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TECHNICAL OUTLINE OF A HIGH TEMPERATURE POOL REACTOR WITH INHERENT PASSIVE SAFETY FEATURES

R.S. HART
Atomic Energy of Canada Ltd,
Mississauga, Ontario,
Canada

Abstract

Many reactor designers world wide have successfully established technologies for very small reactors (less than 10 MW_{TH}), and technologies for large power reactors (greater than 1000 MW_{TH}), but have not developed small reactors (between 10 MW_{TH} and 1000 MW_{th}) which are safe, economic, and capable of meeting user technical, economic, and safety requirements. This is largely because the very small reactor technologies and the power reactor technologies are not amiable to safe and economic upsizing/downsizing.

This paper postulates that new technologies, or novel combinations of existing technologies are necessary to the design of safe and economic small reactors. The paper then suggest a set of requirements that must be satisfied by a small reactor design, and defines a pool type reactor that utilizes lead coolant and TRISO fuel which has the potential for meeting these requirements.

This reactor, named LEADIR-PS, (an acronym for LEAD-cooled Integral Reactor, Passively Safe) incorporates the inherent safety features of the Modular High Temperature Gas Cooled Reactor (MHTGR), while avoiding the cost of reactor and steam generator pressure vessels, and the safety concerns regarding pressure vessel rupture.

This paper includes the description of a standard 200MW thermal reactor module based on this concept, called LEADIR-PS 200.

1. INTRODUCTION

1.1 BACKGROUND

Reactor vendors have achieved success with very small reactors, for example SLOWPOKE, TRIGA, PULSTAR and MAPLE-X, and with large power reactors, for example CANDU, PWR, and BWR. They have however failed to produce commercially viable small reactors (say in the 10 to 1000 MWth range). This is because the very small reactor technology is not amiable to safe and economic scale-up, while the large reactor technologies cannot be economically downsized.

This leaves a very large potential market (the thousands of small Pacific Islands, the Canadian and Russian north and desalination facilities in the middle east, for example) without an economic nuclear energy option.

For nuclear energy to make a substantial contribution to serving the energy needs of these areas, significant improvements must be made in many areas, including those of safety, environmental impact, operations cost, maintenance cost, security cost, capital cost and high temperature capability. This will likely require the implementation of novel technologies, ranging from reactor technologies to control and construction methods.

1.2 SMALL REACTOR REQUIREMENTS

If small reactors are to be commercially viable, they must, on a specific output basis, challenge the capabilities of large modern water cooled reactors; for example, their capital cost per MW_{th} output, operation and maintenance cost per MW_{th} output, and risk to the public on a per MW_{th} basis must not be significantly greater than that of the large plant.

With this objective in mind, the following are suggested requirements for small nuclear power plants.

1. Inherent Shutdown: inherent characteristics that will achieve reactor shutdown under any accident condition without the use of any active detection or shutdown mechanisms.
2. Passive Decay Heat Removal: The removal of decay heat by natural and passive means, without the use of any active detection or operating mechanism,
3. Eliminate Severe Accident Scenarios: Eliminate real and perceived beyond design basis events for which there are not transparent, inherent or passive solutions. For example, pressure vessel rupture, graphite burn, sodium water/air reaction.
4. Low Environmental Impact: Plant discharges of all types, including chemicals and radioactive isotopes must be minimal. A comprehensive waste management scheme (low, medium and high activity) must be included.
5. No safety dependence on Operator: power plant safety should not be dependent on operator action, and should be immune to malicious or incompetent operator action.
6. Low Operating, Maintenance and Security Costs: The nuclear plant must be no more demanding in any aspect of normal operation than a small fossil-fired station. Small size

plants, particularly those without steam raising equipment, should be capable of unattended remote operation.

7. Broad Application Capability: The technology and concepts employed should serve a broad range of applications ranging from low temperatures (district heating for example) to high temperatures (steel making for example).
8. Broad Size Range Capability: The technologies and concepts employed should allow the construction of reactors covering a broad size range (say 10MW(th) to 1000MW(th)) thereby facilitating standardization of technology.
9. Volume Construction: The plant must be fully modularized, and designed for "production line" fabrication with minimal on-site construction activity.

1.3 LEADIR-PS

This outline identifies a reactor concept with the potential of meeting these requirements, called LEADIR-PS, and develops a specific configuration for a 200MW thermal version of this concept called the LEADIR-PS 200.

The LEADIR-PS power plant concept is the result of taking a fresh approach in determining what is needed to produce a safe and economical power plant design that will meet the requirements of the public, the utility and the regulatory.

Early studies concluded that the nuclear heat transport systems of a small reactor could not operate significantly above atmospheric pressure, if all design requirements were to be satisfied. It was noted that all of the very small reactors currently available, and generally regarded as "inherently safe" (SLOWPOKE, TRIGA, MAPLE-X) are pool type reactors.

It was also recognized that problems and unknowns tended to increase, almost exponentially, as the number of novel features increase. Hence, to minimize the development effort necessary, LEADIR-PS utilizes established technologies to maximum extent feasible, and the minimum number of novel technologies.

Many reactor configurations are possible, for example lead coolant and fuel contained within a zirconium pressure tube of the CANDU type, in combination with a graphite moderator. This however raises many concerns, for example, lead zirconium reaction, zirconium graphite reaction, graphite cooling requirements, etc. Very little technical information exists with respect to most of these issues. LEADIR-PS therefore uses only lead and graphite in the core (external to the fuel), and an established fuel design technology which prevents the fuel from contacting the coolant. This minimizes the range of development work required, allowing a focus on the performance of the lead coolant, and on lead/graphite interaction. Considerable literature exists on the latter.

2. OVERVIEW

It is assumed that the "new generation" reactor would be a fission reactor, and be firmly based on established technologies, possibly merging one or more current concepts.

A brief tabulation (Table 1) identifies the key features of Advanced Reactor Concepts now being developed. The modular high temperature gas-cooled reactor (MHTGR) excels in most areas except capital cost; the relatively high capital cost results from the low power density in the MHTGR pressure vessel (about 20% that of the AP600), and the cost of helium confinement systems. A second tabulation of the materials utilized for coolant, moderator and fuel in current or recent reactors was compiled (Table 2). Various combinations of coolant, moderator, and fuel were considered.

The above efforts identified the potential for a lead (or lead alloy) cooled, graphite moderated reactor utilizing the TRISO coated fuel kernels. Essentially, a MHTGR without pressure vessels, utilizing lead coolant.

Reactors based on this concept, and incorporating inherent shutdown and passive safety features are called LEADIR-PS, an acronym for LEAD-cooled Integral Reactor – Passively Safe. A possible configuration for LEADIR-PS, discussed in more detail in Section 3 and Section 4, is presented in Figures 1 and Figure 2.

A key feature of LEADIR-PS, shared with the Modular High Temperature Gas-Cooled Reactor (MHTGR) under development by General Atomics, is that radionuclide releases are prevented by retention of the radionuclides within the fuel particles under all design basis events without operator action or the use of active systems. Thus, the control of radionuclide releases is achieved primarily by reliance on the inherent characteristics of the coolant, core materials, and fuel. Specifically, the geometry and size of the reactor core, its power density, coolant, and reactor vessel have been selected to allow for decay heat removal from the core to the ultimate heat sink through the natural processes of radiation, conduction and convection, while the negative temperature coefficients of the fuel and moderator assure reactor shutdown.

