Engineering Design Principles for Commercial Spent Fuel and Waste Treatment

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ABSTRACT

BNFL has extensive experience of process design, build, commissioning, operation and decommissioning of commercial nuclear processing plant. Nexia Solutions (formally BNFL’s R&D division) has always defined and undertaken the extensive development programmes necessary to underpin the design at all stages of the project lifecycle.

Nexia Solutions has built up a large portfolio of plant designs for a range of spent fuel applications, from fuel conditioning to partitioning and transmutation. In addition, by investigation of a large and diverse portfolio of technologies Nexia Solutions has developed innovative concepts for plant design that could present significant economic savings on conventional approaches.

Using this experience and the lessons learned, Nexia Solutions has developed and refined its own engineering design principles necessary for the successful design of commercial spent fuel and waste treatment plant. Nexia Solutions advocates an integral approach, with both science and engineering designs working in parallel during development. Case studies will be presented to demonstrate how this approach has been adopted and the benefits that have been gained.

The paper will outline the principles employed and demonstrate their potential effectiveness for any major nuclear process plant new build initiatives, both in the UK and internationally.

INTRODUCTION

For over 30 years BNFL has managed and operated the Sellafield Nuclear Licensed Site in the UK. During this time it has overseen the design and construction of the THORP Reprocessing Plant, Sellafield MOX Plant (SMP) and High Level Waste Vitrification Plants alongside an extensive suite of supporting effluent and waste treatment facilities. BNFL, through its subsidiary British Nuclear Group Sellafield Ltd (BNGSL), continue to operate the reprocessing facilities and infrastructure at Sellafield today, as well as overseeing the ongoing remediation of the legacy plants on the site.

Nexia Solutions (BNFL’s Research and Development Subsidiary) has played a key role in underpinning the design and operation of these Sellafield facilities through the application of the integrated design principles, which are outlined in this paper. History has shown that the early and close involvement of the R&D community has been key to the successful delivery of BNFL’s major capital projects.

The recent announcement of the formation of a UK National Nuclear Laboratory with Nexia Solutions as its foundation will allow Nexia Solutions to continue its intimate involvement with capital projects through its mission of the practical application of technology alongside scientific excellence.

The effectiveness of Nexia Solutions’ integrated design principles approach is illustrated in the paper through a series of case studies and worked examples.

DESIGN PRINCIPLES

Engineering is the application of science and technology to deliver benefits; either taking advantage of an opportunity, or to address a problem. The generic challenge facing engineers is expressed in the views of Chaddock (Reference 1), who defines design as, 'the conversion of an ill-defined requirement into a satisfied customer'. It is proposed that four of the foundations for engineering success are;

- Understanding the strategic objective
- Adopting a risk driven programme
- Integration of engineering and science at the R&D stage
- The application of appropriate design philosophies and methods in a timely manner

Understand the Strategic Objective

The first stage in any design process is to develop an understanding of the requirements of the design, in terms of what the plant is to achieve. The aim during design is to develop the most 'successful' engineering solution to the challenge posed. Further to the basic requirements, it is also necessary to develop an understanding of the various constraints that will limit the design (e.g. criticality requirements would be a classic constraint)

However, in order to achieve the optimum design, it is necessary also to gain an appreciation of the other factors / drivers that will determine what is the optimum design. These factors are numerous and often contradictory. The relative importance of these factors to the customer will determine which solution is the best. Examples of these types of drivers may be

- Minimising environmental impact
- Minimise lifetime costs
- Minimise capital / operating costs
- Reducing time to deployment
- Non-proliferation

These factors themselves are complex, but it is necessary to understand the relative importance of these factors if the most appropriate solution to the engineering challenge is to be found. The role of engineering is in the integration of disciplines and experience to identify the optimum solution.

To achieve this effectively, it is necessary to have a very clear definition of the strategic objective. With this defined, constraints and drivers understood, a technical programme can then be developed to engineer a solution.

Risk Driven Programme

Starting only with the definition of the problem, there are clearly large uncertainties and risks associated with ultimately achieving the solution. The purpose of the research and development and design phases of the project are to ultimately define the best solution to the problem. This is an ongoing process of reducing the risk and uncertainty.

The most efficient way of achieving the project objectives is for the understanding of the risks and the associated impact to define and drive the programme. This leads to the adoption of a staged approach to the overall design process, with progress between phases being dependant upon the appropriate reduction of uncertainty and reduction of risk.

There are significant risks associated with the development of any capital scheme. The risks (and benefits) associated with developing a project based on deploying new technology are different from those associated with building a larger scale version of an existing design.

Risks to any capital scheme are not constrained to science, one would not expect the scientists to acknowledge or fully appreciate the engineering issues with regards to the design or implementation of the science.

The identification of the risks and the mitigation of these risks play a fundamental role in the development of such a scheme.

