

SAFETY DESIGN FEATURES OF THE STAR REACTORS

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The reactor concepts addressed in this section are the SSTAR and STAR-LM small lead cooled reactors without on-site refuelling, developed in the Argonne National Laboratory and other national laboratories of the USA. Detailed descriptions of these concepts are presented in [IX-1]; short summaries of the concepts are given in sections IX-1 (SSTAR) and IX-2 (STAR-LM) below. The inherent safety features and passive safety design options of the STAR-LM are similar to those of the SSTAR. Because it would be redundant to list them, they are not reproduced below; the reader is referred to section IX-3 and the following sections on SSTAR.

IX-1. Description of the SSTAR concept

The Small Secure Transportable Autonomous Reactor (SSTAR, [IX-1]) is a 20 MW(e) (45 MW(th)) exportable, small, proliferation-resistant, fissile self-sufficient, autonomous load following, and passively safe lead-cooled fast reactor (LFR) concept for international deployment and deployment at remote sites. Potential users for the SSTAR include customers looking for energy security at small capital outlay; cities in developing countries; and deregulated power producers in developed countries. SSTAR makes an extensive use of inherent and passive safety features; most notably, natural circulation heat transport, lead (Pb) coolant, and transuranic nitride fuel. The SSTAR nuclear power plant incorporates a supercritical carbon dioxide (S-CO₂) Brayton cycle power converter for higher plant efficiency and lower balance of plant costs. The efficiency of the S-CO₂ Brayton cycle increases as the reactor core outlet temperature increases; an efficiency of about 45 % can be attained for a turbine inlet temperature of about 550°C. To take advantage of the economic benefits of such high plant efficiency, there has been interest in operating at higher Pb coolant temperatures. In particular, a peak cladding inner surface temperature of 650°C has been an objective. SSTAR is scalable to a higher power level of 181 MW(e) (400 MW(th)); this is the STAR-LM concept discussed in section IX-2. SSTAR is currently at a pre-conceptual level of development. Engineering design for manufacturing of the components and systems has not been carried out. A probabilistic risk assessment has not been performed. Accident analyses of a set of design basis and beyond design basis accidents have not yet been carried out.

Figure IX-1 illustrates SSTAR, which is a pool-type reactor. The lead coolant is contained inside of a reactor vessel surrounded by a guard vessel. Lead is chosen as the coolant rather than lead-bismuth eutectic (LBE) to reduce the amount of alpha-emitting ²¹⁰Po isotope formed in the coolant by two to three orders of magnitude relative to LBE, and to eliminate dependency upon bismuth which might be a limited resource.

The Pb coolant flows through a perforated flow distributor head located beneath the core; this structure provides an essentially uniform pressure boundary condition at the inlet to the core. The Pb flows upward through the core and a chimney above the core formed by a cylindrical shroud. SSTAR is a natural circulation reactor such that the vessel has a height-to-diameter ratio large enough to facilitate natural circulation heat removal at all power levels up to and exceeding 100 % of the nominal. The coolant flows through flow openings near the top of the shroud and enters four modular Pb-to-CO₂ heat exchangers located in the annulus between the reactor vessel and the cylindrical shroud. Inside each heat exchanger, the Pb flows

downwards over the exterior of tubes through which the CO₂ flows upwards. The CO₂ enters each heat exchanger through a top entry nozzle, which delivers the CO₂ to a lower plenum region in which the CO₂ enters each of the vertical tubes. The CO₂ is collected in an upper plenum and exits the heat exchanger through two smaller top diameter top entry nozzles. The Pb exits the heat exchangers and flows downward through the annular downcomer to enter the flow openings in the flow distributor head beneath the core.

A thermal baffle is provided near the Pb free surface. The baffle consists of a cylindrical shell welded to the reactor vessel and filled with argon cover gas providing thermal insulation the reactor vessel. The insulating effect of the shroud is necessary to protect the vessel from thermal stresses that would result from exposure to the heated Pb coolant during start-up and shutdown transients. SSTAR does not incorporate an intermediate heat transport circuit. This is a simplification possible with Pb coolant which is calculated not to react chemically with the working fluid below about 250°C (i.e., well below the 327°C Pb melting temperature). A passive pressure relief system is provided on the reactor system to vent CO₂ from the reactor, in the event of a heat exchanger tube rupture.

Figure IX-2 shows the 30-year lifetime core configuration. The core has an open lattice configuration of large diameter (2.5 cm) fuel pins arranged on a triangular pitch. This eliminates potential flow blockage accidents since cross-flow paths are always available for cooling. The fuel consists of pellets of transuranic nitride fuel clad with silicon-enhanced ferritic/martensitic steel layer, providing protection against corrosion, co-extruded with a ferritic/martensitic base providing structural strength and irradiation stability. The fuel pellets are bonded to the cladding by molten Pb to reduce the temperature difference between the pellet outer surface and the cladding inner surface.

The active core diameter of 1.22 m is selected to minimize the burn-up reactivity swing over the 30-year core lifetime. The power level of 45 MW(th) is conservatively chosen to limit the peak fluence on the cladding to 4×10^{23} neutrons/cm²; this is the maximum exposure for which HT9 ferritic/martensitic cladding has been irradiated. The core has three enrichment zones to reduce the power peaking and two central low enrichment zones which further reduce the burn-up reactivity swing. The core has strong reactivity feedback coefficients, which enable autonomous load following whereby the reactor power adjusts itself to the heat removal from the reactor as a result of the reactivity feedbacks. Because heat transport is accomplished by natural circulation, the primary coolant flow rate and system temperatures also adjust themselves to transport the heat from the core.

The core does not consist of individual removable fuel assemblies but is a single cassette/assembly. The fuel pins are permanently attached by welding or other means to a core support plate at the bottom of the core. This limits access to either fuel or neutrons. Normally, refuelling equipment is not present on the site. Refuelling equipment including a crawler crane is brought onsite only following the 30-year lifetime. The upper closure head for the guard and reactor vessels is removed; the spent core is removed from the vessel and placed inside of a shipping cask, and transported to a fuel cycle support centre for reprocessing and refabrication under international oversight. A fresh core is installed in the reactor vessel and the refuelling equipment is removed from the site.

Two sets of control rods are provided for independence and redundancy of the scram. Small adjustments of the control rods are carried out to compensate for small changes in the burn-up reactivity swing. The control rod locations have been uniformly distributed throughout the core. Each control rod moves inside of a control rod guide tube occupying a position in the triangular lattice. Spacing between fuel pins is maintained by two levels of grid spacers. Each grid spacer is welded to a control rod guide tube; the grid spacer holds the surrounding fuel pins by means of spring clips allowing for thermal expansion of the fuel pins relative to the

control rod guide tube. The active core is surrounded by a radial reflector, which is an annular “box” containing stainless steel rods and Pb having approximately equal volume proportions. Stainless steel is needed to shield the reactor vessel from neutron fluxes. There is a small Pb flow through the reflector removing the power deposition that takes place there.

