NUCLEAR REACTOR CONCEPTUAL DESIGN: METHODOLOGY FOR COST-EFFECTIVE INTERNALISATION OF NUCLEAR SAFETY[1]

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Abstract

A novel and promising methodology to perform nuclear reactor design is presented in this work. It achieves to balance efficiently safety and economics at the conceptual engineering stage. The key to this integral approach is to take into account safety aspects in a design optimisation process where the design variables are balanced in order to obtain a better *figure of merit* related with reactor economic performance. Design parameter effects on characteristic or critical safety variables, chosen from reactor behaviour during accidents and from its probabilistic safety assessment -*safety performance indicators*-, are synthesised on *Safety Design Maps*. These maps allow one to compare these indicators with limit values, which are determined by design criteria or regulations, and to transfer these restrictions to the design parameters. In this way, reactor dynamic response and other safety aspects are integrated in a global optimisation process, by means of additional rules to the neutronic, thermal-hydraulic and mechanical calculations.

This methodology turns out to be promising to balance and optimise reactor and safety system design in an early engineering stage, in order to internalise cost-efficiently safety issues. It also allows one to evaluate the incremental costs of implementing higher safety levels. Furthermore, through this methodology, a simplified design can be obtained, compared to the resultant complexity when these concepts are introduced in a later engineering stage.

1 INTRODUCTION

The electricity demand in the world is expected to grow significantly in the near future. The competition among its supply sources is becoming fiercer and fiercer. In order to be part of this new power supply demand –not to mention the replacement of the existing reactors reaching their lifetime,– the design of future nuclear power plants must guarantee their good performance considering such issues as economy, safety, and construction, operation and maintenance simplicity. They should be competitive when comparing these aspects with those of the present nuclear and non-nuclear power plants. It is becoming evident that classical methodologies to perform nuclear reactor design must be reviewed and new ones developed aiming at achieving this competitiveness. It is important to carry out this process with a global approach, contemplating design feedback effects between all the systems and involved areas.

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When original reactor designs were developed, the risk concept was not clearly stated yet. Conventional design rules were applied instead. The reactor designs using that policy, were evaluated to function with the nominal values of their main variables. The design of all the necessary systems for reactor operation was done taking into account the main interrelations of the technical parameters, and postponing the economic issue.
Moreover, nuclear power plant safety criteria have always aimed at limiting society risks. This was initially translated into deterministic design criteria and such concepts as design basis accidents and defence in depth [1]. "Safety margins" for the design parameters were applied to consider safety aspects. After having studied and understood risk issues more thoroughly, new rules appeared for evaluate the reactor safety response. Designers started paying more attention to accidents. However, for the sake of not loosing previous experience, the classical design methodology was still applied, adding new rules to already existing designs, so that current regulations are met. According to this policy, the conceptual design should be made under steady state analysis, as conventional rules say, and transient behaviour should be studied afterwards, verifying those "safety margins" fulfil the safety criteria.

More recently, in some advanced reactor designs, the parameters have been optimised to minimise the plant costs, when it works in its nominal point, without taking into account its behaviour when accidents occur yet. Moreover, in many cases safety aspects were evaluated once all the main systems and engineered safety feature designs were defined, being then added as a "patch"; and higher safety levels usually implied an increase in plant costs. Problems have also appeared concerning conflicts between new requirements, classical design concepts and operational demands –in view of the economic reality–, which were previously often ignored. This, along with the fact that the design requirements for advanced reactors include enhanced protection against severe accidents, causes a loss of competitiveness.

Once the technology for increasing generating capacity has been chosen the main tasks include minimizing the risk, minimizing the cost, and maximizing the benefit. These usually carry tradeoffs or compromises, which must be treated wisely. Neither absolute safety –which is actually impossible– nor the most economical technology are sound decisions.

Usually lowering risks has a cost, ultimately paid by society. The lower the risk levels the higher the cost to control them. In other words, the safer the designs, the smaller the returns on people's efforts to make the place they live safer. Conversely, the social costs due to the loss in life expectancy rise for higher risk levels [2]. Therefore, since the resources are limited, costs and benefits (risk reduction in this case) have to be balanced or equalised. The idea is to minimise the total cost, assuming it is quantified appropriately. There are differing approaches to the balance between the desire to develop technologies with the potential for great benefit and the need to make plants safe, and each society may assign different values to life. Consequently, the correct application of this analysis must be carefully studied [3].

