A FRAMEWORK FOR THE LICENSING OF A PEBBLE BED MODULAR REACTOR

Premysl Skopal* Herman Steyn† David Nicholls‡

(*Received July 1998; Final version May 1999*)

Eskom, a South African electricity generating company, is investigating a number of alternatives for potential future generating plant, including nuclear power. They invested R&D resources in the development of the South African Pebble Bed Modular Reactor (PBMR). A licensing framework needs to be developed in order to make commercialisation of the PBMR technology a feasible option. The licensing framework is regarded as a system that is composed of components, attributes, and relationships. This paper analyses the context in which the PBMR would operate and suggests a knowledge base that could be used in the development with the objective to provide a framework for the development of the licensing requirements. A central theme of the Licensing Framework is the use of systems engineering as a technique based on sound scientific and engineering judgement to define areas of concern.

Introduction

Background

The need for electricity is basic to the economic and social well-being in South Africa. South Africa is characterised by elements of both a developed and a developing nation. A prime example of this is the electricity supply industry. At the distribution end of the industry, the biggest task is that of providing electricity to the majority of the population, many of whom will be receiving electricity for the first time.

The other end of the electricity supply industry, the power stations, are clearly part of a developed economy.[1] South Africa's power stations include Kendal, which at over 4 000 MW, is the largest hard coal power station in the world, and Koeberg, the only nuclear power station on the African continent. The increasingly competitive global economy forces every country to carefully assess its competitive advantages. In the case of South Africa, one of these is the low cost of electricity. This low cost is one of the driving forces behind a number of major projects. Eskom is therefore investigating a number of options for potential future generating plant, with specific emphasis on competitive costing. The nuclear studies originally considered stations similar to the existing nuclear plant at Koeberg. However, given the condition of cost-competitiveness and the ongoing debate in the international arena, particularly in relation to environmental constraints, it was concluded that there is more potential in the Pebble Bed Modular Reactor (PBMR) based on High Temperature Gas Cooled Reactors (HTGR) technology proven in Germany.

Acceptance by the public

According to US Nuclear Regulatory Commission (US-NRC) Chairman, Dr Jackson, "Economics lies at the heart of decision making regarding any industrial undertaking, including the use of nuclear energy".[2]

Regulation is one key mechanism used in market economies to ensure that industrial activities are conducted in a manner consistent with society's needs. Eskom and the Council for Nuclear Safety (CNS) should take the measures necessary to give confidence that all stages of the life cycle (e.g. construction, fuel loading, and operation) will not be impeded by regulatory processes. Eskom has to demonstrate technical quality of the design, compliance with the nuclear safety criteria, and ability to recruit and train adequate staff to manage, operate, and maintain the plant. CNS, on the other hand, must have prepared suitable policies, rules, regulations, and procedures to determine the licenseability of the plant. The key objective is to establish a fundamental framework in order to meet the primary responsibility of protecting public health and safety, and the environment. The ultimate customer for the product (PBMR) is the public on the receiving end of the benefits and financial and environmental consequences associated with the PBMR technology. It is important that the technology does not introduce unacceptable environmental hazards and that the licensing process should not be any more costly than necessary.

*Chief Engineer, PBMR Licensing, Eskom - Technology Group, Megawatt Park, Maxwell Drive, Sandton, South Africa

†Professor, Department of Engineering and Technology Management, University of Pretoria, Pretoria, 0002 South Africa

‡PBMR Programme Manager, Eskom

Basic safety concept and avoidance of back-fit cost

In the design of current nuclear systems, the issue of nuclear safety did not take the very high profile that is currently required. This has led, over the last two decades, to substantial cost increases to back-fit requirements. These cost increases have led to nuclear power being seen as not competitive, as well as it failing to gain adequate public acceptance for the safety of the plants. One of the nuclear technologies developed in the 1960s was the high temperature gas cooled reactor utilising coated particle fuel. The key difference between this technology and the current generation of nuclear plant is that the safety objectives can be demonstrated to be met without any specific safety systems. This leads to a substantial reduction in the cost and removes the risk of "back-fits". A power station is a large capital investment. Therefore, the designers and the development team must make sure that the design would comply with stricter future regulatory requirements.

