REACTOR PHYSICS CHALLENGES IN GEN-IV REACTOR DESIGN

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An overview of the reactor physics aspects of Generation Four(GEN-IV) advanced reactors is presented, emphasizing how their special requirements for enhanced sustainability, safety and ecoomics motivates consideration of features not thoroughly analyzed in the past. The resulting concept-specific requirements for better data and methods are surveyed, and some approaches and initiatives are suggested to meet the challenges faced by the international reactor physics community. No unresolvable impediments to successful development of any of the six major types of proposed reactors are identified, given appropriate and timely devotion of resources.

1. INTRODUCTION

The GEN-IV program, through its international forum (GIF), defines the agenda for advanced reactor concept development worldwide [1]. It is organized around six generic categories: fast spectrum reactors cooled by lead (LFR), sodium (SFR), or gas (GFR); and thermal spectrum reactors: the supercritical-water-cooled reactor (SCWR), the graphite-moderated, helium-cooled very-high-temperature reactor (VHTR), and the molten-salt-fueled reactor (MSR). Versions of most of these contenders were first conceptualized and analyzed as far back as the 1960s. Several were pursued through the construction and operation of demonstration units. To understand why there is anything new to say about their physics, one must appreciate the particular emphases embodied in the goals set for GEN-IV reactors. They are:

- Sustainability with respect to resource utilization, waste management and proliferation avoidance,
- Safety and Reliability, as measured against contemporary reactors, with respect to avoidance of reactor core damage and offsite effects, and now including physical security,
- Economics, with life cycle cost advantages compared to other energy sources, including externalities, without higher financial risk.

These goals are not quantified, ranked or weighted and it is expected that candidate reactors and their associated fuel cycles will each have a different mix of attributes. When vigorously pursued, these objectives combine to push the reactor physicist into less-explored regions of neutronic option space in ways that are the subject of this paper.

"Reactor Physics" is, of course, a very broad topic encompassing many subdisciplines. In this paper we have attempted to economize on the discussion of areas covered in other review papers in this issue regarding nuclear data, diffusion and transport methods, fuel management and other operational aids. Likewise history is given short shrift except to note that one can trace reviews having concerns similar to this one back at least fifty years [2, 3].

2. DISCUSSION OF GOALS-DERIVED CHALLENGES

The cause and effect relationship among the GEN-IV goals of sustainability, safety and economics, and reactor physics challenges are the organizing theme of this review. Table 1 links specific GEN-IV goals to some of the principal generic reactor physics strategies that enhance prospects for their realization. It is obvious that some are in conflict, which will require tradeoffs and compromises, while others exhibit synergism. It also makes clear that no one reactor concept can excel in all categories.

Table 2 surveys representative generic examples of preliminary core designs for the six GEN-IV reactor concepts and Table 3 gives some examples of core designs of an unconventional nature. It should be recognized that there is more than one contender in each category, and that all are work in progress. Our objective is to identify the problems faced by the reactor physicists charged with devising the final versions in each case.

Table 1. Potential Influences of GEN-IV Goals on Reactor Physics Design Choices

Top Level Goals Fostering Sustainability via :	**Possible Physics Approaches to Their Realization**
· High Uranium Utilization	· Fast spectrum to increase conversion /breeding ratio; reduce parasitic capture and leakage
· Better Waste Management	· Fast spectrum to fission minor actinides · Load TRU in non-fertile fuel
· Promotion of Proliferation Resistance	· Thermal spectrum to reduce amount and quality of Pu by favoring capture · Avoid use of U-238 or Th-232 blankets to avoid production of high quality fissile material · Use TRU in place of HEU
Enhancement of Safety and Reliability, Through :	
· Mitigation of Reactivity Transients and Accidents	· Enhance negative reactivity feedback: increase Doppler reactivity by increasing epithermal flux; reduce coolant T, hence density-related positive void Δk by undermoderation · Add low σ_a diluent to fuel to increase heat capacity
· Enhanced Physical Security	· Minimize ex-core fuel inventory and maximize time between core access: e.g., use long-life "battery" core
Improving Economics by:	
· Reducing Fuel Cycle Costs	· Reduce required fuel enrichment by reducing parasitic capture and leakage · Increase burnup · Increase power density
· Fewer Refueling Shutdowns	· Increase burnup and/or reduce power density to increase cycle length · On-line refueling

