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A feasibility study of a nuclear power plant with no moving parts

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A FEASIBILITY STUDY OF A NUCLEAR POWER PLANT WITH

NO MOVING PARTS

by

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A THESIS

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Approved by

Xin Liu, Advisor
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Joshua P. Schlegel

ABSTRACT

In a nuclear reactor design, every moving part in a system is considered a failure point. In this study, a proposal is made for designing a nuclear reactor that has no moving parts by coupling an accelerator driven core (removing control system moving parts) to a magnetohydrodynamic generator (removing power generation moving parts) using mercury coolant (removing pumping system moving parts). Further safety is realized by using a subcritical core, where the core is never able to sustain a chain reaction on its own, obviating many safety systems. The design is verified with a Monte Carlo simulation.

ACKNOWLEDGMENTS

I wish to acknowledge the patience of my wife, Laura Warren Schattke, who never stopped believing in me.

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1. INTRODUCTION

Nuclear power plants have the highest level of safety of any electricity production method developed to date, but are still plagued by public fear of the dangers. Accidents like Chernobyl and Fukushima Daiichi fuel the narrative that nuclear power is dangerous, despite the lack of casualties. A new type of power plant which could be shown to be many times safer would allay these fears and allow the use of the full potential of nuclear energy for the betterment of mankind.

Accelerator Driven Systems (ADS) have the potential for great strides in criticality safety, high level waste disposal, and nonproliferation. By running with a k_{eff} less than one at all times, the system produces power in the neutron multiplier region, and a cessation of the neutron source leads to reduction (after decay of neutron precursors) of fission to the negligible ambient spontaneous fission level. The level of heat output is directly related to the neutron multiplication factor (k_{eff}) of the core and the incoming neutron flux. Since most systems have slightly negative temperature coefficients, the system will automatically reach a steady state power after a slightly higher power warm up, meaning that they are more responsive to load changes than a conventional plant.

The limiting of k_{eff} to at most 0.995 (for safety considerations with possible breed-up in the fuel) means that the safe maximum fission multiplier is 200, when cold. Each incoming proton in a 1 GeV beam produces ~25 neutrons, giving 5000 fissions per proton. Each fission produces 200 MeV (Cochran, 1990), meaning each incoming proton produces 1 TeV, a factor of 1000 on input beam wattage. So to reach Gigawatt class electrical power production, a beam of several Megawatts would be required, which would be prohibitively expensive (the world record proton beam power being the 1.4

MW 580 MeV cyclotron at the Paul Scherrer Institute, with a budget of 250 Million Swiss Francs a year). For this reason the technology lends itself to the Small Modular Reactor (SMR) space. Further consideration must be given to the efficiency of the proton beam; since maximum scientific beam efficiency reaches only 10%, and conventional Rankine cycle power plants in the industry reach about 45% electrical power efficiency, bringing the most powerful accelerator to the highest efficiency would only net 616 MW.

More problematically, most beams have significant downtime, the PSI cyclotron mentioned above hitting 80 hours per week uptime (50%) only rarely. For a power plant, power production must be 99.9% of the time or more (one hour or less down in 6 weeks). Most baseload nuclear plants are currently capable of running the full cycle without shutdown, that is, no unscheduled downtime (there were only 69 scrams in the entire industry in 2013 in the US). Unless an ADS can meet this stringent criteria, it will not be a feasible alternative to conventional nuclear, no matter what advantages it has.

A scientific proton beam requires tight control of proton energy and usually works in pulse mode. A medical imaging or therapeutic device requires tight control of position, beam spread and energy, a 30 degree beam spread would be extremely harmful and the device would be useless for therapy. An ADS proton accelerator requires none of the tight energy, location or beam spread controls; spread the beam 30 degrees and it merely flattens the flux profile. This lower requirement allows accelerators which are more efficient and much cheaper to be designed.

Going to a direct electrical generation system, the capital cost for the plant can be greatly reduced, and reliability increased. By employing magnetohydrodynamic

generators this can be achieved cheaply for high wattage. Power from such a system would be DC, so it would also serve to stabilize the grid.

The scope of this work is a demonstration of feasibility, not full engineering of each component.

2. THE HIGH FLUX ACCELERATOR

Existing Accelerator Driven Systems such as the R.A.C.E (Beller, 2004) have used existing scientific beams or specially built scientific beams to produce a neutron source through spallation or photo-neutron interactions. These experiments have demonstrated the multiplication factor of subcritical assemblies, and methods for experimental verification (Jammes, 2007). Drawing 150 Amps at 240 Volts, the RACE-T linear accelerator used 36 kW of power (O'Kelly, 2008). The electron beam produced was just 1.6 kW, an efficiency of just 4.4%. Obviously, a commercial system would hardly be viable if a multiplication factor of 22.5 is required just to break even thermally, and at least 50 is required to break even electrically. Furthermore, they suffered beam losses of 50% even before hitting the target.

An unreliable technology will be completely unsuitable for a commercial plant. The most important considerations are high flux (a large number of particles) and suitable particle energy. A study of what energy would be most efficient must include the cost to accelerate, the results of having a specific energy, and the directionality of the beam and the effect of the beam shape upon the multiplication factor.

2.1 MODELING A SPALLATION SYSTEM

MCNP version 6 was used for modeling, since the new high energy physics code is necessary. Figure 2.1 shows the diagram of the system for modeling. In this diagram, green is Mercury, blue is the core material, and red is the iron case. The white outside is air, and it can be assumed there would be no significant reflection from the environment and any particles leaving the outer surface are ignored. The multiple cells in the core are needed to track the evolution of materials in each cell, since little mixing is expected. The

beam is modeled simply as a point source 5 cm above the center and with a directionality uniformly downward. This is not an exact match for the expected source, but allows comparisons.

