UNITED STATES
NUCLEAR REGULATORY COMMISSION
ADVISORY COMMITTEE ON REACTOR SAFEGUARDS
WASHINGTON, D.C. 20555-0001

June 19, 2000

MEMORANDUM TO: Chairman Meserve
Commissioner Dicus
Commissioner Diaz
Commissioner McGaffigan
Commissioner Merrifield

FROM: John T. Larkins
Executive Director, ACRS/ACNW

SUBJECT: TRANSMITTAL OF FOREIGN TRIP REPORT OF ACRS MEMBER

Attached is a trip report by ACRS Member Robert E. Uhrig on his visit to the PBMR Ltd.

Subsidiary of Eskom Ltd., Centurion, South Africa, March 23-24, 2000.

Attachment: Trip Report by Robert E. Uhrig, ACRS Member, dated April 20, 2000, Subject: Visit to the PBMR Ltd. Subsidiary of Eskom Ltd., Centurion, South Africa on March 23-24, 2000.

cc: ACRS Members
W. D. Travers, EDO
S. Collins, NRR
A. Thadani, RES
W. F. Kane, NMSS
Janice Dunn Lee, OIP
H. Faulkner, OIP

ROBERT E. UHRIG, PH.D., P.E.
5221 N. W. 44TH PLACE
GAINESVILLE, FL 32606-4328
April 20, 2000

Memorandum to:	Dr. John Larkins, Executive Director, ACRS Dr. Dana Powers, Chairman, ACRS
From:	Robert E. Uhrig, Member, ACRS
Subject:	VISIT TO THE PBMR LTD. SUBSIDIARY OF ESKOM LTD., CENTURION, SOUTH AFRICA

On March 23 and 24, 2000, I visited the PBMR (Pebble Bed Modular Reactor) Ltd.[1] subsidiary of Eskom Ltd., the national utility of South Africa, for the purpose of gaining knowledge about its proposed 110-MWe high-temperature gas-cooled (HGTR) modular nuclear power plant based on the German pebble bed technology. Although I have been generally familiar with recent modular reactor programs, this was my first detailed exposure to gas-cooled reactor technology since the early 1980s. My visit was very pleasant and useful from my standpoint. Indeed, I was surprised that David Nicholls, the Chief Executive Officer of PBMR Ltd., the Eskom Ltd. subsidiary charged with developing and building the first modular plant, and General Manager of the Project, spent at least half of his time with me during the 2 days of my visit, much of it in one-on-one conversations. While considerable time was devoted to the design and engineering features of the110-MWe demonstration module, Mr. Nicholls spent even more time discussing the safety aspects of the PBMR design and Eskom's approach to licensing the PBMR plant. This licensing approach has been specifically designed for HGTRs (rather than being an adaptation of the South African light-water reactor [LWR] licensing process) and incorporates certain aspects of risk-informed regulation. In this report, I will describe the understanding I gained of the design of the plant, its current status, and PBMR's approach to safety and licensing this design with the National Nuclear Regulator (NNS), formerly the Council for Nuclear Safety, the South African nuclear regulatory authority.

Personal Perspective and Prejudices. Some two decades ago, I had the privilege of visiting both of the prototype pebble bed reactors, the AVR at the German Nuclear Research Center in Julich and the THTR reactor, a 330-MWe demonstration plant located at Schmeehausen, Germany, that operated commercially for about 3 years in the late 1980s. I was a member of a five-person team from GCRA (Gas Cooled Reactor Associates), a utility-funded group exploring the features and characteristic behavior of various types of gas-cooled reactors. At that time, I

1 "PBMR Ltd." refers to the Subsidiary of Eskom Ltd. while "PBMR" refers to the pebble bed modular nuclear power plant.

was Florida Power & Light's representative to GCRA, a member of its Board of Directors, and Chairman of the Technical Advisory Committee for steam cycle plants. We visited the Dragon fuel test facility and several AGRs (advanced graphite reactors) in the United Kingdom, as well as the German facilities. The emphasis of GCRA at that time was on the prismatic core design with a prestressed concrete pressure vessel using the conventional Rankine steam cycle (i.e., the commercial plant then offered by Gulf General Atomic). Some of GCRA's efforts were devoted to the direct (Brayton) cycle gas-cooled reactor, but the primary emphasis of all parties, including the Department of Energy (DOE), at that time was on the conventional steam cycle. The General Atomic plant was one of the options considered by Florida Power & Light for use at its planned South Dade plant, but two Westinghouse four-loop pressurized-water reactor (PWR) plants were chosen and subsequently canceled before the Preliminary Safety Analysis Report was submitted to the Nuclear Regulatory Commission (NRC).

Status of the PBMR Project. On April 12, 2000, the South African Parliament approved proceeding with the PMBR. This is a significant step forward in this program. The remaining official action of the South African Government is the issuance of a Licensing Feasibility Statement by the NNR, a certification that NNR believes the plant as currently designed can be licensed, subject to a review of the detailed plant design. PBMR Ltd. anticipates receiving a favorable Licensing Feasibility Statement from NNR in the near future. If this is the case, PBMR Ltd. expects to start construction in mid-2001 with synchronization of the plant to the grid at the end of 2004. Several international consulting groups having experience with gas-cooled reactors have been asked by NNR to review the PBMR design. One team of consultants from the International Atomic Energy Agency included Syd Ball of Oak Ridge National Laboratory and Robert Budnitz, a safety consultant previously with the NRC.

It was clear that the design of the PBMR is still evolving and further optimization may still take place. Indeed, only the week before my visit, a major design change in the pressure boundaries was made because of stress analysis considerations that resulted in the simplification of the overall design and reduction of the amount of steel used in the pressure boundaries by about 68 tons. This change involved replacing the large pipe connecting the pressure vessel with the recuperator/pre-cooler vessel with two smaller concentric pipes, thereby reducing the size of the penetrations in the pressure vessel and resulting in a reduction of the thickness required to meet the American Society of Mechanical Engineers Boiler and Pressure Vessel Code (ASME Code). The complete design has been put on computers and the thermal-hydraulic system has been modeled in great detail, allowing easy analysis of changes in the thermal-hydraulic design and the ability to investigate "what if" options.