Development method

The paper proposes a licensing framework, which builds on the model presented in Figure 1. The framework integrates licensing requirements, knowledge base, and the context within which the technology would be licensed. The licensing framework is shaped by the context in terms of requirements, constraints, and culture within the environment. Establishment of the prior knowledge base is proposed for a unified system of information that would identify essential safety issues, goals, and priorities at various stages of the development. The main focus is on the development of the licensing requirements. A special framework is used for the development of the licensing requirements in order to:

- Link existing information to management needs;
- Integrate environment-related data obtained from safety analysis to support ecosystem-based decision making;
- Identify duplication and gaps in existing information collection efforts; and
- Provide a platform for the development of new data and indicators to fill gaps.

A summary of the licensing framework gives an overview of the structure and content of the single phases as well as an indication of resources and quality standards to be applied during the process.

Licensing framework as a system

System characteristics of the licensing framework

The licensing framework is regarded as a **system** that is composed of components, attributes, and relationships. The licensing framework would be formed by a set of interrelated components working together toward a common objective. The components of the licensing framework may themselves be systems, and every system may be part of a larger system within a hierarchy of systems.

Application of systems engineering

The systems engineering approach is applied in the development of the framework. In general, this approach is characterised as a continuous, iterative process incorporating the feedback actions necessary to ensure convergence. Fundamental to the application of systems engineering is the lifecycle approach. The proper attention given to certain factors early in the life cycle may avoid problems later on, while ignoring others may prove to be quite costly. The systems viewpoint looks at a system from the top down rather than from the bottom up. Attention is first directed to the system as a "black box" that interacts with its environment, Next, attention is focused on how the smaller "black boxes" (subsystems) combine to achieve the system objective. The lowest level of concern is then with individual components.[3] The engineering activities must be properly integrated through effective organisation and systems engineering management in order to meet the requirements of the licensing system life cycle. The objective of the process is to provide the right licensing framework, applicable in the South African regulatory environment, at the right time, with a minimum expenditure of human and physical resources.

Cross-functional integration

Many elements are necessary to achieve success in a new product or process development. However, in and of themselves, these elements are insufficient for achieving outstanding development success.

Cross-functional integration is essential for superior development performance along the dimensions of cost, time, and quality. Outstanding development requires effective actions from all of the major functions in the business . The extent to which problem solving is integrated in the development process, shows up most forcibly in relationships between individuals or engineering groups where the output of one is the input for the other. The dependent groups are called the upstream group and downstream group. How these groups work together determines the extent and effectiveness of integration. A critical element of the integration between

