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ARC-100: A MODULAR NUCLEAR PLANT FOR EMERGING MARKETS: Safety Strategy

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ABSTRACT

The ARC-100 reactor concept and its supporting fuel cycle infrastructure is intended to offer a 21st century configuration of nuclear energy, -- one tailored to meet the needs of emerging electricity markets in developing countries as well as imminent global need for carbon-free non-electric energy sources. This new configuration envisions a distributed fleet of small, fast reactors of long (20 year) refueling interval, providing local energy services supported by a small number of centralized facilities handling fuel supply and waste management for the entire fleet. The rationale for the configuration and the design of the ARC-100 reactor have previously been presented in Ref. 1. This paper describes the safety strategy for ARC-100.

Key Words: Sodium Cooled Fast Reactor; Small Modular Reactors; Passive Reactor Safety; Metallic Alloy Fuel; Defense in Depth

1. INTRODUCTION

The ARC-100 reactor concept and its supporting fuel cycle infrastructure comprises a distributed fleet of small fast reactors of long (20 year) refueling interval supported by a small number of centralized facilities handling fuel supply and waste management for the entire fleet. The reactors are sized for local and/or small grids, and are standardized, modularized and pre-licensed for factory fabrication and rapid site assembly. Because the reactor plants are of small power rating (100 MW_e) this envisioned architecture can lead to thousands of power plants distributed worldwide – which places stringent requirements on safety performance of each plant. This paper describes the design approach to safety for ARC-100 – describing how the strategy adds additional layers of defense in depth vis-à-vis that of traditional reactors.

2. REACTOR OVERVIEW

ARC-100 is a 100 MW_e (260 MW_t), sodium-cooled fast reactor operating on a long (20 year) whole core refueling interval. Its initial fuel load is of enriched uranium (≤20%

enriched) in the form of metal alloy fuel slugs, sodium bonded to ferritic-martinsitic cladding. (An extensive database for such fuel pins exists from EBR-II and FFTF operations[2]). The reactor exhibits an internal breeding ratio near unity such that its reactivity burnup swing is small and its core is fissile self-sufficient. It attains 80 MW_td/kg fuel average burnup, and upon pyrometallurgical recycle at completion of its 20 year burn cycle, depleted uranium makeup feedstock is all that is required for the reload core. Upon multiple recycles, the core composition gradually shifts to an equilibrium transuranic fuel composition, which is also fissile self sufficient – requiring only U238 makeup upon recycle.

The forced circulation heat source reactor delivers heat at ~500°C through a sodium intermediate loop that drives a supercritical CO_2 (S-CO_2) Brayton Cycle power converter attaining ~40% conversion efficiency and is capable of incorporating bottoming cycles for desalination, district heat, etc.

The plant is sized to permit factory fabrication of rail and barge shippable modules for rapid assembly at the site. Its features are targeted to meet the infrastructure and institutional needs of rapidly growing cities in the developing world as well as non-electric industrial and/municipal niche applications in all nations.

The neutronics design of ARC-100 and its fuel cycle have been described in Ref. 1. The metal alloy fuel design and its extensive database is described in Ref. 3. The ARC-100 is being commercialized by Advanced Reactor Concepts, LLC, (ARC) a startup company incorporated in Delaware in the fall of 2006. (www.arcnuclear.com)

3. CORE DESIGN

3.1. Core Neutronics

The 260 MW_t core design was done by Argonne National Laboratory, on behalf of ARC, using its validated code suite (DIF3D/REBUS-3) and databases. The optimized core layout is shown in Fig. 1. It consists of fourteen 7-assembly clusters comprising 92 fuel assemblies plus 6 primary control rod assemblies. The clusters are outlined in yellow – 4 clusters surrounding core center and 10 clusters outboard of the center four. Separate from the 7-assembly clusters are 2 safety rod assemblies and a central core clamping assembly. There is also one row (42 assemblies) of replaceable steel reflectors and an outer row (48 assemblies) of removable shield assemblies.

The fueled height of the core is 1.5 meters. There are three radial enrichment zones of 10.1% enrichment (28 assemblies), 12.1% (28 assemblies) and 17.2% (36 assemblies).

