Starting Fast Reactors Again

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1. Introduction

Fast reactors (FRs), or surgenerators, or "breeders", transmute U238 (99,3% of natural uranium) into fissionnable plutonium Pu239. For a given uranium mass, 60 to 100 times more energy may be produced, relatively to light water cooled reactors. At higher temperature, FRs allow better thermal efficiency. Increase of uranium ore cost would open access to huge uranium reserves. Planet energy needs could be satisfied for thousands of years. First fuel for these reactors may be Pu239 produced by LWRs, or U235 enriched uranium. FRs transmute actinides, created in the fuel, into shorter live fission products.

Sodium, their preferred coolant, liquid between 98°C and 883°C, reacts with air and water.

Their energy price is considered low for fuel cycle and high for construction, conducting to 2040 or 2050 before general use, when uranium prices have been increased due to shortage. To reduce energy price and increase safety, allowing an earlier extension, we propose the cold bottom resting vessel and other innovations.

In a "pool reactor", the vessel contains the primary circuit with pumps and exchangers to a secondary circuit, while in a "loop reactor", external pipes connect them. Several sodium vessel designs were proposed :

- vessel with a rounded bottom supporting the core diagrid, suspended to the concrete vault top (pool reactors Phénix, Superphénix, European Fast Reactor project, loop reactor Monju), all the vessel in tension, needing climatization in hot regions (550°C), by sodium cooled in the exchangers (400°C).
- half resting vessel (Russian pool reactors BN-600 and BN-800), the upper cylindrical wall and the roof resting on a ring supported by the basement. A diagrid slab anchored to this ring supports the core, above a rounded bottom in hydrostatic tension. No vessel climatization is needed.
- cold resting bottom vessel. The vessel bottom cooled at less than 90°C rests on the concrete basement and supports the core diagrid through vertical skirts, in a thick space of sodium in thermal gradient. No climatization is needed.
- hot resting bottom vessels, on rollers.

This paper describes innovations for the cold resting bottom in pool sodium reactors:

- diagrid extended on full vessel diameter and also borne in periphery by the cylindrical wall,
- lower space in thermal gradient containing heavy and refractory materials,
- exchangers-pumps vertically driven in the diagrid around the core,
- three handling pits around a cell above the vessel roof, where is lifted the control block,
- supplementary area obtained on the diagrid for used elements decrease.

The concrete vault contains the reactor under ground level. Advantages are cited:
-    general robustness by rigid fixation of the diagrid and elimination of climatization structures,
-    reduced vessel diameter, simplification and lesser weight of structures, easier repairs,
-    protection against core fusion accident and bottom attack by hot mix flow of fuel and steel,
-    sodium leaks frozen before penetrating in the concrete, no empty spaces outside the vessel,
-    limited accident consequences, by resistant exchangers-pumps fixed on two levels,
-    reduced thermal exchanges between "cool" and hot primary sodium, providing better efficiency,
-    reduced cost.

Innovations proposed by the author, which may in some points differ from these here described, are currently examined by the CEA, French Commissariat à l'Energie Atomique, and could contribute to allow earlier extension of fast reactors.

2. Situation

Fast Reactors (FRs), or surgenerators or "breeders", where neutrons are not slowed by a moderator, transmute uranium U238 (99,3% of natural uranium) into fissionnable plutonium Pu239. They may produce, for a given uranium mass, 60 to 100 times more thermal energy than moderated reactors like LWR's, light water cooled reactors, with a better thermal efficiency due to a higher temperature. An increase of uranium ore cost would not compromize economy production, and would open access to huge uranium reserves. Fission nuclear energy could then satisfy our planet energy needs of for thousands of years.

The fast neutron flux in surgenerators, like the moderated flux in LWRs, creates fission products subject to a relatively short half-life (about 300 years), more fissile plutonium and much less minor actinides, heavier than uranium, constituting long half-life wastes. Then the problem of wastes stockage, until raising the current level of radioactivity on our planet, is made much easier. Moreover, their fast flux is able to convert LWR produced minor actinides, introduced in their fuel, into energy and fission products easely stocked. For introduction of a series of fast reactors, they may use LWR-produced Plutonium, or U235 enriched Uranium, the price of which remains acceptable. For current use, they burn only natural uranium or depleted uranium, reserves of which are very important. Use of Thorium is not presently foreseen.

