COMPLETELY AUTOMATED NUCLEAR POWER REACTORS
FOR LONG-TERM OPERATION:

III. Enabling Technology For Large-Scale, Low-Risk, Affordable Nuclear Electricity *

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Abstract

We systematically examine the principal concerns regarding provision of a large fraction of human energy needs with nuclear fission reactor-derived electricity, and offer robust physics- &-engineering responses to each of them. We then propose a representative system-level integration of these solutions to the long-standing problems that have confronted nuclear fission-based power. This integration obviates all fuel supply issues, including the entire set of isotopic enrichment ones, while rendering comparably useful as nuclear fuels all of the actinide elements-&-isotopes. It entirely avoids transport and reprocessing and the full set of ad hoc waste disposal issues, and completely precludes all those involving proliferation/diversion of fissile isotopes into weapons programs. It offers high-grade heat in pressurized helium gas for thermodynamically-efficient, economically-appealing, environmentally-attractive combined-cycle conversion to electricity while robustly avoiding prospects of internal overheating of any portion of the reactor’s core or fuel. It provides highly redundant means of any desired statistical reliability for prevention of core meltdown in LOCA circumstances. It provides zero biospheric hazard in event of either natural or man-made catastrophe. It requires – indeed, admits of – no operator control actions, other than initial start-up and final shut-down commands, so that operator errors are entirely precluded; during the half-century of potentially full-power operational life in between these two commands, it thermostatically regulates in an entirely automatic manner its own nuclear power generation to match the heat removed from its core in a time-varying fashion. The thorium-burning variant of this new class of reactors involves no long-lived actinide isotopes, thereby obviating the present-day keystone issue of long-term reactor waste storage-&-disposal. Each of these novel features is technologically separable, so that these new reactor design concepts may be applied piecewise to enhance prospects nuclear reactor-centered power generation in many different utilization circumstances. However, synergisms arising from their full integration seem likely to be compellingly attractive in most situations, for a constellation of economic and safety reasons. We therefore project a bright future for cheap electricity safely obtained in >10 TWe quantities from nuclear power reactors of this new type, moreover over multi-century time-frames. We observe that pertinent aspects of neutron physics and modern technology together offer a far richer spectrum of possibilities for nuclear power reactors than has been significantly explored through the present; the present architecture is merely exemplary.

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# Also Research Fellow, Hoover Institution, Stanford University, Stanford CA 94305-6010 U.S.A. Prof. Teller died at age 95 between the time this paper was presented at the July 2003 Workshop of the Aspen Global Change Institute and its submittal for publication. His co-authors dedicate this paper to the memory of his indefatigable efforts of the past 58 years toward realization of safe-&-affordable large-scale nuclear electricity supply.

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Global Change Numbers. The prospect of raising the space- and time-averaged absolute temperature of the terrestrial biosphere by ~1% during the 21st century by the combined direct and indirect effects of anthropogenic injection of "greenhouse gases" (principally carbon dioxide, CO2) has given rise to a set of currently-proposed remedial actions directed to partial, economically-mediated proscription of carbon dioxide injection into the atmosphere.

While consensus or even widespread study of these issues has yet to occur, admittedly highly uncertain estimates by senior officials of the U.S. government suggest that increasing the current U.S. wholesale prices of carbon-based fuels (and energy derived therefore, such as electricity) by ~40% will suffice to suppress fossil fuel use to levels such that CO2 injection-rates will be reduced to 1990 levels. [These 1990 injection-rates are politically posited to be a “useful first step” in moderating the rate of global warming, although it’s widely appreciated in the scientific community that injection-rates several-fold smaller than the 1990 one will be required to stabilize atmospheric CO2 concentrations in the vicinity of the present one.]

The economic implications of such price-based suppression of fossil fuel use are of large scale. For example, approximately 78 million barrels of oil is presently are used per day, annually averaged. The recent 12 month-averaged cost of a barrel of oil is ~$25, so that the world's crude oil bill currently is ~$2.0 B/day, or ~$750 B/year. A 40% increment in this cost would amount to $300 B/year. When other fuels (principally coal and natural gas, at present) are also considered, the total proposed price-burden on all fossil fuels world-wide in order to suppress CO2 atmospheric injection amounts to ~$500 B/year, at current costs and consumption levels. [Approximately 25% of this fossil fuel price-burden would be borne by fossil fuel users in the United States, at an annual cost of ~$125 B. This amounts to ~1.2% of current U.S. GDP, or ~6% of the total Federal government tax burden on the U.S. economy. At the current amortization rate for low-risk investments, it is equivalent to a one-time expenditure of ~$3 T for the U.S., or ~$12 T world-wide.)

Large-Scale Nuclear Power Supply. Over the past four decades, nuclear fission power reactors have come into widespread usage throughout the world, particularly in the developed countries. Currently, France derives over 70% of its electricity from nuclear reactors, while Japan realizes more than 40% and the U.S. get 20%. Nuclear-generated electricity in the U.S. presently has a production cost which very closely rivals that of the lowest-cost source, modern coal-fired plants (both of which produce electricity for ~$10/MW-hr, or 1 cent/kW-hr), when the best nuclear plants are compared to the best coal-fired ones. [Obviously, comparisons of best examples are most relevant; nearly arbitrarily poor examples of all major technologies usually exist, but are of little enduring interest.]

Nuclear power reactors are almost exclusively of the light water-cooled (LWR) type originally developed in the U.S. for plutonium production during World War II and adapted (e.g., via substitution of water for graphite as moderator) in the subsequent dozen years for raising steam of quality useful for Rankine cycle-based, turboalternator-implemented electricity generation. Other major adaptive steps taken included the use of isotopically-enriched uranium fuel (enriched in the U235 isotope from the naturally occurring level of 0.7% to 2.5-3.5% for greater fuel specific energy production and thus longer intervals between required refueling) and the elimination of designed-in safety deficiencies (e.g., the positive temperature coefficient-of-reactivity defect which was the proximate cause of the steam boiler-type explosion of the Chernobyl reactor, whose old-style design was long known to include this intrinsic deficiency).
Nuclear power reactors enjoyed widespread penetration of the electricity-producing marketplace during the first two decades after the advent of the first commercial nuclear plants, over the interval ~1957-77. At the time of the Three Mile Island accident in the U.S., official government projections were for exponentially advancing use of nuclear power through the year 2000, with ~500 GWe of installed capacity in the U.S. alone being a mid-range estimate for the end of the 20th century. Such high electrical production levels in turn required more enriched uranium fuel than could be realized from existing reserves of uranium ore, necessitating the development of a breeder-type power reactor, one which could produce more fuel than it consumed.

Major breeder reactor development programs in the U.S., France and Japan have not met with outstanding technical or programmatic success. Furthermore, over the same interval (~1972-85), electrical power demand in the developed countries, which had been increasing rapidly for several decades (e.g., in the U.S. at a ~7% annual rate over 1947-72) dropped quite rapidly (e.g., to a recent ~1.5-2% annual rate in the U.S.), likely due in major part to the rapidly increasing price of crude oil, which effectively set the price-at-the-margin of energy-producing feedstocks, due to its dominant position in the market.

The slumping increase-in-demand for electricity correspondingly diminished requirements for new electrical central-station capacity. Diminishing order-flow increased the unit costs of suppliers, many of whom did not move sufficiently quickly and vigorously to curtail their overhead costs. This effect was particularly marked for nuclear plant vendors, who were also burdened during this interval with a stream of demands by regulators for qualitatively and quantitatively enhanced safety features, demands originated in a plethora of minor accidents-and-incidents but focused in public perceptions by the Three Mile Island accident in 1979. These rapidly-escalating economic burdens, combined with the psychological impact of the major Chernobyl nuclear power reactor accident in 1986, sharply attenuated the demand for new nuclear power plants in most all of the advanced countries during the past decade – with the notable exceptions of France and Japan, both of which seem to place high valuations on the energy supply-security implicit in nuclear-generated electricity.

Throughout this interval, the stiff economic incentives posed to electrical power plant suppliers selling fossil fuel-fired combustion units by order-of-magnitude-increased crude oil prices were motivating improvements in the thermodynamic efficiency with which such fuel is converted into electricity. Stalled for a half-century at 30-35% efficiency in converting thermal energy into electricity, Rankine cycle-based systems slowly crept toward 40% efficiency during the ’80s. The introduction of combined Brayton and Rankine cycle combustion heat-to-electricity conversion systems during the last decade has seen conversion efficiencies climb swiftly toward 60%, a psychological threshold of generating efficiency which the best current "aero-derivative" technology has recently exceeded. Unsurprisingly, these efficiency record-setting combined-cycle systems also have recently set the economic pace in electricity production; until a quite recent spiking in natural gas prices, they offered in the U.S. a total unit energy cost of ~$0.04/kWe-hr, compared to $0.08-0.10/kWe-hr for nuclear-generated electricity. [Total unit energy cost differs notably from production cost by properly including all charges involved in the generation of electricity including the capitalization of the generation facilities; exclusive focus on production costs – principally fuel, operations and maintenance – implicitly assumes that the generating plant came into use entirely free-of-charge, and will either last forever or have zero replacement cost.]

The combination of economic and non-economic burdens on nuclear power, including the recent advent of extraordinarily low total unit energy cost combined-cycle electricity generation, has resulted in the de facto cessation of nuclear power plant sales in most developed countries. The outlook into the
foreseeable future involves little if any change in this basic situation, for most nuclear power reactor development as is underway on significant scales (e.g., the now-concluded Advanced Light Water Reactor program in the U.S.) generally involves relatively minor variations on the basic LWR theme; this track is conceded by some of its original participants (e.g., General Electric) to offer little-if-any hope of economically viable outputs. Such substantial alternatives to LWRs as do exist are either far from commercially significant milestones while already being bedeviled with technical and political problems (e.g., the fast-breeder power reactor development program in Japan), or are burdened with adverse perceptions or extensive albeit virtually milestone-free histories (e.g., the high-temperature gas-cooled – HTGR – program in the United States or the Molten Salt Reactor, being considered by several groups in Russia, Japan, the U.S. and elsewhere).

World-wide, there are slightly over 400 nuclear power plants currently in operation, and less than 3 dozen under construction. Since power-plant lifetimes are ~30 years and construction times are ~5 years, it's clear that the Earth's nuclear power plant population is not only not rising but isn't even in steady-state; rather, it'll decline rapidly to less than half of its current level, if present trends continue. Indeed, two large nuclear electricity-using nations – Germany and Sweden – are formally committed to entirely de-nuclearize over the next couple of decades (although the degrees of actual present-day commitment to these goals are widely questioned).

**What Is To Be Done?** If electricity demand is curtailed through governmental interventions in some countries, elementary economics teaches that particularly intensive users of electrical energy in such countries likely will avail themselves of features of the globalized economy to move their electricity-intensive activities to other countries where such government intervention in the marketplace for electricity is less burdensome. The "dismal science" also declares that the "comparative advantage" of both sets of countries will shift correspondingly – to the net gain of the countries in which electricity is more freely available. Countervailing political pressures of economic origin will then build in the more restrictive countries, which may attempt to reduce their differential comparative disadvantage by inducing the less restrictive countries to match their restrictions – or to comparably burden their electricity-users in other manners. Natural disinclinations of low-cost-electricity countries to freely part with a comparative advantage may then be expected to be a source of international conflict, of natures and to degrees which are currently quite uncertain. In addition, to the extent that there is a greater demand for the materials for electricity generation – e.g., petroleum – than can be reliably accessed in a free market, there will be outside-the-marketplace maneuverings to secure access to such materials “by other means;” early phases of such maneuverings appear to be underway at the present time in of number of locales in central Asia, while the Middle East has long since become accustomed to such activities.

Furthermore, world-wide CO₂ emission at even the per-capita levels of the advanced counties in 1990 would clearly result in very high asymptotic levels of atmospheric CO₂ – since 80% of humanity currently lives in the developing world, where per-capita emission levels are, on the average, an order-of-magnitude lower than in the fully-developed world. On the other hand, elementary considerations of individual energy-use equity obviously preclude emission bounds referenced to national levels at some point in time when some countries were highly developed and highly energy-intensive while other nations were either still developing or hardly developed at all, and thus used relatively little energy; essentially no one will argue publicly that, just because a minority of people inhabiting some nations got
to the world's fossil fuel resources first, the majority of humanity living in all the other nations should remain energetically impoverished into the foreseeable future.

All of this is not entirely hypothetical, for we see the early features of most of these behaviors in today's world. For example, governments of developing countries are publicly resisting world-wide application of CO$_2$ emission limits generally advocated by already-developed countries, while three-fifths of the members of the U.S. Senate – two-thirds of which body is constitutionally required to assent to any treaty obligating the government to impose limitations on atmospheric injection of CO$_2$ from American sources – have placed themselves collectively on record as opposing any treaty requiring curtailment of CO$_2$ emissions unless any such curtailment measures are made to be of simultaneous, world-wide applicability.

The fate of nuclear-centered central station electricity generation is connected to the outlook for relatively low-conflict responses to global warming challenges through the fundamental consideration that nuclear generation is the only large-scale, generally-available, capacity-expandable source of electricity which doesn't involve the release large specific quantities of CO$_2$ (i.e., of the order of a kg/kWe-hr) into the Earth's atmosphere. If growth in electrical demand over the Earth as a unit is to continue at anything like recent rates and yet CO$_2$ emissions into the Earth's unitary atmosphere are to remain constant or perhaps even decrease, only nuclear sources of electricity are actually available to fill the annual energy gap of tens of thousands of terawatt-hours which is thereby engendered, as soon as two decades hence. [Renewable resources either are distributed in a quantitatively inadequate and geographically quite uneven manner – e.g., hydroelectric, wind and biomass-based electricity – or else have intrinsic availability and land-use/environmental-impact limitations – e.g., solar and hydroelectric – which effectively limit their candidacies as generally-applicable responses on the parts of national energy planners. For example, renewable energy sources excluding hydroelectric comprise less than 3% of total U.S. energy supply, after a quarter-century of reasonably intensive government subsidies for development and deployment of such sources, and the Congress recently declined to mandate more intensive deployment of them; the trend in America for hydroelectric generation – which presently accounts for ~8% of all U.S. electricity – is, if anything, timewise downward, due to environmental pressures.]

In this paper, we inquire as to whether and how nuclear fission-based electricity generation can actually contribute to maintenance of an advancing standard-of-living for people everywhere while attaining asymptotic concentrations of CO$_2$ in the atmosphere not greatly in excess of current ones. We are therefore concerned not just with technically sound solutions to the notable issues which have been raised regarding nuclear power during the past quarter-century, but also ones that satisfy real-world economic constraints and which effectively address public perceptions.

