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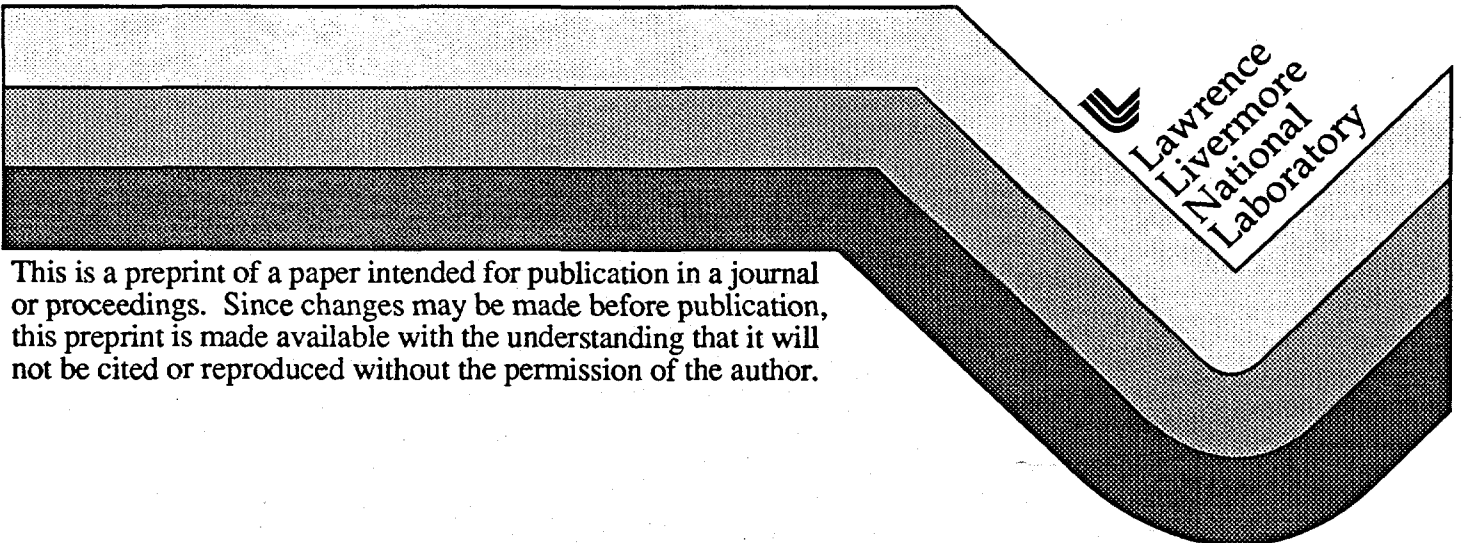
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COMPLETELY AUTOMATED NUCLEAR REACTORS FOR LONG-TERM OPERATION*

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ABSTRACT

We discuss new types of nuclear fission reactors optimized for the generation of high-temperature heat for exceedingly safe, economic, and long-duration electricity production in large, long-lived central power stations.

These reactors are quite different in design, implementation and operation from conventional light-water-cooled and -moderated reactors (LWRs) currently in widespread use, which were scaled-up from submarine nuclear propulsion reactors. They feature an inexpensive initial fuel loading which lasts the entire 30-year design life of the power-plant. The reactor contains a core comprised of a nuclear ignitor and a nuclear burn-wave propagating region comprised of natural thorium or uranium, a neutron reflector which also implements a thermostating function on the reactivity, a pressure shell for coolant transport purposes, and automatic emergency heat-dumping means to obviate concerns regarding loss-of-coolant accidents during the plant's operational and post-operational life.

These reactors are proposed to be situated in suitable environments at ~100 meter depths underground, and their operation is completely automatic, with no moving parts and no human access during or after its operational lifetime, in order to avoid both error and misuse. The power plant's heat engine and electrical generator sub-systems are located above-ground.

Advantages include reduced costs, as well as increased safety and reliability.

Introduction. One of the ancient needs of mankind regarding the physical environment has been for a 'well' of high-grade heat, from which thermal energy could be conveniently drawn, whenever and to the extent desired. With the

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Industrial Revolution, this need became more focused, for heat engines, e.g., those in electrical generating plants, have become the prime movers of virtually all of modern civilization.