SSTAR incorporates a reactor vessel auxiliary cooling system (RVACS) for decay heat removal, should the normal heat removal path involving the Pb-to-CO₂ heat exchangers be unavailable. The RVACS involves heat removal from the outside of the guard vessel due to natural circulation of air, which is always in effect. The RVACS is a safety grade system. To provide for greater reliability of emergency heat removal beyond that corresponding to the single RVACS system, it is planned to also incorporate safety grade direct reactor auxiliary cooling system (DRACS) heat exchangers into the reactor vessel.

Conditions, dimensions, and other parameters for SSTAR are included in Table IX-1. Notable achievements of the SSTAR development include:

- Pb coolant;
- 30-year core lifetime;
- Average (peak) discharge burnup of 81 (131) MW day/kg of heavy metal;
- Burn-up reactivity swing < 1 \$;
- Peak cladding temperature = 650°C;
- Core outlet/inlet temperatures = 564/420°C;
- Peak transuranic nitride fuel temperature = 882°C;
- Small shippable reactor vessel (12 m height by 3.23 m diameter);
- Autonomous load following;
- Supercritical CO₂ Brayton cycle energy conversion efficiency = 44.1 %;
- Plant efficiency = 43.8 %;
- Cost of energy generation < 5.5 US\$ cents/kW-h (55 US\$/MW-h).

TABLE IX-1 CONDITIONS AND DIMENSIONS FOR SSTAR

CHARACTERISTIC	VALUE
Reactor name	SSTAR (Small Secure Transportable Autonomous Reactor)
Power, MW(e) (MW(th))	19.7 (45)
Customer – Assume 4.0 tonnes of oil equivalent per capita per year = 167 GJ per capita per year = 5.3 KW(th)-year per capita per year, of which ~ 1/3 is used for electricity	Electricity for a town of ~ 25 400
Coolant	Pb
Fuel	Transuranic nitride (TRUN) enriched to N ¹⁵
Enrichment, %	1.7/3.5/17.2/19.0/20.7 TRU/HM, 5 radial zones
Core lifetime, years	30
Core inlet/outlet temperatures, °C	420 / 564
Coolant flow rate, kg/s	2150

CHARACTERISTIC	VALUE
Power density, W/cm ³	42
Average (peak) discharge burn-up, MW day/Kg HM	81 (131)
Peak fuel temperature, °C	882
Cladding	Si-enhanced ferritic/martensitic steel layer for corrosion protection co-extruded with a ferritic/martensitic substrate for structural strength and irradiation stability
Peak cladding temperature, °C	650
Fuel/coolant volume fractions	0.45 / 0.35
Core lifetime, years	30
Fuel pin diameter, cm	2.50
Fuel pin triangular pitch-to-diameter ratio	1.185
Active core dimensions; Height/Diameter, m	0.976 / 1.22
Core hydraulic diameter, cm	1.371
Pb-to-CO ₂ heat exchangers (HXs) type	Shell-and-tube
Number of Pb-to-CO ₂ HXs	4
HX tube length, m	4.0
HX tube inner/outer diameters, cm	1.0 / 1.4
Number of tubes (all HXs)	10 688
HX tube pitch-to-diameter ratio	1.255
HX Pb hydraulic diameter, cm	1.030
HX-core thermal centres separation height, m	6.80
Reactor vessel dimensions; Height/Diameter, m	12.0 / 3.23
Reactor vessel thickness, cm	5.08
Gap between reactor vessel and guard vessel, cm	12.7
Gap filling material	Air
Guard vessel thickness, cm	5.08
Air channel thickness, cm	15
Air ambient temperature, °C	36
Working fluid	Supercritical CO ₂
CO ₂ turbine inlet temperature, °C	549
Minimum CO ₂ temperature in cycle, °C	31.25
Max./Min. CO ₂ pressure in cycle, MPa	20 / 7.4
CO ₂ flow rate, kg/s	247
Net generator output, MW(e)	19.7
Supercritical CO ₂ Brayton cycle efficiency, %	44.1
Net plant efficiency, %	43.8