We take the approach of first specifying a set of constraints which we believe that contemporary and future nuclear electrical power sources must satisfy. We then search for solutions which simultaneously satisfy each of these constraints – without a priori assurance that any such solutions exist. This back-solving approach is a reasonably novel one, to the best of our knowledge, one which hasn't been much applied to the design of nuclear power reactors since the 1940s. Indeed, with constraints such as economic and public perceptual ones included, the back-solving approach to design might be entirely novel in this area – and thus perhaps somewhat peculiar. Nonetheless, it seems necessary to return to fundamentals, if the most useful possibilities are to emerge with reasonably high likelihood. Not unimportantly, we take today's world as-it-is, regretting but not attempting to overthrow its less rational
aspects or to perfect its non-ideal features. In brief, we search for large-scale nuclear power possibilities around which broad consensus may rather rapidly form, and thus upon which implementation might rather quickly commence based on international cooperation toward realization of globally-applicable solutions.

**Constraints And Their Motivations.** We consider the following constraints on all actual 21st century nuclear power options to be essential ones, for reasons which we note only in passing, due to their generally obvious character:

- **Fuel Supply And Preparation.** Nuclear power reactors which may be fueled with inexpensive, widely-available fuel are the only ones which are of present interest. Any fuel chosen must be reliably available in sufficient quantity at reasonable extraction costs to give 10 billion people a First World energy standard-of-living for at least 1 century: 10 billion kW-centuries of electrical energy, or ~3 x 10^29 ergs, or 300 tonnes of mass-energy, or ~300 kilotons of actinide element fissioned with 100% conversion to electricity. Furthermore, preparation of the fuel for reactor use must involve sufficiently simple operations as to form the basis of a genuinely world-wide free market for fueling services, one inherently resistant to cartel-formation and political restraints-of-trade.

- **Fueling Operations.** Reactors of present interest should never require re-fueling, once they have commenced operation – for reasons of economics, safety and of suppression of materials diversion. [Modern naval propulsion reactors operate without refueling for the 3-decade operational life of a submarine for reasons of economy and military operational availability, and there's no basic reason why civilian power reactors can't have this feature also.] All the fuel which a reactor needs during its entire operational life should be *built into it*, as it's manufactured. Reactor design and construction – indeed, nuclear power plant construction, as a whole -- are thereby greatly simplified, due to elimination of the necessity to provide for opening, re-sealing and removing and installing fuel assemblies in an in-service reactor's core. Similarly, expensive and hazard-prone periodic refueling is obviated, and costly, risk-prone complications such as biennial spent fuel handling, in-plant storage-&-cooling and transport to reprocessing sites are eliminated.

- **Fuel Reprocessing.** In addition to being entirely unnecessary-in-principle for a robust, enduring nuclear energy economy, reprocessing of spent reactor fuel provides a point at which fissile materials are inherently divertable to military uses, generates a highly problematic waste-stream, and burdens nuclear power generation with non-negligible economic and public-perceptual costs. Reprocessing therefore should be avoided to the greatest extent possible.

- **Radwaste Disposal.** Disposal of long-lived radioactivity generated in the course of operation of reactors of present interest should be performed in a manifestly safe and robust manner, so that the exceedingly low likelihood of entry of non-negligible amounts of reactor-generated radioactivity into the biosphere at any future time can be made reasonably clear even to the lay public.

- **Materials Diversion.** Fuel for reactors of present interest during all times in its existence, from manufacture through final-and-irreversible disposal, must be of a nature as to have no utility,
regardless of quantity, for any military purposes without isotopic enrichment capability being exercised on it.

• **Operational Safety.** Reactors of present interest must be inherently incapable of suffering damage, no matter how seriously their controls should be mishandled by their operators. They must also be incapable of damage due to loss-of-coolant accidents of all degrees of severity. In addition, they should be highly immune to human misbehavior, ranging from insider sabotage through terrorist attacks to military actions. In no circumstances, no matter how abnormal, can they be capable of releasing significant quantities of radioactivity into the biosphere.

• **End-Of-Operational Life And Plant Decommissioning.** Reactors of present interest must be capable of inexpensive, low-risk decommissioning at end-of-operational-life, which must be required no sooner than following a third-century – and perhaps a half-century or longer – of full-power-equivalent operation. Public safety (perceived and actual), resistance to materials diversion and ease of radwaste disposal during all phases of decommissioning are essential.

• **Public Perceptions.** The perceptions of the public regarding the suitability and desirability of nuclear power supply must be attended to, regardless of the closeness of connections with technical realities. In particular, the safety of all aspects of nuclear power generation must be made obvious to the general public, including the taking of risk-reducing steps which might not seem required from a technical standpoint and which might have non-negligible cost.

• **Economics.** Both the total unit energy cost and the energy production cost of nuclear electricity sources of present interest must be competitive with the best alternative fossil fuel-fired options.

**Resulting Basic Design Considerations.** We note that these constraints aren't linearly independent, in that more than one may be simultaneously satisfied by a single design choice and that some particular ways of satisfying one may conflict significantly with satisfying another. Generating optimal design solutions in such circumstances isn't a deterministic process, but may have something of the character of the knapsack-packing problem, in which relative (vs. absolute) optima are sought. We consider the two largest issues to be packed in the nuclear knapsack to the economic and public perceptual ones, and thus address them first.

**Underground Siting.** The public is rationally concerned about large, abrupt releases of radioactivity into the biosphere by nuclear power systems – and also is somewhat less reasonably worried about very small releases under quasi-steady state conditions. Precluding both of these – but particularly the former – is of the greatest important and moreover must be accomplished in an obvious fashion, so that confidence in it may be nearly universal. We therefore consider siting of reactors deep underground to be desirable to the point of necessity, moreover with only "long and slender," automatically-closed passages to the surface – and to the biosphere.¹ That large amounts of radioactivity cannot escape to the biosphere in the course of serious accidents from such locations may

¹We note that Andrei Sakharov independently reached this same basic conclusion in the aftermath of the Chernobyl accident, and strongly advocated underground siting of power reactors in his memoirs.
be made quite obvious. Such underground sites should also be made to be supportive of long-term "housing" of the reactor, after its operational life.

**Minimum-Essential Operator Controls.** All of the great accidents in nuclear power plants, without exception, have been due to maladroit control of the reactor by its human operators; operator malfeasance is also the primary factor in the larger number of much less serious accidents and incidents which erode public confidence. Therefore, we believe that it is essential that operator controls of reactors be reduced to the minimum essential ones, and that all possible uses of these should be incapable of inducing catastrophic reactor malfunction, one endangering public safety. This step, though seemingly a draconian one, should also markedly enhance public confidence regarding always-safe reactor performance.

**Life-Cycle-Oriented Design.** In order to be maximally economical, power reactors should be designed in a strongly life-cycle-oriented manner, with as much attention given to circumstances at and beyond end-of-operational-life and to initial construction as to the power-producing operation and maintenance interval. In particular, we believe that power reactors should be viewed as self-regulating, constant-temperature nuclear fission-powered heat sources which, once ignited, operate in a fully-automatic, highly-redundant homeostatic manner until either fuel exhaustion or commanded-shutdown occurs. We believe that a power reactor should be regarded – and designed – as a pressure vessel-clad fuel assembly with embedded power-regulating features and heat-removal features, supplemented by means for highly redundant, entirely automatic heat rejection into a "can't fail" heat-sink in the presumably rare events during operational life when heat-demand drops abruptly and by a very large factor – but also after final shutdown, when nuclear afterheat associated with longer-lived beta-decay of fission products must be reliably removed.

Furthermore – an admittedly radical step – we believe that the reactor should also be regarded – and designed – as the long-term-stable burial cask of all of the radwaste products which it generates throughout its entire operational life, so that once it is emplaced and its fuel charge ignited, it is not thereafter routinely maintained, disturbed or removed – for tens of millennia. Appropriate materials, optimally employed, can make this possible without large cost increments; indeed, we believe substantial life-cycle savings might be realized, relative to the LWR-centered nuclear fuel cycle, which is presently "unclosed" in most parts of the world.

**Inexpensive, Standardized Construction.** Mass production-oriented manufacture and emplacement/construction of standardized, extensively-evaluated nuclear power-plant designs is an essential feature of both economic and safe nuclear power systems, in our view. Design variability necessarily drives up design costs and reduces the attention that can be given to critical performance evaluation of any particular design. Mass production – an economically rational characteristic in a world in which an average of at least 1 GWe of electrical generating capacity must be added each week into the foreseeable future – of such standardized designs then can be focused effectively on both economic and reliability goal-sets.

**High Efficiency, High Power Density Operation.** Primary determinants, in our view, of the cost of a nuclear power reactor are its mass and volume; we are therefore interested in minimizing both of these parameters for a reference steady-state electric power production level. We thus look toward reasonably high thermal power density designs – ones having heat capacity adequate for safe response to power fluctuations but which also leverage fast-acting, fully-automatic, redundant temperature control features – that output relatively high-temperature coolant susceptible to high-efficiency thermal-to-
electric conversion. We see the use of high-performance materials (e.g., Ta-W alloys) as a key enabling materials technology for such reactors.

**Salient Features Of A Point-Design.** In the Appendix, we offer a conceptual-level point-design of a nuclear power reactor which we believe satisfies the constraints which we have stated above.² We recapitulate some of its salient features.

Use of a hard, or fast, neutron spectrum – not surprisingly, at least retrospectively – is apparently essential to simultaneous attainment of the goals of “no fuel reprocessing” and “no reactor re-fueling,” due to the strongly differing ratios of neutron radiative capture cross-sections for actinides and fission products at epithermal and at fission-spectrum neutron energies. This fast neutron-spectrum design choice in turn facilitates the extensive use of high-Z, highly refractory materials in the baseline reactor core design, for such materials have unacceptably large impacts on the neutron economy of any thermal-spectrum reactor, but are eminently affordable in neutronic terms when using a fission-spectrum. Use of such materials permit very high-temperature reactor operation, e.g., coolant exhaust temperatures of ~1200° K, which in turn admits the possibility of high-efficiency, combined-cycle thermal-to-electric conversion of the heat outputted by the reactor.

We were unable to design a reactor with an inherent exceedingly large thermal coefficient of neutronic reactivity (~0.2%/° K) over a narrow (ΔT ≤ 100° K) temperature range – and yet such great "stiffness" of reactivity with material temperature variation at all points within the reactor's core is necessary for stable high-temperature reactor operation required for efficient conversion of reactor heat to electricity and for essential, defeat-resistant operational safety. We therefore endowed the reactor core as a whole with such an engineered-in feature, using a 3-dimensional lattice of liquid-lithium-bulbed thermostats to control the local material temperature via negative feedback on "local reactivity" implemented with liquid Li, a strong absorber of even fast neutrons. The neutronic spacing of these control elements is design-specified to provide full redundancy, and the deliberately asymmetric on-off characteristics of each thermostating element provide both local and global nuclear power-production stability. The reactor thus acts as a source of nuclear-energized heat at a thermostat-specified high temperature at any heat-extraction rate up to its full-power rating, over any time-interval until its initial fuel-charge is exhausted or it is operator-commanded to shut down.

The distributed thermostat-conferred ability to stiffly and independently control reactivity at all points throughout the core on the basis of local material temperature enabled use of a rather novel propagating mode of nuclear fuel burn which is notably efficient (see detailed discussion below). Leveraging the notable superiority of a fission-spectrum neutron economy, this fuel-burning mode simultaneously permits high (>50%) average burn-ups of entirely unenriched actinide fuels – either natural uranium or thorium – and the use of a comparatively small "nuclear ignitor" region of moderate (sub-weapons-grade) isotopic enrichment in the geometric center of the core's fuel-charge.

We designed full triple redundancy in the primary core cooling, and provided automatically-actuated, fast-acting "hard" cut-offs of the cooling conduits connecting the deep-underground reactor vault with the heat engine-intensive electricity-generating plant on/near the Earth's surface. We also designed full

²Cf. [http://www-phys.llnl.gov/adv_energy_src/ICENE896.html](http://www-phys.llnl.gov/adv_energy_src/ICENE896.html), which documents an initial version of the material in the Appendix.
triple redundancy in secondary core cooling, including automatic actuation for the latter system which connects it into a "can't go away" engineered heat-sink in event of a core over-temperature condition. Emergency core cooling is therefore both simple and exceedingly robust – and, being fully automated, is not susceptible to being defeated by operator error, as it was at Three Mile Island (and also elsewhere). The secondary cooling system is the one which sinks into the "engineered heat-dump" the nuclear afterheat released after the reactor's final shutdown – heat which is thereby purposefully employed to ensure the long-term environmental stability of the sub-surface volume that contains the reactor vault-burial cask which thereafter serves as the final disposal site of the spent fuel.

We have suggested that this novel type of nuclear power reactor might be able to generate electricity at a total unit energy cost even less than that of top-of-the-line combined-cycle gas systems. It uses essentially unenriched, as-mined actinide isotopic fuels of all types, moreover using them to high burn-ups without reprocessing – and thus accesses a huge, near-zero-cost fuel stockpile, one widely distributed geographically and of a magnitude sufficient to supply the entire human race at current U.S. levels for many centuries. Since spent fuel from such reactors is intrinsically highly inaccessible, this type of reactor technology is therefore suitable for world-wide deployment, without rational concern for misuse of reactor products for military purposes.

We strongly suspect that many other designs – some significantly different from the one which we've explored – would also satisfy the constraints which we have suggested above are necessary-&-sufficient for universal acceptability of nuclear power. A priori, it is likely that at least a few of these designs will be markedly superior in some or even all respects to the specific design that we've considered. We urge our colleagues worldwide to pursue such prospects.

Conclusions. If global change is recognized as a real, largely-anthropogenic phenomenon and if suppression of CO₂ emissions into the atmosphere is the means chosen to palliate its effects, then either world-wide energy production will decrease (apparently, drastically) or else some major source of central-station generation – of heat and/or electricity – will be employed to fill the ever-expanding gap between growing energy demand (most especially in the developing world) and diminishing fossil fuel-based energy supply. At the present time, only nuclear fission-based central station technology is sufficiently industrially developed and operationally performance-proven to be a credible candidate for this gap-filler role.

However, nuclear fission power systems expressing current design, construction and operational practices have a substantial set of significant issues facing them. The aggregate effect of these issues has halted – indeed, has even reversed to varying extents – the penetration of electricity markets by nuclear fission technology in most of the developed countries. They seemingly must be satisfactorily addressed if nuclear fission-based power is to be other than a niche player in the 21st century energy picture, i.e., if there is to be a low-risk gap-filler between rising energy demand and constant-to-diminishing fossil fuel-fired energy supply.