Engage in Engineering Activities Early

At the start of any technical project there are uncertainties, both in terms of science and engineering deployment. Nexia Solutions believe that adopting an integrated approach to science and engineering in the developmental stages of a project, focused and prioritized on the basis of risk, delivers the greatest benefits in terms of reducing risk and / or maximizing the chance of success.

Engineering in this context is defined as equipment design and its implementation, the level of detail is commensurate with the level of risk carried. In the same way that science adheres to fundamental scientific principles, the engineering must be grounded on well established nuclear engineering principles.

The historical, and still to this day popular, approach has been for research and development to be dominated by science with engineering following sequentially and subsequently to address the implementation of the science. However, it is proposed that engineering activities be integrated with the science as part of the research and development programme. The reasons for this approach are that:

- Both scientific and engineering uncertainties are risks to the delivery of the project objectives, and are often dominated by engineering issues rather than fundamental scientific issues
- Uncertainties in engineering equipment, integration or deployment may need to drive the scientific work into a different area to solve a deployment issue
- An understanding of the engineering difficulties can help to gain the maximum benefit when defining experimental work, in terms of targeting the most significant risks first, and maximizing the benefit from development expenditure

For example, addressing key design / equipment issues before a process flowsheet is fixed is easier and cheaper than during detailed design, fabrication, build or operation. Incorporating engineering into the development programme from the outset increases the potential to prevent abortive scientific work, and maintain alignment with the strategic objective.

Engineering also introduces other disciplines to the development programme, e.g. material scientists, safety assessors, criticality assessors etc.

Timely Application of Appropriate Engineering Methodologies

There are a wide range of engineering methodologies and techniques that can and have been applied to optimize / enhance the design process; some examples of techniques are listed below. The key to maximizing the benefit from these techniques is to use the most appropriate methods based on the design requirements and apply them at the right time.

- Early equipment design identifies flowsheet and design risks early.
- Design for maintenance and with equipment failure in mind
- Use of engineering based modelling or flowsheet modelling to develop, optimize and validate the design
- Consider the whole lifecycle from day one, the strategic objective should include decommissioning.
- Novel versus conventional
- Learning from operational / decommissioning experience
- Desktop technology demonstration

Experience has shown the value of adopting these approaches in the development and design of a process.

Early equipment design identifies flowsheet and design risks early

Block diagram "Black Box" assumptions introduce risk to the programme, even if the technology has been demonstrated before albeit in a different context, e.g. different scale, non nuclear etc. Major items, in terms of risk, should have their design and implementation addressed through engineering studies in order to quantify and reduce this risk.

Development of the equipment design at the early stage not only minimizes the risk from the perspective of whether it can be engineered and implemented, but it also maintains the opportunity to inform the science programme. It is also possible that whilst the equipment may prove to be deployable, it may impact on the flowsheet in terms of performance, i.e. not perform as the flowsheet intended. Early design provides the opportunity to address these issues whilst flowsheets are still in their evolutionary stage and it is therefore possible to make modifications at relatively low cost and risk to the programme, and in accordance with its strategic aims.

Failure to do so could at worst, result in the programme failing to meet its objective totally, i.e. programme is abandoned, or it could potentially result in a less optimal solution being delivered.

As highlighted earlier, the introduction of engineering also introduces other disciplines to the development programme including safety and environmental professionals. Therefore the engineering will ultimately give confidence that a safety case could be made for that particular process, i.e. demonstrate that the safety and environmental risks are managed effectively.

Design for maintenance and with equipment failure in mind

Equipment or technology selection must be cognizant of the plant item's longevity, particularly in view of the fact that a radioactive environment is both hostile and hazardous.

Are durable materials of construction available for the proposed operating environment and can they be machined for the application in question etc? Will the material retain its integrity for the life of the plant, or will it require replacing? If replacement is considered necessary, how often and more importantly, how? These are not questions of detail, but their answers may well impact on the choice of technology to be deployed, or even result in further engineering development work.

The engineering should consider the cost of its deployment, not only the installation but also the maintenance costs and environmental costs.

It is not unknown for equipment selection issues to halt a development programme, because the underlying issues are insurmountable, or simply too costly to overcome.

Use of engineering based modelling or flowsheet modelling to develop, optimize and validate the design

Engineering based modelling and analysis capabilities present the potential to complement the engineering study work and support the underpinning of the science. These capabilities should be utilised where possible, and as early as possible in the development programme.

Operational Research (OR) type studies can be used to validate the engineering expectations with regards to the process performance. An OR study could be undertaken around a single plant item to ascertain its performance, which could then be developed as the process design evolves to validate the proposed design against that intended by the strategic aim for the project. For example, is the proposed availability for the plant item realistic, and if not, what specific areas should be addressed?