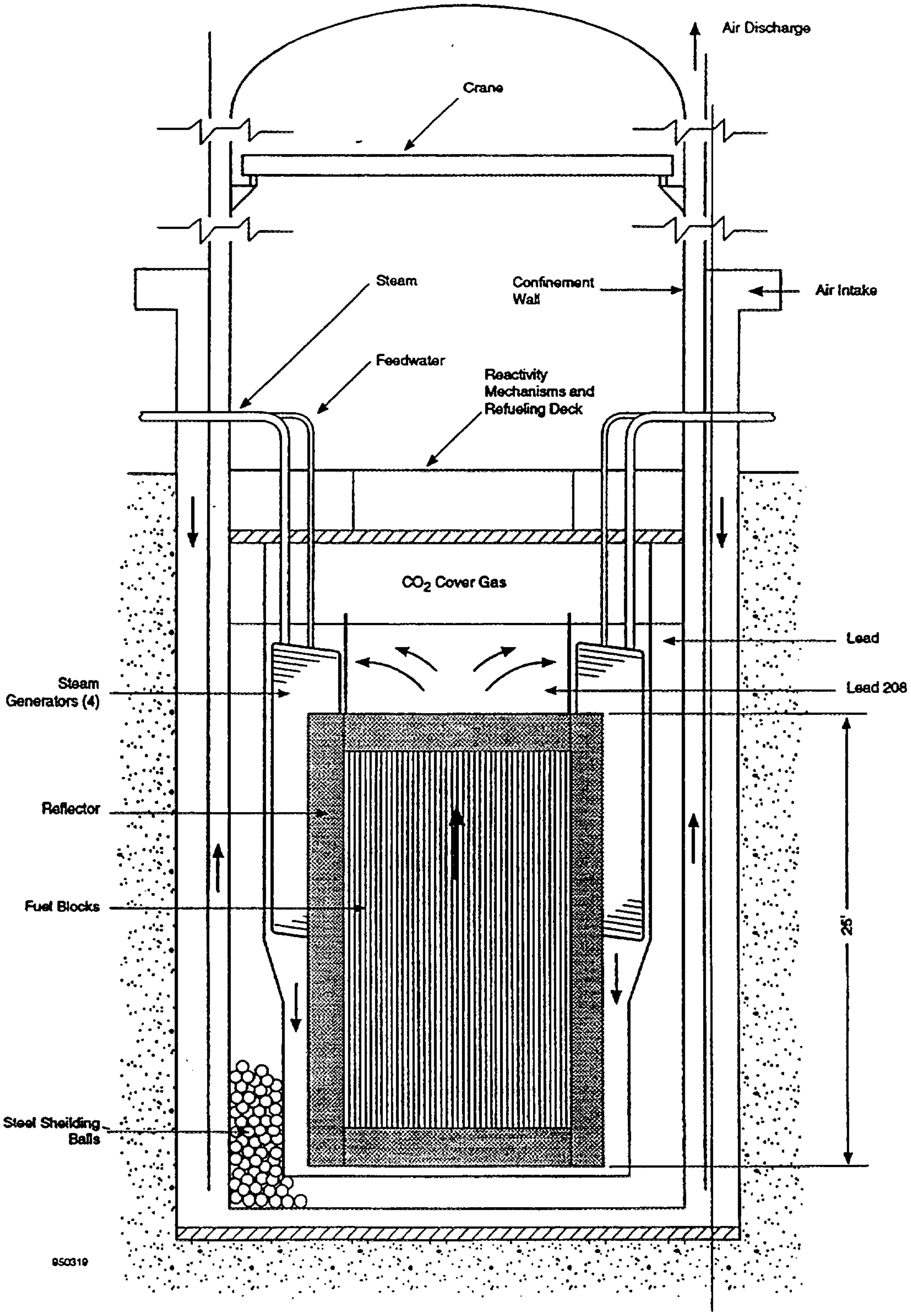

Figure 1: LEADIR-PS 200 Reactor Section

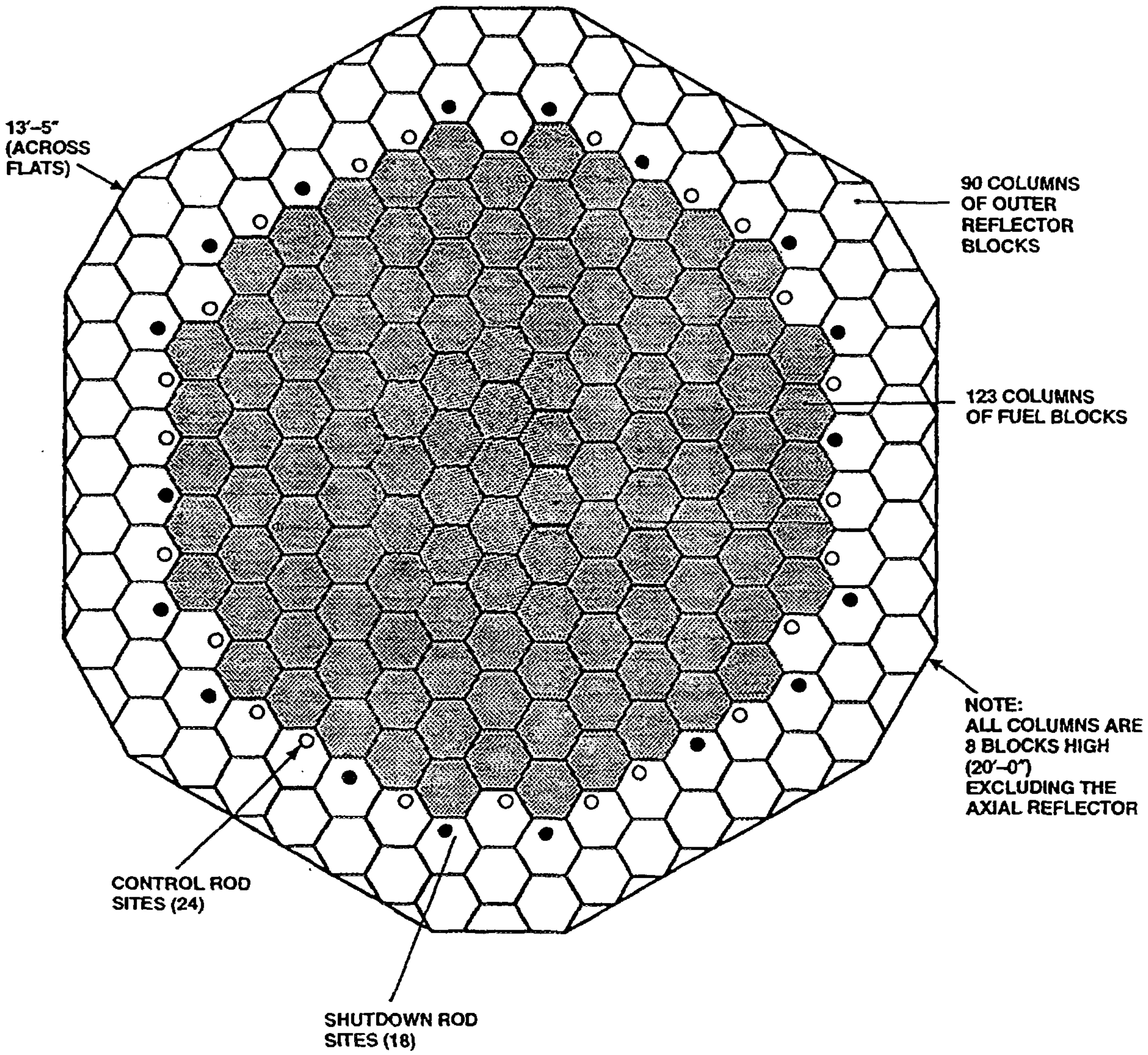

Figure 2: LEADIR-PS 200 Reactor Plan

TABLE 1
ADVANCED REACTOR CHARACTERISTICS

(Relative to Current PWR)

