AUTONOMOUS BATTERY REACTORS

M. Ragheb
9/8/2005

INTRODUCTION

Nuclear energy provides 20 percent of the electricity produced in the USA and 16 percent throughout the world. Significant capital investment is needed to build the standard size 1,000 MWe light water cooled power plants. Most developing countries cannot add large increments of electricity to their electrical grids. They do not have large scale energy infrastructures that could accommodate conventional power plants. Systems that possess automated controls require less maintenance and provide reliable power for an extended period of time reaching 30 years before refueling or replacement could benefit them.

Many of these countries are among the 187 countries that adhere to the Non Proliferation Treaty (NPT) enacted in 1970. According to the terms of this treaty, the five nuclear weapons states: the USA, Russian Federation, UK, France and China, agreed to not transfer weapons technology to the non nuclear weapons states, and to eventually eliminate their nuclear weapons stockpiles. This is not being achieved due to the perceived strategic advantage of nuclear weapons of shielding a nation against both nuclear and conventional attack. Accordingly, many nations are attempting at building nuclear power programs with a peaceful façade but with a suspected nuclear weapons capability intention, leading to conflicts in Iraq, North Korea and Iran. The USA started an effort to control this problem through making available to developing countries an alternative that would reduce the proliferation concerns associated with the expected expanded use of nuclear energy worldwide.

SELF CONTAINED REACTOR APPLICATIONS

The Small Sealed, Transportable, Autonomous reactor or SSTAR reactor design would allow the USA to provide a tamper resistant reactor to non weapons states, while safeguarding sensitive nuclear technology. The nuclear fuel from the sealed reactor would be returned back to the USA for refueling or maintenance, all of this while providing a degree of dependence on the supplier nation for the vital electrical supply, providing economical and political leverage influence and leverage.

Small autonomous or nuclear battery reactors providing 10-100 MWe of power are proposed for remote power applications, instead of the central power stations sizes of 1,000 MWe.

An interesting application arose for the small town of Galena, Alaska. Energy to power electricity is important for the survival of Galena. Winter temperatures can dip below minus 60 degrees Fahrenheit or minus 51 degrees Celsius. Daylight is scarce because of the short days during the winter.

The town is paying 28 cents/kwh for its electricity, about three times the national average. Galena is a 700 persons Athabascan Indian village on the Yukon River, located 275 miles west of Fairbanks and 550 miles northwest of Anchorage, Alaska, is powered by generators burning diesel that is barged in during the Yukon River's ice-free months, posing a spillage hazard.

The Japanese company Toshiba, proposed for it a demonstration small nuclear reactor named 4S for Super Safe, Small, and Simple. It is offering it a free reactor. Galena will only pay for operating costs, bringing down the price of electricity to less than 10 cents/kwh. The 4S is a sodium-cooled fast spectrum low pressure reactor.

If the Nuclear Regulatory Commission in Washington, D.C., approves the plan, the reactor would be the first new one permitted in the USA since the early 1980s. Before the reactor is built at Galena, though, a prototype must be built costing about $600 million, and take six to eight years. Once the prototype is approved, additional plants could be built for about $20 million each. It is necessary to overcome the scale disadvantage that is a common problem to small reactors, and to lower its construction cost.

Lawrence Livermore National Laboratory, LLNL, Los Alamos National Laboratory, LANL, and Argonne National Laboratory, ANL have collaborated on the design of a self contained nuclear reactor with tamper resistant features. Designated as the Small, Sealed, Transportable, Autonomous Reactor, SSTAR, it would produce 10 to 100 MWe and can be safely transported on ship or by a heavy haul transport truck.

SUPER SAFE, SMALL AND SIMPLE: 4S REACTOR

The 4S reactor would be installed underground, and in case of cooling system failure, heat would be dissipated to the earth as a heat sink. There are no complicated control rods to move through the core. Reflector panels around the edge of the core control the number of reflected neutrons and hence the power level, startup and shutdown.