The recently-gained ability to release energy from neutron-induced fission of the nuclei of the actinide elements in principle seems to satisfy this need, for this energy form is remarkably dense and capable of being accessed at essentially any desired power level. Moreover, the actinide elements, though present in the Earth's crust at a mean density of only a few parts per million, have become readily and inexpensively available: a pound of uranium or thorium, with an energy worth equivalent to several thousand tons of coal, presently costs less than \$10.

Public acceptance of nuclear fission reactors has been impeded by reactors which require installation of new fuel assemblies approximately 10 times over the lifetime of a typical power plant, with attendant dangers of accidents, complexity, cost and plant unavailability during refueling operations. The handling and disposal of the spent fuel assemblies has also proved problematic, though for mostly non-technical reasons. The management of nuclear fission heat production on times-scales of minutes to hours has proved troublesome, due to significant fractions of nuclear fission energy appearing considerably after it has been requested, i.e., from beta decay of fission products; such phenomena raise the specter of loss-of-cooling accidents and of possible reactor core meltdown. Perhaps most seriously, severe mismanagement of nuclear reactors by their human operators can cause them to generate very high levels of thermal power over brief durations, which can lead to physical disruption of the reactor (possibly followed by dispersion of significant quantities of reactor products into the biosphere), as happened at Chernobyl. Even more seriously, reactor products may be diverted for military purposes.

It is important to realize that these are not physically required features of a nuclear fission chain reactor, but are merely the common characteristics of a particular class of reactors which descended from submarine propulsion reactors and have been nearly universally employed for civilian electricity generation. Indeed, the impeccable record of nuclear reactor safety in the U.S. naval nuclear propulsion program, which has demonstrated several thousand reactor-years of accident-free operation since its inception, contrasted with that of the disaster-plagued Soviet naval reactor program, emphasizes that design, engineering and operational practices, not underlying physics, are actually the determinants of contemporary nuclear reactor safety and reliability.

At the same time, it would be remarkable if power reactors developed and optimized to reliably deliver a few tens of megawatts in a highly time-variable manner from an extremely compact configuration over a few months' submarine mission duration were also anywhere near optimal for central station thermal power generation, where pertinent time-scales are a few decades, power scales are in thousands of megawatts and economy and safety are the key figures-of-merit. It is a historic curiosity that nuclear power reactor design for central-station generation has evolved so little from its submarine power-plant antecedents.

We therefore examine central-station nuclear power generation *de novo*, and inquire as to how the features of greatest value in this application area may specify improved reactor designs and operational practices.

Desired Design Features. In contrast to naval propulsion reactors, ones in central power stations may reasonably be extremely generous in their mass and volume budgets. In contrast to the exceedingly cost-tolerant military environment, however, economic considerations are of great importance in central power station construction and operation. Similarly, while reliability-of-service may be traded off to a significant extent for maximum performance in military circumstances, civilian electricity generation is somewhat less tolerant of 'forced outages.' The major requirement, however, is safety that is easily understood by the public and is not dependent on absence of human errors.

Such consideration motivate the design of nuclear reactor heat sources for central-station electricity generation which are literally nuclear heat wells: maintenance-free sources of high-temperature heat-as-desired, hopefully created with little more cost or effort than that of digging a hole in the ground.

The average neutron multiplicity per fission is greater than 2 for U^{233} and Pu^{239} , even when the fission is induced by neutrons bringing in zero kinetic energy. This raises the possibility of 'breeding' (one neutron used to generate a readily fissionable nucleus and a second to cause its fission) of the actinides available in the Earth's crust. We have emphasized breeding reactor designs, for reasons of economy, efficient actinide mass utilization, reactor mass and volume minimization and, quite importantly, total avoidance of reactor refueling. In order to bring about long-term operation at a steady level, we use a propagating burn process – "breeding without reprocessing." This means a nuclear 'burn wave' moving out from an initial small configuration enriched in fissile material into a far greater mass of fertile material. The leisurely character of beta decay – central to the breeding process in the actinide isotopes – offers a fundamental physical guarantee that explosive propagation of such nuclear burning is impossible. The reactions in the nuclear fuel will propagate with a characteristic speed of the order of a meter per year.

Indeed, we consider avoidance of reactor refueling to be a fundamental design driver. Furthermore, we demand that the reactor and all of the reactor products should be inaccessible after the reactor starts to operate. The associated advantages are cost avoidance, obviating the periodic outage of the power plant, personnel safety and utilization efficiency, resistance to diversion of reactor products to military use, and obviation of accident and inadvertences associated with human access to the reactor after its construction is completed, inspected and certified. We find compelling reasons neither in physics nor engineering for not loading a reactor with sufficient fuel, appropriately configured, to enable it to operate at full power for a central power-plant's entire lifetime. We specifically require such one-per-lifetime fuel-charging of the reactors which we consider. More specifically, we locate the reactor ~100 meters underground in order to ensure safety of the biosphere in an obvious manner.