	Inherent Shutdown	Passive Heat Removal	High Temp.	Capital Cost	Operating Cost	Reduced Security Needs	Fuel Cycle	Pressure Vessel
APWR	=	=	=	=	+	=	=	=
AP-600	=	+	=	+	+	=	=	=
CANDU 3	=	=	=	+	+	=	+	+
MHTGR	+	+	+	–	+	+	+	=
PRISM	+	+	+	–	=	=	++	+
+ indicates improved		= indicates same as		– indicates worse				

TABLE 2
MATERIALS BASE FOR CURRENT REACTORS

	COOLANT	MODERATOR	FUEL
PWR	H_2O	H_2O	UO^{2+}
BWR	H_2O	H_2O	UO_2+
CANDU PWR	D_2O	D_2O	UO_2
SGHWR	H_2O	D_2O	UO_2
CANDU OCR	ORGANIC	D_2O	UC
MAGNOX/AGR	CO_2	GRAPHITE	UO_2+
HTR	He	GRAPHITE	UO_2+/TH
LMR	Na	–	Pu/U_2+
USSR SUB	LEAD-BISMUTH	?	UO_2+
+ indicates enriched uranium			

However, unlike the MHTGR which utilizes pressure vessels to house both the steam generating equipment and the reactor, and helium coolant at high pressure, LEADIR-PS incorporates the reactor and heat removal equipment in a pool of lead coolant at near atmospheric pressure.

LEADIR-PS thereby avoids the cost and safety concerns related to pressure vessels, and any prospect of the burning of graphite core materials by maintaining these materials submerged in the lead coolant.

LEADIR-PS 200, a standard 200 MW thermal reactor module based on the LEADIR-PS concept, is discussed in this paper.

3. DESIGN BASIS

3.1 REACTOR OUTPUT

Symbiosis of reactor thermodynamics and physics is necessary to achieve inherent shutdown and passive heat removal for all postulated events. Preliminary calculations indicate that this can be achieved with reactor outputs in the range of 1000MW thermal, utilizing the LEADIR-PS concept.

For conservatism, a reactor of 200MWth was selected for consideration in this paper. This is an appropriate output for many market applications.

3.2 REACTOR ARRANGEMENTS

Two established reactor arrangements, (the Prismatic core and the Pebble Bed core) are possible incorporating the LEADIR-PS concept, each with unique advantages and disadvantages. A feature common to both core configurations in the necessity of holding the moderator and fuel elements down, since graphite is buoyant in the lead coolant. Key factors to be considered in selecting the reactor configuration include the cost of the coolant, and the isotope conversion rate for the coolant in the reactor core and neutron capture cross section of the coolant. The prismatic and pebble bed reactor arrangements are discussed below.

Prismatic Core: A prismatic configuration similar to that adopted by General Atomics for the MHTGR is presented in Figures 1 and Figure 2; the reactor core consists of columns of hexagonal graphite blocks containing coolant passages (Figures 3), and as appropriate fuel, housed within a lead filled steel vessel.

The arrangement utilizes force-assisted coolant circulation to minimize the quantity of coolant in the core. This also maximizes the flexibility of the concept; for example, ordinary lead or lead-bismuth alloy could be used as coolant if the cost of lead 208 (see section 3.3) proves to be too high. On the other hand, if lead (208) proves economic, the design can be modified (increased coolant passage diameter) to provide natural circulation of the coolant under all operating conditions.

Pebble Bed Reactor Core: A pebble bed reactor core arrangement, would be similar to the Siemens/KWU HTR concept, consisting of a bed of graphite pebbles, some of which contain fuel particles, surrounded by graphite reflector. In the case of LEADIR-PS however, the fuel pebbles float in the coolant, and new and recycled fuel pebbles are added to the bottom of the reactor, and irradiated fuel removed from the top (opposite to the THTR-300) during semi-continuous or batch refuelling.

The relatively low inter-pebble forces due to the buoyancy of the pebbles in combination with the lubricating properties of lead facilitate the use of control devices within the pebble bed.

In the pebble bed arrangement about 25% of the pebble bed volume is occupied by coolant. This provides sufficient flow area for natural circulation under all operating conditions. However, detailed thermohydraulic analysis is necessary to confirm the performance of this arrangement under all (normal and accident) conditions.

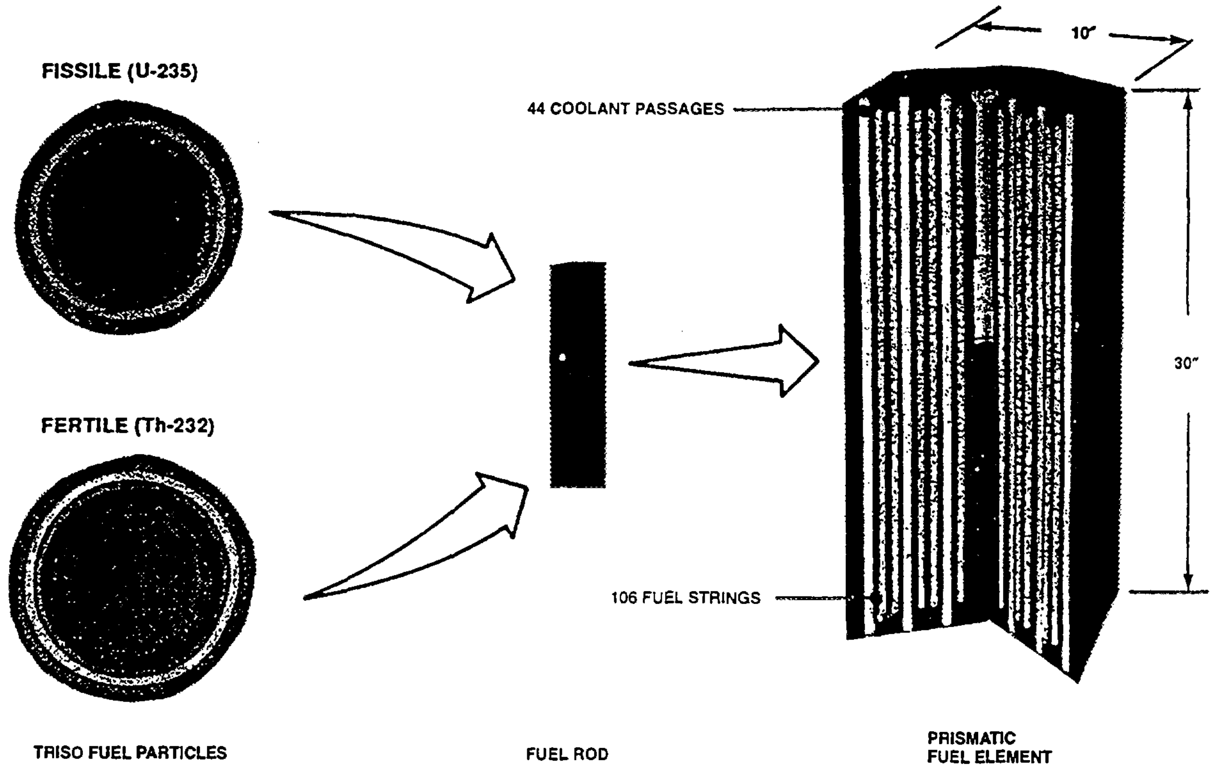

Figure 3: LEADIR-PS 200 Fuel

An annular core configuration, as employed with the prismatic MHTGR core, for reactors with an output above about 600 MW_{TH} also appears feasible with the pebble bed core.

