REPORT

OF THE CONFERENCE ON

HYBRID FUSION-FISSION SYSTEMS

Held in Washington, D.C., May 19 and 20, 2009

THE CENTER FOR HYDROGEN FUSION POWER

(COURANT INSTITUTE OF MATHEMATICAL SCIENCES, NYU)

and

THE BROOKINGS INSTITUTION

(WASHINGTON, D.C.)

Note: The preparation and printing of this report were supported in part by the Department of Energy (DOE) under the grant FG-02-86-ER-53223. This support does not constitute an endorsement by the DOE of the views expressed in the report.

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Contents

General Overview of Fusion-Fission Hybrid Conference

Martin Avery Snyder
Adjunct Senior Research Scientist
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New York University

This Conference was convened to consider two questions: Can hybrid fusion-fission systems deal with the used fuel ("waste") from nuclear fission reactors? And, can such a system be developed in a reasonable amount of time?

It was different from many scientific conferences inasmuch as its purpose was a "call to action" as much as an exchange of ideas. One senior attendee wrote "I enjoyed your meeting immensely. It reminded me of the good old days when we were younger and braver." Broadly speaking, agreement was reached among some 28 scientists and engineers that such a program might work and could help solve the nuclear waste problem, while generating significant additional energy. A more precise statement of what was agreed to follows this introduction. Here we explain what all of this means.

A typical nuclear reaction operates by splitting heavy atoms, usually a specific isotope of uranium, by hitting an atom with a neutron. Some of the neutrons cause splitting with a subsequent release of energy, but others are absorbed by the uranium causing that uranium to be transmuted into other elements that cannot be split (in a conventional reactor) and thus creating a radiotoxic "waste". The energy that is released by this splitting is collected and then used to make electricity. These reactors are called "critical" fission reactors, because when uranium atoms in the proper configuration are split, one of the byproducts is several more neutrons which can do more splitting and hence carry on the reaction in a self-sustained manner. Of course, such a "critical" reaction must be controlled so that it does not become an atomic bomb, but it does not need an external source of neutrons to operate.

When a uranium fuel rod is used in a fission reactor only a small fraction of its available energy content is extracted. If the used fuel rod (the "waste") could be made inert, perhaps by further "splitting," (with a generous source of energetic neutrons), we could solve the problem of waste disposal and generate additional energy. These splitting reactors convert long-lived radioactive atoms into shorter-lived ones (thus reducing the hazard of the material) but they do not produce enough neutrons to proceed in a self-sustained manner. These are "subcritical" reactors and require an external (separate) neutron source for their operation. The "waste burning" procedure produces roughly 25% as much additional energy as was produced in the original utility reactors.

The dream of "fusion energy" is to combine hydrogen atoms to make helium, just like the sun, with virtually endless clean energy. This is probably a distant goal, but such reactions, even at lesser power, do produce neutrons, and these neutrons can be used to drive a subcritical fission reactor. Now let's put it all together.

If we wrap the nuclear waste around a low-power fusion reactor, we can use the fusion neutrons to split ("burn up") the used fuel and make more energy at the same time. This is the essence of the hybrid fusion-fission reactor: a subcritical "blanket" of fissionable material surrounding a lower-power fusion reactor used to generate energetic neutrons. Our Conference discussed whether this might work and how soon. It was generally agreed that the significant steps to be taken entailed engineering and materials advances more than scientific breakthroughs. There are various sorts of fusion devices and it is not clear which will work best in this hybrid scenario. Nor is it yet clear which device can be built economically in a reasonable time frame. How long this will take to do is as much a function of our interest and resolve as it is a function of scientific and technological breakthroughs. Work at this Conference showed that a hybrid system, with appropriate choices (of fuel cycles, for instance), may provide a significantly cheaper way to deal with used fuel than competing technologies (which have already been studied and found to be very expen-sive). This is because preliminary computations show that while it might take 35 "fast reactors" to dispose of the waste from our 104 presently operation reactors, the same job could probably be done with 4-6 hybrid systems. Hybrids will undoubtedly be more expensive to build but we may need far fewer of them.

The punch line here is obvious: effectively dealing with nuclear waste also means we help minimize the problem of proliferation. Proliferation worries stem, in part, from the fact that pure plutonium (a very dangerous bomb-grade material) can be extracted (chemically) from used nuclear fuel. If we had a viable way to treat used fuel, a country wishing to set up nuclear generation of electricity could purchase fuel rods from us (thus saving a large start-up cost) and we could take back the used fuel to treat the waste. In this manner that country would never have the used fuel from which to extract plutonium. This very idea has recently been advanced by Russia to Serbia.

The conclusion of the Conference was that we should move ahead with a robust research and development program to explore the practicality of these ideas and to pursue the engineering and materials challenges. This report is the first to put forward these nascent ideas. Secretary of Energy Stephen Chu was recently asked, in an interview for the MIT magazine *Technology Review*, for his perspective on managing the roughly 50,000 metric tons of nuclear waste stored at some 130 sites across the country, now that the Yucca Mountain storage facility has effectively been cancelled. He replied "we're looking at reactors that have a high-energy neutron system that can actually allow you to burn down the long-lived actinide waste. These are fast neutron [fission] reactors. There's others, a resurgence of hybrid solutions of fusion fission where the fusion would import not only energy, but again creates high-energy neutrons that can burn down the long-lived actinides."

We may be ready for a "prime time" consideration of hybrid fusion-fission systems as waste burners! This waste does indeed pose a serious problem. It may well be that the hybrid systems will provide the best solution for getting rid of the troublesome long-lived actinides.

This R&D program will select which sort of fusion reactor is best-suited to this process. Although this selection will make a particular lab or group of scientists the "primary contractor" for the fusion device, it is clear at the outset that there will be enough high-level development work to keep all interested parties busy.

HYBRID FUSION SYSTEMS

What can they do and can they do it soon? An Interdisciplinary Approach

CONFERENCE of THE CENTER FOR HYDROGEN FUSION POWER
(COURANT INSTITUTE, NYU)
and
THE BROOKINGS INSTITUTION (Washington DC)

TUESDAY, MAY 19

8:00 **Buffet Breakfast**

9:00 **Martin Avery Snyder**

Courant Institute of Mathematical Sciences, New York
Adjunct Senior Research Scientist
President Q.E.D. Inc.

- *Welcome and Conference Overview*

9:10 **Andrew Kadak**

Massachusetts Institute of Technology
Professor of the Practice, Nuclear Engineering

- *Overview of the US nuclear waste situation as seen by the nuclear industry and the government. Governmental, societal, and intrinsic constraints on future development of nuclear waste solutions.*

10:00 **Yousry Gohar**

Argonne National Laboratory
Senior Nuclear Engineer
Section Manager of Applied Physics and Nuclear Data Section

- *Overview of nuclear fuel cycles for the disposal of nuclear waste and fuel production. Governmental, societal, and intrinsic constraints on future development of the optimal fuel cycles.*

10:45 **Break**

11:00 **Michael Zarnstorff**

Princeton Plasma Physics Laboratory
Principal Research Scientist
Distinguished Laboratory Fellow, Princeton University

- *Overview of magnetic fusion drivers for possible use in hybrids for fuel production and/or waste disposal.*

11:45 **Erik Storm**

Lawrence Livermore National Laboratory
Program Manager for Advanced Inertial Fusion Energy

- *Overview of inertial fusion drivers for possible use in hybrids for fuel production and/or waste disposal.*

12:30 Buffet Lunch

2:00 Kathryn McCarthy

Idaho National Laboratory
Deputy Associate Laboratory Director for Nuclear Science and Technology Director of the Systems Analysis Campaign for the Department of Energy Advanced Fuel Cycle Initiative

- *Challenges in recycling used nuclear fuel*

2:45 Break

3:00 BREAKOUT SESSIONS – see separate notes at end of program

SESSION A – Fusion Drivers: IFE, mirrors, ST's, stellerators, et al.

SPEAKERS

Dimitri Ryutov, Lawrence Livermore National Laboratory (*mirrors*)

Michael Kotschenreuther/ Swadesh Mahajan, University of Texas (*spherical tokamaks*)

Leonid Zakarov, Princeton Plasma Physics Laboratory (*First FFH* (*first superconducting tokamak FFH*) *as a reference device for hybrids*)

Jeffrey Harris, Oak Ridge National Laboratory (st*ellerators*)

Erik Storm, Lawrence Livermore National Laboratory (*LIFE inertial fusion*)

SESSION B – Fusion Technology Issues: materials, magnets, heating sources, fusion/blanket interface, et al.

CHAIRMAN: Andrew Kadak

SPEAKERS

Swadesh Mahajan/ Michael Kotschenreuther, University of Texas

(*possible uses of fusion to deal with nuclear waste*)

Drew Hazelton, SuperPower, Inc., Principal Engineer, high temperature superconductor applications (*status of 2G HTS Superconductors for advanced magnet technology*)

Greg Moses, University of Wisconsin (*topic to be announced*)

Roald Wiegland, Idaho National Laboratory (*past and current nuclear fuel cycle issues*)

WE WILL ADJOURN ACROSS THE STREET TO THE BROOKINGS INSTITUTION FOR COCKTAILS AND DINNER 6 - 8:30 AT THE BROOKINGS INSTITUTION

8:30-9:00 **Wally Manheimer**,

U.S. Naval Research Laboratory (retired)

- *An integrated energy park scenario*

WEDNESDAY, MAY 20

8:00 **Buffet Breakfast**

9:00 **Albert Machiels**

Electric Power Research Institute
Senior Technical Executive

- *Overview of non-fusion solutions to the problems of waste disposal and fuel production.*

9:45 **Steven Frantz**

Morgan Lewis & Bockius, attorneys at law
Partner, Energy Practice Group

- *Statutory and Regulatory Provisions Governing Fusion Power*

10:45 **Comments by Roald Sagdeev, Distinguished Professor of Physics, University of Maryland. Harold Weitzner will then lead discussions on the proper role for the hybrid – main use, time scale, comparisons, etc.**

12:00 **Lunch**

Following lunch we will try to arrive at Consensus answers to the Conference questions:

- What Can Hybrid Systems Do?
- Can They Do It Soon?

Writing assignments will be made to produce a conference report.

PURPOSE AND FORMAT OF BREAKOUT SESSIONS AND SUBSEQUENT DISCUSSIONS

After the overview presentations the attendees will separate into two breakout sessions, one focused primarily on fusion issues, the other on fission issues. It is important that each session have crossover members so that both fusion and fission experts will be present at both.

The main goal of the breakout sessions is to have more detailed and in depth discussions of the scientific and engineering issues facing each community. The end result will hopefully be a consensus on the future role of hybrids for energy security in the United States. Possible outcomes might be one of the following:

- The hybrid represents an excellent opportunity to improve the viability of the nuclear renaissance and should be pursued on a short time scale – on the order of 10 -20 years.
- The hybrid represents a good opportunity to improve the viability of the nuclear renaissance and should be pursued on a medium time scale – on the order of 20 -35 years.
- There is no real need for the hybrid in the foreseeable future and fusion should focus primarily on the pure production of electricity.

With this high level goal in mind, the specific issues addressed in each breakout session should include the following:

The Fusion Breakout Session

- Does the fusion hybrid compare favorably or unfavorably with respect to other alternatives such as breeders, accelerator hybrids, deep-burn gas-cooled modular helium reactor (MHR) reactors, repositories, deep bore holes, etc.? Issues to consider are technological readiness, economics, proliferation resistance, and environmental impact.
- What are the main generic technology and engineering problems facing a fusion hybrid, either MFE or IFE? In approximately how many years can one reasonably expect a solution to these problems and at what cost?
- How do the various MFE and IFE hybrid schemes compare with one another in terms of scientific and technological readiness, economics, and environmental impact?

Most of the e-mail discussion with fusion attendees so far appears focused on the third bullet with multiple requests to make a presentation at the breakout session. We would not be able to address the more important higher level issues represented by the first two bullets if we filled up the breakout session with too many lengthy presentations. As such we request that each speaker be limited to an absolute maximum of a 20 minute talk plus 10 minutes discussion to describe their hybrid option. Nonetheless, we expect the speakers to make the case that their fusion system is a probable and possible (?) solution to the problem of waste disposal, or integrated energy system, as appropriate.

We emphasize that much of the discussion should be focused on the first two bullets since the US currently does not have a serious fusion funded hybrid program and many scientists have yet to be convinced that such a program is a good idea.

The Fission Breakout Session

- Does the fission industry need hybrids? If so, what is the main application and when is it needed?
- Do the DOE Divisions that support nuclear power need the hybrid? If so, what is the main application and when is it needed?
- Assuming that the hybrid addresses an important problem facing the future of fission is this the best technology to address the problems or do other alternatives seem more attractive either technologically and/or economically?

The issue here is that the fission community is the main customer for the hybrid and up until now there has not been a great need for this technology. Has the situation changed and if so why?

Participant Consensus of Conference Results

One of the critical problems facing the world today is an assured and clean supply of energy. The only greenhouse gas-free source of base load electricity available now, capable of considerable and reasonably rapid expansion, is nuclear fission, currently producing over 20% of the electricity in the United Stated. As President Obama has noted several times, the expansion of nuclear power is tempered by concerns of used fuel management and the proliferation of dangerous materials which might be used for illicit purposes other than energy generation.

With this background this Conference reviewed the current state of fusion technology to see if a combination of fusion and fission systems (the so-called hybrid reactor) could successfully address these challenges in a reasonable time frame. Even with more than 70% of the U.S. population favoring expanding nuclear energy the used fuel issue is a major deterrent to further development. At a recent MIT conference Senator Tom Carper (D-Del.), who chairs the Senate Subcommittee on Clean Air and Nuclear Safety, stated “we need another Manhattan Project to figure out what to do with all the spent fuel.”

A fusion fission hybrid is a nuclear facility with a central core where the fusion reactions take place, surrounded by a blanket of used nuclear material coming from the reprocessed used fuel from light water reactors. The fusion reactions generate neutrons that would enter the blanket region fissioning the fuel and transmuting the other longer lived radioactive isotopes into shorter lived isotopes allowing for easier disposal.

The key findings of the conference are that in the hybrid mode, the fusion device does not have the extremely difficult plasma physics requirements for harnessing the power of fusion energy as exist for the direct production of electricity by either magnetic or inertial confinement. This implies that a fusion device, which is capable of providing a large number of neutrons needed for used fuel treatment (transmutation), is a nearer term possibility. These low power gain machines, however, still must deal with a series of complex engineering and technology problems, whose overall difficulty is comparable to that required for pure fusion electricity.

In its transmutation mode, the hybrid will also be able to produce power using the blanket as an additional source of heat for power production. An additional technological challenge is associated with the integrated design of the surrounding blanket which has both the fission mission of burning waste and the fusion mission of breeding tritium. This has not been done before.

In terms of the nuclear fuel cycle, the fundamentally same proliferation resistant technologies need to be developed to allow for transmutation by either pure fission or hybrid reactors. The key technology development issue is the fuel form used in either type of system.

The technological challenges facing the hybrid have been known for decades but progress in resolving the issues has been slow because of dwindling research funds particularly in the engineering and materials area. This situation needs to be corrected and leads to the third finding.

The Conference concluded that what is needed now is a robust Research and Development program to carefully and promptly define these problems and offer preliminary assessments of possible solutions.

Only then can a fair assessment be made as to the usefulness of hybrid systems as compared to competing technologies such as sodium cooled fast reactors and particle accelerators used as a neutron source.

The conventional time frame to deploy such a facility is probably 25-30 years. This timeline is consistent with expectations of alternative transmutation systems being considered. With a “Manhattan-like Project” as envisioned by Senator Carper and with a commensurately aggressive funding plus a presidential mandate a fifteen year time frame might be possible. Even with the added resources the technological problems may be sufficiently difficult as to warrant another decade of R&D. While the challenges associated with marrying fusion and fission technologies are large and should not be understated, the possible gains are also large which would benefit the advancement of both fusion and fission technologies. How seriously we regard the problems to be solved will no doubt strongly influence how long it will take to solve them.

Fusion Drivers for the Hybrid

Harold Weitzner
Director, Magnetofluids Division
Courant Institute of Mathematical Sciences
New York University

There are many variants of significantly different fusion neutron sources that could be appropriate for the fusion fission hybrid. During the conference there were two talks that laid out the options: for magnetic fusion drivers, Zarnstorff, and for inertial confinement, Storm. In a breakout session advocates of several magnetic fusion drivers presented their ideas and there was a continued discussion of the inertial fusion options. The participants at the meeting clearly lacked the time for a thorough and critical evaluation of any and all of the options, Nonetheless, it is possible to obtain some sense of the status of the drivers, vis-à-vis the requirements for the hybrid. The proponents typically presented the best case for their ideas and were able to describe some of the unresolved issues associated with each proposal.

The consensus was that there are indeed credible proposals for fusion sources to drive a hybrid system. No existing facility is precisely what is needed for the hybrid. Thus, each proposal is an extrapolation from the existing data base of experimental and theoretical understanding. The extent of the extrapolation is largely in the eye of the beholder. None is an unreasonable stretch from what is known now, but none is absolutely assured. The need for additional experimental facilities is very possible for many of these concepts. Whether such facilities could be an initial phase of a final fusion driver is also an open question. International collaboration has been an essential element of the world fusion programs, and many of the proposals depend heavily on work that has been and will be done outside this country.

Each of the proposals has a number technological and engineering challenges. Although they can be described with the same words they are, for the most part, different in scope for each design. They all need to insure sufficient availability and adequate length of duty cycle. For some options thermal cycling may cause problems. They all require materials that can handle the heat and neutron loading planned. Problems of accessibility and repairability in a hostile environment are common. Blanket designs are not fully thought out. External energy sources, and is some cases current sources are needed and may cause difficulties. If one were to select one or several of the options one could easily start the consideration of these problems in parallel with the needed development of the driver.

This section aims to give a brief description of a number of the fusion drivers as seen by their advocates. We repeat there was no attempt to choose among the possibilities. This text would be best read in conjunction with the presentations, which contain pictures that make the descriptions clearer. The options divide naturally into inertial confinement schemes, Storm, and magnetic confinement schemes, Zarnstorff. The magnetic confinement schemes split into open systems, Ryutov, in which the magnetic field lines are not confined in space, and closed systems in which the magnetic field lines through the plasma remain in some bounded domain, typically something that looks like a donut, or a torus. Each group will be described separately.

The inertial confinement option discussed, Storm, is based on and is dependent on continued successful operation of the NIF facility and the successful, subsequent ignition experiments. A broad group of possible options, called LIFE, Laser Inertial Fusion Engine, will be the follow-on to NIF. Different energy sources, lasers, heavy ion beam accelerators, or Z pinches are possible; different targets are considered, and various ignition chambers are possible. A preferred design is not yet a settled issue. It is expected that different modes of hybrid operation could be designed, ranging from purely spent fuel destruction, to spent fuel destruction plus some energy production, to the possibility of a complete cycle of net energy production coupled with burn up of all fission products. The choices will be made at a later date and depend on needs, engineering constraints, and NIF experience. It is generally accepted that the engineering issues are the most critical problems, and one could accelerate the program if one carried out engineering studies in parallel with the current and planned experiments.

The unique "open" magnetic fusion option, Ryutov, is based on the axisymmetric mirror machine. The U.S. stopped experimental research on mirror machines over fifteen years ago, although theoretical and engineering studies have continued. There have been active experimental programs in Russia and in Japan, and U.S. scientists have participated in research on these machines. In an axisymmetric mirror, the magnetic fields are produced by relatively simple superconducting coils. The plasma is heated by powerful neutral beam accelerators. Fusion occurs primarily in the plasma core near the region of largest magnetic field, and the plasma is stabilized by special chambers at the ends of the device. The Russian experiment, GDT, gas dynamic trap, has demonstrated much of the performance needed for the hybrid, although a number of non-trivial questions remain. The hybrid would require a scale-up from GDT and better performance that it has shown. The issues can likely be resolved, but in addition, more thorough hybrid designs are necessary to assess the requirements of the GDT system.

The remaining magnetic fusion options all have plasmas that look very much like a torus. Several are symmetric around the torus and are loosely derivative of the tokamak. One system, the stellarator, is not fully symmetric around the torus. The designs based on a conventional tokamak, Mannheimer and Stacey (the latter not present at the meeting), in a conventional arrangement, are expected to be fuel and energy producers, as well as spent fuel destroyers. These designs require satisfactory completion of the ITER program before one could go on the design a hybrid. The problems they face are exactly the problems ITER has been designed to explore and solve.

There are however variations on the tokamak concept which have development paths not dependent on ITER. Two are based on design of a torus with a relatively small aspect ratio, i.e. ratio of the radius of the ring to the thickness of the torus itself. These configurations have been studied experimentally and theoretically robust stability at high normalized (but not absolute) plasma pressure has been demonstrated. A standard problem for all the toroidal devices is how to treat the plasma edge.

One device, Kotschenreuther/Mahajan, uses a specially designed divertor to handle the edge problems. Their design has other novel features including a replaceable fusion core. Outside the fusion core is the region with the spent fuel which is to be treated. Their approach solves a number of difficult technical and scientific problems. Additional design issues can be studied and treated in the Princeton NSTX experiment. Another variation, Zakharov, aims to solve the edge problem and issues of stability in the plasma core in order to obtain a quiescent, better behaved plasma. A flowing liquid lithium surface on the first wall has been shown to greatly improve plasma properties. There is also some theoretical validation of these ideas. Further tests could also be done on NSTX. While awaiting further confirmation one could easily start hybrid design studies. This approach is closely connected to work in Hefei, China.