Sodium cooled reactors (SFRs) take advantage of factors like:
-    coolant temperatures largely below boiling point, preventing core dry-out by coolant evaporation,
-    very good heat transfer capability and natural circulation behaviour of the sodium coolant,
-    an argon pressure slightly above atmospheric pressure, sufficient on sodium surface,
-    use of ductile structural materials allowing leak detection before rupture,
-    a stable core with negative reactivity feedback to power increase,
-    high combustion rates before fuel subassemblies cladding failure,
-    as shown by extended studies, a low energy produced in case of accidental bursts,
-    a large experience, which allowed to eliminate several dysfunctions.

About twenty sodium cooled fast reactors have been or are constructed in the world. Phenix and Superphenix in France, now stopped, showed excellent fuel elements reliability and ease of control;. In Russia, BN-600 performs satisfactorily since 1980 and should operate until 2025. BN-800 is under construction.

Phenix performed well with exception to problems in steam generators, quickly mastered. Superphenix was lengthly stopped due to problems on secondary parts, equally mastered, and to extended administrative procedures. Overcosts appeared due to some options and to the number of technical actors. "Ecological" campaigns, based on the Tchernobyl accident, in a moderated reactor inherently unsafe and incorrectly operated, and a loss of secondary sodium to air on the Monju breeder in Japan, led the French government to stop Superphenix in 1998, in an unmotivated decision ; it is now being dismantled. Nuclear opponents still claim that surgenerators are dangerous and cannot become economical, in a context of, they suppose, uranium scarcity and renewable energy abundance.

On the contrary, we think that the world needs much energy, without limited recourse to fossil fuels. Fast reactors are clearly to be developed. Decisions for starting them again shall evidently be based on advantages for safety and overall economy. Low probability risks of aggressions by terrorism or by earthquakes shall be taken into account and their consequences prevented. Simplified designs and reduction of steel and sodium masses shall be sought.

The international Forum "Generation IV", launched in 2001 by USA, Japan and France, followed by some fifteen countries, defined tracks for improved nuclear reactors. Japan and France will conduct the research on sodium cooled fast reactors. Japan will reactivate the 250 MWe Monju breeder reactor stopped in 1995. For 2020, France will build the sodium cooled 600 MWe Astrid, which should validate new technical features and by transmutation reduce radioactive waste. Larger units should follow.

Running expenses of sodium cooled surgenerators should become low relatively to LWR's, when fuel reprocessing units will be ready, but their construction cost is deemed high: a supplement over 20% on the installed kW has been cited. Resulting profitability versus LWRs is often foreseen only for about 2040, when uranium price will be sufficiently increased due to demand. Surgenerators safety remains debated. In order to reduce their cost and to establish an evident safety, several innovations are here proposed, based on the concept of the cold resting bottom vessel with a diagrid support in thermal gradient, and on new propositions.

3. Present Sodium cooled fast reactors

Main features of to-day reactors will be recalled. Temperatures are rounded.

The steel sodium vessel of pool SFRs is suspended in a safety vessel which for EFR project (1998), along our 1978 proposition, became a concrete caisson or "vault", with internal cooled steel skin, imbedded in soil or resting on parasismic supports. The sodium vessel top contains, below an argon cover, a primary sodium at 550°C ("hot" temperature) coming from the core. This sodium enters exchangers, which heat the secondary sodium directed to external generating units for electricity production, and is discharged in a lower plenum at "cool" temperature (400°C). Taken by primary pumps, this sodium is injected under pressure (about 0,5 MPa or 5 atmospheres) in the diagrid, a flat hollow structure resting on the vessel bottom and supporting fuel subassemblies. In pool option, heat exchangers and pumps are contained in periphery of the sodium vessel. Direct reactor cooling loops (DRC) using natural convection are added for emergency cases.

The sodium vessel is usually suspended in periphery to the vault top. In Phenix, Superphenix and EFR, an internal wide-mouthed vessel extends from diagrid to the sodium vessel top and, completed by baffles, directs a flow of cool sodium to climatize the vessel wall, before mixing in hot sodium.

In Russian reactors, the concrete basement supports by articulated plates (BN600) or by a cylindrical shell (BN800 in construction) a resisting ring on which are fixed the wall

cylindrical part, a full diameter slab supporting the diagrid, and a rounded bottom. No climatization is needed in the wall, due to elimination of vertical tensile stresses.