Average specific power is 12.5 kw_t/kg HM and average power density is 69.6 kw_t/ℓ. These are quite low compared to traditional fast reactor designs which have specific powers of 50 to >100 kw_t/kg HM. By derating specific power and power density values as compared to traditional fast reactor values, the fuel discharge burnup remains within

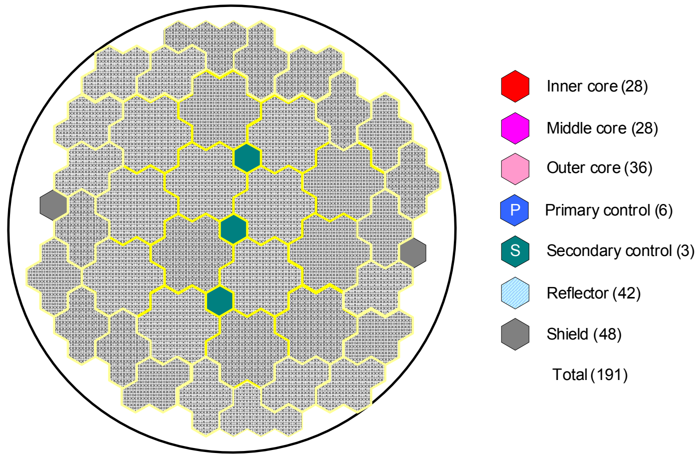

Figure 1. refueling cluster layout and core radial enrichment zoning of ARC-100.

the proven range of the metal alloy fuel irradiation database even with a 20 year burn cycle. The peak discharge burnup is 143.4 MW_t days/kg HM.

Derating fuel specific power also reduces decay heat levels per unit fuel mass and thereby permits reload fuel handling to be conducted on a 7-assembly cluster basis – and with minimal cooling time after reactor shutdown.

Table I summarizes the top level design parameters.

Table I. design parameters and optimized core loading

Parameters	Unit	Value
Thermal power	MW_t	260
Number of driver assemblies		92
Number of control assemblies		
Primary		6
Safety		2
Core barrel inner diameter	m	3.0
Active fuel height, cm	cm	150.0
Initial heavy metal loading	tonnes	20.7
Specific power density	MW/tonne	12.5
Average Power Density	kw_t/ℓ	69.6

3.2. Core Thermal/Hydraulics

Core inlet temperature is 355°C; core ave outlet temperature is 510°C. Average coolant velocity through the lattice is 4.6 m/sec and core pressure drop is 35.7 psi.

The core average pin linear heat rate is 13.9 and the maximum is 25.5 kw_t/m. This leads to an average fuel meat temperature rise of:

$$\Delta T_{fuel} = 104^{\circ} C \ \left(T\left(fuel\ centerline \right) - T\left(clad\ inner\ surface \right) \right)$$

which is only about 2/3 of traditional values for metal alloy pins.

Table II summarizes Core Thermal/Hydraulics Performance and shows margin to design limits for 3-sigma design parameters. The ARC-100 thermal conditions are mild and the margins to thermal limits are large.

A strongly negative radial expansion coefficient dominates the Doppler coefficient – indicating that reactivity vested in coolant temperature rise will dominate that which is vested in fuel temperature rise above coolant temperature (a favorable attribute for passive safety).

Table II. core steady-state thermal/hydraulic performance

Parameters	Unit	Value
Coolant temperature (inlet/outlet)	ºC	355 / 510
Coolant pressure drop	psi	35.7
Coolant flow rate per pin (ave./hot channel)	kg/s	0.112 / 0.148
Average coolant velocity in lattice	m/s	4.6
Linear heat rate (ave./peak)	kW/m	13.9 / 25.5
Cladding outer surface temperature (ave./peak)	ºC	435 / 553
Cladding inner surface temperature (ave./peak)	ºC	442 / 556
Fuel centerline temperature (ave./peak)	ºC	546 / 686
Average fuel surface to centerline temp. rise	ºC	104
3 Sigma Design Values vs Limit		
- Fuel centerline temperature (limit/margin)	ºC	1081/394
- Fuel/cladding eutectic temperature (limit/margin)	ºC	725/169
- Linear heat rate	kW/m	37/11

4. ARC-100 SAFETY STRATEGY

The fundamental safety function for any nuclear power plant is to assuredly contain and control its radioactivity under all conditions – normal or off-normal. The ARC-100 concept envisions widespread deployments of small plants in large numbers – sited in diverse environments nearby to users – which places stringent requirements on reliability and safety performance of each and every ARC-100 plant.