The remaining fusion option discussed is the stellarator, Harris. Although this country has one of the major theoretical programs in this field, the experimental program is limited to two university modest sized experiments. The lack of symmetry around the torus opens the possibility of a plethora of design options. These configurations resolve two plasma physics problems in that they easily allow steady state operation and appear to be disruption free. There is no clear "best" choice at this time. There is a very successful experiment in Japan, LHD in operation, and Germany has under construction an entirely different kind of stellarator, W7-X. Stellarators have operated successfully for an hour or more with plasmas relevant for fusion. Stellarators are generally considered difficult to build, but easy to operate. The US had a stellarator of considerable interest under construction at Princeton, which was cancelled in the middle as a result of cost overruns. A variation of the LHD, although not an optimal design, has been proposed as adequate for hybrid purposes. More advanced designs will have to wait for results from W7-X. The concept is ready for serious hybrid design studies.

Fusion-Fission Hybrids – What can they do?

Jeffrey Freidberg
KEPCO Professor of Nuclear Science and Engineering
Associate Director Plasma Science and Fusion Center
Massachusetts Institute of Technology

A fusion-fission hybrid is a nuclear facility consisting of a fusion core, either Magnetic (MFE) or Inertial Fusion Energy (IFE), surrounded by a fission blanket. The fusion core acts as an independent source of high energy neutrons which can be used for a variety of applications in the fission blanket depending upon its design. These applications are (1) the production of energy (i.e. burning), (2) the production of fissile fuel (i.e. breeding), and (3) the management of nuclear waste (i.e. burning and transmutation).

To understand the different applications it is useful to keep in mind that there are two qualitatively different types of nuclear reactions that come into play – neutron capture and nuclear fission. In neutron capture a neutron is absorbed by a nucleus ultimately producing a new element. This is important for fuel production where neutron capture by a fertile material such as U-238 or Th-232 produces fissile fuel in the form of Pu-239 or U-233. It can also be important in waste disposal where long lived radioactive fission byproducts such as Tc-99, I-129, and Cs-135, with million year half-lives, can absorb a neutron and transmute into another radioactive element with a much shorter half life

The second process of interest is nuclear fission, where a neutron collides with the nucleus of a fissile material, for instance U-235 or Pu-239 and splits it into several smaller pieces including additional neutrons. The fission process generates large amounts of energy, used to produce electricity, and the excess neutrons create a chain reaction that self-sustains the nuclear reactions.

Consider now the various applications of hybrids. In general there is some amount of burning, breeding, and transmutation in any of the applications but for purposes of distinction assume the blanket has been designed with one of these processes as its primary mission. The discussion at the conference indicates that (1) a focus on energy will probably not be the most economical option, (2) a focus on fuel production may be a good long term application but will not be needed for about 50 years, and (3) a focus on transmutation may be the shortest term application (i.e. 25 – 30 years) but there are major technological and economic issues that need to be addressed. The details of this summary are described below.

The first application of interest is energy production. The advantage here involves safety. With an independent source of neutrons the fission blanket can be operated sub-critically. That is, without the fusion neutron source the blanket does not create enough neutrons to sustain a chain reaction. However, this is not a major safety feature since existing light water reactors are designed with negative feedback with respect to temperature excursions thereby making a criticality accident all but impossible. The most important danger to protect against is a loss of coolant accident after the reactor has been shut down. Both a hybrid and a Light Water Reactor (LWR) would face similar safety issues so there is no gain here for the hybrid.

In practice current reactors provide safety by defense in depth and newer designs have passive safety where natural convection, without any human action or mechanical intervention is sufficient to cool down the reactor core in the event of a loss of coolant. Furthermore, there is a very high probability that a fusion-fission hybrid would cost substantially more than a light water reactor making the economics unattractive for stand-alone energy production. The conclusion is that if the main goal is to produce nuclear energy safely and economically the best choice for the foreseeable future is the LWR.

The next application of interest is the production of fissile fuel. There is enough natural uranium to last for about 50 – 100 years even with substantial growth in the number of LWR nuclear reactors in the world. Still, after this period it may become too expensive to mine new uranium and here the hybrid offers a good opportunity to expand the fuel supply. Specifically, most of the spent fuel in a reactor, about 93%, consists of the fertile material U-238. As stated, bombarding this material with high energy neutrons produces Pu-239 which can be used as a fissile fuel in a thermal LWR. Similarly, breeding can take place with Th-232 which produces U-233, another fissile fuel well suited for LWR power production. The net result is that breeding fuel using hybrids can extend the use of LWRs for thousands of years, a clear advantage.

There are several competitors that must be considered, namely the fast breeder, the accelerator driven hybrid, and extraction from ocean water. The fast breeder is currently the front runner and has been much more developed than the hybrid. There is a general feeling that in terms of capital cost the following hierarchy holds: LWR <Breeder<hybrid. This hierarchy depends on the application mission. For example, even though a fusion hybrid may be more expensive than a breeder reactor, fewer may be needed for the mission thus making the hybrid system cost lower. Reliance on the fast breeder for fuel may require converting the entire fleet of LWRs to breeders which could also be more costly than LWRs. This would entail an economic penalty as compared to hybrids which would enable continued use of LWRs.

Accelerator driven hybrids are qualitatively similar to fusion-fission hybrids except that the fusion source is replaced by a high energy (i.e. GeV) particle accelerator. Such accelerators are at a more advanced stage of development than fusion devices but many think their capital cost per neutron may be higher. Lastly, there is a vast resource of uranium in the oceans although in very dilute quantities. Ocean extraction sets a ceiling on the price for fuel that must be bested by hybrids if they (hybrids) are to be the source of choice. Overall, the economics will play a major role and is very difficult to predict so far into the future. Also, fuel is a relatively small fraction of the cost of nuclear produced electricity so large fluctuations in uranium price may be tolerable without having too much of an impact on the cost of electricity. For the near term future it makes sense to continue mining uranium from the earth and continuing with an R&D level development program for the various options. It should be noted that the byproduct of uranium enrichment, mostly uranium 238, is available for breeding which could extend the fuel supply for thousands of years.

The last hybrid application of interest is waste management which was largely the focus of this conference. To help understand the issues note that when fuel is first introduced into an LWR it consists of enriched uranium 4% U-235 and 96% U-238. The fuel remains in the reactor for about 3 – 4 years after which its reactivity has decreased sufficiently that it must be replaced. The resulting spent fuel is comprised of approximately 92% U-238, 1% U-235, 1% Pu-239, 0.1% minor actinides, and 5% fission byproducts. All of the radioactive elements naturally decay into stable elements on a time scale proportional to their half-life. A large fraction of the spent fuel has half-lives on the order of 30 years or less. Thus, after storing the spent fuel for a humanly comprehensible time on the order of 50 – 100 years a large fraction of the spent fuel decays into harmless elements. In a sense this is ideal waste – it largely self destructs in less than a century.

The troublesome components of spent fuel are the long-lived components which consist primarily of plutonium, the minor actinides americium, neptunium, curium, and the fission byproducts Tc-99, Cs-135, and I-129. It is important to keep in mind that the volume of these long lived radioactive elements is very, very small. For example, the volume of minor actinides produced by a 1 GWe LWR during one year of operation corresponds roughly to 0.14 cubic feet, equivalent to a six-pack of beer.

There are two hybrid approaches that can be used to eliminate the publicly unacceptable long lived radioactive elements. In the first approach the spent fuel is chemically reprocessed in order to physically separate it into its separate components. Some minor actinides can then be cast into a fuel form which can be fissioned when bombarded by high energy neutrons such as produced in a hybrid. In addition to eliminating the waste, energy is produced – a good side benefit. The remaining minor actinides can be transmuted into isotopes with shorter half lives as well. However, as a result of the fission process, a certain fraction of the reactions involve neutron capture, thereby producing more actinides. The end result is that the amount of minor actinides can be substantially reduced but never completely eliminated. A geological repository will still be needed, although its effective capacity can be increased by more than an order of magnitude.

The long-lived fission byproducts can also be bombarded with high energy neutrons, transmuting them into other radioactive elements with shorter half-lives. These can be stored with the bulk of the spent fuel and decay to harmless stable elements in a relatively short time.

There are two difficulties with this approach. Reprocessing of spent fuel is a complex chemical process of separations to extract useful materials from the waste. Technologies for separations have been developed and are currently deployed in Europe, Japan and Russia. These technologies involve separating plutonium which is considered by many to be a proliferation risk even under strict safeguards. Presently alternative reprocessing schemes are being considered that would avoid the use of separated plutonium while still being able to take advantage of its energy potential. Second, the development of actinide fuels and transmutation targets is in its infancy which much research and development needed. In the transmutation mode, technology development for the hybrid and for fission "burner" systems is approximately the same. For the hybrid, the form of the fuel, liquid or solid is still to be determined based on the design of the systems.

The second approach to deal with the long lived radioactive products involves deep burn. With an independent source of neutrons one can leave the fuel in the reactor for a much longer period of time. As the fuel reactivity naturally decreases during burn, additional neutrons produced by the hybrid core serve to keep overall reactivity at the desired level to produce power. What this process does in remove many of the undesirable actinides and fission products without necessarily needing to reprocess. In the end, there is a comparable amount of waste as would be produced in the usual 3 – 4 year fuel lifetime but containing less long lived isotopes.

The major difficulty with all of these options is economics. The addition of the fusion core adds considerably to the capital cost of the plant. The same amount of energy could be produce using standard

LWRs and the question that then arises is whether the cost differential associated with the hybrid is the most economical way to eliminate the waste.

The main competitors to the hybrid for waste management are deep burn fast reactors, geological repositories, interim storage, on site storage, and actinide burial in deep bore holes. All of these are further developed than fusion-fission hybrids but are not moving forward because the US has yet to decide a path forward for nuclear waste management.

In the long term the hybrid may offer a competitive solution to waste management, once the path forward is established. In the short to mid term (the next 10 -50 years) the likely default approach will be to continue on-site storage, perhaps adding centralized interim storage somewhere in the US. Should the Nuclear Regulatory Commission find that Yucca Mountain is an acceptable disposal site, it provides another option to consider for either direct disposal of spent fuel or processed wastes. If the hybrid can be show to offer an economical solution to waste management, this could change the default situation.

This summary does not attempt to make a choice between magnetic or inertial fusion energy but rather focuses on possible applications. To make such a choice will require considerable engineering, design and cost estimation for each application mission. The combination of technology readiness and economic competitiveness will be the determining factor between magnetic and inertial fusion systems and other alternative technologies for each application.

Nuclear Power Issues

Roald Wigeland
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There are a number of potential concerns about the use of nuclear power covering a wide range of issues. Although many of these concerns are not new, their perceived importance has been instrumental in past decisions on the directions of nuclear energy research and development in the United States. The disposition of the used nuclear fuel and other radioactive wastes is not yet resolved, and there is still substantial uncertainty about the eventual solution to the nuclear waste issue. The use of civilian nuclear power and the ability to proliferate nuclear weapons capability can be connected, resulting in additional concerns about the risks of using nuclear power. Other issues such as safety, economics, and sustainability that were more prominent in the past are still relevant. Finally, in the aftermath of the terrorist attacks of September 11, 2001, security and the risk from terrorist threats feature prominently on the list.

While it is probably not possible to arrive at a consensus on the relative importance of these concerns, it is possible to identify the source of the concerns and consider the required characteristics for approaches that may offer the potential to lessen or even eliminate the concerns. The ongoing Advanced Fuel Cycle Initiative (AFCI) Options Study supported by DOE-NE was started earlier this year to take a broad look at nuclear power and the issues. The goal of the study is to identify and analyze potential options for their ability to resolve the issues with nuclear power, beginning with documenting the issues and concerns, followed by an accounting of all of the previous studies looking at nuclear power and the issues, and asking the question if we can continue with the current 'once-through' approach followed by disposal of used fuel, or do we need a different strategy for the future use of nuclear power? The results are intended to inform decisions on the future directions of nuclear energy R&D, assessing how far existing or evolutionary technologies can go in addressing the issues and identifying what technological breakthroughs may be needed to be able to succeed.

The AFCI Options Study has identified six general areas where there are issues with the current use of nuclear power in the United States and internationally. Each of these issues results from one or more characteristics associated with the use of nuclear power.

Nuclear waste - In general, the radioactive wastes from using nuclear power, including the used fuel, high-level waste (HLW) and low-level waste (LLW), can be hazardous for a very long time mainly due to the presence of long-lived radioactive isotopes. While the potential risk from LLW is low, and therefore this material has been typically buried using near-surface disposal, the used fuel and HLW represent a much higher risk due to the amount and hazard of the contained materials. The risk from exposure has prompted decisions that the only acceptable disposal path for used fuel and HLW is isolation until the hazard has been sufficiently reduced through radioactive decay, a process that may take hundreds of thousands of years or longer. Even though deep geologic disposal is the currently preferred method for isolation, uncertainty about the ability to provide sufficient isolation dominates research and development of disposal pathways, as for the proposed repository at Yucca Mountain.

Proliferation Risk – Uranium enrichment technology to create low-enriched uranium for reactor fuel can be used to produce high-enriched uranium for nuclear weapons. Neutron irradiation of uranium or thorium can produce materials such as plutonium-239 or uranium-233 present in used nuclear fuel that would be suitable for use in nuclear weapons. The technologies for processing the used fuel to recover such materials for further treatment may also be used to separate them for potential nuclear weapons use. The spread of processing technology information and equipment may need to be controlled if the proliferation risk is to be addressed.

Safety – Nuclear power reactors use fissionable materials to produce large quantities of energy in a relatively compact nuclear reactor. Controlling the energy production, ensuring adequate heat removal, and retaining the radioactive materials within the reactor are all important in order to satisfy safety requirements. The safety of nuclear power has been an issue in the past, especially in the aftermath of the Three Mile Island and Chernobyl accidents and concerns persist today about the ability to use nuclear power safely. Due to the radioactive materials, all facilities and activities, including processing, transportation, and storage, may have safety-related risks due to the potential for accidents that can disperse radioactive materials.

Security – Due to the presence of radioactive materials in the used fuel in the facilities required for use of nuclear power, such as reactors and used fuel storage, there is a risk that a terrorist attack or sabotage could result in radioactive release and exposure of the public and the environment. The ability to provide security of the radioactive materials and facilities to prevent such events is a growing concern.

Economics – Cost competitiveness of nuclear power has been an issue for several decades, primarily due to the large capital investment at risk in building nuclear power reactors, given uncertainties about licensing, time required for plant construction prior to operation, permission to operate the plant once constructed, and cost recovery once the plants have been approved for operation.

Sustainability – The ability to sustain nuclear power depends on resolving existing issues and will also depend on the availability of resources in the future. Overall environmental impact may be an issue if the impact is judged to be significant.

For all six of these general areas of concerns, technology and design choices are available that impact these issues to one degree or another. The acceptability of the choice of a specific technology could depend on the extent to which these concerns are addressed.

Addressing the Issues

In consideration of these issues, the desirable attributes for potential nuclear energy systems, including fusion-fission hybrids, can be identified. The waste management issues are related to the hazards represented by the long-lived actinides and fission products, and systems that transmute these elements can have a favorable impact on waste management. For many of these elements, transmutation can be accomplished with further neutron irradiation, preferably fast neutrons for the actinide elements. One approach is the fast neutron reactor, and such systems have been studied, developed, and successfully operated using uranium and plutonium fuel. However, with the advent of the need for transmutation of transuranic elements and fission products, there is the possibility that a reactor-based approach may not be the most suitable option in all cases, partly due to the reactivity implications from including such materials in the fuel and partly from the practical challenges associated with designing and fabricating such fuels for use in a reactor. In addition, there are indications that systems like fusion-fission hybrid reactors may work faster at waste disposal than fast reactors, and thus may require significantly fewer devices to service our fleet of existing light water reactors. Depending on the intended purpose of the fusion-fission hybrid and the approach taken, such as transmutation of actinides with recycle of irradiated fission blanket materials, the remainder of the system could involve facilities and operations that are comparable to those for reactors including processing and fuel fabrication facilities, all of which will contribute to generation of radioactive wastes. All of these performance characteristics need to be explored further and verified before a comparison can be made between the different systems. For these reasons, systems such as the fusion-fission hybrid system should be examined in detail, although it is also important to acknowledge that some of the same reactor-related issues may be relevant for the hybrid systems.

The fusion / fission hybrid systems are typically proposed with a ‘small’ fusion device of 10-20 MW that is used to generate neutrons which are then transported into an adjacent region where the neutron irradiation of actinides and fission products would occur, a ‘fission blanket’. In all cases, there is the challenge of designing a fission blanket that can be placed in the vicinity of the fusion device. The fission blanket may also need to generate a substantial amount of energy which would require significant neutron multiplication in the blanket. The hybrid fission blanket would require addressing the same engineering issues that confront reactor designers, including adequate cooling of the materials. The actinides and fission products could be contained in ‘fuel’ in a manner similar to that used for reactor fuel, although the approach may not be the traditional approach of fuel inside metallic cladding. Options such as having the materials dissolved in the coolant or as small particles of ‘fuel’ in the coolant could be considered for the hybrid, in the same manner as they are being considered for reactors. Materials issues similar to those for reactors are also present, depending on the design and the projected neutron fluence, just as these issues affect reactor design. The fission blanket faces the same issues of potential variation in power production across the fission blanket as one has in reactors and the coolant system design must account for such variations. In many ways, the design of the fission blanket is comparable to design of a reactor core, with all of the same issues, and offers opportunities for research and development that could be suitable for either approach.

The fusion device will also have development and engineering challenges, although the small power output of the device may make the challenges less severe as compared to a fusion reactor. The fusion-fission hybrid would also need a power production system to offset the power required to run the fusion-fission hybrid, possibly producing excess power in some designs resulting in net power generation from the facility. Given that the fission blanket is similar to a reactor core, systems that have been developed for use with reactors could also be considered for the fusion-fission hybrid and should not present any unusual challenges.

Presentations

Presentations

Conference of the Center for Hydrogen Fusion Power
Courant Institute – New York University
The Brookings Institution – Washington, D.C.

Hybrid Fusion Systems
May 19 – 20, 2009

Status of the United States Nuclear Waste Management Program

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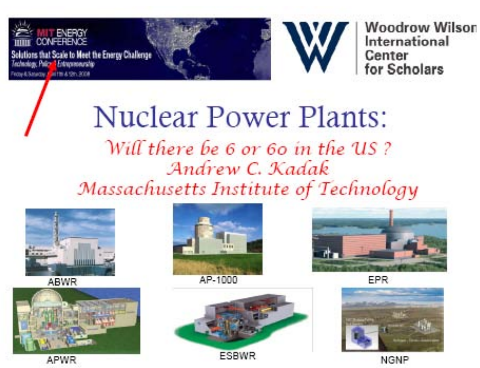
Good morning and thank you for the invitation to address the topic of the United States nuclear waste management program. Before I begin my remarks I would like to say that these are my personal comments and since I serve as a Presidential appointee on the United States Nuclear Waste Technology Review Board, my comments do not necessarily represent the thoughts or positions of the Nuclear Waste Board.

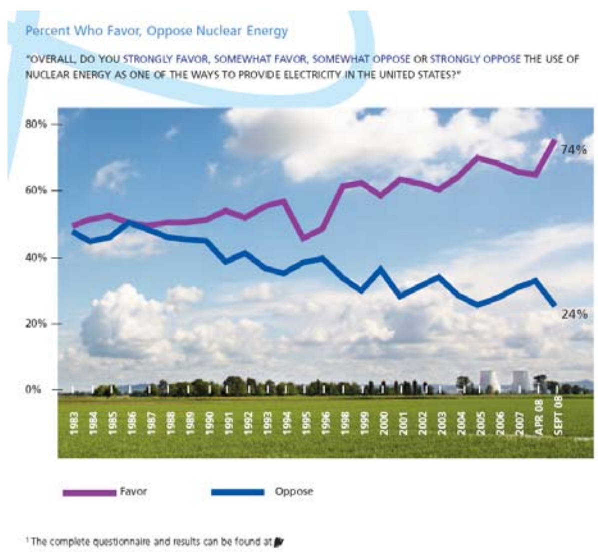
First allow me to review the status of the United States nuclear program to provide some perspective on the problem. We have 104 operating reactors in the US that provide approximately 20% of the electricity for this nation. There have been no new orders since the mid 1970's, before the Three Mile Island accident. At present, there is however renewed interest in new nuclear plants. Twenty six new license applications have been filed with the Nuclear Regulatory Commission for construction and operating licenses. Of those 26, four have firm contracts to build new reactors. The current state of the commercial nuclear technology is evolutionary light water reactors. These reactors are improvements over the current designs based on years of operating experience to improve their safety, reliability and cost of production.   Some are more robust relying on active safety systems and others are more passive relying more on natural gravity feed systems to provide emergency core cooling.



One of the challenges of these new reactor designs is that despite efforts to simplify designs and reduce complexity, these plants are very capital intensive. A typical 1500 Mwe plant can cost over $ 6 Billion in overnight capital cost. While the fuel and production costs are low, the upfront capital cost makes investment in such plants a financial challenge. Thus the decision to build a new plant is a significant one despite the long term cost savings and contribution to reduction in CO_2 emissions. Should price on carbon be included in the cost of fossil power, nuclear plants can be competitive in the near term as well.

One of the critical questions is how many new reactors will actually be built and what are we going to do with the waste from the existing and new reactors. Today, the public is generally more confident about the safety of reactors since the Three Mile Island accident that occurred over 30 years ago. The industry has made substantial improvements in the safety of the plants and their performance.