In this paper, we have sketched what we believe to be satisfactory responses to these issues, and have given examples – detailed in the Appendix – of how these responses may be expressed in an actual design for 21st century nuclear power reactors. Indeed, we have attempted to convey in outline the technical bases for our belief that all issues facing nuclear power – including the compelling economic and public perceptual ones – may be simultaneously addressed.
We don’t assert that all of the issues that we’ve tabled will be universally regarded as of comparable importance, nor do we expect that all of the design approaches that we’ve developed will be seen by everyone as being equally applicable to local situations. We recognize that some combinations of design features will be seen as of greater applicability to specific needs and interests than others. We’ve attempted to sketch a path forward that addresses the rational concerns of all types that have paused nuclear fission-based electrification, expecting that differing weighting of such concerns may lead to a wide spectrum of particular design choices.
APPENDIX

OVERVIEW. As noted above, a fundamentally new design of nuclear fission power reactors for 21st century electricity generation applications is needed for at least four fundamental reasons: concerns about catastrophic-scale nuclear reactor accidents, the economically non-competitive posture of modern nuclear electricity relative to the best fossil-fired generation technology, worries about nuclear weaponry proliferation (via diversion of reactor products to make nuclear weapons), and the potential long-term shortage of nuclear fuel for high-intensity world-wide electrification.

An entirely fresh look at nuclear-energized large-scale power generation is called for, particularly in the light of rapidly increasing demand for electricity in the capital-poor Third World and growing concerns as to the environmental consequences of meeting this demand with fossil fuel-fired systems. It isn't at all clear that basic parameters of currently available types of nuclear power reactors will permit them to meet such demands.

This Appendix sketches a concept-level point-design of a full-scale member of a class of power reactors which we believe may be suitable for satisfying world-wide needs for electricity in the 21st century.

We consider a reactor serving as a ≤2 GW heat source for electric power production at the 1 GWe level, emplaced ~100 meters underground and operating for 30 years without human access after the start of power production, the purpose of such isolation being to avoid both error and misuse. The power plant's heat engine(s) and electrical generators are located above-ground, and are connected with the nuclear heat source by coolant conduits carrying high-temperature helium gas rather than water. Heat-to-electricity conversion efficiencies as high as 60% may be achieved by using such a reactor to drive a combined-cycle system centered on aeroderivative turbines (technologically descended from jet engines) similar to those already widely used in the most efficient natural gas-fueled generating stations (which have also been the economically pace-setting ones in the U.S., until the recent natural-gas price-spike).

Our current reference-design reactor contains a cylindrical core comprised of a small nuclear ignitor and a much larger nuclear burnwave-propagating region. The latter contains natural thorium or (possibly depleted) uranium fuel, and functions on the general principle of fast breeding. The entire core is surrounded by a neutron reflector and a radiation shield. Uniform temperature throughout the core is maintained by a redundant multiplicity of thermostating modules which, through the action of simple automatic controls transporting isotopically-enriched lithium when the local material temperature rises into the regime corresponding to a coolant-gas-temperature design-value of ~1000 K, regulate the local neutron flux and thereby control the local power production. Triply-redundant primary means of transporting heat up to the generating station are provided, and entirely independent, triply-redundant energy-dumping means are included in this design to passively transport afterheat out of the core in the event of a loss-of-coolant accident or after the end-of-operational-life.

When the core's initial loading of nuclear fuel is exhausted after a third- to half-century of full-power operation, the reactor is permanently shut down by the addition of a neutron absorber to the core. The core’s spent fuel is allowed to beta-decay in the reactor, which is designed to also
perform burial-cask service. The surrounding hot dry sand of the engineered heat-dump provides long-term protection against environmental conditions which might otherwise eventually induce leakage of residual radioactivity into the biosphere. [Thorium fuel utilization entirely precludes the generation of \( \text{Np}^{237} \), the only long-lived actinide isotope of biospheric contamination interest.]

**MOTIVATIONS OF THE PRESENT PAPER.** Nuclear reactors for central-station electricity generation do not currently enjoy widespread public acceptance in most technically advanced nations, even though they are objectively comparatively safe relative to alternate modes of generating equivalent quantities of energy for civil purposes. What is needed in present circumstances is that they be seen to be *obviously* safe.

Compared to other large-scale electrical energy sources, modern nuclear fission reactors are safe. Three Mile Island, the location of one of the two big malfunctions during the past two decades, saw an accident expensive in dollars and disastrous for the utility owner, but injurious to no one. The Chernobyl nuclear reactor accident was far more serious and did kill dozens of people outright (and perhaps hundreds of others, on a statistical basis). Nonetheless, the human-life-loss per kilowatt-hour of nuclear electricity generated over the past several decades is still far below the loss-of-life per kilowatt-hour arising from, e.g., coal-fired electricity generation over the same interval.

The remarkable fact about these two large-scale accidents is that both of them crucially involved human error in power plant operation, a contingency only little considered in the design of these systems. (In addition, the Chernobyl design was burdened with positive temperature- and void-coefficients of neutronic reactivity.) It is our opinion that such accidents can be ruled out satisfactorily if we can separate a functioning power reactor and its associated radioactivity from any human interference (following an extended interval of design-debugging and -optimization).

The first new design measure to achieve *obvious* safety is to construct power reactors underground. This has also been advocated vigorously by Andrei Sakharov, following similar reasoning. Logically, the reactor's mass-transporting connections to the surface also must be automatically and robustly shut down, in event of a major malfunction.

A second new design measure is to make the function of the reactor fully automatic and *obviously* safe from all types of human error. The exclusion of human access – and thus all types of close-up inadvertence – requires that the reactor fuel elements should not be replaced, that the reactor should normally function without human maintenance and that, after the conclusion of power production, the reactor and the fission products in its spent fuel should remain in place indefinitely. Indeed, present plans to collect reactor products at a safe central location has the intrinsic difficulty of hazards arising from accidents during the initial removal and storage and the subsequent transportation of the spent fuel assemblies.

We are therefore studying reactors which deliver high-grade (i.e., high-temperature) heat-on-demand. A reactor of interest must *automatically* deliver more thermal power when more electricity is demanded from the associated central station – and it must not overheat when the power demand is reduced.
A fundamental requirement for any practical power reactor is that it should be economically competitive. One aspect of this requirement is met by providing a high degree of intrinsic and obvious safety at low cost, so that expensive safety mechanisms, personnel and regulations become unnecessary. Another is to minimize operations-and-maintenance costs and a third is to achieve exceptionally high thermal-to-electric conversion efficiencies, so that nuclear heat attains highest-feasible economic value.

A critical consideration to be kept in mind is the recent rather drastic decrease in the cost of fossil-fired electricity generation due to technological advance. As noted above, during the past decade, electrical plants have been put into operation which work with 60% thermal efficiency and produce electricity with a total unit energy cost (TUEC) of $0.04 per kilowatt-hour, moreover in quite modest minimum sizes (e.g., a few tens of megawatts) and with environmental impacts (e.g., atmospheric and thermal pollution) which have already been reduced to remarkably low levels. This TUEC for such “combined-cycle” electricity is roughly half of that available from modern American nuclear power plants, which also produce twice as much waste heat per electrical kilowatt-hour. Advanced nuclear fission power reactors – and, indeed, all emerging nuclear energy sources – must be economically competitive with the best modern conventional alternatives. Moreover, the costs of these alternatives must be expected to decrease, as the new combined-cycle generation technology matures.

A second fundamental requirement is connected with the long-term availability of nuclear fuel. At present, 3000-4500 tonnes of uranium metal are required to fuel a single 1 GWe plant for a 30 year interval (depending on whether or not reprocessing is done). Sources of only 3 million tonnes of uranium metal are identified in the United States, unless the production cost of uranium metal is increased significantly over $100 per pound. Thus, fuel for 1000 GWe of nuclear power – roughly the present-day level of non-nuclear generating capacity in the U.S. – can be assured only for less than a half-century, unless breeder reactors are developed and deployed. Considering world-wide requirements and assuming an average per capita consumption of only one-third that of the U.S., a total electrical generating capacity of 10,000 GWe – i.e., 10 TWe – would be required. The known world-wide reserves of uranium ore accessible at $100/pound of uranium metal produced would suffice for LWR-based electric power production only for a modest fraction of a single century, accentuating the requirement for much more efficient use of nuclear fuel.

**GENERAL FEATURES OF THE NEW TYPE OF REACTOR.** Our work through the present time has focused on the conceptual-level design of a new type of nuclear power reactor aimed at simultaneously providing all these basic features and requirements which appear to be prerequisites for widespread nuclear electricity generation in the first half of the 21st century. Naturally, specifics must be considered if substantial progress is to be made. We are currently analyzing a baseline point-design of a representative member of this new type of power reactor from the standpoints of materials-and-structures, heat transfer and nucleonics, and have simulated its structural, thermal and nuclear performances with digital computer-based models. We present some interim results of these ongoing analyses. (The models themselves are discussed in Appendix 1.A.)
We consider primarily thorium-fueled reactors, for thorium is widely distributed geographically in high-grade ores, and is cheaply available. Such a reactor must be a breeder, for reasons of efficient nuclear fuel utilization and of minimization of requirements for isotopic enrichment. It must be a fast breeder because the high absorption cross-section of fission products for thermal neutrons does not permit the utilization of more than about 1% of thorium (or of the more abundant uranium isotope, $^{238}\text{U}$, in uranium-fueled versions), without removal of fission products. The pertinent neutron cross-sections are shown in Figures 1 and 2.

The conventional approach is to remove fission products by reprocessing or by actively transporting the fission products away from the nuclear reaction zone. This requires human intervention, which we wish to exclude entirely or, alternatively, relatively complicated arrangements of uncertain reliability or safety. Diversion of fissile materials to military purposes is a risk inescapably associated with either the intermittent or continuous reprocessing of nuclear fuel. [Also, closing nuclear fuel cycles via reprocessing and obviously safe long-term storage of fission products has yet to enjoy universal satisfaction, even in most of the technologically advanced countries.]

We are considering designs in which the nuclear reactions are driven primarily by fast neutrons, most of which have energies within a factor-of-ten of the MeV-scale temperatures at which they are evaporated from nascent fission fragments. Several substantial advantages are thereby obtained. First, the pertinent ratios of cross-sections are much more favorable to breeding, and thus to a potentially high fuel burn-up. Second, the preferred structural materials, such as Nb and Ta, have relatively small absorptions at these high neutron energies, so that comparatively large amounts of them may be employed without imposing significant damage on the reactor core’s neutron economy. Third, the net neutron multiplicity of fission is significantly greater than the breeding threshold-value of 2.0 at fission neutron energies than it is at thermal neutron energies, and notably so for $^{233}\text{U}$. Fourth, neutron-engendering processes peculiar to fast neutrons, such as fast fission of $^{232}\text{Th}$ and $^{238}\text{U}$ and $(n,Xn)$ reactions on all actinides, while each relatively unimportant, collectively contribute non-negligibly to the overall neutron economy of fast reactor systems.

We are therefore now investigating the extent to which this general type of design permits the simultaneous attainment of one-time fueling with low average enrichment materials for a third-to half-century of full-power production and of obvious great safety margins.

**FUNDAMENTAL FEATURES OF THE REACTOR CORE.** Our analyses have led us to provisionally conclude that this new type of power reactor in a 1 GWe-scale format will be a right circular cylinder of approximately 3 meters diameter and 10-15 meters length (corresponding to 0.33-0.5 centuries of full-power operation). This core basically consists of a small nuclear ignition region containing fuel enriched in $^{235}\text{U}$ (albeit not to an extent supportive of diversion to assembly of a nuclear weapon), embedded in a much larger {breeding+burning} section containing $^{238}\text{U}$ (either natural or depleted uranium) or, preferably, $^{232}\text{Th}$. Core-averaged fissile isotopic content (e.g., $\sim$0.5-1% by mass) is comparable to that of natural uranium. This, together with the feasibility of very high average fuel burn-up in the designs which we consider (e.g., 50%), indicates a total requirement for $\sim$100 tonnes (rather than 3000-4500 tonnes) of as-mined fuel for a 1 GWe reactor's third-century of full-power operational life. Core nuclear physics and engineering nucleonics are discussed in Appendix 1.B.
As core coolant, we propose to employ pressurized helium, rather than water. This permits the utilization of thermal energy at substantially higher temperature, avoids all hazards arising from water reactions with high-temperature materials, and provides favorable independence of the core’s neutronic reactivity on coolant-voiding. Key features of the core’s coolant system are shown in Figure 3. Core thermal transport issues are also discussed in Appendix 1.C.

Reactor core construction materials, e.g., Nb, Ta, W and Re, are widely available. They are chosen primarily for their superior long-term, high-temperature mechanical and chemical properties, which are retained to adequate extents under large fluences of high-energy neutrons. Core structural design issues also are treated in Appendix 1.C.

Management of nuclear power production in the reactor's core is fully automatic in all respects, over the entire third- to half-century interval between nuclear ignition and final core shutdown at the power plant's end-of-operational-life. Participation of human operators is needed only at the commencement of the core's ignition and at the final, irreversible negation of its reactivity.

Fully automatic regulation of nuclear power production is performed by uniformly distributed, functionally fully-redundant thermostating modules. Each of these acts to absorb strongly the local neutron flux when the local material temperature exceeds the design-value, thereby quenching local nuclear power production and assuring thermal homeostasis of every portion of the core, over wide ranges of coolant flow and temperature, fuel composition, neutron spectrum and neutron flux. Each thermostating module acts by reversibly inserting neutron-avid liquid Li$_6$ into a small (<100 cm$^3$) compartment located in the coolant-flow from a source outside the neutron reflector, under the drive action of a thermostating bulb filled with neutron-indifferent liquid Li$_7$ which is emplaced in adjacent, substantially hotter nuclear fuel. A 3-D lattice of such thermostating modules, each functionally-independent from all of its fellows and emplaced during manufacture throughout the core, serves to regulate the matter temperatures everywhere, at all times. See Figure 4.

**REACTOR CORE OPERATION UNDER NORMAL CONDITIONS.** At the commencement of the reactor's operational life, the centrally-positioned nuclear ignitor module is driven critical by one-time removal of neutronic poison and, through concurrent nuclear fission and high-gain breeding actions, commences to launch a nuclear deflagration wave into the adjacent unenriched fuel. This wave first diverges radially from the centrally positioned, on-axis nuclear ignitor until portions of it reach the outer edge of the cylindrical fuel mass, where it is resolved into two oppositely-directed, axially-propagating waves. One such wave moves toward each of the two ends of the cylindrical core at a (exceedingly low peak) speed determined at all times by the instantaneous thermal power demand on the reactor (and upper-bounded by the leisurely beta-decay of Pa$^{233}$/Np$^{239}$, the rate-limiting step in Th$^{232}$-U$^{233}/$U$^{238}$-Pu$^{239}$ breeding). When only very low power is demanded, the neutronic reactivity is driven to zero by action of the thermostatic controls, and the deflagration-wave stalls; when heat is removed from the core at a greater rate, the thermostating controls cool and thus raise the neutronic reactivity to slightly positive levels, and the [burning+breeding] wave re-commences its advance.