The modular reactor would be factory constructed and delivered to the site on barge. Its components are small enough to be delivered by truck or helicopter. The 10 MWe would cost 2,000 $/kWe or $20 million. The reactor would require minimal maintenance over its 30 years lifetime. The electrical power plant would require the same number of employees as diesel powered plant.

The design is described as inherently safe. It uses liquid sodium at atmospheric pressure, not highly pressurized water, to extract the heat away from the core.

Sodium allows the reactor to operate about 200 degrees hotter than most power reactors increasing its thermal efficiency, but still keep the coolant depressurized. Light water reactors operating at high pressure could lose their pressurized coolant through flashing if suddenly depressurized as a result of a pipe rupture or leak.

The design uses uranium enriched to 20 percent in U^{235} and would generate power for 30 years before decommissioning.

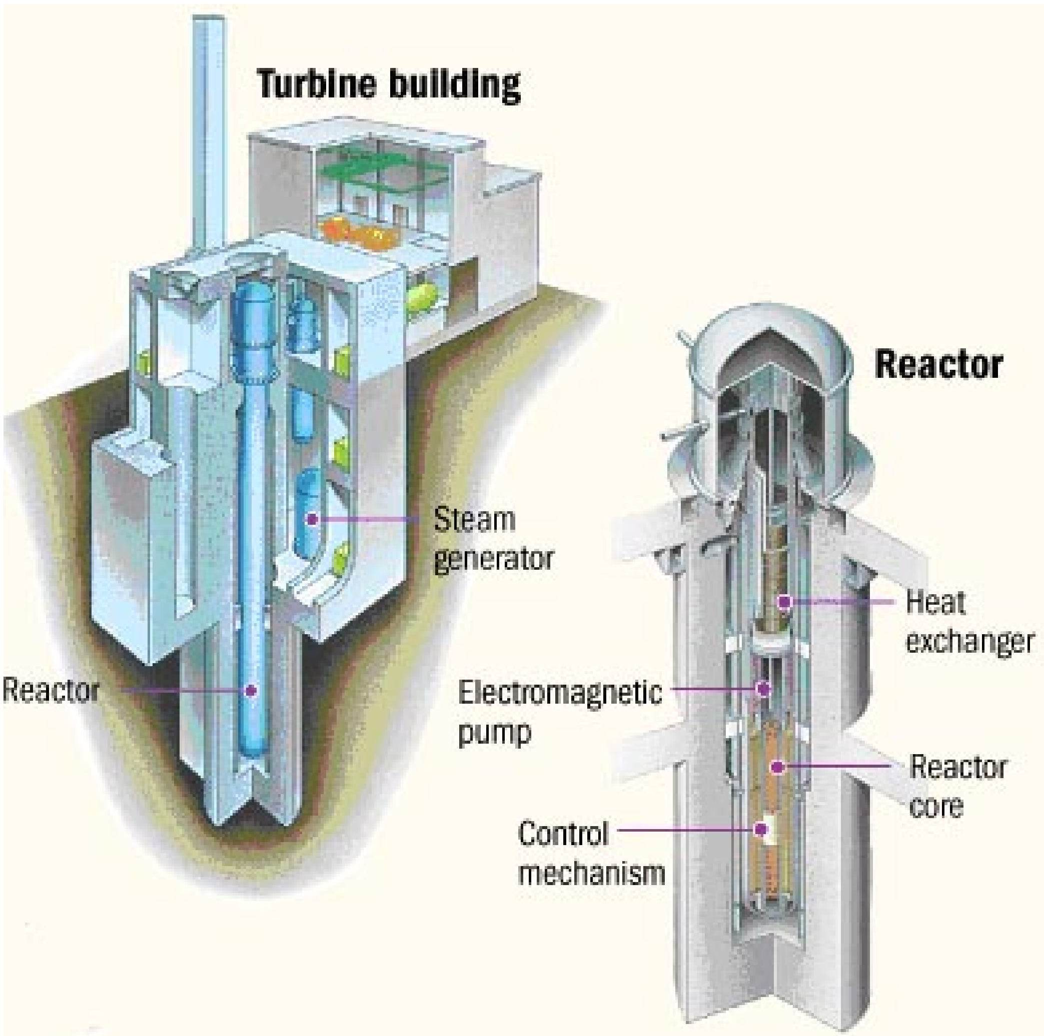

Fig. 1: 4S Toshiba reactor configuration.