Process modelling can be applied to represent dynamic chemical processes on plant and also to model the whole plant flowsheet, either dynamically or at steady state. The models can be used to effectively design experiments to ensure full value for money. Chemical modelling can be developed to predict the fundamental chemistry behaviours within processes and this can be linked into the lumped parameter models. The models can evolve with the design and be used to predict plant behaviour and validate options.

Computational Fluid Dynamics can predict the more complex flows of fluids, such as optimizing the use of passive or natural ventilation for a building, instead of relying on an installed ventilation system. Impact, seismic and structural analysis uses modelling techniques to underpin the safe design and operation of plant and transport of nuclear material.

Consider the whole lifecycle from day one, the strategic objective should include decommissioning

Increasingly, regulatory approval for nuclear plant demands the demonstration that the design caters for the plant's decommissioning, i.e. that environmental impact is reduced and minimized in terms of workforce dose, effluents and solid waste arisings. Many of the decommissioning problems facing the industry today could have been avoided or mitigated if more consideration had been given to the decommissioning phase during the process development and design. To do this effectively, the decommissioning requirements must be introduced to the design early on, and this could and should impact on the development programme.

The impact this may have on the development and design need not be significant. There is the opportunity to reduce the overall cost if the decommissioning aspects can be incorporated into the plant design, rather than being backfitted at end of plant operations.

Novel versus Conventional Design

A new problem may necessitate the adoption of a novel approach in order to solve it, or to develop a more cost effective solution to an existing problem. The introduction of novel design itself adds to the programme risk. Accordingly the reason for pursuing a novel approach must be clearly understood, supported by analysis of the perceived benefits against the cost of development and deployment.

In order to implement a novel solution effectively, it must be identified and considered during the process development and itself be subject to engineering development.

Learning from operational / decommissioning experience

Process design and development should take full advantage, not only of previous reported development programmes, but also of plant operational and decommissioning experience available, especially when the strategic aims are similar to previous plant designs.

Desktop technology demonstration

Technology demonstration does not have to imply demonstration on an experimental scale. Application of the above methodologies provides the potential to demonstrate technologies on the desktop, or to be more explicit, gives the opportunity to demonstrate whether certain technologies are not practical and so should not be pursued to development rig work.

The integration of engineering within the research programme can minimize the chance of the wrong development rig being designed and built. Whilst the demonstration of technology failure at rig scale can be a valid result, it is also a costly one.

CASE STUDY ONE

Selection of a pyrochemical process for recycle of fast reactor fuels to underpin BNFL’s development programme

In 2001, BNFL started a major review of its pyrochemical development programme. The development had reached a stage where the science and fundamentals of the process were understood and there was now a need to consider industrialisation and scale up of the process from the laboratory.

At the time, BNFL recognised that there were two competing pyrochemical processes that could be used for spent fuel treatment; a Russian process based on electrowinning of oxides developed at RIAR in Dimtrovgrad, and an American process based on electrorefining of metals developed at the Argonne National Laboratory.

In both cases the science of the process was well understood and viable flowsheets had been developed. The technology had been demonstrated at large scale in active pilot facilities, although no commercial facilities had been built, so there was information available on which to base early engineering studies.

An initial technical review, carried out internally in BNFL, had shown that both processes could provide a solution to recycle of metal and oxide fast reactor fuel. The earlier stage of BNFL’s development programme had also targeted key aspects of the process to replicate the science and therefore underpin these internal reviews.

Before constructing a development programme for industrialisation, BNFL carried out 2 engineering studies on facilities for the recycle of fast reactor fuels based on the technology demonstrated at the 2 overseas facilities. The result of these studies, combined with the technical reviews, was that the Russian technology presented a less complex and more economical option for oxide fuel recycle.

However, the initial engineering studies had shown that the efficiency of the main separation stage and wasteform development, in each of the processes, was a main contributor to the cost, but not the most important step in the process with respect to viable commercial plant construction.

In the case of the Russian process, materials of construction for the electrowinning vessel and their subsequent impact on operability and secondary waste streams, was the main issue. As a result, the BNFL programme then directed R&D into materials selection to look for alternatives, rather than conduct further work on separations and wastes.

In the case of the US process, the oxide reduction stage prior to main separation stage dominated costs due to the required fuel preparation. Therefore, the BNFL programme directed R&D into alternatives for existing reduction technology.

The results of this new direction for the programme were that no viable materials could be found for the Russian technology and a reworked engineering study, taking into account existing materials, proved that the technology was not as attractive as previously considered. For the US process, viable alternatives were available for the existing reduction technology and the programme was adjusted to include work on these and discontinue further investigation of the existing technology.

In terms of the effect on the overall development programme, BNFL directed all future plans for scale up to be based on the US process.