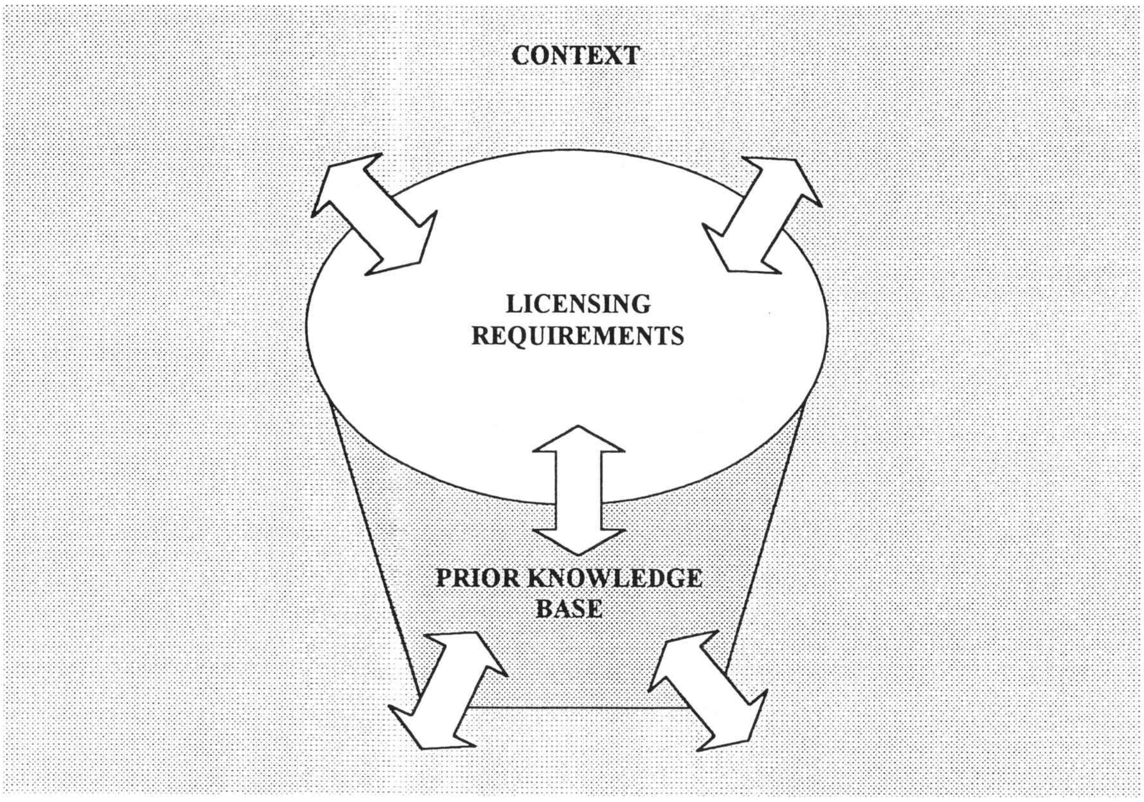

Figure 1 Elements of the licensing framework

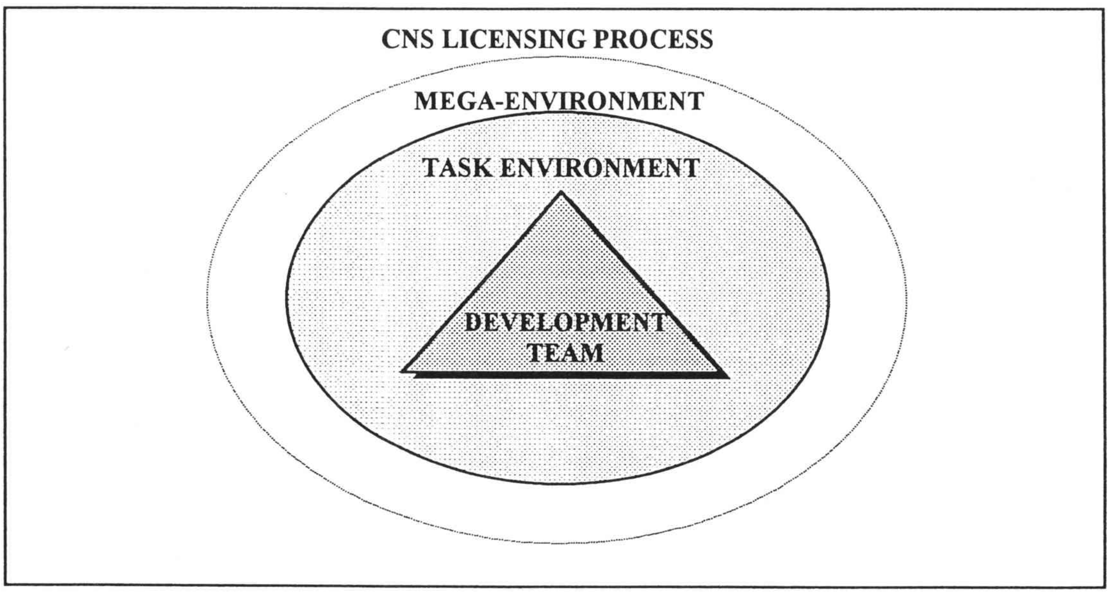

Figure 2 Environment of the licensing framework

the upstream and the downstream group is the pattern of communication. The key issue is the extent to which work is done in parallel. Development of the licensing framework involves upstream-downstream interaction internally within the development team and externally between the development team and the CNS specially appointed project group. Licensing personnel and designers must work closely together from the early stage of development. The absence of clearly defined regulatory rules and criteria requires parallel actions of both groups in order to prevent costly re-works and time delays. Effective integration places heavy demands on the organisation. The engineering process must link problem-solving cycles in time; communication must be rich, precise, and intense; and the relationship between upstream and downstream groups must support and reinforce early and frequent exchange of constraints, ideas, and objectives. Achieving integration across functions at each level requires support and focused action from senior management. Senior management establishes the context in which functional interaction and individual problem solving occur.

Proposed structure of the licensing framework

The licensing framework is intended to define a general structure to facilitate technical and administrative decisions within the problem areas. Eskom is responsible for development of a licensing framework that would comply with technical, legal, and environmental requirements. The development would require greater co-operation, co-ordination, and integration among the involved participants.

The essential characteristics of the licensing framework include: broad-based participation to achieve implementation; clear responsibility and sufficient authority; human and financial resource support; flexibility and continuity to achieve an agreed-upon road map; education and outreach; and commitment to action planning within a strategic framework. The "bottom-up" approach ensuring linkages needs to be complemented by "top-down" management to ensure programmes and initiatives are complementary and reinforcing. "Top-down" support for co-ordination and integration would be demonstrated, for example, by (1) senior management acknowledging the need for co-ordination and integration in programme mission statements, and (2) assigning staff via annual work plans to promote co-ordination and integration.

