ICENES 96

COMPLETELY AUTOMATED NUCLEAR REACTORS FOR LONG-TERM OPERATION II:

Toward A Concept-Level Point-Design Of A High-Temperature, Gas-Cooled Central Power Station System

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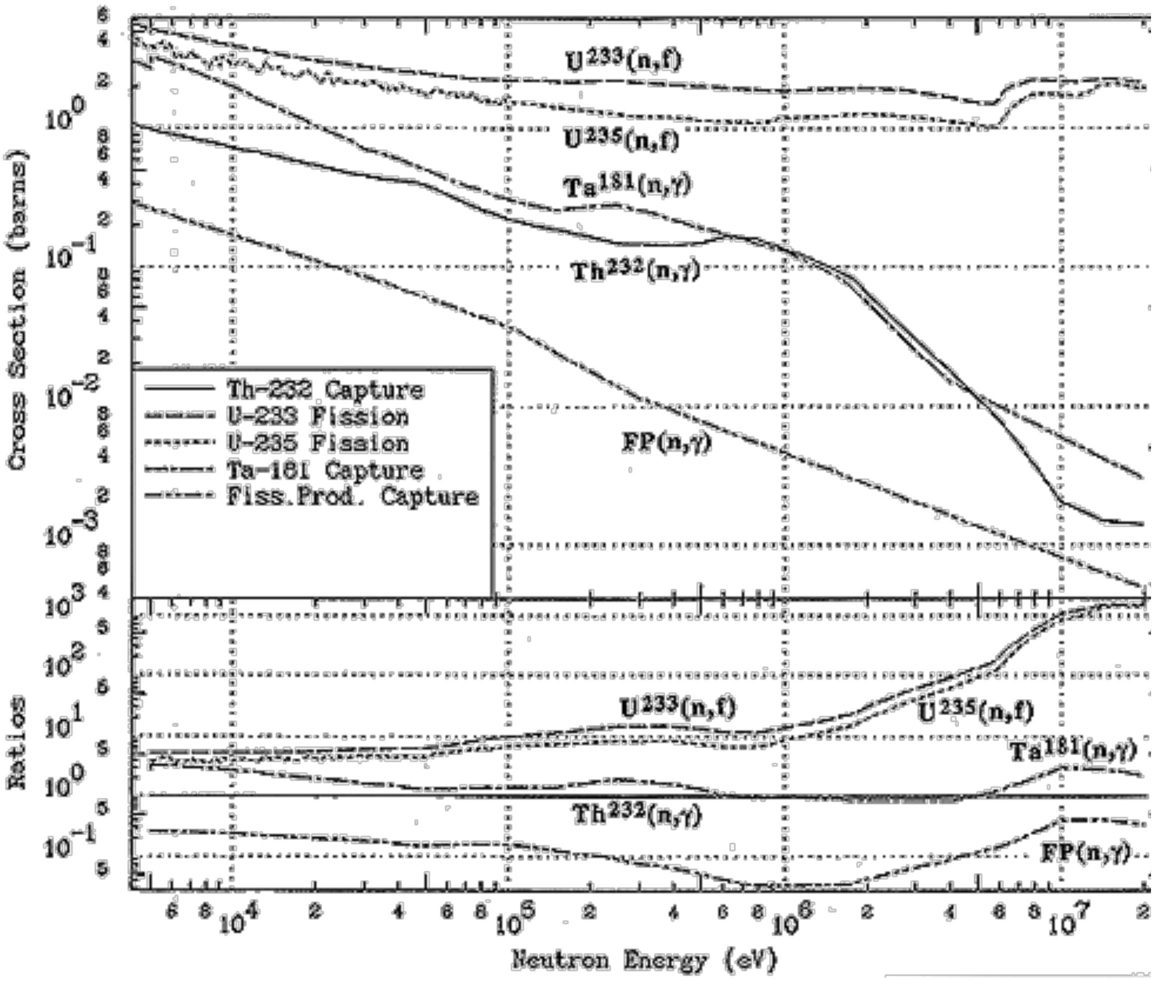
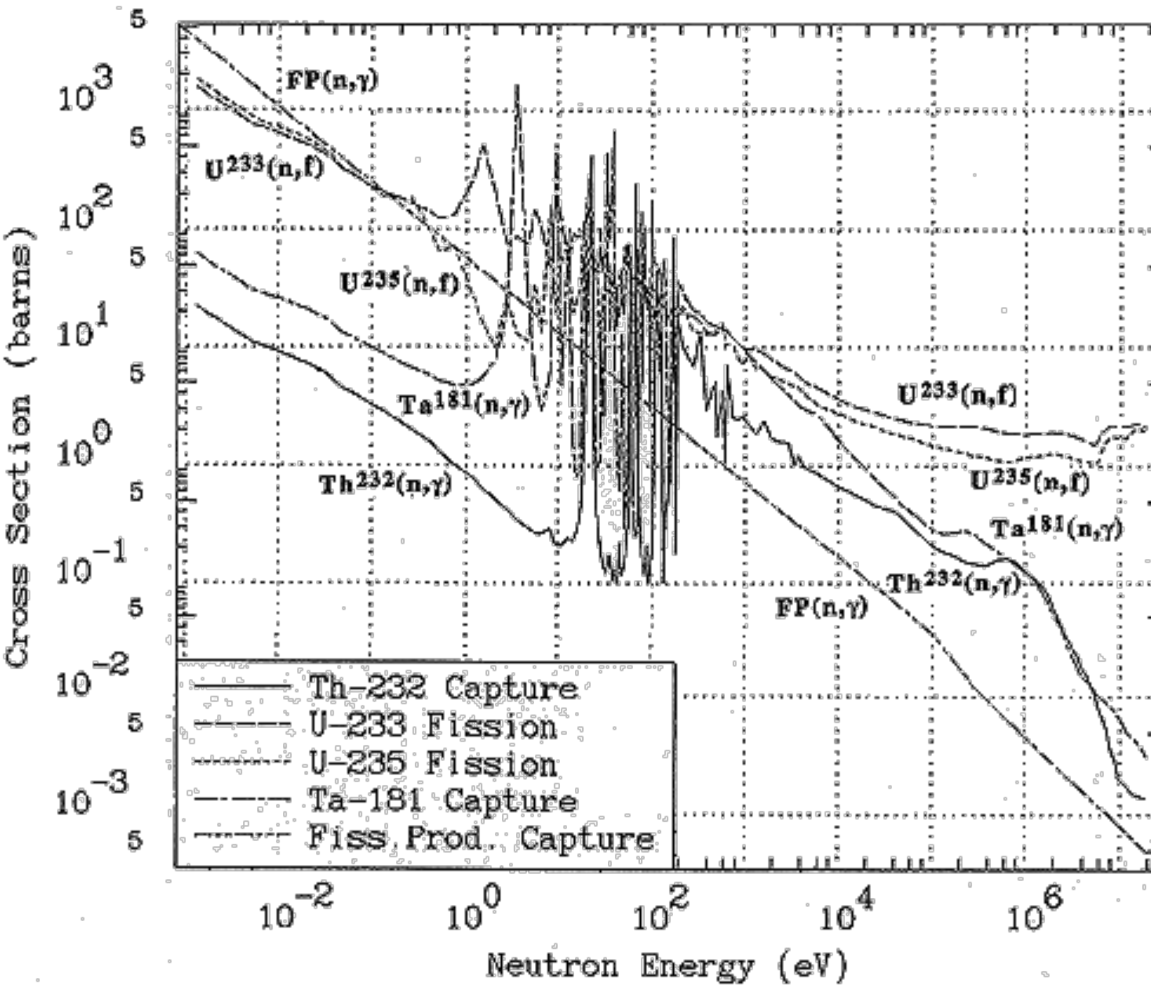