The diagrid surface is loaded by fuel subassemblies and other elements, contained in identical hexagonal vertical wrapper tubes fixed to cylindrical spikes to be inserted in holes of the diagrid along a triangular net. Fuel subassemblies contain in median part uranium-plutonium pins heating the sodium and, above and below, axial blanket uranium pins to be transmuted into plutonium, and shielding materials. The core also receives wrapper tubes for control rods driven by vertical bars from an upper controlling block and left in lower position for nuclear arrest, when this block is displaced for allowing fuel elements transfers. The diagrid external part is loaded by breeding and shielding elements lowering the flux transmitted to exchangers and to the vessel. Spent fuel elements are stored in periphery for one or two years before discharge and treatment. Inserted spikes receive sodium by inlet ports around the shroud tubes, and individual sodium flows are controlled by gagging pieces in the spikes and by adaptation of inlet ports. Element take-off by pressure on spikes is prevented by openings to the lower space. A leak of "cool" sodium is admitted to the lower plenum, allowing an ascending flow along the vessel for climatization.

In "pool reactors", intermediary heat exchangers (IHXs) with secondary sodium stand around the core, suspended to the vault roof by concentric secondary sodium pipes. For suspended vessels, exchangers penetrate the internal wide-mouthed vessel without leaks, using bell-shaped argon joints or solid segments, before feeding cool sodium down in the plenum. Pumps, of which columns arrive to the plenum through this internal vessel, drive sodium into the diagrid by side connected pipes.

In "loop reactors", pipes through the roof conduct hot sodium to external exchangers with secondary sodium, heating steam generators, and pumps reinject the cooled sodium to the reactor. For direct heating of mechanical energy cycles by primary sodium, steam generators with double exchange tubes have been proposed. Gas cycles without secondary sodium were also proposed..

The two excentered plugs system is usually used for handling subassemblies while bars commanding the control rods are left in place. Two vertical handling columns are used, one takes place in the control block on the smaller plug, for the inner handling zone of the core, and the other one on the large plug with a rotating lateral arm, for the outer handling zone. Subassemblies are exchanged between the diagrid and a lateral rotor, covered by a fuel handling flask for exchanges with external halls. These two plugs are fixed to the roof during reactor operation. Leak-tighness during rotations was given by skirts immersed in circular channels filled with a melted alloy, but now would be obtained using solid segments. This system with only rotations allows to keep at constant level the bar control block and the detectors placed on the top of the core.

For these sodium cooled breeding reactors, special risks are attached to:

- chemical reactions of sodium in case of contacts with air or water,
- the fact that the core is not in its most reactive configuration and that a lack of cooling flow could induce a sodium void with reactivity burst and fusion of a part of the core, producing a hot "corium" finally able to pierce the vessel bottom.

For LWR's, lack of cooling flow would not lead to nuclear excursion but could also induce a fusion. Vessel integrity is essential for both types of reactors. Applying the "defence in depth" principles, these risks are addressed by successive protection levels, not detailed here. Innovations below would contribute to these protections.

The European Fast Reactor (EFR) project, published in 1998, will be taken as reference to innovations. It is described in Part 6.

4. Proposition for a cold resting bottom vessel with integral diagrid

The author has proposed (French patent 80 27759) for sodium cooled pool reactors a vessel with a flat bottom, resting on the bottom of a concrete vault imbedded in soil, maintained "cold" at about 90°C (melting sodium temperature 98°C).

In the cited patent, an empty lower space for inspection by detectors and potential reparability was indicated between the vessel bottom and the vault bottom steel skin, but is to be suppressed, along the french patent 88 11370 concerning a loop reactor. Better robustness is obtained by direct vessel support on the thick concrete and elimination of empty spaces favorizing leaks below the core. The here proposed sodium vessel bottom is only constituted by the vault steel skin, thick of about 4 cm, maintained by welded bars to a layer of sodium resisting concrete, cooled by fluid circulation in tubes, and monitored against cracks. A leak through any crack is prevented by sodium freezing above the skin. It has been asked to allow its reparability but this should not introduce empty spaces: after a very low probability disorder, it would remain possible to freeze sodium and cut a passage for repair through the concrete.

An "integral diagrid" is now patented **(Figures 1 and 2)**. The entirely cylindrical wall of the sodium vessel itself constitutes the lateral wall of the full diameter flat diagrid, also supported by concentric steel skirts at about 2 meters height. Temperature remains "cool" to 400°C on the diagrid thickness.

In this closed space below the diagrid, the space is filled by stratified sodium, without forced circulation, in gradient between 90°C and 400°C. A 150°C/m gradient would give in pure sodium (conductivity 140W/m°) a flux of 21 kW/m², not easely evacuated by the bottom cooling system. Solid refractory materials are added, detailed in Part 7. The flux could be reduced to less than 5 kW/m², transmitting 715 kW on a section of 143 m² for a diameter of 13.5m.