ARC-100 has been designed using the defense in depth and single failure criteria philosophies as in traditional reactors. The need for enhanced levels of safety (reduced probability for offsite radioactivity release per deployed ARC-100 plant) as compared to traditional plants has been approached by

- introduction of additional layers of "defense in depth"
- reduction of internal stored energy

which taken together can terminate all accident sequence progressions short of core disruption, and even so:

- reduction of radioactive source term and
- increase in source release attenuation factor.

It will be convenient to discuss the ARC-100 safety strategy in terms of its design functional features and to relate those features back to the cardinal safety strategies enumerated above.

4.1 Contain Radioactivity Hazard Using Redundant Encapsulation Structures

The initial load of <20% enriched UZr alloy fuel is not radioactive. However, upon irradiation, radioactive fission products and transuranic elements are formed in the fuel. In addition to the fuel, the primary sodium coolant becomes slightly radioactive with a fifteen hour half life gamma-emitting Na-24 activation product. Certain elements in the internal structural materials also become activated. After a few atom percent fuel burnup, the vast majority of radioactivity resides in the fuel itself.

These radioactive isotopes comprise a radioactive hazard that must be contained inside the reactor under both normal and off-normal conditions. To do so, three layers of steel encapsulation are employed for ARC-100 – similar to traditional reactors: the steel fuel cladding; the steel reactor tank (vessel) and its cover deck; and a steel "guard vessel" and its cover dome are nested around the fuel to triply encapsulate it. All primary sodium is doubly contained – within the reactor tank and its "guard vessel". The guard vessel and its cover dome perform the familiar "containment boundary" function of traditional plants. The only conduits penetrating across the tank and the containment walls are secondary sodium pipes carrying reactor-generated heat to the Balance of Plant (BOP) and the NaK pipes for three DRACS passive decay heat removal systems. All penetrations are through the lid of the reactor tank – above the free surface of the sodium.

High levels of quality control are employed in the manufacture, installation, in-service inspection and maintenance of these three nested encapsulation structures and they comprise an effective, reliable and robust containment of radioactivity under all normal conditions.

To assure containment under all possible off-normal conditions it is further necessary to protect their structural integrity against both external and internal threats.

Protection against External Threats

External threats are comprised of the ensemble of natural phenomena (high winds and missiles, fire, flood, tsunami, earthquake, etc.) and of man-made phenomena (airplane impact, tank shells, etc.). To protect against such external threats, all three encapsulation structures are positioned in a silo; the silo and all ancillary equipment important to safety are then housed in a dedicated "shield" building; and the whole lot is (horizontally) seismically isolated. Figure 2 shows the plant layout. The goal – addressed through the added layers of protection afforded by silo emplacement and seismic isolation – is to facilitate the use of site-independent design specifications to permit standardized, pre-licensed modular design practices.