With spallation on the central liquid mercury column, and counting secondary spallations from the interactions with the heavy metals in the core, runs of at least 10^6 protons of various energies generated the data in Figure 2.2, showing the relationship of beam energy to neutrons produced. An energy of at least 25 MeV is needed to spallate
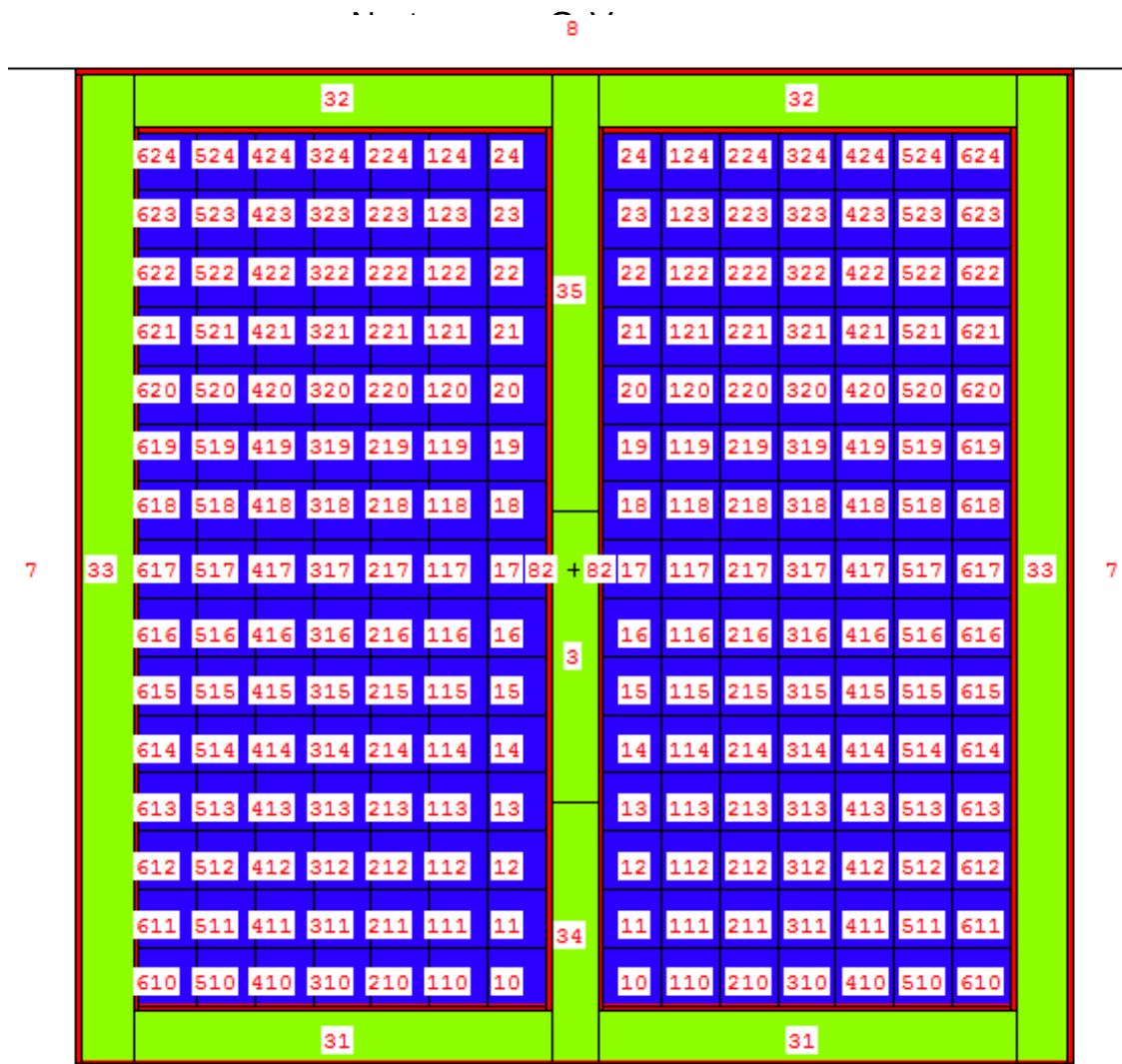
Figure 2.1. Layout of core. Cross section of cylinder.

neutrons off of heavy metal targets (Geurtin, 2005). It is clear that efficacy is linearly related to beam energy, but beam energy is inversely related to efficiency; there would be a "sweet spot" of beam energy where you get the most neutrons per input watt, which will be highly dependent on the accelerator technology used.

2.2 FINAL CONSIDERATIONS FOR ACCELERATOR

Ad Astra engineering has been making the VASIMR rocket engine, using ideas pioneered in the early 1980s. The concept is a plasma stream from a magnetic bottle's center cusp is limited to particle energies at least of a velocity determined by the magnetic field of the constricting coil (see Figure 2.3). By using multiple stages, microwave frequencies can be chosen for each stage to accelerate the particles efficiently for the next stage. The final stage exit magnet strength will determine the particle energy profile at the exit of the device.

Neutrons per GeV

Figure 2.2. Neutrons per GeV of beam energy at various proton energies

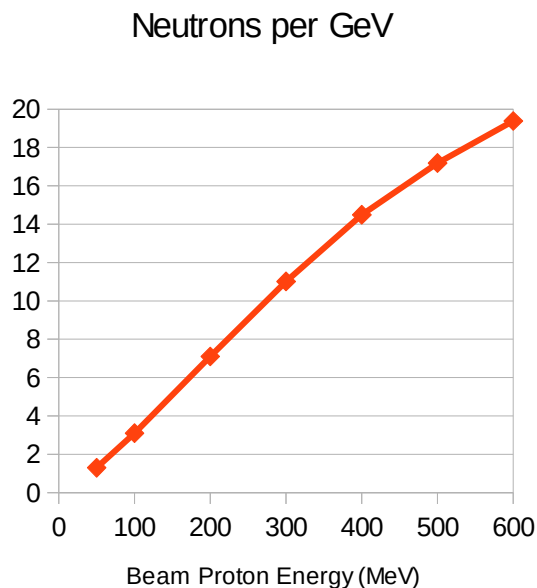The initial plasma formation is in a helicon chamber. Jung (2004) reports being able to reach plasma densities of 10^{12} n/cm. With a 13 kV exciter stage, the velocity is then 1.1×10^6 m/s; this then gives 1.1×10^{11} particles per square meter to reach our required flux; this corresponds to 0.11 m^2, or 18.9 cm radius, much larger than the device Jung created, but certainly within the realm of engineering. The actual plasma density is dependent on the strength of the magnetic field; Jung found 100 Gauss to be effective, but the exact field strength for best plasma density would have to be determined experimentally. The next stages of the accelerator are magnetic bottles with Cyclotron Resonance Heaters. (VASIMR is a single stage device).