The licensing framework would integrate formulation of licensing requirements, knowledge basis, and the context within which the licensing framework is being developed. The structure of the licensing framework is shown in Figure 1.

The focus is on development of the licensing requirements. Understanding the context in which the PBMR would operate and the availability of the knowledge base are essential for the development of the licensing framework.

Context

Ecosystem and environment

"Context" refers to the environment within which the framework is being developed. This includes the organisational focus of Eskom, including the requirements to advance the South African government's environmental objectives and other relevant objectives. Keri Lawson[5] implies that the context also refers to the broader social issues which impact on the framework development within Eskom to the extent that these are incorporated within various policies developed by Eskom. The success or failure of the licensing framework is ultimately determined by the extent to which it is understood and used by the development staff.

Systems theory helps highlight the importance of the environment to organisations. According to the systems approach, an organisation is likely to be more successful if it operates as an open system that continually interacts with and receives feedback from its external environment. The external environment can be divided into two major segments: the general environment, or mega-environment, and the task environment.[6] The general conditions that exist within an organisation determine the internal environment. The internal environment encompasses such factors as organisation members, the nature of their interactions, and the physical setting within which they operate. The internal environment is a reflection of the organisational culture that is a system of shared values, assumptions, beliefs, and norms that unite the members of an organisation.[6]

The licensing framework would be developed by Eskom and would be exposed to the licensing process conducted by the CNS. The general or mega-environment and task environment (including the organisational culture related to Eskom) would effect the development of the framework in the sense that the final product of the development – a licensing system for PBMR – must fit into the environment where it is to operate. The licensing process prescribed by the CNS would become part of the mega-environment.

Figure 2 displays the relationship between the environments and organisations forming the licensing system. All elements of the environment must be considered during the development of the licensing framework. Application of the quality standards, ISO 9000 and ISO 14000, would be required in different phases of the project. According to Kellermann,[7] ISO 9000 core documents describe the activities that a company has to control in order to ensure consistent quality of the product or service it supplies. It deals with the management, design, and production issues, including testing. The level of quality of the product or service is determined by agreement between the supplier and the purchaser.

The level of quality in the case of ISO 14000 is agreed to between the supplier and society. ISO 14000 therefore requires that the supplier:

- Complies with all the national environmental legislation relevant to his operation.
- Conducts studies to determine impacts additional to the regulatory requirements and to manage them.[7]

The intention is to prove that the PBMR power station will not disturb normal day-to-day public activities. The potential radioactive releases would have to be limited to the level where:

- Public activities are not disrupted by emergency plans and drills.
- The risk of contamination of the off-site land is eliminated.

To achieve the above goals the radioactive releases should be less than those required for the emergency notification and sheltering plans. The complementary design objective of limiting the consequences of severe accidents is to ensure with a high degree of confidence that the need for urgent protective actions would in effect be limited to the immediate vicinity of the plant, and possibly to the plant site boundary. This would minimise societal and environmental impact. This, in turn, would enable simplification of the emergency planning for the PBMR design. The need for both urgent and long-term off-site protective actions, such as rapid evacuation and permanent relocation, would be eliminated. The International Atomic Energy Agency (IAEA) recommends that, even if the need for off-site emergency action is eliminated, some emergency planning for contingencies may still remain, as part of an overall public protection policy. The determination of what constitutes "no significant radiological consequences", as specified by the IAEA, is the responsibility of national authorities, and takes into account local conditions and national or international regulations.[8]

Licensing process specified by the Council for Nuclear Safety

The approach adopted by the South African Nuclear Safety Authority – Council for Nuclear Safety (CNS) – for licensing of nuclear installations in South Africa would be followed also in the case of PBMR commercialisation. The basic philosophy advocated by the CNS requires that:

1. the design basis of the plant respects prevailing international norms and practices, and
2. a quantitative risk assessment demonstrates compliance with the CNS safety criteria.[9]

A typical CNS licensing process starts with the conceptual stage. The conceptual licensing stage for PBMR is supposed to be initiated by the preliminary discussion between Eskom and the CNS and then to be continued by implementation of the individual licensing phases. The conceptual phase of the licensing process would be completed by approval of the Preliminary Safety Analysis Report (PSAR) and followed by application for the Construction Permit. The remaining licensing stages can start after completion of the conceptual licensing phases. It is expected that the licensing process would follow the structure used by the CNS for Koeberg nuclear power station.