In conclusion, although reactors designed with the classical methodology are safe enough, in general no balance is achieved between safety and economics. All of this suggests that a new integral approach should be sought.

2 REACTORS DESIGN

Reactor design is an intrinsically complex task, due to the quantity of parameters whose dimensions have to be determined and the existing relations between them. For the sake of simplicity the problem is faced from different aspects. At the engineering conceptual stage, the quantification of mechanical, thermal-hydraulic and neutronic parameter influence on reactor costs is of interest.

With the purpose of finding a unit cost for the generated energy, a breakdown of the main items that affect cost is performed. The first approach, at the conceptual design stage, is rather rough and includes capital, operating and maintenance, and fuel cycle costs.

Due to the complex calculations and analyses inherent to the design process and along with the increasing computer calculation capacity, computational tools arise as support for the design team. These programs, such as the IREP code [4-5] explained in what follows, make the necessary internal iterations to obtain a coherent set of design and operational parameters that define a reactor, considering the main feedback existing between these parameters. In some cases, the applications also allow to optimise economically the most important parameters of the core, primary and secondary systems, in order to reduce the cost of electricity generation.

This optimisation should be performed from the conceptual stage of design, because of the engineering costs. Further important advantages of this include visualising tendencies (through sensitivity analysis) and design feedback, granting the design team more arguments to support engineering decisions.

2.1 IREP Code

The design of integral-type reactors is of particular interest because of their intrinsic characteristics that make them economical and safe, as shown by the present tendency of several designers of reactors of small and medium power, with the objective to satisfy the demands of the market [6], [7], [8]. An example of a program that performs the aforementioned tasks, for the design of integral type reactors, the IREP code –Integrated Reactor Evaluation Program, was developed in the Argentinean National Atomic Energy Commission (CNEA), under the CAREM program, and sponsored by the IAEA.

It performs the neutronic, thermal hydraulic, mechanical and economical evaluation of the reactor, and gives the levelled electricity generation costs as a main result, providing all the technical outcomes of the different areas as well. This code allows carrying out an automatic optimisation of the most influential parameters in the generation cost of the electricity generated by the designed reactor, as shown in Figure 1.

A basic explanation of the process is given in this paragraph. Before performing the optimisation, a series of main engineering decisions such as the reactor power are given to the steady-state calculation routines. At the beginning, a set of the main design parameters that correspond to an initial design are introduced to these routines, which have the mechanical, thermal-hydraulic, neutronic and economic models to calculate the plant. The results, which include the figure of merit, namely the generation cost, enter the optimiser routine. A few design restrictions such as the minimal CPR for the steady state verify that none of these restrictions is violated while this routine looks for a more economical design.

The new set of design parameters replaces the previous one and the process continues iteratively.