Table 2. Some Representative GEN-IV Reactor Core Characteristics

Parameter	LFR	SFR	GFR	VHTR (2)	SCWR (1)	MSR
Power (Range), MWth	125- 3000	400- 4000	1500-3000	600	4000	2500
Fuel (3)	U · Zr or UN Steel Clad Rods	U · Zr or UO_2, Steel Clad Rods	UC-SiC Cercer Plates, Blocks or Rods (4)	Triso Particles	UO_2, Steel Clad Rods	UF_4 Dissolved in Coolant (2)
Moderator	none	none	none	Graphite Pebble or Hex Block	Water Rods	Graphite
Spectrum	Fast	Fast	Fast	Thermal	Thermal	Thermal
Coolant	Pb or Pb · Bi	Na	He or CO_2	He	Supercrit. Water	Molten Fluoride Salts
Power Density, kW/l	100	300	100	4-8	70	20 (2/3 of fuel is ex-core)
Fuel Enrichment, %	15 (Pu)	16 (Pu)	16 (Pu)	8	6.3	3.3
Specific Power, kW/kg HM	30	80	38	100	30	30
References	[4]	[5]	[6]	[7]	[8]	[9]

Remarks : 1. There is also a CANDU version of the SCWR [10]; a fast reactor version of the SCWR is also an option [11, 12].
2. There is also a (fuel-free) molten salt cooled version of the VHTR [13].
3. Fuel shown as uranium-based actually employs plutonium with or without minor actinides as the fissile loading.
4. UN and $U^{15}N$ are also candidates.
5. Also see Bibliography for conference paper sessions by reactor type.

Table 3. Selected Examples of Out-of-the-Ordinary Core Configurations

The CANDLE Core [14] In this concept, designed for ultralong-life batch-loaded cartridge cores, fission is initially confined to the bottom region of a tall cylindrical core, then progressively moves upward as burnup progresses.
Streaming Assemblies [15] These are assemblies designed for lead or lead-bismuth cooled fast reactors. They have a significant, sealed, voided internal duct, which introduces a dominant negative neutron leakage component of reactivity.
Tall Annular Cores [16] This arrangement is used in both prismatic and pebble-fueled versions of small HTGRs to facilitate passive radial heat removal by conduction under post-accident conditions.
Water Tubes in the SCWR [8, 17] Supercritical water is not dense enough by itself to sufficiently moderate a thermal reactor. Hence designers need to provide significantly additional moderation. Solid ZrH_2 rods have been considered, but the use of liquid water in separate downflow tubes now appears to be the preferred alternative. Either way an extremely heterogeneous lattice results.

Table 4. Overview of GEN-IV Reactors and their Principal Reactor Physics Challenges

Concept	Coolant / Moderator	Significant (Non-Routine) Issues
A. Fast Spectrum		
LFR	Lead Alloy / —	· Cross sections and kinetics parameters for minor actinide burning · Spectra and reaction rates at core/reflector interfaces
SFR	Sodium / —	· Local coolant void reactivity
GFR	Helium / —	· Core expansion reactivity feedback in block-type cores · Coolant void reactivity
	CO_2 / —	· Coolant void reactivity
B. Thermal Spectrum		
VHTR	Helium/Graphite	· Dealing with pebble movement · Fuel double heterogeneity · Spatial power oscillations of tall, thin annular cores · Graphite scattering kernel · Pu-239 0.3eV resonance effect on MTC · Upper cavity streaming
MSR	Molten Salt/Graphite	· Delayed neutron decay ex-core
SCWR	H_2O / H_2O *	· 3D coupled thermal-hydraulics/neutronics · Coolant void/flood reactivity · How to provide moderation
	H_2O / D_2O (CANDU-X version)	· Coolant void/flood reactivity
All		· Burnout of long-lived burnable poisons
C. Accelerator-Driven Subcriticals**		· As above depending on design of driven assembly · Spallation product generation · Ultra high σ(E) values (1 < E < 20 MeV) · Quantification of subcriticality

* A fast reactor version is also feasible, but not a high current priority.
** More appropriately addressed under AFCI Program, hence not given further specific attention in this review.