Reference Design: The prismatic core was selected as the basis of this preliminary development and evaluation of the LEADIR-PS concept. This was largely due to the relatively simple analysis, particularly thermohydraulic analysis, afforded by the prismatic arrangement, and the larger data base available for the prismatic MHTGR design. The reference design utilizes periodic off-power refuelling; however, the configuration can also accommodate on-power refuelling (semi-continuous or batch), even if force assisted circulation is used.

3.3 MATERIALS CONSIDERATIONS

General: It is necessary to identify materials for coolant, moderator, and fuel, and for the structure and components of the reactor and reactor systems, which are compatible under all operating conditions. Basic compatibility was established for the combination of lead coolant, graphite moderator, and TRISO fuel, and for lead and the reactor and reactor systems, structures and components. Specifics are discussed below.

Coolant: Various lead and lead alloy coolants were considered. The principal advantage of alloying is a reduction in melting point; lead bismuth eutectic for example, melts at 125°C compared to 327°C for pure lead. Various tritectics have melting points in the mid-ninety celsius range. For this study, pure lead coolant was selected, again, based on the desire for simplicity; alloys such as those containing bismuth add complexity. Lead coolant has a high temperature capability (boiling point of 1555°C at atmospheric pressure). The solubility of graphite in lead is very low while the solubility of silica-carbide is negligible. The lead (208) isotope is the preferred primary coolant due to its very low neutron absorption cross-section (about 1×10^{-3} barnes); it is also a non-moderator. These factors combine to yield a near zero reactivity void coefficient in the well thermalized graphite moderated core.

Lead (208) constitutes about 52% of most naturally occurring lead deposits, and is therefore abundant; however, an economic isotope separation method is necessary to ensure the economic viability of utilizing lead (208) as a coolant., There is also the potential for obtaining lead (208) from specific actinide decay chains; for example the thoria chain yields essentially pure lead 208, although quantities are small.

Moderator: There is extensive experience with graphite moderated reactors. For example Magnox, AGR, RBMK, and HTR in the US and Germany. Hence, graphite performance in high radiation fields, and at a variety of temperatures is established. Graphite is an effective moderator, and does not chemically react with molten lead. The solubility of lead in graphite is very low (about 0.01% by weight at 1000°C for example). A particulate graphite addition system may be necessary to limit graphite displacement from the reflector and fuel blocks.

Fuel: The fuel and fuel element design is derived from that of the MHGR, and illustrated in Figure 3. The TRISO fuel is protected from the lead by the graphite fuel element structure. However, there is no chemical reaction between molten lead and the silica-carbide coating of the TRISO fuel particles, and the solubility of silica-carbide in lead is negligible.

The adapted fuel element design requires a substantial amount of graphite, which contributes to fuel cost and waste disposal costs, if utilized on a "once through" basis. The possibility of removing the fuel pellets from spent fuel elements, and reuse of the fuel element graphite blocks was investigated briefly and is considered feasible. Initial LEADIR-PS200 reactors should operate on the "once through" principle; the technology to recycle the graphite fuel element blocks can be developed later.

Structures & Components: There are a variety of materials available for the structures of the reactor, and for the systems components. These are discussed in more detail in Appendix A.

3.4 POWER CONVERSION

Two basic options exist for electricity generation; a conventional steam turbine driven generator, or a closed cycle gas-turbine driven generator; these are discussed below.

Steam Turbine Generator: This approach is relatively complex and costly, but yields high thermal efficiency (above 40%) in the generation of electricity. Since this paper focuses on the reactor concept, a conventional steam turbine generator is assumed.

Closed Cycle Gas Turbine Generator: A preliminary evaluation of closed cycle gas turbine power module performance utilizing CO2 was completed.

Power turbine, circulator, and generator, operating at 10,000 rpm are housed within a pressure containment, with a turbine inlet pressure of 900psia. The power module is about 1.5m diameter by 4m long, and produces 30MW(e) with an electrical conversion efficiency of about 30%. Exhaust heat is rejected to a low temperature energy user (district heat, water desalination, etc.) at 100°C. Electrical frequency is reduced to 50 or 60 cycle by a solid state converter.

Two such power modules are required for LEADIR-PS 200. The closed cycle gas turbine is very attractive, facilitating modular construction, module exchange maintenance and overhaul, and remote (unattended) operation.

The gas turbine power module could be developed and tested in parallel with and independently from the reactor development program, and adapted when proven.

3.5 DESIGN METHODS

The design process utilized published information on the General Atomics MHTGR to the extent feasible. Physics analysis to confirm the characteristics of the Lead (208),and other lead and lead alloy coolants, and the fundamental neutronic and thermohydraulic core behaviour was completed.

Simple axia symmetric heat transfer models were used for temperature distribution calculations; the accuracy of many of the physical lead and lead alloy properties (viscosity, coefficient of expansion, etc.) used are questionable; refinements in the design may be required.

4. PLANT DESCRIPTION

4.1 OVERVIEW

LEADIR-PS 200 is a standard reactor power module that produces 200MW thermal. It incorporates inherent and passive features that preclude the release of significant activity under any credible situation, without the action of active systems. For example, LEADIR-PS 200 can withstand any combination of loss of forced coolant circulation, loss of normal heat sinks, and reactivity excursion from full power without fuel temperatures exceeding a level at which significant incremental fuel particle failure would be observed.

A section through the LEADIR-PS 200 reactor is shown in Figure 1.

The reactor core, consisting of an array of fuel block columns incorporating TRISO fuel, surrounded by graphite reflector blocks (see Figure 2) is submerged in a pool of Lead (208 isotope) coolant (Figure 1). Four steam generating coils are located around and above the reactor core. During normal on power operation coolant pumps assists natural convection in circulating the coolant downward through the steam generating coils, and hence upward through the reactor core.

The primary lead coolant pool is surrounded by a secondary lead pool consisting of ordinary lead, contained within the reactor vessel structure. The secondary lead pool and steel shielding provides a short term heat sink for the most severe design basis events, allowing the volume of the primary pool to be minimized; it also reduces heat loss during normal operation.

It is necessary to achieve a balance between minimizing normal operating heat losses from the reactor, and assuring sufficient reactor cooling under accident conditions (loss of all active heat sinks for example). In the configuration analyzed, a layer of solid lead forms on the outer wall of the secondary lead pool during plant operation, thereby reducing normal heat loss while retaining heat rejection capability under accident conditions. A natural convection air cooling system surrounds the reactor vessel, to cool the reactor cavity and maintain concrete temperature at an acceptable level.

The inner and outer walls of the reactor vessel are steel, connected by reinforcing webs; each wall is fully capable of containing the lead coolant in the event of a rupture in the other wall. These walls, together with the steel balls in the innerspace, provide neutron shielding for the concrete.

4.2 REACTOR CORE

A cross-section of the prismatic reactor core is shown in Figure 2. It consists of 984 fuel blocks in an arrangement of 123 columns, 900 radial graphite reflector blocks arranged in 90 outer columns, and 426 axial graphite reflector blocks, with one block located at each end of each fuel and reflector column.