Fuel moderately enriched in fissile material is generated behind each of the two wave-fronts. These two increasing masses of enriched fuel then continue to burn, until fission product
accumulation and fertile isotopic depletion (at >50% core-averaged fuel burn-up, in high-burn-up core design-variants) finally drives the core's neutronic reactivity negative. Figure 5 illustrates typical conditions ahead of, within, and behind this pair of nuclear deflagration waves, and Appendix 1.B discusses core nucleonics in more detail.

Heat from the burning fuel is removed from the reactor and transported to the surface by a coolant-flow consisting of pressurized helium-gas. The helium is circulated axially through the core of the reactor by a 2-D hexagonal lattice of pipes, as depicted in Figure 3. The nuclear fuel is emplaced between the pipes and transfers heat to them by thermal conduction, whereupon it heats the circulating helium. The coolant loops are designed with complete three-fold redundancy and, under normal operating conditions, are actively powered by pumps at the power plant’s heat-engine. The primary in-core structure of the reactor is the array of coolant pipes; these are currently planned to be constituted of a tantalum alloy in order to achieve the required long-term, high temperature creep resistance. The entire reactor is emplaced within a containment vessel which, because it is located outside the hot, neutron-rich core, can be implemented with a conventional high-quality steel alloy. Details are discussed in Appendix 1.C, and key features are depicted in Figures 3 and 6.

From an operational standpoint, the reactor, which is emplaced deep (e.g., ≥100 meters) underground to provide a substantial additional measure of biospheric safety, is fully automated. As already noted, no operator controls of any kind are provided, other than the one to start the reactor up initially and another one to finally shut it down after a third- to half-century of (nominally, full-)power production – supplemented by a zero-power-demanding control feature to support emergency accessing of the reactor compartment. Fuel is loaded into the reactor only when its core is built, and spent fuel is never removed from it. The reactor is designed to be maintenance-free, never to be accessed after it first commences operation. Requirements for specially-trained, nuclear-cognizant personnel during plant operation are thus strictly minimized.

**REACTOR CORE BEHAVIOR UNDER ABNORMAL CONDITIONS.** The ability of each of the set-of-three independent primary coolant loops to remove the thermal power from the reactor’s core naturally invites partitioning of the coolant conduits and the heat engines on the surface into three distinct modules, each capable of entirely adequate core cooling. Doing so drastically reduces the likelihood of a common-mode loss-of-coolant accident, relative to the likelihood of such events in typical reactors.

Independent of this triply-redundant primary cooling, a further large safety margin is provided by fully automatic, entirely passive rejection of nuclear afterheat into the underground environment surrounding the reactor, via another triply-redundant set of coolant loops within which the coolant is convected entirely passively. The engineered heat-dump into which the heat is transported is design-rated to accept the full-power afterheat of the reactor for an indefinitely long duration, and is described in Appendix 1.D.

Thus we design to preclude core damage due to excessive temperature, both in the course of arbitrarily severe loss-of-coolant accidents during full-power operation and in a zero-maintenance scenario following final reactor shutdown, in an extremely reliable, six-fold redundant manner. See Figure 6.
Nuclear afterheat will be removed during loss-of-coolant accidents and after end-of-operational-life using the same basic method (convection by gaseous helium) as during normal full-power operation. We constrain our design very conservatively by the assumption that none of the three independent primary coolant loops nor any of their circulating pumps will be available in these two circumstances. To perform appropriately in such situations, we provide a second coolant system, as indicated in Figures 3 and 6. This secondary, entirely independent coolant system consists, as did the primary system, of a triply-redundant array of cooling loops. Helium coolant-gas is circulated at sufficient rates through these pipes by a passive thermosyphon, whose driving pressure head is simply due to the fact that the reactor is emplaced below the engineered heat dump to which the afterheat is rejected for indefinitely long periods. Details are provided in Appendix 1.D.

Redundant, engineered, one-time-operation coolant pipe closures act to robustly seal off the reactor from the biosphere, either under operator direction at end-of-operational-life or automatically in the event of large-scale fission product entrainment in the coolant-gas stream, functionally backing-up automatically actuated mechanical valves. These are described in Appendix 1.E.

**REACTOR DECOMMISSIONING CONSIDERATIONS.** The reactor vessel, positioned in the engineered heat-dump, serves as the spent-fuel burial cask. The core's post-end-of-life afterheat is passively transported through the triply-redundant, passively-convected coolant loops and coupled into a highly redundant network of heat pipes threading throughout the surrounding engineered heat-dump. Indeed, the operation of this engineered heat-dump after final shutdown serves to generate a ~100 meter-diameter "bubble" of hot, dry sand around the reactor vessel. This spatially-extensive engineered heat-dump, described in Appendix 1.D, also serves to decouple the reactor vessel from the ambient groundwater environment, thereby ensuring the vessel's long-term mechanical integrity and thus its suitability as the burial cask for the spent fuel.

Active measures to decommission the reactor and to remove spent fuel from its core (including several tonnes of residual fissile material) are thereby completely obviated. Burial cask integrity is ensured for multi-millennia intervals, sufficient to see total beta activity in the core decay by a million-fold, to residual levels much less than 10 kilocuries.

**DESIGN VARIANTS.** This new type of power reactor has a great deal of inherent variability implicit in its design. We have emphasized a particular design variant with great inherent safety realized by automatic power control and afterheat removal. Moreover, we have focused attention on one which generates high-temperature heat, believing that a unit of 1000 K heat indeed has an economic worth twice that of a thermal unit at the 600 K temperature typically delivered by LWRs, and that the likely-somewhat-greater costs of a high-temperature heat-supply will be significantly exceeded by the assuredly-greater economic benefits of combined-cycle generation.
It must be noted that major variations on the fundamental theme sketched above likely are feasible. For instance, we have evaluated a 600 K water-heating design (of appropriately minimized intra-core coolant volume) which functions in nucleonic, structural and most heat transfer senses quite similarly to the helium-heating one just discussed. We have also examined uranium-fueled cores, and have verified that they function basically the same as thorium-fueled ones in nucleonic senses (though the latter have superior high-temperature mechanical properties, avoiding Pu and its low melting-point).

A major design variable is the peak specific fuel power. For a typical thorium-fueled core design with our baseline peak fuel specific power of 200 W/gm, we pre-expand the metallic fuel by 3-to 4-fold above its full-density specific volume, i.e., so that the initial mean fuel density is 3-4 gm/cm³. (Doing so lowers the intra-fuel peak pressure occurring at maximum burnup, albeit at some loss in the fuel's thermal transport qualities, and lowers worst-case structural requirements.) Operating at lower peak specific power in the fuel or with significantly different initial fuel mean density offers the prospect of reactor cores – and thus reactors – of quite different configurations.

It’s also quite feasible to operate with much lower fuel burn-ups than the remarkably high ones of our baseline designs. The neutronics of such cores are more congenial than those of high burn-up, high fission-product density cores – although the total fuel volumes and masses usually are substantially larger in the generally much less compact cores (e.g., in cores in which greater designed-in leakage or absorption drives the deflagration wave forward at higher speeds). The principal disadvantages of such designs are that fuel utilization efficiencies are necessarily lower, and mean isotopic enrichments are higher (as the ignitor masses tend to be relatively larger).

In summary, this new type of nuclear power reactor is remarkably rich in design possibilities.

**SOME NATIONAL ENERGY STRATEGY CONSIDERATIONS.** From a national energy systems standpoint, reactors of this new type act to supply high-temperature heat-on-demand throughout their entire operational lives, and thus constitute a base for reliable, large-scale electrical energy supply at a predictable, capped cost over multi-decade intervals. Since they have no day-to-day operator controls and are never re-fueled or serviced, they generate no requirements for highly-trained personnel or special materials (e.g., enriched fuel) after they first commence operation. Their exceptionally efficient use of unenriched fissionable material – thorium or natural (or depleted) uranium – obviates all long-term fuel supply issues. Each such 1 GWe reactor uses (in its ignitor) only ~0.0001 of the fissile material – enriched uranium – already in international commerce.

Since they are never re-fueled, these new types of reactors present no spent-fuel handling, transport, reprocessing, or disposal issues, and they greatly reduce military diversion concerns. This last point may be of the greatest importance.

The high-grade, high-pressure heat produced-on-demand by this new type of reactor is intended to support combined-cycle electricity generation, with its especially favorable economic and environmental impact indices, e.g., half of the TUEC for electricity and half of the waste heat rejected to the environment of modern LWRs.
Because of its extraordinarily great, multi-layered set of safety features, this new type of reactor may ultimately be suitable for underground siting in urbanized areas. Such siting would also substantially reduce capital charges for transmission systems, as well as make reasonably high-grade waste heat readily available, e.g., for space heating and cooling applications.

**MATERIALS AVAILABILITY AND COST CONSIDERATIONS.** High quality manufacture of this new type of power reactor, either for indigenous use or for export, is within the capabilities of any technologically developed country. Fuel cladding and intra-core coolant piping materials used in ~25 tonne total quantities per 1 GWe core may have to be imported, but these materials are available from multiple commercial sources at a cost of ~$1.5 M.

Moderately enriched uranium for use in the ignitor modules of reactor cores can be competitively procured in any needed quantity from Russian, European or American sources by any NPT-member nation, at a cost of the order of $1 M. Enriched lithium isotopes for use in filling the thermostating modules are similarly available in pertinent quantities, at a cost of ~$0.5 M. The ~75 tonnes of natural uranium or thorium required to comprise the main fuel charge of a 2 GW, half-century full-power core are readily available on the international market for a total present-day cost of ~$3 M. Fabrication costs are typically 10X basic materials costs, but may be ~20X for these unusual materials. The cost of the core’s ~100 m³ stainless steel pressure-vessel cost is estimated at ~$20 M, and the projected serial-production unit cost of its 1000 Li-loaded thermostats is ~$3 K. The estimated reactor {core+vessel} cost thus is ≤$150 M, using a 20X materials cost-multiplier. External coolant {piping+pumps+closures}, heat-dump, diagnostics, etc., can be expected to aggregate to a few-fold this reactor {core+vessel} cost, but the total marginal cost-to-create this high-grade nuclear heat-source rather confidently can be expected to be <$1/We, i.e., a contribution to the TUEC from it over the following third-century of ≤$0.01/kWe-hr.

**SOME ECONOMIC CONSIDERATIONS.** At the present time, the economic pace-setting technology for large-scale central station electricity production is natural gas-fired combined-cycle generation. The typical total unit energy cost (TUEC) of such conventionally-generated electricity was ~$0.04 per kilowatt-hour in the U.S., prior to the natural gas price-surge of the past year or so. Of this amount, approximately $0.010 represents capital costs, $0.004 is attributed to operations and maintenance, and ~$0.025 was expended to buy the natural gas fuel.

According to our present estimates (see above), the additional capital cost-equivalent of the new type of nuclear heat source (≤$0.010 per kWe-hr) will be comparable to the $0.010 per kW-hr capital cost-equivalent of a gas-fired, combined-cycle turboalternator system. Thus, the total capital charges of a combined-cycle central station energized by the new type of reactor will contribute a total of ~$0.020 per kW-hr to the TUEC; the already-minor cost contribution due to operations and maintenance ($0.004 per kW-hr) is likely to be reduced by substitution of a closed helium gas-stream for an open natural-gas combustion one. The principal avoided-cost of the new type nuclear reactor-energized variant relative to the gas-fired variant of combined-cycle generation would be the dominating one of the natural gas fuel-cost; in profound contrast, initial nuclear fuel costs are capitalized and nuclear refueling costs would be zero, as refueling is
never done. (The capital cost of the system to reliably dump afterheat is a small fraction of total plant capital costs, as noted above.) Thus, the recent-past pace-setting TUEC of $0.04 per kWe-hr for combined-cycle gas-fired generation – which is currently ~$0.07 kWe-hr, due to sharp gas price increases -- may be decreased to less than $0.03 per kWe-hr for this nuclear-energized combined-cycle electricity.

However, careful engineering and economic analysis of a complete design will be necessary to develop significant confidence in these estimates. Working with additional collaborators, we hope soon to have a reasonably detailed design available for consideration by the entire nuclear engineering community.

CONCLUSIONS. Large-scale, central-station electricity production using nuclear heat sources has become a net-unattractive prospect in a number of technically advanced countries. This situation has persisted for two decades in some cases, and has even driven de-nuclearization political decisions in Germany and Sweden. It is perhaps not a severe exaggeration to suggest that the crisis facing nuclear power is a fundamental, structural one, compounded of substantial technical and economic components. Even more crucial is the need to deal with public perception.

If popular opinion is to accept – let alone invite – re-introduction of nuclear power generation in the majority of the technically-advanced nations, the several existing and largely independent arguments against its usage must be effectively answered. Minor variations on widely deployed nuclear power technologies may not suffice.

In token of the seriousness with which we view the current situation, we are attempting to develop one such fundamentally new approach, which we have sketched above. In a number of salient respects, it substantially simplifies the obviously safe winning of high-temperature heat from nuclear power reactors for use in modern heat-engines. See Figure 7.

This new approach offers the prospect of assured proper reactor utilization not just when the best-trained and most highly-motivated technicians are its operators, but also when the least-trained and most careless operators may be in charge. It permits nuclear power generation capabilities to be made available with high confidence regarding materials diversion to countries which may not have highly stable political arrangements. It fully addresses nuclear fuel supply issues, even when intensive, world-wide nuclear electrification is considered. It potentially doubles the economic value of a unit of nuclear-derived heat, by delivering it at substantially higher temperature for conversion to electricity with combined-cycle technology. We expect that this set-of-features may significantly lower both the economic and the non-economic costs of long-term, large-scale nuclear electricity production, reducing such costs to highly competitive levels.

Consequently, we believe that this new approach, or one basically similar to it, may satisfy via nuclear power much of humanity’s requirements for electricity in the 21st century. Indeed, some such novel approach may be necessary, if nuclear power is to fulfill its potential.
Appendix 1.A: Modeling

In order to investigate and quantify physical-technological feasibility, we have employed digital computer-based performance simulation of several different types of models of the new class of reactors which we discuss. These models support detailed studies of the nucleonics, the structural and the heat-transport aspects of reactor functioning.