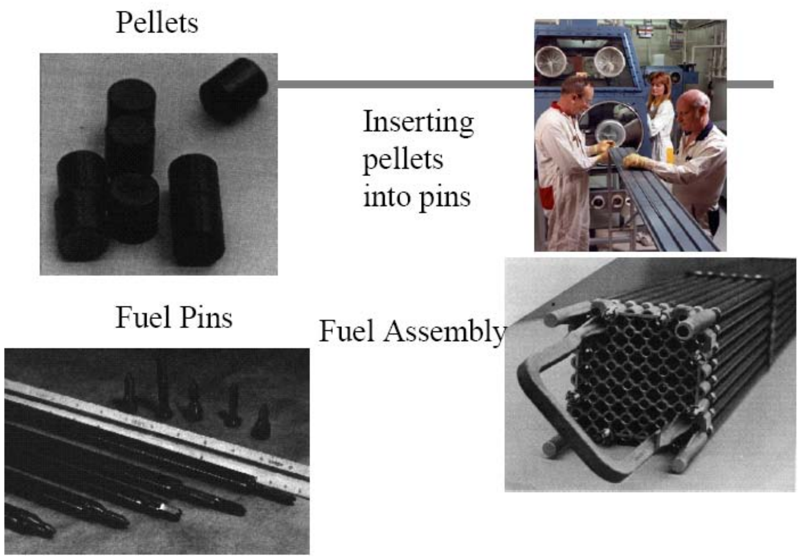
Support for new nuclear construction is at an all time high.



Recent surveys indicate that approximately 75% of the people in the US believe that nuclear power should be used as part of our future energy mix. This dramatic change in position over the early 80's is due to several factors. First is the excellent safety record; second is that these nuclear plants are very reliable performers operating at over 90% capacity factor (which is a measure of its useful output over the course of the year); and third, an increasing awareness and concern about global warming and the emissions from fossil plants.

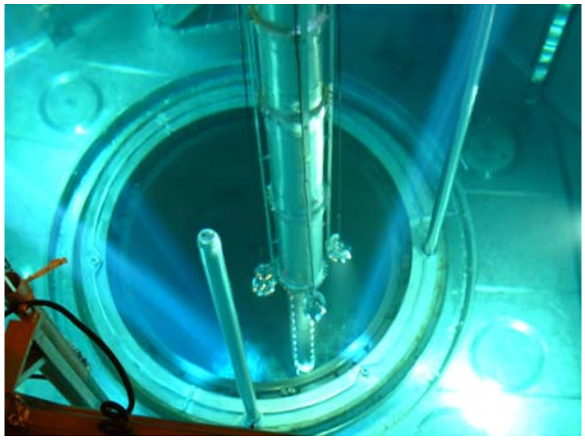
Even though much is made of reducing our dependence on foreign oil, actually very little oil is burned in electric generating plants (less than 8%). It should be note that close to 50% of our power comes from coal fired plants. This is obviously a problem due to the emissions from these plants, but coal is a naturally abundant resource in the US and an inexpensive alternative. Future coal plants will likely be required to have more stringent pollution control systems and the ability to capture the carbon dioxide emitted and store or sequester it in underground geological repositories. The technology for carbon capture and sequestration is not commercialized or necessarily demonstrated. Most studies, including the recent MIT coal study produced in 2006, suggest that the cost of power could go up by 30-40%, should carbon capture and sequestration be required. This, of course, would not be a good thing for the American economy, but needed if human caused climate change is real.

Now back to the question of nuclear waste. At present we produce about 2,000 metric tons of spent nuclear fuel each year from the existing operating reactors. This translates to approximately 7,000 fuel assemblies per year for the nation.



Fuel assemblies are made up of fuel rods in which the chalk size diameter uranium pellets are contained in zircaloy tubes, arranged in 12 foot long bundles containing anywhere from 110 to 290 fuel pins.

Once out of the reactor, these fuel assemblies are very radioactive and generate about 120 kilowatts of heat when initially discharged which reduces to less than 5 kilowatts in one year after discharge. This decay heat initially requires that these spent fuel assemblies be stored in water cooling pools that are found at the reactors.



Due to the failure of the Department of Energy to provide a disposal site which was supposed to open in 1998 according to the 1987 Nuclear Waste Policy Act, the spent fuel storage pools are being filled to capacity. Thus, the utilities operating nuclear plants are forced to store fuel in dry cask storage canisters shielded by concrete on storage pads at the reactor sites. In some communities there is considerable controversy about expanding these because they believe that these storage sites will be become permanent storage sites for the used fuel, which was not what the local communities signed up for when they originally supported the construction of these plants.

Maine Yankee Spent Fuel

All the high level waste for 25 years of operation !
Message - not a lot of waste to be disposed of in the repository

In the Department of Energy's defense, Congress selected, out of several alternatives, the Yucca Mountain site for the nation's nuclear waste repository. Yucca Mountain borders the Nevada testing site, the location of atmospheric and underground nuclear weapons tests.

YUCCA MOUNTAIN IN THE BACKGROUND

Other view from the Mountain

Nevada was also chosen because it was a dry, arid area with a low population. The Department of Energy, many of the nation's national laboratories and the US Geological Survey have been studying Yucca Mountain for over 10 years, much to the objection of the state of Nevada. The culmination of these studies and analyses was a license application filed with the Nuclear Regulatory Commission in June 2008 to construct and operate a nuclear waste repository for the spent fuel from commercial plants, the Navy Nuclear program, and the nation's laboratories, including defense laboratories.

Congress, in its wisdom, restricted the size of the repository to a maximum of 77,000 metric tons of heavy metal nuclear waste. This artificially imposed limit was established to assure that there would be a need for a second repository and thus showing the state of Nevada that they would not be singled out as the only repository site for the nation. This strategy did not work however since the state leaders are strongly opposed to the Yucca Mountain project. Studies have shown, however, that Yucca Mountain can hold many times this amount of nuclear waste if legislatively permitted.

At the present time, due to the strong objections of the senior senator from Nevada, and the newly elected President's position taken during the campaign that he would prevent Yucca Mountain from opening, the future of the Yucca Mountain is in doubt. While the NRC is reviewing the license application, the administration has zeroed out any DOE money to be spent on the project development or continued studies. There have been some proposals that call for a Blue Ribbon Commission to essentially start over and review the entire issue of what we are going to do with our nuclear waste.

This review, which has not yet begun, is supposed to examine all possible means of waste management, including reprocessing and recycling of the spent fuel, using fast reactors for transmutation which means to convert the waste materials into other materials that have a shorter radiological half life, or can be completely consumed by the fission process in the hopes of reducing the hazard of the material and the volume of waste to be disposed of. This may be an opportunity for the fusion-fission hybrid as a transmutation machine as I am sure we will hear about in the next few days. It should be pointed out, there is, at present, no plan to begin searching for another repository site should President Obama's desire to cancel the Yucca Mountain project succeeds.

Ultimately it will be Congress that determines the fate of the nation's repository program. What is interesting about this entire political situation is that regardless of what waste management strategy is chosen, a geological repository for the residues will be needed in any case.

So where do we stand at present? The NRC is reviewing the license application which must be completed in approximately 3 years to determine whether the site can meet the standards established by the Environmental Protection Agency. Utilities are continuing to store spent fuel at their reactor sites. Proposals for regional storage sites are being suggested which would require the shipment of spent fuel from the utilities to 2 or 3 regional locations for interim storage for as long as necessary.

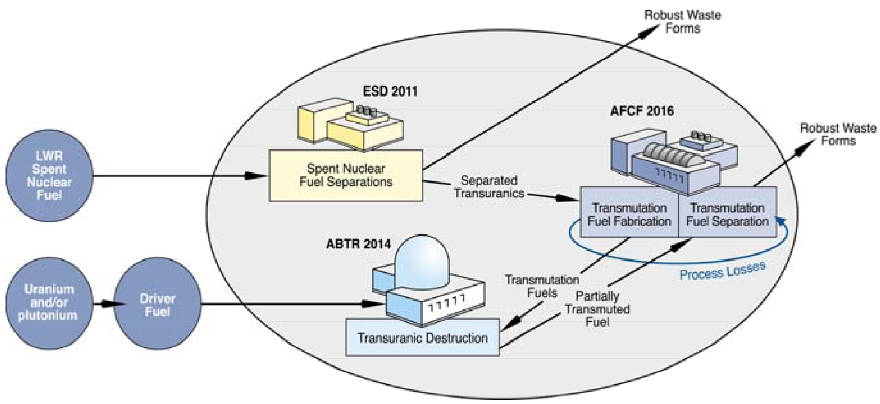
Until such time that the nation decides what it's going to do with the spent fuel generated from our nuclear power stations, the cleanup of waste from former sites of the weapons program such as those in Hanford Washington, DOE research laboratories and the nuclear navy, we will be in a state of limbo. While whatever studies are going on, the spent fuel from our commercial reactors continues to accumulate. By 2020 we will have about 300,000 spent fuel assemblies in storage. By 2040 that number will increase to 420,000.

In the United States, it is the government's responsibility by law to dispose of nuclear waste. There are several challenges facing the government. First, all US utilities have contracts with the DOE to take spent fuel in 1998. Based on the breach of the contracts, most utilities have sued the DOE for failure to meet the contract terms. Estimates have been made that show this liability could reach as high as $ 11 billion coming from the US taxpayer. To pay for waste disposal, utilities collect one tenth of a cent per kilowatt hour for electricity produced by nuclear plants which they give to the government. This money plus earnings on the payments have totaled about $ 19 billion. Congress uses that money to balance the budget and only allocates a small portion of that amount to the development of a nuclear waste repository. The utilities have threatened that if Yucca Mountain project is canceled, they will not only seek to have the payments stopped, but also have all the monies paid into their fund returned since the government has no plan for spent nuclear waste disposal if Yucca Mountain is cancelled.

In short, we have a political mess. Out of this mess comes opportunity for innovative ideas for what to do with the nuclear waste. In June of 2008, when the DOE filed its license application with the NRC, there were high hopes that finally there could be some disposition as to whether the Yucca Mountain site was a suitable waste disposal site for this country. That question may not ever be answered if things continue to proceed as they are. If this question is not answered and, if we do not have a place to dispose of nuclear waste, the likelihood of any community stepping forward and volunteering to host a regional interim storage facility is quite low in my opinion. This is the likely reaction since they will not have any assurance that the waste will move for many years, if ever.

In the recent past, the former administration proposed the Global Nuclear Energy Partnership (GNEP) to deal with a number of problems due mostly in the non-proliferation concerns. The US government does not want other nations to develop reprocessing and enrichment technologies that could be used to make nuclear weapons. The GNEP program called for providing fuel to nations, reprocessing their spent fuel and transmutation of the waste with even the possibility of disposing its waste if these countries would agree to forgo enrichment and reprocessing.

GNEP Facilities



MIT needs Nuclear Chemical Engineers !

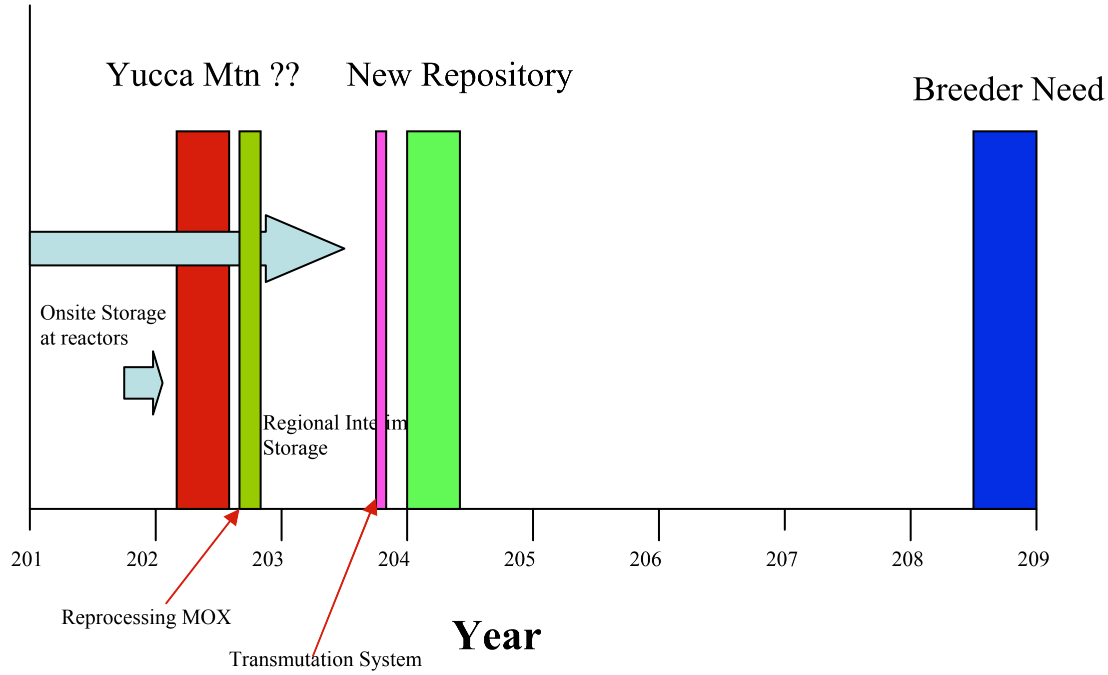
The keystone of the GNEP program was the assurance of a reliable fuel supply and waste management service. The US would build proliferation resistant reprocessing plants that would separate fission products for decay, separate actinides for conversion into fuels to allow for fissioning of some and transmuting others into less long lived isotopes. The transmutation process would not only reduce the volume of nuclear waste, but also reduce the long term radioactive hazard from hundreds of thousands of years to potentially less than a thousand.

Due to the DOE's premature announcements about the ability to technically execute these programs, Congress became skeptical and has essentially canceled the program replacing it with a more research focused program called the Advanced Fuel Cycle Initiative (AFCI).

Now to the question of urgency and role of the fusion-fission hybrid in this process. It is pretty clear that the commercial industry is able to store spent fuel for 60 years or longer without any difficulty at their existing reactor sites or at interim storage facilities. However, that is not a solution to the waste management problem. The solution comes with ultimately disposing of the nuclear waste in geological repositories which the National Academy of Sciences and numerous other organizations worldwide believe is the best strategy. However, the question of **what** to dispose of is now being discussed.

My thoughts on the timing on the deployment of future fuel cycle activities is shown on this chart.

Projected Time Table



The role of the fusion hybrid as a transmutation device is being actively discussed with several proposals on the table. Where it fits on this time line will depend on the ability to demonstrate sustainable fusion reactions. We, at MIT, several years ago, actually did a several small studies on fusion fission hybrids showing that technically it could be done but there were questions on detailed design issues and economics, which is where many such conceptual proposals encounter difficulties. Should the fusion-fission hybrid for waste transmutation continue its development, it will have to compete with other transmutation reactors including the sodium cooled fast reactors which are further along in development, possibly light water thermal reactors, and accelerator based transmutation systems. Whichever technology can show superior economics and technological reliability for the mission will win.

The urgency of solving the nuclear waste problem is really one of perception rather than reality. Utilities can store nuclear waste safely for many years so that is not the question. What is the question is what is it that we will ultimately dispose of which is a political policy question. We do not know when such a decision will be made and how long it will last. While it is a good idea to review waste disposal options, the reality is that a repository is needed regardless of what form the waste takes. It is hoped that the commission will focus on the key questions of what is the best fuel cycle associated with the long term sustainable nuclear energy option. MIT has such a study now underway.

Until that commission completes its job, no policy decisions will be made; no law changes will be attempted. At present the law of the land says that Yucca Mountain is the place to dispose of spent fuel in a once through cycle.

How this issue will be solved in the future is not clear.

The best advice I can give you regarding the fusion-fission hybrid is to put this technology on the table for the blue ribbon commission for not only transmutation of nuclear waste but also for the production of fissile fuel for light water reactors using the breeding of thorium 232 or Uranium 238 to produce U-233 or Pu-239 respectively.

I hope I've helped you better appreciate the status of the US nuclear waste program, I'd be happy to answer any questions.

Requirements, Characteristics, and Options of Fusion-Fission Power Systems

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THE CENTER FOR HYDROGEN FUSION POWER
(COURANT INSTITUTE, NYU)
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Washington DC
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Requirements, Characteristics, and Options of Fusion-Fission Power Systems

Presentation Outline

- General Requirements
- System Characteristics
- Possible Options
- Fusion-Fission Power Systems Examples

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General Requirements

- Generate Energy and transmute actinides and long lived fission products at the same time
- Can be deployed in the near term and contribute a large fraction of the future energy need
- Operate and contribute to close the nuclear fuel cycle of the past, current, and future fission power reactors
- Eliminate or reduce significantly the need for a long-term geological storage for the spent nuclear fuel
- Utilize existing developed technologies and operational procedures, which require only confirmatory R&D and avoid expensive long term R&D programs

General Requirements (continued)

- Use small fusion drivers (power and size) to reduce the impact on the system performance
- The cost (capital and operation) of the fusion driver should represent a small fraction of the system cost
- The proposed systems should improve nuclear safety, enhance proliferation resistance, minimize waste and natural resource utilization, and reduce the capital and operating costs of the spent fuel disposal cost
- Minimize the fuel processing requirements and the associated nuclear waste to close the fuel cycle

System Characteristics

Fusion driven systems can provide a complete, economical, attractive, proliferation resistant solution for disposing of spent nuclear fuel, transuranic materials, and highly enriched uranium inventories. *It can be designed to breed fissile materials.*

Complete

- Transuranic can be utilized without leftover to store or guard.
- Long-lived fission products can be transmuted to eliminate/minimize the need for its storage.

Economical

- The energy content of the transuranic elements is fully utilized.
- The generated energy produces revenue for the system.
- The required new resources are reduced, which improve the lifecycle cost.
- The R&D requirements are minimized, which reduce the total cost and the deployment time.

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System Characteristics (continued)

Attractive

- The required D-T fusion power is very small, which can be realized with the current technologies (Q < 1.0).
- The volume of the radioactive waste generated from the system is relatively small.
- Such fusion drivers provide the opportunity to obtain operating experience for future fusion energy systems.
- The need for the geological repository sites is eliminated or significantly reduced.
- The operation of such systems can improve the public acceptance of the nuclear energy.

Proliferation Resistance

- Pure fissile material streams are eliminated, which are the main concern with respect to proliferation resistance.
- Intrinsic barriers to proliferation such as material attractiveness and ease of recovery are strengthened.

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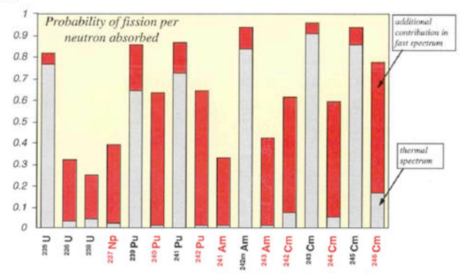
Fusion Driver Options

- **Neutron Spectrum (thermal or fast)**

  Fast neutrons have neutronics advantages for transmuting transuranics and long-lived fission products:

  - Transuranic elements have better ratio of fission to parasitic capture for fast neutrons than for thermal neutrons.
  - Neutron loss to the fission products is relatively small in fast spectrum.
  - Power peaking is less for fast systems.
  - Fast neutron leakage can be thermalized for transmuting some long-lived fission products.



(Francesco Venneri, ATW Program)

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Fusion Driver Options

The following operating features are required for optimal utilization of actinides and transmutation of long-lived fission products:

- **Constant concentration of actinides and long-lived fission products**

  The large change in the concentration of actinides during operation reduces the output power and the transmutation rates of the system. This can be avoided by adjusting the concentration or increasing the fusion power during the operation.

- **High availability for enhanced performance**

  Eliminating the down time for loading and shuffling actinide materials and burnable poison enhances the availability factor.

- **No burnup limit**

  The fuel processing steps to extract the unutilized materials are eliminated, which reduce the operating cost and increase the availability factor.

The mobile fuel (molten salt or liquid metal fuel carriers) is an appropriate option to provide these features.

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Mobile fuels

- Liquid metals, molten salts, and helium are the appropriate coolants for achieving fast neutron spectrum. Fission reactors used these coolant and fusion blankets are developing them for fusion energy systems. The following coolants can also act as fuel carriers:
  - Liquid Metals (Pb-Bi, Pb)
  - Molten salts (Li_2BeF_4, ^7LiCl-KCl, ^7LiF-NaF-ZrF_4, etc.)
  - Lithium Lead Eutectic
- Molten salt fuel
  - **At present, molten salt reactor is operating in Russia.**
  - **The US Molten salt reactor had operated successfully in the 60's.**
  - **Molten salt chemistry control demonstrations are required for controlling the salt composition and avoiding corrosion issues.**
  - **Different molten salts with nonfertile fuel may need further testing.**
- Solid fuel form
  - **Transuranic solid fuel requires development, fabrication, processing, and irradiation testing facility.**
  - **Burnup limit requires fuel recycling, which increases the capital and the operating costs.**

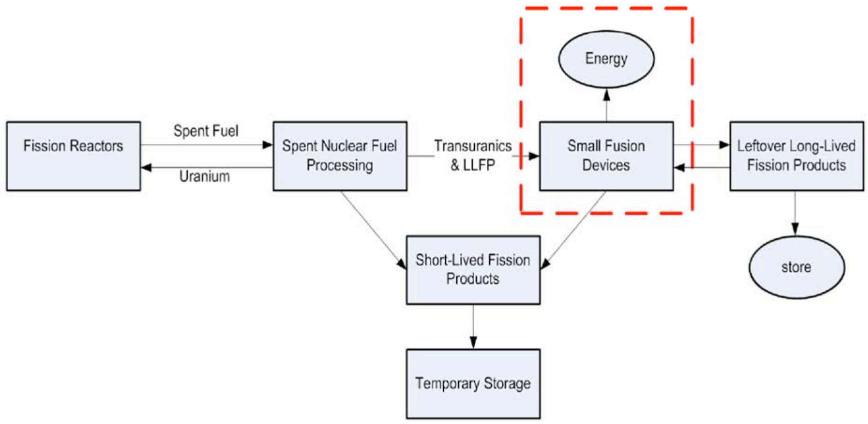
US Commercial Spent Nuclear Fuel Inventory

- **In 2015, the estimated U.S. inventory of spent nuclear fuel is 70,000 tons, which compose of:**

Uranium	**66872 tons**
Short-lived fission products	**2279 tons**
Transuranics	**689 tons**
Long-lived fission products	**160 tons**

- **The spent nuclear can be processed to remove the uranium isotopes and short-lived fission products.**
- **The transuranics, long-lived fission products, and 3.3 tons of uranium (Separation efficiency of 99.995 w%) can be used in fusion drivers.**

Spent Nuclear Fuel Disposal Flow Chart Using Fusion Drivers



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Power and Transmutation Example - 1

- A fusion driver using lead carrier with continuous feed of transuranics and long lived fission products for maintaining a constant composition with constant fusion power has the following characteristic:

Transuranic utilization, Kg/MW.y of fusion neutron power	68.0
Long-lived fission products transmutation, Kg/MW.y	8.50
Number of fission reactions per D-T neutron	10.65
Fusion neutron power for utilizing the actinides of 70000 tons of spent nuclear fuel over 40 full power years, MW	253
Total transuranic utilization, tons	689
Total long-lived fission products transmutation, tons	86
Fusion neutron power per driver assuming 15 drivers each generating 1 GW_e per driver, MW	16.9

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Power and Transmutation Example-1 (continued)

- Lead-bismuth fuel carrier has better neutronics performance than lead. It has been used as fission reactor coolant and spallation target for generating neutrons for accelerator driven systems. At present, It is under development around the world for accelerator driven systems.
- The 70000 tons of spent fuel can be disposed of with the use of fifteen small fusion drivers. Each has a fusion neutron power of 16.9 MW operating for 40 full power years. Such drier will have neutron wall loading of less than 0.1 MW/m^2, which simplifies the driver design.
- Each driver will generate about 1 GW_e, and the total added power is 15 GW_e. This represents a 15% increase in the US nuclear power generation without adding CO2 or spent nuclear fuel to the environment.