Designing with a modest 300 MeV beam, and choosing magnetic field (B) as 10 T, well within the current state of the art, if E=300 MeV =4.8654×10^{-11} J and B=10 T then

$$\mu = \frac{E}{B} = 4.8654 \times 10^{12} \; . \tag{1}$$

Since magnetic field to pressure ratio (β) is

$$\beta = \frac{2En}{B^2 / 2\mu} \tag{2}$$

our β=1 limit for n is calculable as

$$n = \frac{B^2 / 2\mu}{2E} = \frac{B^3}{4E^2} = \frac{1 \times 10^3}{4\left(4.8654 \times 10^{-11}\right)^2} = 1.056 \times 10^{23} \tag{3}$$

which is much more than needed, so the resulting plasma should have a very low β (meaning it can be well confined). Since the density of air is 1.225 kg/m^3, this corresponds to 0.11 Torr. If the acceleration begins with atmospheric pressure at room

temperature, (~2200 m/s or 0.025 eV) then the system will have much less than this pressure when the particles are moving at several hundred million eV.

Since the end goal is the best number of neutrons per watt, the system is designed for final energy based upon the efficiency at each energy with a final device. The VASIMR continuous flow axial accelerator achieves 56% efficiency at particle energies in the tens of keV (Longmier 2011), it would be presumptuous to assume a higher energy system could match that in the hundreds of MeV range; but with the Fermi National Accelerator Laboratory confident that they can get a 10% efficient scientific beam in the GeV range, assuming this accelerator design will reach ~30% efficiency is reasonable.

To have a design total beam energy of 1 MW; 33% efficiency would mean the energy budget for producing the beam is 3 MW. 1 MW beam energy at 300 MeV is a 3.33 mA beam, that is a beam flux of 2.083×10^{16} protons a second, giving rise to 6.882×10^{16} neutrons per second (or 6.88×10^{10} per beam watt). It should also be noted that the beam power is not lost, but is a heat addition to the core coolant.

This will use a mole of mercury every 10^{10} seconds or so. There will likely be the production of helium and tritium in spallation products, a couple moles over the life of the plant. All larger spallation fragments and fission fragments will be sequestered in the sealed design, either dissolved in the mercury or carrier salt, or plating out on the surfaces of the vessel.
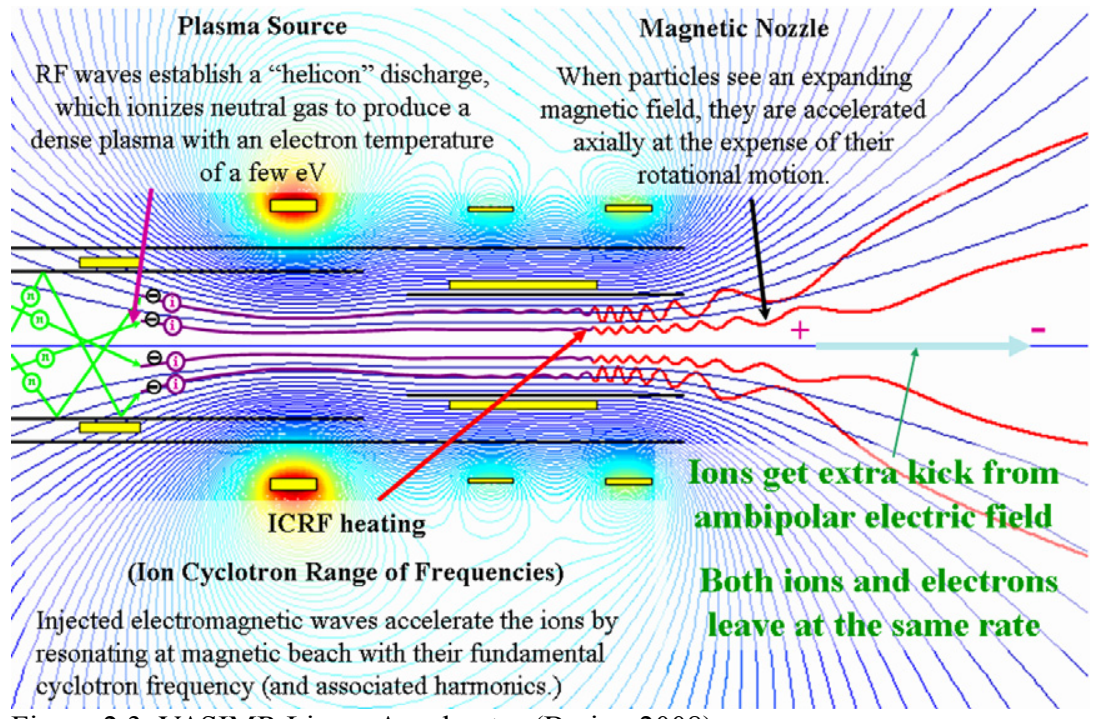
Figure 2.3. VASIMR Linear Accelerator (Bering 2008)

3. SUBCRITICAL CORE

Subcritical multiplication occurs in a nuclear reactor when the neutron multiplication factor (k_{eff}) is below unity, and the core is exposed to an external source. This can be expressed as the infinite series

$$n_{tot} = \sum_{j=1}^{\infty} n_0 k_{eff}{}^{j} = n_0 \frac{1}{1-k_{eff}} ,$$

(4)

this series having a definite solution. Once k_{eff} goes to unity, an external source will just keep adding neutrons, leading to linear growth, and above unity, the series will exponentially grow to infinity. One of the things a designer of a subcritical system must do is verify the system will not reach criticality under any circumstances.

3.1 MATERIALS SELECTION

A commercially viable small modular reactor must be possible according to the laws of neutron physics, cheap to assemble, made of low priced materials, and demonstrably safe in catastrophic accidents. These criteria drive the choice of candidate materials for the reactor, and the final choice is made on neutronic calculations. Only if the neutronics will not work would a designer revisit the use of exotic or more dangerous materials or more complex construction. The complex assemblies, expensive materials, and dangerous choices made in the operating generation of light water reactors have led to multiple accidents and concomitant monetary losses.