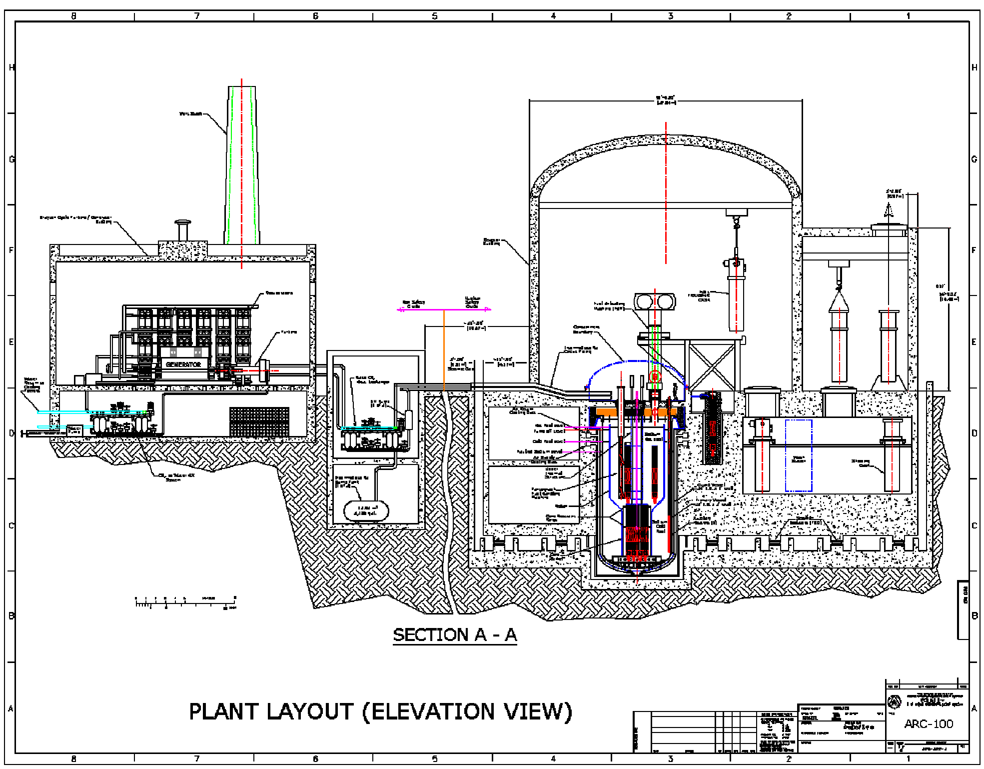

Figure 2. plant layout.

Protection against Internal Threats

Opportunities for attacks on the barriers from internal threats have been reduced in ARC-100 vis-à-vis traditional plants primarily by means of judicious materials choices – choices which reduce internal stored potential energy and which broaden margins between operating point and damage conditions.

First, choice of sodium liquid metal coolant rather than traditional water (or gas) allows an ambient pressure primary system – eliminating stored energy of high pressure and importantly, thereby eliminating the driving force for the Loss of Coolant Accident (LOCA). Moreover, sodium and stainless steel are chemically compatible – eliminating corrosion-induced tank degradation.

Second, choice of metal alloy fuel having thermal conductivity ten times that of traditional oxide fuel dramatically lowers the temperature rise in the fuel relative to the coolant – thereby reducing the thermal energy stored inside the system (that would have to be dissipated in order to move to a safe shutdown state). Crucially, the small temperature rise in the fuel reduces the positive reactivity potential "stored" in the Doppler effect (that would have to be overcome by negative reactivity in order to move to a safe shutdown state).

Third, choice of metal alloy fuel with steel cladding rather than UO_2 fuel with Zircalloy cladding eliminates the opportunity for hydrogen production internal to containment[1] which can occur in situations when steam contacts overheated zirconium clad fuel rods in traditional reactors. This eliminates the chemical explosion hazard that has been a threat to containment integrity in accident sequences for LWRs – as vividly displayed at TMI and Fukushima.

Finally, the fuel is operated at low specific power (kW_t/kg fuel) and the temperature margins between ARC-100 operating point and containment structure damage points are several hundred degrees centigrade and the coolant remains in the liquid phase throughout that range-providing operating space for passive safety response. The relevance of this to protecting the integrity of containment is discussed in the next section.

Traditional reactors use large-volume, thick-walled containment structures in light of the external hazards and the potential internal pressures created by LOCA and/or H_2 explosion events. By eliminating the internal hazards by design, ARC-100 is able to use a cost-effective, low-pressure small-volume containment structure protected from external threats by silo emplacement, seismic isolation and a separate, dedicated shield structure.

In summary, ARC-100 makes use of the traditional three nested layers of encapsulation (cladding, vessel, and containment structure) to confine radioactivity. An enhanced level

[1] Sodium and water will react to produce hydrogen. However, for ARC-100 there is no water source inside containment. Secondary sodium fires are discussed in a later section.

of assurance for maintaining containment integrity under off-normal internal challenges is attained by use of metal alloy fuel and sodium coolant positions. Enhanced protection from external threats is provided by adding seismic isolation, silo emplacement and a dedicated shield structure. (These choices also facilitate use of a low-volume containment structure and a standardized, modularized construction approach which have favorable economic consequence.)

4.2 Removing Heat from the Reactor Core

The encapsulation structures would become compromised by prolonged exposure to high temperatures well above their design limits. While a large temperature margin exists between operating point and damage point, it is none-the-less essential to always maintain internal heat production in balance with heat removal in both the operating range and in the shutdown range.

Under normal operational conditions, primary sodium is circulated by primary sodium pumps through the core pin lattice where it is heated, then transported to two intermediate heat exchangers immersed in the primary sodium tank where the heat is transferred to two loops containing non-radioactive secondary sodium. Core inlet and outlet temperatures are 355°C and 510°C. Two forced circulation intermediate sodium piping loops carry the heat across the primary tank lid and containment boundaries and across the seismic isolation gap to the BOP where the heat is delivered through sodium-to-S-CO_2 heat exchangers to the Brayton cycle working fluid. Expansion and recompression of the S-CO_2 through rotating machinery converts ~40% of the heat to electricity while ~60% is rejected as waste heat at ~31°C through S-CO_2–to-water heat exchangers. The cooling water carries the heat to forced-draft recirculation cooling towers where it is finally rejected to the ambient air.