Evaluation of the general environment

The mega-environment, or general environment, is the segment of the external environment that reflects the broad conditions and trends in the societies within which an organisation operates. The mega-environment consists of five major elements:[6]

- Technological
- Economic
- Legal-political
- Socio-cultural
- International.

Because these elements reflect major trends outside the organisation, they tend to be beyond the ability of a single organisation to affect or alter directly, at least in the short term. Understanding the general environment helps the management of a PBMR project to establish vision, direction and shared values towards the marketplace. The general environment also effects the availability of prior knowledge base and resources.

Evaluation of the task environment

The task environment depends largely on the specific products and services that an organisation decides to offer and on the locations where it chooses to conduct its business. Whilst a single organisation usually has difficulty exerting a direct influence on the mega-environment, it may be more successful in affecting its task environment. Major elements in an organisation's task environment typically include the following:

- Customers and clients
- Competitors
- Suppliers
- Labour supply
- Government agencies

Each organisation must assess its own situation to determine its specific task environment.[6]

Understanding the task environment ensures early involvement of all stakeholders for defining requirements and enables sharing of information on future plans. Inclusion of the general and task environment analysis into the development of the licensing framework is required by the systems approach as a discipline for seeing wholes. It is a framework for seeing interrelationships rather than things, for seeing patterns of change rather than static "snapshots".

Prior knowledge basis

Current licensing practice

Typically, important safety matters for licensing of present reactors include fuel design and performance, reactor cooling system, accident selection and analysis, role of the operators, design of the control room and the emergency control room, emergency preparedness, and quality standards for equipment. Licensing requirements have been developed to accommodate the complexity of the design aimed at the potential for a rapid progression of events, large source term, and potential for human error or equipment malfunction, which may initiate an accident.

Licensing approach to PBMR

The first module of PBMR would be treated as the reference one that should demonstrate safety characteristics and overall performance of the new technology. The extensive testing would form part of the commissioning programme before Eskom would raise an application for certification of the standard design. The final licensing stage of the reference module would be focused on step-by-step testing at different power levels.

Prior work in the field

The PBMR concept has certain design characteristics that make it inherently safe. Generally accepted passive safety characteristics of the HTGR that will simplify the design and the licensing process include:

- High heat capacity of the reactor core
- Negative reactivity coefficient
- High temperature capability of the core components
- Inertness of coolant
- High retention of fuel products by ceramic fuel coatings
- Ability to cool the reactor by available heat transfer mechanisms following any postulated accident.

In the safety analyses of HTGRs, probabilistic risk assessment studies have been done for evaluating risk and consequences. In these studies, comprehensive safety/risk assessments are made for a wide spectrum of accident conditions, taking into consideration a detailed evaluation of the frequency of specific events, as well as an evaluation of the corresponding consequences due to fission product release to the environment.[10]

Experience with licensing of HTGRs in Germany, USA, and UK has been particularly valuable for the development of PBMR. The licensing issues experienced at nuclear power stations with HTGR technology in these countries would be studied and where applicable adopted for licensing of the PBMR. According to available information the licensing authorities in countries operating HTGR technology have not found outstanding safety issues which would prevent power stations based on this technology from obtaining a license.

Development of the licensing requirements

Framework for the development

The licensing requirements would be developed based on an assessment of current practice across nuclear programmes and technical design of the PBMR within the context of the licensing environment. The framework proposed in Figure 3 provides a diagrammatic summary of how the development of licensing requirements could be structured and managed.

The licensing framework is not intended to encompass the development of operational procedures *per se*, although licensing engineers recognise the utility of such efforts. A central theme of the licensing framework is the use of systems engineering as a technique based on sound scientific and engineering judgement to define areas of concern rather than numerical conclusions that may convey an artificial sense of precision. Basic elements of the framework in Figure 3 are intended to guide engineers to assess the relationship between potential risks and effects. Risk analysis typically involves significant uncertainty associated with required assumptions and extrapolations. Accordingly, it is anticipated that as knowledge and understanding of the technology matures, the licensing requirements have to be modified. For these reasons, the set of elements defining the licensing requirements is best viewed as a dynamic, continuously evolving instrument intended to mirror new insights into an understanding of the relevant processes. Ideally,according to the US Environmental Protection Agency,[11] the legal/regulatory framework and the paradigms that influence decision-making should be compatible with the scientific ones used in the research and assessment. However, this has often not been the case. A conceptual framework should strive to integrate the scientific, legal/regulatory, and philosophical paradigms that underlie information generation and use.