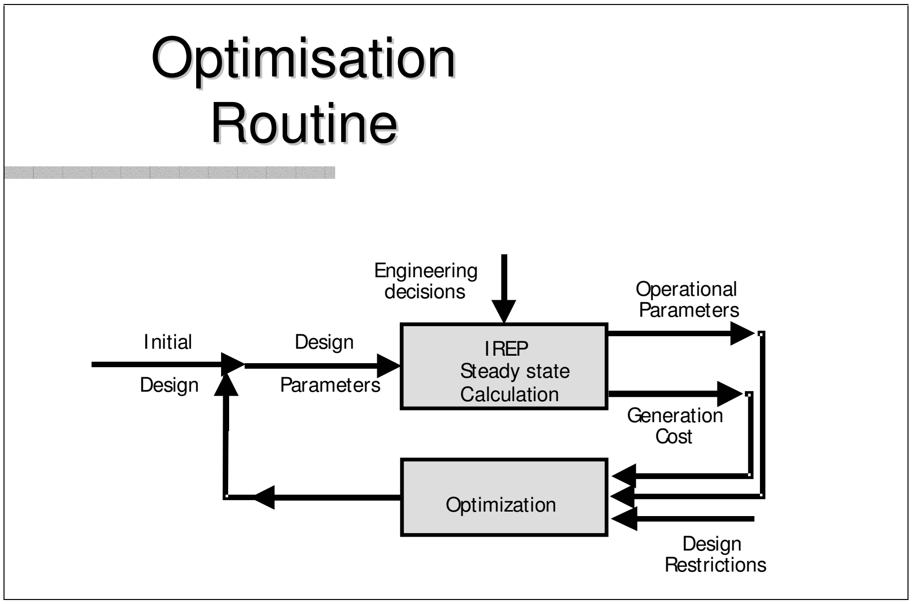

Figure 1: IREP: optimisation process

2.2 Safety Targets

Though safety principles do never guarantee that nuclear power plants will be absolutely free of risk, when adequately applied, the plants should be effective in meeting society needs for useful energy. The most general nuclear safety objective is "to protect individuals, society and the environment by establishing and maintaining in nuclear power plants an effective defence against radiological hazard." [9, 10]. In accordance with the safety objectives, some fundamental principles are applied, such as employing the safety culture in every stage of the design and plant cycle, or making use of the strategy of defence in depth [11]. The regulatory bodies, which check and verify that the designs are safe enough, set quantitative safety targets with this goal. The design teams usually have their own design restrictions, including those for guaranteeing that the reactors will be safe and others related to economics and to the feasibility of being built. Both the design teams and the regulatory bodies apply the safety principles —and they must do so. However, there are often some unnecessary restrictions imposed, that prevent the improvement of the designs and their performance, without enhancing the safety response. A flow chart showing these and other contributions to the design restrictions is shown in Figure 2.

Formulating risk policy is a political issue, whereas implementing it is a technical one. Official bodies should (and must) set the rules to control and verify that things have been well done, by comparing the reactor safety response with the established safety targets. These targets should be as global as possible and with as few specific details as possible, so new designs avoid find unnecessary obstacles to be licensed. This will have two main effects: faster licensing processes and flexibility for enhanced designs. Both of them will assist the nuclear industry to satisfy society's main demands: safety and cost-effectiveness.

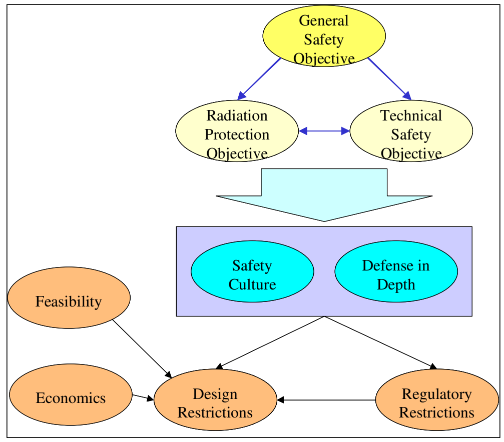

Figure 2: Paths that contribute to the design restrictions.

2.3 Safety Costs: "Approaching a new approach"

In case of severe accidents, society would be harmed by exposure to the ionising radiation, and this damage has an associated cost. Since the injured is a third party, for those whose activities engender this harm, this is an external cost. From society's viewpoint, these costs should be minimised by the industry, which, by preventing damage, is said to absorb or internalise the external costs. These constitute the safety-related costs. Questions arise concerning whether, in present designs, this internalisation is efficient or not. Namely, suggesting the money spent for preventing the harm might be –in many cases– more than the cost of the damage being prevented. The idea is to keep protecting people from unwanted consequences, but using the most efficient manner. There are many ways to protect society from ionising radiation. The problem at hand is to accomplish it efficiently. Besides, not only do safety features protect society –a third party– from exposure to ionising radiation, but they are useful for conserving the owners' assets (investment costs) as well. Thus, it is not always easy to discern where the dividing line is, though this should not be important since it is the risk of both effects that want to be minimised.

Although the classical methodology or more advanced ones such as the one used in IREP code fulfil the requirements of design relative to safety, the lack of balance between economy and safety is evident. It is necessary that in the conceptual design stage, economy and safety should be evaluated together to balance properly these two fundamental aspects of design. It is important to perform this process with a global approach, contemplating the design feedback between all the systems and involved areas. Safety aspects are part of the most important contributors to costs, so they must be considered in an efficient way.

As other authors have already noticed, the new approach must consider new methods for cost-benefit and ALARA analyses, employing modern PSA techniques and fulfilling basic safety requirements instead of overly detailed prescriptions, with realistic models and assumptions. Other approaches [12] comprise the formulation of policies in a few key areas, which then translate into thousands of detailed design requirements. However, the reference claims fundamental cornerstones of this kind of approach enhance safety through simplification. Therefore, a new integral design approach must be developed to fulfil the market conditions that require that the produced electric power is economical and safe.