Eskom's Need for Additional Generating Capacity. Eskom Ltd. supplies virtually all the electrical power for South Africa and exports power to neighboring countries, primarily Mozambique, Botswana, and Namibia. It currently has about 34,000-MWe generating capacity in commission (about the same amount as the Tennessee Valley Authority, the largest utility in the United States) that provides it with a reserve margin of more than 12.5 percent. However, its load is growing at about 2.5 percent per year, and thus it will need additional generating capacity on line in about 5 years. Its overall cost of generation is slightly below 1.0 cent per kWh with its coal plants (located near coal mines predominatly in northern South Africa) producing electricity for as little as 0.75 cent per kilowatt. Since its load is growing rapidly in the coastal region (far from the coal mines) that includes Cape Town, Eskom decided that it wanted plants near this load center that were capable of load following and producing power at a cost competitive with new-built coal plants, that is, for about 1.5 cents per kWh. Other plant specifications are given in Table 1. The location away from the coal fields and limitations on other energy resources (primarily water power) made nuclear plants a natural choice. However, its experience with the Koeberg nuclear plants (900-MWe French plants based on an early Westinghouse design) indicated that the total cost of electricity using new-built light-water nuclear technology would exceed 3 cents per kWh in South Africa and was not likely to be reduced. A comprehensive investigation of the various options then led to the PBMR design. To date, Eskom has invested $30 million in development costs and anticipates that an additional $90 million will be required to complete development. Each 110 MWe is expect to cost an average of $110 million, or about $1000 per KWe capacity.

PBMR Design. The PBMR is a graphite-moderated, helium-cooled, pebble bed type reactor that uses a Brayton direct gas turbine cycle to convert the heat into electrical energy by means of a gas turbo-generator. Figure 1[2] is a schematic flow diagram of the PBMR plant. A regenerative heat exchanger is used to improve the thermodynamic efficiency. Figure 2 is a sketch of the main power system showing the flow of helium between the reactor core and the gas turbo-generator.[3] (Note: the pressure boundary connecting the pressure vessel with the vessel containing the turbo-generator has been changed since this drawing was produced.) The thermal power output is limited to about 270 Mwt per module.

The plant power level is normally controlled by adjusting the helium pressure. To increase the power, helium from a high-pressure tank is injected into the system. To lower the power, helium is bled into a lower pressure tank from which it is compressed and injected into the high-pressure tank for future use in controlling the power level. Simulation studies indicate that the power can be changed over the range from about 5 percent to 100 percent with almost constant plant efficiency of about 42 percent. For rapid decreases in power, a bypass valve around the turbo-compressors is provided.

Pebble Bed Reactor Core Design. The PBMR core is based on German high-temperature gas-cooled pebble bed reactor technology demonstrated in the AVR and THTR reactors. It used spherical pebbles 60 mm in diameter, each impregnated with about 15,000 enriched (8% U-235) uranium particles coated using the three-layer Triso process shown schematically in Figures 3

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2 All figures were provided by PBMR Ltd and are presented here with its permission.

3 The pressure boundary connecting the pressure vessel to the vessel containing the turbo-generator has been changed since this drawing was produced.

and 4. This fuel has been utilized extensively in Germany and to some extent in the United States. Figure 5 shows data from a German test facility indicating that these fuel particles can withstand a temperature of about 1700 degrees C with no damage and up to 2200 degrees C with damage limited to about 0.01% of the fuel.[4] These test results are based on the release of the fission product Krypton–85 during annealing for 100 hours as an indication of fuel damage. The maximum operating fuel temperature under normal conditions is about 1200 degrees C, with an average fuel temperature of about 1000 degrees C. This will provide helium with an average temperature of about 900 degrees C to the gas turbine. Studies of the depressurized loss of forced circulation (DLOFC) indicates that the maximum fuel temperature would not exceed 1450 degrees C (see Figure 6). Even if the control rods are withdrawn simultaneously with a DLOFC, the maximum fuel temperature is not expected to exceed 1600 degrees C.

The core has a cylindrical inner region where the pebbles contain only graphite and an annular outer region where the pebbles contain fuel. This arrangement flattens the neutron flux and limits the maximum fuel temperature in the core under both operating conditions and accident (DLOFC) conditions. The core contains approximately 100,000 moderating balls and 300,000 fuel balls. About 5000 pebbles are removed from the core each day and separated into moderator and fuel categories by a gamma ray monitor. Moderator pebbles are recirculated to the center region of the core and fuel pebbles are assayed neutronically to determine if the amount of fuel remaining warrants recirculation to the fuel region. On average, each fuel pebble is recirculated 10 times before being sent to a spent fuel storage facility that is large enough to store all spent fuel pebbles used in 40 years of operation. The outer 5 mm of each pebble is graphite without fuel particles so that minor damage to the pebble's surface due to handling and recirculation does not release fuel particles into the system.

Since the power level is controlled by adjusting the helium pressure, the primary need for external reactivity changes is to compensate for xenon changes for which control rods are used. Both control and safety rods are located in the solid moderator reflector outside the pebble bed core. Reactivity loss due to burnup and removal of fuel pebbles is compensated for by the addition of newer fuel pebbles at the top of the core to maintain minimal excess reactivity.

Instrumentation and Control. The instrumentation and safety systems will be assembled from traditional commercial off-the-shelf components used in nuclear power plants around the world. Plant trips will be initiated by conventional "bi-stable" units. The reactor will be fitted with separate and diverse control and shutdown systems for purposes of defense in depth to bring the reactor to a subcritical state. The reactivity control and shutdown systems are designed to individually make the reactor subcritical at normal operating temperatures and keep it there for an indefinite period of time. Digital components will be used where they are available

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4 Notwithstanding these test results, some fuel experts believe that 1900 degrees C is a practical upper limit for the temperature in silicon carbide coated fuel, even during accident conditions.

commercially, but custom-built digital components will not be utilized if a satisfactory analog-type system is available. The control system adjusting the helium pressure is expected to incorporate a simulation model of the thermal-hydraulics of the plant (the same model currently being used in the design of the plant) in order to achieve the desired rate of change of power.
Plant Configuration and Staffing. The initial PBMR plant will be a single 110-MWe module for demonstration and testing purposes. The standard plant configuration will be 10 modules, with a total generating capacity of about 1100 MWe, operated by a crew of three supervisory operators supported by administrative and maintenance personnel. Operation of each individual modular plant will be entirely automated. A "two-unit" plant would consist of two arrays of 10 modules with an augmented administrative and maintenance staff. The total staff on site for the 1-, 10-, and 20-module configurations would be 52, 80, and 126 total staff members respectively.