Passive Decay Heat Removal

The pumps which drive the cooling circuits under normal conditions rely on offsite electrical power which can be expected to fail from time to time. Therefore in ARC-100 the normal heat transport circuits are not relied on for assured decay heat removal. Instead, decay heat removal is assured by use of three dedicated, redundant natural circulation DRACS loops of 65 kw_t each. At decay heat levels, natural circulation of primary sodium cools the fuel pin lattice and carries heat to the DRACS in-tank heat exchangers. Then, each DRACS circuit carries heat from the heat exchanger immersed in the primary sodium tank, through a vertical natural circulation piping loop which crosses the primary sodium tank lid and the containment boundaries carrying heat up to its dedicated NaK-to-air heat exchanger located on the exterior of the shield building. These three redundant, circuits operate all the time, “wasting” 195 kw_t of heat production but thereby assuring that adequate decay heat removal capacity is always available – absent need for any active intervention such as sensing, valve realignments, or starting of pumps or emergency power sources. The piping and exterior heat exchangers are separated to avoid simultaneous loss of all three exchangers to an external hazard, – and even a single operating DRACS loop is sufficient to maintain primary system temperatures within safe ranges at all times after the reactor shutdown. (The large temperature margin to structural damage temperatures and the large thermal inertia provided by the mass of the primary system coolant and in-tank structures inventory can safely absorb the initial excess of decay heat generation over DRACS capacity). The DRACS operability can periodically be confirmed by nonintrusive heat balances.

All tank penetrations are through its lid – above the sodium level, and the spacing between the primary tank and the interior of the guard vessel is chosen such that the core lattice and DRACS heat exchangers will remain covered by sodium so that a natural circulation flow path to the DRACS heat exchanges will be preserved even if the primary tank springs a leak into the guard vessel. Natural draft air cooling of the guard vessel exterior serves as a diverse, passive decay heat removal channel to back up the three redundant passive DRACS channels.

In summary, ARC-100 uses diverse, redundant passive decay heat removal circuits for highly assured decay heat removal. No external source of electrical power or stored energy is required because the systems are always operating at atmospheric pressure with single phase coolant, and no active sensing nor valve re-alignments are needed for startup because the systems operate continuously. Each of the redundant/diverse systems can, acting alone, maintain the reactor at non-damaging temperatures. They are backed up by a natural draft air cooling of the guard vessel exterior.

4.3 Matching Heat Production Rate to the Presented Heat Removal Rate

Whether under normal conditions or off-normal conditions it is essential that the heat production rate of the fuel lattice should not (for an extended period) exceed the rate of heat removal from the reactor tank – because such a condition would eventually raise the temperature of the primary system to damaging levels and radioactivity containment function would be defeated. Short transient mismatches within safe temperature ranges are buffered in ARC-100 by the large thermal inertia of the tank contents and in fact are relied on to engender passive reactivity feedbacks that render the operating state a dynamically stable one.

At power, the heat removal rate from the tank depends exclusively on the secondary sodium loop heat removal rates at the two intermediate heat exchangers (IHX) immersed in the primary tank.[2] The <u>active</u> control system for the <u>BOP</u> has been designed to adjust intermediate sodium flow rate and its inlet temperature to the IHX so as to match S-CO_2 heat removal to the rotating machinery and heat rejection equipment. The intermediate sodium loop conditions at the IHX are sufficient to define the heat demand requested by the BOP.

Traditional reactors employ an active control system to coordinate the reactor heat production to match the BOP heat consumption. It consists of sensors for power, temperature and flow measurements, logic circuits and control and safety rod drives. The

[2] The 195 kw heat removal through the DRACS circuits remains nearly constant and in any case is only 0.00075 of the 260 MW_t heat rate.

control rods can be withdrawn (adding reactivity) to overcome long-term reactivity loss due to fuel burnup and fission product poisoning or they can be inserted to reduce short term reactor power to match reduced BOP demand. The control system manages and coordinates temperatures and flow rates for both the reactor and BOP to match grid demand and adjusts control rod position as necessary to cause the reactor power to match the heat demand from the BOP.