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Power and Transmutation Example - 2

- **Molten salt (Flibe) was used as fuel carrier for fission reactors. Also, Flibe is under development for fusion reactors and it is an option for the Generation IV reactors and the Accelerator Driven Systems.**
- **The ORNL MSBR program developed Flibe technologies in the 60's. The ANL fast breeder program developed molten salt technologies for the IFR fuel cycle in the 90's.**
- **Transuranic fluorides are dissolved in the Flibe of the self-cooled fusion blanket concept, which simplifies the geometrical configuration.**
- **As a design option, a separate coolant loop can be used to cool the slowly circulating Flibe carrying transuranics.**

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Power and Transmutation Example-2 (continued)

- Chemical control methods are required to insure compatibility with the structural material and low tritium permeation rate, two methods were successfully tested.
- This blanket concept operates at a low-pressure, which simplifies the mechanical design.
- Flibe has a negative temperature coefficient related to the blanket reactivity, which enhances the safety performance.
- The US, Russia, and Japan operational records of the molten salt (Flibe) reactors were successful. Uranium, thorium, and plutonium were used in the Flibe.
- Flibe are chemically and thermally stable under reactor operating conditions, which minimize the radioactive waste generation.

Power and Transmutation Example-2 (continued)

Self cooled Flibe blanket performance parameters with plutonium

Lithium – 6 fraction	0.0	0.0025
PuF_3 weight fraction	0.00051	0.0056
Blanket energy multiplication factor	242.6	264.0
Local tritium breeding ratio	0.488	10.74
Transmutation rate, kg/MW.y	72.56	79.69
Number of fissions per D-T neutron	16.3	17.9
Neutron wall loading, MW/m^2	0.1	0.1
Blanket poloidal length, m	5	5
Surface heat flux, MW/m^2	0.025	0.025
Flibe temperature change, °C	100	100
Flibe velocity, m/s	1.06	1.15
Flibe inlet and outlet from the top		

Fusion-Fission Power Systems Conclusions

- Fusion option has unique attractive characteristics, which can provide a complete, economical, attractive, proliferation resistant option for disposing spent nuclear fuel by utilizing the actinides for power generation and transmuting the long-lived fission products.
- Modest fusion requirements are needed and a demonstration can be performed with small driven fusion device using the current technologies.
- There is an urgent need to develop detailed conceptual engineering designs optimized for this application for comparison with the other options. Favorable Comparison will accelerate the fusion driver development. In addition, an R&D program is needed to confirm different technological aspects.
- Mobile fuel form permits the fusion driver to achieve optimum performance, reduce the total cost (capital, operating, and development), and shorten the deployment time.

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Overview of MFE Drivers for Fission/Fusion Hybrids

M.C. Zarnstorff

DOE Princeton University Plasma Physics Laboratory

18 May 2009

U.S. DEPARTMENT OF ENERGY Office of Science

PPPL PRINCETON PLASMA PHYSICS LABORATORY

Outline

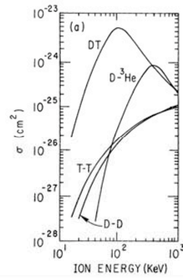
- Fusion Introduction
- Magnetic confinement fusion status
- Options and opportunities for hybrids
- Conclusions

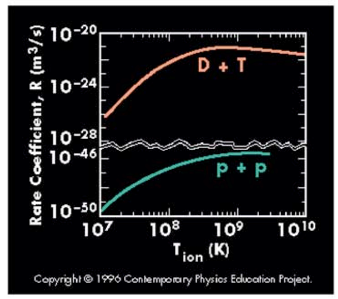
2

Fusion Requires High Temperature Plasmas

- D + T → α (3.5 MeV) + n (14.1 meV)
  highest cross section at lowest energy
- For thermal distributions, reaction rate peaks ~ T = 800 MºC (~70 keV)
- Rate coefficient $\langle \sigma v \rangle \propto T^2$
  for T ~ 170 MºC (~ 15 keV)

  So, reaction rate $n_D n_T \langle \sigma v \rangle \propto n^2 T^2 \propto p^2$
  ⇒ want to maximize pressure
- For self-heated plasma
  fusion heating rate (α) = energy losses
  ⇒ $n\,\tau_E > 3 \times 10^{20}$ (m^{-3} sec^{-1}) for T = 20 keV
  τ_E is the energy confinement time
  (J.D. Lawson, 1957)

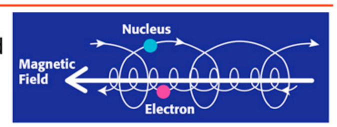




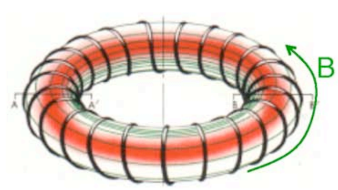
Magnetic Confinement

- Charged particle motion ⊥ to B is constrained by gyroradius

  for 110 MºC (10 keV), 10^{20} m^{-3}
  B = 1 T
  Distance between collisions ~ 10 km
  Gyroradius ρ_i ~ 1 cm



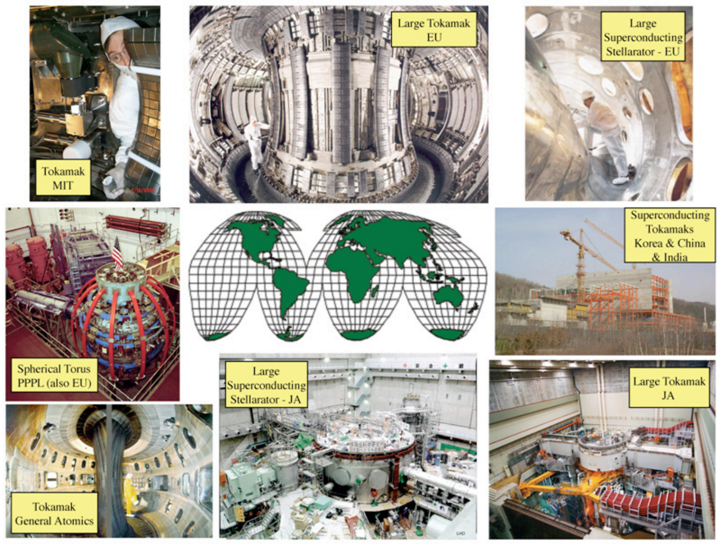
- Only successful way to confine motion ‖ to B is to bend B into a torus



- Toroidal geometry causes magnetic field to be stronger on inside than out, causes particl to drift. Need to make magnetic field helical. Simplest method: drive current in plasma
  ("Tokamak")

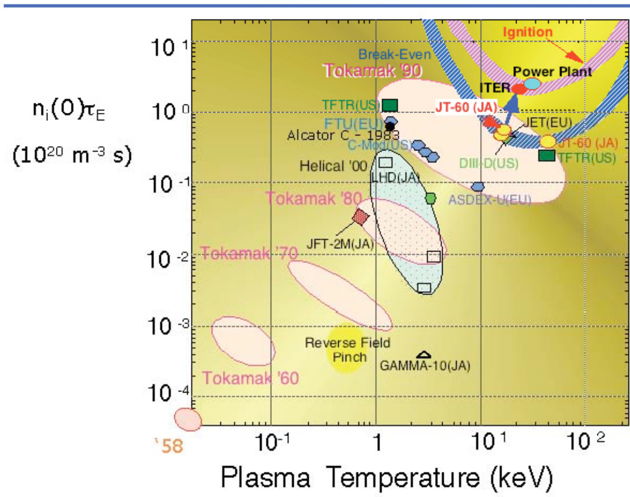
4

Fusion Development is a Worldwide Activity



5

Fusion Temperatures Attained,
Fusion Confinement One Step Away



$n_i(0)\tau_E T_i$ increased by $\sim 10^7$ since 1958

$Q_{eq} \sim 1.25$ achieved in 1996

T up to 45 keV

JAEA

6

Significant Fusion Power (>10MW) Produced 1990s

- 1991 JET 90/10-DT, 2 MJ/pulse, Q ~ 0.15, 2 pulses
- 1993-97 TFTR 50/50-DT, 7.5MJ/pulse, 11 MW, Q ~ 0.3, 1000 D-T pulses,
  - Alpha heating observed, Alpha driven TAEs - alpha diagnostics
  - ICRF heating scenarios for D-T
  - 1 MCi (100 g) of T throughput, tritium retention
  - 3 years of operation with DT, and then decommissioned.
- Advanced Tokamak Mode Employed for High Performance
  - Improved ion confinement TFTR, DIII-D, $Q_{DTequiv}$ ~ 0.3 in DIII-D 1995
  - $n\tau_E T$ record => $Q_{DTequiv}$ > 1 in JT-60U DD using AT mode 1996
  - Bootstrap and current drive extended
- 1997 JET 50/50-DT 22MJ/pulse, 16 MW, Q ~ 0.65, ~100 D-T pulses
  - Alpha heating extended, ICRF DT Scenarios extended,
  - DT pulse length extended
  - Near ITER scale D-T processing plant
  - Remote handling

7

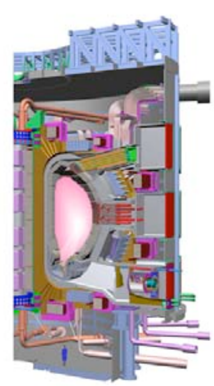
Tokamak Results Motivate ITER

Partnership of EU, Japan, China, India, S.Korea, US

→ ITER: 500 MW for 400s, power gain Q > 10;
Q > 5 for >3000 sec.

understanding of:
- non-linear self-heating of burning plasma
- transport and stability of reactor-scale plasma
- energetic α-particle instabilities

→ Plans to progress to DEMO
- last step before commercialization
- build upon ITER results and understanding
- plans for fusion development:
  Japan: "National Policy for Future Nuclear Fusion Research and Development" 2005
  EU: "Fast Track" plans



ITER (≥ 2018)

Goal: energy without proliferation risks
without long-term radioactive waste
from plentiful fuel

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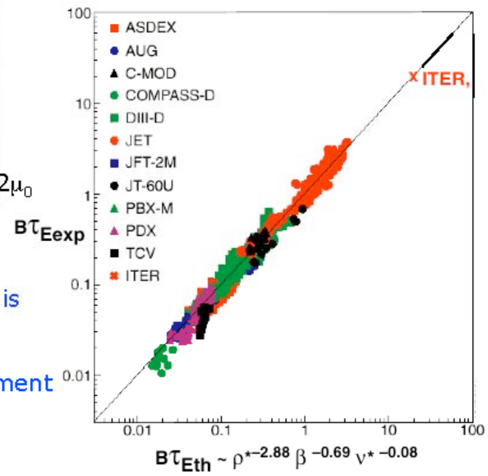
8

Projection of Confinement to ITER is not Large

Dimensionless Parameters
$\omega_c\tau = B\,\tau$ $\rho^* = \rho/\mathbf{a}$ $\nu^* = \nu_c/\nu_b$ $\beta = \langle p \rangle / B^2/2\mu_0$



Largest extrapolation is in ρ^*

Experimental confinement shows expected ρ^{*-3} variation

9

Issues for fusion?

ITER: 500 MW for 400s, gain > 10

Fusion DEMO: ~2500 MW, continuous, gain > 25, ~ same size and field.

Challenges:

- **Higher pressure, by at least factor of ~2.2**
- **Steady state with little externally driven current. No inductive current**
- **Reliable operation. Essentially no disruptions or other transient loads**

- **High heat flux plasma facing components (at least 10 MW/m2)**
- **Compatible power & particle exhaust structures**

- **Long-lived structural materials, in presence of 14 MeV neutrons**
  $\Gamma_n \sim 4$ MW/m^2

- **T-breeding cycle**

Focus of ongoing research

10

Hybrid Reactors Reduce Requirements

Missions:

- Transmutation of fission waste
- Breeding / burning of fissile fuel (sub-critical)

Typical characteristics

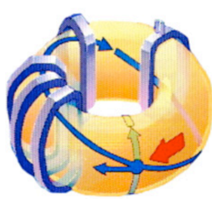
- Studied periodically since 1970's
- May only need Q ~ 1 (already demonstrated)
- Γ_n ~ 1 MW/m^2 of 14 MeV neutrons to drive fission blanket
- P_{fus} ~ 100 – 300 MW
- ~ 80% of power from fission blanket
- May only require moderate availability

Similar to fusion "Component Test Facility" neutron source.

Thus, may allow earlier contribution by fusion to energy systems

11

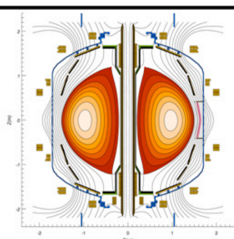
Hybrids can be conceived for all Successful MFE Configurations



Tokamak

+ Most experience

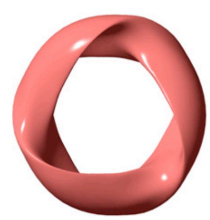
- Driven steady-state
- Active instability control



Spherical Torus

+ High plasma pressure at low magnetic field: high β.
+ Simple geometry, maintenance.

- Driven steady-state
- Active instability control



Stellarator

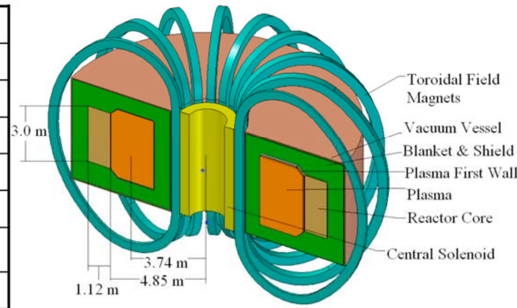
+ Passive stability
+ No drive required
+ Reliable, no disruptions

- Complex 3D coils

12

Tokamak Hybrid

R (m)	3.75 m
A	3.4
κ	1.7
P_{CD} (MW)	~100
P_{fus}	500 MW
S_n	1.8 x 10^{20}/sec
$\Gamma_{neutron}$	1.8 MW/m^2
β	4.4%
I_p (MA)	10
B_{plasma}	5.9 T

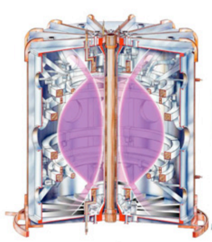


GCFTR-3 (2007)
See W. Stacey et al.

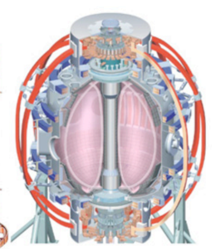
- Superconducting coils
- ITER-like physics
- Fission blanket inside TF coils.

13

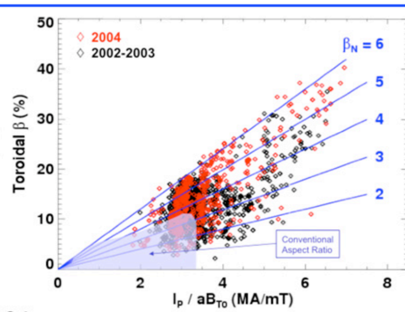
Low aspect ratio gives high pressure limit



MAST



NSTX

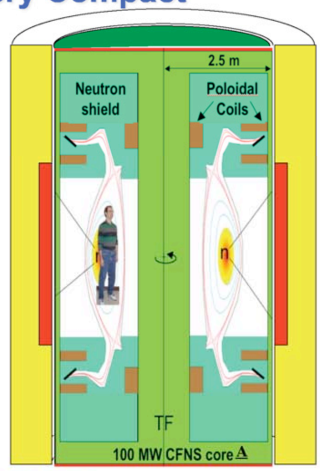


- $\beta_t \approx 40\%$ achieved in NSTX 2004
- What is the optimum aspect ratio for overall system performance?
- Low aspect ratio may allow a copper coils in a D-T environment
- May allow much simpler maintenance.
- Exploring liquid Li surfaces to handle high heat fluxes, improve confinement.

14

ST-based Hybrid is Very Compact

R (m)	1.35
A	1.8
κ	3
P_{CD} (MW)	50
P_{fus}	100 MW
$\Gamma_{neutron}$	1.1 MW/m^2
β	15-18%
I_p (MA)	10-14
B_{coil}	7 T
B_{plasma}	2.9 T



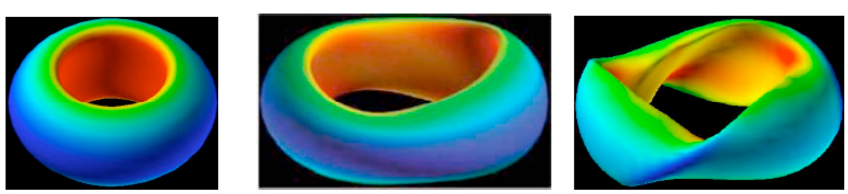
- Normal conductor coils
- Sustained by neutral beams
- Simplified maintenance: remove fusion core

See M. Kotschenreuther & Mahajan
Also L. Zhakarov, including liquid Li boundary

IFS

15

3D Shaping (Stellarators) Gives Reliable Steady-State



Tokamak $\iota_{coil} = 0$ $\iota_{coil} / \iota_{tot} = 20\%$ NCSX $\iota_{coil} / \iota_{tot} = 75\%$

- 3D shaping prevents disruptions; generates steady state equilibrium without need for current drive.
- Quasi-axisymmetry (QA) keeps magnetic field strength independent of toroidal angle. Preserves tokamak transport properties.
- Can be applied at any amplitude to axisymmetric tokamak.

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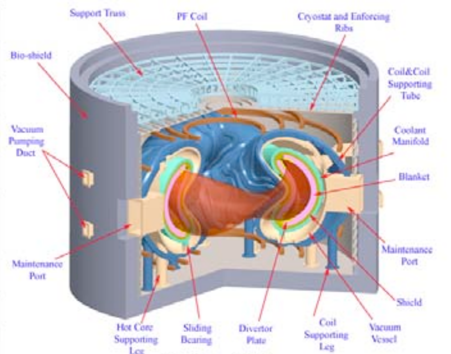
Stellarator Hybrids

R (m)	4.25 m
A	4.5
κ	1.8
P_{heat} (MW)	~25
P_{fus}	100 MW
$\Gamma_{neutron}$	0.5 MW/ m^2
β	6%
I_p (MA)	10
B_{plasma}	5 T



Aries-CS (Pfus~2.5 GW)

- Similar to Aries-CS design.
- 0-D model to estimate size.
- Robust steady state, without disruptions.
- Need to develop simplified coils design to simplify maintenance.

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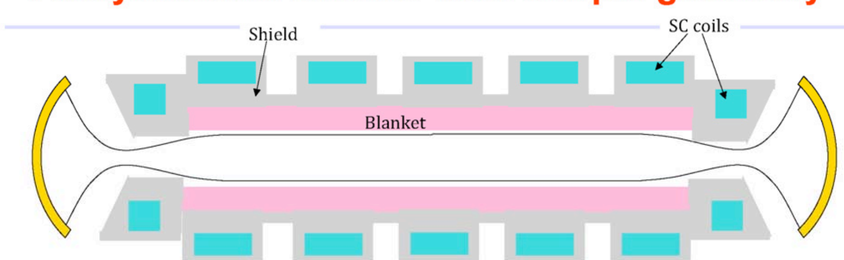
Axisymmetric mirrors offer simple geometry



Fusion power 100 MW
Q_{fus}=0.5, $\eta_{heating}$=0.4

Length 50 m (mirror-to-mirror 30 m)
Plasma diameter 1 m
B_0=2.5 T, B_{mir}=15 T (SC)

Required power amplification in the blanket ~ 10-15
(power to the grid ~ 200 - 500 MW)

The physics model is based on the results from the GDT facility (Novosibirsk)
Requires Te ~ 0.6 – 1 keV Currently have Te ~ 0.2 keV.