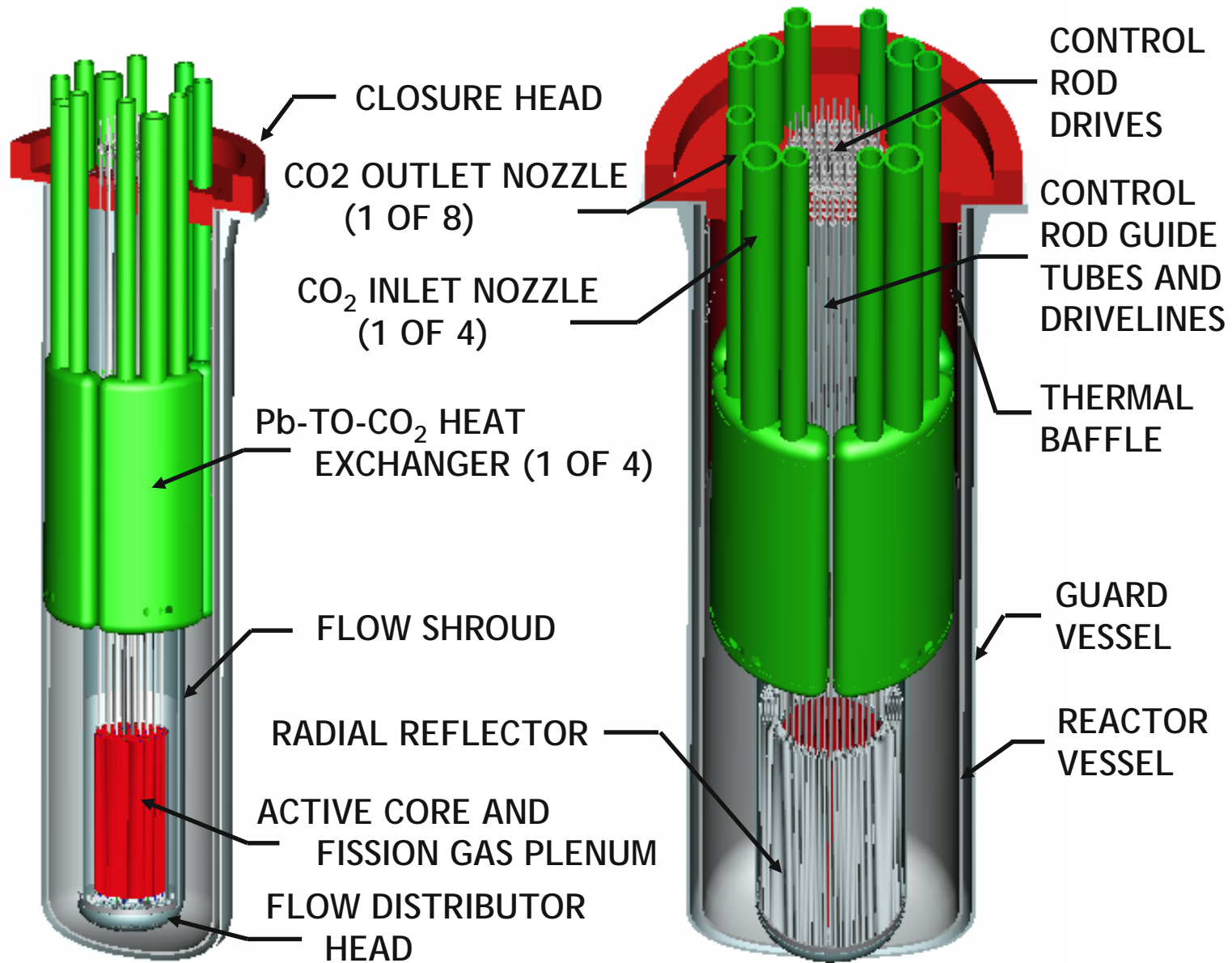


FIG. IX-1. General view of the SSTAR layout.

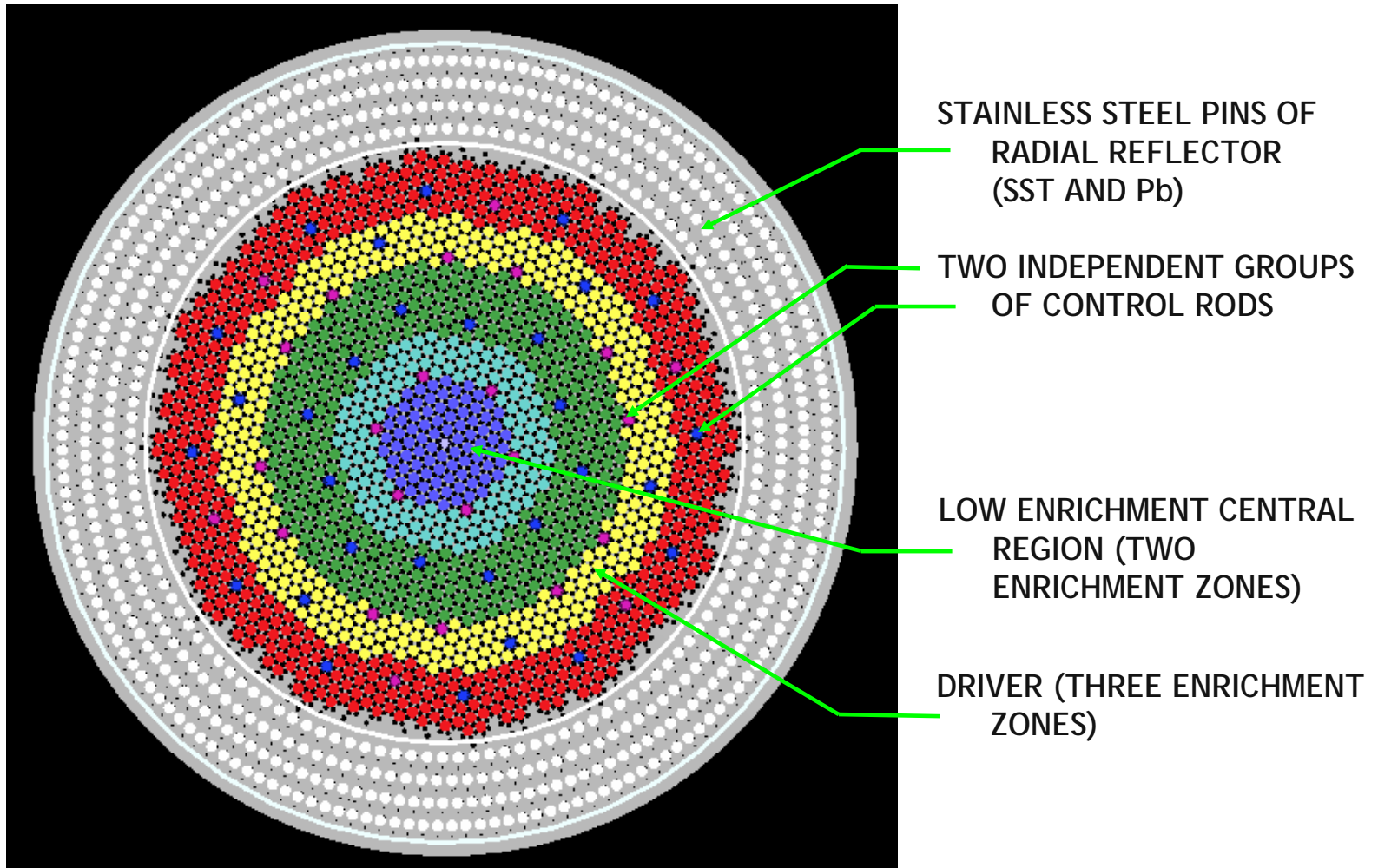


FIG. IX-2. Core configuration of SSTAR.

Table IX-2 presents reactivity feedback coefficients typical of SSTAR core configurations.

TABLE IX-2. REACTIVITY FEEDBACK COEFFICIENTS OF A 45 MW(th) SSTAR WITH 20-YEAR CORE LIFETIME

CHARACTERISTIC/ REACTIVITY COEFFICIENT	BOC	PART OF THE CYCLE ~ 13 YEARS	EOC
Delayed neutron fraction	0.0036	0.0035	0.0034
Prompt neutron lifetime, s	1.8×10^{-07}	1.8×10^{-07}	1.8×10^{-07}
Coolant density, cents/°C	-0.035	-0.001	-0.015
Core radial expansion, cents/°C	-0.16	-0.16	-0.16
Axial expansion, cents/°C	-0.08	-0.07	-0.07
Fuel Doppler, cents/°C	-0.07	-0.07	-0.06
Coolant void worth, \$	-1.68	-1.63	-1.83

IX-2. Description of the STAR-LM concept

The Secure Transportable Autonomous Reactor-Liquid Metal (STAR-LM, [IX-1]) is a scaled-up version of SSTAR at a power level of 181 MW(e) (400 MW(th)) for high efficiency electric power production with optional production of desalinated water using a portion of the reject heat. The STAR-LM reactor vessel size is assumed to be limited in height by a rail shipment limitation of 18.9 m. The power level of 400 MW(th) approaches the maximum value at which heat transport can be accomplished through single-phase natural circulation given the reactor vessel height limitation. The scaled-up version can alternately be used for hydrogen and oxygen generation using a Ca-Br thermo chemical (“water cracking”) cycle, if cladding and structural materials for operation with the Pb up to about 800°C can be developed; this high temperature version is named STAR-H2, see the corresponding concept description in [IX-1]. Conditions and dimensions for STAR-LM are provided in Table IX-3. The reactivity feedback coefficients are given in Table IX-4.