The diagrid receives fuel subassemblies and other elements, and feeds them under pressure by cool sodium. It is made of three plates, the bottom one leaktight, defining an upper layer at high pressure and a lower one at smaller pressure, precluding elements taking-off. Central elements are fed by the upper layer, with leaks to the lower layer feeding peripheric elements.

Above the diagrid, the vessel wall temperature increases, until reaching the hot sodium temperature (550°C), progressively due to the isolation produced by lateral elements and exchangers on the diagrid periphery. Like in other SFRs, an argon cover separates the sodium surface from the vaut roof maintained at about 150°C in order to avoid a mesos (sodium oxides) accumulation. A steel plate is fixed below the roof for insulation, by means excluding fall of pieces.

The annular space between vessel wall and the cooled skin of the vault is filled by argon and may contain isolating panels, possibly renewable through upper trap-doors, using rotation displacements around the vessel. In case of accidental temperature jump in the vessel, sodium may be injected in this space, allowing a contribution of the vault cooling net. Such an injection, or a temporary heating, could clean this space after a mesos deposition.

Vessel wall dilatations induce displacements in height and diameter of its hot circular board. which could possibly be joined to the vault roof, maintained at 150°C, by a leak-tight bellow. If exchangers penetrate the roof at his limit, such a bellow should extend externally.

It is preferred to shape the vessel upper part along a short external cone **(Figure 3)**, the slope of which corresponds to dilatation direction. This cone remains at short distance of a corresponding internal cone around the vault roof, with a clearance filled by a side by side collection of sectors in metallic isolating matter applied to the roof cone and protected below

by a steel flexible sheet which could slide on the external cone under a low stress. These sectors are assembled to curved chocks forming a ring, compressed by the roof weight and by tie-rods. The isolating matter and the sheet could be renewed with corresponding chocks, after a limited elevation of the roof by jacks. A leak-tight belt is winded around the chocks.

As the thin space between cones is not leak-tight, a small argon flow penetrates from the annular space around the vessel to the space below the roof. This flow is purified and re-injected.
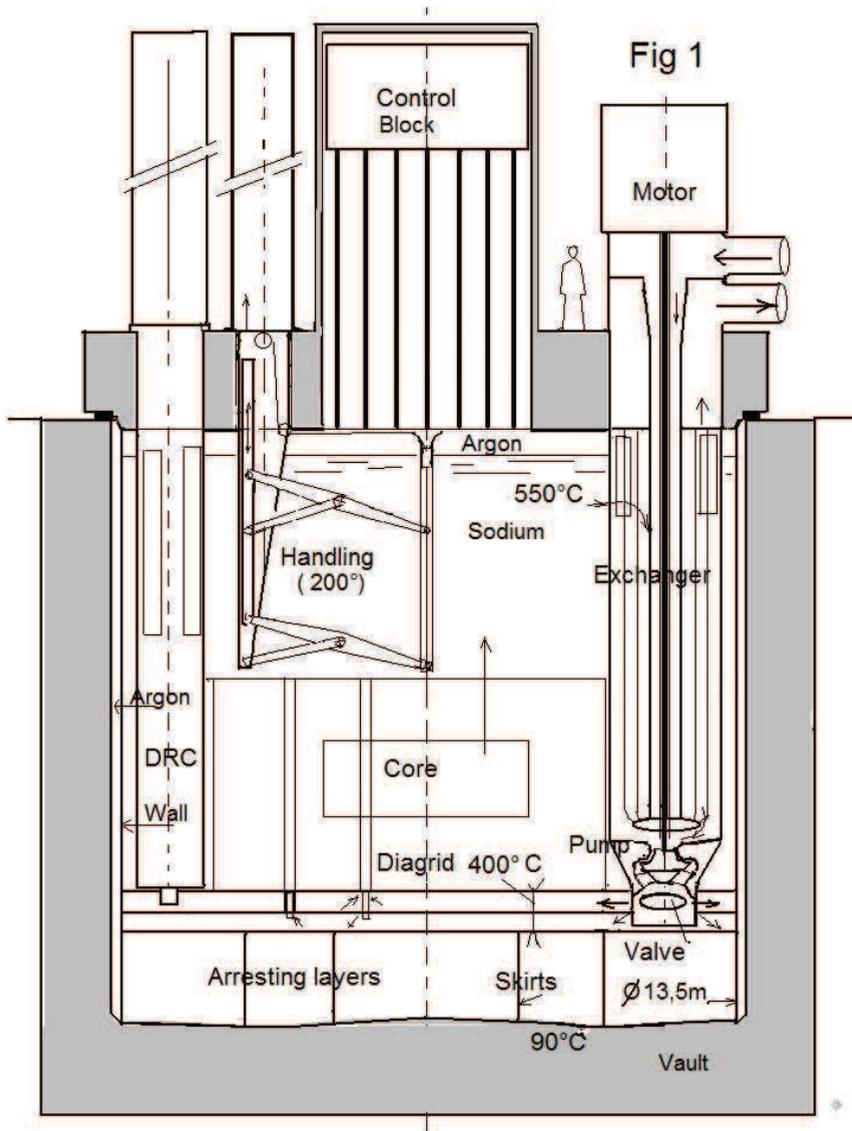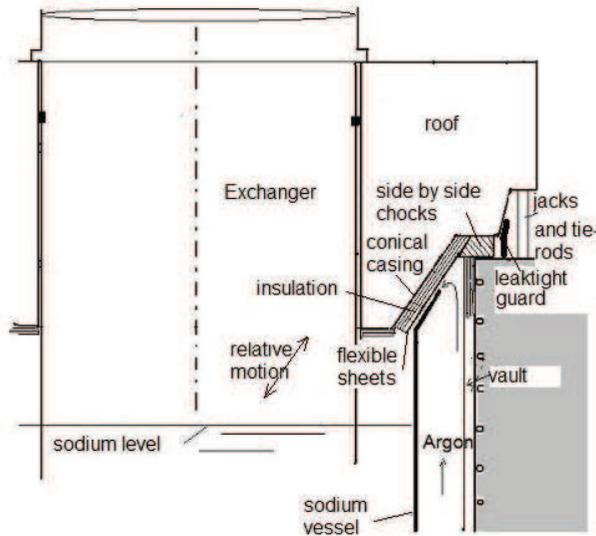