3 PROPOSAL

As already mentioned, integral optimisation of the design parameters should be carried out from the conceptual stage of design, in order to keep the reactor safe and competitive. To accomplish this, the proposal for the conceptual global design process can be resumed in the following stages:

1) **Preliminary conceptual design and qualitative optimisation based on designers' judgement**. Stage based on designers' expertise and research results, recognising alternatives that aim to simplify the design and to reduce initiating events and diminish their incidence, among other design goals for taking the soundest decisions. Different alternatives for safety and process systems are proposed at this stage, for being evaluated in the next one. Thus, the design basis is now obtained.

2) **Integrated conceptual design and quantitative optimisation**. This second stage consists of an integral design optimisation process in order to improve a figure of merit. To perform this, neutronic, thermal-hydraulic, mechanical, safety and economical dimensioning modules are required. Safety ones are used to simulate the plant performance in steady state and in transients or accidents and to characterise it by means of safety performance indicators**.** This evaluation is performed for each set of parameters that defines a possible reactor design that may be found during the optimisation process. Safety goals determined by regulators and designers are embodied in practical quantitative safety targets. They are applied as limits to the selected safety performance indicators and therefore considered as restrictions on the design parameters. Then the economic figure of merit is calculated given the main design parameter values. Finally, the optimisation gives a new set of parameters improving the value of the figure of merit. This stage is repeated until the design converges.

3) **Final conceptual design stage based on experts' judgement**. Evaluating the alternatives results, the best design options are chosen. Eventually, feedback to previous steps will be necessary.

4 OPTIMISATION METHODOLOGY: GENERAL CONCEPTS

The most innovative concepts of the present work are introduced in the second stage. This will be developed in this and the next sections.

In order to face the posed design optimisation problem, an objective is selected, a feature that is being analysed and should be reached with the design. It is a result of the design parameters, which witnesses how good or bad a design is, in relation to the proposed goal. It is called **figure of merit**, and will be noted as $M(\vec{x})$ where $\vec{x}$ is the set of design parameters. Aiming at designing competitive nuclear power plants, adopted strategies may include the reduction of capital costs or other economic figures of merit. Several results of the design process can be selected as figure of merit for economical optimisation. They are typically electricity generation cost, cost of investment by power unit ($/kw), total investment cost (releasing power as a parameter to optimise) and net present value of the project (assuming a known price of sale of the energy unit).

To verify reactor safety criteria fulfilment, the concept of **safety performance indicators** is introduced, also known as response functionals or observable variables. Each one of these variables is chosen in order to characterise and represent reactor safety levels or reactor degree of exigency during an accidental sequence. An example of a safety indicator is the time that the water level inside the RPV in an integral-type PWR takes to reach the core top during a loss of coolant accident (LOCA). The Minimal Critical Power Ratio reached during a reactivity insertion accident is another one. Probabilistic safety indicators, such as the core damage probability, can also be considered. Operational performance indicators are studied in reference [13].
There are also **restrictions**, which are limits that a particular design must fulfil and are applied to the design parameters as well as to the safety indicators. It is evident that the value of each safety indicator will be function of the design parameters. During the optimisation process developed, while looking for an appropriate set of design parameters that optimises a given figure of merit related with cost, safety indicators are compared with imposed limits. In case any of these limits were violated, the direction of the design parameters movement is changed in order to keep the reactor safe enough. Therefore, the safety indicators will be used to evaluate the safety degree and to determine the direction the design parameters must move towards, within the general scheme of optimisation, as explained below.

Besides verifying safety criteria, the safety indicators can be also taken as a figure of merit to be improved instead of a cost related one. Cost-related or other design restrictions can either be considered or not, depending on the designers' choice. For instance, this could be used to find a feasible design (does not violate any restriction) when some safety restrictions are being violated, for a posterior economic optimisation inside the feasible design region. Other uses would be to search the safest design alternative for a given generation cost or the "safest limited-budget design". The safety criteria fulfilment could be verified after these ALARA-optimisations take place.