Table 4 summarizes concept-specific issues selected from the broader generic menu listed in Table A.1 in the Appendix based on our own experience, a review of the somewhat sparse literature, and consultation with experts, as to issues requiring attention. The minutes of international workshops organized by Argonne National Laboratory in 2003 and 2004 on GEN-IV related reactor physics needs and capabilities were of particular help in this regard. Unfortunately there are no corresponding papers on this subject in widely available publications that can be referenced for the reader interested in more detail. Major underlying themes are as follows:

2.1 The Challenge of Enhancing Safety Assurance

It is a widespread working assumption that passive features exploiting inherent physical phenomena, such as heat transfer by conduction and natural convection, can significantly reduce the likelihood of core damage. But enhancement of natural convection in fast reactors favors increasing coolant volume fraction (concurrently reducing fuel volume fraction) to reduce pressure drop. This in turn reduces reactivity unless compensated by increasing fissile enrichment and/or changing to high density fuel forms (e.g., UC, UN or U-Zr alloy in place of UO_2). In general, more coolant means a larger positive coolant void reactivity, again inviting compensatory measures such as "pancaking" (decreasing the core height-to-diameter ratio) or using special streaming assemblies. These measures tend to decrease core conversion ratio, which increases the reactivity loss during burnup, hence requiring more and/or higher-worth control rods to hold down the higher initial excess reactivity.

In gas-cooled thermal reactors using graphite moderator, the approach has been to remove decay heat by radial conduction from the core periphery to the reactor vessel and thence to the reactor cavity cooling system. This limits core volume (hence power rating) and favors a tall annular configuration to reduce the radial conduction path length. The consequential increased neutron leakage requires higher fissile enrichment than in the larger HTGR designs of yesteryear (if on a LEU fuel cycle). Vulnerability to spatial power oscillations is also increased.

2.2 The Challenge of Stronger Safeguards

In fast reactors the desire to avoid the presence of segregated isotopically high purity Pu-239 has led to the replacement of breeding blankets by fertile-free reflectors. This in turn has prompted a search for weakly moderating high-albedo reflector materials, and created an incentive to increase core breeding ratio (to sustain fissile inventory and reduce reactivity loss as burnup progresses); this helps explain why in the INERI GFR, Zr_3Si_2 is the material of choice, while lead fills this role admirably in LMRs. However, increased coolant void reactivity is a common result of reducing leakage.

Another consequence has been the favoring of fuel forms amenable to reprocessing without segregated plutonium separation: for example, U · TRU · Zr alloy for lead and sodium cooled fast reactors because of its amenability to pyroprocessing. The resulting spectrum hardening and higher fuel thermal conductivity reduces negative Doppler feedback, but enhances axial expansion—creating a different mix of transient-limiting phenomena than for cores using ceramic fuels such as TRU-containing UO_2, UC or UN.

In thermal reactors safeguardability by itself has not had as important an impact on core neutronics except, in the recent past, abandonment of the HEU/Th cycle for HTGRs. The issue has been more focused on whether on-line refueling in pebble bed HTGRs or in CANDUs weakens accountability.

2.3 The Challenge of Improving Waste Disposal

Here the thrust under the advanced fuel cycle initiative (AFCI) program has been to recycle and fission or transmute the most radiotoxic actinides to as close to extinction as practicable, so as to reduce the HLW disposition task to one primarily of fission product partitioning and sequestration, with its much shorter time horizon. There are two schools of thought: use of a fast spectrum to favor fission over capture (transmutation) versus a thermal spectrum irradiation combined with storage for decay of end-of-chain species such as curium.

Higher TRU (plutonium plus minor actinides) inventories lead to a reduced core average delayed neutron fraction, β and in thermal reactors a harder spectrum, which reduces the worth of control absorbers. TRU-only loadings have a less negative Doppler coefficient of reactivity, which for fissile-dominated compositions could even be positive.