Fig. 1.
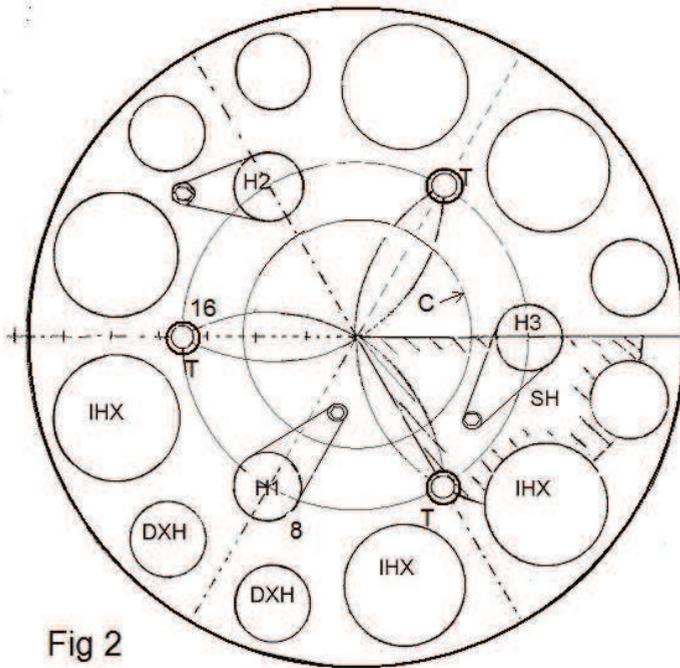
Fig. 2.

Fig. 3.

Fatigue behaviour in the vessel wall due to temperature variations of the diagrid is here examined. Vessel bottom and bottom plate of the diagrid are assumed rigid. For half variation of 150° in the diagrid of radius 6.75m, the radial displacement reaches 12 mm, inducing in the 2 m high wall embeddings a curvature of radius 53m. For a thickness of 4 cm, flexural stress reaches 90 MPa without fatigue effect at 400°C. Internal skirts are less stressed. The height could be reduced if exceeding the need for protecting the bottom.

Above the diagrid, the vessel wall must in operation resist laterally only to the sodium hydrostatic pressure and may reach the hot sodium temperature, with a thickness for instance of 3cm. In case of accidental loading and specially of earthquakes, this vessel wall resists due to its centering at bottom, and at top by conical contact toward the robust vault roof. Dynamic effects are limited by friction of sodium to rigid exchanger walls in vessel periphery, centered on two levels, and as proposed below, by butting of core elements on their walls.