PBMR Ltd. Design Philosophy. The design of the PBMR is driven by two factors: safety and economics. PBMR Ltd. has chosen what it considers to be an ultra-safe nuclear power generating technology. It maintains that once inherent safety is assured with high-quality, high-temperature fuel having a strong negative temperature coefficient, all other design decisions are driven by economics. It maintains that there is a very substantial margin in the Triso fuel over the maximum temperature that could be reached under the worst accident conditions. It points out that in the PBMR, the fuel is the last thing that would be damaged in an accident whereas in the LWR technology, the fuel is the first thing that is damaged (e.g., as at Three Mile Island-2 (TMI-2). The PBMR design provides a large core with low power density (about 5 MWt per cubic meter) and lots of surface area to dissipate heat. It maintains that there is an inverse relation between plant thermal output and safety and has chosen a small modular plant.

Although a probabilistic risk assessment (PRA) has not been carried out for the PBMR, risk considerations are important to its designers. PRAs carried out for the HTGR designs of the early 1980s, even for those with steam cycles that involved the two-phase behavior of pressurized water in plant accident scenarios, gave core damage frequencies (CDFs) at least an order of magnitude smaller than for the LWRs of that era. Given the improvements of the PBMR design over the HTGR plants and the use of a single-phase coolant, the CDF of the PBMR should be even lower. PBMR Ltd. maintains that risk associated with the PBMR is reduced by the use of high-integrity Triso fuel particles, the large negative temperature coefficient, the inert single-phase coolant, the high heat capacity and the low power density of the large core, and the long thermal time-constants associated with the pebble design. Each of these factors individually contributes to reducing the probability of a core-damaging accident, and the synergistic interactions of these factors reduce the risk further. It is the contention of the PBMR designers that the resultant risk is so low that accident-mitigating systems, such as engineered safeguard features or a conventional containment structure, would contribute little to reducing the risk associated with the operation of the PBMR and would certainly not be cost-effective.

Having achieved what it considers to be assured safety, all other PBMR Ltd. decisions are driven by economics. It has competitive bids on major components such as the gas turbo-generator, the recuperator, and circulators. The German fuel fabrication plant will be duplicated in South Africa with considerable assistance from experienced German fuel fabricators. It sees no need for plant containment in the traditional sense; only a civil structural "confinement" is used. Putting in additional safety systems that are not justified on technical grounds is viewed as being out of the question. Indeed, it indicates that the whole project will be canceled if costs are driven up by what it considers to be unjustified additional requirements just to give "warm fuzzy feelings" to regulators and politicians.

Never previously in history has a nuclear power plant design been pursued with such a focus on economics . PBMR Ltd.'s goal is 1.5 cents per kWh so that this "Generation 4" nuclear power plant will be competitive with new coal plants in South Africa. Right now, PBMR Ltd. calculates that the cost of electricity for a 10-module plant with 80 plant staff members constructed in 24 months at a cost of $100 million per module (with 25% owners cost) will be 1.6 cents per kWh, using a load factor of 93 percent, a discount rate of 6 percent, and a 30-year amortization period. If such a cost level is achieved in South Africa, it is virtually guaranteed that the PBMR plant will be economically competitive anywhere in the world (see retail electricity prices for various countries in Figure 7), and PBMR Ltd. has a business plan that would result in literally hundreds of plant modules being installed in the next two decades.

PBMR Ltd. Approach to Licensing and General Design Criteria. Historically, the approach to licensing non-LWR plants has been to adapt LWR licensing procedures (i.e., those currently documented in the licensing agency's standard review plan) to reflect the different technology involved. Sometimes this practice leads to reasonable results in which the difference in technology is not large (e.g., a heavy water moderated and cooled plant that uses the Rankine steam cycle has many characteristics similar to an LWR plant). In other cases where the technology is substantially different, such adaptations can lead to absurdities. For instance, many years ago, I remember a Gulf General Atomic HTGR design being analyzed for a "non-mechanistic leak" of helium coolant through a 1 square-foot hole in a prestressed concrete pressure vessel. There was no technical basis for the 1 square-foot hole or the non-mechanistic leak, and the contribution to safety of such an analysis was not apparent.

To avoid such a situation with the NNR, the South African nuclear licensing authority, which has no previous experience with gas-cooled nuclear power plants, PBMR Ltd. developed a philosophical basis, called the Safety Case Development Framework, for licensing a gas-cooled reactor from which a set of general design criteria (GDCs) could be established. I will try to summarize this Safety Case Development Framework as I understand it.

Basic Tenets of the Safety Case Development Framework.[5] The PBMR is a nuclear reactor

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5 Materials beyond this point (except for the last section) are taken, with permission, from a draft document provided by PBMR Ltd.

system designed to derive maximum safety benefits from its natural characteristics. This gives significantly advantageous safety performance compared to LWR designs that must rely on engineered safety systems to achieve an acceptable level of safety. The most important characteristics of the PBMR design are (1) the proven ceramic fuel elements that ensure containment of fission products in billions of tiny fuel elements up to temperatures significantly greater than the maximum temperature associated with the worst accident sequence, a depressurized loss of forced circulation with simultaneous control rod withdrawal, (2) the negative temperature coefficients of reactivity associated with increasing fuel temperatures, (3) the low power density associated with a large core geometry that has a large heat capacity, (4) use of an inert single-phase coolant, and (5) low excess reactivity. This means that natural shutdown can be achieved without engineered safety systems because no credible faults can lead to the loss of fuel integrity, thus assuring containment of the fission products. No operator action is required for several hours following a faulted condition.

The fundamental safety design philosophy is based on the premise that the fuel adequately retains its integrity and hence contains radioactive fission products under normal and accident conditions and thereby assures radiological safety. This is achieved by relying on fuel whose performance has been demonstrated under simulated normal and accident conditions and whose integrity is, therefore, not challenged even under any accident conditions. To ensure this fuel integrity is maintained, the plant design for normal and accident conditions (1) includes sufficient heat removal capability such that the maximum fuel temperatures remain in the proven safe region, (2) limits chemical and other physical attacks on the fuel, and (3) provides adequate measures to ensure the shutdown of the reactor and to control reactivity indefinitely under all conditions.