FIGURE 1. Cross-sections for the dominant neutron-driven nuclear reactions of interest for the Th^{232}-fueled variant of the new class of nuclear power reactors, over the neutron energy range 10^{-3} - 10^{7} eV. It is obvious that losses to radiative capture on fission product nuclei dominate neutron economies at near-thermal energies, but are comparatively negligible above the resonance capture region.

The advantages of operating with a fast neutron spectrum when attempting to realize a high-gain fertile-to-fissile breeder are manifest. These advantages are compelling when recycling (i.e., periodic or continuous removal of fission products) is precluded.



FP(n,γ)
U233(n,f)
U235(n,f)
Ta181(n,γ)
Th232(n,γ)
U233(n,f)
U235(n,f)
Ta181(n,γ)
Th232(n,γ)
FP(n,γ)
Th-232 Capture
U-233 Fission
U-235 Fission
Ta-181 Capture
Fiss Prod. Capture
Cross Section (barns)
Neutron Energy (eV)

FIGURE 2. Cross-sections for the dominant neutron-driven nuclear reactions of primary interest for the Th^{232}-fueled variant of the new class of nuclear power reactors, over the most interesting portion of the neutron energy range, between $>10^4$ and $<10^{6.5}$ eV, in the upper portion of the Figure. The neutron spectrum of the new type of reactor peaks in the 10^5 eV neutron energy region. The lower portion of the Figure contains the ratio of these cross-sections vs. neutron energy to the cross-section for neutron radiative capture on Th^{232}, the fertile-to-fissile breeding step.