This resting bottom and the integral diagrid appear as robust and resisting to accidents. The flat bottom cylindrical shape allows a better arrangement of internals relatively to suspended vessels with a rounded bottom, and reductions on overall volume, weight and price.

5. Proposition for exchangers-pumps

Leaving intermediate exchangers, the sodium usually arrives in a plenum around and below the diagrid, before being taken by pumps and injected into the diagrid. Here exchangers-pumps are proposed, excluding such a plenum. Each one, comprising a vertical exchanger and a pump fixed below, injects cool sodium (400°C) down into the diagrid. The loss of charge in exchangers, no more limited by the height difference, usually of a few meters, between hot sodium level on vessel top and entry level in the pumps, may reach almost the exchanger height, about 10 m. Accepting an increased loss of charge may allow an optimization with smaller or more efficient exchangers.

A secondary sodium circuit comprises an inlet pipe connecting the external secundary pump to the exchanger, and an outlet pipe from the exchanger to the steam generator. These pipes, vertical and concentric in the roof, separate above, becoming horizontal. In the exchanger envelope, the secondary sodium arrives to an annular distributor for exchange tubes going to an upper annular collector. In the axis of the inlet pipe, the pump is driven by an upper motor and a shaft contained in an axial tube, with hydrostatic bearings fed along the shaft by primary sodium under pressure, in sufficient number to avoid vibrations,

At sodium vessel top, the primary hot sodium emitted by the core enters the exchanger-pump by upper peripheral ports. Once cooled and taken by the pump, this sodium is injected into the diagrid upper space by ports of a vertical large pump foot, penetrating in the lower space to preclude lifting effects like for fuel elements. Leaks contribute to feed this low pressure space with flow for peripheral elements. In the pump, a purging valve collects gas possibly carried by the flow and sends it up to vessel cover, avoiding cooling disorder in the core.

In the light of the EFR project (1500 MWe), equivalent circuits for the same power may, for the cold resting bottom reactor, use six exchanger-pumps IHXP's with a height of 12 m. Each of them is suspended by a rim in a pit in periphery of the roof and planted into the diagrid, leak-tighness being provided by piston rings. Six decay heat exchangers DHX's for safety, working in natural convection for both their lower sodium circuit and their upper air circuit,

are also centered in the roof periphery and in the diagrid. These rigid components, centered at two levels, reduce the charge on the wall in case of accidents.

All resting elements may be extracted for examination and repairs, and the diagrid inner space may be examined using the holes for exchanger-pumps.

In order to increase the stocking area for used elements it is interesting that the handling system would access the full area of the integral diagrid, between the exchangers.

6. Proposition for the handling system

The handling system, working normally in sodium cooled at about 200°C, should cover the large integral diagrid shown above, including allowable areas between exchangers in periphery. The usual two rotating plugs handling system covers an unsufficient diameter, and, with a rotor proposed in the vessel for vertical exchanges, needs a large surface on the roof. It makes it difficult to examine the lower surface of the rod controlling block, where hot sodium, arriving from many core channels, creates thermal cycling and fatigue. This system gave however satisfaction in several reactors and remain compatible with other innovations here proposed.

Another system is here proposed, for which the space above the core is made free from commands to the control rods. While these rods are left in the core, commanding bars are independently lifted through pits in the vessel roof, under action of their mechanisms situated above this roof in a leak-tight cell, allowing examination and repairs. This gives space below the roof for three manipulators, centered in three pits around the cell. Each manipiulator comprises a rotating column from which an articulated "pantograph" projects horizontally a vertical handling tube containing a lifting hook to cover positions on relevant part of the diagrid.

Before introduction of a subassembly or element in a channel on the diagrid, it is necessary to orient the hexagonal tube. On the handling tube is used an hexagonal funnel, mechanically oriented before projection, its rounded edge allowing sliding of the cables suspending the hooks.

Between manipulator pits, at intersections of their maxima projections, three transit pits pierce the roof, above three unoccupied locations on the diagrid in the blanket area, encircled by steel hexagonal elements. Transfer of elements between any location on the diagrid and a given transit pit is obtained using only one manipulator, or two manipulators and an intermediary unoccupied location. One transit pit could be chosen for evacuating cooled fuel subassemblies after a lengthy stockage, using large flasks filled by gas for several elements, while a second pit would be chosen for experimental or presumed faulty individual elements, needing earlier discharge under liquid sodium. This second pit would use on the diagrid a larger channel between blanket elements for containing a leak-tight sodium pot in which a subassembly may be kept during the full transit way to examination halls, inside a special flask. These transit ways through two pits appear to need less installations than usual systems, but the third pit could also be equipped for transits, in order to reduce operation delays.