Case Study One Conclusion

If no engineering study had been conducted at this early stage, separation and wasteform development would still have been seen as the most important stages in the process, as these are the ones which dominate thinking from the perspective of flowsheet and science.

BNFL would still have pursued development of the science and flowsheet of the Russian process, based on the assumption that the demonstrated technology was fit for purpose as a commercial plant design.

The US technology would have still been included in the programme, as there was not a clear cut case to discriminate between the two, but the programme would have had to include work on fuel preparation techniques matched to the existing technology for oxide reduction.

CASE STUDY TWO

Development of a test rig to demonstrate the pumping of Molten Salts.

Nexia Solutions has undertaken a technical programme of work for many years in support of pyrochemical techniques for spent nuclear fuel and legacy fuel management. Throughout the programme, the emphasis has been on pragmatic industrialization. One of the key approaches to the programme has been the establishment of a single integrated project team comprising both scientists and engineers, which itself assures ongoing dialogue and a better mutual understanding of the technical issues.

The issue of industrialization was addressed at an early stage in the development programme. It was recognized that pyrochemical processing on an industrial scale represents a number of new challenges when compared to commercial nuclear spent fuel processes, especially with the usual nuclear engineering constraints such as accessibility for maintenance. Given that the ultimate aim for pyrochemical processing would be a commercial scale facility, then the issue of availability, plant throughput and building size need to be addressed and optimized.

One particular issue that was identified for further examination was the transfer (or pumping) of molten salt from one process step to another (Reference 2). Pumping in conventional nuclear processes itself represents challenges to the industry and has led to the development and refinement of fluidic technologies. In the case of molten salts, the problem is further complicated by the melting point of the salt being in the region of 400ºC and the requirement to maintain that temperature to prevent "freezing" meaning an operating temperature in the region of 450 to 500ºC.

Operational Research (OR) and reliability studies were undertaken and they confirmed that batch transfers of molten salt by mechanical transfer to be not only too slow for commercial means, but less reliable than conventional continuous transfers. However, continuous transfer of molten salt at 500ºC was not proven and therefore represented a significant technical risk to the programme. The avoidance of mechanical transfers is considered key to the industrialization of nuclear processes, hence the risk mitigation step of developing and demonstration of continuous transfers was taken.

The Molten Salts Dynamics Rig (MSDR) was designed and built to examine the transfer of molten salts inactively and at large scale. The transfers took place at approximately 500ºC at up to $4m^3/h$. The rig consisted of an argon inerted closed loop, fitted with a number of pumps, sensors and other peripheral equipment. A number of experiments were undertaken to investigate continuous transfers using a centrifugal pump, an argon lift, a Reverse Flow Diverter (RFD) and gravity.

The development programme on the rig successfully demonstrated the 4 transfer techniques as viable methods for the continuous transfer of molten salt on an industrial scale, as well as providing transfer characterization curves for the RFD, the centrifugal pump and the argon lift. It also demonstrated the successful operation of a freeze valve and further demonstrated the design principle that it would be sufficient to only inert the process equipment, and not the cell environment.

Case Study Two Conclusion

The integration of engineering and science in the developmental project team ensured the early deployment of engineering activities and directed early development to mitigate significant engineering and industrialization risk. The programme demonstrated that continuous transfers of molten salts would be possible on an industrial scale, using conventional transfer technologies. This effectively reduced a number of risks on the programme at a very early stage, and gives confidence to flowsheet design, plant design and layout in terms of throughput.

CONCLUSION

Nexia Solutions has extensive experience of underpinning the design and operation of spent fuel and waste treatment facilities. From this experience and a significant involvement in a broad range of research and technology development programmes, Nexia Solutions has developed a series of engineering design principles. Application of these principles has been shown to reduce the cost, ultimately reduce the time to implementation and reduce risk. Four foundation principles for success have been identified.

- **Understand the strategic objective -** It is absolutely necessary to have a very clear definition of the strategic objective and an appreciation of the factors that will determine the optimum solution to this strategic objective.
- **Adopt a risk driven programme –** The research and development and design phases are an ongoing process of reducing risk and uncertainty.
- **Engage in engineering activities early** - **Adopting** an integrated approach to science and engineering in the development, focused and prioritized on risk, delivers the greatest benefits. Dealing with key engineering risks early is cheaper than later in the process.
- **Timely application of appropriate engineering methodologies** – There are a wide range of methodologies that can be used to optimize the design and reduce the associated risks.

Engineering methodologies, such as designing for lifecycle, using engineering modeling, process intensification and integration all have a role to play in optimizing design and reducing risk. The greatest benefits can be derived from applying the appropriate technique at the most appropriate time during the research, development and design phases of a project.

The case studies given have shown the benefits to this approach to BNFL’s pyrochemical development programme. In this case, the early engagement of engineering within the development phase changed the potential course of the project.

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