The fuel block structure is shown in Figure 3. The fuel blocks are similar but smaller than those utilized in the MHTGR; the width of the blocks is reduced to 10″ from 15″, and the main coolant passage diameter is increased from 5/8″ to 3/4″; the ratio of fuel to moderator is maintained, while allowing larger coolant passages to reduce coolant circuit pressure drop. The graphite radial and axial reflector blocks have the same external dimensions as the fuel blocks. The columns of reflector blocks that contact the fuel blocks each contain 12 coolant passages. Many of the radial reflector blocks contain control rod, shutoff rod, or heater locations. The axial

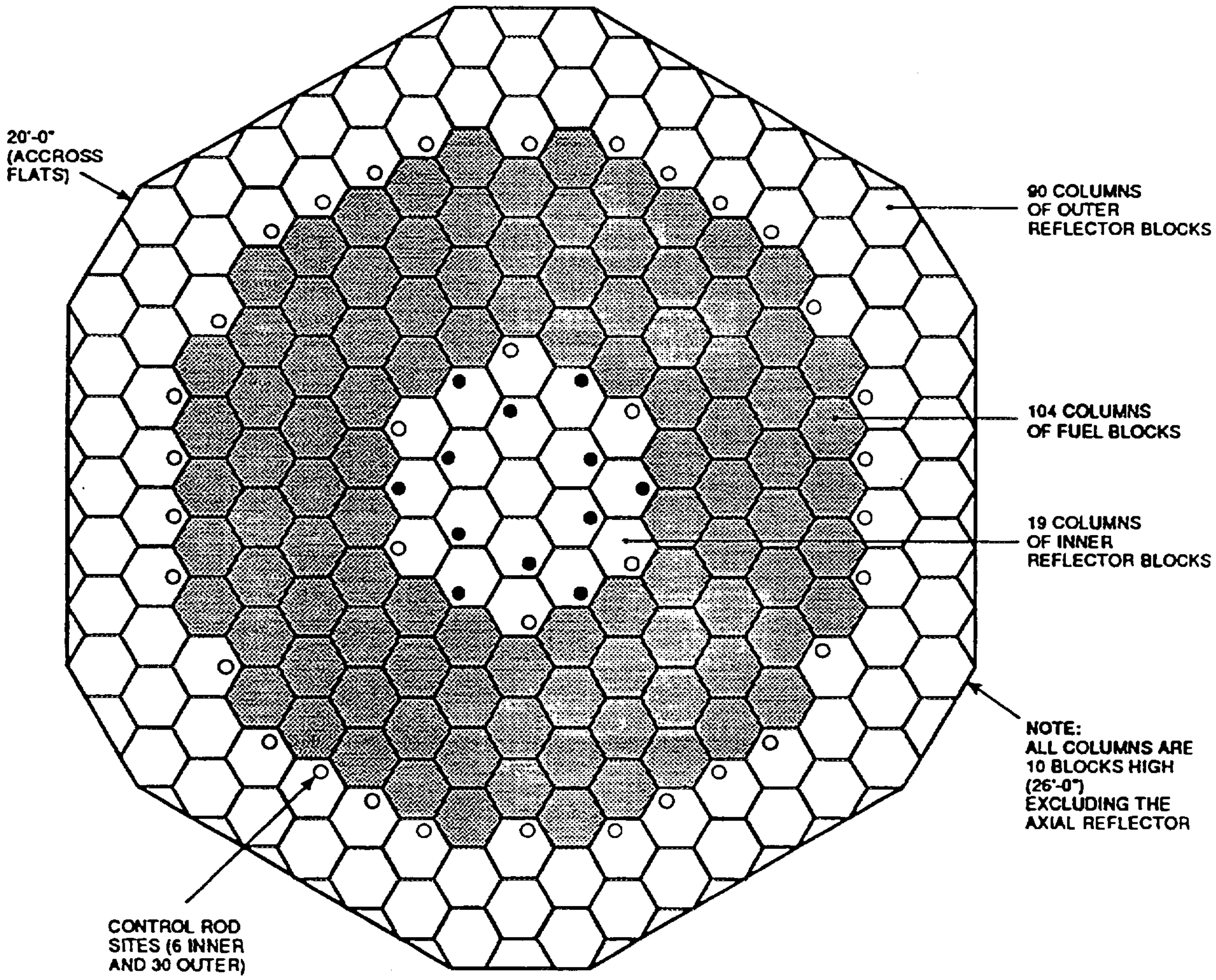

Figure 4: LEADIR-PS 500 (500 MW_{TH}) Reactor Section

reflector blocks contain coolant, control rod, or heater passages that correspond to the fuel or reflector blocks of each column.

The suitability of the LEADIR-PS concept to reactors of larger output was assessed, and a reactor output limit of about 1000 MW_{TH} established. Reactors with outputs above about 600 MW_{TH} require an annular core configuration (similar to MHTGR). The central reflector blocks provide additional heat capacity to accommodate postulated accident conditions, and locations for the control and shutdown rods necessary for reactor control and shutdown.

An arrangement of the core for a 500 MW_{TH} reactor, utilizing an anular core is shown in Figure 4.