5 DESIGN MAPS

Considering then that the parameters dimensioning influences both the figure of merit and the safety indicators limited by restrictions, the concept of Design Map is reached. A Design Map is mainly a way to visualise this dependence and a useful tool to verify the fulfilment of the restrictions throughout the optimisation. One of Design Maps main advantages is that they allow moving design parameters in their vector space improving the function of merit, without violating the adopted design criteria by means of verifying that the restrictions imposed to the safety performance indicators are fulfilled. Before describing them in detail, some previous concepts will be defined [14], [15], [16]:

- ***Design Parameters:*** noted as $\vec{x} = (x_1, x_2, \ldots, x_n)$. It is the vector that represents the n design parameters allowed to vary and used in each one of the steps of the optimisation process. It is important to notice those input parameters to the code, such as pressure of operation, and enrichment, can be included in $\vec{x}$; but some output parameters such as volumes, temperatures or reactivity coefficients are calculated with the design routines.
- ***Safety Performance Indicator***: it is noted with the letter ***O*****.** It is an output variable of the whole system and indicates the level of exigency on a certain system or component of the plant during an accident or transient, characterising reactor safety. A safety indicator is a variable that witnesses the reactor safety levels, since according to its

value it is possible to determine whether the reactor is in safe condition or not. The idea is that for each accidental sequence, one or more indicators or observable variables can be defined. It is important to identify all the observable variables, which can be critical for assuring the reactor safety in every transient and in the postulated initiating events, because the success of the design will depend on the restrictions applied to them. Probabilistic limits are also supported by the methodology, included as further safety indicators.

5.1 Description

Once these previous concepts and the general methodology have been defined, it is possible to define, describe and analyse what the Design Maps are. They are characterised by:

- A function that relates a safety performance indicator *O* with some design parameters included in $\vec{x}$ or some combination of them that will be denoted $h(\vec{x})$. It includes only some of the parameters or in some cases a function of dimensionless numbers of the system and not directly the design parameters. Each safety indicator O_j can depend on different combinations of functions $h_j(\vec{x})$.
- A limiting value determined by the design criterion applied to a safety indicator. This value is established in order not to reach non-wished conditions. The criterion will be written in general form as $O_j \geq l_j$, or $O_k \leq L_k$, where l_j represents a lower limit for the safety indicator *j*, and L_k is the upper level for the safety indicator *k*.

A Design Map is a representation of the safety indicator dependence, in a $(n+1)$ dimensional space, on the *n* design parameters, in order to translate to the design parameters the restriction applied to the safety indicator. The main advantage of design maps is the possibility of jointly varying the parameters that influence one or more observables as well as the function of merit, in order to obtain a better design, maintaining the values of the observables in a safe condition.

Simplified alternatives of graphical representations of Design Maps for an integral type reactor are shown in Figures 3 and 4, [17]. In the first one, a multiple parameter single map for a partial LOHS sequence can be seen. The dependence of down-comer flow area, dome volume and density reactivity coefficient on the safety indicator “maximum pressure during the transient” can be observed. In the next figure, a combined Design Map for LOHS and main steam line partial rupture is shown. The selected safety indicators during these accident sequences, where the failure of all the safety systems is postulated, are short-term maximal pressure and minimal –in space and time– DNBR and their dependence on the void reactivity coefficient, a function of design parameters, can be observed. Respective restrictions determine an “acceptance region” or a “safe zone”.

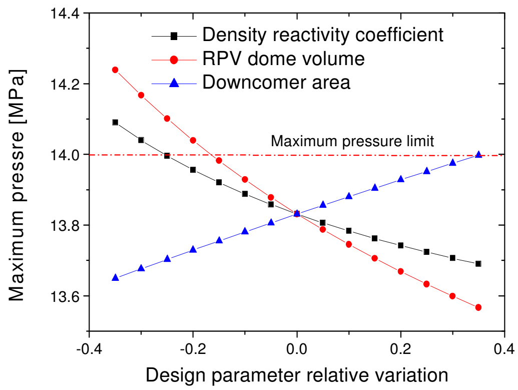

Figure 3: Partial LOHS, multiple-parameter design map.

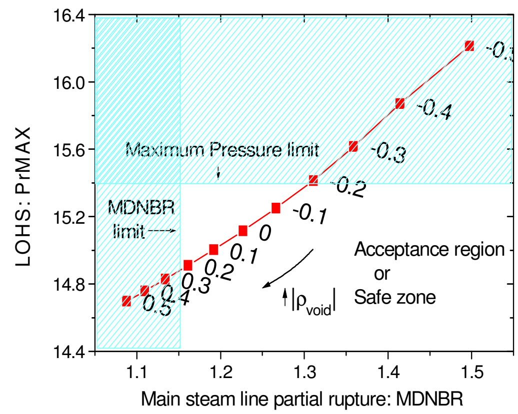

Figure 4: Combined design map for LOHS and main steam line partial rupture, dependence on void reactivity coefficient.