It is clear that losses to radiative capture on fission products are comparatively negligible over the neutron energy range of interest, and furthermore that atom-fractions of a few tens of percent of high-performance structural material, such as Ta, will impose tolerable loads on the neutron economy in the reactor core. These data also suggest that core-averaged fuel burn-up in excess of 50% will probably be realizable, and that fission product-to-fissile atom-ratios behind the nuclear deflagration wave when reactivity is finally driven negative by fission-product accumulation will be ~10:1. Indeed, both of these basic results are observed in detailed nucleonics model studies of the new type of reactor, as is summarized in Figure 5.

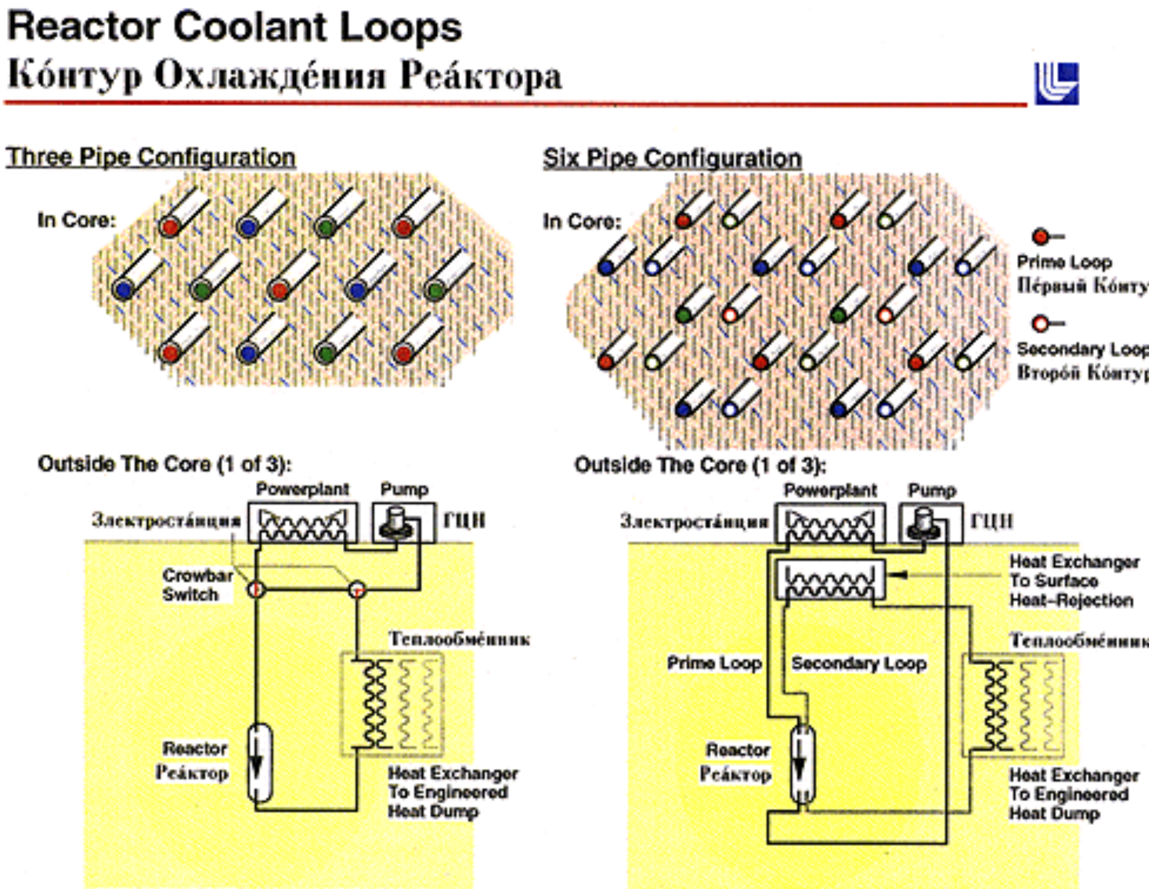


FIGURE 3. Two configurations are depicted for heat-transfer from the core's fuel-charge into helium coolant streams are shown, a simple triply-redundant one on the left and the presently-preferred baseline-design one on the right, which is comprised of entirely independent primary and secondary cooling systems, each one of which is triply redundant. Details and salient performance indices are discussed in Appendix C and the performance-modeling of these configurations is sketched in Appendix A.