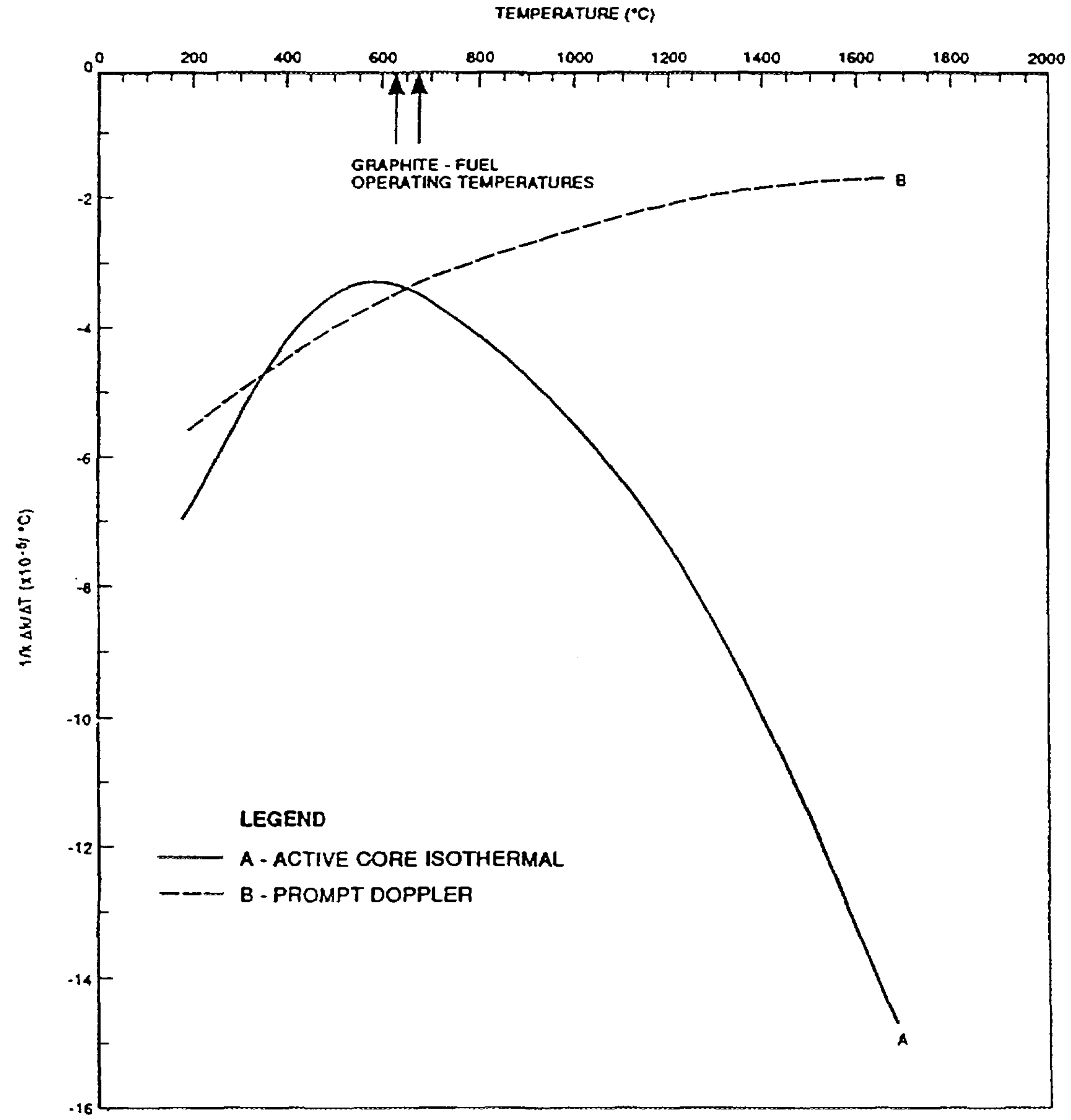

Figure 5: Temperature Coefficient - Equilibrium Core

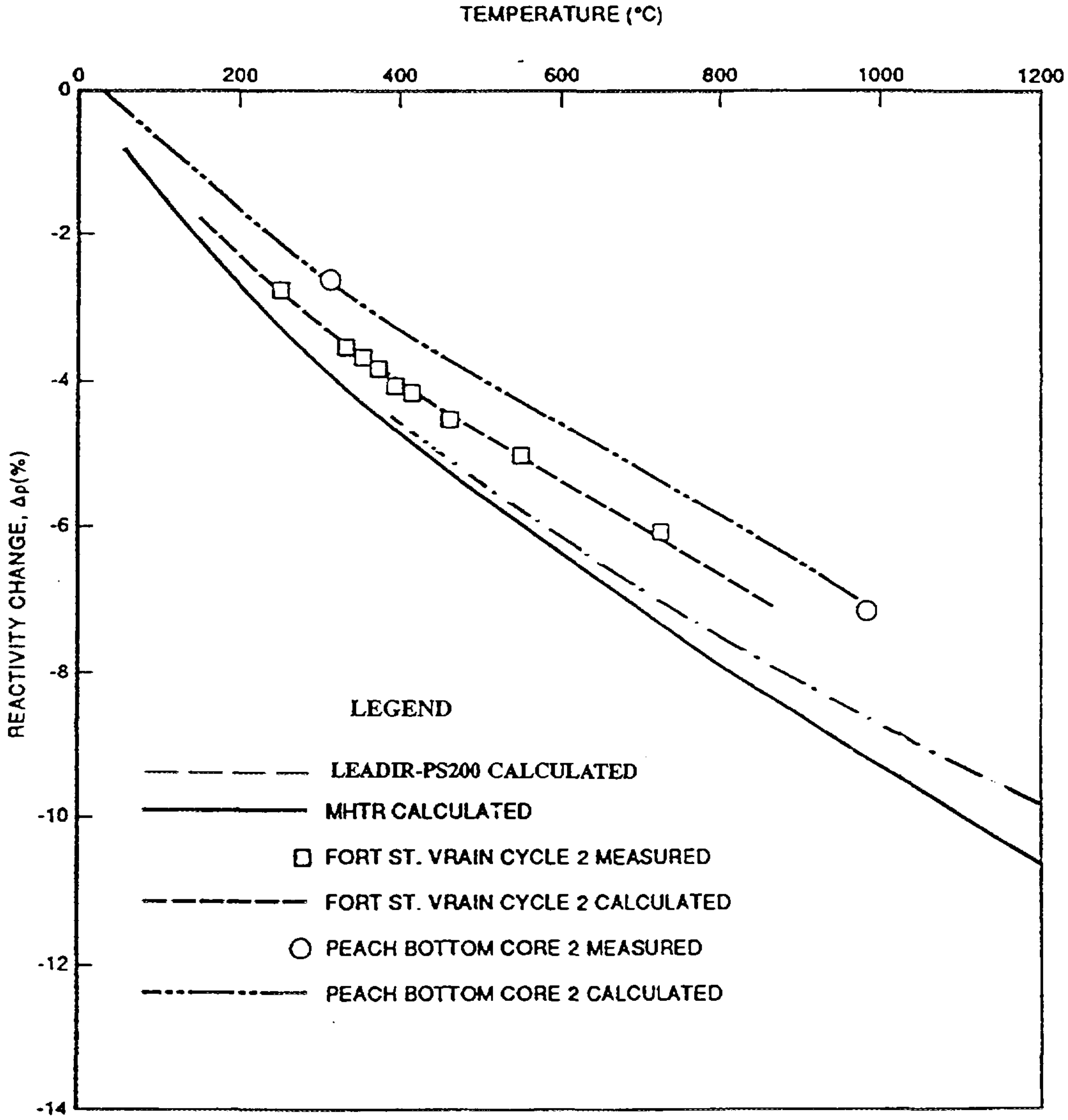

Figure 6: HTGR Temperature Reactivity Effects

4.3 PROCESS CONDITIONS

The reactor coolant (Load 208) conditions were selected so that the temperature leaving the steam generator coils was comfortably above the melting point of lead, in a range of relatively low viscosity. The core outlet temperature was selected to be high enough to provide good electricity conversion efficiency using gas turbine generators, but low enough to assure that the fuel and graphite elements operated well below the experience limit of HTG reactors. The key process parameters are presented in Table 3.

Table 3

Key process parameters

Lead Temperature	– Core inlet		360°C
	Core outlet	- max.	730°C
		- avg.	700°C
Lead Flow	- Core total		11000 lb/sec
	- Coolant passage (each)		2.2 lb/sec
Coolant Pump Power			1000 Kw
Steam Temperature			550°C
Feedwater Temperature			200°C

4.4 OPERATION

The variable speed coolant circulating pump varies coolant flow as a function of reactor power, thereby maintaining a constant core coolant inlet temperature over the normal power operating range. Feedwater flow to each of the steam generators is also varied as a function of reactor power to maintain a constant degree of super heat in the steam.

Independently controlled isolation devices are provided on the feedwater line and steam line to each steam generator.

Incidence during which the primary lead coolant pool solidifies are very infrequent. However, in the event that the lead coolant solidifies during a cold shutdown, coolant flow is re-established by providing steam at 350°C to the steam generators, or by the use of electric heaters that can be positioned in the reflector.

4.5 REACTIVITY CONTROL

Reactor control is provided by 24 control rods located in the outer reflector. A backup shutdown system consisting of 18 shutdown rods is also provided;

In the event that all normal reactivity control systems fail, the negative temperature coefficients of the graphite moderator and fuel (Figures 8 and 9) shut the reactor down well before the integrity of the fuel is threatened.

4.6 HEAT REMOVAL

Heat removal is normally via the steam generators utilizing the normal plant feedwater system. Two of the steam generators are provided with feedwater from an independent system for decay heat removal.

In the event that normal heat removal systems fail, heat is transferred to the reactor cavity cooling system via a combination of convection, conduction, and radiation. In the event that the cavity cooling system is unavailable, decay heat is transferred to the surroundings, primarily via radiation.

In the event that overcooling of the steam generators should occur to the extent that they “freeze”, windows retained by a medium melting point material located between the steam generators near the top of the primary pool will open when the coolant temperature reaches 1000°C thereby allowing the coolant to bypass the steam generators and maintain natural circulation. If purely natural circulation is utilized, the flow geometry can be arranged so that the windows are simple openings, without incurring steam generator flow bypass during normal operation.

Should coolant circulation down the outside of the outer radial reflector blocks somehow be prevented, natural circulation is established upward through the fuel columns, and downward through the reflector columns.

The system is also designed such that, in the very unlikely event of both the primary and secondary pool walls failing, the core remains covered by lead and fuel cooling is assured.

4.7 REFUELLING

For the reactor core configuration selected, about 1/3 of the fuel blocks are replaced every 2 years during the refuelling/maintenance outage.