Fundamental Safety Design Philosophy. PBMR Ltd. contends that an appropriate analysis demonstrates that the Fundamental Safety Design Philosophy has been met with adequate margins. The design has been systematically analyzed to ensure that all potential accident and operating conditions have been identified and evaluated. This analysis will be updated with any changes to the design during the plant's life and reviewed periodically. The design is such that any single failure of an element of the safety case does not invalidate the Fundamental Safety Design Philosophy through the use of "defense in depth."

The design ensures for all pathways that any dose received by the operators and public and radioactive releases to the environment in normal operations, as well as risks from accident conditions, not only meet all NNR regulatory limits and constraints but also are "as low as reasonably achievable." The PBMR design minimizes the generation of radioactive waste throughout its life cycle (including decommissioning) and includes appropriate processing, conditioning, handling, and storage systems.

An extensive test and commissioning program will be used to demonstrate the performance of all systems, structures, components, and materials important to safety. This program ensures that any physical phenomena that have a unique application to the safety of the PBMR design are adequately demonstrated on the first module. To support the safety of the plant, the PBMR operates inside a series of defined programs throughout its operating life. These include (1) operations, (2) radiation protection, (3) maintenance, and (4) inspection and testing. The plant design facilitates and makes provision for these programs. Over its entire life cycle, the PBMR will be supported by a quality management system

Key Technical Features and Characteristics of Safety. The PBMR uses passive safety design features and inherent characteristics to contain fission products at the source of their generation —within ceramic coated fuel particles—for the full range of licensing basis events. Aspects of PBMR technology that allow reliance on passive features and inherent characteristics are as follows:

High Heat Capacity/Low Power Density. The high heat capacity of the graphite-moderated core, in concert with its large size and the relatively low power density of the core, results in a very slow response to imbalances in heat generation and removal during both operating and accident conditions. The large heat capacity of the PBMR core and the large margin between the maximum fuel temperature under accident conditions and the fuel failure temperature are primary factors in the ability of the PBMR to withstand an indefinite loss of coolant circulation.

High Temperature Capability. The graphite structural elements of the core maintain strength (which actually increases at high temperatures) to temperatures far in excess of those reached in conceivable accident conditions. This process assures that the core remains in a stable configuration. Low-probability accident analysis is greatly simplified and uncertainties are reduced by eliminating the potential for reconfiguration of core materials, that is, a severe core disarray accident.

Inert, Single-Phase Coolant. Because the helium coolant is chemically and neutronically inert and is not required for decay heat removal, whole classes of accident events are reduced or eliminated. Since there is no phase change of the coolant under accident conditions, the complex semi-empirical relationships for flow and heat transfer characteristics of water as a function of geometry, pressure, boiling regime, and so on, are avoided.

Reactor Cavity Cooling System (RCCS). The RCCS removes heat from the reactor cavity by circulating water through arrays of cooling vessels. The thermal capacity of these vessels filled with water is sufficiently large that heat can be transported away by boiling for a long period even without active circulation. The RCCS maintains acceptable reactor cavity concrete temperatures under normal operating conditions and, in conjunction with the features previously discussed limits the reactor internals and reactor vessel to acceptable temperatures under accident conditions.

Civil Structures. The reactor building is a low-pressure confinement and is designed to support and protect the reactor and equipment. Parts of the civil structures important to safety provide protection from (1) environmental factors (seismic events, flooding, etc.), (2) external events (including aircraft crashes),(3) internal blowdown forces, and (4) internally generated missiles.

Classification of Systems, Structures, and Components (SSCs). The classification of SSCs is a necessary input into the design rules because it determines the quality assurance requirements and the importance of the particular SSC in meeting the PBMR Fundamental Safety Design Philosophy Statement. The standard used is American National Standards Institute (ANSI) 51.1, which divides SSCs into four groups: Safety Classes 1 to 3 and Non-Safety-related. The primary boundary is Safety Class 1. The systems engineered to directly support the cooling of the fuel in case of a loss of coolant and emergency reactivity control are Safety Class 2. Those systems that provide support to Safety Class 2 SSCs are Safety Class 3. In application to the PMBR, the barrier for containment of fission products is the coatings on the fuel particles, and thus they are considered Class 1. The function of heat removal following a loss of cooling event is achieved by conduction, convection, and radiation heat transfer through the core structure, the core barrel, and the reactor pressure vessel to the structures in the reactor cavity. These are, therefore, Safety Class 2 components. In the same way as the ultimate heat sink on an LWR, the RCCS and related civil structures are classified as Safety Class 3. Due to the inherent characteristics of the PBMR, there are no conditions in which external emergency addition of negative reactivity is required to limit fuel temperature; thus, there is no specific system needed for this function.

Philosophy for Derivation of General Design Criteria for PMBR. As indicated earlier, many criteria and analyses designed for LWRs are often not applicable to gas-cooled reactors. However, there are general criteria, for example, quality assurance and external events, which are universal and can be used for any nuclear reactor design. Furthermore, the PBMR Fundamental Safety Design Philosophy (PFSDP) previously discussed together with the PBMR Basic Licensing Criterion LG-1037 issued by the South African NNR, which provides a basis for deriving GDC's for the PBMR.

A specific example will help illustrate the process. Event trees can be used to identify challenges to the fuel integrity. One such challenge can come from reactivity control. The appropriate GDC specifies that the coefficient of reactivity of the core must be negative with increasing temperature of the fuel under all possible circumstances. A complete set of safety-relevant GDCs can be generated using the following steps: For each of the Fundamental Safety Design Philosophy Statements, challenges are identified, or the implications of the statement are detailed in order to formulate GDCs. After an internal review of these steps, the resultant GDCs are formulated for the PBMR to negate these challenges.