The full layout of the heat transport system based on the dual, triply-redundant six-pipe system is shown in Figure 6.

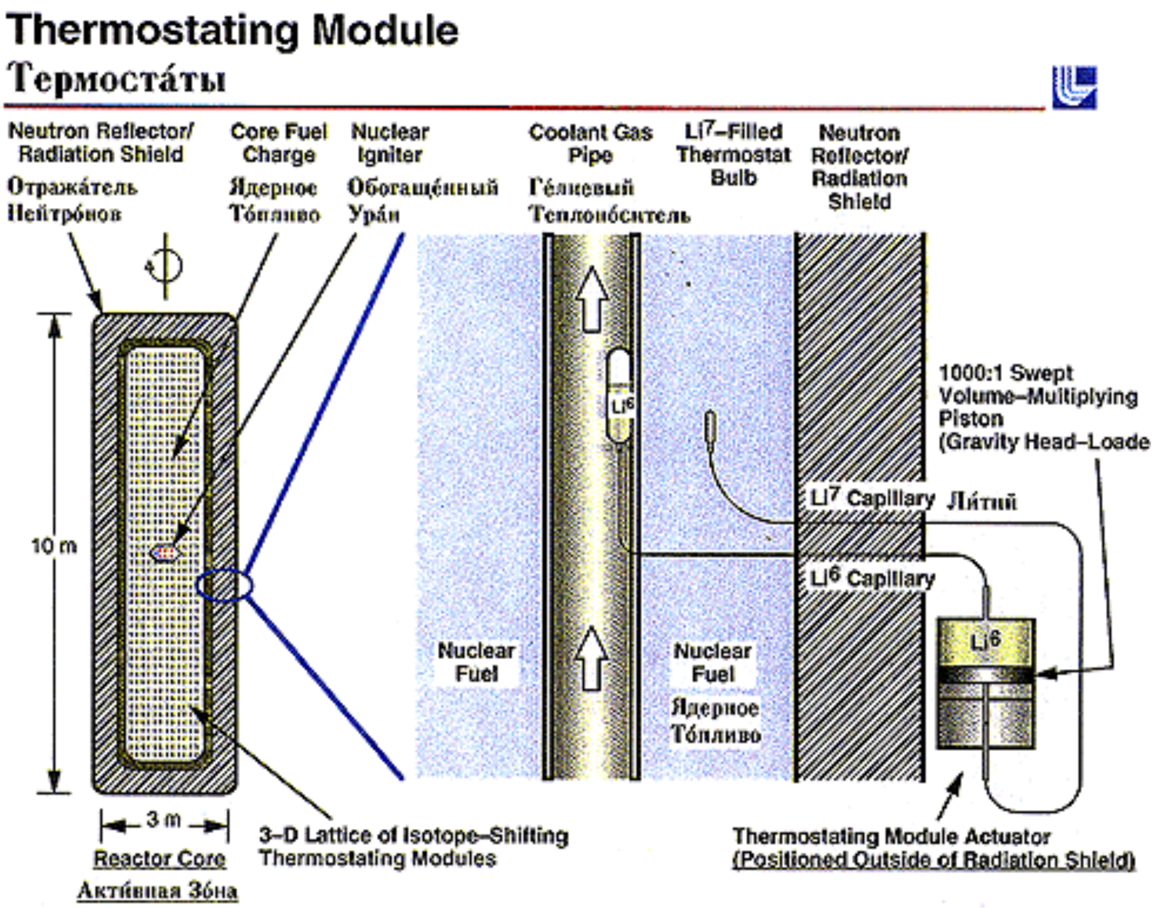


FIGURE 4. The fuel power density in the reactor core is continuously regulated by the collective action of a distributed set of independently-acting thermostating modules, over very large variations in neutron flux, significant variations in neutron spectrum, large changes in fuel composition and order-of-magnitude changes in power demand on the reactor. This action provides a large negative temperature coefficient of reactivity just above the design-temperature of the core.