Simplicity of reactor construction is highly desirable, for reasons of overall economy, reliability and certifiability of construction and corresponding facility of reactor proliferation. We therefore emphasize reactor designs which consist of very little more than a pressure vessel for containing reactor coolant surrounding

a shield/reflector and the reactor's fuel charge. The monolithic pressure shell should be formed around its contents, with significant penetrations made only for coolant introduction and removal. All actuators and other mechanical devices should be required to operate only once, to commence initial reactor operation. At all later times, the reactor works without moving parts (except possibly at time of final shutdown).

We suggest that high-pressure helium should be used as the core coolant and that the electricity generation should occur on the Earth's surface. The reactor should have a strong negative temperature coefficient. Thus the removal of more heat from the reactor's core will accelerate the nuclear fission process. The reactor thus delivers energy on demand, and control rods become unnecessary.

Completely automated reactor operation is a requirement. Its great desirability is highlighted by the incident at Three Mile Island and the catastrophe at Chernobyl. Both of these reactor accidents were caused by human operator malfunction. We emphasize designs in which the reactor maintains a design core temperature within quite limited variation. Having power-regulating features in the design which throttle the nuclear reaction rate to correspond closely to the power extracted from the reactor appears to us to be feasible – and crucial to the prospect of eliminating human operator tampering with the reactor.

Due to beta decay-engendered nuclear after-heat, both during reactor operation and after the end of the reactor's operational lifetime, it is desirable to provide a large-scale, automatically-acting 'heat dump' into which unwanted heat threatening to damage the 'heat well' may be gracefully rejected. For this purpose, we provide passive (likely heatpipe-based) means for transporting a specified total amount of heat from the reactor core out into the surroundings, to be sunk in the heat capacity of the matter there present. Single-actuation back-ups operating at temperatures above the upper design limit of the reactor (e.g., burst disks sealing high-pressure heatpipes) may serve for post-end-of-life final heat-dumping purposes. Such systems provide intrinsic, redundant, fully automatic protection against core meltdown.

Finally, as already noted, we consider it desirable to the point of necessity to design reactors for operation deep underground, with minimal accesses to the biosphere provided, and these only for coolant flow. At least a hundred meters of compacted earth (but not shatter-prone rock) should stand over the reactor. In order to preclude radioactivity reaching the Earth's surface in case of an accident, coolant conduits could be emplaced so as to be compatible with multiple, redundant emergency single-actuation passage-closure. (Such closures, usually based on highly engineered chemical high explosives, have been demonstrated repeatedly to provide hermetic sealing of even very large pipe-loaded passages in underground circumstances, and will provide a definitive means of sealing off the underground reactor compartment from the biosphere.)

Large quantities of radionuclides have been successfully contained, with outward transport distances measured in meters, in engineered underground circumstances, for several decades, e.g., at the Nevada Test Site. Radioactivity has been generated in Nevada by experimental explosives involving several orders of magnitude more impulsively generated energy than a reactor core could possibly

generate. (It is also appropriate to recall that beta decay, though slow, is of finite rate. A mass of fission products becomes less radioactive than the same mass of freshly-mined pitchblende within a few centuries of being generated.) Underground siting of nuclear reactors of all types appears to us to be the essence of common sense – the added cost has been estimated to be ~10%.

Design Modeling Tool-Set And Calculations. The general plan is to ignite the reactor's fuel charge at one end of a cylindrical configuration and then propagate the nuclear burn-wave down the cylinder's axis. The ignitor section uses U^{235} , U^{233} or Pu^{239} . Near the axis of the cylinder, the composition is that of a fast breeder with characteristically good neutron and fissile isotope economy. A smaller radius coaxial cylinder of low-density material may be employed in such a charge, in order to facilitate axial neutron transport. Toward the outside of this cylindrical fuel charge, a thermal neutron spectrum thorium breeder composition develops under action of neutrons processed by the surrounding reflector shell, e.g., comprised of graphite. This is used to bring about the required negative temperature coefficient of the overall reactor core, as will be discussed below.