NUCLEONICS. For maximum design flexibility and fidelity-of-modeling, we have examined the neutron transport and nuclear reactions in our model reactor designs with Monte Carlo-based means. To perform this function, we have employed the general-purpose TART95 neutron and gamma-ray three-dimensional transport- and reaction-modeling code-set developed and distributed by the Lawrence Livermore National Laboratory (LLNL). This software package represents a development effort whose scale is of the order of $10^2$ man-years and an associated code-validation effort of the order of $10^3$ man-years in size. TART95 and its ancestors have very frequently been employed for calculation of the reactivity of critical assemblies. However, they lack time-dependence, in that they generate snapshots-in-time of the transport phenomena which they model. We have used the latest-released version of the LLNL ENDF (Evaluated Nuclear Data Library) as the physical data source for this code, which we have employed exclusively in the 175 neutron energy-group mode, with TART95's most recently upgraded thermal scattering and resonance cross-section multi-band-averaging features.

Model reactor designs in our studies are resolved into several hundred spatial zones, usually possessing axial symmetry, and a few hundred different materials. Sixteen isotopes are usually carried in each zone, representing both fertile and fissile isotopic components of nuclear fuel, in addition to reflector and coolant elements, structural materials, and various neutronic poisons (including fission products, carried as an ENDF-standard mix). Thus we ensure proper reactivity dependence on temperature and accurate representation of the course of long-term, possibly high fuel-burnup reactor operation. Our models often employ homogenized materials, whenever the physical scale-lengths of different materials are less than or equal to neutronic mean-free-paths for neutron energies of interest. Indeed, we constrain zone dimensions to be less than a neutronic mean-free-path for any principal reaction (e.g., radiative capture or fission), over the entire neutron spectrum of interest. We employ different spatial zones, many carrying a unique material composition, in our models to account for substantially different material (or isotopic) compositions throughout the reactor.

The behavior of the isotopic fractions in each zone of a model problem are integrated in time with a fourth-order Runge-Kutta integration scheme, which couples the standard fissile and fertile isotopes of the actinide elements to each other and to fission products, using the reaction rates just calculated for the conditions in each of the spatial zones of the problem by TART95. (We typically follow ~155 neutron-driven reactions in each zone, including all fission, radiative capture, elastic and inelastic scattering, (n,Xn), (n,p), (n,d), (n,t), and (n,a) reactions, each in a properly energy-dependent manner, whenever the corresponding cross-sections are at-or-above the 0.01 millibarn level.) Neutron absorption on all non-actinide isotopes is implicitly accounted
for. The newly-updated isotopic abundances in each zone are then inputted as a newly-reformulated “problem” to the TART95 code for another cycle of neutron transport and reaction calculations, thereby completing the basic set of operations of a single integration time-step.

The magnitude of the time-step of the kinetics integration is determined by the maximum permitted fractional change (usually 5-10%) in any of the major isotopic concentrations in any zone of the problem. (As would be expected, this 'critical value' is typically the fissile isotopic or the fission product concentration in the leading edge of the nuclear deflagration-wave propagating into the unenriched fuel-charge.) Between 150 and 500 time-steps suffice for an integration simulating 3 decades of reactor operation, depending on choices made regarding initial conditions and time-step controls.

The top level of our nucleonics modeling program-set, which we call BURNBRED (for 'burn' and 'breed'), combines the TART95 neutron transport-and-reaction package with the isotope kinetics integration package, and provides input, control and editing functions. For the present study, it has been hosted on an IBM-type personal computer (IBM PC) system. A model run for GW-scale reactors of ~250 materials, ~400 zones and 16 isotopes per zone operating over a simulated 3 decades requires 30-100 hours of computing time. In one simulation, several trillion floating-point arithmetic operations are performed and several billion bytes of intermediate neutronic reaction data-sets are processed using the computing system's hard-disk memory.

Such calculations often include use of a heat-transport feature in the BURNBRED package which permits the modeling of thermostatic module control of the time-dependent neutronic reactivity variation of the reactor's core, relative to a priori specifications of coolant flow through the core.

While time-dependent reactor modeling by our Monte Carlo-based approach would certainly be an extravagant expenditure of computing resources by standards of even a decade ago, the total [capital+operating (electricity)] costs of a single few-day-long calculation on our modern PC is of the order of $3. The human time-to-assimilate the results of such a problem-run and specify the design of the next problem to be modeled is usually not much smaller than the duration of the run itself; thus a far faster computer could not be effectively employed. Indeed, the computing system which we employed for much of this work (centered on a Pentium 166 MHz chip interfaced to 512 Kbytes of pipeline-burst cache memory) has been benchmarked to be roughly twice as fast as a single CPU of the fastest supercomputer generally available, the CRAY-YMP, when executing the extremely memory-reference-rich and highly scalar (e.g., branch-intensive) instruction-sequences characteristic of our modeling tool-set.

**STRUCTURES AND HEAT TRANSFER.** The present baseline-design core configurations, discussed in Appendix 1.C, have been largely designed and analyzed with semi-analytic methods organized into spreadsheets.

These analyses determine the coolant pumping requirements by balancing the fluid drag in the coolant-tubes threading the core's fuel-charge (which tubes dominate total loop losses) against the available pressure-head. The fluid drag is modeled using turbulent pipe friction formulae, while the pressure-heads are either specified (for the pumped primary coolant flow) or calculated.
(for the thermosyphoned secondary coolant flow) from the thermal-gradient-derived density profiles.

The heat transfer from the fuel into the coolant pipes is studied with finite element codes (discussed below). These detailed results are then scaled with size and power levels for use in the design-&-analysis spreadsheets. The transfer of heat from a pipe wall into the coolant-stream is calculated using turbulent boundary-layer heat-transfer coefficients.

The stress levels encountered in the coolant tubes are readily found, once the pressures and wall thicknesses are known. The former are determined by the pumping-power analysis just sketched, while the amount of tube-wall material is limited to levels that can be tolerated within the core's neutron economy.

These relations are then combined to develop and analyze specific reactor designs. The coolant mass-flows required are set by the inlet and outlet temperatures, while the size-scale of the coolant tubes is determined by the desired temperature drop across the fuel (i.e., from its hottest point to the nearest coolant-tube wall). The aggregate area of coolant tubes and the fuel's specific volume are set by desired values of the overall neutronic thickness of the fuel-charge (i.e., the core fuel-charge's density-radius product) and the peak temperatures of the coolant-pipe material. These factors then determine the inlet pressures needed in both the primary and secondary loops in order to circulate the coolant. These pressures and the quantities of coolant-pipe material available dictate the stress levels in the pipe walls.

The transfer of heat from the porous, burning fuel-charge into the coolant-pipes threading through it is studied with detailed finite-element thermal codes. These analyses employ volumetric heat production in the fuel, thermally nonlinear conduction through the fuel and the walls of the coolant tubes, and boundary-layer heat-transfer coefficients to finally deliver the heat into the bulk of the coolant-gas. These detailed analyses are particularly useful when considering the performance of the 2-D lattice of coolant-tubes during situations when some of the loops comprising the lattice are inoperative.

The structural behavior of the present array of fuel and coolant-gas tubes is straightforward; the coolant tubes are cylindrical and their stresses can be found analytically. Other, earlier designs which we have considered involved coolant tubes and fuel configurations with much more complex cross-sections; these systems have been studied with coupled thermal and mechanical finite-element codes. These codes remain available for more detailed analyses of future reactor designs, whether these are based upon the present simple configurations or are ones utilizing more complex layouts.
Appendix 1.B: Nuclear Physics and Nucleonics

Pertinent Nuclear Physics. The propagation of burning waves in combustible materials likely has been of fundamental human interest since the rise of the species. Ordinary chemical combustion, involving the release of $\leq 10^{-10}$ of the rest energy of certain types and configurations of matter as a deflagration wave is passed through it, has been a prime foundation-stone of all human culture and, lately, civilization. Chemical detonation waves, involving combustion energy release on time-scales (usually much) less than that in which a sound-wave would pass over the pre-release material configuration, have been a central feature of large-scale armed conflict during the past half-millennium.

Quite recently, burning-waves powered by nuclear processes have come within human grasp. Detonation of remarkably small masses of actinide elements highly enriched in rare or short-lived isotopes permit the release of $\leq 10^{-3}$ of the rest energy, and has been central to military preparations of the past half-century in the more technically advanced human cultures.\(^3\) Use of actinide fission-powered detonations to launch detonation waves powered by nuclear fusion reactions in configurations of very light elements similarly enriched in rare or short-lived isotopes has permitted the release of $\leq 3\times10^{-3}$ of rest energy,\(^4\) moreover in configurations of potentially unlimited mass and physical scale.\(^5\) (Indeed, these recent technical capabilities are sometimes suggested to have rendered impractical large-scale armed conflict between advanced cultures.\(^6\))

Means for extracting larger fractions of rest energy from matter under any circumstances – e.g., gravitational engines\(^7\) – continue to appear well beyond contemporary human reach. More disappointingly, attaining wave-mediated rest mass conversion from nuclear reactions, either fission or fusion, within 'practical' constraints and on the scales suitable for powering human civilization, have seemed to lie at least slightly beyond reach through the present. This latter capability presently appears to within human grasp, and is the subject of this section.

\(^3\)See, e.g., G. Goncherov, “Thermonuclear Milestones,” *Physics Today* 44-61 (Amer. Inst. of Physics, Nov. 1996), for a Russian viewpoint. A comparably authoritative history from a Western viewpoint has yet to appear in open publication, due to classification restrictions.


Nuclear Detonation and Deflagration Waves. Propagation of burning-waves through combustible materials has the fundamentally attractive feature of releasing power at an *a priori* predictable level; moreover, if the material configuration has the requisite time-invariant features, the ensuing power production may be at a steady level. Finally, if wave propagation-speed may be externally modulated in a practical manner, the energy release-rate and thus power production may be controlled as desired.

However, nuclear combustion waves which burn fuel with high efficiency, i.e., into isotopic depletion, characteristically release ~10^{-3} of the material's rest mass, or ~10^{18} ergs/gram, and the sound-speed in such combusted material is characteristically \((10^{-3})^{1/2} \approx 3 \times 10^{-2}\) of lightspeed, i.e., ~10^{9} cm/sec. Now, the largest single heat sources which humans conveniently use in the present era are ~10 GW, or 10^{17} ergs/sec, corresponding to 10^{-1} grams/sec of nuclear fuel being combusted at high efficiency. Thus, a 'string' of nuclear fuel of \(\{10^{-1} \text{ gm sec}^{-1}/10^{9} \text{ cm sec}^{-1}\}\), or 10^{-10} gm/cm would be required to be inputted into a nuclear combustion unit, if combustion at the largest practical scales were to be performed by a single nuclear detonation wave. It is not trivial to continually input such a fuel string to a combustion site at effective speeds of 10^{9} cm/second and it is difficult to understand how to radially compress the string sufficiently strongly to support wave propagation, the requirements of nuclear detonation physics considered.

Specifically, even a string of equimolar deuterium-tritium mixture, a material which supports nuclear detonation wave-propagation more readily than any other, requires a minimum density-radius product of ~1 gm/cm², in order that nuclear reactions may proceed to a propagation-adequate extent before radial hydrodynamic rarefaction quenches post-detonation temperatures and causes the wave's axial propagation to stall. A DT string would have to be compressed to ~10^{10} gm/cm³ density in a 10^{-10} cm radius fuel-string in order to satisfy the current requirement, a technologically daunting specification. In marked contrast, a 'string' of typical fissile material (e.g., U^{235}, Pu^{239}) must have a density-radius product ~10^2 gm/cm² in order to propagate a detonation wave; assembling such a string would clearly be even more daunting than in the DT case and, indeed, would require far more energy than is available from the corresponding fission energy release, even if the necessary compression were to be done adiabatically on a zero-temperature isentrope, doing hydrodynamic work only against the pressure of Fermi-degenerate electrons. Steady-state nuclear detonation waves therefore appear fundamentally unattractive for power production in the context of current human technology.

Nuclear deflagration waves are rare in nature, due to the non-trivial requirement to prevent the initial nuclear fuel configuration from disassembling as a hydrodynamic consequence of energy release during the earliest phases of wave propagation. Gravitational confinement and configuration-maintenance of the nuclear fuel comprises the only known schema. The best known example of a naturally-occurring nuclear deflagration wave is the 'Hiyashi flash' marking the onset of the red giant phase of stellar evolution, during which a radially diverging nuclear deflagration wave propagates in a grossly sub-sonic manner outward from its ignition site in a

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hydrogen-exhausted stellar core, burning He$^4$ in extremely temperature-sensitive albeit nearly isobaric circumstances – i.e., quasi-statically – to form C$^{12}$.

It is the basic purpose of the present section to point out that it is apparently quite feasible to initiate and propagate a nuclear deflagration wave in easily-accessible terrestrial circumstances, moreover in a high fuel-efficiency manner. Interestingly enough, the nuclear fission-powered deflagration waves of present interest, like the Hiyashi flashing of Fermi-degenerate thermonuclear fuel in red giants, also propagates in a grossly sub-sonic manner, moreover in fissionable fuel whose pressure also is essentially independent of its temperature, so that its hydrodynamics is likewise ‘clamped’. It thus seems feasible to control this wave’s propagation speed in a manner conducive to large-scale civilian power generation, e.g., in an electricity-producing reactor system.

**Neutronics, Beta-Decay and 'Glacial' Deflagration Wave Motion in Actinides.** That nuclear fission of selected isotopes of the actinide elements – the *fissile* ones – can be induced by capture of neutrons of any energy permits the release of nuclear binding energy at any material temperature, including arbitrarily low ones. That nuclear fission of essentially any actinide isotope releases more than a single neutron per neutron captured, on the average, admits the possibility-in-principle of a diverging neutron-mediated nuclear-fission chain reaction in such materials. That nuclear fission by some actinide isotopes releases more than two neutrons for every neutron which is captured (over certain neutron-energy ranges, on the average) admits the possibility-in-principle of first converting an atom of a non-fissile isotope to a fissile one (via neutron capture and subsequent beta-decay) by an initial neutron capture, and then of neutron-fissioning the nucleus of the newly-created fissile isotope in the course of a second neutron capture.