The 4S is designated as a nuclear battery. The power comes from a core of non-weapons-grade uranium about 30 inches in diameter and 6 feet tall. It would put out a steady stream of 932 degree Fahrenheit heat for three decades but can be removed and replaced like a flashlight battery when the power is depleted.

The reactor core would be constructed and sealed at a factory, then shipped to the site. There it is connected with the other, non nuclear parts of the power plant to form a steel tube about 70 feet long with the nuclear core welded into the bottom like the eraser in a pencil. The assembly is then lowered into a concrete housing buried in the ground, making it as immune to attack or theft as a missile in its silo.

The reactor has almost no moving parts except for a magneto-hydro-magnetic pump and doesn't need many operators. The nuclear reaction is controlled by a reflector that slowly slides over the uranium core and keeps it in a critical condition.

Because of its design and small size, the reactor cannot overheat or melt down. The nuclear reaction heats liquid sodium in the upper portion of the reactor assembly. It circulates by convection, eliminating pumps and valves that need maintenance. The water coolant liquid extracts the heat from the primary Na coolant and does not activate. Because the reactor assembly is enclosed in a thick steel tube, it will withstand earthquakes and floods.

Liquid sodium eliminates corrosion, which is a possible cause of light water nuclear power plant accidents. The probability of radioactive material leakage for this system would be low.

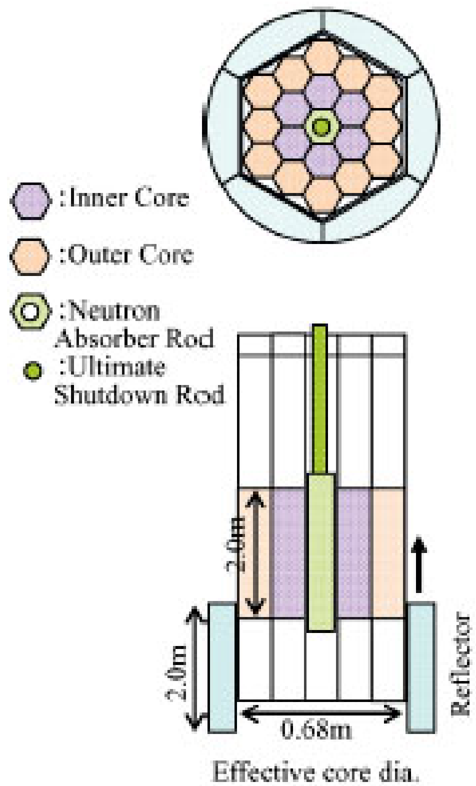

Fig. 2: Core design of the 4S reactor concept.

TECHNICAL SPECIFICATIONS

The 4S reactor design has been described as a nuclear battery. The plant is a small, sodium cooled fast reactor with a rather technologically advanced, compact steam turbine secondary system. Though it is based on sound engineering design work dating back to 1988, there are some areas where the designers and manufacturers will be pressing the boundaries of the known in terms of chemistry, materials, equipment reliability and fluid flow.

The core heat source for this plant is quite compact; it is only about 0.7 meters in diameter and about 2 meters tall. This section of the plant would be at the bottom of the 30 meter deep excavation inside a sealed cylinder, a location that helps to provide the driving force needed for natural circulation cooling and that provides an impressive level of nuclear material security. The active core material is a metallic alloy of uranium, plutonium and zirconium. The material has been extensively tested but it has not been commercially produced and used as a reactor fuel.

Table 1: Specifications of the 4S reactor design.