A mercury coolant and spallation target allows the reactor to run at Mercury's 356.58 °C boiling point at atmospheric pressure. By running the thermal cycle at about the same temperature as a LWR but at one atmosphere, the large database of materials science in this temperature realm is usable, and no new exotic materials choices will be

needed. Should a higher temperature be desired, the additional pressure with mercury vapor will be much lower than with water. Mercury is unique as a coolant, as a monatomic gas with a reasonably high boiling point and high density.

The use of economically priced austenitic stainless steel is allowed if the amount of chromium in the neutron flux is kept minima, since chromium is a fairly high cross section material. There are literally decades of experience with stainless steels in all conceivable nuclear environments, including mercury. The same stainless steel will be used for all parts of the system, to avoid any galvanic issues or stresses from differences in thermal expansion rates. This cost will not be prohibitive, because the amount of material to contain a few atmospheres of pressure maximum is minimal (discussion of pressures in the system and thicknesses of piping will be in the power section).

Fluoride salts will corrode stainless steel if the electronegativity of the combining salt is too high, but the corrosive effect is low enough that a few extra millimeters provide years of corrosion protection. However, a solid fluoride salt mix would almost completely relieve corrosion as an issue (as opposed to a molten salt, where atomic motility is great). Table 3.1 shows some relevant properties of candidate salts. The fluoride salt for the matrix, since this is a fast reactor, should not significantly moderate, and should remain stable even at high burnup. The choice of magnesium fluoride was

Table 3.1. Matrix Materials

Material	Atom Density mol/cc	Fast σ_a	Fast σ_s
BeF_2	0.04224	0.0282	14.14
LiF	0.10158	70.71	5.63
MgF_2	0.05052	0.082	11.42
NaF	0.06092	0.0027	6.79

because magnesium is an alkaline earth metal, with an electronegativity of 1.31. The high

reactivity means that any dissociation in the crystal matrix will quickly react with

magnesium rather than the steel of the vessel. Other choices are beryllium fluoride,

lithium fluoride, or sodium fluoride. It is clear from the large absorption cross section that

lithium fluoride would poison the reaction. The higher moderation (scattering cross

section) by BeF_2 or LiF means that the system will have a lower steady state fissile

content. In MCNP modeling of same-size systems, with same molarity of BeF_2 the k_{eff} at

startup is 0.868 vs. 0.970 for MgF_2 (there is somewhat less mass of salt at the same

molarity for BeF_2), and the breeding is slower in BeF_2 carrier salt.

3.2 MODELING THE CORE

MCNP 6 models were used to simulate the core in various configurations, in order

the examine characteristics for engineering. CINDER was used for detailed burn

calculations to find the production of isotopes not covered by the minimal version

included in MCNP. To simulate the action of the beam quickly for MCNP BURN card

use, which requires kcode, a rod of plutonium was modeled in the center of the core in

order to give the k_{eff} found with spallation. This approach produces less energetic

neutrons, meaning actual experienced fast fissions will be higher and the steady-state ^{233}U

fraction will be slightly higher.

The core of the system is the spallation target area, a 10 cm diameter area of

mercury coolant. A simple steel tub containing the subcritical fluoride salt mixture is

fastened to the boiler bottom, since it would float on mercury. This tub, of ~1.5 m radius

and ~3.0 m height (size determined after several simulation runs to be just subcritical),

generates the heat by fission, which is then removed at the surface by the mercury

coolant. A goose-neck vessel contains the liquid mercury, and separates the vapor so that clean dry mercury vapor makes it to power production.

The primary containment is an unpierced high temperature steel tub, welded closed with the entire fissile load for the plant. With breed-up well into the hundreds of Gigawatt days per metric ton, the core is able to be sealed for the service life of the plant. This core must be sized small enough that even when it breeds to steady-state and rests (for the ^{233}Pa to decay to ^{233}U), it will still be certain to be subcritical at all temperatures. The salt mixture will be poured in batches in order to be homogeneous and solid. Some cracking, localized melting during service, or other issues are inconsequential; likewise collection of "hot spots", stratification, separation of fission products from the matrix and other such effects can be ignored, as long as the surface of the core tub is maintained at a moderate temperature by the mercury. One possible issue would be the collection of fluorine and noble gases in the head space; however, fluorine is very reactive and it is expected that recombination within the matrix will be very robust, especially with the additional protons from beta radiation making the salt less and less stoichiometricly balanced as the fuel burns (fluorine converting to the noble gas neon removes oxidation potential, and magnesium converting to aluminum gains reduction potential)

An initial loading of 8.6% fissile ^{233}U in fertile Thorium, and 65% molar heavy metal salts leads to a core that is slightly moderated, and the size gives an initial k_{eff} of 0.987; since the subcritical multiplying factor is $1/(1-k_{eff})$ this gives 80 fissions per neutron. At a production rate of 6.88×10^{16} neutrons per second, this gives 5.51282×10^{18} fissions; counting 185 MeV recoverable energy per fission, this leads to a core initial heat output of 163 MW(th) from a 1 MW beam at startup.

Figure 3.1 shows the breed-up results as the system runs through various levels of burn. Since breeding is directly related to the fluence, and so is energy output, this is a good measure of core performance. These runs assume only local homogeneity; in actual practice the use of a large volume with only surface cooling would lead to melting of the fluoride salt fuel, which would then set up convection currents and increase mixing. Figure 3.1 shows the k_{eff} of a core which is planned as steady state, running 8.6% ^{233}U and 91.4% Th heavy metal (the Protactinium fraction is very low at this power level, about 0.01%).