TABLE IX-3. CONDITIONS AND DIMENSIONS FOR STAR-LM

CHARACTERISTICS	VALUE
Reactor name	STAR-LM (Secure Transportable Autonomous Reactor-Liquid Metal)
Power, MW(e) (MW(th))	181 (400)
Customer – Assume 4.0 tonnes of oil equivalent per capita per year = 167 GJ per capita per year = 5.3 kW(th)-year per capita per year, of which ~ 1/3 is used for electricity	Electricity for a city of ~ 226 000
Coolant	Pb
Core inlet/outlet temperature, °C	438 / 578

CHARACTERISTICS	VALUE
Coolant flow rate, kg/s	19 708
Power density, W/cm ³	44
Average (peak) discharge burn-up, MW·day/kg HM	83 (136)
Fuel	Transuranic nitride (TRUN) enriched to N ¹⁵
Enrichment (TRU), %	13.3/18.2/21.3; 3 enrichment zones
Peaking factor (BOC/EOC)	1.63 / 1.64
Burn-up reactivity swing, %Δk/k (\$)	0.61 (1.97)
Cladding	Si-enhanced ferritic/martensitic steel layer for corrosion protection co-extruded with a ferritic/martensitic substrate for structural strength and irradiation stability
Peak cladding temperature, °C	650
Fuel/coolant volume fractions	0.21 / 0.66
Core lifetime, years	15
Fuel pin diameter, cm	1.30
Fuel pin triangular pitch-to-diameter ratio	1.54
Active core dimensions; Height/Diameter, m	2.00 / 2.46
Core hydraulic diameter, cm	2.08
Pb-to-CO ₂ HXs type	Shell-and-tube
Number of Pb-to-CO ₂ HXs	4
HX tube length, m	6.0
HX tube inner/outer diameters, cm	0.5 / 0.9
Number of tubes (all HXs)	63 288
HX tube pitch-to-diameter ratio	1.632
HX Pb hydraulic diameter, cm	1.742
HX-core thermal centres separation height, m	8.25
Reactor vessel dimensions; Height/Diameter, m	16.9 / 5.5
Reactor vessel thickness, cm	5
Gap between reactor vessel and guard vessel, cm	12.7
Gap filling material	Pb-Bi eutectic

CHARACTERISTICS	VALUE
Guard vessel thickness, cm	5
Air channel thickness, cm	15
Air ambient temperature, °C	36
Working fluid	Supercritical CO ₂
CO ₂ turbine inlet temperature, °C	560
Minimum CO ₂ temperature in cycle, °C	31.25
Max./Min. CO ₂ pressure in cycle, MPa	20 / 7.4
CO ₂ flow rate, kg/s	2,205
Net generator output, MW(e)	181
Supercritical CO ₂ Brayton cycle efficiency, %	45.7
Net plant efficiency, %	45.2

TABLE IX-4. REACTIVITY FEEDBACK COEFFICIENTS OF A 400 MW(th) SSTAR WITH 15-YEAR CORE LIFETIME.

CHARACTERISTIC/ REACTIVITY COEFFICIENT	BOC	PART OF THE CYCLE ~ 13 YEARS	EOC
Delayed neutron fraction	0.0035	0.0032	0.0031
Prompt neutron lifetime, s	5.34×10^{-07}	5.04×10^{-07}	4.98×10^{-07}
Coolant density, cents/°C	0.18	0.21	0.22
Core radial expansion, cents/°C	-0.14	-0.15	-0.15
Axial expansion, cents/°C	-0.19	-0.20	-0.21
Fuel Doppler, cents/°C	-0.12	-0.11	-0.10
Coolant void worth, \$	11.64	12.20	12.20

IX-3. Passive safety design features of SSTAR

The SSTAR safety design approach is based upon the defence-in-depth principle of providing multiple levels of protection against the release of radioactive materials by the following:

- (i) Design to achieve a high level of reliability such that specific traditional accident initiators are eliminated or accident initiators are prevented from occurring;
- (ii) Provision of protection in the event of equipment failure or operating error; and
- (iii) Provision of additional protection of the public health and safety in an extremely unlikely event, which is not expected to occur during the lifetime of the plant or which was not foreseen at the time when the plant was designed and constructed.

Inherent safety features

The inherent safety features of SSTAR take advantage of the key inherent properties of Pb coolant, transuranic nitride fuel, and a fast neutron spectrum core, together with the specific design options including a pool reactor vessel containing all major primary coolant system components and natural circulation heat transport.

The Pb primary coolant has a high boiling temperature of about 1740°C, which is well above the temperatures at which the stainless steel structures lose their strength and melt. The Pb is, therefore, a low-pressure coolant and does not flash should a leak develop in the primary coolant system boundary. All major primary system components including the core and Pb-to-CO₂ heat exchangers are contained inside of the reactor vessel, which is surrounded by a guard vessel. The coolant level inside of the reactor vessel is such that, in the event of a reactor vessel leak, the faulted level of coolant contained by the guard vessel always exceeds the Pb entrances to the Pb-to-CO₂ heat exchangers. The lack of coolant flashing or boiling due to the high Pb boiling temperature, combined with the pool system configuration and a guard vessel, preclude the loss of primary coolant. It also assures that heat removal from the core and heat transfer to the in-vessel heat exchangers or the vessel wall for heat removal by the RVACS continues by means of natural circulation of a single-phase primary Pb coolant.

The lead coolant is calculated not to react chemically with the working fluid above about 250°C, which is well below the Pb melting temperature of 327°C. In particular, there is no formation of combustible gas or exothermic energy release. Lead does not react vigorously with either water or air. Compatibility of Pb and the working fluid makes it possible to eliminate the need for an intermediate cooling circuit, enhancing the plant reliability.

Lead has a low absorption of neutrons. This permits the core to be opened up by increasing the coolant volume fraction without a significant reactivity penalty. Increasing the coolant volume fraction increases the hydraulic diameter for coolant flow through the core, reducing the core frictional pressure drop. As a result, natural circulation is more effective and can transport a greater core power. It is possible to design LFRs in which natural circulation is effective at power levels exceeding 100 % of the nominal, eliminating the need for main coolant pumps. Eliminating main coolant pumps eliminates loss-of-flow accident initiators. The open lattice core configuration with wide openings for a coolant cross-flow eliminates flow blockage accident initiators in which the coolant flow entering at the bottom of the core is postulated to be locally blocked.