A problem still in need of creative approaches is transmutation of the long-lived repository-escape-prone fission products I-129 and Tc-99.

2.4 The Challenge of Highly Efficient Production of Electricity and Hydrogen

This goal favors operation at the highest temperature materials will allow. The most serious impact is on reactors designed for generation of hydrogen using thermochemical processes to split water, where core outlet temperatures as high as 1000°C are sought. HTGR-type thermal spectrum reactors with their graphite moderator, helium coolant and coated particle fuel are well suited to this task: the German AVR achieved 950°C in the final stages of its operation; the Japanese HTTR has recently done likewise. Hence, the VHTR faces no entirely new physics problems solely due to this application. Much the same can be said for molten salt cooled and molten salt fueled cores. However, devising a fast reactor having this capability does break new ground. For example, the INERI GFR calls for a UC/SiC plate type cercer fuel in a 50/50 volume percent ratio. This introduces a degree of moderation which, while tolerable, is new to the fast reactor physicist.

2.5 The Challenge of Cost Effectiveness and Resource Sustainability

Economic analyses have in general lagged neutronic studies. Part of the reason is that the real objective function is total energy cost at the busbar. Capital and O&M costs typically exceed fuel cycle costs. Thus even modest increases in fuel costs are tolerable if other costs are significantly reduced. A prime example is the small modular HTGR where it is expected that modularity will lead to capital cost reductions. Higher thermal efficiency also offsets fuel cost increases.

Another excuse for lack of financial precision is that reactor physicists are mainly focused on in-core performance, whereas ex-core fuel cycle costs—namely those of enrichment, fabrication, reprocessing and waste disposal —are not entirely under their control. Moreover, these cost centers are themselves the subject of intensive concurrent attention and innovative modification to meet the goals of GEN-IV/AFCI.

2.5.1 Approximate Fuel Cycle Cost Estimates

The direct cost of fuel (ignoring carrying charges) is approximately:

$$f_c = \frac{C}{24\eta B_d} = \frac{C}{8.76\eta\ sp\ LT}\ mills/kWhre \tag{1}$$

where

- C = cost per kg of fuel as of start of irradiation, \$/kgHM
- η = plant thermodynamic efficiency, MWe/MWth
- B_d = fuel discharge burnup, MWd_{th}/kgHM= 0.365 sp L T
- sp = specific power, kW/kgHM
- T = duration of fuel residence in core, yrs
- L = plant capacity factor (average fraction of rated full power achieved)

For a reactor burning uranium enriched in U-235, using nominal market values for ore and SWU costs one has, very roughly:

$$C \approx C_{FAB} + 365\,(X - 0.9)\ \$/kgHM \tag{2}$$

where

- X = enrichment in U-235, weight percent
- C_{FAB} = fabrication cost, \$/kgHM

Thus a hypothetical fast reactor having X=18%, C_{FAB}=500 \$/kgHM, η=0.42, and B_d=120 MWd/kgHM, would have C=6740 \$/kg and thus f_c=5.6 mills/ kWhre, comparable to that of today's LWRs.

Fueling with TRU is subject to greater uncertainty. Consider a fast reactor assembly made up using TRU discharged from a thermal reactor:

$$C = C_{FAB} + C_{REP} \cdot \frac{X_f}{X_t}\ \$/kg\,HM \tag{3}$$

where

- C_{REP} = cost of LWR fuel reprocessing, \$/kgHM
- X_f = weight percent TRU in fast reactor reload fuel
- X_t = residual weight percent TRU in spent LWR fuel

Hence, for C_{FAB}=2600 \$/kgHM, X_f=15%, X_t=1%, C_{REP}=800 \$/kgHM, C=14,600 \$/kgHM (costs adapted from [18]); one has f_c=12 mills/kWhre.

The same fast reactor recycling its own fuel and having X_t=X_f (i.e., an effective conversion ratio of 1.0), would, assuming C_{REP} is 2000 \$/kgHM, have:

$$f_c = 3.8 \text{ mills/kWhre}$$

These large differences between U-235 startup, TRU startup, and steady-state self-generated reload fuel costs are the source of considerable misunderstanding in the debate over AFCI deployment, as are the appropriate costs for C_{REP}, in particular. This is due in part to the uncertain credit for facilitating waste disposal. Another confounding issue is the difference between new reprocessing plant costs and old reprocessing plant costs (where capital costs can be regarded as "sunk" and forward charges need cover only operating costs).

