of the PALLAS-reactor it is required to have the highest level of proven technology in accordance with best engineering practices. For this reason wherever possible qualified commercial-off-the-shelf (COTS) items are preferred.

The benefits PALLAS wants to gain from utilising COTS items includes providing standardised functionality, professionalised proven and reliable customer and maintenance support, lowering CAPEX and OPEX, providing a high TRL level, limiting licensing and operational risks, reducing long lead time of mission and safety critical components and ensuring the application of higher quality.

With regards to technology readiness PALLAS prefers to use technology from the following range to limit licensing and operational risks:

- TRL 9: The technology is operationally in use in an active facility
- TRL 8: The technology is undergoing active commissioning
- TRL 7: Technology undergoing inactive commissioning. It can include works testing and factory trails but it will be on the final designed equipment, which will be tested

using inactive simulants comparable to that anticipated during operations. Testing at or near full throughput will be expected.

Nuclear fuel for the reactor is required to be qualified in similar operating conditions as the PALLAS-reactor and categorised within the NUREG-1313 envelope.

3.4 Production Performance

The main objective for the PALLAS-reactor is to irradiate medical and industrial radio isotopes in accordance with customer needs and for this reason, the design and operation of the PALLAS-reactor supply chain is to be prioritised towards medical and industrial radio isotope irradiation.

The availability of the PALLAS-reactor and supply chain is at least 300 Full Power Days (FPD). The continuous availability of production streams/supply chain includes:

- Receiving the products
- Storing of products
- Irradiating of products
- Handling of products
- Transferring and dispatching of products.

To accomplish a continuous availability in production, PALLAS prefers a design that proves to have sufficient redundancy, independence, reduction in possibility of occurrence of human errors, as well a diversity and effective maintenance schemes (including predictive maintenance). The ambition and goal of PALLAS is also to enhance the quality of the irradiated product by reducing variation of the fluxes and decay losses, thereby decreasing the required handling time of the product.

The reactor is to be effectively and designed such that it optimally makes use of the available space in the reactor.

At this moment it is foreseen that Mo-99 can be considered as a priority product as it is currently anticipated to be the highest revenue generating product by PALLAS. However, the flexibility and design for adaptability of the PALLAS-reactor needs to provide provisions for a future change in market demand.

3.5 Flexibility of PALLAS-reactor

Flexibility refers to the multi-functional use of the PALLAS-reactor where the capacity can be adjusted within a defined operating envelop according to the market need. PALLAS acknowledges changing future markets and therefore to attract investors and customers the design needs to be flexible to address current and future growth requirements. Figure 4 presents the operating envelope of the PALLAS-reactor as well as the reservation for future adaptations.

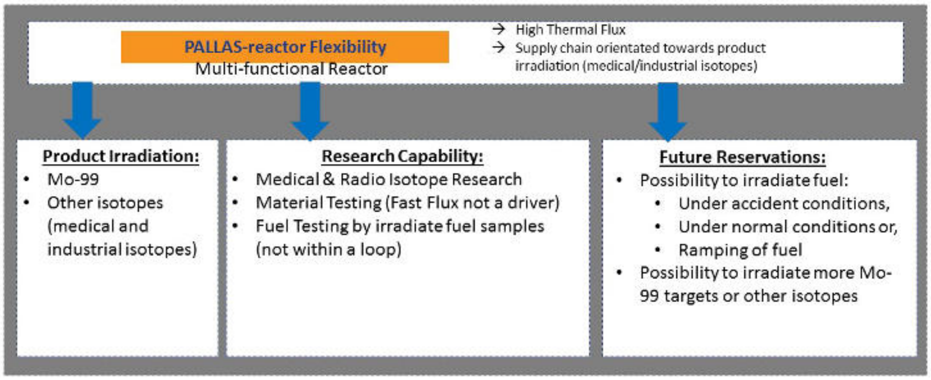

Figure 4 PALLAS-reactor flexibility within a defined operating envelope

3.6 Non-complex Design

A non-complex design for the Nuclear Island is preferred which entails the following:

- Using minimum number of structures, systems and components (e.g. pumps, valves, instruments, electrical components etc.) to comply with functional and safety requirements as per the Technical Requirements;
- Having a simplified plant layout, pipe routing and equipment arrangement to facilitate construction and maintenance;
- Simplifying the system design and control logic;
- Simplifying manoeuvring, handling, loading and unloading of irradiation facilities.

3.7 Design for Adaptability

Design for adaptability is taken into account for the PALLAS-reactor so that it will provide an increased value over its life time. Within the operating envelope and future reservation ability the evolution of stakeholder needs and the resulting desire to adapt system properties to those needs is key to high lifecycle value of enduring systems.

The underlying reason for implementation of design for adaptability within PALLAS-reactor, as per [2] , is uncertain forecast information of market changes (production and research requirements). For this reason PALLAS requires the ability to adapt to new requirements when circumstances change. Examples of adaptability in these changing circumstances are for instance scaling up the cooling capacity or reuse of irradiation positions to irradiate new products. Having this in place will prolong the life of the PALLAS-reactor.