The two types of hooks for subassemblies or for the sodium pot use differential motions of their two cables, coming from a winding-drum in the manipulator pit. These cables are guided in the pantograph angles by the funnel and by a pulley near the manipulator axis.

When the pantograph is retracted, the full manipulator may be lifted in a leak-tight container fixed on its pit, where it is kept out of flux under gas at moderate temperature. For

maintenance, this container is disconnected, and transported above the roof. Connection of a manipulator container or of a transport flask on a pit may use a gas bag inserted through a narrow lateral inlet and inflated for leaktightness, while lids are exchanged.

Manipulators may receive cameras for observing the space above the diagrid, or tools for repairs, for instance in case of malfunction in one of them. They may also be used for placing butting steel elements between some blanket elements resting on the diagrid and the robust exchangers in periphery, rigidly centered on two levels, able to prevent large displacements of all elements in case of accidents or earthquakes. These butting elements are placed before introduction of exchangers.

Manipulators are largely dimensioned for obtaining the necessary rigidity and precision. They are operated under automatic and visual control.

7. General implantation

The 1500 MWe EFR project, taken as reference, is described below.

Its thermal power is 3600 MW and electric power 1470 MWe. The sodium vessel is suspended in periphery of the vault top. Vessel height is 16,2m (8,6m for the cylindrical part, 7,6m for the rounded bottom), below a 0,85m thick steel roof. Diameters are 18m internally for the vault, 17,2 m for the vessel, 16,25m for internal wide-mouthed vessel, 8,2m for diagrid with a surface of 53 m², 7.2m for the handling machine large plug. The diagrid is supported by a steel strongback resting on the rounded vessel bottom. Six intermediary heat exchangers, heating independently six external steam generating units, have a diameter of 2,3m in the exchanging part and 2,85m in the roof pit (6,4 m²) for a height of 7,7m in exchanging part and 13,2m between bottom and roof surface. Three primary pumps, for a flow rate of 19 tons/s, penetrate the roof through 2m diameter pits. Six smaller DRC (direct reactor cooling) exchangers, using natural convection in sodium and air, remove heat in case of unavailability of the main cooling system..

Figure 2 proposes a plan for the same reactor core with a vessel reactor diameter reduced to 13.5m, six exchangers (IHX), shown with a diameter of 2.5m, and six DRCs assumed to a diameter of 1.7m. Distance of these components to the vessel wall is 0.25m. The three handling systems H1, H2, H3 are shown with a pit diameter of 1.2m. The projection radius is taken at 3.5 m. The diameter CB of 4.5 m needed in the cell for the EFR conical skirt around the control block could be kept.

Area SH corresponds to half the area covered by one manipulator. Total covered surface reaches 77 sqm instead of 53 sqm for EFR, allowing for the same power a large extension of stockage in reactor, delays before discharge being increased for instance to three years.

Before a detailed project is established, it is clear that proposed innovations allow a very reduced vessel section, for a given power SFR.

The vessel height would be reduced by about 2m below the diagrid due to the cylindrical general shape without rounded bottom. The diagrid thickness is maintained to 1.15m. IHX's height must be increased by the pump height for about 2m. Then the overall height would not be modified, but above the roof by the cell receiving the control block.

8. Safety aspects

Safety as related to these innovations for sodium cooled reactors is shortly discussed here.

It was precedently admitted that the core disruptive accident (CDA) producing corium was limited to seven fuel subassemblies. It is now deemed that, even with large preventing measures, a core catcher should be able to cope with a full core fusion. This was one reason for proposing the cold resting bottom vessel with a thick refractory lower space excluding the risk of vessel piercing, other reasons being economy and robustness.

In this lower space designed to stop an important hot corium flow, an horizontal core catcher may be extended below the full diagrid surface, using for instance graphite pieces with a very high melting temperature, coated by steel in order to avoid chemical effects in normal run. Upper windows in supporting skirts allow communications. The large surface reduces the melt corium thickness and favorizes its cooling, by sodium vaporization, by transmission to bottom, and by mixing with granular refractory or absorbing materials, preventing recriticality.