Also note that for thermal recycle in a reactor requiring a TRU enrichment of 7% to achieve B_d=60 MWd/kgHM, one would have for C_{FAB}=1100 \$/kgHM and η=0.32:

$$f_c = 14.5 \text{ mills/kWhre}$$

which is a serious economic impediment.

Finally, the challenge of long-lived "nuclear battery" cores is evident if one considers that carrying charges increase direct costs by a factor of approximately $(1+x\text{T}/2)$, where x is the discount rate: % per year/100. Thus for x = 10%/yr and T=20 years, the undiscounted fuel cycle cost is roughly doubled. Since these cores are typically small, the resulting propensity for higher enrichment compounds the economic penalty.

In summary, the current US waste fee of 1 mill/ for once-through LWR spent fuel translates into about 400 \$/kg. This is less than 20% of the per kilogram cost of either fresh U-235/U-238 fuel or of PUREX reprocessing plus MOX fabrication. Hence in the US waste disposal savings alone are unlikely to be enough to justify changes in free-market commercial fuel management practices. This circumstance also highlights the need for R&D on processing that can reduce the cost of TRU recovery from LWR spent fuel.

2.5.2 Long Range Cost Perspective

Concern over scarcity-driven escalation in uranium prices is not nearly the dominant concern it once was due to new ore discoveries, improved recovery methods such as solution mining, and the slower than anticipated growth of nuclear power. Steady improvement in enrichment technology has also led to better overall uranium utilization, and there is room for considerable further improvement. This has widened the time window for cost-driven deployment of reprocessing, recycle and breeding technology, and increased the incentive for doing so in a more cost-effective manner using creative new technology. In short, nuclear reactors are expensive machines burning cheap fuel. This circumstance leads to a proportional diminution in the financial resources devoted to near-term reactor physics, which in turn emphasizes the importance of prioritization in future program plans.

3. RESULTING METHODS, MODELS AND DATA NEEDS

3.1 Computational Methods

Since another article in this journal deals specifically with the subject of methods and models, only some of the more exceptional aspects will be discussed here. By and large, existing physics methods, and modest extensions thereof, have been adequate to the task at hand, as have cross section databases such as ENDF/B, JEF and JENDL. Exceptions of note have been the need for work on modernization of the treatment of pebble bed cores (because of their stochastic pebble flow and random location of fuel particles within a pebble), and for more attention to minor actinide cross sections at high energies. In general, accuracy is currently data, not methods limited. Figure 1 is a revealing example of the differences one can encounter for LMR cores heavily loaded with minor actinides using the same code but different cross section compilations. The uncertainty will be further compounded if one endeavors to predict the core behavior and isotopics of multi-pass recycle to near-extinction.

As another example encountered in our work, Figure 2 shows that even for U-238 cross sections in the epithermal unresolved energy region, i.e. 150-200 kev (near peak flux for hard spectrum fast reactors)—cross section sets can differ widely.

One welcome development over the past decade has been the emergence of affordable parallel computer clusters

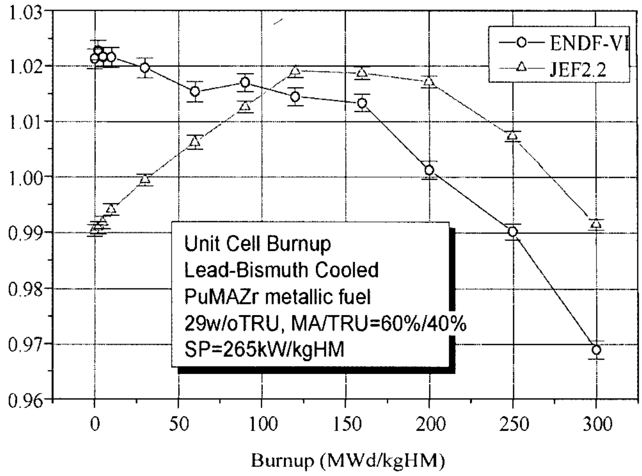

Fig. 1. Burnup history variation for LMR MA-fueled cores using different s sets [19]