See D. Ryutov

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Conclusions

- Tokamaks has demonstrated plasma performance Q ~ 1, similar to that required for a fission / fusion hybrid
- A number of MFE hybrid designs have been developed, appear to have reasonable characteristics
- Near-tokamaks (ST, stellarator) offer possible advantages, share physics basis.
  ST: compact, simple maintenance
  Stellarator: robust, disruption free steady state.
- Need to separately decide whether hybrids are useful, worth additional investigation.

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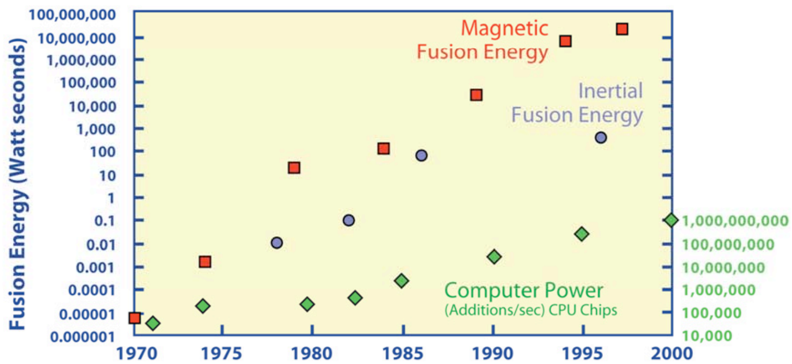
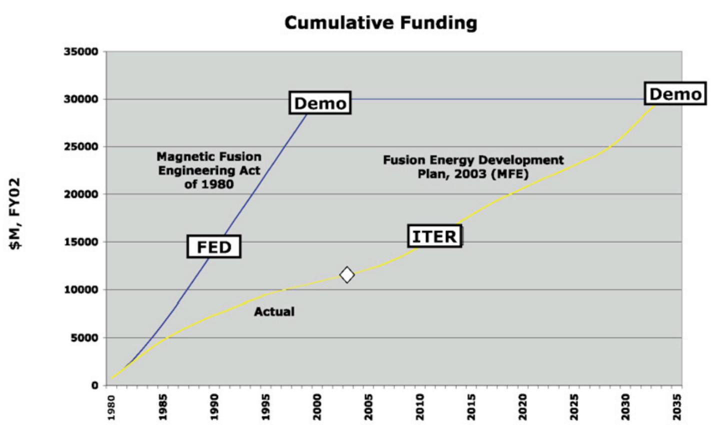
Progress in Fusion has Outpaced Computer Speed

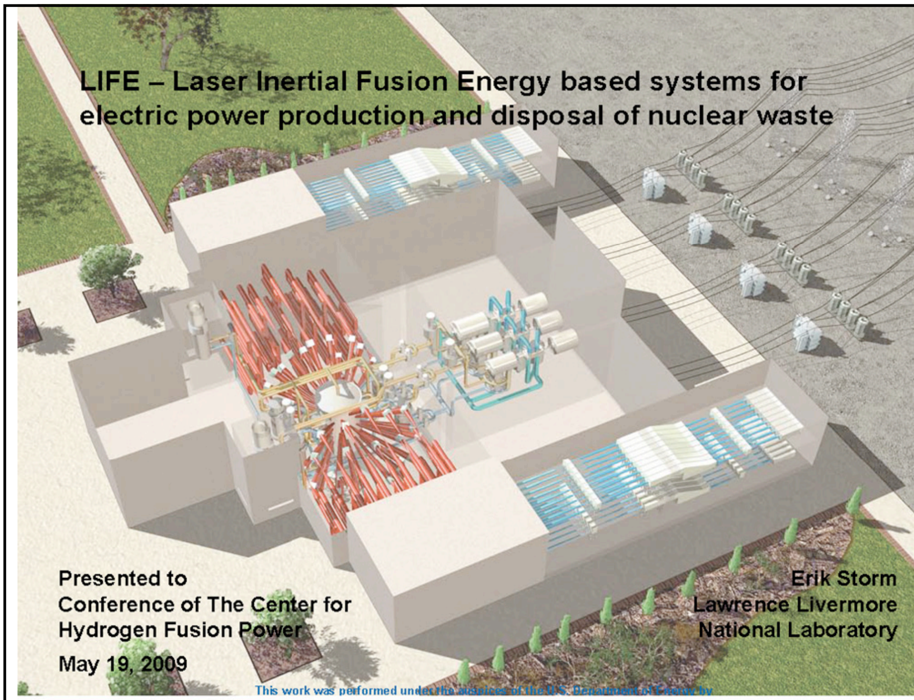


Progress is paced by the construction of new facilities.

The Estimated Development Cost for Fusion Energy is Essentially Unchanged since 1980



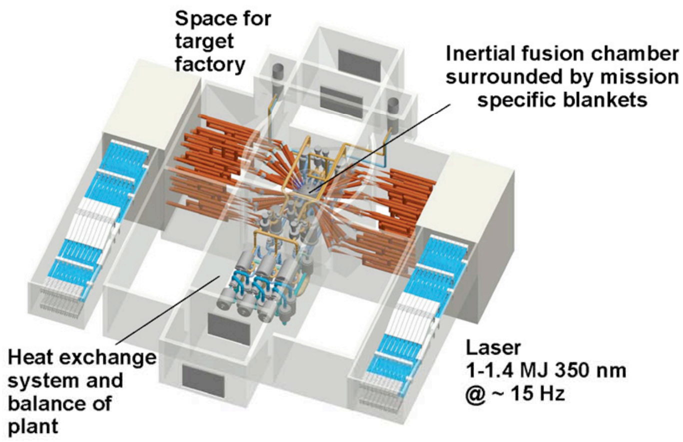
Fusion Development is on Budget.



LIFE – Laser Inertial Fusion Energy based systems for electric power production and disposal of nuclear waste

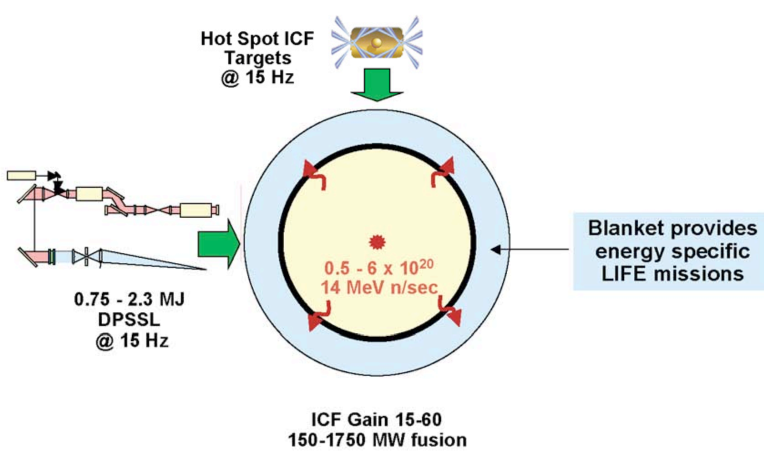
- LIFE - a Laser Inertial Fusion Engine provides a point source of 14 MeV neutrons for fusion-based energy missions
- LIFE would provide a once-through, closed cycle option to:
  - Burn SNM and nuclear waste as well as fertile fuels (DU, Nat U)
  - While providing GWe levels of baseload electricity
- The science and technology "building blocks" for LIFE are credible extensions of NIF, ignition on NIF and ongoing developments in diode pumped solid state lasers and the world nuclear power industry
- The inherent separability of LIFE, would allow a LIFE demonstration fusion engine by 2020 that could be scaled to fusion based nuclear energy and waste burning missions and would also offer an early option for pure fusion LIFE systems

One of LIFE's missions is to provide a option for a once-through, closed nuclear fuel cycle

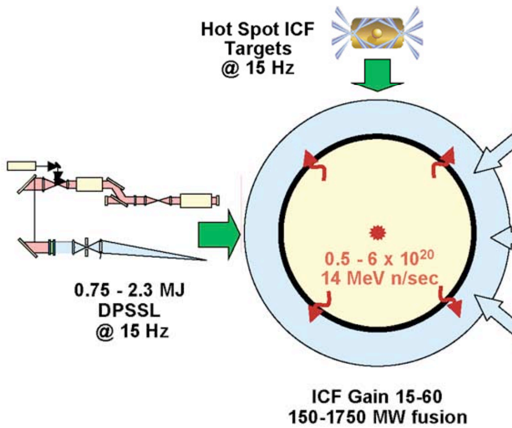


However, LIFE is (really) a Laser Inertial Fusion Engine to provide a point source of 14 MeV neutrons for fusion-based energy missions

LIFE – a Laser Inertial Fusion Engine to provide a point source of 14 MeV neutrons for fusion-based energy missions



Different LIFE blankets provide unique energy and SNM/Nuclear waste burning systems



LIFE blankets options

- Li-based coolant for pure fusion energy and T for other LIFE missions
- Coolant with natural U, DU or Th pebbles for sustainable, once-through closed nuclear fuel cycle energy (> 99.9% burn-up)
- Coolant with fertile or fissile pebbles for once-through closed fuel cycle energy while burning SNM and LWR waste (> 99.9% burn-up)
  - WG-Pu, HEU
  - TRU or TRU+FP from SNF
  - SNF (without reprocessing)

A fully functioning laser-driven inertial fusion engine is a sine qua non for LIFE

There are many possible driver, target and chamber combinations for IFE-based systems

Drivers	Targets	Chambers
DPSSL	Indirect-drive fast ignition	Thick liquid wall
KrF laser	Direct-drive fast ignition	Wetted wall
Heavy ion accelerator	Indirect-drive hot-spot ignition	Dry wall
Z-pinch pulse power	Direct-drive hot-spot ignition	
	Other advanced concepts	

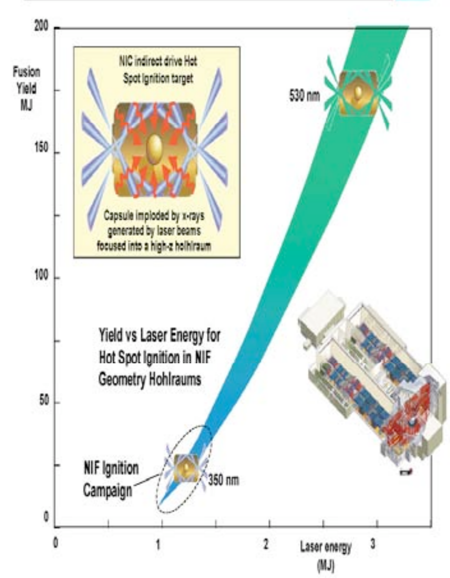
Not all permutations are feasible or attractive or suited to hybrid options

We think that DPSSL, indirect-drive targets and compact dry wall chambers are well suited for Inertial Fusion based energy and hybrid applications

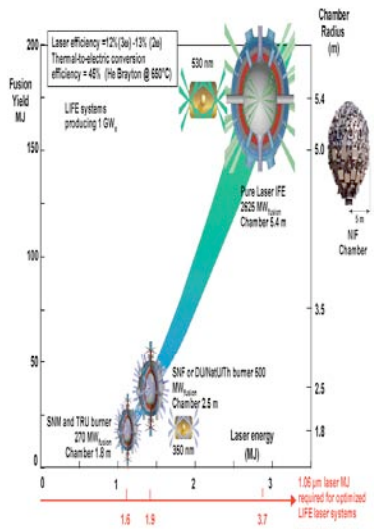
Drivers	Targets	Chambers
DPSSL	Indirect-drive fast ignition	Thick liquid wall
KrF laser	Direct-drive fast ignition	Wetted wall
Heavy ion accelerator	Indirect-drive hot-spot ignition	Dry wall
Z-pinch pulse power	Direct-drive hot-spot ignition	
	Other advanced concepts	

- For hybrid systems, low yield, compact high neutron loadings (MW/m2) are desirable
- Thick liquid or wetted walls "throw away" too many neutrons
- Direct drive targets are forced to large chambers for 1st wall survival
- Intrinsic brightness of KrF lasers are marginal for indirect-drive
- Heavy ion accelerators are not well suited for direct-drive, nor for low yield options
- Z-pinch pulses optimize for very high yield/low rep rate systems

NIF target yields are enabling for LIFE and will be demonstrated with NIC



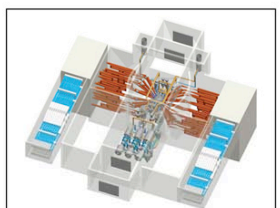
LIFE missions could be realized with lasers ~ 1/3 - 2/3 NIF's 1.06 μm capability and chambers that are 1/3 to 1 x NIF size



But we can - and should be able to do better

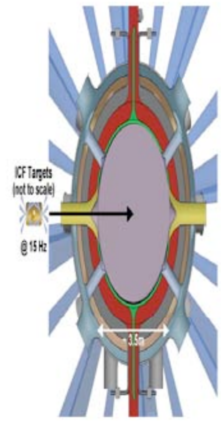
Let us first focus on LIFE systems to burn SNM or nuclear waste from LWRs

We believe that a NIF-based LIFE with "today's technology" is credible and would provide once-through closed cycle for waste burning

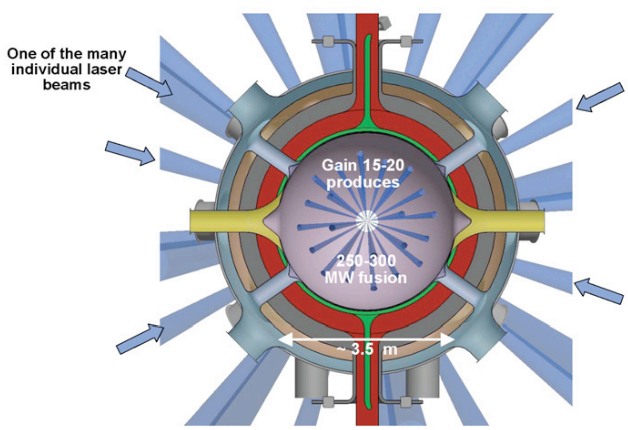

NIF-based LIFE to burn SNM or TRU and provide 1 GWe

- NIF-like lasers
  - APG-1 glass; He cooling; Edge emitting diodes
- NIC-like targets
  - Hot spot ignition; 15-20 MJ @ ~ 1 MJ
- Target production, injection and engagement
  - Studies and scaled experiments at GA
- Fusion environment, 1st wall and final optics
  - Xe-filled, compact chambers; ODS-FS 1st wall
  - Thin Fresnel fused silica lens – self annealing color centers
- High burn-up Fuels
  - Refractory-clad SHC pebbles; 100 dpa for > 99% FIMA with WG-Pu, TRU; (150 dpa for > 99% FIMA with DU, Nat U, Th, SNF)
  - Molten salt – radiation damage not an issue

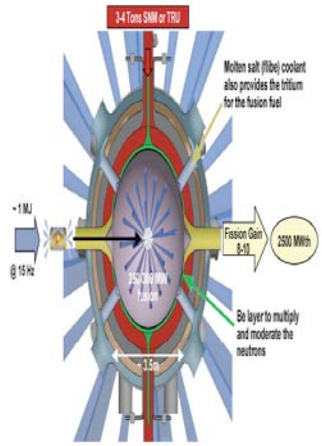
The NIF/NIC-based SNM/TRU LIFE burner starts with NIC targets injected into a chamber @ 15 Hz



A 15 MW laser (~ 1 MJ @ 15 Hz) is focused on the target producing 200-300 MW of fusion

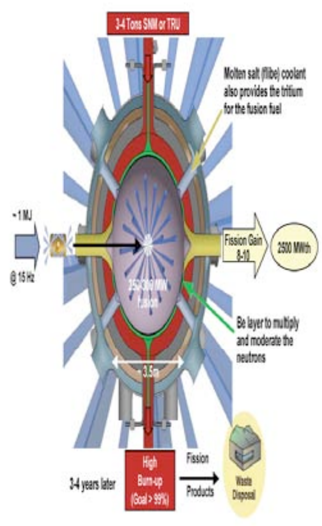


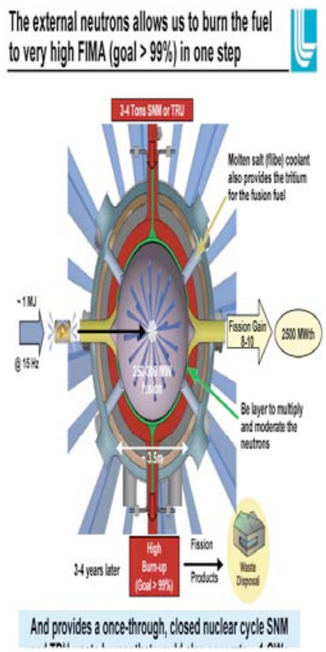
SNM or TRU loaded pebbles, a Be blanket and flibe coolant provide the fission gain and tritium for the fusion targets



3-4 tons of SNM or TRU provides 2500 MWth/1000MWe for 3-4 yrs

The external neutrons allows us to burn the fuel to very high FIMA (goal > 99%) in one step

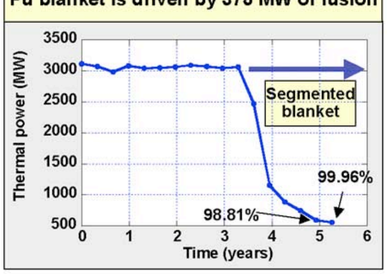




An early WG-Pu engine design demonstrates a LIFE system to burn SNM

- System fueled with 7 MT of weapons grade plutonium (WG-Pu)
- Fuel (whether in "TRISO"-like loaded or Solid Hollow Core Pebbles) blended 80% ZrC + 20% Pu
  - Also loaded with 400 wppm boron as burnable poison
- Fusion power is 375 MW (25 MJ @ 15 Hz) Flat top thermal power is 3000 MW --- Blanket gain of 8

Pu blanket is driven by 375 MW of fusion



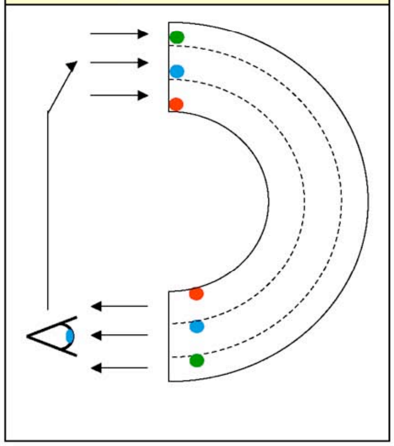
Isotope	Initial mass	Final mass
^{239}Pu	6.56 tons	1.3 mg
^{240}Pu	406 kg	<1 μg
^{241}Pu	9.1 kg	1.2 mg
^{242}Pu	1.4 kg	<1 μg
^{241}Am	15.4 kg	<1 μg
Total actinides	6.99 tons	2.83 kg (2.04 kg ^{246}Cm)

Optimized systems have blanket gains of 12-15 for WG-Pu and 10-12 for TRU
And could be loaded with 3-4 MT and have burn times of 3-4 years

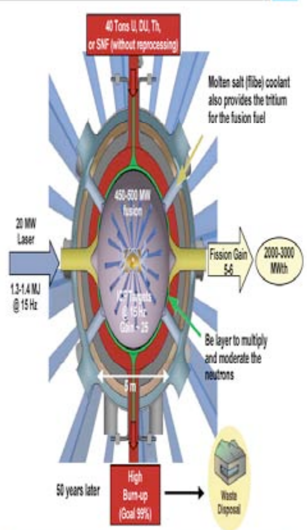
Improved performance is realized by segmenting the blanket and extending the lifetime

- Different blanket regions (e.g. front, middle, back) experience different neutron fluxes
- When the front region is fully burned, successive layers are promoted and new fuel is added to the back
- Full power mode can be extended indefinitely

Segmented blankets would enable fuel burn-up to be tuned as desired



A LIFE engine can also be configured for burning fertile fuel - DU, Nat U, Th or SNF

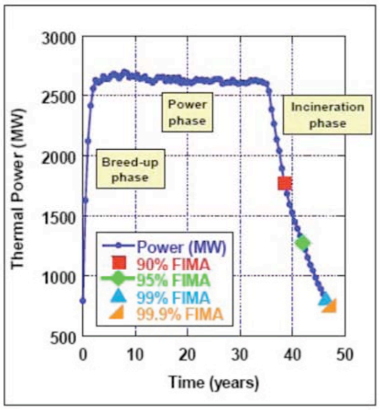


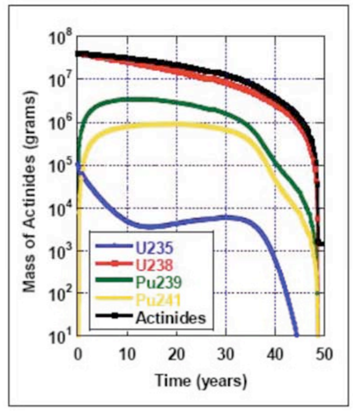
40 tons of fertile fuel could provide 2000-3000 MWth for 50 yrs

LIFE provides decades of steady-power from a depleted uranium* fuel loading

Thermal power and content of fertile and fissile material as a function of time for an optimized LIFE engine loaded with 40 tons of DU, driven by 500 MW of fusion

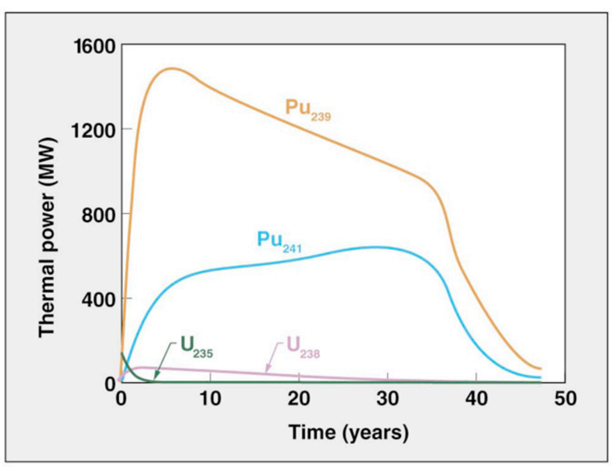
(Performance would be similar for natural U or non-reprocessed SNF)