The main advantage of design maps is the possibility of jointly varying the parameters that influence one or more observables as well as the function of merit, in order to obtain a better design, maintaining the values of the observables in a safe condition. For example, it could happen that in order to keep the core uncovery time constant (observable), for a given LOCA in an integral-type reactor, it is convenient from an economic point of view (figure of merit), to reduce RPV water volume by means of increasing liquid volume in the Emergency Injection System.

5.2 Generation and utilisation of Design Maps

One of the options for creating design maps is to accomplish this *a priori*, before carrying out the optimisation process. In order to perform this, each design parameter amplitude and discretisation needs to be defined. The *n*-dimensional matrix of parameters is then scanned, simulating the different accident sequences for each possible reactor design. The resultant safety indicators, along with the set of design parameters,, are stored in disc, to be then accessed from the optimiser as a database. An alternative approach is to obtain the observable values while the optimisation is being carried out, which would be an *online* method of map calculation. Both alternatives make several calls to reactor calculation models, which indicates that models must be as simple as possible, to reduce the computing time. This must be taken into account when choosing one of the options.

Models for accident or transient simulations need not only reactor geometric features (volume of the pressure vessel, height, diameters, etc.) but reactor operational values as well (pressure, power, temperatures, reactivity coefficients, etc.). This may imply the need for running the dimensioning module (steady state dimensioning routines) to obtain some of these parameters in the steady state, before being used as initial conditions for accident simulation. It is important to mention that as this methodology is applied at the conceptual engineering stage, models for accident simulation are therefore relatively simple and sufficient conservativeness must be assured.

6 OPTIMISATION

This section describes how the methodology developed works. Having created the design maps (either *a priori* or *online*), the process goes on with the optimisation of the parameters that influence the selected figure of merit. Based on the design parameters, the value of the figure of merit, $M(\vec{x})$, is calculated in each step of the optimisation. Afterwards the partial derivative of M with respect to each one of the design parameters –selected with sensitivity analysis– is evaluated. Thus, the optimal jump of the parameters vector is determined, parallel to the gradient of the function of merit.

During the optimisation process successive $\delta\vec{x}_0$ vectors are found approaching towards the point $\vec{x}$, in the n-dimensional space of the design parameters, whose function of merit is the best in the neighbourhood of the departure point. Throughout this process, the imposed restrictions to these indicators will be eventually reached.

If in any step of the optimisation, for the new $\vec{x} = \vec{x}_{old} + \delta\vec{x}_0$, at least one safety performance indicator crosses its limit, it is necessary to reduce the parameter vector jump, in order to verify that $O_j(\vec{x}_{old} + \delta\vec{x}) = limit$. In the next step, that restriction must be respected and, as the figure of merit improvement pointed to cross it, it is not convenient to go backwards. Therefore, the solution is to keep the observable variable constant and equal to its limit. This means that the parameters vector jump must be perpendicular to each one of the observable gradients that should be kept constant. In other words, $\delta\vec{x}$ must have null components in the directions determined by these gradients. However, it is also required that $\delta\vec{x}$ goes on being as similar to the vector determined by the search of a better figure of merit as possible. To do this, a subspace generated by the gradients of the observable variables whose limits were reached is built. Hence, for this subspace an orthogonal basis is obtained with the Gram-Schmidt orthogonalisation process. Next, all of its projections on each one of the components of this basis are subtracted from the parameters vector jump $\delta\vec{x}_0$. Then the new parameters vector jump remains projected on the (n-K) dimensional subspace, which is orthogonal to the space constituted by the gradients of the limited observable variables.

The optimisation method selected is known as the Gradient Method [Arora, 1989 -14], and was chosen due to its many advantages for handling complex and dynamic restrictions, which depend on the design parameters, such as those for the safety performance indicators. Therefore, its relative slowness is outweighed by its advantages. Nevertheless, this optimisation method has some further disadvantages in addition to its convergence speed. The "best design" found with such an optimisation, depends on the wisdom used to choose the starting point, due to the localness of the optimum provided by this procedure. It also relies on the path chosen to perform it, whether the design parameters are released simultaneously or separately, etc. These phenomena appear with all the methods that seek local optimums, such as this one. Despite the fact that the ultimate design goal is always to find the global optimal design, these methods are indeed useful. The starting point problem is strongly connected to the designer judgement mentioned on step #1 of the design process described in section §3. It can be dealt with by evaluating the figure of merit for several rather different designs –the feasible design domain being swept either randomly or periodically– and choosing the best option. The path issue can be faced either roughly, sweeping the possibilities and choosing the best result, or considering the sensitivities of both the figure of merit and the safety performance indicators when changing the design parameter values; although the last option might fail for large variations.