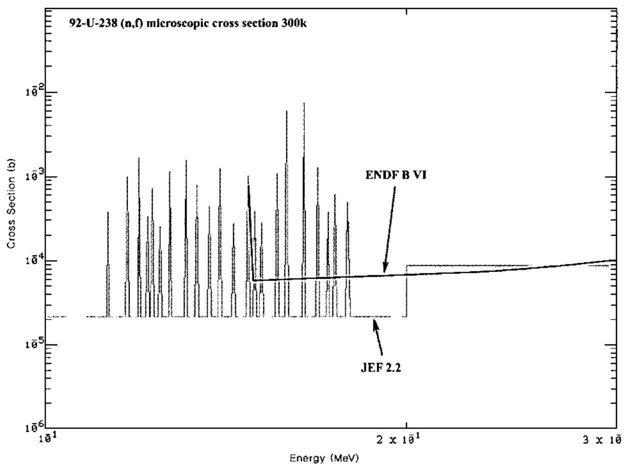

Fig. 2. Comparison of 238U fission cross-section libraries

Table 4. Selected Modeling Needs: A Partial List

Better treatment of the following for problem specific configurations:
· Spatial energy shielding, including interference between isotopes; and also covering both near-thermal and unresolved region energies
· Approximations to transport theory: diffusion, P_n, S_n
· Nodal homogenization and de-homogenization
· Uncertainty analysis to focus attention on key needs for improving data and models
· Sensitivity theory to help interpret integral experiments and infer their impact on discrete representations
· Even faster Monte Carlo and hybrid methods to enable more widespread use in time-dependent computations

that can run programs coupling Monte Carlo (e.g., MCNP) and nuclide history (e.g., ORIGEN) codes capable of whole-core burnup calculations [20]. This has permitted evaluation of the innovative and often highly heterogeneous configurations contrived to meet the needs of many GEN-IV applications: for example, moderator-tubes in an SCWR or streaming assemblies in an LFR. They have proven invaluable for benchmarking simpler, faster deterministic methods. To some extent this capability also helps compensate for the scarcity of critical facilities in which large unorthodox cores can be mocked up. However, some criticals will still be needed because a number of GEN-IV concepts lie significantly outside the compiled database of existing criticals.

In all likelihood, it will still be several decades before this approach will be practical for space-time kinetics calculations in two and three dimensions. Meanwhile, it would be helpful if robust, theoretically sound methods were developed to enable use of Monte Carlo methods to generate few-group cross sections and nodal parameters for use in deterministic transient codes. The principal difficulty lies in extraction of high precision group-to-group downscatter cross sections.

Specialists in each subfield are admittedly better-suited to suggest how models, including those of long-standing, others currently under development, or hypothesized new ideas, can respond to physics challenges such as those enumerated in Table 4. Nevertheless, in Table 5 a partial roster is essayed.

3.2 Licensing Related Needs

Physics methods must go beyond the "good enough for engineering purposes" standard to satisfy the more rigorous, documented modern validation and verification requirements needed for licensing. Thus even tried-and-true older codes of long standing may have to be vetted to the extent that re-invention may be the easier alternative. If past practice holds, licensing authorities such as the US NRC will want to have an independent capability for checking key aspects of vendor submissions.

Table A.2 summarizes the likely agenda of reactivity-related scenarios that must be analyzed. Another issue to be faced over time is the development of new standards, and modification of the old LWR-oriented reactor physics standards.

On a more philosophical level, the protocol for addressing "maximum credible accidents" needs to be addressed. A particularly relevant example is the classical "hypothetical core disruptive accident (HCDA)" required for consideration in fast reactors in the 1960-80 timeframe [21]. If PRA analysis shows that mechanistic scenario event trees lead to probabilities lower than those for LWR pressure vessel rupture, one could make an argument for eliminating this line of inquiry.