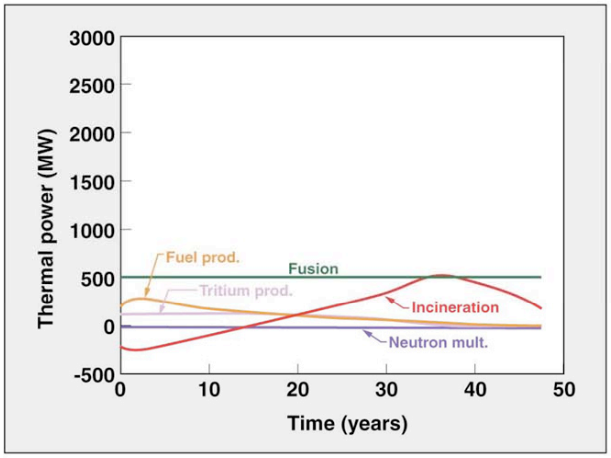


Level of LIFE fuel burn-up (FIMA) will be a trade-off between economic and proliferation constraints

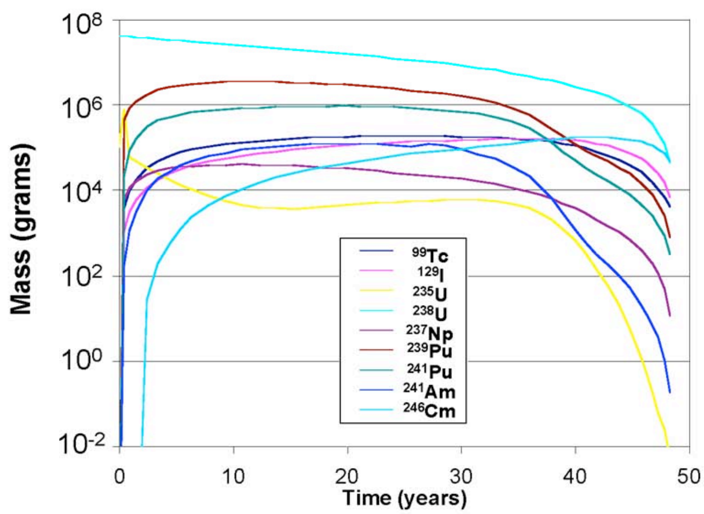
Several isotopes are fissioning in the LIFE engine



Non-fission reactions make a significant contribution to the thermal power



LIFE fuel burn-up can be adjusted as desired



LIFE fuel burn-up can be adjusted as desired

Remaining quantities of actinides for an initial load of 40 tons of DU as a fraction of burn-up (FIMA)

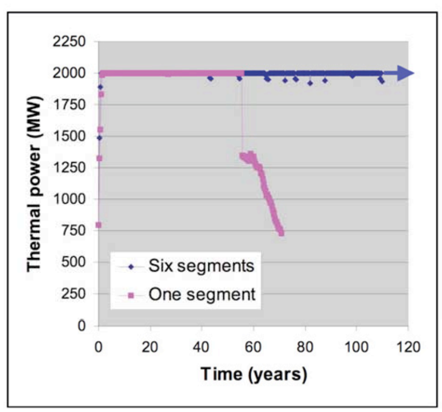
	Burn-up			
Isotope	90%	95%	99%	99.5%
^{235}U	8.4 kg	6.2 kg	35 g	190 mg
^{237}Np	9.1 kg	6.5 kg	479 g	44 g
^{239}Pu	496 kg	314 kg	6.4 kg	1.0 kg
^{241}Am	121 g	47 g	11 g	320 mg
^{246}Cm	137 kg	145 kg	101 kg	57 kg

- 40 tons of depleted uranium becomes essentially 40 tons of fission products

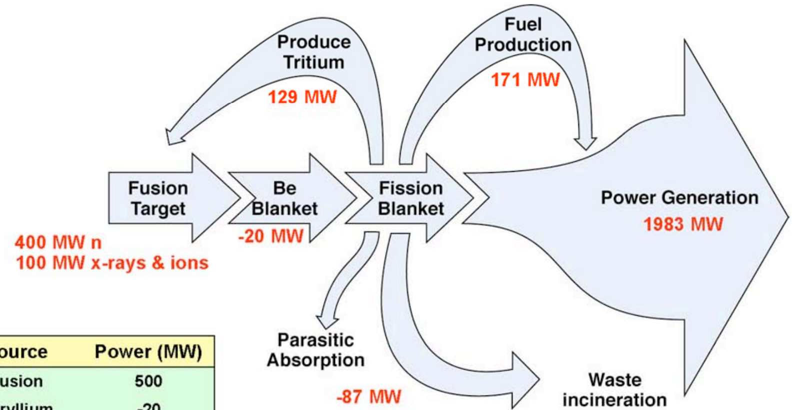
With > 99 % burn-up, LIFE produces > 20 X less high level waste per GWe than once-through LWRs and has insignificant quantities of actinides per MT IHM at end of operation

As with a SNM and TRU burner, segmented blankets for DU, Nat U and SNF can be operated as long as desired

- Different blanket regions (e.g., front, middle, back) experience different neutron fluxes
- When the front region is fully burned, successive layers are promoted, and new fuel is added to the back
- Full power mode can be extended indefinitely

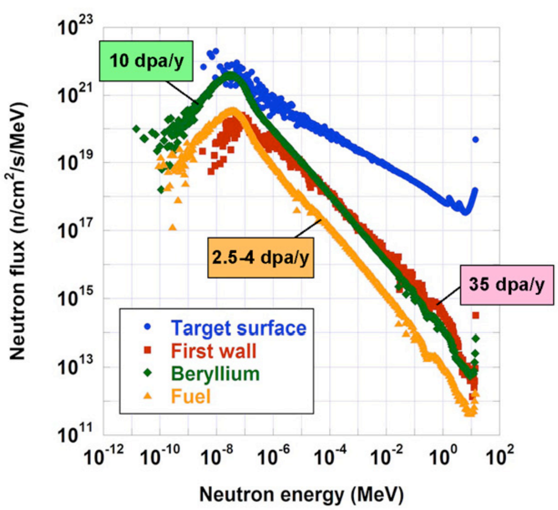


Neutron power flow for DU case at time of peak ^{239}Pu (~10 years); TBR = 1.09



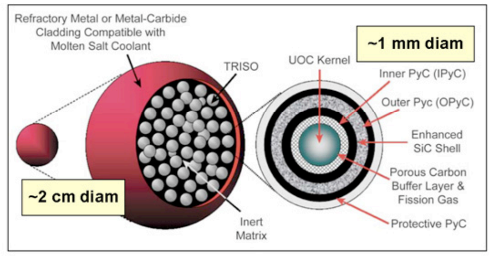
Source	Power (MW)
Fusion	500
Beryllium	-20
Tritium prod.	129
Fuel prod.	171
Fission	1983
Incineration	-87
Total	2676

The neutron spectrum varies considerably in the different regions of a LIFE engine

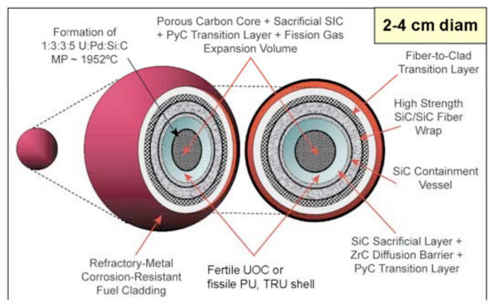


LIFE could potentially use a variety of fuels

- Enhanced TRISO for WG-Pu and HEU



- Solid hollow core and Encapsulated powder pebbles for fissile fuels (WG-Pu, TRU) or fertile fuels (DU, Nat U, Th and SNF)



LIFE offers multiple options for the destruction of LWR spent nuclear fuel

SNF from LWRs
↓
40 years of decay-in-storage
↓ ↓
Direct burn in LIFE engines, gain 5-6 **or** UREX chemical separation → Dispose of U as low-level waste **or** → Burn in LIFE engines, gain 5-6

UREX chemical separation ↓
PuMAFP
↓ ↓
LIFE PuMA+FP burner, gain ~3 **or** UREX+ → PuMA → LIFE PuMA burner, gain ~10-12

LIFE offers multiple options for the destruction of LWR spent nuclear fuel

Values assume an inventory of 200,000 tons of SNF from existing LWRs and fleet of ALWRs through 2100

SNF from LWRs

↓

40 years of decay-in-storage

↓ ↓

Direct burn in LIFE engines, gain 5-6 (200,000 tons SNF, 1000 plants × 240 yrs)

or

UREX chemical separation

→ Dispose of U as low-level waste

or

→ Burn in LIFE engines, gain 5-6 (189,000 tons U, 1000 plants × 240 yrs)

UREX chemical separation ↓ PuMAFP

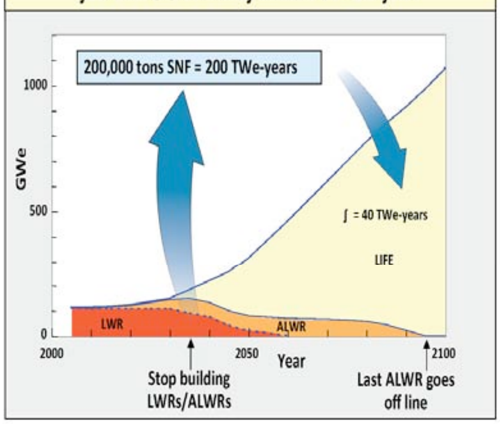
PuMAFP ↓ LIFE PuMA+FP burner, gain ~3 (2,800 tons PuMA + 8,000 tons FP, 60 plants × 60 yrs)

or

PuMAFP ↓ UREX+ → PuMA → LIFE PuMA burner, gain ~10-12 (2,800 tons PuMA, 40 plants × 60 yrs)

LIFE "afterburners" could destroy the LWR waste in ~200 years

Without chemical separation, LIFE could satisy ~50% of the year 2100 U.S. electricity demand for ~200 years



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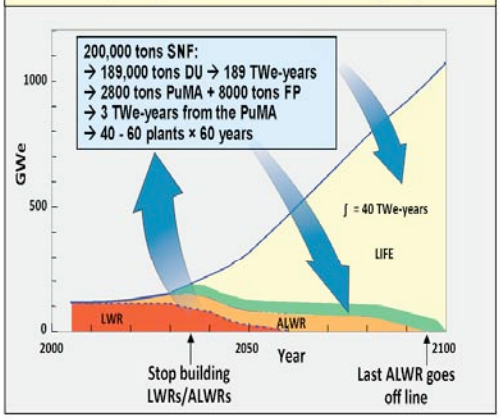
With chemical separation, LIFE "afterburners" could destroy the LWR waste in 60 years

40 LIFE PuMA burners or 60 LIFE PuMAFP burners , operating for 60 years, could destroy the high-level LWR waste accumulated by the year 2100



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LIFE waste ("LIFEium") is fundamentally different from SNF from LWRs

Per GWe "LIFEium" has > 200 X lower long-term radiotoxicity and > 25X less mass

"LIFEium" contains insignificant quantities of SNM (e.g. < 5 gm ^{239}Pu/MTIHM)
- **The proliferation argument against chemical separation is eliminated**

Chemical separation of "LIFEium" would have significant waste-management benefits
- **Remove stable and short-lived elements to reduce quantity of waste needing geologic disposal; reduced repository heat load**
- **"Designer" wasteforms for elements with problematic, long-lived isotopes (15-20% by mass of the waste)**
- **Potential for further transmutation of long-lived fission products**

LIFE Waste aged 40 years → Chemical partitioning and immobilization

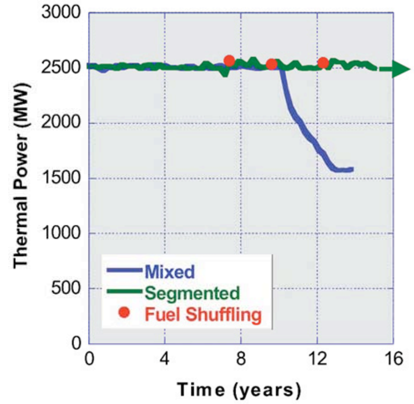
Stable & short-lived nuclides → Decay storage

Long-lived nuclides → Geologic disposal

→ Possible transmutation ?

LIFE could burn SNF as PuMA+FP

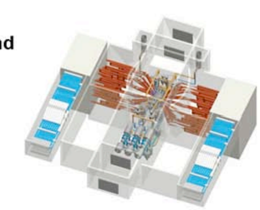
- Due to the large fraction of fission products, PuMA+FP LIFE burners would have a blanket gain of 2.5-3x
- Segmented blankets can improve the back end of the power curve through periodic refueling



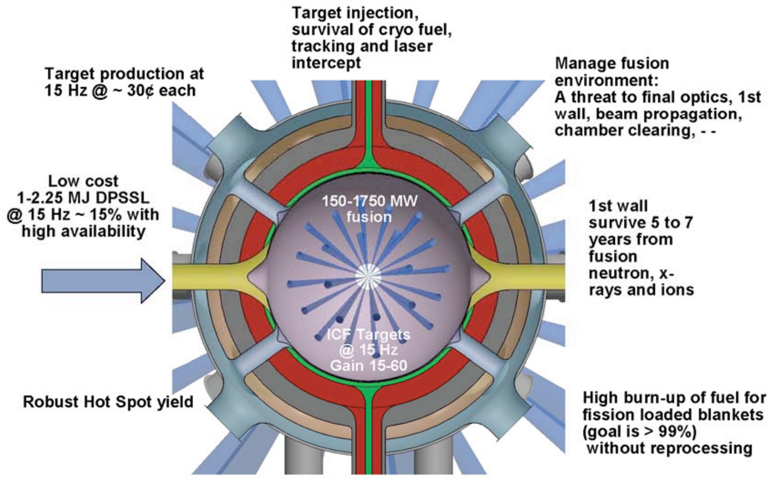
Segmented blankets will improve performance for all versions of the LIFE engine

LIFE offers key benefits relative to other nuclear and hybrid fusion-fission systems

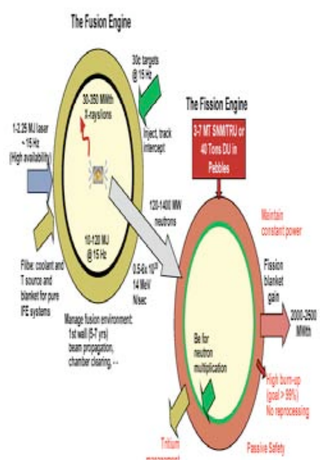
- LIFE would be a unique fusion-fission system:
  - Operates with a variety of different fuels
    - DU, NatU, SNF, Th, Excess SNM, TRU from processed SNF
  - Once-through closed fuel cycle to > 99% burn
  - Deeply sub-critical at all times (k_{eff} fertile< 0.7; k_{eff} fissile < 0.90-0.95) and passive removal of decay heat makes it inherently safe
- For the fertile fuel-loaded baseload energy missions
  - No enrichment and no reprocessing
  - No weapons attractive materials at start or end minimizes proliferation concerns
- Simple technological solutions
  - Low-yield
  - Dry wall
  - Fast development path
  - Makes its own fuel (fusion & fission)
  - Incinerates its own actinide waste

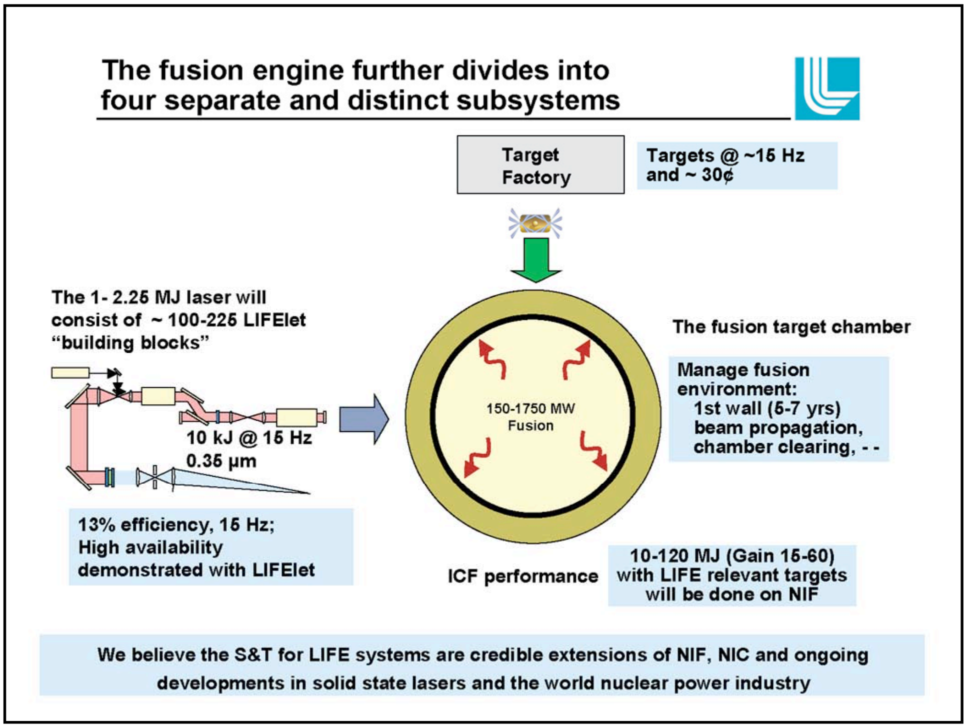


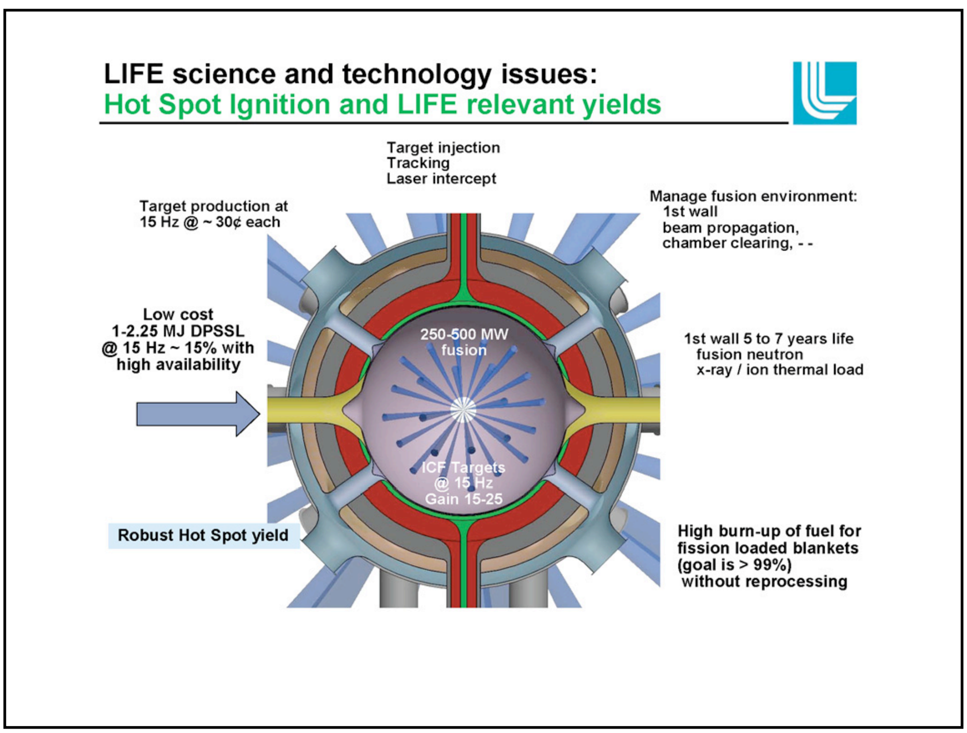
LIFE does face some technical and scientific challenges

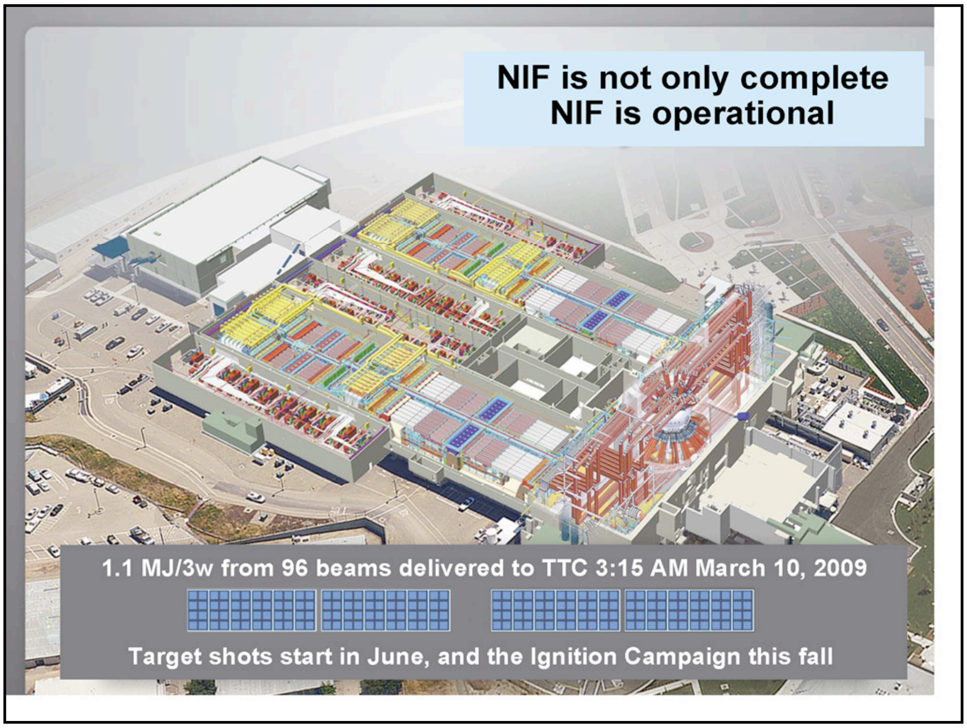


LIFE divides naturally into a Fusion and Fission engine with different and distinct challenges