Electrical output	10 MWe
Thermal output	30 MWth
Core Lifetime	30 years
Fuel	Metallic U-24Pu-10Zr
Primary electromagnetic pumps	2, serial
Secondary electromagnetic pumps	4, parallel
Intermediate heat exchanger tube length	2.6 m
Steam generator type	Once through, Double wall tube, helical coil
Seismic isolation	Horizontal

The 30 year lifetime for the core is achieved through a variety of mechanisms. The core is a metallic alloy cooled by sodium and the overall reactivity is controlled through the use of a movable reflector instead of neutron absorbing control rods. Because of these features, which differ from those of conventional water cooled reactor technology, more of the neutrons that are released by fission either cause a new fission or are absorbed by fertile materials like U^{238}. When fertile materials absorb neutrons, they become fissile and useful as fuel the next time that they are struck by a neutron. It is unclear from available technical materials whether or not the 4S actually produces more fuel than it uses, that is, whether or not it is a breeder reactor, but it is clear that the efficient use of neutrons for converting non fuel materials into fuel materials helps to increase its projected 30 years lifetime.

A hexagonal core barrel was adopted and the reflectors were arranged at the position near the fuel assembly, as a result, a relative increase in the reflector worth was achieved (Fig. 2). Additionally, the required reflector worth was decreased by adopting a fixed absorber.

A loop type cooling system was adopted for the miniaturization of the reactor vessel and the physical superiority reduction of the nuclear reactor system (Fig.3). The cooling system was designed as one loop, and composed of the integrated equipment that included the primary and secondary electromagnetic pumps (EMPs), intermediate heat exchanger (IHX) and steam generator (SG).

SAFETY ASPECTS

The safety of the plant is achieved by maintaining a negative temperature coefficient of reactivity throughout the life of the core, and by providing sufficient natural circulation and heat removal capabilities to prevent overheating the core. A negative temperature coefficient of reactivity means that an increase in core temperature will cause a decrease in core power. If the temperature increases too much, the core will shut itself down.

A shutdown reactor still produces heat from the decay of radioactive materials, so there must be some mechanism provided to remove the generated heat. That is the job of the natural circulation and heat removal characteristics.

The use of sodium cooling contributes to the heat removal ability because it is a liquid over a wide range of temperatures, even if the cooling system is kept at atmospheric pressure. In water cooled reactors, which are often required to maintain pressures of 2000 psi, a loss of pressure can be a problem because the cooling medium will flash from a liquid to a gas, which has a much lower ability to remove heat. Since the major possible cause of a pressure loss is a cooling system leak, the hot high pressure water also implies the need for a very strong and pressure tight secondary containment system. The need to maintain a high pressure drives many of the design features and operating procedures for light water reactors; liquid metal cooling changes the equation and shifts some of the concern away from pressure maintenance.