A related issue is the advisability of installing in- or ex-vessel core catchers. It will be recalled that the former actually caused the fuel melt accident that led to the shutdown of the Fermi-1 LMFBR. The reactor physics challenge here is the prediction/avoidance of re-criticality in the face of hard-to-predict scenarios involving material re-location.

In lead-cooled reactors new phenomena and sequences must be analyzed because their fuel can have density comparable to that of lead, and clad, structure and control materials are lighter—hence some post-accident constituents can float: in sharp contrast to their behavior in sodium or gas coolants.

4. CONCLUDING REMARKS : MEETING THE CHALLENGES

The physics community is faced with the concurrent analysis of more reactor concepts than at any time since the 1960s–the six major genera, with at least two species each, but with limited resources and the expectation of higher levels of precision and licensing validation and verification standards. Fortunately there has been an enormous expansion in computational capabilities—both hardware and software—which will facilitate this task. Of particular note are the maturation of Monte Carlo methods and advances in parallel computation. For example, for the past two years we at MIT have been using an inexpensive ($15,000) "Beowulf" type, 30 node, parallel cluster to do whole core fast reactor burnup calculations as well as to study beginning of life pebble bed reactor physics using a code coupling MCNP to ORIGEN. This allows completion in one day of problems that formerly took a month of workstation time. Moreover, it uses chip technology now at least two generations behind leading edge capabilities. Hence in a few more years, in combination with additional software refinements, speedup by another factor of more than five is foreseeable. So far the off-cited concern of loss of insight amidst all of this black-box number crunching has not materialized, since entry-level classroom teaching is still based on simple physical models, which foster understanding (at the expense of accuracy).

A brief overview of problems facing the reactor physics community in the design of cores for GEN-IV reactor concepts has been presented. It appears fair to say that, given an appropriate commitment of resources, all can be satisfactorily resolved. This level of confidence is supported by reactor operations over the past half-century. To the authors' knowledge, only one instance of major misprediction (cycle burnup duration for an early PWR) is worthy of note; and this and minor deficiencies elsewhere were fixable in an economically tolerable and rather straightforward manner. On the other hand, many, if not most, of the two dozen or so small one-of-a-kind demo units built in the 1960s timeframe encountered engineering (often materials) shortcomings that exceeded the financial resources of the developers to remedy, and have thus departed the scene. The physics design of the late unlamented Chernobyl reactor is nevertheless a cautionary tale, but one which testifies not to physics misprediction, but to lack of a conservative overarching design ethos (not to mention a cavalier operating culture). We conclude with a menu of suggested initiatives as shown in Table 5.

The last one listed is worth particular mention in as much as there is evidence of decreasing support for methods development research at universities, hence tenure-enhancing careers for young professors, and a growing tendency to relegate teaching reactor physics to a "service-course" function. At the same time the challenge of promoting autonomous reasoning in an environment dominated by increasingly impenetrable computer models is greater than ever.

Table 5. Some Suggested Initiatives

· Continue, formalize and expand international efforts to prioritize, coordinate and pool reactor physics work
· But, preserve some diversity in methods and data sets; and devise and compare numerical benchmarks
· Support continued operation of selected critical facilities and test reactors; promote further physics tests and integral experiments
· Improve minor actinide cross section data
· Coordinate and aggressively expand the use and capabilities of Monte Carlo methods
· Expand the scope of new reactor physics startup and operating tests to help make up for the shortage of new criticals and to promote the concept of proving safety by demonstration
· Strengthen interactions with other project staff concerned with thermal-hydraulics, fuel performance modeling, licensing, PRA and especially economic assessment to insure that physics constraints are given appropriate consideration in design tradeoff iterations
· Engage in the debate over GEN-IV goals and how they are best realized
· Attract and educate the new generation of reactor physicists; support university teaching and research at the PhD level

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APPENDIX

To avoid making the preceding writeup excessively discursive, familiarity with a reactor physicist's full agenda of concerns has been presumed. Here, for the benefit of the non-specialist, some useful background has been summarized in the form of two tables. The first lists neutronic parameters of interest and the second is a breakdown of reactivity changes as they enter into transient and accident analyses. Concept-specific aspects derived from these generic rosters have been selected for attention in the main text.