There is thus the possibility of two distinct types of nuclear burning of actinide elements: [1] the relatively rare fissile isotopes may be combusted, even in neutronically lossy circumstances, merely by arranging for at least one neutron resulting from the neutron-induced fission of such a nucleus to subsequently induce another fission; [2] most really high-Z ($Z \geq 90$) nuclear species can be combusted, if arrangements can be made for, on the average, one neutron from a given nuclear fission event to radiatively capture on a non-fissile-but-'fertile' nucleus which will then convert (e.g., via beta-decay) into a fissile nucleus and a second neutron from the same fission event to capture on a fissile nucleus and to induce fission. In particular, if either of these arrangements can be made to be a steady-state one, then sufficient conditions for propagating a nuclear deflagration wave in the given material have been satisfied.

The first case, if not made to be a steady-state one via appropriate control of its neutron economy, admits of nuclear combustion-waves of arbitrarily high propagation-speed, up to that of the average fission neutron (~$10^9$ cm sec$^{-1}$). Deflagration waves in such circumstances thus may in principle accelerate and eventually assume the character of nuclear detonation waves.

The second case has a qualitatively different character, due to the requirement for beta-decay in the process of converting a fertile nucleus to a fissile one; the maximum speed of wave advance is of the order of the ratio of the distance traveled from by a neutron from its fission-birth to its radiative capture on a fertile nucleus to the half-life of the (longest-lived nucleus in the chain of) beta-decay leading from the fertile nucleus to the fissile one. Since such a characteristic fission
neutron-transport distance in normal-density actinides is ~10 cm and the beta-decay half-life is $10^5 – 10^6$ seconds for most cases of interest, the maximum wave-speed is $10^4 – 10^5$ cm sec$^{-1}$, or $10^{-13} – 10^{-14}$ of that of a nuclear detonation wave; its literally glacial speed-of-advance makes clear that its intrinsic character is that of a deflagration wave.

Moreover, it is clear that the deflagration wave of this second case propagates not only very slowly but quite stably. If such a wave attempts to accelerate, its leading-edge counters ever-more-pure fertile material (which is quite lossy in a neutronic sense), for the concentration of fissile nuclei well ahead of the center of the wave becomes exponentially low, and thus the wave's leading-edge stalls. Conversely, if the wave slows, however, the local concentration of fissile nuclei arising from continuing beta-decay increases, the local rates of fission and neutron production rise, and the wave's leading-edge accelerates.

Finally, if the heat associated with nuclear fission is removed sufficiently rapidly from all portions of the configuration of initially fertile matter in which the wave is propagating, the propagation may take place at arbitrarily low material temperature – although the temperatures of both the neutrons and the fissioning nuclei may be ~1 MeV!

**Nuclear Deflagration in Configurations of Naturally-Occurring Actinides.** To what extent may such conditions be realized with readily available materials? Fissile isotopes of actinide elements are rare terrestrially, both absolutely and relative to fertile isotopes of these elements. However, fissile isotopes can be concentrated, enriched and synthesized. The use of both naturally-occurring and man-made ones, e.g., U$^{235}$ and Pu$^{239}$, respectively, in initiating and propagating nuclear detonation waves is well-known.

Creation and exploitation of deflagration waves in configurations of fertile actinide isotopes does not appear to have been much explored. To be sure, a breeder reactor has something of the character of a quasi-stationary nuclear deflagration wave, with reprocessing serving as a *deux ex machina* for removal of neutronic poisons (e.g., fission products) and periodic refueling for necessary periodic spatial rearrangements of fertile and fissile isotopic masses. A molten-salt (breeder) reactor is a somewhat more pure expression of a standing nuclear deflagration wave through which material is pushed, in that material motion is (quasi-)continuous, rather than episodic; correspondingly, fuel material is (quasi-)continually reprocessed. However, the operation of either of these two types of reactor leaves open the central issues of whether it is feasible to initiate or propagate deflagration waves in a fertile material configuration from which fission products are *not* removed and within which fertile and fissile isotopes are *neither added, subtracted nor spatially transported*.

Simply put, the question of present interest is *"Can the nuclear analog of a candle exist in our universe and, if so, can such an entity be operated on Earth in truly steady-state conditions?"* Consideration of necessary and sufficient conditions both for existence and for terrestrial operability of such a candle seems appropriate.
Consideration of pertinent neutron cross-sections\textsuperscript{10} (reproduced in Figures 1 and 2) rather immediately suggests that a nuclear deflagration wave can burn a large fraction of a 'candle' of naturally-occurring actinides, such as Th\textsuperscript{232} or U\textsuperscript{238}, only if the neutron spectrum in the wave is a 'hard' or 'fast' one. That is, only if the neutrons which carry the chain reaction in the wave have energies which are not very small compared to the $\sim 1$ MeV at which they are evaporated from nascent fission fragments can relatively large losses to the spacetime-local neutron economy be avoided when the local mass-fraction of fission products becomes comparable to that of the fertile material (recalling that a single mole of fissile material fission-converts to two moles of fission-product nuclei). [Indeed, even neutronic losses to preferred neutron-reactor structural materials, e.g., Ta, which has excellent high-temperature properties, may become substantial at neutron energies $\leq 0.1$ MeV, although such practical considerations lie beyond the present question of the feasibility-in-principle of a nuclear 'candle.']

Of lesser but still fundamental significance are the (comparatively small) variations with incident neutron energy of the neutron multiplicity of fission, $\nu$, and the fraction of all neutron capture events which result in fission (rather than merely $\gamma$-ray emission).\textsuperscript{7} The algebraic sign of the function $\alpha(\nu - 2)$ constitutes a necessary condition for the feasibility of nuclear deflagration wave propagation in fertile material vis-a-vis the overall fissile isotopic mass budget, in the absence of neutron leakage from the 'candle' or parasitic absorptions (e.g., on fission products) within its body, for each of the fissile isotopes of present interest; the necessity for wave propagation of this function, averaged over the neutron spectrum prevailing in the wave, being positive is manifest. It is thus of considerable interest that it is significantly positive for all fissile isotopes of interest, from fission neutron-energies $\sim 1$ MeV down into the resonance capture region.

Indeed, it is just the quantity $\alpha(\nu - 2)/\nu$ which upper-bounds the fraction of total fission-born neutrons which may be lost to leakage, parasitic absorption or geometric divergence during wave propagation. It is notable that this fraction is 0.15–0.30 for the major fissile isotopes over the range of neutron energies which prevails in all effectively unmoderated actinide isotopic configurations of practical interest: $\sim 0.1$–1.5 MeV. In profound contrast to the situation prevailing for neutrons of (epi-)thermal energy (see Figure 2), in which the parasitic losses due to fission products dominate those of fertile-to-fissile conversion by 1–1.5 decimal orders-of-magnitude, fissile element generation by capture on fertile isotopes is favored over fission-product capture by 0.7–1.5 orders-of-magnitude over the neutron energy range 0.1–1.5 MeV. The former results suggest that fertile-to-fissile conversion will feasible only to the extent of 1.5–5% percent at-or-near thermal neutron energies, while the latter indicate that conversions in excess of 50% may be expected for near-fission energy neutron spectra.

Quantitative aspects of sufficient conditions for nuclear deflagration wave propagation in specific material compositions and geometries seemingly may be addressed only by computer-assisted case analyses. However, bounding results of analytic character may be realized by considering very large, "self-reflected" actinide configurations, for which neutron leakage may be effectively ignored. Inspection of Figure 2 and analytic estimates of the extent of neutron

\textsuperscript{10}R. Howerton, D. Cullen, M. MacGregor, S. Perkins and E. Plechaty, "The LLL Evaluated-Nuclear-Data Library (ENDL)," UCRL-50400 (Univ. Calif. Lawrence Livermore Nat'l. Lab., 1979).
moderation-by-scattering entirely on actinide nuclei\textsuperscript{11} suffice to establish feasibility of wave propagation in sufficiently large configurations of the two types of actinides that are relatively abundant terrestrially: Th\textsuperscript{232} and U\textsuperscript{238}, the exclusive and the principal (i.e., longest-lived) isotopic components of naturally-occurring thorium and uranium, respectively.

Specifically, transport of fission neutrons in these actinide isotopes will likely result in either capture on a fertile isotopic nucleus or fission of a fissile one before neutron energy has decreased significantly below 0.1 MeV (and thereupon becomes susceptible with non-negligible likelihood to capture on a fission-product nucleus). This conclusion manifestly is a robust one: fission product nuclei concentrations must significantly exceed fertile ones and fissile nuclear concentrations may be an order-of-magnitude less than the lesser of fission-product or fertile ones before it becomes quantitatively questionable, as is apparent from inspection of Figure 1. Consideration of pertinent neutron scattering cross-sections suggests that right circular cylindrical configurations of actinides which are sufficiently extensive to be effectively infinitely thick – i.e., self-reflecting – to fission neutrons in their radial dimension will have density-radius products $>>200$ gm/cm$^2$, i.e., they will have radii $>>10$–$20$ cm of solid-density U\textsuperscript{238}–Th\textsuperscript{232}.

These are remarkable estimates. They imply that circular cylinders of natural uranium or thorium metal of less than a meter diameter – likely substantially less, if efficient neutron reflectors are employed – may (stably) propagate nuclear deflagration waves for arbitrarily great axial distances.

These analytic bounds and estimates have been confirmed and quantified by use of benchmark-quality Monte Carlo-centered neutron transport and reaction physics models\textsuperscript{12} and employing evaluated nuclear data libraries,\textsuperscript{7} in extensive studies employing modern personal computers.\textsuperscript{13,14} For example, circular cylinders of solid-density Th\textsuperscript{232} of 25 cm radius, overcoated with an annular shell of 15 cm of C\textsuperscript{12} (as graphite), propagate deflagration waves with $\geq70\%$ burn-up of the Th\textsuperscript{232} initially present. Replacing the Th\textsuperscript{232} with half-density U\textsuperscript{238} yields quite similar results – albeit fertile isotope burn-up of $\geq80\%$ is realized (as would be expected from inspection of Figure 2).\textsuperscript{10}

Thus, it is feasible to realize a pure expression of nuclear deflagration, one with a genuinely propagating character and maintenance of steady-state conditions for intervals of indefinite

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duration, moreover in remarkably compact configurations of naturally-occurring actinide isotopes.

**Implications for Nuclear Power Reactors.** The basic nuclear power engineering implications of these results for large-scale nuclear power generation are discussed elsewhere. Among the salient engineering physics results realized are the following:

- It appears readily feasible to impose local material temperature feedback on the local nuclear reaction rate, moreover at an entirely acceptable expense in the deflagration wave's neutron economy. Such a large negative temperature coefficient of neutronic reactivity confers an ability to control quite readily the speed-of-advance of the deflagration wave, for if very little thermal power is extracted from the burning fuel, its temperature rises and the temperature-dependent reactivity falls, the nuclear fission rate at wave-center becomes correspondingly small and the wave's equation-of-time reflects only a very small axial rate-of-advance. Similarly, if the thermal power removal rate is large, the material temperature decreases and the neutronic reactivity rises, the intra-wave neutron economy becomes relatively undamped and the wave advances axially relatively rapidly. It appears feasible to build such power reactors of essentially any steady-state thermal power rating (simply by increasing fuel charge diameter in order to maintain peak power density in the fuel at a reasonable level) – and of any desirable total energy production (simply by increasing the length of the fuel charge to conform the desired quantity of released rest energy to the required thousand-fold greater mass of actinide).

- It is necessary to 'waste' 5–10% of the total fission neutron production in the practical reactor designs considered, and the local material-temperature thermostating modules are conveniently utilized for this purpose. (Another ≤10% is lost to parasitic absorption in the relatively large quantities of high-performance structure materials employed in baseline designs, in order to realize ≥60% thermodynamic efficiency in conversion to electricity and to gain exceptionally high system safety figures-of-merit; the Zs of these materials, e.g., Ta, W and Re, are ~80% of that of the actinides, and thus their radiative capture cross-sections for high-energy neutrons are not particularly small compared to those of the actinides, as is indicated for Ta in Figures 1 and 2. A final 5–10% is lost to parasitic absorption in fission products. As noted above, the neutron economy characteristically is sufficiently rich that ~0.7 of total fission neutron production is sufficient to sustain deflagration wave-propagation in the absence of leakage and rapid geometric divergence. This is in quite sharp contrast with (epi)thermal-neutron power reactors employing low-enrichment fuel, for which neutron-economy discipline in design and operation must be rather strict.)

- The high (50-80%) burn-ups of initial actinide fuel-inventories which are characteristic of these nuclear deflagration waves permit singularly high-efficiency utilization of as-mined fuel, moreover with no reprocessing. See Figure 5. (Indeed, in baseline designs of this type of power reactor, all the fuel ever used in the reactor is installed during manufacture of the

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15See, e.g., reference 13 for first-level details of a particular feedback approach addressed to high-temperature gas-cooled nuclear power reactors. Many other feedback mechanisms, some probably quite different, likely exist and may prove markedly superior for particular circumstances.
reactor's core, and no spent fuel is ever removed from the core, which is never accessed after nuclear ignition. Pre-expansion of the as-loaded fuel permits higher-density actinides to be replaced with lower-density fission products without any overall volume changes in fuel elements, as the nuclear deflagration wave sweeps over any given axial element of actinide 'fuel,' converting it into fission-product 'ash.')

- Launching of nuclear deflagration waves into Th$^{232}$ or U$^{238}$ fuel-cylinders is readily accomplished with 'ignitor modules' enriched in fissile isotopes. As would be expected, higher enrichments result in more compact modules, and minimum mass modules may employ moderator concentration gradients. (Actual ignitor module design likely will be determined primarily by non-technical considerations, i.e., resistance to materials diversion for military purposes in various scenarios. Such modules may employ U$^{235}$ in U$^{238}$, in sufficiently low concentration as to be effectively non-detonatable in any quantity or configuration – e.g., ≤20% – in contrast, for example, to technically more optimal Pu$^{239}$ in Th$^{232}$. Quantities of U$^{235}$ already excess to military stockpiles suffice for ≥10$^4$ such ignitor modules, corresponding to a total inventory of nuclear power reactors sufficient to supply 10 billion people with kilowatt-per-capita electricity.)

Perhaps the single most notable implication of the present results is that exceptionally simple and safe nuclear reactors capable of zero-reprocessing (i.e., one-pass) burning of the entire actinide inventory of the Earth's crust are feasible. Providing such reactors and their immediate environment with suitable 'burial cask' features potentially permits decommissioning of such power-plants to consist simply of abandonment-in-place, particularly if they are located underground.$^{13, 14}$

**Nuclear Physics Conclusions.** While nuclear deflagration waves of any type appear to be quite rare in nature, it nonetheless appears feasible to create them on Earth, using only readily available materials arranged in simple, compact geometries which however can contain arbitrarily great fuel mass (and thus releasable nuclear energy). Inserting an obligatory beta-decay step in the physics of such wave-motion insures that it cannot possibly 'run away' into a detonation wave and, indeed, guarantees that it can propagate at a maximum speed which is literally glacial: ≤10$^{-4}$ cm/sec.