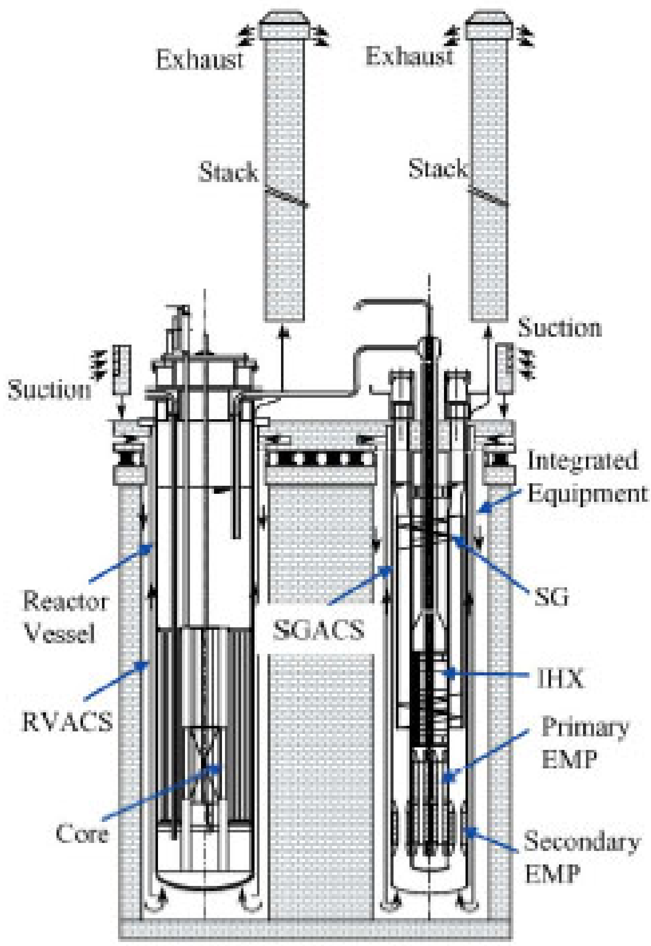

Fig. 3: Parallel configuration of the 4S reactor showing its core and Intermediate Heat Exchanger (IHX).

Liquid sodium cooling also allows the 4S system to produce higher quality steam than is available in a light water reactor because higher coolant temperatures are readily achievable. The system will produce steam temperatures on the order of 500 degrees C or 932 degrees F, which is considerably higher than the 260 degrees C or 500 degrees F temperatures available in conventional water cooled reactors. Higher temperature steam improves thermodynamic efficiency and allows the production of more power per unit size of machine.

The small fast reactor 4S has been under development in Japan since 1988. The core of the 4S doesn't receive severe damage under ATWS or Anticipated Transient Without Scram (ATWS) accidents because of its negative reactivity coefficients leading to a passive reactor shutdown under accident conditions. The core can be cooled with the decay heat removal system or DHRS using the natural circulation force under the PLOHS or Protected Loss Of Heat removal System (PLOHS) postulated accident event.

It is thought that this small fast reactor can contribute to a multipurpose utilization of nuclear power as an electrical power supply, heat supply, and desalting of seawater, in remote regions like islands where the power transmission infrastructure cannot be maintained.

SMALL, SEALED, TRANSPORTABLE AUTONOMOUS REACTOR (SSTAR)

The Small Sealed, Transportable, Autonomous reactor or SSTAR reactor design is conceived to allow the USA to provide a tamper resistant reactor to non weapons states, while safeguarding sensitive nuclear technology. The nuclear fuel from the sealed reactor would be returned back to the USA for refueling or maintenance, all of this while providing a degree of dependence on the supplier nation for the vital electrical supply, providing economical and political leverage influence and leverage.

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The SSTAR is meant to be a self contained reactor in a tamper resistant container about 15 meters in height and 3 meters in diameter with a weight that does not exceed 500 tons, making it transportable by train , heavy haul trucks and ships. It is intended for cost effective process heat, electricity, hydrogen, and fresh water production. It could be deployed anywhere in the world. It also meets the needs of the USA Nuclear Regulatory Commission (NRC) which oversees more than 100 reactors built in the 1970s and 1980s in the USA. The present concept could provide a secure, cost effective replacement for these aging nuclear power plants, as well as fossil fuel power plants, particularly in isolated remote sites.

TECHNICAL SPECIFICATIONS

The SSTAR is a Pb cooled fast neutron spectrum reactor capable of producing 10 to 100 MWe of power with a reactor system that can be shipped in a shipping cask. Fast neutron reactors do not use moderators such as water and graphite. Instead heavier non moderating elements such as Na, Na-K eutectic, Pd or Bi are used as coolants. The neutron energy in this case is around 250 keV, instead of 0.025-0.05 eV in thermal neutron energy reactors. With a fast neutrons spectrum, fast reactors are capable at breeding their own needs in fissile fuel in the form of Pu^{239} from U^{238}, and then internally burn it for their own need without being refueled over their lifetime which can reach 30 years. The spent fuel can then be returned in its reactor vessel to a secure fuel recycling facility closing the fuel cycle and minimizing the high level wastes associated with nuclear reactors, since it is designed to burn most of its own waste over its 30 years design lifetime.