Located throughout the core's fuel-charge in a 3-D lattice whose cell constant is a mean free path of a median-energy-for-fission neutron, each of these modules consists of a pair of metallic compartments, each one of which is fed by a capillary tube. The small thermostat-bulb compartment located in the fuel always contains Li^7, whose neutron absorption cross-section is essentially zero for neutron energies of interest, while the relatively large one positioned in a cooler location on the wall of a coolant tube may contain variable amounts of Li^6, which has a comparatively large neutron absorption cross-section. (Lithium, melting at 453 K and 1-bar-boiling at 1615 K, is a liquid across the entire operating temperature range of the reactors of interest, and its two stable isotopes each have useful nuclear properties.) As the fuel temperature rises, the thermostat-bulb-contained Li^7 expands, and a small fraction of it is expelled ($\sim 10^{-3}$, for a 100 K temperature change), potentially under kilobar pressure, into the capillary tube which terminates on the bottom of the cylinder-and-piston assembly located outside of the radiation shield and physically lower than the Li^6 intra-core compartment. There the modest volume of high-pressure Li^7 drives a swept-volume-multiplying piston which pushes a three order-of-magnitude larger volume of Li^6 through a core-threading capillary tube into an intra-core compartment adjacent to but cooler than the thermostat-bulb which is driving the flow. There the Li^6, whose spatial configuration is immaterial as long as its smallest dimension is less than a neutron mean free path, acts to depress the local neutron flux, thereby reducing the local fuel power density. When the local fuel temperature drops, Li^6 returns to the cylinder-and-piston assembly under action of a gravitational pressure-head, thereby returning the Li^7 to the thermostat-bulb whose now-lower thermomechanical pressure permits it to be received. A total loading of 10^4 moles - 60 kg - of Li^6 is sufficient for the $\sim 10^3$ thermostating modules of the reference 1 GWe reactor.

This arrangement provides the desired high-gain negative feedback of local-temperature-above-the-set-point on the local nuclear power density. Similar thermostating modules thermally connect the three passively-convected helium-gas coolant loops to the heatpipe network of the engineered heat-dump when the multiply-sensed core temperature rises above the design set-point.

Both the Li^6 and the Li^7 compartments contain small apertures which are helium gas-translucent. These "helium dumps" serve for overall pressure equalization and also to dispose of gas formed by neutron captures. (Tritium co-formed in the Li^6 compartment forms a thermally-stable hydride with the fractionally-consumed Li^6.) Li^7 is chosen for its nuclear and thermomechanical properties, and not as a nuclear variant of Li^6.