4 Value Engineering

Value engineering is described as an explicit set of disciplined procedures designed to seek out optimum value for investment and the purpose of implementation thereof is to get the largest functionality at the lowest total costs over the life of the PALLAS project.

$$Value = \frac{Function}{Cost}$$

Within PALLAS the main objectives for implementation of Value Engineering includes the early identification of Capital Expenditure and Operational Expenditure as well as optimization of the technical requirements and design during the early stages of the design as presented in Figure 5. The reasons for wanting to implement this in an early stage are:

- Value change propositions have a higher impact on cost savings early on in the process,
- Once the formal licensing process has been initiated value change propositions may negatively impact licensing.

Three phases of Value engineering activities are planned for the PALLAS-reactor. These phases are to be implemented within the conceptual design.

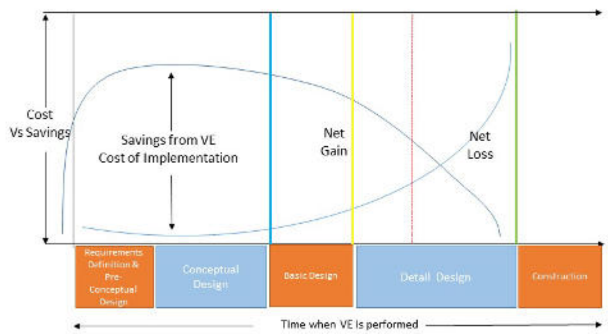

Figure 5: VE Application

Phase 1 (Scope Definition):

PALLAS followed an extensive process to determine the current scope/ main functions of the PALLAS-reactor. The process involved:

- Development of a functional breakdown structure for the PALLAS reactor including a large scope of production and research activities,
- Interaction with various external stakeholders,
- Performance of an affordability study with emphasis on the cost impact of research activities including the impact of fast flux conditions and complex fuel testing loops,
- Investigation of possibility of business opportunities,
- Value Engineering workshops as part of the Value Engineering process where Business Case and Engineering interacted to determine the scope of the PALLAS-reactor.

As part of this process, Figure 6 presents a simplified functional breakdown structure, the re-prioritisation of the functions defined as H-High, M-Medium, L-Low and change of functions to support the process of defining a scope supported by value engineering methods. Also, from a technical point of view the following considerations were respected during these workshops:

- Flexibility of the PALLAS reactor.
- Design for Adaptability.

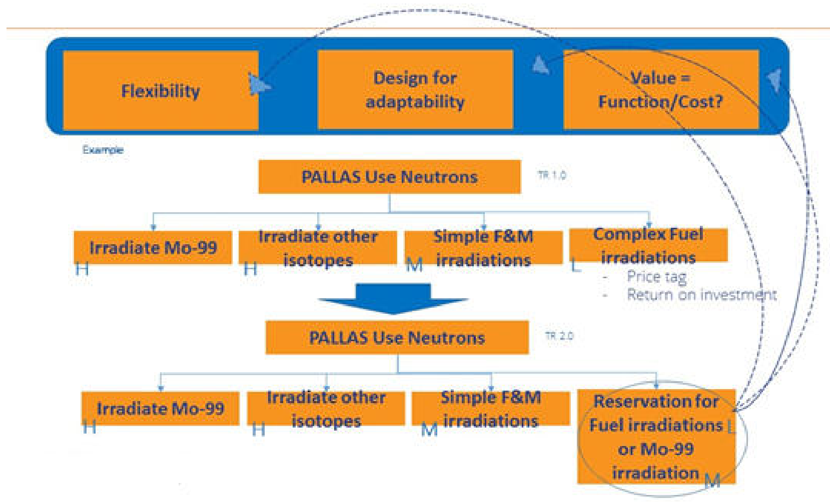

Figure 6: Value Engineering During Requirements Definition

As output an affordable scope wide enough for a board set of investors was defined for the PALLAS reactor. This scope is subject to change depending on investor and customer needs.

Phase 2(Preparation Phase):

Preparation for implementation of Value Engineering that includes the determination of value of specific functions for PALLAS.

Phase 3 (Implementation Phase):

The implementation phase includes:

- Agreement of roles and responsibilities between Contractors and PALLAS on Value Engineering
- Set up Value Engineering teams and way of work (plan workshops and method of processing of Value Engineering driven change proposals)
- Prepare a Value Engineering plan (prioiritise Value Propositions)
- Obtain up to date market information and revise input from Business Case accordingly
- Implement Value Engineering to optimise design (during concept design)

5 Design-to-Cost

As part of the integrated view of determining an optimal set of design drivers for investment and value engineering focusing on determining the value to the investor/customer, PALLAS also needs to consider cost as a design parameter within the development of the PALLAS-reactor by using design-to-cost best practices. Design-to-cost forms part of cost management techniques to be implemented in order to control project cost during design and construction of the PALLAS-reactor.

6 References

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