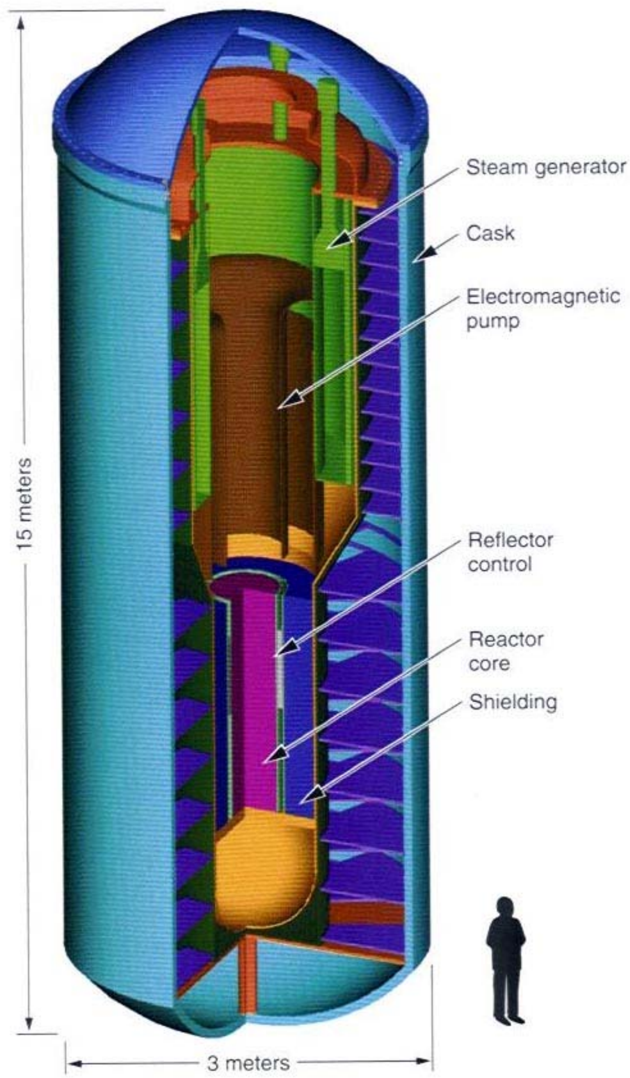

Fig. 4: Schematic of Small, Sealed, Transportable, Autonomous Reactor, SSTR.

It addresses proliferation concerns is that no recycling of the fuel is necessary during the reactor's operation. The reactor has embedded detection and signaling systems identifying actions that threaten the security of the reactor. The design can include a passive method of shutting down and cooling of the reactor in xase of controls or hardware failures.

ECONOMICS

Using Pb or a Pb-Bi alloy as coolants instead of water eliminates the need for large high pressure vessels and the associated piping that are needed if water were used a s coolant, since it can be operated at close to atmospheric pressure, which also entails a safety feature.

The steam generator can be integrated into the pressure vessel leading to compact reactor size.

Without a refueling downtime and no spent fuel rods to be managed, fewer personnel are needed and the reactor can operate at a high capacity factor.

Liquid metal fast reactors operate at a high temperature around 800 degrees Celsius. This makes the production of hydrogen in addition to electricity possible. The hydrogen can be used in fuel cell vehicles.

TECHNICAL CHALLENGES

Lead, when alloyed with bismuth tends to corrode the fuel cladding and structural steel necessitating the control of oxygen in the coolant and the development of materials that can tolerate the high corrosion environment, as well as the long term exposure to fast neutrons leading to swelling and loss of ductility.

Passive cooling systems using natural convection need to be developed for a safe operation of the reactor over its lifetime. Packaging and transportation systems for the activated reactor vessel must be designed for its safe transport at the end of its design life.

LICENSING

The USA Nuclear Regulatory Commission (NRC) intends on licensing the SSTAR design using a new license-by –test approach rather than the existing license-by design approach presently followed. This is a process similar to the approach of certification airplanes followed by the USA Federal Aviation Administration (FAA). In the new approach, the prototype of the new reactor must demonstrate in a test environment that it can withstand rigorous safety tests including the failure of the active shutdown and the shutdown heat removal systems.

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