The inherently high safety levels of the PBMR technology result from the ability of coated particles to retain radioactive fission products even at high temperatures. The safety analysis would concentrate mainly on the integrity of the fuel particles. The safety features that have a major influence on the ability to control release of radioactivity into the environment include:

- Capability of the core heat transfer following the loss of forced cooling
- Prevention of a core fire (fast corrosion)
- Stability of the core geometry
- Limitation of the nuclear heat-up preventing unacceptable increase of the fuel temperature.

Senior management review and control

Whilst senior managers do not directly perform specific design tasks, their role in the project and the nature of their interaction with the development team (and the team leader) is an important element of the overall framework.[4] The way in which senior management reviews, evaluates, and modifies the project and its goals over time signals to those working on the project the degree to which responsibility has been delegated to them, and creates powerful incentives and motivation during the course of the development. Seemingly routine patterns, such as the timing, frequency, and format of reviews, can have a significant impact on the overall effectiveness of the development.

Management should not only manage schedules but ratlier key events in the project itself as well.

Included in this element would be approach of the management to problem solving and testing. Management should avoid a functional decomposition approach to problem solving and testing that is, according to Clark & Wheelwright,[4] one of the most commonly observed approaches in engineering-driven firms. Such approach would be inappropriate in two major respects. Most important is that functional problem solving invariably proves to be sub-optimal, requiring additional cycles late in the project when changes are costly and when expediency is likely to dictate compromises on performance and product quality. These compromises would not have been made, had those same issues been raised and addressed much earlier. Thus the degree of integrity and integration in the final product or process suffers as a consequence. The second problem would be lost opportunity. Testing cycles offer a wonderful opportunity to bring together the various functions, determine the degree of progress made to date and consider how alternative solutions might play together at an intermediate stage. In essence, testing can be an important vehicle for cross-functional discussion, problem solving, and integration.

Real time corrections

The ambiguity and uncertainty associated with any product or process development effort often makes feedback and revisions duhng the course of the project a necessity. This element deals with issues such as ongoing measurement and evaluation of project status, rescheduling, re-sequencing, and re-defining the remaining tasks. Perhaps more subtle but also an important aspect of this element is the balance between early conflict resolution and subsequent adaptability, the relationship between unexpected early challenges and subsequent potential delays, and choices between deferring rescheduling to maintain motivation versus rescheduling early to maintain project credibility.[4] Real-time adjustments are typically characterised by discipline, early conflict resolution, and high level of cross-functional problem solving.

The underlying dynamic during the early stages of development is managing the risk inherent in making decisions without complete information. The truism at this stage is that one will always have more information tomorrow; therefore delaying the decision is a rational action.[12] However, it is important to understand that no decision does not mean no cost. Decisions made early affect the entire development, whereas decisions made later have less leverage. Many decisions have to be taken by intuition. Research suggests that the root of intuition is experience. A study of the microcomputer industry[12] showed that the executives who were described as intuitive were most attuned to real-time data. Management would have to organise the information flow for constantly refreshing themselves with real-time data.

PHASES:

CONCEPTUAL	DEVELOPMENT	IMPLEMENTATION	FEEDBACK/ TESTING

KEY ELEMENTS OF THE PROCESS:

INVESTIGATION	DESIGN	FORMAL COMMUNICATION	RESPONSES

Societal Responses (Decisions – Actions)

TASKS WITHIN THE PROCESS ELEMENTS:

Context:	**Licensing Requirements:**	**Forms of Communication:**	**Economic and Environmental Agents:**
• Ecosystem • Licensing Process Specified by CNS • General Environment • Task Environment **Prior Knowledge Base:** • General Licensing Practice • Fundamental safety Criteria • HTGR Safety Features and Design Concepts • Simulator	• Design Safety Criteria • Safety and Risk Analysis • Hazard Categories • Defense in Depth • Classification of Components • Safety Analysis Report • Ecosystem Protection Criteria	• License Applications • Safety Analysis Reports • Presentations • Media Briefings • Public Meetings • Etc.	• Administration • Households • Enterprises • International • Etc.