The high heavy liquid metal coolant density ($\rho_{\text{Pb}} = 10\,400 \text{ kg/m}^3$) limits void growth and downward penetration following a postulated in-vessel heat exchanger tube rupture such that the void is not transported to the core but instead rises benignly to the lead free surface through a deliberate escape channel between the in-vessel heat exchangers and the vessel wall.

The transuranic nitride fuel has a high thermal conductivity which, when combined with bonding of the fuel pellets to the cladding by means of liquid Pb between the pellets and cladding, reduces the peak fuel temperatures during normal operation and accidents. This reduces the stored energy in the fuel and decreases the positive reactivity contribution resulting from cooldown of the fuel as the fuel and coolant temperatures equilibrate during accidents as the core power decreases.

Transuranic nitride fuel has a high decomposition temperature estimated to exceed 1350°C such that the fuel maintains its integrity at temperatures above which the stainless steel structural materials lose their strength or melt.

Nitride fuel is expected to be compatible with both the Pb bond and ferritic/martensitic steel cladding.

Nitride fuel has a high atom density making it possible to reduce the volume which must be occupied by fuel further enabling an increase of the coolant volume fraction without the loss of the ability to achieve a core internal conversion ratio of unity and a low burn-up reactivity swing, which in turn reduces the effects of rod withdrawal accident initiators.

Nitride fuel has a low volumetric swelling per unit burn-up, which makes it possible to reduce the size of the gap between fuel pellets and cladding filled by the Pb bond, further facilitating an increase of the coolant volume fraction.

Nitride fuel has a low fission gas release per unit volume. This reduces the thermal creep of the cladding resulting from the hoop stress loading due to internal pressurization of the fuel pin by a released fission gas.

The fast neutron spectrum core with Pb coolant and transuranic nitride fuel has strong reactivity feedbacks, which provide significant negative reactivity upon a heat-up or equilibration of the system temperatures. The strong reactivity feedback reduces the core power to match the heat removal from the reactor system inherently, shutting down the reactor in the event when the two shutdown systems fail to scram it.

The strong reactivity feedback of the fast neutron spectrum core with Pb coolant and transuranic nitride fuel enable autonomous load following whereby the core power adjusts itself through inherent mechanisms to match the heat removal from the reactor system without operation of control rods, thereby simplifying the operation and eliminating the potential operator errors.

The low burn-up reactivity swing of the 30-year lifetime fast neutron spectrum core decreases the excess reactivity requirements, reducing the amount of reactivity insertion accompanying the unintended withdrawal of one or more of the control rods.

Passive safety systems

The SSTAR currently incorporates a single safety grade emergency heat removal system, which is the reactor vessel auxiliary cooling system (RVACS). The RVACS cools the exterior of the guard vessel by natural draught of air, which is always in effect. Because the RVACS represents only a single safety grade system, it would be required to have a high reliability with respect to seismic events or sabotage. For example, a seismic event could result in blockage of the airflow channels. At particular sites, flooding or dust storms might be the factors. It is planned to add safety grade passive direct reactor auxiliary cooling system (DRACS) heat exchangers, located inside of the reactor vessel, to provide for independent and redundant means of emergency heat removal.

Passive pressure relief from the primary coolant system is provided to enable CO₂ to escape from the primary coolant system without over-pressurizing the primary coolant system boundary, in the event of a heat exchanger tube rupture.

Active safety systems

The SSTAR incorporates two independent and redundant safety grade active shutdown systems. The core layout in Fig. IX-2 shows the primary and secondary control rod locations.

IX-4. Role of passive safety design features in the defence-in-depth

Some major highlights of the passive safety design features in SSTAR, structured in accordance with the various levels of defence in depth [IX-2, IX-3], are brought out below.

Level 1: Prevention of abnormal operation and failure

The aim of the first level of defence in depth is to prevent deviations from normal operation and to prevent system failures. The inherent safety features of Pb coolant, nitride fuel, and a fast spectrum core together with natural circulation heat transport and the pool vessel configuration reduce the probability of failures through the elimination of reliance upon components, systems, or operator actions that would otherwise need to be considered as sources of failure. Specific traditional postulated accidents such as loss-of-flow or local flow blockage are eliminated.

The cladding and structures are protected from significant corrosion by the Pb coolant by control of the dissolved oxygen potential in the coolant within a suitable regime that avoids the formation of lead oxide while allowing protective Fe_3O_4 solid oxide layers to be formed initially upon structures at lower temperatures. The systems for monitoring the dissolved oxygen potential and maintaining the oxygen level in the desired regime shall be designed to have high reliability. It is envisaged to keep sufficiently low the probability of failure of the systems in modes that could threaten the long-term integrity of the cladding or other structures, or result in the formation of solid debris that might locally block flow channels.

Level 2: Control of abnormal operation and detection of failure

The aim of the second level of defence is to detect and intercept deviations from normal operational states in order to prevent anticipated operational occurrences from escalating to accident conditions. Due to the inherent safety features and passive safety design options of SSTAR, the expectation is that anticipated operational occurrences will not escalate into accidents. Therefore, it is expected that detection is not a necessity in order to avoid escalation into accident conditions.

Level 3: Control of accidents within the design basis

For the third level of defence, it is assumed that, although very unlikely, the escalation of certain anticipated operational occurrences or postulated initiating events (PIEs) may not be arrested by a preceding level and a more serious event may develop. Traditionally, escalation into a more serious event requires the occurrence of additional failures following the onset of the accident initiator. Although specific traditional postulated accidents such as loss-of-flow or local flow blockage are eliminated, other traditional postulated accidents such as reactivity insertion due to withdrawal of one or more control rods, loss-of-normal heat sink, heat exchanger tube rupture, loss-of-load, or station blackout remain. Due to the inherent safety features of SSTAR, the core and heat exchangers remain covered by the molten Pb coolant and natural circulation heat transport removes the core power, which is removed from the reactor system either by the normal heat removal paths or by the RVACS. The system fuel and coolant temperatures remain within acceptable values well below the temperatures at which the structures begin to lose their strength or at which a failure of the cladding could occur. There is no need for reliance upon active systems or operator actions to provide for cooling of the core or heat removal from the reactor system.

For liquid metal cooled fast reactors, an example of an additional failure in addition to the accident initiator has been the assumption of a failure to scram the reactor by the primary and secondary shutdown systems. For SSTAR, it is not necessary for either of the two independent and redundant shutdown systems to operate as well as for operators to take action to insert control rods. The inherent feedbacks of the fast spectrum core with Pb coolant and nitride fuel cause the power level to decrease such that the core power matches the heat removal from the reactor system. The reactor core self regulates the power level to match the heat removal through either the normal heat removal path involving the in-vessel Pb-to- CO_2 heat exchangers or the emergency heat removal path through the RVACS.

If one or more in-vessel Pb-to-CO₂ heat exchanger tubes were to fail, the passive pressure relief system would release CO₂ from the reactor system protecting the reactor vessel and upper closure head from over-pressurization.