In advance of refuelling, the reactor is placed in secure shutdown condition via the insertion and securing of all shutdown and control devices. With the temperature stable at an average of 340°C and reactor decay power below 0.5%, the automated refuelling assembly is installed above the refuelling hatch in the mechanisms deck. The refuelling assembly includes a circulation and cooling system for the CO_2 reactor pool gas blanket, and fuel manipulator arm. Except for a cooling system to permit operation above 330°C and the use of CO_2 in place of He, this system is conceptually similar to that employed on the MHTGR.

Alternately, semi-continuous on-power or batch refuelling can be accommodated. Preliminary calculations show that if the fuel blocks of each column connected by a tie rod, are employed the coolant bypass of the core when a fuel column site is vacant is acceptable, even when force assisted circulation is employed.

The lead coolant serves as an excellent lubricant during the refuelling operation, and allows for sufficient clearance between the prismatic blocks to assure refuelling capability. Even under severe seismic conditions, the lead between the prismatic blocks precludes damage due to column impact.

During refuelling, a portion of the fuel removed from the reactor core is returned to the core, together with new fuel elements, while the remainder is placed and sealed into interim storage flasks. The cylindrical flasks which accommodate a column of six fuel elements, are then placed in sealed fuel storage pits located to one side of the reactor. A natural convection air cooling system removes decay heat from the fuel located in the fuel storage pits. After two years this fuel is transferred to a central irradiated fuel management site, or part to the next refuelling process, and the fuel storage pits are reused.

4.8 MAINTENANCE

LEADIR-PS 200 is designed to operate for extended periods (2 or more years) without maintenance. Major maintenance, much of it by "change-out" is completed during scheduled maintenance/refuelling outages every two years. This work is completed by a dedicated maintenance team that, together with the necessary equipment and tools, travels from one LEADIR-PS 200 plant to another to complete the maintenance outages. Assuming a 2 week maintenance outage, a single maintenance crew could service 40 or more LEADIR-PS 200 units. Equipment overhaul and major services are provided by a central maintenance facility.

LEADIR-PS 200 does make provision for unscheduled maintenance, should component failures occur. For example; facilities are provided to allow the removal of a steam generator or control rod with the reactor at power. The reactor coolant pump can be removed with the reactor operating at reduced power. Unscheduled maintenance, which is minimal, is provided by a separate maintenance crew, that is available to a large number of LEADIR-PS 200 plants.

4.9 OPERATION

LEADIR-PS 200 plants utilizing steam turbine generating equipment will likely require the 24 hour per day presence of an 'operator'. This operator will have the capability to shut the reactor down, and to take a number of protective actions, but no authority to start the reactor, or otherwise control the unit.

Control of LEADIR-PS 200 plants will be provided via a central operations facility, capable of monitoring and controlling 20 or more LEADIR-PS 200 units. This facility would also co-ordinate an emergency response team that could respond to any LEADIR-PS 200 accident condition (team member to be available, but not on duty at anytime). Members of the maintenance crew will be present during reactor startup following a maintenance outage. These people will be specifically trained to assist the central control and monitoring group during this procedure.

4.10 SECURITY

Extensive automated security systems will be provided in LEADIR-PS 200. These will detect the unauthorized entry of persons onto the premises, and detect any unauthorized attempt to enter the LEADIR-PS 200 buildings. The security system will provide data to both local authorities (such as police) and to the central control and monitoring facility.

5. SAFETY FEATURES

5.1 GENERAL

The safety features of the LEADIR-PS 200 are dominated by the safety characteristics common to HTGRs as well as features unique to the particular configuration of the LEADIR-PS 200 module. The general safety characteristics are dominated by the inherent characteristics of the coolant, core materials, and fuel as described below.

- LEAD COOLANT — Lead coolant has several advantages including a boiling point well above the assured shutdown temperature of the core; therefore minimal coolant level measurements are required and pump cavitation cannot occur. Further, there are no significant reactivity effects associated with the lead (208) (it is essentially transparent to neutrons) and no chemical reaction between coolant and fuel or moderator is possible.

- GRAPHITE CORE — The strength of the graphite core and the stability of the ceramic fuel coating at high temperatures result in a wide margin between operating temperatures and temperatures that would result in core damage. Further, the high heat capacity and low power density of the core and the heat capacity of the coolant pools result in a very slow and predictable temperature transients.
- COATED FUEL PARTICLE — The multiple ceramic coatings surrounding the fuel kernels constitute tiny independent pressure vessels which contain fission products. These coatings are capable of maintaining their integrity to very high temperatures in the 1600° to 1800°C (2910 – 3270°F) temperature range. Zirconium carbide coatings are capable of even higher temperatures in the 2200°C (4000°F) range.

The physical configuration of the reactor power module assures decay heat removal by passive means in the event that all normal heat sinks are lost, without the action of the operator or any active system, for all credible events.

The design allows the complete separation of the Nuclear Steam Plant (NSP) from the conventional plant; the NSP does not impose any safety demands on the conventional plant beyond those of a typical fossil-fired station.

5.2 RESPONSE TO POSTULATED EVENTS

LEADIR-PS 200 does not pose a safety concern to the public for any credible event; events that are a risk for other reactor types are non-concerns. Coolant channel blockage for example, although very unlikely, does not have significant consequences. Even if all coolant channels in a fuel column were blocked peak fuel temperatures in the block (at full power) would only reach about 1000°C, well below the threshold for fuel failures.

Steam generator tube ruptures are also accommodated. Immediately following the ruptures significant steam generation occurs; however, the lead coolant quickly solidifies in the region of the rupture and steam releases approach those due to the flashing of feedwater only. There is no lead-water reaction, and no public safety concern results.

The location of the reactor core below grade, and submerged in lead also makes the core impervious to most external events. Even an aircraft crash with an ensuing fire would not pose a threat to the public.

5.3 RESPONSE TO TRANSIENTS

LEADIR-PS 200 has a graceful and safe response to all anticipated transients. For example, an overcooling event (as could be caused by loss of feedwater control or spurious opening of steam relief valves in combination with control system failure) causes the core inlet temperature (normally 350°C) to fall; as the freezing point of 327°C is approached the coolant viscosity increases, coolant flow decreases, and in the absence of any control system action, the negative temperature coefficients of the fuel and moderator reduce reactor power. Heat removal is maintained by natural convection.

6. THE FORMULA FOR SUCCESS

6.1 DEVELOPMENT

To minimize development cost and time, maximum use of existing technologies and expertise is required. Hence, cooperation between countries and institutions with relevant experience, for example, with graphite moderator, lead coolant, TRISO fuel, and plant and equipment design is essential. There are two principal areas requiring development, both related to the coolant. These are:

a. To identify a process and estimate the cost of producing lead 208. If this proves to be prohibitively expensive, the concept remains viable with the use of ordinary lead coolant, but requires some modification.

b. To identify the effects of radiation on lead 208, and establish methods of chemistry and isotopic control.

6.2 MASS PRODUCTION

The small reactor will not be economical if produced and operated in small numbers (say 5 or 10 units). A significant population of small plants of near identical design is required. This offers a number of essential advantages:

a. The development, design, and licensing costs are distributed over many units.

b. The economics of mass production and volume construction are realized.

c. The economy of remote monitoring and operation achieve their potential. For example, a single control centre could operate 20 or more units located in diverse locations.

d. Economies of maintenance is realized. For example, if the small reactor requires a maintenance outage of two weeks every two years, a skilled crew could complete the on-site maintenance of 20 or more units a year (i.e. maintain 40 or more units).

e. Central service and overhaul facilities can economically and efficiently service reactor components, on a volume basis, affording maximum economic benefit.

f. Refuelling can also be completed by a dedicated crew, serving 40 or more units if refuelling were required every 2 years.

g. Waste management and disposal can also be efficiently coordinated.

h. Long term research, development, problem solving, and product advancement can be shared by a large user base.