Moreover, even minimal attention to thermal-neutronic feedback suffices to insure that such waves will accelerate or decelerate to quite precisely accommodate the instantaneous rate of thermal power removal from the burning nuclear fuel – and thus that the material temperature at any point within the fuel cannot rise above some pre-determined design-value.

Such nuclear deflagration wave-motion may be realized readily with existing technology. Exploitation of such wave phenomena in feasible albeit novel nuclear power reactors of the type discussed elsewhere in this paper that would burn only existing inventories of already-refined actinides could supply the entire human race with kilowatt-per-capita electricity for a few centuries. Alternately, high-grade (≥1%), readily recoverable thorium ore represents several millennia of such electricity supply via nuclear deflagration-wave energy-release.
**Nucleonics.** The first phase of the nucleonics of the new type of reactor likely is familiar to students of fast breeder reactors. A centrally-positioned nuclear ignitor moderately enriched in U\(^{235}\) has a neutron-absorbing material (e.g., a borohydride) removed from it by operator-commanded electrical heating, and becomes neutronically critical. Local fuel temperature rises to the design set-point and is regulated thereafter by the local thermostating modules. Neutrons from the fast fission of U\(^{235}\) are mostly captured at first on local U\(^{238}\) and Th\(^{232}\).

(Uranium enrichment of the ignitor may be reduced to levels not much greater than that of LWR fuel by introduction into the ignitor and the fuel region immediately surrounding it of a radial density gradient of a refractory moderator such as graphite; high moderator density enables low-enrichment fuel to burn satisfactorily, while decreasing moderator density permits efficient breeding to occur. The optimum ignitor design involves trade-offs between proliferation robustness and the minimum latency from initial criticality to the availability of full-rated-power from the fully-ignited fuel-charge of the core; lower ignitor enrichments require more breeding generations and thus impose longer latencies. We consider use in the ignitor of uranium enriched to \(\leq 20\% \) U\(^{235}\) to be highly proliferation-resistant. Even though such material could be diverted to use as relatively high-performance feedstock for isotopic enrichment to weapon-useful material, the complexity of doing so is not qualitatively smaller than an *ab initio* effort using natural uranium.)

**Fuel Ignition.** The core’s maximum (unregulated) reactivity slowly decreases in the first phase of the ignition process because, although the total fissile isotope inventory is increasing monotonically, this total inventory is becoming more spatially dispersed. By proper choice of initial fuel geometry, fuel enrichment vs. position, and fuel density, it may be arranged for the maximum reactivity to still be slightly positive at the time-point at which its minimum value is attained. Soon thereafter, the maximum reactivity begins to increase rapidly toward its greatest value, corresponding to the fissile isotope inventory in the region of breeding substantially exceeding that remaining in the ignitor. A quasi-spherical annular shell then provides maximum specific power production. At this point, we refer to the core's fuel-charge as "ignited." Similarities to "standard" types of fast breeder reactors now become fewer, quite distant ones.

The spherically-diverging shell of maximum specific nuclear power production continues to advance radially from the ignitor toward the outer surface of the fuel cylinder. When it reaches this surface, it naturally breaks into two spherical zonal surfaces, with one surface propagating in each of the two opposite directions along the axis of the cylinder. At this time-point, the full thermal power production potential of the core has been developed, and we characterize this epoch as that of the launching of the two axially-propagating nuclear deflagration waves. (We choose to ignite at the center of the core’s fuel-charge and thus to generate two oppositely-propagating waves simply in order to double the mass and volume of the core in which power production occurs at any given time, and thus to decrease by two-fold the core’s peak specific power generation, thereby quantitatively minimizing thermal transport challenges.)

From this time forward through the break-out of the two waves when they reach the two opposite cylinder-ends, the physics of nuclear power generation is effectively time-stationary in the frame of either wave, as is suggested by the snapshots of Figure 5. The speed of wave advance through the fuel is proportional to the local neutron flux, which in turn is linearly dependent on the thermal power demanded from the reactor core (via the collective action on the wave’s neutron budget of the thermostating modules).
Thermal Homeostasis Maintenance. When more power is demanded from the reactor via lower-temperature coolant-gas flowing into the core, the temperature of the two ends of the cylindrical core (which are closest to the coolant-gas inlets) decreases slightly below the thermostating modules' design set-point, Li\textsuperscript{6} is thereby withdrawn from the corresponding sub-population of the core’s constellation of thermostating modules, and the local neutron flux is permitted thereby to increase to bring the local thermal power production to the level which drives the local material temperature up to the set-point of the local thermostating modules.

However, this process is not effective in heating the coolant-gas significantly until its two divided flows move into the two nuclear burn-fronts. These two portions of the core’s fuel-charge – which are capable of producing significant levels of nuclear power when not suppressed by Li\textsuperscript{6}-loading – then act to heat the coolant-gas to the temperature specified by the design set-point of their modules – provided that the nuclear fuel temperature doesn’t become excessive (and regardless of the temperature at which the coolant-gas arrived in the core). The two coolant flows then move through the two sections of already-burned fuel centerward of the two burn-fronts, removing residual nuclear fission and afterheat thermal power from them, both exiting the fuel-charge at its center. This arrangement clearly encourages the propagation of the two burn-fronts toward the two ends of the fuel-charge, by "trimming" excess neutrons primarily from the trailing edge of each front. See Figure 5.

This description implies that the core's neutronics are essentially self-regulated. As long as the fuel density-radius product of the cylindrical core is $\geq 200 \text{ gm/cm}^2$ (i.e., 1-2 mean free paths for neutron-induced fission in a core of typical composition, for a reasonably fast neutron spectrum), this is basically the case. The primary function of the neutron reflector in such core designs is to drastically reduce the fast neutron fluence seen by the outer portions of the reactor, such as its radiation shield, structural supports, thermostating modules and outermost shell. Its incidental influence on the performance of the core is to improve the breeding efficiency and the specific power in the outermost portions of the fuel, though the value of this is primarily an enhancement of the reactor's economic efficiency: outlying portions of the fuel-charge are not used at low overall energetic efficiency, but have isotopic burn-up levels comparable to those at the center of the fuel-charge.

Final Shutdown. Final, irreversible negation of the core's neutronic reactivity may be performed at any time by injection of neutronic poison into the coolant-gas stream, likely the primary loops which extend to the surface but possibly also the afterheat-dumping loops connecting the reactor to the engineered heat-dump. At the present time, it appears that lightly loading the coolant-gas stream with a material such as BF\textsubscript{3}, possibly accompanied by a volatile reducing agent such as H\textsubscript{2}, will serve satisfactorily to deposit metallic boron rather uniformly all over the inner walls of the coolant-tubes threading through the reactor's core, via exponential acceleration of the otherwise slow chemical reaction $2\text{BF}_3 + 3\text{H}_2 \rightarrow 2\text{B} + 6\text{HF}$ by the high temperatures invariably found there. Boron, in turn, is a highly refractory metalloid, and will not migrate from its site of deposition. Its more-or-less uniform presence in the core in $<100$ kg quantities will suffice to negate the core's neutronic reactivity for indefinitely prolonged intervals without involving the use of powered mechanisms in the vicinity of the reactor.

Neutron Economics. During its operational lifetime, the reactor core generates several dozen kilomoles of neutrons in excess to the minimal needs of its neutron economy. These are
available to make up losses due to parasitic absorption by structural materials and fission products, to leakage, etc. In the design which we overview in this paper, we have conservatively allocated half of this excess to make up such losses, and half to be absorbed in the thermostating modules by Li\(^6\). In a more highly optimized design, the total losses due to structural materials and leakage will be increased to ~80% by introduction of more such material in order to realize even lower peak stresses and higher long-term reliability of proper system performance, and perhaps for other functions such as more extensive internal support to the nuclear fuel against gravitational loads. (After all, the Li\(^6\) in the thermostating modules merely functions as a "neutron dump," in analogy to the "engineered heat-dump" reviewed in Appendix D; structure performs functions of positive utility.)
Appendix 1.C: Thermal and Mechanical Designs

The basic function of the type of reactors discussed in this paper is to serve as a high temperature heat source; thermal energy is constantly removed from it and used to generate electricity. In order to maximize both the safety and the economic return of this reactor, we require it to function in a hands-off fashion over a long interval. Accordingly, the reactor must safely and reliably operate, without maintenance or repairs, at high temperature for several decades. These requirements, together with particular features associated with the reactor’s nuclear operation, dictate fundamental features of the thermal and mechanical design of the reactor.

The reactor generates huge amounts of thermal energy, which must be continually removed in the form of ~2 GW of thermal power. From the global viewpoint, this removal is done to generate electricity but, from the reactor’s view, its purpose is simply cooling of a magnitude always sufficient to maintain core temperature compatible with structural integrity. The reactor is designed with two sets of coolant loops: a large primary set for use during normal operations, and a smaller secondary loop-set for removal of afterheat during loss-of-coolant accidents and for multi-century intervals after the reactor’s shutdown.

The coolant loops contain both in-core and out-of-core portions. The in-core parts are particularly challenging because they function at high temperature in a severe environment and cannot be accessed or maintained. By contrast, the out-of-core portions of the primary loop-set are cool, readily accessible, and can be serviced normally. The out-of-core portion of the secondary loop-set must be designed for hands-off, no maintenance operation, but is relatively cool and located in a much more benign environment than the core of the reactor. Thus, in the present discussion, we’ll concentrate on the design of the heat transfer system internal to the reactor.

The reactor core is a reasonably high aspect ratio cylinder; its fuel-charge is ignited in its middle and burns axially in both directions; at a given time, most power production occurs in two fairly narrow disks of the fuel-charge. The coolant loops direct coolant-gas flow axially along the length of the reactor in many small pipes, passing through and cooling the two burn-fronts. The fuel is placed between the pipes, transferring heat to them conductively. The entire fuel-charge is contained within a pressure vessel which provides the global confinement of the fuel and the reaction products thereof.

There are many possible choices for the coolant and structural materials of the reactor; we will discuss only our baseline-design set. The reactor coolant is chosen to be pressurized helium gas. (Helium has good heat-carrying capability and is inert from both chemical and nuclear perspectives, so its use will not constrain the reactor’s performance.) The in-core structural material, which is also used for the coolant pipes, is tantalum. (Tantalum is chosen because of the high temperature regime in which we require the reactor’s core to operate and the need to maintain excellent creep resistance over a nominal third-century full-power operational life, as well as its generally good mechanical workability and chemical corrosion resistance. From a nuclear standpoint, it is not an ideal material, acting as a significant neutron absorber, even when using a fast neutron spectrum; therefore, limitations are imposed on the fraction of tantalum that
can be used.) The pure element is not employed, as much stronger Ta-based engineering alloys exist; our baseline-design utilizes properties typified by alloys ASTAR-811C and NAS-36. Little is known about how the properties of these alloys change in the course of high-fluence fast-neutron irradiation, although similar materials typically gain strength but lose ductility. Since we will only operate at low strain and stress levels, these alloys should remain serviceable. Another issue centers on the effects of partial transmutation during their in-core service life; some of the tantalum will be changed into tungsten, and some of the tungsten into rhenium. These elements are initially present (W at the 10% level and Re at the 1% level, respectively) in the alloys, and are themselves strong, refractory materials, so this gradual change of the material elemental composition during service-life may be quite benign, although this has not yet been demonstrated. Material selection for the primary fuel-containment vessel is much less challenging, since this pressure-shell will be outside the reactor’s core, and thus will operate in a less stringent thermal and neutron environment, as well as not posing a neutronic threat to the core’s neutron economy; a high-strength steel alloy will likely be utilized.

Helium gas is used to transport heat out of the core both during normal operations and for afterheat removal; the principal distinctions between these two functions arise in how the gas is pumped and how the heat is ultimately removed, outside of the core. The primary coolant loop transports more heat, but does so under normal operational conditions. Pumps are used to circulate the gas flow between the underground reactor and the surface powerplant. The secondary loop transports less heat, but under more stringent conditions, either during loss-of-coolant accidents or entirely unattended, over very long intervals of post-operational life. We cannot depend on pumps for powering gas circulation in the latter case, but instead will use the natural thermosyphon action present from having a heat source located below a heat sink. [Obviously, heat-pipes may also prove to be an attractive option for this passive heat removal function.

We have focused on two different configurations, indicated in Figure 3, for the placement of coolant pipes within the core; many other possibilities exist. The simpler of the two geometries is an array of three separate-and-distinct periodic manifolds of parallel pipes interpenetrating to form a 2-D hexagonal grid. The fuel is positioned, initially as an open-celled metallic thorium (alternately, uranium) foam, in the space between the pipes. Each piece of fuel is in (physical, and thus thermal) proximity to pipes belonging to each of the three separate coolant manifolds, so there will still be coolant flow proximate to each and every fuel-parcel, despite failure of one or even two of the coolant manifolds. In this particular design-variant, there is not a separate secondary set of coolant loops to remove afterheat; instead, the same coolant pipes and gas which perform the primary cooling also serve to remove the afterheat. While this configuration is effective under normal operations as well as most loss-of-coolant scenarios, the use of common-function coolant-loops does pose some issues.

For this reason, a more complex, but more robust, six-pipe layout has been more seriously considered. The pipes are once again laid out in a 2-D hexagonal close-packed grid, but now consist of two different species: three coolant pipe-sets are integrated into three separate-and-distinct primary coolant manifolds, while the other three separate-and-distinct coolant manifolds comprise an independent secondary cooling system. Any given parcel of fuel is thermally well-coupled to each of the six different coolant-pipes, so we can maintain local cooling for both normal operations and loss-of-coolant accidents, if one or even two of each of the primary and secondary coolant system were to fail.
The actual design of a reactor coolant system must simultaneously satisfy several conditions. Clearly, we must have sufficient coolant flow to remove the reactor’s heat at acceptable peak temperatures, and enough pressure-head must be available to push this flow through the reactor’s core. The coolant pressure is selected by balancing its flow-enhancing benefits against its structural penalties. Large-diameter coolant pipes and a correspondingly large aggregate flow area ease the pumping task, but increase the internal temperature drops within the fuel and across the pipe-to-gas-flow boundary layer. One way to reduce these temperature drops is to reduce the packing density of the fuel, but doing so increases the core’s volume and its fuel inventory. There are clearly tradeoffs to be made during the detailed engineering design of a reactor; we present one particular set of preliminary choices below.

The physical dimensions of a six-pipe reactor core of 2 GWt rating are given in Table 1. The primary and secondary coolant-pipes have the same diameters (although not the same wall thickness) and are closely packed (i.e., are nearly touching).