Observations and Implications for the NRC and ACRS of the PBMR Program

The development of the PBMR is a logical next step for Eskom Ltd. in meeting its need for new economical electrical generating capacity. However, the PBMR is innovative, imaginative, and very different from other nuclear power plants operating throughout the world. As a result, it is controversial. Although Eskom Ltd. has experience operating two PWR power plants, the proposed plant uses a totally different type of reactor. Indeed, it is even different from the traditional HTGRs and the AGRs in that it uses the direct Brayton thermodynamic cycle and recirculating pebbles containing the fuel. However, it has many features in common with one of the Generation 4 concepts being studied under the aegis of the DOE in its NERI (Nuclear Energy Research Initiative) program.

Although hard numbers are difficult to find, it has been generally estimated that the cost of developing new reactor concepts (e.g., the PWR, the BWR, and the HTGR) to the commercialization stage has been about $500 million each in the dollars of that time (probably equal to $1 billion today). Yet, Eskom expects to carry the PBMR program through the construction of one module for $120 million for development, plus $110 million for the construction of the first module. In effect, it will carry out tests on the first PBMR module that are more typically carried out on thermal-hydraulic or other test facilities. PBMR Ltd. believes that the pebble bed gas-cooled reactor concept has been proven to be extraordinarily safe through operation of the AVR and the THTR reactors in Germany and is backed up by hundreds of reactor-years of operating experience with AGR reactors in the United Kingdom. The Triso fuel with its large negative temperature coefficient of reactivity, the large core and low power density, as well as the use of an inert single-phase coolant, provide defense in depth beyond that of LWR plants. Hence, PBMR Ltd. believes it is logical and more advantageous to build and test one modular reactor than to spend an equal amount of money on tests and analyses.

Once safety considerations have been dealt with adequately, all other decisions regarding the design of the PBMR are being driven by economic considerations. PBMR believes that this is the only way that the cost of electricity from PBMR will be competitive with alternative power systems in South Africa. If the PBMR is competitive in South Africa where the cost of electricity is among the lowest in the world, it would undoubtedly be more than competitive in the vast majority of countries throughout the world. However, there are many considerations other than cost that go into a decision to buy a nuclear power plant. The credibility of the safety analysis and reliability of the plant are of primary importance to regulatory authorities and potential customers. The "gold seal of approval" for nuclear power plants is either the issuance of an operating license for a plant or the certification of the design by the NRC. If the PBMR is successful in South Africa, it seems inevitable that NRC will be asked to review and certify the design of the PBMR.

Given the current competitive situation associated with deregulation of the utility industry, and the emergence of IPPs (independent power producers) and "Merchant Power," it is not likely that U.S. utilities will build any more nuclear power plants in the near future. Nor are IPPs or merchant power producers likely to build nuclear power plants because of their sophisticated nature and regulation by the NRC. However, it is very likely that, given a successful PBMR plant, NRC will be asked to certify the design by PBMR Ltd. or one of its customers.

The first issue that is likely to arise in such a review is the absence of a traditional containment vessel. The populations of nations having nuclear power plants have come to expect containment vessels as part of all nuclear power plants. Indeed, it is "common wisdom" that the TMI-2 containment prevented the spread of radioactivity over the countryside and the lack of containment at Chernobyl was responsible for the widespread dispersal of fission products over much of Europe. While there are elements of truth in both of these statements, neither is categorically true. PBMR Ltd. maintains that a conventional containment is unnecessary for the PBMR and is a financial burden that could make the PBMR uncompetitive with other South African power alternatives. Whether this is the case in other countries is not clear.

The PBMR is the forerunner of the "Generation 4" type nuclear power plants. Non-traditional ultra-safe reactor designs in the past, such as PIUS, have stirred considerable interest but none, to the best of my knowledge, were ever seriously considered for construction. However, Eskom Ltd. has already spent $30 million on the development of the PBMR over the past 5 years and indicates that it is willing to spend a total of at least $230 million on the design, development, and construction of the first modular PBMR plant. The PBMR is really the first serious attempt to introduce a new commercial nuclear power plant type since the HTGR of the early 1980s. It has virtually no discharges into the environment and does not contribute to global warming. It would appear to be economically competitive with power plants using fossil fuels almost anywhere in the world. If the cost and safety goals established by Eskom Ltd. are met, we can expect to see literally hundreds of PBMR modules being built around the world in the next decade or two.

Table 1. Plant Specifications

Max. sent out power	100-115 MW
Continuous stable power range	0-100%
Ramp rate (0-100%)	10%/min
Step change	10% of current power
Load Rejection w/o trip	100%
Cost	$1000/kWe
Construction Schedule	24 months
General Overhauls	30 days per 6 years
Outage rate	2% planned & 3% forced
O&M and Fuel costs	$4-5/MWh
Emergency Planning Zone	<400meters
Plant Operating Life Time	40 years