The safety rods are controlled by separate, dedicated sensors and logic circuits. They can be inserted (scrammed) to shut off reactor power and take the reactor to a deeply subcritical state.

It is evident that in the control approach used for traditional reactors, a potential hazard exists in that a miscalibration of sensors, a logic fault, or a control rod drive malfunction could cause an inadvertent control rod withdrawal – adding reactivity and leading to a mismatch of heat production in excess of heat removal to the BOP. This hazard in traditional control schemes is managed by use of diverse/redundant equipment and rigorous quality assurance in design, manufacture and maintenance. But ARC-100 uses a simpler approach.

Passive Load Follow

The ARC-100 reactor is designed with an internal breeding ratio near to unity such that reactivity loss due to fuel burnup is zero. Combined with minimal reactivity loss due to fission product buildup, it is possible to minimize (to almost zero) the positive reactivity vested in control rods – so that an inadvertent single rod withdrawal would add only a safe amount of positive reactivity.

Beyond that, while retaining the traditional safety scram system, ARC-100 completely eliminates the control system malfunction hazard by eschewing an active controller for control rod position and instead using passive reactivity feedbacks to cause reactor power to self adjust itself to match the heat removal to the BOP through the intermediate loop. The reactor operates at fixed primary pump speed and fixed control rod position. The active controller for the BOP responds to grid demand by adjusting S-CO2 inventory, BOP valve alignments and secondary sodium flow rate in such a way that the secondary sodium flow rate and its inlet temperature to the IHX conveys the BOP heat demand request – which is then matched by the reactor on the basis of its innate passive reactivity feedbacks – decreased BOP demand causes increasing coolant temperature which causes power to decrease; increased BOP demand causes decreasing coolant temperature which causes power to increase. The practical feasibility of this passive load follow strategy has been confirmed in tests conduced on the EBR-II power plant.[4]

Passive Safety

The ranges of variation of secondary sodium parameters (temperature and flow rate to the IHX) are constrained by innate natural phenomena, and within their physically-attainable range of variability the reactor will self adjust its power level up or down while remaining within safe temperature conditions.[5] For example, suppose secondary sodium flow inadvertently stops – creating a “Loss of Heat Sink” (LOHS) accident initiator. Coolant temperatures would rise and scram circuits would insert safety rods and shut the reactor down – as in traditional reactors. But even if the scram circuit failed to act, passive negative reactivity feedbacks due to increased primary sodium temperature would safely take reactor power down to decay heat levels.

As another example, suppose the secondary sodium temperature at the inlet to the IHX inadvertently began to decrease beyond the operational range – spuriously seeming to request more heat be sent to the BOP. Reactor power would increase owing to positive passive reactivity feedbacks caused by lowered temperature and the scram circuits would insert safety rods to shut the reactor off. But even if the scram circuits failed to act, primary sodium and fuel temperatures would none-the-less self-adjust to higher but still safe ranges. If the secondary sodium continued to cool all the way down to solidification temperature (its lower physical bound) the accident would revert to the LOHS accident discussed previously.

The passive feedbacks, when combined with the several hundred degree margins between operating and damage temperatures and ponderous response time, provide a highly reliable additional layer of defense in depth which can terminate an accident progression short of core damage even if the active scram system fails to act. Temperatures may rise a few tens of degrees – but remain in the safe range. Evaluations show that ARC-100 can safely accommodate the full range of Anticipated Transients Without Scram (ATWS) accident initiators – including all BOP-initiated events such as LOHS or station blackout as well as reactor – initiated events such as Loss of Pumping Power without scram and single rod runout TOP without scram (see Table III). Tests conducted at the EBR-II power plant have confirmed the practical feasibility of passive safety response.[6]

Table III. Passive Reactivity Feedbacks

		UNIT	BOL	MOL	EOL
A. power coefficient		¢	-3.4	-3.7	-3.9
B. power/flow coefficient		¢	-21.6	-27.3	-24.6
C. inlet temperature coefficient		¢/°C	-0.22	0.26	-0.24
$\Delta\rho_{TOP}$, TOP initiator		¢	8	23	11
Sufficient conditions	A/B<1		0.16	0.14	0.16
	1 < CΔTc/B < 2		1.61	1.50	1.52
	$\Delta\rho_{TOP}/\|B\| <1$		0.37	0.84	0.45

The values of the passive reactivity feedbacks can be measured in situ using non-intrusive methods to periodically confirm that they lie within the ranges required for passive safety even as the reactor ages and the fuel evolves with burnup.