In order to investigate the physical feasibility of such design constraints and concepts, we have resorted to digital computer-based simulation of the behavior of some representative model systems.

For maximum design flexibility and modeling fidelity, we have performed the neutron transport and nuclear reactions in our model reactor designs with Monte Carlo-based means. 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 a man-century and an associated code-validation effort of the order of man-millennia. TART95 and its ancestors have very frequently been employed for calculation of the reactivity of critical assemblies, but effectively completely lack time-dependence.) We have used the current LLNL ENDL (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 thermal scattering and resonance cross-section multi-band-averaging features both invoked.

Model reactor designs in our studies typically are resolved into a few dozen spatial zones, usually possessing axial symmetry. A dozen or more isotopes are carried in each zone, representing both fertile and fissile isotopic components of nuclear fuel, in addition to reflector, moderator and coolant elements, structural materials, and various neutronic poisons (including fission products, carried as an ENDL-standard mix), in order to ensure proper reactivity dependence on temperature and accurate representation of the course of long-term, possibly high fuel-burnup reactor operation.

The kinetics of the isotopic fractions in each zone of model problems 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 then-obtaining particular conditions of the problem by TART95 (which typically followed 140 neutron-driven reactions in each zone). Neutron absorption in all non-actinide isotopes is implicitly accounted for, in a properly neutron energy-dependent manner. The newly modified isotopic abundances in each zone are then inputted to the TART95 code for another cycle of neutron transport and reaction calculations. This completes the basic set of operations of a single integration time-step.

The magnitude of the time-step of the integration, as is characteristic of such studies, 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 fuel burn-wave propagating in the unenriched fuel-charge.) Typically, 100-300 time-steps suffice for an integration simulating 3 decades of reactor operation.

The top level of our computer modeling program, which we call BURNBRED (for 'burn' and 'breed'), integrates the neutron transport/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 typical model run for GW-scale reactors of a few dozen zones and a dozen isotopes per zone operating over a simulated 3-decade interval requires 10-30 hours of computing time, during which time of the order of a trillion floating-point arithmetic operations are performed and several billion bytes of intermediate results are written to the computing system's hard-disk memory.

While time-dependent reactor modeling by this Monte Carlo-based approach would certainly be an extravagant expenditure of computing resources by traditional standards, the total [capital+operating (electricity)] costs of such a single day-long calculation on our modern PC is of the order of \$1. At least as importantly, 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 far smaller than the duration of the run itself, so that a much faster computer could not be effectively employed. Indeed, the computing system used was measured to be within three-fold as fast as the fastest computer available, the CRAY-YMP, for the extremely memory-intensive and highly scalar calculations performed by this modeling tool-set.

Some Preliminary Results. While we are reporting on work in progress, it is appropriate to relate some early basic results, as well as to comment on a few which we reasonably confidently anticipate.

Unenriched, Out-Of-The-Ground Actinides Burn Well. First, modeling results indicate that it is feasible to propagate in steady-state a nuclear breeding-and-burning wave down the length of a 'stick' of pure (i.e., unenriched with fissile isotopes) Th^{232} , apparently for an essentially arbitrary distance, from a small ignitor region at the stick's end. See Figure 1. A graphite reflector-clad thorium cylinder of <1 meter total diameter is seen to generate >1 GW continuous power levels, at nuclear breeding/burn-front propagation speeds of <1 meter/year,

corresponding to specific and volumetric power densities at least as high as would possibly be required in a central-station power plant. See Figure 2. We expect to demonstrate soon the same basic results for cylindrical sticks composed of natural – or even depleted – uranium. (We note that there is presently of the order of a million tons of depleted uranium, mostly stored in steel drums as the high-purity hexafluoride, in superpower stockpiles. These stockpiles are generally regarded as having little or no economic value. The energy content of a single ton of such depleted uranium in reactors of the type we discuss is nearly 3 GW-years; a thousand tons would provide the thermal energy to generate all the electricity used in the U.S. in a year, at a relatively low 30% conversion efficiency.)

High Fuel Burn-Ups Are Characteristic. Second, burn-ups of initial fuel inventories well in excess of 10% are observed to be characteristic, with large-scale burn-ups higher than 50% often being seen. While such results are not surprising in principle, simply considering the radiative capture cross-sections of fertile and fission-product isotopes and the fission cross-sections and neutron-emission multiplicities of corresponding fissile isotopes, they are novel in the power-plant context, where ~3% burn-ups of enriched fuel are typical. These order-of-magnitude higher fuel burn-ups imply smaller fuel assemblies for a given total nuclear energy production, as well as more efficient use of actinide fuel resources – without any reprocessing.