Core catchers have been extensively studied for LWR's, assuming large corium flow. They were also examined for sodium cooled reactors. Tests used simulation of corium by chemically produced hot materials. It seems that reactions in case of core melting would be less explosive with sodium than in water reactors, and that core catcher cooling is more efficient with sodium than with water. Such studies should be extended to structures as proposed here.

Solid horizontal layers below the diagrid may use steel plates (conductivity 82 W/m°, fusion 1200° to 1500° depending on composition), graphite (100 W/m°, 3850°), other refractory materials like alumina (8 W/m°, 2054°), depleted uranium oxide, and lead allowing corium flotation, in pieces coated by steel. These layers with different conductions would favour horizontal extensions of temperatures and reduce concentrated effects. A conical shape of skirts may prevent displacements of light pieces.

Cracks are not to be expected in the skin submitted to compression, under cold sodium. They could be however detected below the welds, using channels in the concrete, normally plugged by sand. In operation, sodium leaks through bottom cracks are prevented by sodium freezing.

Fusion in the core is normally prevented in each fuel element by fitting up fuel pins without obstacles to the sodium flow, using for instance helicoïdal spacers.

The cold resting bottom with integral diagrid provides rigidity and robustness, preventing resonances of suspended vessels and probably avoiding recourse to parasismic supports below the vault. The strongly supported diagrid may resist large accidental loads.

Deliberate aggressions should also be taken into account. They would be excluded only by deeper and costly installations beneath the ground, to be justified by probabilistic assessments. A protection is given by above roof structures. Insertion of the vault and of the full primary sodium into the ground gives protection against primary sodium fires. It is recommended that the secondary sodium circuits, with parts above reactor roof for allowing natural convection, would be protected by partial digging and embankment surrounding.

Frequent incidents came from water-sodium contacts in steam generators. No innovation is here presented.

9. Advantages for these innovations

1. Large simplification, with reductions of steel and sodium masses and consequently of construction cost. A minimum sodium volume could however remain required to provide a sufficient thermal inertia in case of accidents.

2. The space below the diagrid may contain cold and refractory materials in large thicknesses, preventing any piercing by corium.
3.   Robustness provided by simplified cylindrical structures fixed on two levels.
4. Embedding the vault in ground protects against aggressions, accidents and earthquakes.
5. Bottom leak-tight to cracks, due to sodium freezing.
6. Voids exclusion below the core protects against core dry-out.
7. Thermic losses reduced and efficiency correspondingly increased
8. Negative reactivity coefficient added by opposite dilatations of structures and control bars.
9. Large area diagrid allowing a several years decay for used elements.
10. Only one circulation of neutral gas (argon).
11. An emergency cooling obtained by replacing argon around the vessel by sodium.
12. Cooled sodium in the bottom space, under low circulation, may trap sodium oxides.
13. The handling system may reduce delays and allow easier observations and repairs.
14. At reactor end of life, the vault remains available for new structures or waste stockage.

Proposed innovations, allowing better safety, easier inspections and repairs, and lower costs, could give advantages of SFRs to LWRs and allow shorter delays before a large utilization.

The author would appreciate to receive comments to his propositions.

Other innovations are currently proposed to French Commissariat à l'Energie Atomique.

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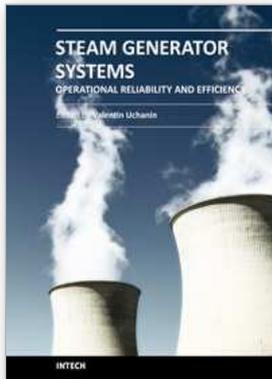
Steam Generator Systems: Operational Reliability and Efficiency

Edited by Dr. Valentin Uchanin

The book is intended for practical engineers, researchers, students and other people dealing with the reviewed problems. We hope that the presented book will be beneficial to all readers and initiate further inquiry and development with aspiration for better future. The authors from different countries all over the world (Germany, France, Italy, Japan, Slovenia, Indonesia, Belgium, Romania, Lithuania, Russia, Spain, Sweden, Korea and Ukraine) prepared chapters for this book. Such a broad geography indicates a high significance of considered subjects.

How to reference

In order to correctly reference this scholarly work, feel free to copy and paste the following:

Didier Costes (2011). Starting Fast Reactors Again, Steam Generator Systems: Operational Reliability and Efficiency, Dr. Valentin Uchanin (Ed.), ISBN: 978-953-307-303-3, InTech, Available from: http://www.intechopen.com/books/steam-generator-systems-operational-reliability-and-efficiency/starting-fast-reactors-again

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