In summary, an added layer of defense in depth has been incorporated into the ARC-100 safety strategy such that even if active scram fails to terminate an accident sequence, reactor heat production will be maintained in balance with heat removal using passive reactivity feedbacks which keep temperatures in a safe range. Probabilistic Risk Assessments (PRA's) have illustrated the efficacy of this approach to reduce probability of entering into Hypothetical Core Disruptive Accidents. The goal is to attain a level of no licensing concern and to attain risk reduction of loss for containment integrity to a level of $<10^{-7}$/year.

4.4. Reduced Source Term and Enhanced Source Term Mitigation for Short Term Release

The discussions in the previous sections show how for the full range of accident initiators, the ARC-100 safety strategy is able to terminate all accident sequences prior to any of them progressing to the core disruption stage and to ultimately take the reactor to a stable secure end state that preserves the integrity of the nested containment structures. Notwithstanding that, in this section is shown that – even given the extremely unlikely event of loss of integrity of all three redundant layers of containment, radioactivity releases would be reduced compared to traditional reactors.

The source term comprising the radioactivity release hazard includes fission products of short, intermediate, and long half lives. After they are created from fission, they all decay insitu in the reactor core according to their decay half lives – those of intermediate and long half life will build up cumulatively over the refueling interval, with limited insitu decay, but short-lived isotopes quickly decay insitu such that only the most recent fissions contribute to their inventory. And upon a accidental release, it is the short half life isotopes that deliver their ionizing radiation at a high rate.

In a qualitative way, the short-lived isotope source term scales with the fissions accumulated during the most recent several weeks of power operation. ARC-100's source term compared to a traditional 1000 MW_e LWR is therefore only a tenth as large because the ARC-100 power rating is only a tenth as large as a traditional LWR.

Among the short lived fission products, I-131 has a large yield and, as a gaseous fission product, it constitutes the major contributor to short-term offsite dose for traditional reactor accident sequences. For the oxide fuel of traditional reactors, iodine remains a free gas which is released upon loss of fuel cladding integrity. However, for ARC-100's metallic alloy fuel, the release fraction is essentially nil because the iodine chemically bonds to uranium metal as non-volilate uranium trioxide, UI_3.[7] Even were fuel to melt and unbind iodine, the iodine would be trapped in the sodium coolant as sodium iodide. The main short term radioactivity release hazard is simply eliminated in ARC-100.

For the intermediate and long-lived fission products insitu decay is less effective in reducing source term and these isotopes tend to accumulate with burnup. Assuming no insitu decay, when a 20 tonne fuel loading of ARC-100 fuel at 80 MW_td/kg ave burnup is compared to a 1000 MW_e LWR of ¼ core annual refueling of 40 MW_td/kg ave discharge burnup (a total incore inventory comprised of one quarter each of 10, 20, 30 and 40 MW_td/kg burned fuel), the ratio of integrated incore fissions inventory is 4/5. At a scoping level of detail, the incore fission product inventory of moderate half life at end of life of 20 year ARC-100 compared to a traditional LWR (1000 MW_e) at end of 1 year refueling interval is 20% less.

The incore inventory of transuranics at end of refueling interval depends on production rate per unit power as well as on insitu consumption. For ARC-100, the discharge fuel contains ~4.9% transuranics. A traditional LWR discharge fuel contains ~1.5% transuranics. The ratio of transuranics in the ARC-100 core at end of 20 year refueling interval to that in a 1000 MWe LWR at end of a one year refueling interval is essentially unity. Transuranic isotopes are solid phase alpha-emitting isotopes that constitute a hazard only if they become airborne as an aerosol. Conditions capable to cause transuranics to become airborne in ARC-100 – e.g., fragmented fuel or very high temperature – never occur because as discussed above, all accident sequences are terminated short of fuel disruption.

In summary, the source term of an ARC-100 never exceeds that of a traditional LWR and in fact the short term release hazard is dramatically reduced owing both to a lower power rating and to an innate capacity of metallic alloy fuel to bind up the radioactive iodine.

4.5. Local Faults and Industrial Hazards

It is conceivable that a manufacturing flaw of the fuel pin cladding or of the fuel pin fissile loading could lead to a local fuel pin cladding failure – such an event should not be allowed to propagate to adjacent pins and disrupt a larger segment of the lattice.