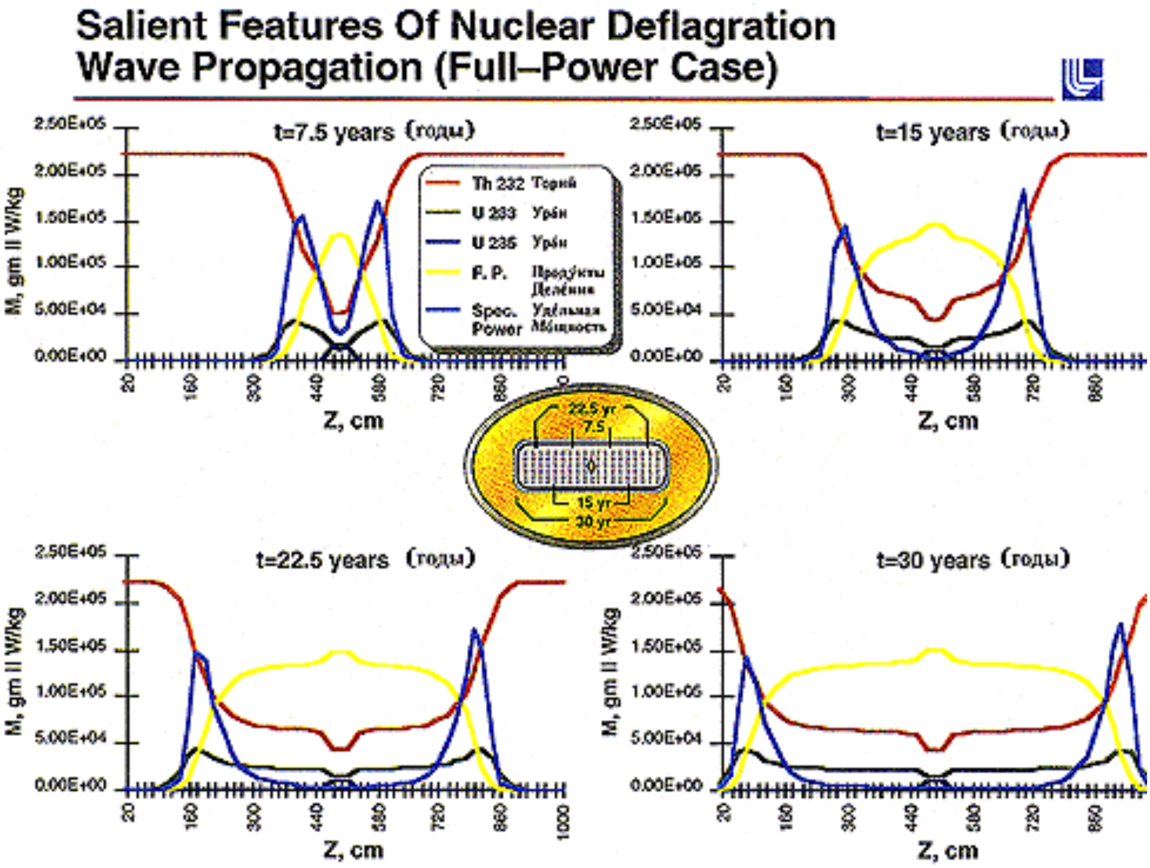


FIGURE 5. Some of the salient features of the fuel-charge of the core of the reference reactor are depicted, at four equi-spaced times during the operational life of the reactor after nuclear ignition is commanded and in a scenario in which the full ~2 GWt of rated power is continuously demanded. The corresponding positions of the leading edge of the nuclear deflagration wave are indicated in the insert. Masses (in gm) of various isotopic components in a set of representative near-axial zones and fuel specific power (in W/kg) are the ordinate-values, while the axial position along the 10-meter-length of the fuel-charge is the abscissal value.

Note that the neutron flux from the most intensely burning region behind the wave-front necessarily breeds a fissile-rich region at the front's leading-edge, thereby serving to advance the wave. After the wave's front has swept over a given mass of fuel, the fissile atom concentration continues to rise for as long as radiative capture of neutrons on available fertile nuclei is considerably more likely than on fission product nuclei, while ongoing fission generates an ever-greater mass of fission products. Nuclear power-production density necessarily peaks in this region of the fuel-charge, at any given moment.

Finally, well behind the wave's advancing front, the concentration ratio of fission product nuclei (whose mass averages half that of a fissile nucleus) to fissile ones climbs to a value comparable to the ratio of the fissile fission to the fission product radiative capture cross-sections (see Figure 2), the "local neutronic reactivity" goes negative, and both burning and breeding effectively cease - as is clear from comparing the various snapshots with each other, far behind the wave-front.