RESOURCES:

Eskom / Suppliers	Eskom	Society

APPLICABLE QUALITY STANDARDS:

ISO 9000

ISO 14000

Figure 4 Summary of the licensing framework

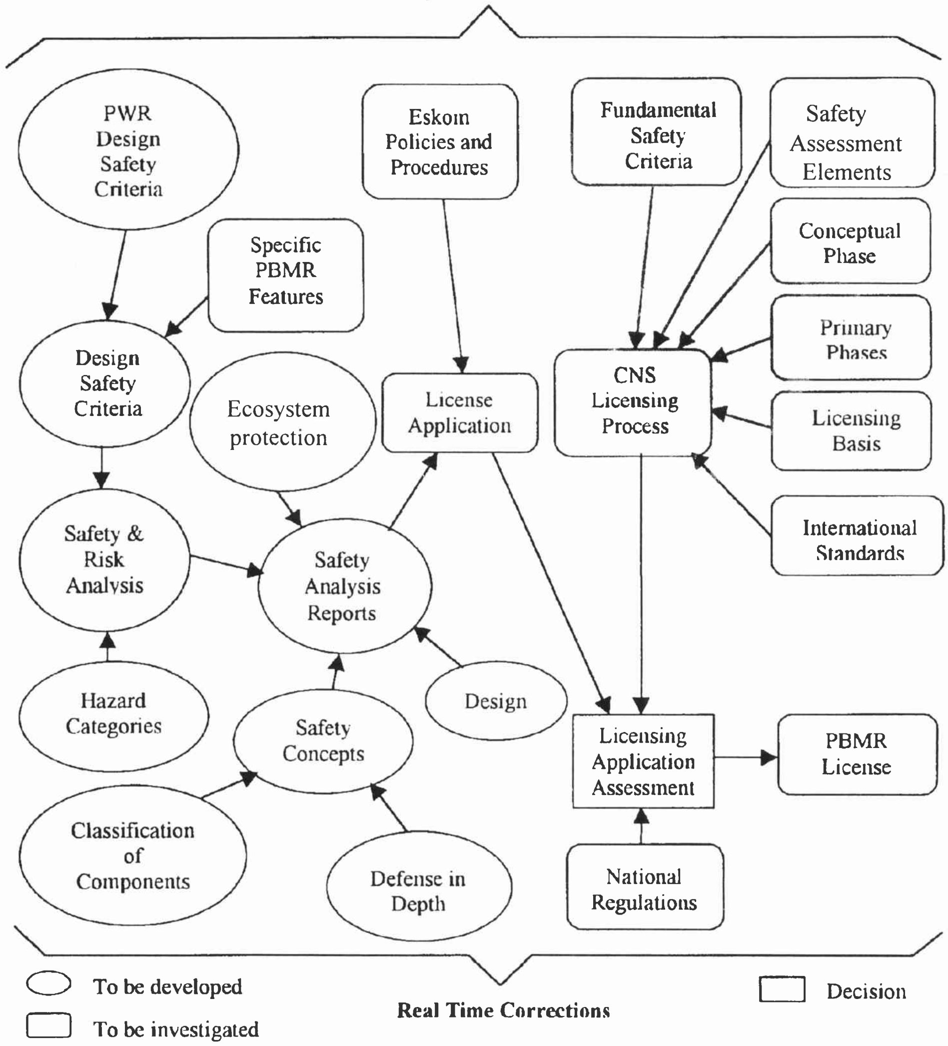

Figure 3 Framework for the development of the licensing requirements

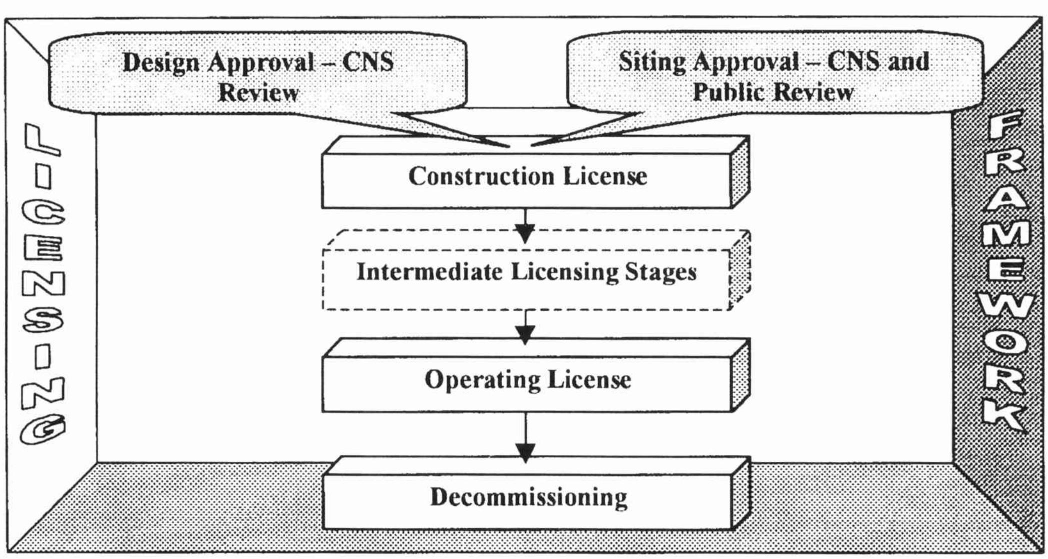

Figure 5 Sequence of the licensing process

Summary of the licensing framework

Development of the licensing requirements is summarised in Figure 4. This framework represents a basis for co-operative learnng to generate a common understanding of problems and to build consensus for actions. Two different types of tasks would be performed in the implementation of the licensing framework.

The first belongs to investigation of known documents, concepts, and processes. The PBMR development team must make sure that the PBMR design can accommodate the relevant existing requirements. The second type of task requires development of new concepts and approaches.

Societal responses are defined by the US Environmental Protection Agency[11] as purposeful actions to address observed or predicted ecological, human health or welfare changes, or impacts that are considered undesirable. The actions can be voluntary, legally mandated, or incentive-driven, and can be aimed at cleanup, mitigation, restoration, prevention, or adaptation.

- The societal response category can be subdivided by type of entity making the response, e.g. Government actions, including environmental legislation, changes in fiscal/economic policies, regulations, monitoring, etc.
- Individual/household attitudes and actions, e.g. changes in consumption pattems.
- Private sector activities, including product and process re-design, waste treatment and disposal, cleanup efforts, changes in technologies used, etc.
- Co-operative efforts, including research, education, land use planning commissions, public-private partnership, international agreements, etc. The tasks requiring investigation cover mainly the environmental issues and available technical knowledge.

Licensing requirements would be developed in order to reflect specifics of the PBMR technology. Those elements of the plant design, that are significant for safety, would be reviewed by the CNS for approval. The siting process would be subject to public review and final adjudication in addition to the CNS approval. The licensing and financial risks beyond this stage would be greatly reduced and Eskom could proceed with a high degree of confidence on matters of schedule and costs. Sequence of the process is briefly summarised in Figure 5. Legal basis for the licensing would be the Nuclear Energy Act and the Environment Conservation Act.