Thermostated Reaction Operation Appears Feasible. While the neutron spectrum in the reactor designs which we contemplate are reasonably 'hard,' in the sense that the average neutron energy is far above kT (T the temperature of the reactor's fuel assembly), we have demonstrated in simulation several basic design features that moderate to (epi)thermal energies and reflect the majority of the neutrons leaking from the reactor's core back into the fuel. This class of neutrons is seen to typically involve about 15% of a core's overall reactivity. As the temperature changes in the thermal neutron-dominated outer thorium region, the neutron population multiplication can be influenced in a temperature-dependent manner by two effects. One is the presence of a thermal poison, such as europium, with a resonance absorption in the neighborhood of 1 eV, which will absorb more neutrons when the neutron temperature rises. The other is the presence of some hydrogen, e.g., in the form of $(CH_2)_N$, in the reflector. Actually, the high epithermal scattering cross-section of protons of ~20 barns increases to considerably more than 50 barns for neutron energies less than 0.1 eV, with the result that, at higher temperatures, the neutrons will penetrate more deeply into the reflector and will be reflected back into the thorium correspondingly less. This effect can be further enhanced if the reflector temperature is lower than the temperature of the core, in which case a neutron, after penetrating the reflector from the core, will be slowed down in the reflector at greater depth and then trapped there with greater likelihood. These two effects may reinforce each other. Unfortunately, it is not yet clear whether all this will suffice for an appropriate stabilization of the nuclear reaction rate and of the core's temperature.

These reactors thus are hybrids, in that the fraction of their reactivity which is fast is somewhat less than unity, while their 'thermal' or 'slow' reactivity, though much less than unity itself, nonetheless is controlling as far as the reactor's neutron population-reproduction is concerned. We expect that doping of the moderator/reflector shell around the reactor's fuel charge with such epithermal

poisons will permit the reactor to be thermostated over a wide operating power range, e.g., from 10 to 100% of full design power.

Low Fissile Mass Ignitors Seem Attainable. Experience in modeling these cylindrical nuclear fuel sticks suggests that variable fissile isotopic enrichment which increases toward the origin and the axis of the cylinder may suffice for ignition purposes and will involve use of quite modest (<0.1 ton) total inventories of U^{235} or Pu^{239} . While special attention to geometric and compositional features will be required to simultaneously satisfy reactivity, mass-minimization, cooling and swift-ignition requirements, we have no doubt that these U^{235} (or Pu^{239})-cored cylinder-ends may be used to efficiently and robustly ignite the thorium (or natural uranium) sticks.

Our present uncertainty is concerned only with the total mass of fissile material which may be required for an ignitor. *Our simulation results already in-hand demonstrate that 0.1 tonne of U^{233} in a simple configuration is sufficient to swiftly ignite a GW-scale thorium stick, without special shaping of the fissile isotope's spatial distribution.* We expect design refinements, presently underway, will permit this already very modest quantity of ignitor material to be reduced 2- to 3-fold, so that only 30-50 kg of U^{235} or Pu^{239} will be required to implement an ignitor.

Since the mass of a typical thorium stick – which may be called upon to produce ~100 GW-years of thermal power over its 3-decade operational lifetime, at ~50% burn-up – is of the order of 20 tonnes, a fissile mass-budget even as high as ~0.1 tonne for the ignitor will represent an order-of-magnitude improvement in fissile mass-demand over the ~3% enriched fuel characteristic of present-day LWRs.

All of these results are early ones, and share a proof-of-concept character. We have yet to look in detail at a number of issues central to a practical central-station power reactor, such as the large average density change in the nuclear fuel associated with high fuel burn-up or with the details of GW-scale heat removal from the reactor core. For instance, we consider it possible that designs involving significantly smaller fuel burnups will prove to be more interesting overall. We intend to look into all such questions in the near future, and we are confident that solutions of adequate quality will become available soon thereafter.

Conclusions. In the foregoing, we have attempted to motivate a fresh look at the design, implementation and operation of nuclear reactors for central-station electricity (and perhaps space-heat) generation. Present LWRs, while demonstrably sufficient for such purposes, are also far from optimal for them. Substantial improvements in economy, reliability and safety appear attainable via the approaches which we have reviewed.