At 150 MW from a core of the size used (somewhat larger than a final core must be) there is a heat rate of 7.08 MW/m^3 and a heat flux of 3.46 MW/m^2. Thermodynamically, the low Peclet number means that the temperature gradient across the liquid metal is very low, so even a moderate pressure rise will assure boiling only at
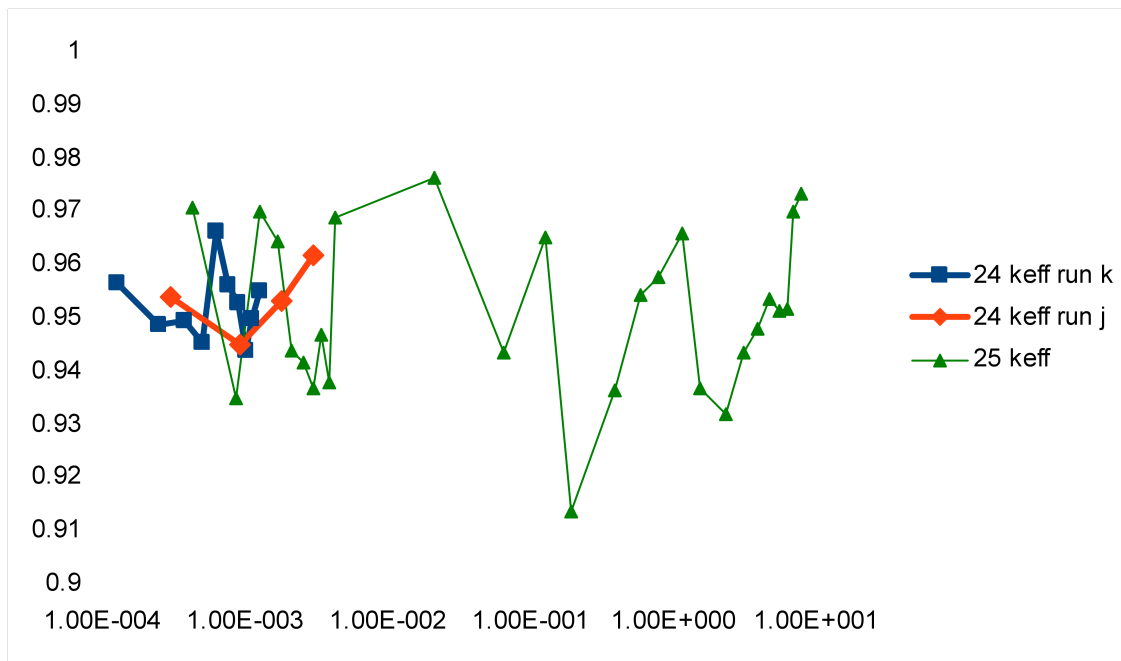
Figure 3.1. Burndown k_{eff}.

the top surface. Any local boiling in the central column will lower the place where the proton beam strikes, lowering the k_{eff} of the core, and reducing the heat output. Because of the high density of mercury, the majority of the core is under a pressure of about one atmosphere (since 1 atm=760 mm Hg) With the high heat transfer rate through liquid metal, most of the heat will transfer to a boiling region above the core. Mercury has a specific heat of 0.135 kJ/kg and a heat of vaporization of 61.42 kJ/kg, so 150 MW will boil 2000 kg/sec (7100 tons/hr) from an entering temperature of 250°C. This is about 220 m^3; at 1200 m/s velocity, this would need a pipe of 0.18 square meters, 24 cm radius.

The demonstration of the strength of the Thorium cycle for in-situ steady state burning is shown in the actinide inventories in Figure 3.2. The plutonium isotopes are in minute concentrations, and the Uranium fissile load climbs slightly during this early part of the burn. Note the ^{232}U inventory remains small (27 ppm at end of run), which means

Figure 3.2. Actinide Inventory

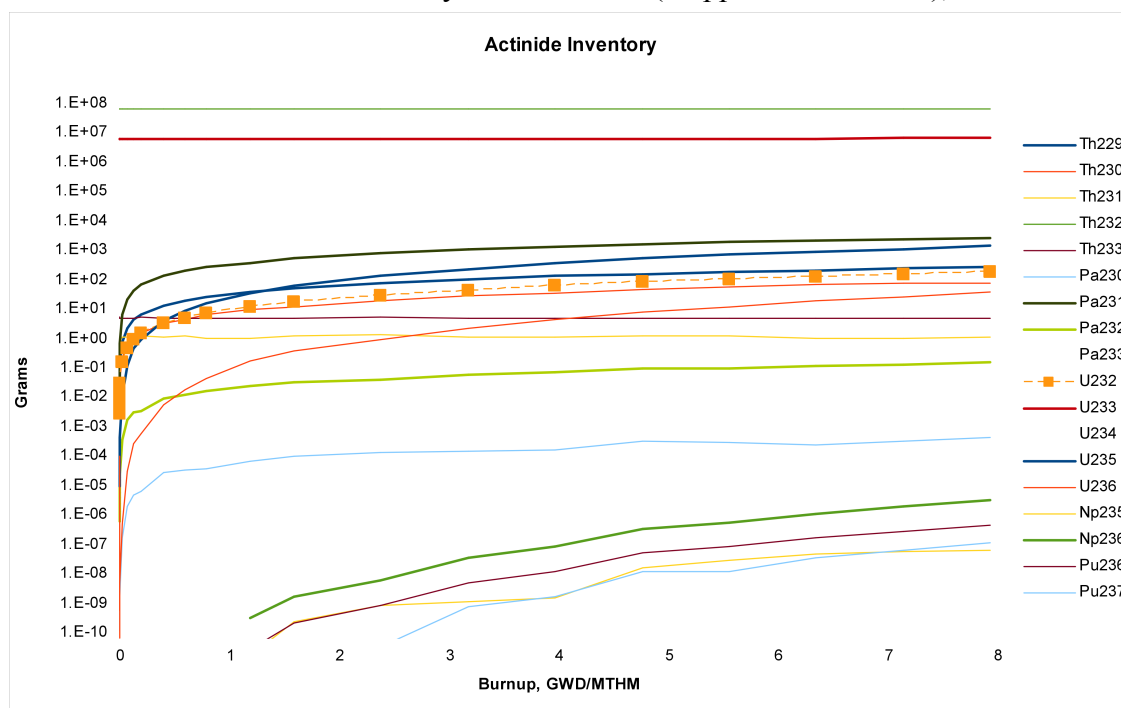the system will have to be rendered proliferation resistant through some other means. Transuranic actinide production in general is minimal, and the waste from this core would be easy to dispose of.

4. POWER GENERATION

Power generation is accomplished with a MHD system. In a disc-type MHD generator, a pair of Helmholtz coils are placed to generate a magnetic field as the plasma flows from the center of a disc to the edge, and the plasma currents then flow around the edge of the disc, allowing the drawing off of the current at opposite sides of the disc directly into electricity with high-temperature contacts.