A framework is a tool, not a structure cast in stone. It may evolve as our understanding of possible impacts of the new technology on the environment evolve.

Conclusion

Eskom should incorporate a systematic and comprehensive ecosystem approach to the establishment of the PBMR technology. This would guide the state, provincial, and local government structures, along with industry, public organisations, and private citizens in South Africa, to adopt a new approach to the nuclear generation option represented by the PBMR technology. The licensing framework should establish an effective mechanism to facilitate the integrated approach to resource management and ensure meaningful participation of all stakeholders. The central idea of the framework is that the licensing process would be most effective if it is mission-driven instead of being driven by a set of rules.

References

1. Maduna PM. Opening Address. *IAEA Conference*, Rosebank Hotel, Johannesburg, 1996.
2. Jackson SA. Annual Lecture of the Council for Nuclear Safety, Pretoria, 1963.
3. Blanchard BS & Fabrycky WJ. *Systems Engineering and Analysis.* Prentice Hall, 1990.
4. Clark KB & Wheelwright SC. *Managing New Product and Process Development.* Free Press, 1993.
5. Lawson K. *A Maori Policy Analysis Framework for the Ministry of Health.* Te Aho, 1995.
6. Bartol KM & Martin DC. *Management.* McGraw-Hill, 1994.
7. Kellermann M. International Management Standards (an Overview). Presentation at the University of Pretoria, 1997.
8. IAEA. *Development of safety principles for the design of future nuclear power plants.* Vienna, 1995.
9. Clapisson A, Hill TF, Henderson NR, Keenan NH, Metcalf PE & Mysenkov A. An overview of the Licensing Approach of the South African Nuclear Regulatory Authority. *IAEA Conference*, Rosebank Hotel, Johannesburg, 1996.
10. IAEA. *Gas Cooled Reactor Design and Safety.* Vienna, 1990.
11. US Environmental Protection Agency. *A Conceptual Framework to Support Development and Use of Environmental Information in Decision Making.* 1996.
12. Mayer C. *Fast Cycle Time: How to Align Purpose, Strategy, and Structure for Speed.* The Free Press, 1993.