Fig. 3 Fuel Element

HTR Pebble Cross-section

Cut-away Coated Particle

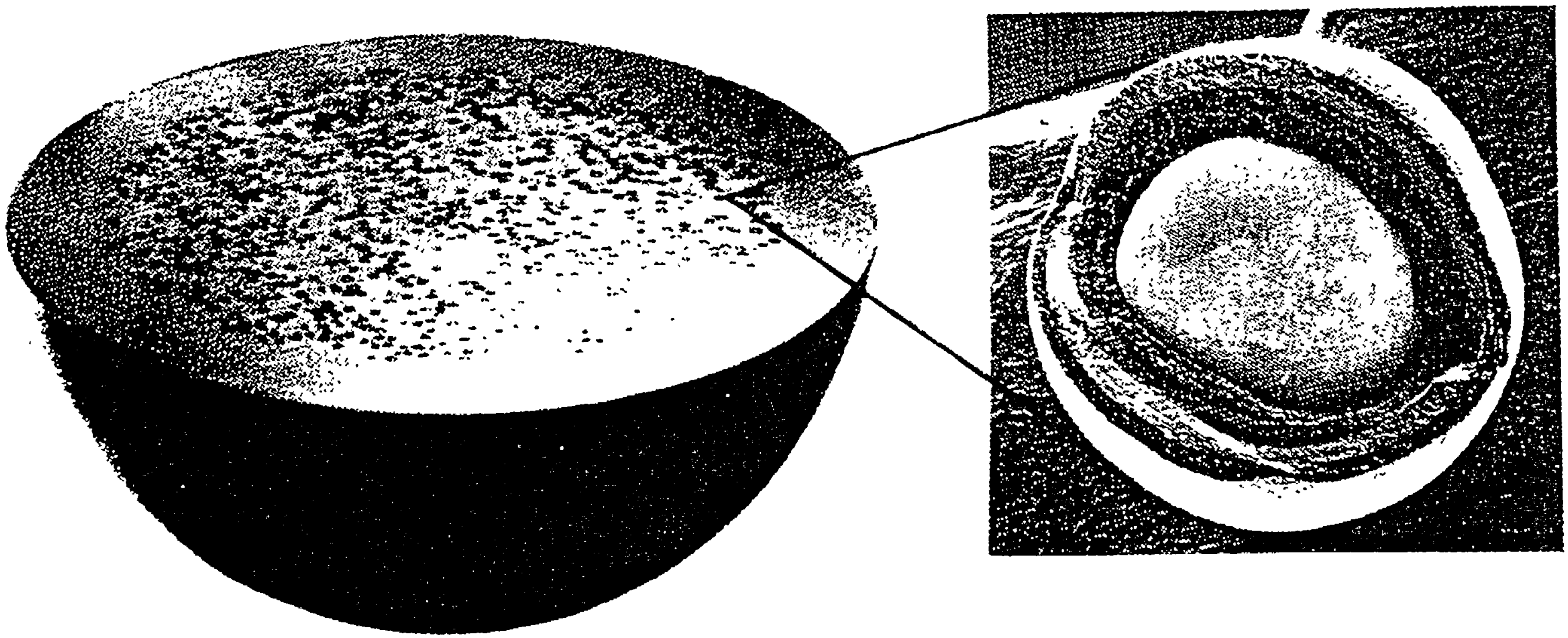

Fig. 1 Gas Circuit Outline