If modification of the biosphere by the aggregate effect of fossil-fueled prime mover operations world-wide indeed turns out to be substantial – the current evidence for which we don't consider to be particularly persuasive – then it may be necessary to rapidly adopt power generation technologies world-wide which are more

environmentally benign. Novel approaches may be particularly important in developing countries.

Nuclear power stations which have their never-refueled, never-disturbed reactors situated deep underground seem to be outstanding candidates for environmentally harmless electricity generation. Their ease of fabrication and operation may recommend them particularly strongly for rapid, low-risk, low-cost adoption as large-scale, long-lived heat sources for central power stations. Their resistance to materials diversion for military purposes and their huge margin of intrinsic safety may make them politically quite attractive.

We therefore expect rational allocation of resources to lead naturally first to exploration, then to development and finally to widespread proliferation of such reactors. In the Third World, the need for more electricity is apt to increase rapidly. It is important to satisfy this need, even in countries for which there is less than complete confidence in political stability. This puts particularly great emphasis on the availability of reactors for electricity generation which are difficult to misuse for military purposes and easy to operate without expert personnel.

Thus, the inexpensive, readily realized 'nuclear heat wells' which we hope to develop may well prove to be an attractive option for large-scale electricity supply development in the early 21st century.

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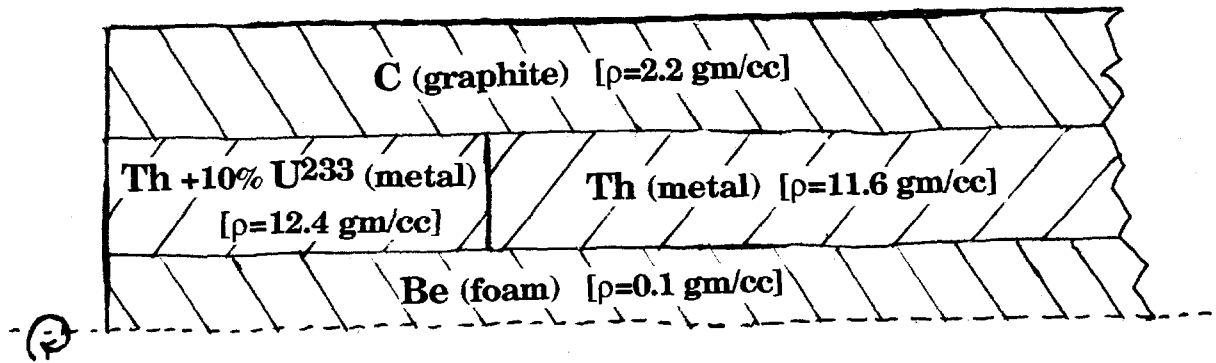


Figure 1. A diametral plane section of a typical reactor core, comprised of a thorium cylindrical fuel stick with an enriched ignitor section on its left end, surrounded by a graphite neutron reflector. The cylindrical core of the stick is hollowed out, with a radius of 10 cm, and filled with low-density material which is neutronically translucent, in order to enhance to an optimal extent the near-axial transport of excess neutrons from the region of maximum neutron production. The outer radius of the stick is 25 cm, and the outer radius of the reflector is 40 cm. The axial length of the ignitor section is 50 cm, or one fuel stick diameter. The compositions and densities of the reactor core components are indicated. A wave of nuclear [breeding+deflagration] is launched by the ignitor towards the right of the stick. This wave then propagates at a mean speed of ~ 0.5 meters/year, releasing ~ 1.5 GW of steady-state thermal power as it advances.