The proposed optimisation routine should work properly for the process performed either by calculating the observable variables with the *online* approach or for those cases in which they are obtained reading their values from a design map obtained *a priori*. These safety indicators must be evaluated for the numerical calculation of their gradients and when a new restriction is violated, to reduce the parameter jump vector. It can be seen that it is faster to perform an optimisation by means of design maps obtained a priori in those cases where the calculation model is too slow to be called so many times in each optimisation step. For the cases in which the speed of execution of the calculation model is not too significant, there are no disadvantages of doing it online. A diagram of the whole calculation paths in the global design process is shown in Figure 5. In the bottom loop, an unrestricted optimisation path can be observed. In the upper part, the verification path for restriction fulfilment by means of the design maps is shown.

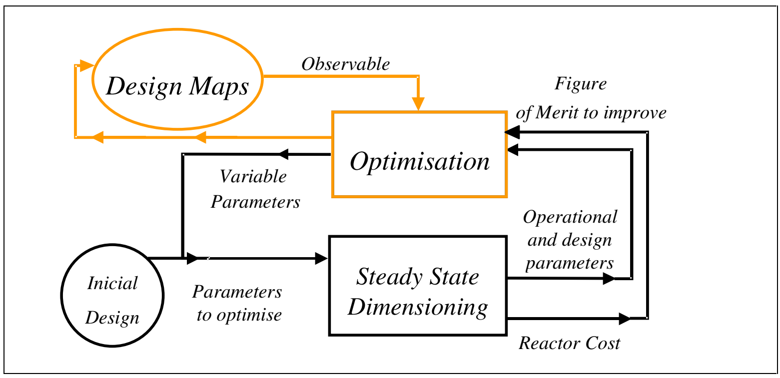

Figure 5**:** Calculation diagrams. Figure of merit: reactor cost

7 CONCLUSIONS

The present work presents a methodology to balance safety and economy of a nuclear power plant, aiming at achieving an efficient internalisation of the external costs. One of the main outcomes is that it is possible to optimise a reactor design internalising its safety costs efficiently. This process tends to cost reduction, a greater simplicity and a better strategy for prevention and mitigation. All of this is performed by integrating safety evaluation with neutronic, thermal-hydraulic and mechanical calculations in the design optimisation. This methodology provides the instruments necessary to be able to guarantee that the adopted criteria for reactor safety (restrictions applied to safety-related performance indicators) are verified in each one of the optimisation steps toward optimal cost.

Moreover, a relevant issue is that the present methodology allows one to incorporate reactor dynamic response during transients or accidents in an early engineering stage for design parameter integral optimisation, by using safety design maps. This is done through new rules for neutronic, thermal-hydraulic and mechanical calculations additional to those necessary for steady state dimensioning.

This is a promising methodology for equalising and optimise reactor and safety systems design in an early engineering stage. Therefore, a balance between reactor inherent capability and safety systems to cope with the postulated initiating events can be achieved. This equilibrium prevents the search for economic performance from causing less safe reactors and, likewise, guarantees the design competitiveness in spite of the unavoidable safety costs. Furthermore, by means of this methodology a simplified design can be obtained, compared to the resultant complexity when these concepts are introduced in a later engineering stage.

The present methodology has been implemented in a computational tool called IREP 3 and is being tested to balance the inherent safety in integral pressurised water reactors versus safety system capability to cope with LOCA and/or LOHS sequences. Likewise, this methodology may also be used to balance different but complementary safety systems to withstand a given initiating event. Moreover, it can be used to decide the best way to perform a safety function such as depressurising the reactor during a small LOCA by means of an Automatic Depressurisation System or by a Residual Heat Removal System.

A further application could be evaluating the additional costs of higher safety levels, or those due to the uncertainties in the limits applied to safety performance indicators.