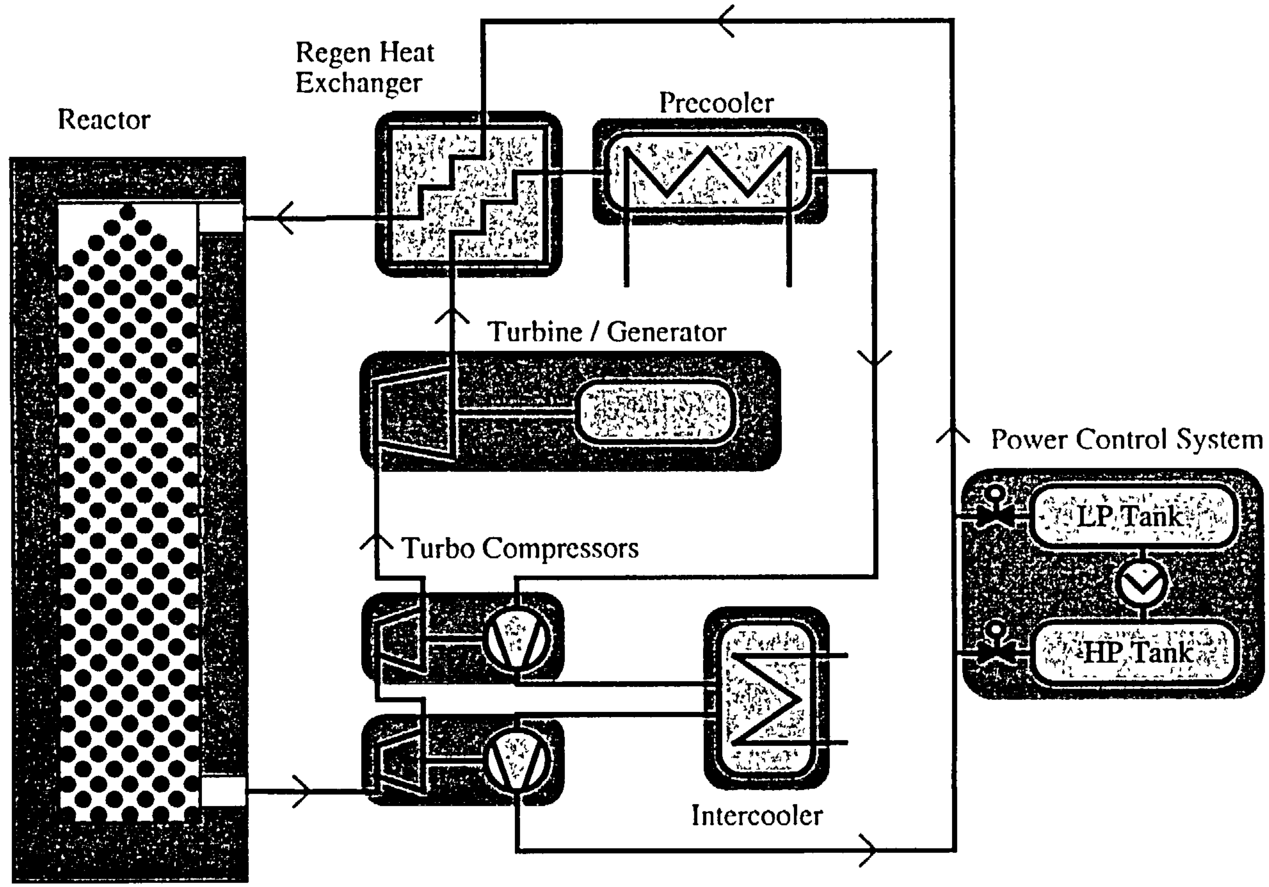

Fig. 2 Main Power System

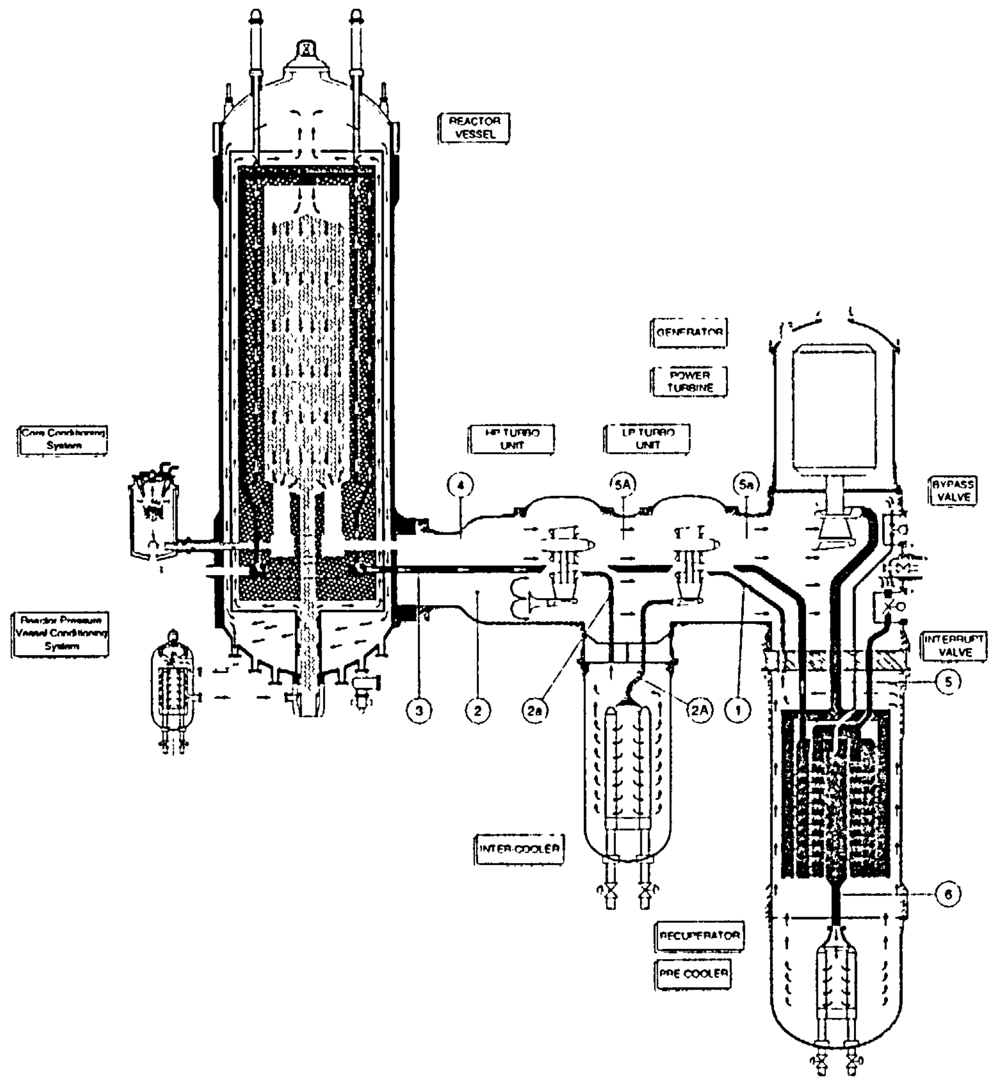

Fig. 6 Loss of Coolant Event

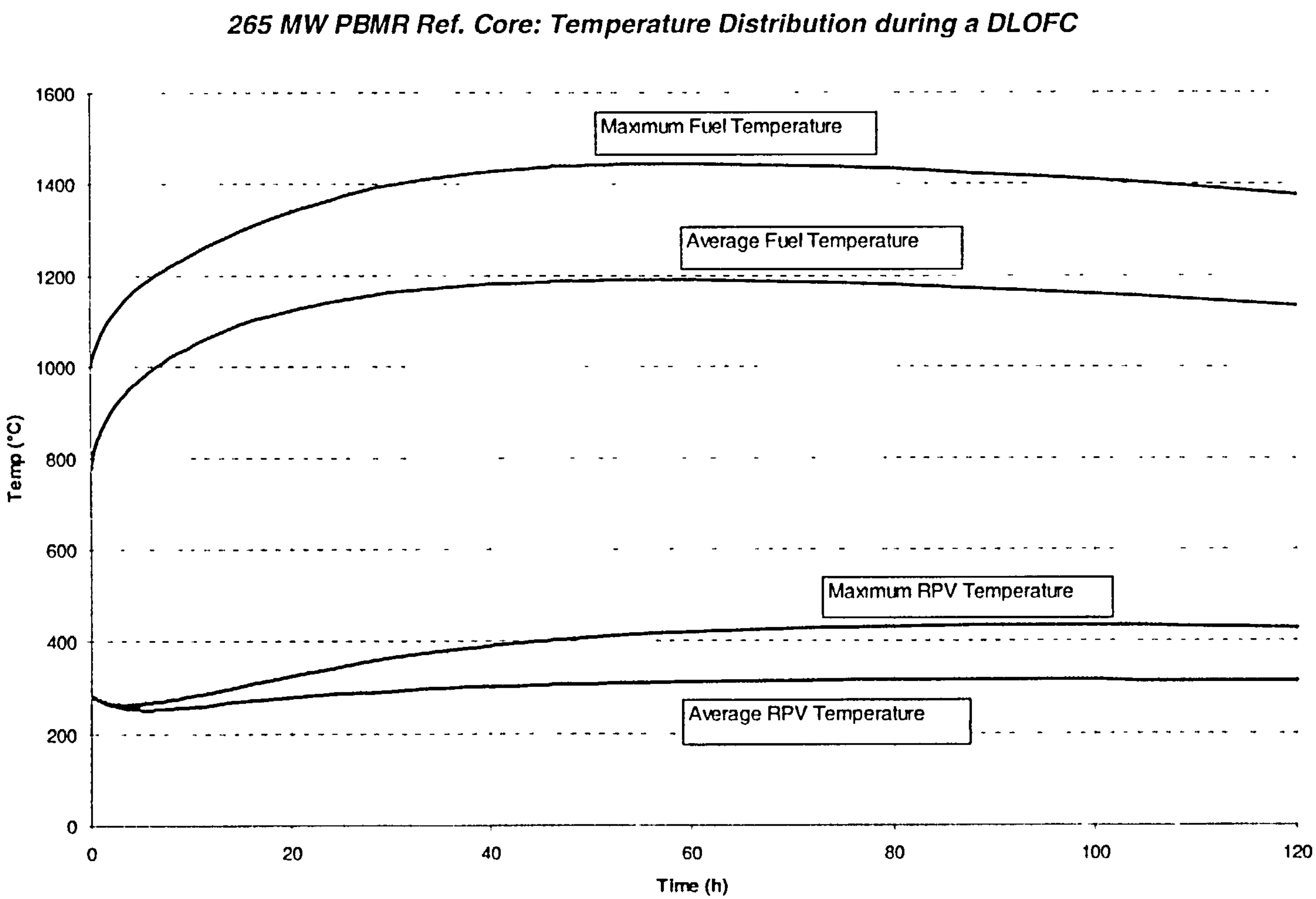