To generate plasma from mercury steam, another helicon is used. The plasma is then fed directly into the MHD. After power generation, a tube and fin convective flow air cooled heat exchanger neutralizes the plasma and condenses the mercury. Liquid mercury then flows back to the core by gravity.

Coal plant MHD generators with plasmas that have fairly high neutral percentages have reached 20% efficiency; while fully ionized systems should reach much higher efficiency, for the purposes of energy balance, assuming 20% is reasonable. The 150 MW(th) then produces 30 MWe.

Mercury steam from the nuclear boiler at 2 atmospheres pressure (400°C, 210 kpa, 41.661 kJ/kg) is swirled through a droplet separator to have clean, dry steam enter the power equipment. This then goes through a Helicon to ionize it (first ionization energy is 10.43 eV) and then into our MHD. The steam then goes through a fin and tube condenser to bring it below boiling, back to 250°C (10 kpa, 34.42 kJ/kg). This pressure differential assures good steam flow at all times. Each kilogram of mercury in this system has 7.2 kJ of enthalpy available; for this level of feasibility, we assume perfect regeneration of the enthalpy from the exit side of the MHD to the condensed cold mercury.

5. CONCLUSION

The advantages in safety of a fully sealed nuclear power plant with no moving parts are manifest and great. Each of the parts of this reactor design is feasible, within current state of the art, and using no exotic materials. The most important part of the reactor, with the most research being needed, is the high flux low price accelerator, but even a retired medical imaging cyclotron could be used to demonstrate the concept.