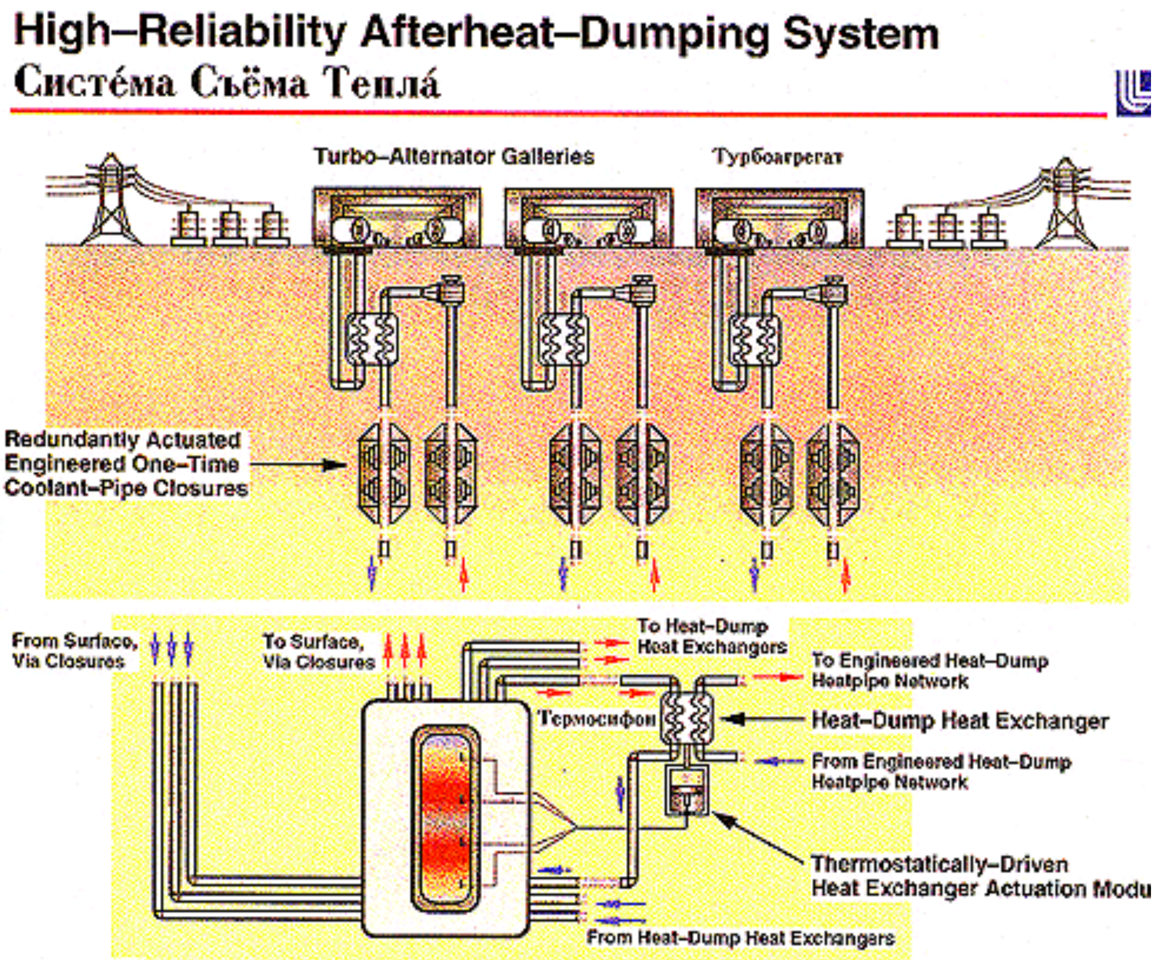


FIGURE 6. Managing all aspects of beta-decay-engendered afterheat extremely reliably is a prerequisite for long-term safety of nuclear power operations, and extraordinary attention is devoted to this crucial function in the new class of reactors.

In our preferred baseline-design, we provide three completely independent, physically separated cooling-loops for the reactor core, each one of which is capable of removing the full-rated thermal power from the core, continuously. This feature will likely interact synergistically with the highly modular nature of aeroderivative turbine-based electrical generation, for which quanta of generation are typically of 30 MWe scale, as well as safeguard in a uniquely robust manner against all "standard" types of severe loss-of-coolant accidents.

Engineered, one-time-operation coolant-pipe closures, actuated by plant operators as well as automatically by redundant, fail-active control logic and backed-up with automatically-actuated mechanical valves, assure underground containment of coolant which may become significantly contaminated with fission products. (Continuation of reactor operation may be compatible with action of any one pair of such closures, for two independent cooling conduit-pairs would still be available for use.)

If all (near-)surface-based facilities fail, the reactor's core will be cooled indefinitely by passively convected helium (at the relatively low thermal power flux associated with nuclear afterheat) via thermosyphon principles operating in three other, independent coolant-loops which thread through the core and into heat exchangers interfacing with a highly redundant heatpipe network which permeates the reactor-surrounding engineered heat-dump. Multiple thermostatic modules in the core redundantly sense rising core temperature and connect each of the three passively-convected coolant-loops with the heatpipe network by inserting liquid lithium metal into the heatpipes connecting the two loops in the three heat exchangers, against a gravitational head. This low impedance thermal connection persists until the core temperature returns to normal, at which time the intra-core thermostatic modules permit the inserted lithium to drain from the intra-exchanger heatpipes of the three heat exchangers, greatly increasing their thermal impedance and effectively shutting off heat transfer from the core to the engineered heat-dump.

The engineered heat-dump is designed to absorb the full-power peak afterheat thermal loading of ~150 MWt (i.e., >6.5% of 2 GWt) effectively indefinitely, as well as to sink the ~0.5 MT of total afterheat energy present in the core at end-of-operational-life. Its composition is dominated by dry sand, emplaced concurrently with installation of the reactor and coolant piping. The highly redundant character of the

heatpipe network permeating it assures reliable, very long-term operation. The hot, dry sand surrounding the
reactor assures the long-term integrity of the reactor's shell, in its final role as burial cask for the core and its contents.