<table>
<thead>
<tr>
<th>Table 1</th>
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<tbody>
<tr>
<td><strong>Length</strong></td>
<td><strong>Diameter</strong></td>
<td><strong>Depth</strong></td>
<td><strong>Fuel Mass</strong></td>
</tr>
<tr>
<td>Meters</td>
<td>Meters</td>
<td>Meters</td>
<td>Metric tons</td>
</tr>
<tr>
<td>10.0</td>
<td>2.4</td>
<td>100</td>
<td>75</td>
</tr>
<tr>
<td>Total Pipe Area</td>
<td></td>
<td></td>
<td>1.3</td>
</tr>
<tr>
<td>Meters²</td>
<td>Centimeters</td>
<td></td>
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<td>0.45</td>
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The basic power and thermal parameters of this reactor are given in Table 2.

<table>
<thead>
<tr>
<th>Table 2</th>
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<tbody>
<tr>
<td><strong>Peak Specific Power</strong></td>
<td><strong>T_in - Inlets</strong></td>
<td><strong>T_out - Primary</strong></td>
<td><strong>T_out - Secondary</strong></td>
</tr>
<tr>
<td>Watt/gm</td>
<td>Deg K</td>
<td>Deg K</td>
<td>Deg K</td>
</tr>
<tr>
<td>200</td>
<td>500</td>
<td>1000</td>
<td>1200</td>
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We require circulation of 770 kg/sec of helium in order to extract the full 2 GWt power from the reactor and 33 kg/sec in the secondary loop to remove peak afterheat. The in-core pipes dominate the total loop flow resistance; to reduce this as much as possible the coolant flow is split into two streams, each traveling half the length of the reactor, i.e. between an outlet at the middle and two inlets at each of the two ends. When calculating the pumping work needed to circulate the coolant, we’ve assumed that only two of the three pipe manifolds are operational; if all three are functional less work is required, while if only one is available the reactor will automatically operate at less than full power.

In Table 3, we list the inlet pressures needed to insure flow circulation under these conditions, as well as the amount of pipe material used and the resultant peak stresses encountered. During normal operation of the reactor, the pipe walls in both the primary and secondary coolant loops reach peak temperatures of about 900°C and are subject to creep. The reactor core will normally be pressurized (thereby shifting the task of pressure containment away from the high temperature, neutronically irradiated pipe walls and onto the relatively cool, unirradiated
material of the reactor vessel); however, the pipes are designed for adequate creep resistance anyway. During a loss-of-coolant accident, the secondary-loop coolant-pipes reach peak temperatures of 1100°C, but this lasts only a comparatively very brief interval, rapidly dropping as the core’s afterheat power declines; these higher temperature loads thus cause prompt, but not creep, stress.

| Table 3 |
|---------|---------|---------|---------|---------|
| P_{in} - Primary | P_{in} - Secondary | Wall - Fuel Ratio | Creep Stress | Prompt Stress |
| **Bars** | **Bars** | **Atom-fraction** | **Kpsi** | **Kpsi** |
| 53 | 84 | 0.33 | 35 | 43 |

We note in passing that we also provide a modest-scale heat-pipe-based heat-transport system coupling into the sand immediately surrounding the reactor in order to thermally ballast the reactor’s pressure-shell during loss-of-coolant accidents and after end-of-operational-life. Its mechanical integrity relative to hot creep is thereby ensured.
Appendix 1.D: Engineered Heat-Dump

All nuclear reactors continue to generate thermal power via beta-decay-energized nuclear afterheat long after their reactivity has been negated. While this power is at most 6-7% of the reactor's output power prior to shutdown, it is still far greater (by as much as a factor of $10^4$) than can be tolerated within the reactor core or its immediate surroundings; the afterheat energy must be extracted from the core and disposed of. There are two issues associated with such heat rejection: the long time-interval over which the rejection must occur, and the requirement to reject this heat at peak power levels during loss-of-coolant accidents, when all or part of the normal heat-transport system of the reactor may be unavailable. In order to aptly address these issues, we have designed the new type of reactor with a passively operating coolant-transport system, discussed in Appendix 1.C, which is capable of removing afterheat at the required power levels from the reactor itself. In this Appendix, we briefly discuss the other necessary aspect of afterheat removal: where the afterheat energy goes after it is removed from the reactor core.

We design to deposit the entire afterheat energy into a simple thermal sink, utilizing the heat capacity of loosely-packed sand under which the reactor is emplaced. The primary attraction of such a choice is that this overburden will always be present, while convective sinks might not be, given the long time-intervals and severe loss-of-coolant scenarios for which we believe any power reactor system must be designed. Another significant advantage is that this heated overburden will, during the long interval of post-operational life, act as something of a shroud, thermally inhibiting the permeation of groundwater into the immediate vicinity of the reactor, particularly if it is utilized with clay barriers deployed as in modern engineered sanitary landfills. (Water may thereby be confidently excluded as a possible corrosion agent which might impair the reactor's role as the spent-fuel's burial-cask.)

The total afterheat energy which the engineered heat-dump must absorb is, in the worst-case of abrupt end-of-life shutdown of the reactor from full-power-production without benefit of any post-end-of-operational-life cooling, about $1.5 \times 10^{15} \text{ J} \approx 0.35 \text{ MT}$. Since the material removed to emplace the reactor is unlikely to be an optimal heat-sink material (primarily due to its thermal characteristics), we specify that it be replaced with sand. This material can absorb ~ 1 kJ/cc, starting from room temperature and going up to near-melting, implying typical heat-dump dimensions of a rectangular prism about 130 meters on a side and 100 meters in depth. This volume will be positioned above the reactor, and won't extend significantly underneath it (except for a modest distance, for groundwater-sealant and seismic decoupling purposes). There are two principal reasons for this choice: avoidance of more excavation to greater depth than really necessary, and exploitation of the gravitational head made available by positioning the heat-sink above the heat-source to power a natural thermosyphon which will serve to reliably and entirely passively circulate heat-transfer fluids between the -source and -sink.

We have already described, in Appendix 1.C, the helium gas-loaded thermosyphon which removes afterheat from the reactor and transports it up through the subterranean heat-dump. In addition to this system, we also require a transport system to distribute the afterheat energy in an adequately uniform manner throughout the heat-sink, since the thermal diffusivity of sand is insufficient for this function on the requisite time-scales.
We specify a two-component heat-pipe network to serve as this transport system. The afterheat energy is initially lifted vertically from the reactor and towards the surface by the action of the thermosyphon. At periodic intervals along this thermal trunk-line, heat is coupled into a first set of "arm" heat-pipes, which transport it quasi-horizontally (with a slight upward tilt in order to gravitationally assist heat-pipe functioning) across the width of the heat-dump. A second set of "finger" heat-pipes, thermally tapping into each "arm" at periodic intervals, carries heat sideways (in the direction orthogonal to the "arm"), thereby distributing it throughout the entire quasi-horizontal layer of sand. This arrangement of many parallel heat-pipes, coupled thermally but not fluidically, provides a highly redundant -- and thus functionally robust and systemically reliable -- heat distribution system threading the entire engineered heat-dump.

Our present, incompletely optimized design employs a set of stainless-steel heat-pipes whose working-fluid is mercury, and is comprised of approximately 50 "arms" and 2000 "fingers." The fingers are spaced approximately 4 meters apart. This arrangement is sufficient to sink the peak afterheat power of \( \leq 150 \text{ MW} \) from our baseline-design reactor, and to adequately dispose of the monotonically declining afterheat power at all times thereafter.

During the initial phase of heat-dump operation, the afterheat energy heats only the cylinders of sand proximate to the fingers. After approximately a month of operation, these cylinders begin to merge into each other and the entire heat-dump is thereafter heated semi-uniformly. The array of finger heat-pipes directly contacts sufficient sand to readily disperse the earliest phases of afterheat, at times when the afterheat power level is highest and thermal diffusion has not spread this heat-pulse into the sand very far from the finger pipes.

As noted in Appendix 1.C and depicted in Figure 6, we also employ thermostatically-actuated thermal switches (with a contrast-ratio of >100:1). These serve to connect the heat-dump with the ascending coolant-pipes only when the reactor core's temperature exceeds the design set-point, thereby adequately preserving the thermal capacity of the heat-dump for use when needed.
Appendix 1.E: Coolant-Pipe Closures

In order to provide extremely reliable, very swift closing of coolant pipes under emergency conditions (e.g., when significant fission-product entrainment in coolant-gas is sensed), we provide one-time-operation closures which are known to offer the required features. Such fast closure systems would be used in addition to a redundant system of automatically-actuated conventional valves.

In underground testing of nuclear explosives and their military effects, it is often required to close steel pipes of 1-3 meters diameter enclosing gas or vacuum interiors on time-scales of milliseconds, with extremely high reliability of complete closure and maintenance of pre-existing internal conditions. Highly engineered, high-explosive-energized means for plastically flowing the relatively thick-walled pipes of carefully chosen composition and geometry into a cold-welded-closed configuration have been demonstrated repeatedly to be eminently suitable for such functions.

Use of such pipe closures precludes contamination of high-value experiments by explosive debris transiting the pipe’s interior at far higher speeds than would possibly occur under even emergency circumstances in the situations of present interest. These closures are of such quality that they maintain high-vacuum conditions downstream of the closure-point after the closure-event (in spite of the appearance of occasionally very high pressures on the upstream side). We therefore designate them for reliable, one-time closing of the coolant piping between the reactor vessel and the heat-engine(s) of the power plant, in event of major entrainment of fission products in the helium gas coolant stream (presumably due to pipe-failure within the reactor core).
ACKNOWLEDGMENTS. We gratefully acknowledge helpful discussions with many colleagues on nuclear engineering issues. Tom Reed provided a great deal of useful technical and politicoeconomic feedback, as well as overall impetus. George Zimmerman offered characteristically insightful guidance on computer-based modeling issues, and Dermott Cullen has aided in many ways, most particularly in the peculiar use and with respect to *ad hoc* performance enhancements of the TART95 code package, as well as in creation of illuminating graphics. Gordon Wenneker contributed in a most appreciated manner in the creation of presentation aids. Victoria Wood graciously and patiently donated use of her personal computer.
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 (~0.1 eV) energies, but are comparatively negligible above the resonance capture region (between ~3-300 eV).

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 fuel recycling (i.e., periodic or continuous removal of fission products) is precluded. [The radiative capture cross-sections for fission products shown are those for intermediate-Z nuclei resulting from fast neutron-induced fission that have undergone subsequent beta-decay to negligible extents. Those in the central portions of the burn-waves of the reactor fuel-cores of present interest will have undergone some decay and thus will have somewhat higher neutron avidity, but parameter studies have indicated that core fuel-burning results are rather insensitive to the precise degree of such decay.]
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 $\geq 10^5$ 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 (as the resulting Th$^{233}$ swiftly beta-decays to Pa$^{233}$, which then relatively slowly beta-decays to U$^{233}$, analogously to the U$^{239}$-Np$^{239}$-Pu$^{239}$ beta decay-chain upon neutron capture by U$^{238}$).

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 $\sim 10:1$. Indeed, both of these basic results are observed in detailed nucleonics model studies of the new type of reactor, as summarized in Figure 5.
Three Pipe Configuration

In Core:

Outside The Core (1 of 3):

Power plant
Crowbar Switch
Reactor
Heat Exchanger
To Exchanger
Heat Dump

Pump

Six Pipe Configuration

In Core:

Outside The Core (1 of 3):

Power plant
Prime Loop
Secondary Loop
Crowbar Switch
Reactor
Heat Exchanger
To Surface
Heat-Rejection

Secondary Loop

Prime Loop

Heating Exchanger
To Exchanger
Heat Dump

Pump
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 1.C and the performance-modeling of these configurations is sketched in Appendix 1.A.

The full layout of the heat transport system based on the dual, triply-redundant six-pipe system is depicted in Figure 6.
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, one easily sufficient (even after two-thirds of the modules are assumed to have failed randomly) to override the positive reactivity found anywhere in the burning fuel.

Located throughout the core’s fuel-charge in a 3-D lattice whose cell constant is roughly 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 (~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 absorptively 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 \(\leq 10^4\) moles – \(\leq 60\) kg – of Li\(^6\) is sufficient for the filling of 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 over a third-century time-interval. [The reactor core modeled here is a different design variant from the one detailed in Appendix I.C, having fractionally larger diameter and lower peak nuclear power density.] The corresponding positions of the leading edge of the nuclear deflagration wave-pair at various time-points after full ignition of the core's fuel-charge are indicated in the insert. Masses (in kg of total mass per cm of axial core-length) of various isotopic components in a set of representative near-axial zones and fuel specific power (in W/g) at the indicated axial position are the ordinate-values, while the axial position along the 10-meter-length of the fuel-charge (center-ignited at time $t = 0$ with a $^{235}$U-enriched ignitor module) is the abscissal value. The central perturbation is due to the presence of the ignitor module (indicated by a diamond in the insert).

Note that the neutron flux from the most intensely burning region behind the wave-front necessarily breeds a fissile isotope-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. [The differing actions of two slightly different types of Li$^6$-loaded thermostating units on the left and the right sides of the ignitor module account for the corresponding slightly differing power production levels.]

Finally, well behind the wave’s advancing front, the concentration ratio of fission product nuclei (whose mass rather closely 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” thereupon goes slightly negative, and both burning and breeding effectively cease – as is clear from comparing the various snapshots with each other, far behind the wave-front.
Redundantly Actuated Engineered One-Time Coolant-Pipe Closures

From Surface, Via Closures

To Surface, Via Closures

To Heat-Dump Heat Exchangers

To Engineered Heat-Dump Heatpipe Network

Heat-Dump Heat Exchanger

From Engineered Heat-Dump Heatpipe Network

Thermostatically-Driven Heat Exchanger Actuation Module

From Heat-Dump Heat Exchangers
Managing all aspects of beta-decay-engendered afterheat extremely reliably is a prerequisite for long-term safety of nuclear power operations, and extraordinary design attention is devoted to this crucial function for the new class of reactors considered herein.

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-capacity are typically of 30 MWe scale (but currently extend to 450 MWe in a single 60% efficiency unit), 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-gas 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.
• Completely independent, triplicated coolant loops, each full power-rated.
• Engineered one-time closures of coolant gas pipes.
• ~100 meter diameter bubble of hot/dry sand, for long-term environmental isolation.
• Engineered, highly redundant heat-dump, rated for full-power afterheat acceptance, indefinitely.
• Highly redundant, distributed thermostatic control of core temperature; triple-redundant, entirely passive afterheat transport.
• Massively redundant, distributed thermostatic control of core fuel power density.
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 \( \geq 100 \) 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.