APPENDIX

MCNP CODE

```
ThorMer Preliminary Version 2
c The Thorium Mercury ADEP
c Jonathan Schattke 9/27/13
c Run 04: neutron source information
c Run04a: adjust target area
c Run05a: mock point source, kcode - FAIL
c Run05b: mock point source, kcode 1 cycle burn - FAIL
c Run06: attempt to get MCNP to produce fission product list
c         and neutron spectrum in fuel
c Run06a: get fuller product list
c Run07:  k_eff at 1% U233
c Run07a: k_eff at 2% U233
c Run07b: k_eff at 3% U233
c Run07c: k_eff at 4% U233
c Run07d: k_eff at 5% U233
c Run07e: k_eff at 6% U233
c Run07f: k_eff at 7% U233
c Run07g: K_eff at 8% U233
c Run07h: k_eff at 9% U233
c Run07j: k_eff at 8.12% U233, expected steady state
c Run08: Radial Spatial distribution of fission at 8.12% Homogeneous
c Run08b: Radial Spatial distribution of fission at 0%
c Run09: Axial Spatial distribution of fission at 0%
c Run09a: Axial and radial distribution of fission, 0%
c Run10: axial and radial distribution, flux enhancement w/ Natural Uranium
c Run11: axial and radial distribution, BeF2 salt
c Run12: disribution, ThN:(MgF2)2
c Run13: axial and radial distribution, flux enhancement w/ Natural Uranium,
ThF4:(MgF2)2, breed step 1
c Run14: a&r dist, UF4 first ring, ThF4/MgF2 balance
c Run15: a&r dist, 5% enriched UF4 first ring
c Run16: a&r dist, 5% enriched UF4 first 2 rings, t0
c Run17: a&r dist, 5% enriched UF4 first 2 rings, t1 (~0.5%)
c Run18: a&r dist, 5% enriched UF4 t0
c Run19; a&r CINDER, (5% PuF4/95% ThF4):1 MgF2:1
c Run20: a&r dist, simplified rings
c Run21: a&r as above, 5%enriched U
c Run22: a&r as 20, BeF moderator
c Run23: adjust size to assure no keff>1 possible
c Run24: adjust size, start at expected steady state U233
c Run24a: adjust size to 60cm, start at expected steady state (8.6%)
c Run24b,c,d,e: more sizes, increasing sizes 70,80,85,95
c Run24f: 95cm 500MeV verify same k_eff
c Run24g,h: 120cm 300MeV, 150cm
c Run24j,k,m: characterization of 150cm core keff over startup
c Run25: increase HM molarity to increase keff
c
c Cells
10   10   -4.85   10 -11 110 -111 vol=4.71239E+04
11   11   -4.85   10 -11 111 -112 vol=1.25664E+04
12   12   -4.85   10 -11 112 -113 vol=6.28319E+03
13   13   -4.85   10 -11 113 -114 vol=6.28319E+03
14   14   -4.85   10 -11 114 -115 vol=6.28319E+03
15   15   -4.85   10 -11 115 -116 vol=6.28319E+03
16   16   -4.85   10 -11 116 -117 vol=6.28319E+03
17   17   -4.85   10 -11 117 -121 vol=6.28319E+03
18   18   -4.85   10 -11 121 -122 vol=6.28319E+03
19   19   -4.85   10 -11 122 -123 vol=6.28319E+03
20   20   -4.85   10 -11 123 -124 vol=6.28319E+03
21   21   -4.85   10 -11 124 -125 vol=6.28319E+03
22   22   -4.85   10 -11 125 -126 vol=6.28319E+03
23   23   -4.85   10 -11 126 -127 vol=1.25664E+04
24   24   -4.85   10 -11 127 -130 vol=4.71239E+04
110 110 -4.85   11 -12 110 -111 vol=9.42478E+04
```

```
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112 112 -4.85   11 -12 112 -113 vol=1.25664E+04
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114 114 -4.85   11 -12 114 -115 vol=1.25664E+04
115 115 -4.85   11 -12 115 -116 vol=1.25664E+04
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420 420 -4.85   14 -20 123 -124 vol=6.43241E+05
421 421 -4.85   14 -20 124 -125 vol=6.43241E+05
422 422 -4.85   14 -20 125 -126 vol=6.43241E+05
423 423 -4.85   14 -20 126 -127 vol=1.28648E+06
424 424 -4.85   14 -20 127 -130 vol=4.82431E+06
c 70   9 -19.8   -9 210 -200
70   50  -13.6 -9 210 -200
80   100 -7.8   40 -10 100 -111
81   100 -7.8   40 -10 111 -112
82   100 -7.8   40 -10 112 -113
83   100 -7.8   40 -10 113 -114
84   100 -7.8   40 -10 114 -115
85   100 -7.8   40 -10 115 -116
86   100 -7.8   40 -10 116 -117
87   100 -7.8   40 -10 117 -121
88   100 -7.8   40 -10 121 -122
89   100 -7.8   40 -10 122 -123
90   100 -7.8   40 -10 123 -124
91   100 -7.8   40 -10 124 -125
92   100 -7.8   40 -10 125 -126
93   100 -7.8   40 -10 126 -127
94   100 -7.8   40 -10 127 -130
95   100 -7.8   20 -30 -130 100
96   100 -7.8   10 -20 -130 120
97   100 -7.8   10 -20 -110 100
3    50  -13.6 210 -200 9 -40
3.1 50  -13.6 140 -100 40 -30
3.2 50  -13.6 130 -160 40 -30
3.3 50  -13.6 140 -160 30 -50
3.4 50  -13.6 140 -210 -40
3.5 50  -13.6 200 -160 -40
4    100 -7.8  140 -160 50 -60
4.1 100 -7.8  160 -170 -60
```

```
4.2 100 -7.8  150 -140 -60
5   0         -150
7   0         60 150 -170
8   0         170

c surfaces
c 10 series: cylinders
9     cz 2.05
10    cz 5
11    cz 15
12    cz 25
13    cz 35
14    cz 45
15    cz 55
16    cz 75
20    cz 150
30    cz 151
40    cz 4
50    cz 161
60    cz 162
c 100 series: xy planes
100   pz -151
110   pz -150
111   pz -75
112   pz -55
113   pz -45
114   pz -35
115   pz -25
116   pz -15
117   pz -5
120   pz 151
121   pz 5
122   pz 15
123   pz 25
124   pz 35
125   pz 45
126   pz 55
127   pz 75
130   pz 150
140   pz -161
150   pz -162
160   pz 161
170   pz 162
c 200 series: tally cell surfaces
200   pz 10
210   pz -30

phys:n 1000
c phys:p 1000
mphys
mode N $ H P / D T S A
imp:N,H,/,D,T,S,A 1 87R 0 0 0
nps 1e5
c imp:N 1 87R 0 0 0
c kcode 10000 0.946 15 65
c BURN &
c     TIME= 0.2 0.2 0.2 0.2 0.2 0.2 0.2 0.2 0.2 0.2 & 8 20  30 30  92 90 92 &
c     182 184  364 366 364  366 364 366 364 366 & $ ..1m .1q ..1y .
2y ..5y ....10y
c LATER: PFRAC with each step having maximum power for a 1 MW beam at the k_eff
c     POWER= 40.0 &
c     MAT 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 &
c  110 111 112 113 114 115 116 117 118 119 120 121 122 123 124 &
c  210 211 212 213 214 215 216 217 218 219 220 221 222 223 224 &
c  410 411 412 413 414 415 416 417 418 419 420 421 422 423 424 &
c     AFMIN=1e-16 &
c     BOPT 1.0 -24 1.0
c Materials
c m9 Criticality source to simulate beam, Pu
m9    94239 1
c 10 series: fuel (5%Pu,95%Th)F4/MgF2
c Mat'l Density fraction
```

```
c UF4    6.59331 0.05375 0.2835124204
c ThF4   6.3     0.57125 2.9925
c MgF2   3.148   0.375   1.574
c                        4.8500124204
m10  92233 .086    90232 .914
        9019 5.2
        12024 0.47394  12025 0.06  12026 0.06606
m11  92233 .086    90232 .914
        9019 5.2
        12024 0.47394  12025 0.06  12026 0.06606
m12  92233 .086    90232 .914
        9019 5.2
        12024 0.47394  12025 0.06  12026 0.06606
m13  92233 .086    90232 .914
        9019 5.2
        12024 0.47394  12025 0.06  12026 0.06606
m14  92233 .086    90232 .914
        9019 5.2
        12024 0.47394  12025 0.06  12026 0.06606
m15  92233 .086    90232 .914
        9019 5.2
        12024 0.47394  12025 0.06  12026 0.06606
m16  92233 .086    90232 .914
        9019 5.2
        12024 0.47394  12025 0.06  12026 0.06606
m17  92233 .086    90232 .914
        9019 5.2