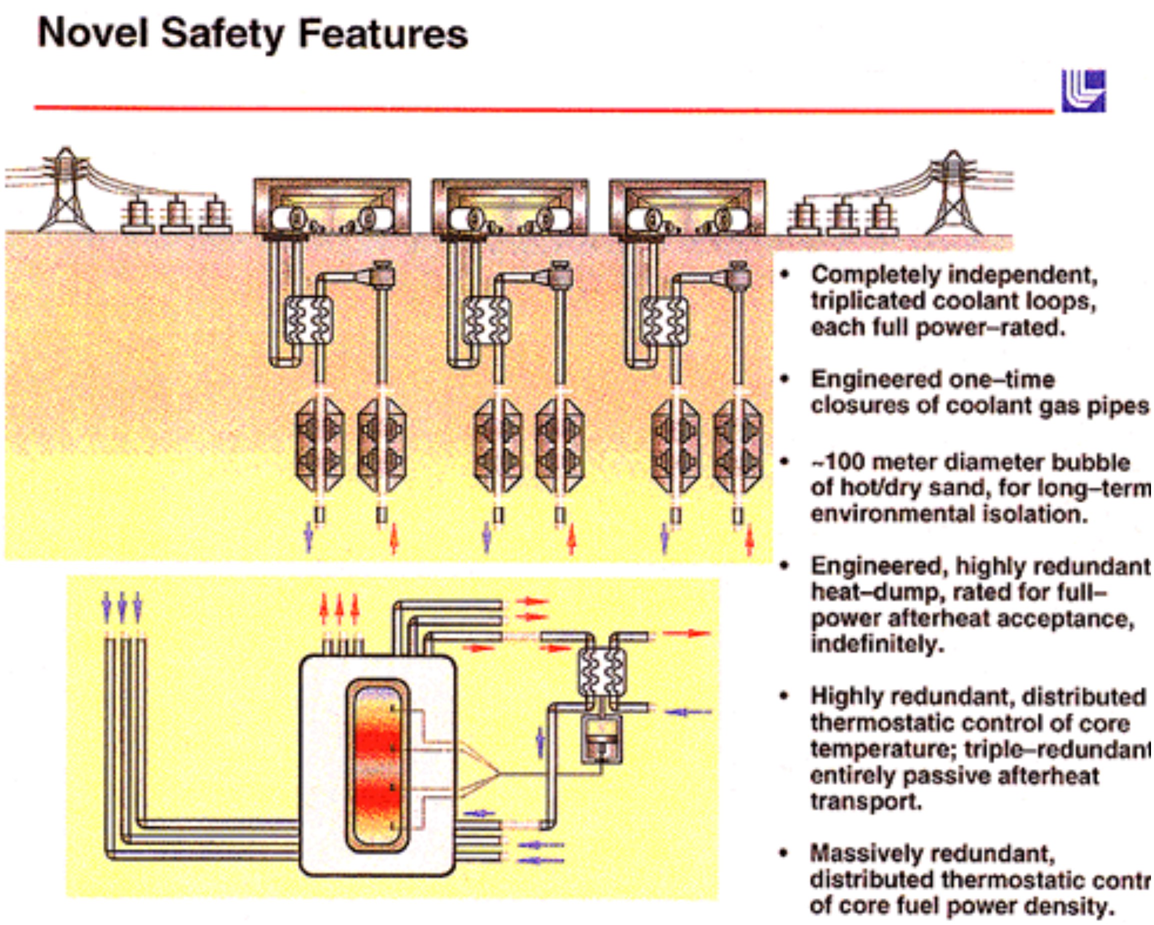


FIGURE 7. The new class of reactors has six novel features which are intended to make obvious to any reasonable person its great safety as a large-scale source of high-grade heat.

Three completely independent, physically separated, full-core-power-rated coolant-loops are the first line of defense against all types of "standard" loss-of-coolant accidents.

Engineered, one-time-operation, automatically-actuated coolant-pipe closures backing-up automatically-actuated conventional mechanical valves assure that coolant-gas-carried fission products can never reach the surface - and the biosphere - in significant quantities.

The location of the reactor at an underground depth 100 meters interposes a very great amount of both mass and distance between the biosphere and the radioactivity-loaded core, allowing several independent and highly effective safety measures, both active and passive, to be taken - and completely precluding the possibility of either swift or covert diversion of reactor products for military purposes.

The engineered heat-dump acts automatically, without human action and, indeed, denying the possibility of effective human intervention, to sink all of the afterheat of the reactor's core, effectively forever, no matter what may be the circumstances in which such heat rejection is invoked.

The highly redundant, distributed thermostatic control of the reactor core's temperature is the second, entirely independent line-of-defense against all types of loss-of-coolant accidents, as it serves to connect the core's fuel-charge - automatically, swiftly, with near-zero thermal impedance and triply-redundantly - to a heat-sink of effectively infinite capacity and adequately high peak thermal power rating: the engineered heat-dump.

The highly redundant, distributed, entirely automatic thermostatic control of the core fuel-charge's temperature permits elimination of all possible types of human operator error by making feasible the completely automatic operation of the reactor over the full range of thermal power demand from 0 to 100%, from the moment of initial start-up through the time of final shutdown.