If the reactor vessel were to fail in addition to the accident initiator, the guard vessel would retain the primary Pb coolant such that the core and in-vessel heat exchangers remain covered by a single-phase Pb primary coolant.

If the normal heat removal path or a shutdown heat removal path were to fail, then the RVACS would remove the power generated in the core and transported to the reactor vessel by natural circulation of the Pb coolant. As discussed above, DRACS heat exchangers shall also be incorporated into the reactor vessel to enhance the reliability of emergency heat removal beyond that provided by the RVACS. Therefore, it is not expected that a second failure would result in an escalation into a more serious event in terms of the release or transport of radioactivity from the fuel pins.

Level 4: Control of severe plant conditions, including prevention of accident progression and mitigation of consequences of severe accidents

The aim of the fourth level of defence is to address severe accidents in which the design basis may be exceeded and to ensure that radioactive releases are kept as low as practicable.

The SSTAR incorporates a guard vessel surrounding the reactor vessel and an upper closure head, which covers both the guard and the reactor vessels. A hermetic seal is established between the upper closure head and the guard vessel. Thus, the guard vessel and the upper closure head perform the function of a containment vessel surrounding the reactor vessel and retaining radioactivity as long as over-pressurization of the guard vessel and the upper closure head system does not occur. A containment structure is provided above the upper closure head. In the event of a rupture of one or more Pb-to-CO₂ heat exchanger tubes, the CO₂ would vent through the upper closure head into the volume of the containment structure.

Level 5: Mitigation of radiological consequences of significant release of radioactive materials

The fifth and final level of defence is aimed at mitigation of the radiological consequences of potential releases of radioactive materials that may result from accident conditions. It is envisioned that the exclusion zone surrounding a SSTAR reactor may at the least be reduced in size as a result of the inherent safety features and the expected low probability for radioactive material release relative to light water reactor designs having a similar power level.

IX-5. Acceptance criteria for design basis and beyond design basis accidents

The U.S. NRC is considering developing a comprehensive set of risk-informed, performance-based, and technology-neutral requirements for licensing of power reactors [IX-4]. These requirements would be included in the NRC regulations as a new 10 CFR Part 53 and could be used as an alternative to the existing requirements in 10 CFR Part 50. The new 10 CFR Part 53 will constitute a new set of risk-informed requirements for both LWR and non-LWR designs. The NRC approved a recommendation from the NRC staff to issue an advanced notice of proposed rulemaking (ANPR) in April 2006 on approaches for making the technical requirements for power reactors risk-informed, performance-based, and technology neutral. The staff was to complete the ANPR stage by December of 2006 and provide its recommendation on whether and, if so, how to proceed with rulemaking by May of 2007, having considered the views of the Advisory Committee on reactor safety. The December 2006 date was intended to provide stakeholders time to submit comments. On April 18, 2006,

the NRC issued an update of the risk-informed regulation implementation plan (RIRIP). The RIRIP covers many activities of which “Develop structure for new plant licensing” is only one.

The new 10 CFR Part 53 is to be technology-neutral to accommodate different reactor technologies, risk-informed to identify the more likely safety issues and gauge their significance, and performance-based to provide flexibility, and will include defence-in-depth to address the uncertainties. It would be written to be applicable to any reactor technology, thus avoiding the time consuming and less predictable process of reviewing non-LWR designs against the LWR oriented 10 CFR 50 regulations, which requires case-by-case decisions (and possible litigations) on what 10 CFR Part 50 regulations are applicable and not applicable and where new requirements are needed. The examples include liquid metal cooled reactors, IRIS, HTGRs, as well as reactors under development under the U.S. Department of Energy Generation IV nuclear energy systems initiative [IX-5]. The need for a technology-neutral framework was identified from the PBMR review experience. The technology-neutral framework is not intended to be used for designs currently under review. The new 10 CFR Part 53 would require a broader use of design specific risk information in establishing the licensing basis, its safety analysis and regulatory oversight on those items most important to safety for that design. It would stress the use of performance as the metrics for acceptability, thus providing more flexibility to designers to decide on the design factors most appropriate for their design.

It is expected that the development of SSTAR would take place on a timescale consistent with application of the new 10 CFR Part 53. The new technology neutral framework would therefore, be applied to SSTAR. It remains to be seen what criteria would be applied to assess the performance of a design such as the SSTAR during specific accidents.

IX-5.1. List of design basis and beyond design basis accidents

In the meantime, while the 10 CFR Part 53 regulations are still being considered, a limited set of traditional design basis accidents have been identified for the SSTAR including loss-of-heat sink, in-vessel heat exchanger tube rupture, transient overcooling, transient overpower/reactivity insertion, and loss-of-load.

A corresponding set of beyond design basis accidents has also been identified that involves failure to scram due to the assumed failure of both safety grade active shutdown systems.

IX-5.2. Acceptance criteria

For all abovementioned accidents, the acceptance criteria include the requirement that system temperatures remain sufficiently low to preclude cladding failures and release of radioactivity from the fuel pins into the coolant.

IX-6. Summary of passive safety design features for SSTAR

Tables IX-5 to IX-9 below provide the designer’s response to the questionnaires developed at the IAEA technical meeting “Review of passive safety design options for SMRs” held in Vienna on 13 – 17 June 2005. These questionnaires were developed to summarize passive safety design options for different SMRs according to a common format, based on the provisions of the IAEA Safety Standards [IX-2] and other IAEA publications [IX-3, IX-6]. The information presented in Tables IX-5 to IX-9 provided a basis for the conclusions and recommendations of the main part of this report.