The situation is somewhat analogous to the aircraft industry. A few 737s are not economical, but many 737s operated by many airlines are. Similarly, the economies of volume production and operation of small reactors can be realized even if they are in diverse locations, or even in difference countries. LEADIR-PS is amieable to volume production and operation.

7. CONCLUSIONS AND RECOMMENDATIONS

Confirmation of the market for small reactors is necessary before expending significant effort on their development. Given the limited financial resources of most nuclear vendors, this must go beyond traditional market studies, and firmly establish the intentions of potential users. This is best accomplished by interested users forming and supporting, a buyers organization. This organization would set requirements for the small reactor (including comprehensive economic and performance requirements) conceptually similar to the EPRI requirements for Advanced Light Water Reactors, and co-ordinate and promote the international co-operation necessary to develop a viable small reactor. Support by potential users throughout the process should consist of both finances and expertise. The expert contribution of potential buyers could be substantial, if their respective nuclear development programs were co-ordinated and directed at a common goal.

The LEADIR-PS design which utilizes a novel combination of established technologies and a minimum of new technology to meet the suggested small reactor requirements should be seriously evaluated by the potential small reactor users.

Ferrous alloys have demonstrated varying compatibility with liquid Pb, Pb-Li and Pb-Bi eutectics. In general, ferritic stainless steels such as HT-9 and Fe-9Cr-lMo exhibit superior corrosion resistance in these environments relative to austenitic stainless steels like 316. While exposed to flowing (0.35 l/min.) Pb-17Li at 550°C [1], HT-9 possessed a uniform corrosion rate of 20 um/year. The dissolution rate activation energy was estimated to be 92.5 kJ/mol. Ferritic steels are usually attacked in a uniform manner under these conditions [2], with some intergranular attack occasionally observed. At temperatures greater than 370°C, the weight loss for HT-9 is lower than for Fe-9Cr-lMo [3].

The behaviour of austenitic stainless steels in liquid Pb-Li is quite different. A porous ferrite surface layer forms on the steel, depleted in Cr, Ni, and Mn [2,4,5]. The thickness of the ferrite layer is a function of temperature, cold work, and grain anisotropy. Strong Ni and Cr depletion in the ferrite layer has been observed [4,5]; Ni content falls from 12 % to 0.5-1 I, and Cr content is reduced from 17 X to 3-5 %[4]. It should be noted that the selective leaching of Cr is generally not observed for ferritic steels. A steady state corrosion rate of 30 um/yr was observed for 316L exposed to 400°C Pb-17Li [4]. In addition, the presence of oxygen in liquid Pb-Li increases the ferrite thickness from 45 um to 70 um, and results in greater Ni depletion [5].

In general, the corrosion resistance of ferritic stainless steels is 5-10 times greater than that of austenitic steels in Pb-Li[2]. For a corrosion limit of 20 um/yr, the peak operating temperature is 500°C for ferritic steels and 410°C for austenitic steels[3]. Consequently, the use of austenitic stainless steels is not recommended [6]. For temperatures in excess of 450°C, ferritic steels require Zr or Ti corrosion inhibitor additives, so their suitability for temperatures as high as 750°C is questionable.

Vanadium, niobium, tantalum and molybdenum and their alloys have demonstrated good corrosion resistance in liquid Pb-Li [8]. These materials have dissolution rates in the range 0.001 to 0.004 g/m^2/day at 645°C [8], which is far superior to the performance of Fe-based alloys. However, the cost associated with many of these materials would make their application impractical for a full-scale reactor.

Several materials have demonstrated acceptable corrosion resistance in liquid lead. Fecr-alloy (Fe,0.2 C,13 Cr,4 Al) presented no visible signs of attack after 551 days in 700°C liquid Pb[9]. In addition, Tantiron (Fe,13.5 Si,0.5 Mn,l C) showed no visible signs of attack after 56 days in 720°C liquid Pb [9]. Mo has shown no detectable attack after 300 days in 800°C Pb [9]. In particular, the alloy Mo-30W demonstrates outstanding corrosion resistance. The solubility of various metals in liquid lead are presented in Table-I for comparison. Iron and Cr are lightly soluble in liquid Pb, but sufficient to cause solution attack. A summary of the corrosion performance of several materials in a liquid lead or liquid Pb-Li environment is provided in Table II.

Table III lists the neutron absorption cross sections for many of the metals described above, as well as their cross section relative to the typical reactor material, zirconium. Materials with a very large cross section relative to zirconium would result in a reduction in the thermal utilization factor 'f' and hence a reduction in N_{ff}. Consequently, Ta, W, V, Mo and Ni based alloys would be impractical choices for a reactor core. From this literature survey, it appears that Fecralloy would provide the greatest promise as a containment material for liquid lead. In addition Tantiron may be an alternate choice. More extensive studies on the applicability of inhibitors such as Ti should be undertaken to determine their affect on the corrosion resistance of these materials.

Table I - Solubilities of Fe, Cr, and Ni in liquid Pb. After [2]

Temperature (°C)	Solubility (ppm by weight)		
	Fe	Cr	Ni
400	0.2-0.08	0.002	1800

Table II - Corrosion performance--of various materials in liquid Pb and pb - Li After (7,8,9).

Material	Comment
In liquid Pb-Li	
Fe-9Cr-lMo	good resistance @ 600°C. limited @ 800°C
HT-9	good resistance @ 600°C, limited @ 800°C
1.4922 (12 Cr,0.5 Ni,0.5 Mn,1 Mo, 0.5 V)	Ni leached out, slightly greater dissolution than V
316L	poor resistance
Mild C-steel	good resistance @ 600°C, limited @ 800°C
Low Cr-steel	good resistance @ 600°C, limited @ 800°C
2-9% Cr steel	good resistance @ 600°C, limited @ 800°C
V, Nb, Ta and alloys	good resistance, dissolution rate < 0.004 G/m^2/day
In liquid Pb:	
Hastelloy-N (Ni,16,5 Mo, 7 Cr,5 Fe,1 Si,8 Mn)	severe attach after 4 days at 700°C
Croloy 2.25 (Fe,2.25 Cr,1 Mo,0.5 Mn)	severe attach after 4 days at 700°C
Croloy 2.25 + plasma sprayed Mo	no visible cracks/minimal wt. gain after 56 days at 720°C
Croloy 2.25 + calorizing coating	no visible attack after 56 days at 720°C
Croloy 2.25 + Ti inhibitor	no visible attack after 85 days at 700°C
Fecralloy (Fe,0.2 C,13 Cr,41)	no visible attack after 551 days at 700°C
Tantiron (Fe,13.5 Si,0.4 Mn,1 C)	no visible attack after 56 days at 720°C
Alumina	no wetting or attack after 282 days at 700°C
Silicon Nitride	no wetting or attack after 56 days at 720°C
Mo	no detectable attack after 300 days at 800°C

Table III - Neutron absorption cross sections for various materials [10]

Element	Atomic #	Capture Cross-section (b)	Cross-section relative to Zr
Zr	40	0.182	1
Fe	26	2.50	13.7
Al	13	0.232	1.3
Ni	28	4.54	24.9
C	6	0.0034	0.02
Si	14	0.16	0.9
Mo	42	2.65	14.6
Nb	41	1.15	6.3
Ta	73	22	120.9
W	74	18.5	101.6
V	23	5.06	17.8
Ti	22	6.1	33.5

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