The metallic alloy fuel is chemically compatible with sodium coolant. Tests have shown that no low density chemical compound would form at a local breach capable to eventually choke off coolant flow and lead into failure propagation. In fact, extended duration Run Beyond Cladding Breach (RBCB) is permissible for ARC-100.

Industrial Hazards

Sodium will burn in air and will react vigorously with water. ARC-100 manages these internal hazards by excluding water from inside containment and by maintaining an air-free (Ar and N_2) atmosphere inside the reactor tank and the guard vessel, respectively.

The secondary sodium piping is exposed to the natural elements in its pipe runs to the BOP lying outside the shield structure. However, the secondary sodium is non-radioactive so a fire constitutes a benign industrial accident. Moreover, (as discussed above) pipe break with loss of cooling function of the intermediate sodium loops does not cause a hazard to reactor and containment integrity because the reactor will self adjust its power downward using passive feedbacks even if the scram system fails. Finally, the BOP is not relied on for decay heat removal.

The inventory of S-CO_2 Brayton Cycle working fluid constitutes an asphyxiation hazard in the BOP. This is an industrial hazard, not a nuclear hazard. It is addressed using standard industrial procedures of sensing/alarm and by exploiting CO_2's high density to drain it into the basement of the BOP building where it is diluted/dispersed to the atmosphere using forced ventilation.

4.6. Safety during Fuel Handing

Probabilistic Risk Assessments (PRAs) of reactors that employ passive safety features often indicate that as the risk of accidents involving the reactor per se are driven downward and diminished, their risks eventually will lie below those risks associated with traditional refueling operations. Refueling operations usually require the removal of the outermost of the three nested encapsulation barriers to radioactivity release. Subsequent emplacement of used fuel in on-site storage pools outside containment always removes at least one and perhaps two encapsulation barriers.

The ARC-100 strategy for risk reduction during refueling operations rests on:
- extremely infrequent refueling operations (once per 20 years of full power operation)
- minimal exchange operations required per whole core refueling cycle (by refueling of 7-assembly clusters)
- no onsite fuel storage (immediate shipment of transport casks containing the used fuel)

  and
- reduced source term and source term release fraction per handled item

The ARC-100 has a high fuel incore inventory (20 tonnes) but it operates at a low specific power (~12 kW_t/kg fuel). (This makes it possible to sustain 20 full power years of operation on a single fuel charge while remaining within the bounds of the extensive existing metallic alloy fuel irradiation database.[3]) Because the specific power is so low, the decay heat per kg of fuel is low enough to allow fuel handling within two weeks after reactor shutdown. Then, fuel handling is done by 7-assembly cluster to minimize reactor downtime. Fourteen 7-assembly cluster transfers are all that is required to refuel the entire core. Given this, the time at risk for fuel handling related mishaps is of the order of one month every 20 years ($f \simeq 1/240$) – a time at risk which is at least a factor of 10 less than the value associated with refueling operations at traditional reactors.

The fourteen casks containing the fourteen used 7-assembly clusters are shipped immediately to the regional recycle facility rather than being stored on site. This also, is facilitated by the low specific power of the fuel.

The previous section has included a discussion of the reduced source term of short-lived fission products per kg of fuel and of the intrinsic trapping of the iodine which chemically binds to the metallic uranium.

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[3] An internal conversion ratio of near unity mitigates burnup reactivity loss which is what limits refueling interval for traditional reactors. The 20 year refueling interval for ARC-100 is set by fluence limits on pin cladding – not by fuel burnup or fission product poisoning as in traditional reactors.

In summary, the radioactive release hazard attendant to ARC-100 refueling operations is at least a factor of ten reduced from that obtaining for traditional reactors.

5. CONCLUSIONS

Safety has been of paramount importance in guiding the ARC-100 design. Traditional defense in depth and single failure criterion philosophies have been supplemented by introducing passive decay heat removal and passive power self regulation as additional layers of defense in depth. Defense against external threats has been strengthened by silo emplacement and seismic isolation. Finally, short term source term risk is mitigated by intrinsic chemical binding of radioactive iodine in the fuel matrix itself. These features have all been confirmed during testing programs previously conducted at the EBR-II reactor.[8]

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T.K. Kim, Nuclear Engineering Division at Argonne National Laboratory optimized the core neutronics design given specification of design goals by ARC. C. Grandy and L. Krajtl did the plant layout.

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