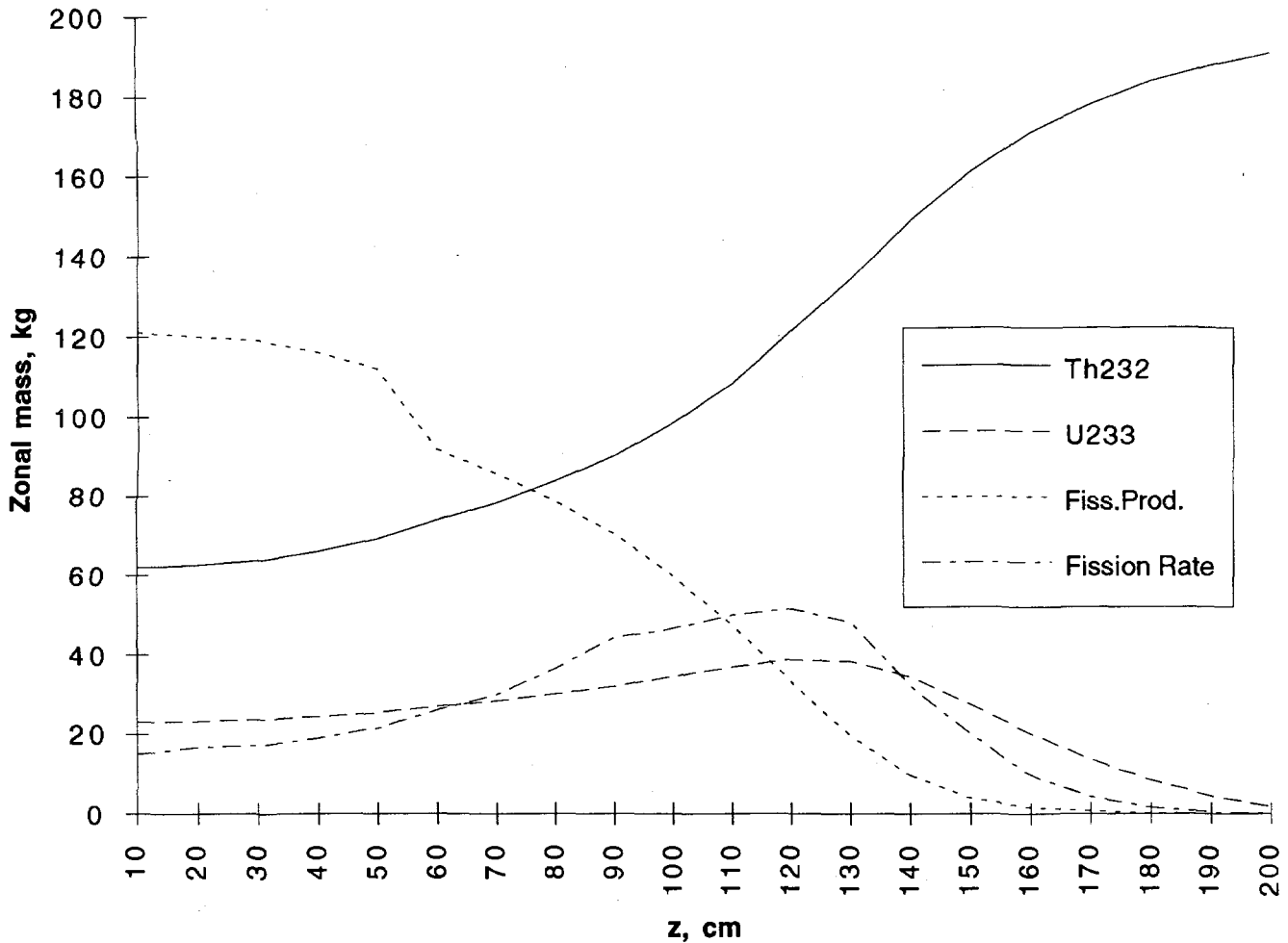


Figure 2. Masses of each of the 20 zones (each of 10 cm axial thickness) of the thorium-containing section of the simulated reactor configuration of Figure 1, at 2.0 years of simulation time, plotted as a function of axial distance from the left side of the ignitor section. The ignitor section, initially enriched to 10% U^{233} (i.e., a zonal mass of 21.9 kg of U^{233}), extends from 0 to 50 cm, as is indicated by the persistent discontinuity in the slope of fission products vs. axial coordinate. The high burn-up of the thorium fuel is particularly notable – ~65% – in the ignitor section, but is also quite high – $\geq 50\%$ – in initially pure thorium which has passed through its epoch of peak burning, e.g., between 50 and 90 cm. The leading-edge of the nuclear [breeding+deflagration] front, defined as the location where the U^{233} concentration has risen to the initial U^{233} concentration in the ignitor section, has advanced to ~155 cm, and the -coordinate of the peak specific nuclear fission point has advanced from 0 cm at time=0 to ~120 cm. The more than three-fold variation in specific nuclear fission rate from $z=0$ to $z=120$ cm (specific nuclear power is given in relative units) is in marked contrast to the less than two-fold difference in U^{233} concentration between these two points; this is explained, of course, by the ~5 times higher fission product concentration in the ignitor section, which competes effectively with the U^{233} for neutrons at the smaller z coordinates.