        12024 0.47394  12025 0.06  12026 0.06606
m18  92233 .086    90232 .914
        9019 5.2
        12024 0.47394  12025 0.06  12026 0.06606
m19  92233 .086    90232 .914
        9019 5.2
        12024 0.47394  12025 0.06  12026 0.06606
m20  92233 .086    90232 .914
        9019 5.2
        12024 0.47394  12025 0.06  12026 0.06606
m21  92233 .086    90232 .914
        9019 5.2
        12024 0.47394  12025 0.06  12026 0.06606
m22  92233 .086    90232 .914
        9019 5.2
        12024 0.47394  12025 0.06  12026 0.06606
m23  92233 .086    90232 .914
        9019 5.2
        12024 0.47394  12025 0.06  12026 0.06606
m24  92233 .086    90232 .914
        9019 5.2
        12024 0.47394  12025 0.06  12026 0.06606
m110  92233 .086    90232 .914
        9019 5.2
        12024 0.47394  12025 0.06  12026 0.06606
m111  92233 .086    90232 .914
        9019 5.2
        12024 0.47394  12025 0.06  12026 0.06606
m112  92233 .086    90232 .914
        9019 5.2
        12024 0.47394  12025 0.06  12026 0.06606
m113  92233 .086    90232 .914
        9019 5.2
        12024 0.47394  12025 0.06  12026 0.06606
m114  92233 .086    90232 .914
        9019 5.2
        12024 0.47394  12025 0.06  12026 0.06606
m115  92233 .086    90232 .914
        9019 5.2
        12024 0.47394  12025 0.06  12026 0.06606
m116  92233 .086    90232 .914
        9019 5.2
        12024 0.47394  12025 0.06  12026 0.06606
m117  92233 .086    90232 .914
        9019 5.2
```

```
        12024 0.47394  12025 0.06  12026 0.06606
m118  92233 .086    90232 .914
        9019 5.2
        12024 0.47394  12025 0.06  12026 0.06606
m119  92233 .086    90232 .914
        9019 5.2
        12024 0.47394  12025 0.06  12026 0.06606
m120  92233 .086    90232 .914
        9019 5.2
        12024 0.47394  12025 0.06  12026 0.06606
m121  92233 .086    90232 .914
        9019 5.2
        12024 0.47394  12025 0.06  12026 0.06606
m122  92233 .086    90232 .914
        9019 5.2
        12024 0.47394  12025 0.06  12026 0.06606
m123  92233 .086    90232 .914
        9019 5.2
        12024 0.47394  12025 0.06  12026 0.06606
m124  92233 .086    90232 .914
        9019 5.2
        12024 0.47394  12025 0.06  12026 0.06606
m210  92233 .086    90232 .914
        9019 5.2
        12024 0.47394  12025 0.06  12026 0.06606
m211  92233 .086    90232 .914
        9019 5.2
        12024 0.47394  12025 0.06  12026 0.06606
m212  92233 .086    90232 .914
        9019 5.2
        12024 0.47394  12025 0.06  12026 0.06606
m213  92233 .086    90232 .914
        9019 5.2
        12024 0.47394  12025 0.06  12026 0.06606
m214  92233 .086    90232 .914
        9019 5.2
        12024 0.47394  12025 0.06  12026 0.06606
m215  92233 .086    90232 .914
        9019 5.2
        12024 0.47394  12025 0.06  12026 0.06606
m216  92233 .086    90232 .914
        9019 5.2
        12024 0.47394  12025 0.06  12026 0.06606
m217  92233 .086    90232 .914
        9019 5.2
        12024 0.47394  12025 0.06  12026 0.06606
m218  92233 .086    90232 .914
        9019 5.2
        12024 0.47394  12025 0.06  12026 0.06606
m219  92233 .086    90232 .914
        9019 5.2
        12024 0.47394  12025 0.06  12026 0.06606
m220  92233 .086    90232 .914
        9019 5.2
        12024 0.47394  12025 0.06  12026 0.06606
m221  92233 .086    90232 .914
        9019 5.2
        12024 0.47394  12025 0.06  12026 0.06606
m222  92233 .086    90232 .914
        9019 5.2
        12024 0.47394  12025 0.06  12026 0.06606
m223  92233 .086    90232 .914
        9019 5.2
        12024 0.47394  12025 0.06  12026 0.06606
m224  92233 .086    90232 .914
        9019 5.2
        12024 0.47394  12025 0.06  12026 0.06606
m410  92233 .086    90232 .914
        9019 5.2
        12024 0.47394  12025 0.06  12026 0.06606
m411  92233 .086    90232 .914
        9019 5.2
```

```
        12024 0.47394   12025 0.06   12026 0.06606
m412  92233 .086    90232 .914
        9019 5.2
        12024 0.47394   12025 0.06   12026 0.06606
m413  92233 .086    90232 .914
        9019 5.2
        12024 0.47394   12025 0.06   12026 0.06606
m414  92233 .086    90232 .914
        9019 5.2
        12024 0.47394   12025 0.06   12026 0.06606
m415  92233 .086    90232 .914
        9019 5.2
        12024 0.47394   12025 0.06   12026 0.06606
m416  92233 .086    90232 .914
        9019 5.2
        12024 0.47394   12025 0.06   12026 0.06606
m417  92233 .086    90232 .914
        9019 5.2
        12024 0.47394   12025 0.06   12026 0.06606
m418  92233 .086    90232 .914
        9019 5.2
        12024 0.47394   12025 0.06   12026 0.06606
m419  92233 .086    90232 .914
        9019 5.2
        12024 0.47394   12025 0.06   12026 0.06606
m420  92233 .086    90232 .914
        9019 5.2
        12024 0.47394   12025 0.06   12026 0.06606
m421  92233 .086    90232 .914
        9019 5.2
        12024 0.47394   12025 0.06   12026 0.06606
m422  92233 .086    90232 .914
        9019 5.2
        12024 0.47394   12025 0.06   12026 0.06606
m423  92233 .086    90232 .914
        9019 5.2
        12024 0.47394   12025 0.06   12026 0.06606
m424  92233 .086    90232 .914
        9019 5.2
        12024 0.47394   12025 0.06   12026 0.06606
m50   80000 1
c 100 series: structure Fe
m100 26054 0.058
       26056 0.9172
       26057 0.022
       26058 0.0028
sdef erg=300 pos=0 0.1 10 vec=0 0 -1 dir=1 axs 0 0 -1 rad d1 ext 0
si1    24.5
sp1    -21
FC4 Neutron flux in fuel and beam collision region
F4:n 3 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 &
 110 111 112 113 114 115 116 117 118 119 120 121 122 123 124 &
 210 211 212 213 214 215 216 217 218 219 220 221 222 223 224 &
 410 411 412 413 414 415 416 417 418 419 420 421 422 423 424 &
 80 81 82 84 84 85 86 87 88 89 90 91 92 93 94
e4    5.00000e-09 1.00000e-08 1.50000e-08 2.00000e-08 2.50000e-08 3.00000e-08
       3.50000e-08 4.20000e-08 5.00000e-08 5.80000e-08 6.70000e-08 8.00000e-08
       1.00000e-07 1.52000e-07 2.51000e-07 4.14000e-07 6.83000e-07 1.12500e-06
       1.85500e-06 3.05900e-06 5.04300e-06 8.31500e-06 1.37100e-05 2.26000e-05
       3.72700e-05 6.14400e-05 1.01300e-04 1.67000e-04 2.75400e-04 4.54000e-04
       7.48500e-04 1.23400e-03 2.03500e-03 2.40400e-03 2.84000e-03 3.35500e-03
       5.53100e-03 9.11900e-03 1.50300e-02 1.98900e-02 2.55400e-02 4.08700e-02
       6.73800e-02 1.11100e-01 1.83200e-01 3.02000e-01 3.88700e-01 4.97900e-01
       6.39279e-01 8.20850e-01 1.10803e+00 1.35335e+00 1.73774e+00 2.23130e+00
       2.86505e+00 3.67879e+00 4.96585e+00 6.06500e+00 1.00000e+01 1.49182e+01
       1.69046e+01 2.00000e+01 2.50000e+01 t
print  20 40 50 60 70 72 98 100 102 110 126 120 130 140 160
        161 162 190 200
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