TABLE IX-5. QUESTIONNAIRE 1 – LIST OF SAFETY DESIGN FEATURES CONSIDERED FOR/ INCORPORATED INTO THE SSTAR DESIGN

#	SAFETY DESIGN FEATURES	WHAT IS TARGETED?
1	<p>Lear (Pb) coolant – ambient pressure coolant having a high boiling temperature (1740°C); does not react chemically with working fluid (CO₂); does not react vigorously with air or water/steam;</p> <p>Pb has low neutron absorption enabling core with an opened up lattice, reducing core frictional pressure drop;</p> <p>Coolant high density retards bubble/void transient growth during blow-down of working fluid into the coolant;</p> <p>Pb is a liquid metal coolant with low Prandtl number, providing high heat transfer coefficients</p>	<ul style="list-style-type: none"> - Elimination of loss-of-coolant due to flashing; - Assurance of a single-phase natural circulation heat transport in all operational transients and accidents at higher temperatures than in traditional liquid metal reactors; - Avoidance of combustible gas formation and exothermic energy release due to interaction of coolant and working fluid; - Avoidance of energetic reactions of coolant with air or water/steam
2	<p>Nitride fuel – advanced fuel having a high decomposition temperature (> 1350°C) and high melting temperature;</p> <p>Nitride fuel has high thermal conductivity which, when combined with Pb bond, reduces the difference between fuel and coolant temperatures;</p> <p>Nitride fuel has low swelling and fission gas release, high atom density</p>	<ul style="list-style-type: none"> - Reduction of stored energy in fuel by reducing positive Doppler and axial expansion reactivity contributions upon fuel cooldown; - Avoidance of melting or decomposition of fuel at higher temperatures than in traditional liquid metal-cooled reactors; - Reduction of a potential for fission gas pressure loading of cladding and pellet-cladding interactions; - Reduction of fuel volume fraction enabling an increase in coolant volume fraction;
3	Natural circulation heat transport	<ul style="list-style-type: none"> - Elimination of loss-of-flow accidents; - Assurance of heat removal from the core;
4	Vessel pool configuration with surrounding guard vessel	<ul style="list-style-type: none"> - Elimination of loss-of-coolant accidents; - Elimination of core uncovering; assurance of a natural circulation heat transport path to ultimate heat sink
5	Open-lattice core configuration	Avoidance of flow blockage accidents
6	Large reactivity feedbacks from fast spectrum core enabling passive load following and passive shutdown	<ul style="list-style-type: none"> - Improvement of reactor safety robustness with respect to human error during operation and/or maintenance; - Elimination of a failure to decrease reactor power to decay heat levels, in the event of a failure to scram.
7	Low burn-up reactivity swing over long core lifetime/refuelling interval, reducing reactivity investment in each control rod	Reduction of challenges from potential rod withdrawal accidents
8	Vessel air-cooling by natural circulation of air – always in effect	Assurance of removal of afterheat from the reactor system

#	SAFETY DESIGN FEATURES	WHAT IS TARGETED?
9	Escape path for gas/void to reach free surface, provided by design	- Assures that gas/void is not transported to the core in the event of in-vessel heat exchanger tube rupture
10	Passive pressure relief from primary coolant system	Avoidance of over-pressurization of primary coolant system following a heat exchanger tube rupture
11	Supercritical carbon dioxide Brayton cycle energy conversion; CO ₂ working fluid does not react chemically with Pb primary coolant	Elimination of combustible gas formation and exothermic reactions between primary coolant and working fluid
12	Containment (guard vessel + upper closure head); separate containment structure above upper closure head	Traditional defence in depth: prevents activity release in the event of vessel failure
13	Safety grade reactor trip system	Its functions are traditional – even though passive response is adequate

TABLE IX-6. QUESTIONNAIRE 2 – LIST OF INTERNAL HAZARDS

#	SPECIFIC HAZARDS THAT ARE OF CONCERN FOR A REACTOR LINE	EXPLAIN HOW THESE HAZARDS ARE ADDRESSED IN A SMR
1	Prevent unacceptable reactivity transients	- Low burn-up reactivity swing over long core lifetime/refuelling interval reduces the need for reactivity investment in control rods; - Large inherent reactivity feedbacks of a fast spectrum core provide negative reactivity contribution upon rise in coolant and fuel temperatures, compensating positive reactivity insertion, reducing reactivity to zero, and stabilizing power and system temperatures.
2	Avoid loss-of-coolant	- Vessel pool configuration with surrounding guard vessel; - Ambient pressure Pb coolant with high boiling temperature (1740°C) eliminates flashing of primary coolant.
3	Assure heat removal from core	- Natural circulation heat transport with ambient pressure single-phase Pb coolant to remove core power; - Provision of natural circulation-driven air cooling of guard vessel enables removal of reactor power at decay heat levels, in the event of loss of heat removal through the in-vessel heat exchangers.
4	Avoid loss-of-flow	- Natural circulation heat transport at power level > 100% of the nominal. - Open-lattice core configuration prevents flow blockage.
5	Avoid overcooling of reactor system	To be defined

#	SPECIFIC HAZARDS THAT ARE OF CONCERN FOR A REACTOR LINE	EXPLAIN HOW THESE HAZARDS ARE ADDRESSED IN A SMR
6	Avoid combustible gas generation or exothermic chemical reactions	<ul style="list-style-type: none"> - Pb primary coolant and CO₂ working fluid do not react chemically; - Pb coolant does not react vigorously with air or water/steam.
7	Prevent consequences of in-vessel heat exchanger tube rupture.	<ul style="list-style-type: none"> - High inertia/density of Pb coolant retards transient bubble/void growth during blow-down of CO₂ working fluid into the coolant; formation of small bubbles that could be transported to core region does not occur; - Escape path for gas/void to pool free surface, provided by design, avoids a potential for transport of void to the core; - Passive pressure relief from primary coolant system precludes over-pressurization of coolant pressure boundary.
8	Maintain integrity of fuel pin cladding.	Heat removal from the core by single-phase natural circulation and large reactivity feedbacks of fast-spectrum core limit the system temperatures during operational transients and postulated accidents to values well below those at which cladding strength is significantly reduced or nitride fuel decomposition occurs.
9	Maintain coolant pressure boundary	<ul style="list-style-type: none"> - Heat removal from core by single-phase natural circulation; - Large reactivity feedbacks of a fast spectrum core, and emergency decay heat removal by vessel air cooling of the guard vessel limit system temperatures during postulated accidents to values well below those at which vessel steel strength is significantly reduced; - Passive pressure relief from primary coolant system precludes over-pressurization of coolant pressure boundary.
10	Limit radiation exposure of public and plant personnel.	<ul style="list-style-type: none"> - Progression to core melt is deterministically eliminated by passive safety features; - Containment consisting of guard vessel and upper closure head is provided for defence-in-depth; - Additional containment structure is provided for additional mitigation of radioactivity release.

TABLE IX-7. QUESTIONNAIRE 3 – LIST OF INITIATING EVENTS FOR ABNORMAL OPERATION OCCURRENCES (AOO) / DESIGN BASIS ACCIDENTS (DBA) / BEYOND DESIGN BASIS ACCIDENTS (BDBA)