Fig. 4 Fuel Design

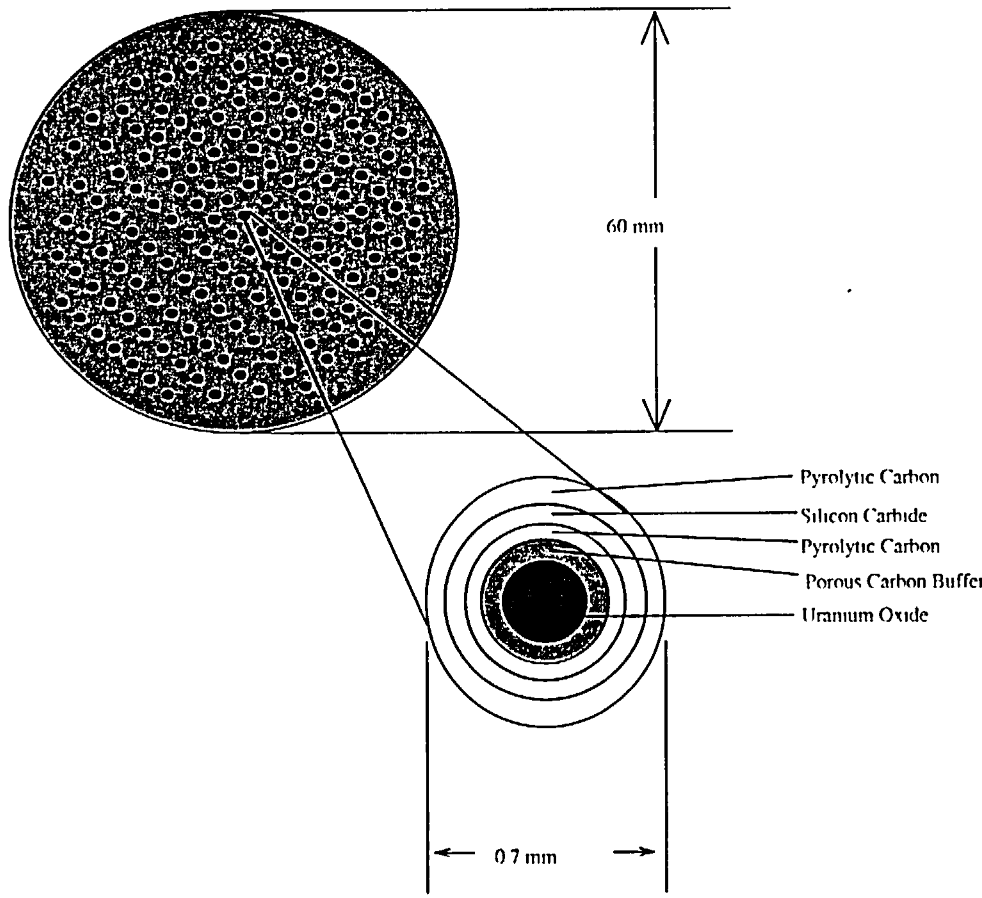

Fig. 5 Fuel Performance

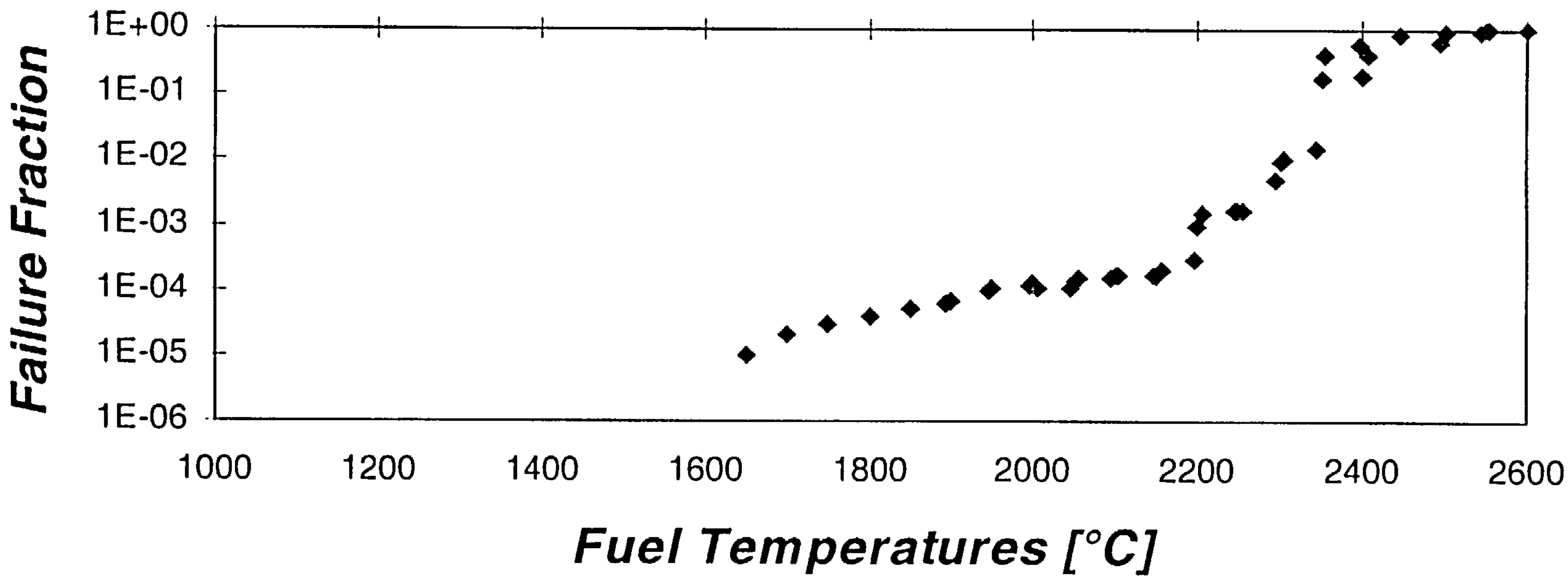

Fig. 7 Retail Prices/Country