The fusion engine further divides into four separate and distinct subsystems
Target Factory
Targets @ ~15 Hz and ~ 30¢
The 1- 2.25 MJ laser will consist of ~ 100-225 LIFElet "building blocks"
10 kJ @ 15 Hz
0.35 μm
150-1750 MW Fusion
The fusion target chamber
Manage fusion environment:
1st wall (5-7 yrs)
beam propagation,
chamber clearing, - -
13% efficiency, 15 Hz;
High availability demonstrated with LIFElet
ICF performance
10-120 MJ (Gain 15-60) with LIFE relevant targets will be done on NIF
We believe the S&T for LIFE systems are credible extensions of NIF, NIC and ongoing developments in solid state lasers and the world nuclear power industry

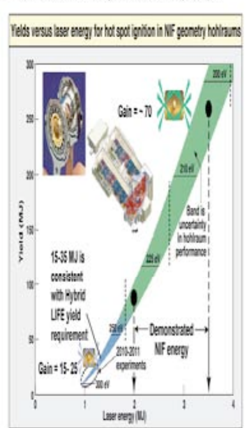

LIFE science and technology issues:
Hot Spot Ignition and LIFE relevant yields
Target injection
Tracking
Laser intercept
Target production at 15 Hz @ ~ 30¢ each
Manage fusion environment:
1st wall
beam propagation,
chamber clearing, - -
Low cost 1-2.25 MJ DPSSL @ 15 Hz ~ 15% with high availability
250-500 MW fusion
1st wall 5 to 7 years life
fusion neutron
x-ray / ion thermal load
ICF Targets @ 15 Hz Gain 15-25
Robust Hot Spot yield
High burn-up of fuel for fission loaded blankets (goal is > 99%) without reprocessing



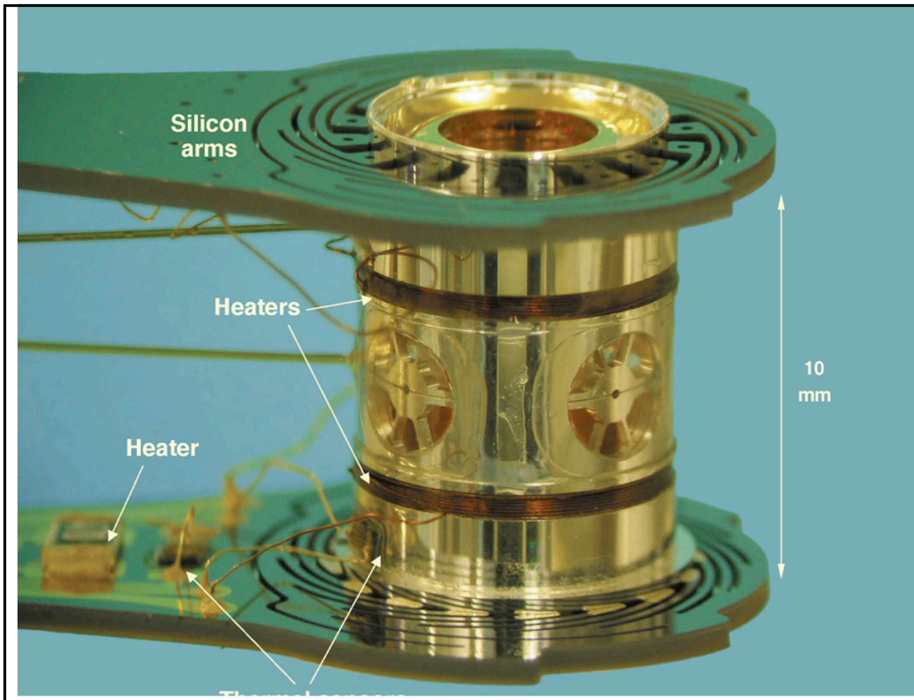
NIF target yields are enabling for LIFE and will be demonstrated with NIC

NIF Hot-spot Ignition Campaign will start in 2010

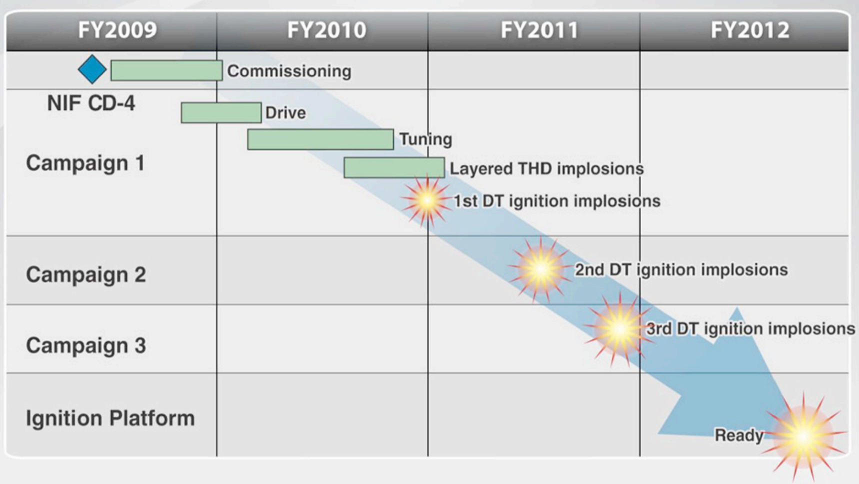
- Target, cryo technologies and diagnostics have been developed
- The scientific basis for HIS targets has been extensively developed



We anticipate LIFE-level yields by 2012 and with LIFE type targets by 2013



NIF will execute four major ignition campaigns in the next four years

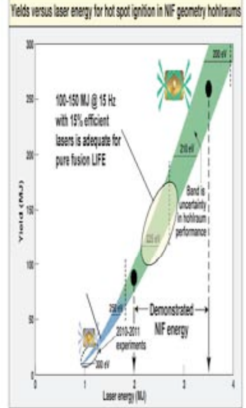


Yields and gains required for a pure fusion LIFE system will also be available with NIC-like targets

NIF Hot-spot Ignition Campaign will start in 2010

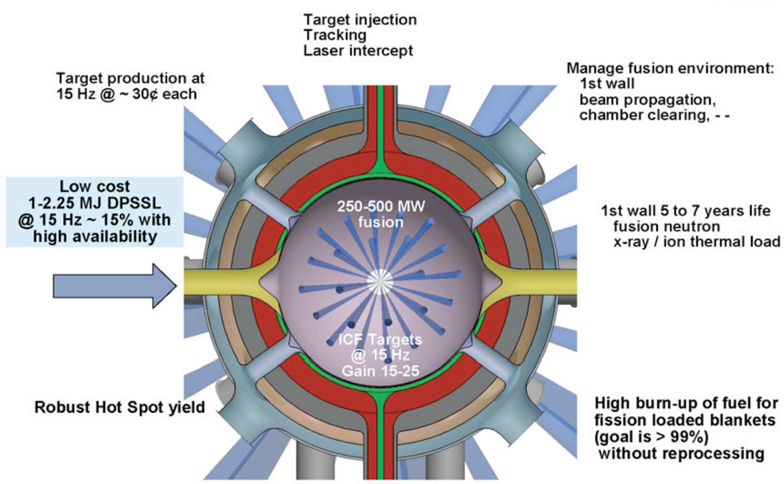
- Target, cryo technologies and diagnostics have been developed
- The scientific basis for HIS targets has been extensively developed

Yields versus laser energy for hot spot ignition in NIF geometry hohlraums

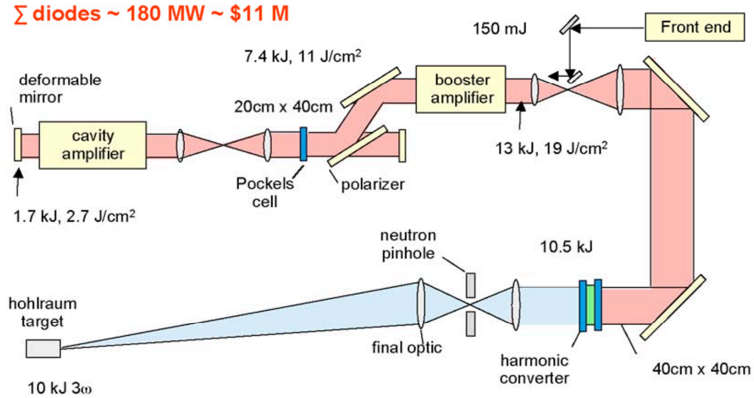


Operating at 0.53 µm is also favorable for laser opeartion

LIFE science and technology issues:
15-20 MW high efficiency lasers



A LIFE laser 150 KW "building block" could be a NIF-like beamline producing 10 kJ at ~15 Hz

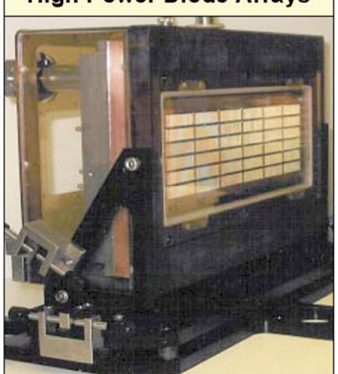


A 1 MJ system would only require ~ 100 beams

Efficient high power laser diodes and high flow rate He cooling allows this NIF-like beamlet to operate at 15 Hz

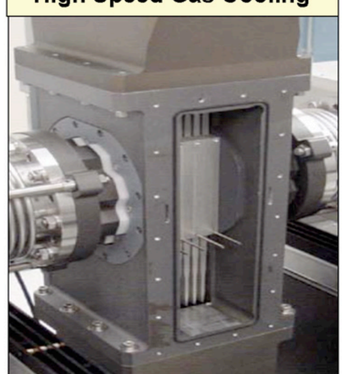
Laser diodes and He gas cooling enable a NIF-like architecture to meet LIFE high rep rate high efficiency requirements

High Power Diode Arrays



100 kW peak power

High Speed Gas Cooling

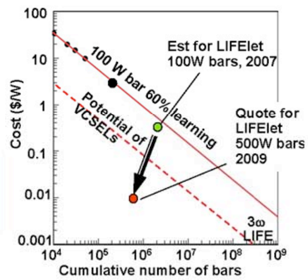


3 W/cm² cooling (average)

These technologies have been developed as part of the Mercury Project

There has been good progress in several technology areas for the LIFE laser

- Diode objectives for a LIFElet (one beam of a LIFE laser) have been met
  - Edge emitting diodes are already at \$0.012/W
  - Optimized packaging concepts for total cost of \$ 0.05 - 0.06/W



180 MW of diodes for LIFElet would cost ~ \$11 M
At LIFE quantities, vendors expect another 10X reduction

- More efficient conversion schemes suggest that 80% conversion from 1ω to 3ω is realistic
  - Separate foot and main pulse converter
  - Convert only main pulse - Foot pulse is low intensity, LPI is not an issue

Overall laser efficiency is now 13%

- New techniques for producing Yb:S-FAP are being explored
  - Transparent ceramic concepts
  - Schott proprietary crystal growth

Use ~ 1/3 as many diodes or pump for less time and increase efficiency to ~ 17%

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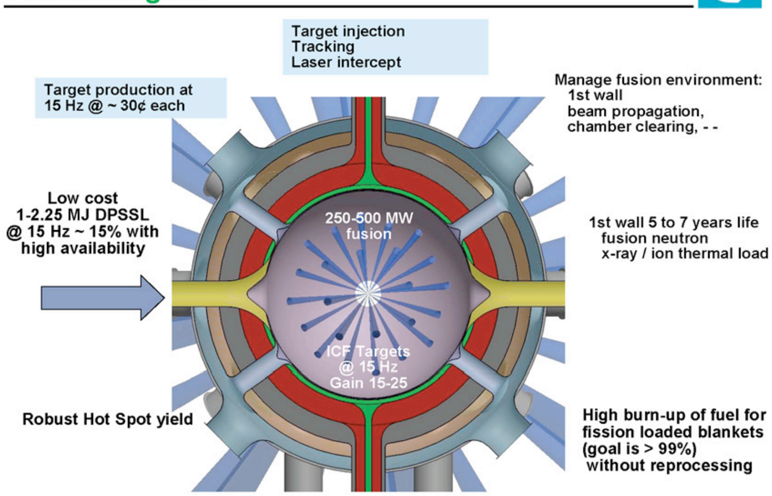
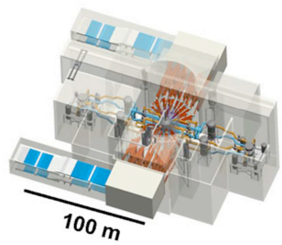
LIFE science and technology issues: Fusion targets



System and economic criteria for LIFE targets are more stringent than NIF



	NIF	LIFE
Rep-rate	$<10^{-5}$ Hz	10 - 15 Hz
Cost	~$100,000	~$0.2 - $0.4
Waste stream	< 1 gm	10^{6} gm/year
Chamber placement	~10 μm^3,	~1 - 5 mm^3
Chamber impact- mass/ shot	gm	100 mg
Number/year	100	6x 10^{8}

The material costs are low

Item	Material	Cost ($)	Process
Hohlraum/cone	Pb	< $0.01	Deep-draw
Capsule			
Ablator	CH	$0.000003	Micro-encapsulation
Foam	CH	$0.00007	CO_2 extraction
DT		$0.00001 (D)	Permeation
Total costs		$0.01	

Total estimated target material cost = $0.01

Target cost will be in production processes

Costs are in mass-production at high precision

Estimated production costs based on typical factory

Item	Number	Cost/year ($M)
Operating personnel	69 people at $300K/yr	21
Capital depreciation	$200,000,000 typical factory/5 years	40
Maintenance	5% cost of equipment	10
Electricity	Factory typical	8
Total factory cost/yr		79
Production cost per target	631 million/year (20 Hz operation)	$0.13
Target material cost (Pb)		$0.01
Target material recycle costs		$0.10
Total target cost		$0.24

Together with GA we are developing a research plan for target fabrication to meet cost/precision objectives

There are examples of mass produced components that are comparable to LIFE requirements in volume, precision and cost

	LIFE	Mil Spec Bullet
Number/year	3.1-6.3 x 10^8	9 x 10^9
Dimensional tolerance	± 50 μm	± 40 μm
Cost	$0.20-0.30	$0.21

Bullets are an interesting comparison, as they are multi-component, multi materials, that tolerate high acceleration and high velocity

However

LIFE targets with ~ 2 mg/cc foam filled Pb hohlraums, Cryo-DT in ~2 mg/cc carbon foams CH shells and μm precision assembly will clearly require significant development

Injection demonstration at GA to simulate the full length of a LIFE fueling system have demonstrated many objectives

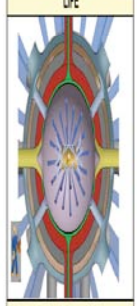
- Injection at 6 Hz (burst mode) 400 m/sec to 200 µm demonstrated
- Additional R&D needed for Cryogenic targets and >10 Hz

LIFE targeting requirement is similar to that of other demanding systems

Airborne Laser

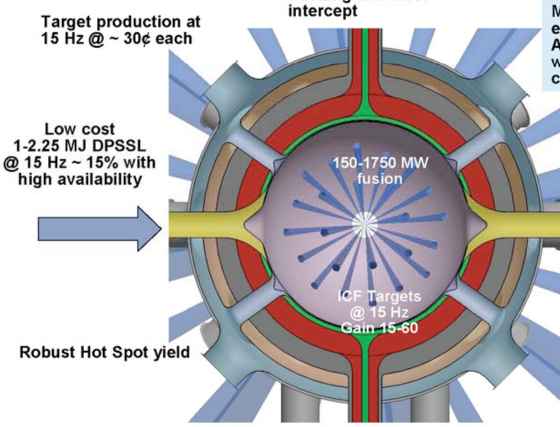
~1 µrad angular precision (~10 cm, 100 km)

LIFE



2 µrad precision (HS, 50 µm, f = 25 m)

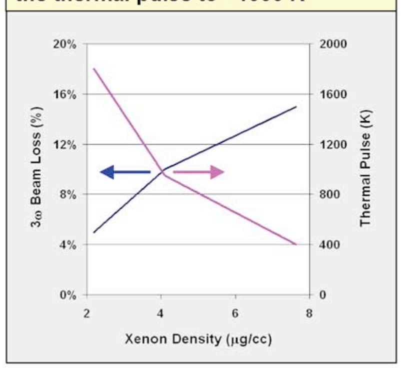
LIFE science and technology issues: Managing fusion environment and 1st Wall



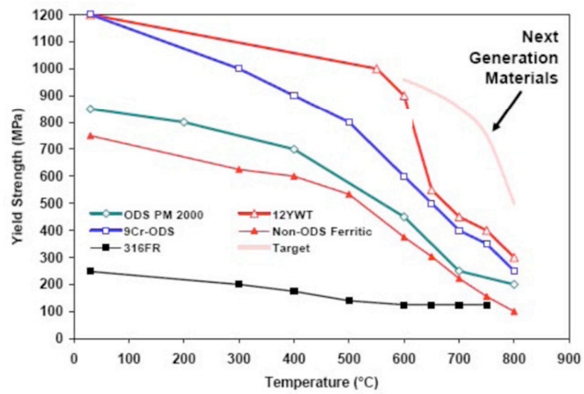
Thermal robustness of indirect-drive targets allow use of chamber fill gas and compact chambers

- First wall is oxide dispersion strengthened ferritic steel over-coated with 500 μm W
- X-rays from target pre-ionize gas near target and causes partial laser absorption by inverse bremsstrahlung
- Gas stops all ions (~ 4MJ) and ~ 90% of 4.5 MJ of x-rays
- Absorbed energy is re-radiated over 100's μsec
- Experiments and modeling at LLNL, UCSD and UW for ~ 1800 K pulses

Xenon densities of ~4 μg/cc reduce the thermal pulse to <1000 K



ODS-Ferritic Steel is a good baseline material for LIFE 1st wall

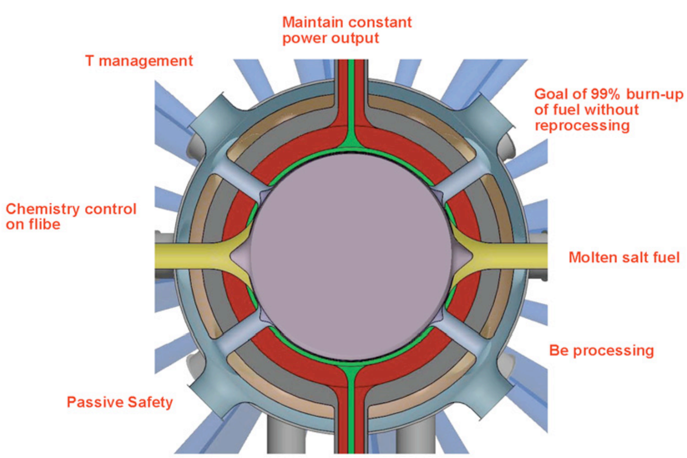


1st wall in a LIFE system sees a neutron load of ~ 35 dpa/yr

ODS steel tested in BOR-60 sodium-cooled fast flux reactor (> 85 dpa) - (85 dpa would give a 1st wall lifetime of ~ 3 years)

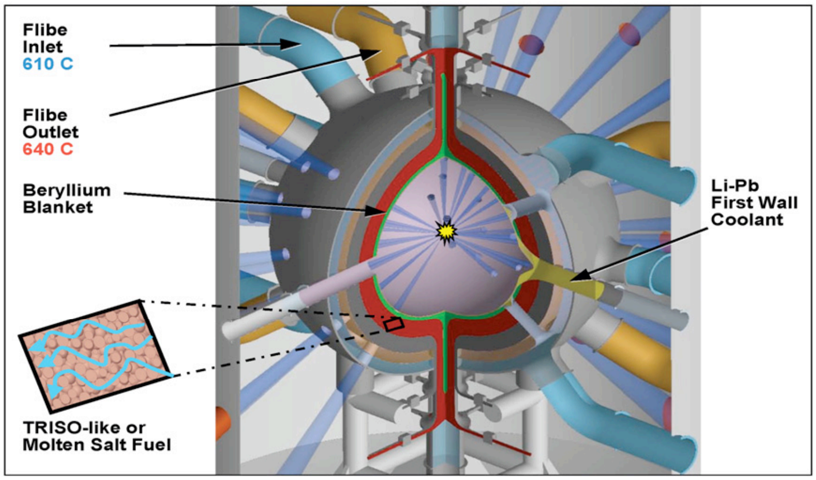
Ion beam irradiation at 500 °C project to 150 dpa, (1st wall lifetime of ~ 5 years)

LIFE science and technology issues: Fuels and fission engine systems optimization

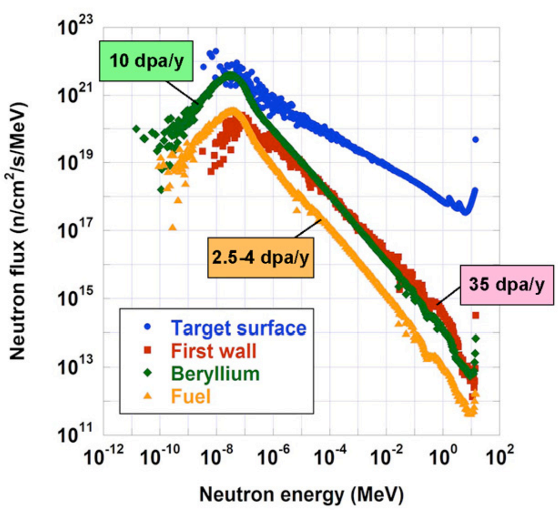


Ongoing developments in the world nuclear power industry give us confidence that these challenges are tractable