Table A-1. Physics Parameters of Interest to the Core Designer

A. OUTPUT

Static/Quasi-Static	
· Multiplication Factors:	· Cold · Hot · Hot Full Power (HFP) · HFP, Equilibrium Xe and Sm (Thermal Reactor)
· Spatial Power Distribution:	· Peak and Average
· Control Absorber Worth:	· Control Rods (Including One of Max. Worth) · Burnable Poison (Thermal Reactors) · Soluble Poison (PWR)
· Conversion Ratio (Over Burnup Cycle)	
· Gamma Heating and Transport	· Core, Coolant, Reflector
· Instrumentation Response	· In and Ex-Core
Kinetics and Load-Follow	
· Delayed Neutron Fraction	
· Prompt Neutron Lifetime	
· Reactivity Coefficients:	· Doppler (Normal and Voided) · Coolant Expansion and Void · Fuel Expansion and Bowing (Fast Reactors) · Control Rod Drive Line Expansion (Fast Reactors)
· Space-Time Power Evolution, and Spatial Power Oscillations	
· Post-Shutdown Decay Heat Generation	
Fuel Management/Burnup	
· Reactivity as Function of Burnup · Isotopic Concentrations as Functions of Burnup · Refueling Strategy: Enrichment, Fraction Refueled, Frequency, Loading Pattern · Clad and Pressure Vessel Fluence, Average and Peak Displacements per Atom (DPA)	

B. INPUT

Cross Sections as Functions of Energy, Especially:
· At High Energies (e.g., > 0.1 MeV) · For Minor Actinides · For Less Familiar Materials, e.g., Pb and Bi
Criticals
· k_{eff}, Reaction Rate Distributions, Rod Worths · Transient Response Parameters
Integral Data
· Spectrum-Averaged Reaction Rates (As Functions of Spectrum, Temperature)

Table A-2. Typical Reactivity Contributors Relevant to GEN-IV Transient and Accident Analyses

Reactivity Addition	Reactivity Removal (Active and Passive)
· Control Rod Ejection (of most reactive rod) (or drop-out if bottom-inserted design) · Control Rod Bank Withdrawal · Xenon and Samarium Decay (in thermal spectrum reactors) · Sudden Coolant Inlet Temperature Reduction (assuming negative MTC and power conversion system transient) · Coolant Boiling/Voiding/Density Decrease (especially in fast reactors) · Fuel Compaction (fast reactors) (inward bowing or meltdown; flow or seismic-induced motion of block fuel) · Coolant Neutron Poison Dilution or Absence (if poisoned water reflood is used in SCWR or GFR) · Control Rod Drive Train Thermal Contraction (relative to core) · Refueling Accidents (drop fresh element into near-critical core)	· Control Rod Insertion or Scram · Doppler Absorptions due to Fuel Heatup · Coolant/Moderator Temperature Increase (if MTC is negative) · Fuel Assembly Outward Bowing (in fast reactors) · Special Devices: Gas-expansion module, GEM in SFRs Poison particle inpour in HTGRs

Note that scenarios specific to PWR or BWR plants of GEN I, II and III vintage are excluded from this compilation

Bibliography

In addition to references on specific topics cited in the text, there are several conference proceedings which each contain a significant collection of papers on GEN IV reactors and their physics. The following are of note:

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PHYSOR 2004 Chicago, Ill April 2004

International Congress on Advances in Nuclear Power Plants:

ICAPP 2002 Hollywood, FL June 2002
ICAPP 2003 Cordoba, Spain May, 2003
ICAPP 2004 Pittsburgh, PA June 2004
ICAPP 2005 Seoul, Korea May 2005*

GLOBAL Conference:

Global 2003 New Orleans, LA Nov. 2003

ASME ICONE Topicals

International Conference on Nuclear Engineering:

ICONE-10 Arlington, VA April 2002
ICONE-11 Tokyo, Japan April 2003

*Available in 2005

Proceedings of ANS topicals are available through the American Nuclear Society, www.ans.org/store/.

Proceedings of ASME Topicals are available through the American Society of Mechanical Engineers, www.asme.org/catalog/.