Another advantage is that in case of need, one of the safety performance indicators can be used as figure of merit to be improved. This situation could occur if a safety related variable violates a restriction in a given reactor design. Cost could, or could not, be considered as a new observable subject to restrictions in the same way as the rest of the safety indicators are.

In addition, the developed methodology offers the possibility of handling probabilistic limits to avoid the occurrence of non-wished events, such as core melt probability. Moreover, the uncertainty treatment can also be handled, considering both the uncertainties in the design parameters (and their effects on the costs and on the safety performance indicators) and those due to the models used by the code. These objectives will constitute the next development steps.

It is important to mention that this methodology does not replace the judgement of experts and detailed accident simulations must still be done in order to verify reactor safety. Finally, a great deal of work remains to be done in order to explore and to make concrete the potential benefits of the methodology. This is why there are some aspects that are described as a general concept or idea without giving explicit examples or specific detailed guidelines.

REFERENCES

[1] Kröger, W.; Fischer, P. U.: "*Balancing Safety and Economics*". Nuc. Eng. & Design, 195 (2000) 101-108. June 1999

[2] Garland, Wm. J.; Snell, V. G.: "*Nuclear Reactor Safety*". McMaster University Course. Hamilton, Canada, January 2001

[3] Allen, F. R.; Garlick, A. R.; Hayns, M. R and Taig, A. R.: "*The Management of Risk to Society from Potential Accidents*". The main report of the UKAEA Working Group on the Risks to Society from Potential Major Accidents. 1992, SRD, AEA Technology, Colcheth, Cheshire, UK

[4]*"Integrated Reactor Evaluation Program – Code Description and Users Manual"*. Version 1.0. International Atomic Energy Agency – Argentine National Atomic Energy Commission. Bariloche, 1997

[5] Argentinean Integrated Small Reactor Design and Scale Economy Analysis of Integrated Reactor, 3rd International Conference on Nuclear Option in Countries with Small and Medium Electricity Grid, organised by IAEA, Dubrovnik, Croatia, June 2000

[6] Carelli, M. D. et al: "Safety by Design: A New Approach to Accident Management in the IRIS Reactor". International Seminar on Status and Prospects for Small and Medium Sized Reactors. Cairo, Egypt, May 2001

[7] Chang, M. H.; Yeo, J. W.: "Advanced Design Features Adopted in SMART". International Seminar on Status and Prospects for Small and Medium Sized Reactors. Cairo, Egypt, May 2001

[8] Ishida, T.; Kusunoki; N. Odano, N.; Nakajima, N. and Ochiai, M.: "Design of Passively Safe Small Reactor for Distributed Energy System and Technology Development". International Seminar on Status and Prospects for Small and Medium Sized Reactors. Cairo, Egypt, May 2001

[9] "*Basic Safety Principles for Nuclear Power Plants*". 75-INSAG-3 Rev. 1. INSAG-12. A Report by the International Nuclear Safety Advisory Group. IAEA, Vienna, 1999

[10] "*Safety of Nuclear Power Plants: Design*". Safety Standards Series, NS-R-1. IAEA, Vienna, 2000.

[11] "Safety Assessment and Verification of Nuclear Power Plants". Safety Standards Series, NS-G-1.2. IAEA, Vienna, November 2001

[12] Taylor, J. J.; Santucci, J.: "*Safety, Technical and Economic Objectives of the Electric Porwer Research Institute's Advanced Light Water Reactor Programme*". Proceedings of Symposium on "Advanced Nuclear Power Systems: Design, Technology, Safety and Strategies for their Deployment" organised by the IAEA. Seoul, Korea, 18-22 October 1993

[13] "Operational Safety Performance Indicators for Nuclear Power Plants". IAEA-TECDOC-1141. 2000

[14] Arora, Jasbir S.: *"Introduction to Optimum Design"*. McGraw-Hill, 1989

[15] Dieter, George E.: **"**Engineering Design: A Materials and Processing Approach". McGraw-Hill, 1989

[16] Zanocco, P.; Giménez, M. y Delmastro, D. *"Integrated Reactors Design Criterion based on Transients"*. VII Congresso Geral de Energía Nuclear, Bello Horizonte, Brasil, 1999

[17] ATWS characterisation as support for integral type reactor conceptual design., P. Zanocco, M. Giménez y D. Delmastro. XXVI Annual Meeting of the Argentine Nuclear Technology Association, Bariloche, 1999.