#	LIST OF INITIATING EVENTS FOR AOO / DBA / BDBA TYPICAL FOR A REACTOR LINE (LIQUID METAL COOLED FAST REACTORS)	DESIGN FEATURES OF SSTAR USED TO PREVENT PROGRESSION OF THE INITIATING EVENTS TO AOO / DBA / BDBA, TO CONTROL DBA, TO MITIGATE BDBA CONSEQUENCES, ETC.	INITIATING EVENTS SPECIFIC TO THIS PARTICULAR SMR
1	Loss-of-flow due to pump coast-down	Natural circulation heat transport at power levels > 100 % of the nominal; elimination of main coolant pumps	Not an accident initiator
2	Subassembly flow blockage	Open-lattice core configuration and coolant chemistry control reduce the possibility of a flow blockage	Not an accident initiator
3	Loss-of-heat sink	<ul style="list-style-type: none"> - Core and heat exchangers remain covered by ambient pressure single-phase Pb coolant, and single-phase natural circulation removes the core power under all operational transients and postulated accidents; - Vessel air cooling removes decay heat power levels from the reactor system; - In failure-to-scrum accidents, passive shutdown reduces and maintains the reactor power to low level representative of decay heat 	Cessation of heat removal from in-vessel heat exchangers by CO ₂ working fluid with or without scram
4	In-vessel heat exchanger tube rupture	<ul style="list-style-type: none"> - Transient bubble/void growth is retarded by high inertia/density of Pb primary coolant; - Pb primary coolant and CO₂ working fluid do not react chemically eliminating combustible gas formation and exothermic energy release; - Absence of formation of small bubbles entrained into the coolant and provision of an escape path to pool free surface eliminates a potential for transport of bubbles/void to the core; - Passive pressure relief from primary coolant system precludes over-pressurization by CO₂ 	

#	LIST OF INITIATING EVENTS FOR AOO / DBA / BDBA TYPICAL FOR A REACTOR LINE (LIQUID METAL COOLED FAST REACTORS)	DESIGN FEATURES OF SSTAR USED TO PREVENT PROGRESSION OF THE INITIATING EVENTS TO AOO / DBA / BDBA, TO CONTROL DBA, TO MITIGATE BDBA CONSEQUENCES, ETC.	INITIATING EVENTS SPECIFIC TO THIS PARTICULAR SMR
5	Transient overcooling	To be defined	Transient overcooling due to initiating event on S-CO ₂ Brayton cycle secondary side
6	Transient overpower/ reactivity insertion accident.	<ul style="list-style-type: none"> - Inherent negative reactivity feedback due to increase in fuel and coolant temperatures returns net reactivity to zero, stabilizing the reactor power and system temperatures at higher than nominal values; - Potential reactivity insertion due to rod withdrawal is reduced due to low burn-up reactivity swing, reducing the need for reactivity investment in control rods to compensate for burn-up effects 	
7	Loss-of-coolant	Eliminated due to vessel pool configuration without external piping at low elevations and ambient pressure Pb coolant	Not an initiator

TABLE IX-8. QUESTIONNAIRE 4 - SAFETY DESIGN FEATURES ATTRIBUTED TO DEFENCE IN DEPTH LEVELS

#	SAFETY DESIGN FEATURES	CATEGORY: A-D (FOR PASSIVE SYSTEMS ONLY), ACCORDING TO IAEA-TECDOC-626 [IX-6]	RELEVANT DID LEVEL, ACCORDING TO NS-R-1 [IX-2] AND INSAG-10 [IX-3]
1	Selection of Pb as a coolant	A,B	1,3
2	Selection of transuranic nitride as a fuel	A	1,3
3	Natural circulation heat transport	B	1,3
4	Vessel pool configuration with surrounding guard vessel	A	1,3,4
5	Open-lattice core configuration	A	1
6	Large reactivity feedbacks from fast spectrum core enabling passive load following and passive shutdown	A	1,3
7	Low burn-up reactivity swing over long core lifetime/refuelling interval, reducing reactivity investment in each control rod	A	1
8	Vessel air cooling by natural circulation	B	3
9	Escape path for gas/void to reach free surface, provided by design	A	3
10	Passive pressure relief from primary coolant system	C	3
11	Supercritical carbon dioxide Brayton cycle energy conversion - CO ₂ working fluid does not react chemically with Pb primary coolant	A	1
12	Containment	A	3, 4

TABLE IX-9. QUESTIONNAIRE 5 - POSITIVE/ NEGATIVE EFFECTS OF PASSIVE SAFETY DESIGN FEATURES IN AREAS OTHER THAN SAFETY.

PASSIVE SAFETY DESIGN FEATURES	POSITIVE EFFECTS ON ECONOMICS, PHYSICAL PROTECTION, ETC.	NEGATIVE EFFECTS ON ECONOMICS, PHYSICAL PROTECTION, ETC.
Pb coolant	Lack of chemical interaction with working fluid enables elimination of intermediate heat transport circuit reducing capital and operating costs	<ul style="list-style-type: none"> - Weight resulting from high Pb density may require greater vessel thicknesses, increasing capital costs; - Coolant chemistry control/ filtering systems needed to prevent corrosion/corrosion effects contribute to increased cost
Transuranic nitride fuel	<ul style="list-style-type: none"> - Transuranics are self-protective in safeguards sense; - Transuranic nitride fuel together with fast spectrum core and closed fuel cycle reduces fuel costs 	
Natural circulation heat transport	Natural circulation cooling, enabled by Pb coolant properties, eliminates main coolant pumps, contributing to reduced plant cost	Need for height separation of thermal centres between heat exchangers and core may require taller reactor and guard vessels, increasing capital costs
Large reactivity feedbacks from fast spectrum core enabling passive load following and passive shutdown	Enhances reliability and reduces operator requirements potentially reducing operating costs	

PASSIVE SAFETY DESIGN FEATURES	POSITIVE EFFECTS ON ECONOMICS, PHYSICAL PROTECTION, ETC.	NEGATIVE EFFECTS ON ECONOMICS, PHYSICAL PROTECTION, ETC.
Low burn-up reactivity swing over long core lifetime/refuelling interval, reducing reactivity investment in each control rod	Core is fissile self-sufficient with conversion ratio near unity such that the spent core can be reprocessed to further utilize its energy content, influencing positively upon fuel economics	
Escape path for gas/void to reach free surface in primary coolant system, provided by design		Requires slightly greater reactor and guard vessel diameters, increasing capital costs
Supercritical carbon dioxide Brayton cycle energy conversion; CO ₂ working fluid does not react chemically with Pb primary coolant	<ul style="list-style-type: none"> - Lack of chemical reaction between primary Pb and CO₂ working fluids enables elimination of intermediate coolant circuit, reducing capital and operating costs; - Use of supercritical carbon dioxide Brayton cycle with smaller turbo-machinery components than Rankine saturated steam cycle reduces plant capital and operating costs 	<ul style="list-style-type: none"> - Research and development costs will be required for supercritical CO₂ Brayton cycle; - Need to contain CO₂ with potential activity entrained from Pb coolant released from the reactor system following in-vessel heat exchanger tube rupture impacts upon containment requirements, potentially increasing the containment building costs; - Need to preclude radiolytic decomposition of CO₂ may require additional shielding of in-vessel Pb-to-CO₂ heat exchangers, potentially increasing the reactor system costs

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- [IX-7] INTERNATIONAL ATOMIC ENERGY AGENCY, Safety Related Terms for Advanced Nuclear Plants, IAEA-TECDOC-626, Vienna (1991).