LIFE features a dedicated first wall coolant with a pebble-based multiplier and fuel

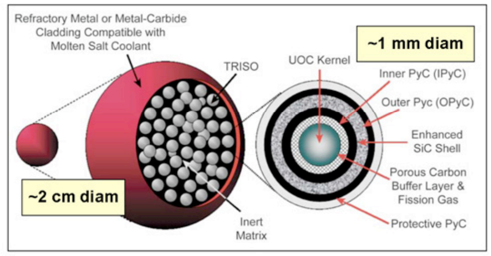


The neutron spectrum varies considerably in the different regions of a LIFE engine

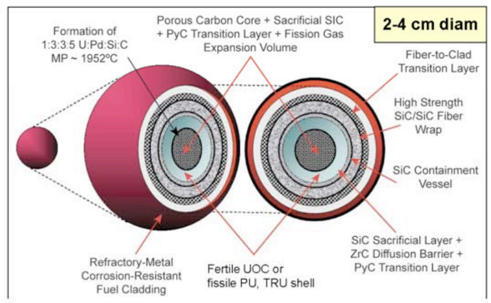


LIFE could potentially use a variety of fuels

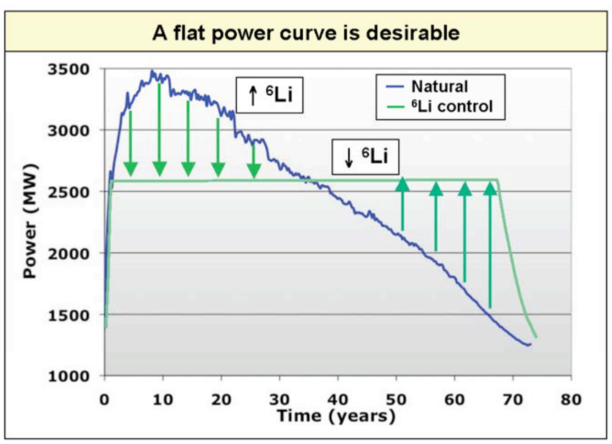
- Enhanced TRISO for WG-Pu and HEU



- Solid hollow core and Encapsulated powder pebbles for Fissile fuels (WG-Pu, TRU) or fertile fuels (DU, Nat U, Th and SNF)



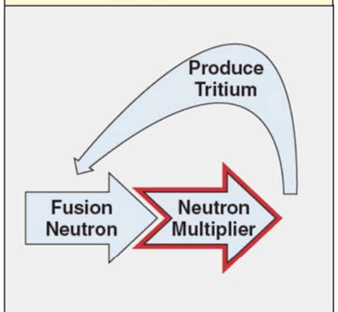
LIFE uses ^{6}Li as a burnable poison to control the thermal power and produce tritium



Systems achieving 90%+ balance of plant utilization may be possible through tritium management

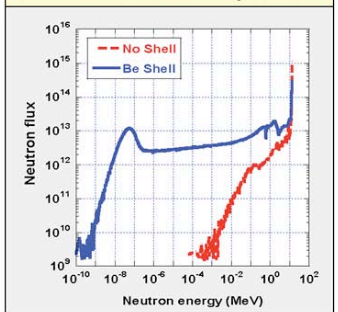
Beryllium multiplication and moderation enables rapid production of fissile material

Neutrons are multiplied via $^{9}Be(n,2n)$ reactions



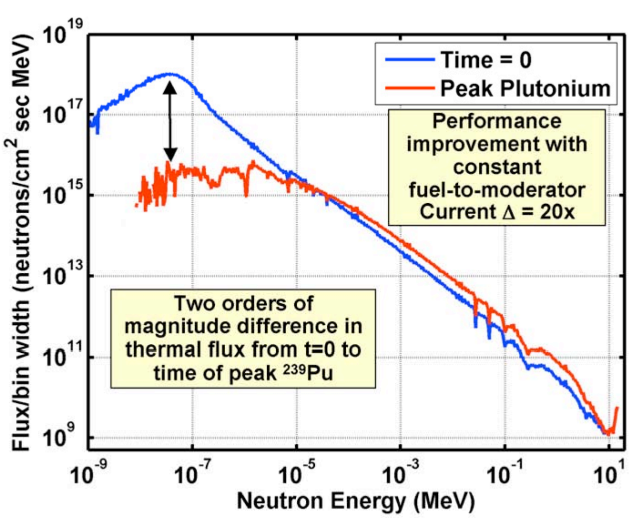
Beryllium produces ~1.8 neutrons for every fusion neutron

10 cm of Be considerably softens the neutron spectrum

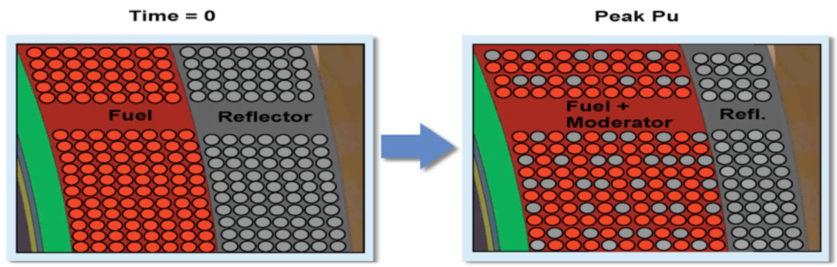


More thermal neutrons are available to produce tritium and fissile material

Neutron spectrum in fission blanket shows a significant change due to varying fuel-to-moderator ratio



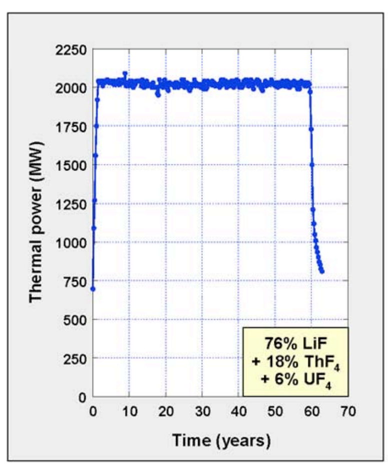
Pebble based fuel and reflector design allows for continual adjustment of fuel-to-moderator ratio



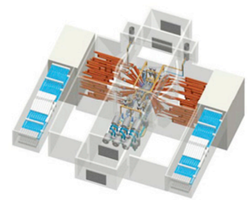
Optimizing fuel-to-moderator ratio throughout burnup could significantly improve performance

Molten salt fuel is an attractive option for burning fertile fuels

- Radiation damage to fuel is a non-issue
- Rare earth elements removed to avoid precipitation (on-line processing)
- Plutonium maintained below solubility limit → can adjust Th/U ratio to control $[Pu]_{max}$
- Blanket gain of 6-10× possible with on-line refueling



We believe that LIFE could provide pure fusion energy and a variety of once-through, closed fuel cycle energy and nuclear waste burning options



- NIF-like lasers
  - APG-1 glass; He cooling; Edge emitting diodes
- NIC-like targets
  - Hot spot ignition
- Target production, injection and engagement
  - Studies and scaled experiments at GA
- Fusion environment, 1st wall and final optics
  - Xe-filled, compact chambers; ODS-FS 1st wall
  - Thin Fresnel fused silica lens – self annealing color centers
- High burn-up Fuels
  - Refractory-clad SHC pebbles; 100 dpa for > 99% FIMA with Pu, TRU; (150 dpa for > 99% FIMA with DU, SNF)
  - Molten salt – radiation damage not an issue

But we can - and should be/will be able to do better

High temperature materials, compact laser systems and advanced ICF targets would be Game Changing for LIFE

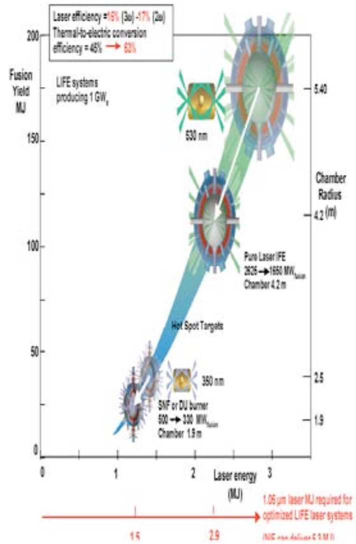
- Ceramic, long storage media DPSSL could provide:
  - Highly compact architectures
    - At the extreme, eliminate laser bay and switchyard
  - 3 x fewer diodes, lower cost and wall-plug efficiencies of 15-20%

- ODS-FS 1st walls limit us to ~ 650-700° C. This is too low for H production, and limits $\eta_{th\text{-}el}$ to ~ 45%
  - At 900 °C (SiC ?) : $\eta_{th\text{-}el}$ ~ 60% and η_H ~ 53%
  - At 1100°C (W ?) : $\eta_{th\text{-}el}$ ~ 64% and η_H ~ 64%

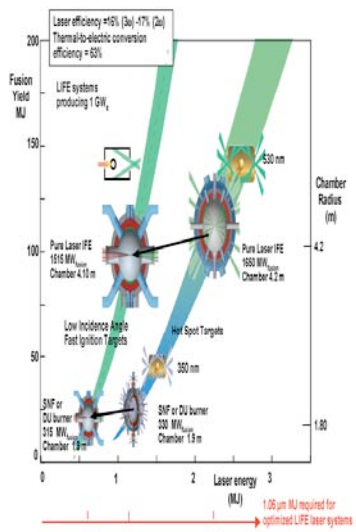
- Low incidence angle (~20°) FI would allow more attractive chambers and reduce laser MJ requirements by 2 X

Such LIFE options could provide even more attractive systems for disposal of SNM and nuclear waste and electricity or hydrogen production

The impact of high temperature materials and higher efficiency lasers have a significant impact on the LIFE system size



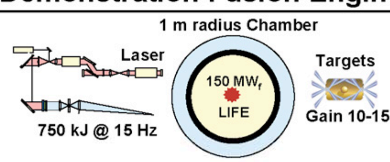
With advanced target performance LIFE laser requirements are further reduced



The separability of ICF and LIFE makes a rapid demonstration path possible

- Demonstration of LIFE fusion yield with targets produced with low-cost fabrication technologies that scale to LIFE production quantities will be demonstrated on NIF
- Mass production technologies for the fusion targets at required precision will be done off line
- Target delivery, tracking and engagement and chamber clearing will be demonstrated with surrogate targets and low power lasers in a separate facility
- The technology for the 15-20 MW LIFE diode pumped solid state laser (DPSSL) will be prototyped at the modular level.
  - — One LIFE-let ~150 kW is the "building block"
- Management of the fusion environment to demonstrate laser beam propagation, full life-cycle testing of thermal pulsing of 1st wall, and adequate lifetime of final optics will be performed in scaled experiments
- Ion beam-based accelerated testing coupled with multi-scaled modeling and irradiation in reactors will be used to design, test and validate fuels and structural materials

LIFE Vision: A 150 MW Demonstration Fusion Engine by 2020

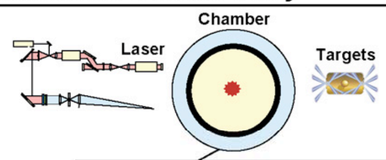


With
- 16% efficient advanced long storage media DPSSL
- High temperature composite material chamber
- Flibe coolant
- 60 % thermal to electric conversion

This demo LIFE engine would be self-sufficient in T and power

And would enable multiple mission-specific 1 GWe LIFE systems that could provide 100 GWe for the nation by 2050

LIFE Vision: Pure fusion could provide an early option for baseload market entry



Demo LIFE engine scales to multiple mission-specific 1 GW_e options

1700 MW_f

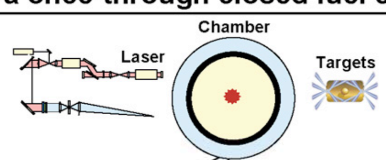
Mission	Pure Fusion: Inexhaustible energy
Benefit	Baseload energy with no high level waste. Earliest market entry
Blanket	Lithium-based coolant (no beryllium)
Developments	Development limited to systems scale-up.

The fusion option would require modest amount of further technology development

With NIC-like targets, the main changes would be:

- Laser: 0.75 MJ/0.35 µm to ~ 2.25 MJ/0.53 µm
- Target chamber radius: 1 m to 4.2 m

LIFE Vision: WG-Pu and HEU can be burned to > 99.9% in a once-through closed fuel cycle



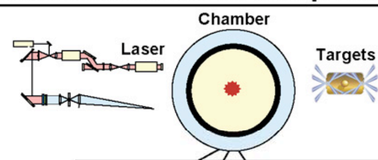
Demo LIFE engine scales to multiple mission-specific 1 GW_e options

	1700 MW_f	150-200 MW_f
Mission	Pure Fusion: Inexhaustible energy	Burn SNM in closed, once-through cycle
Benefit	Baseload energy with no high level waste. Earliest market entry	Proliferation risk reduction
Blanket	Lithium-based coolant (no beryllium)	Be-Li coolant w/ WG-Pu or HEU pebbles
Developments	Development limited to systems scale-up.	Fuels for > 99% burn (Credible options exist)

A LIFE SNM burner:

- Requires the lowest fusion power
- Once-through closed cycle burn of SNM to > 99 %
- Would have significant advantages over other options to dispose of SNM
- Credible options for > 99% burn have been identified

LIFE Vision: Burning SNM from spent nuclear fuel (SNF) could reduce HLW footprint by > 20 X



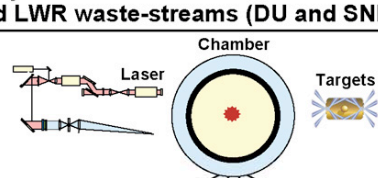
Demo LIFE engine scales to multiple mission-specific 1 GW_e options

	$1700\ MW_t$	$150\text{-}200\ MW_t$	$200\ MW_t$
Mission	Pure Fusion: Inexhaustible energy	Burn SNM in closed, once-through cycle	Destroy TRU from Spent Nuclear Fuel
Benefit	Baseload energy with no high level waste. Earliest market entry	Proliferation risk reduction	Proliferation risk reduction and > 20x reduction of HLW
Blanket	Lithium-based coolant (no beryllium)	Be-Li coolant w/ WG-Pu or HEU pebbles	Be-Li coolant with TRU pebbles
Developments	Development limited to systems scale-up.	Fuels for > 99% burn (Credible options exist)	Chemical separation Fuels for > 99% burn (Credible options exist)

Chemical separation of SNF would be required, but the TRU could be burned to > 99.9% in a once-through closed cycle

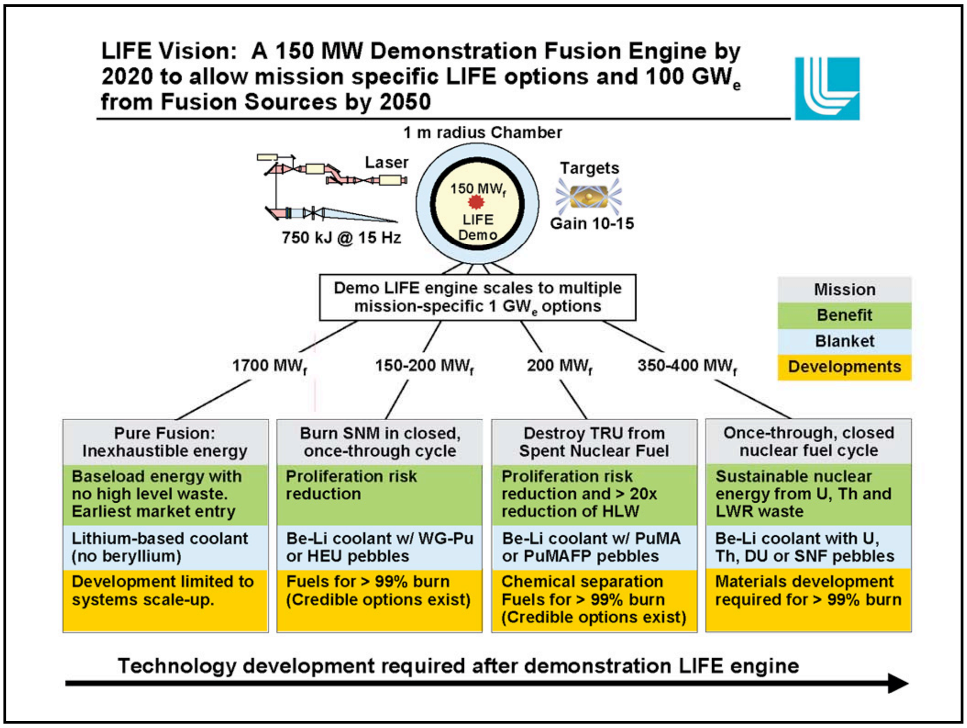
20 MT of SNF would become ~ 15 MT DU (LLW) and ~ 5 MT fission products with < 300 g actinides

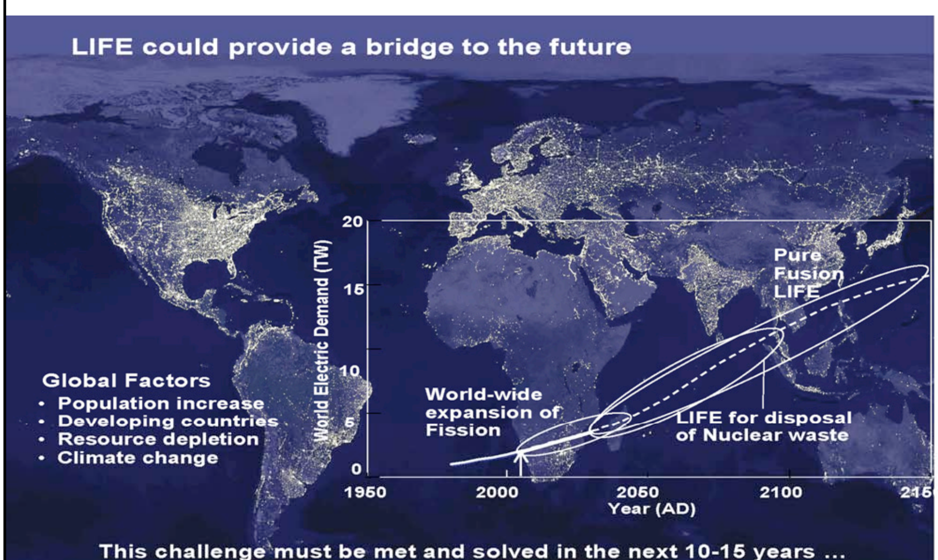
LIFE Vision: LIFE would provide a once-through, closed nuclear fuel cycle to extract > 99.9 % of latent energy from U and Th and LWR waste-streams (DU and SNF)



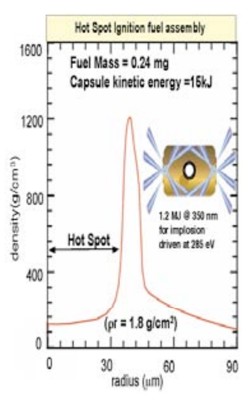
Demo LIFE engine scales to multiple mission-specific 1 GW_e options

	$1700\ MW_t$	$150\text{-}200\ MW_t$	$200\ MW_t$	$350\text{-}400\ MW_t$
Mission	Pure Fusion: Inexhaustible energy	Burn SNM in closed, once-through cycle	Destroy TRU from Spent Nuclear Fuel	Once-through, closed nuclear fuel cycle
Benefit	Baseload energy with no high level waste. Earliest market entry	Proliferation risk reduction	Proliferation risk reduction and > 20x reduction of HLW	Sustainable nuclear energy from U, Th and LWR waste-streams
Blanket	Lithium-based coolant (no beryllium)	Be-Li coolant w/ WG-Pu or HEU pebbles	Be-Li coolant w/ PuMA or PuMAFP pebbles	Be-Li coolant with U, Th, DU or SNF pebbles
Developments	Development limited to systems scale-up.	Fuels for > 99% burn (Credible options exist)	Chemical separation Fuels for > 99% burn (Credible options exist)	Materials development required for > 99% burn

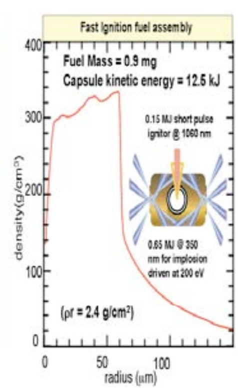

LIFE Vision: A 150 MW Demonstration Fusion Engine by 2020 to allow mission specific LIFE options and 100 GW$_e$ from Fusion Sources by 2050
1 m radius Chamber
Laser
750 kJ @ 15 Hz
150 MW$_f$
LIFE Demo
Targets
Gain 10-15
Demo LIFE engine scales to multiple mission-specific 1 GW$_e$ options
Mission
Benefit
Blanket
Developments
1700 MW$_f$
150-200 MW$_f$
200 MW$_f$
350-400 MW$_f$
Pure Fusion: Inexhaustible energy
Baseload energy with no high level waste. Earliest market entry
Lithium-based coolant (no beryllium)
Development limited to systems scale-up.
Burn SNM in closed, once-through cycle
Proliferation risk reduction
Be-Li coolant w/ WG-Pu or HEU pebbles
Fuels for > 99% burn (Credible options exist)
Destroy TRU from Spent Nuclear Fuel
Proliferation risk reduction and > 20x reduction of HLW
Be-Li coolant w/ PuMA or PuMAFP pebbles
Chemical separation Fuels for > 99% burn (Credible options exist)
Once-through, closed nuclear fuel cycle
Sustainable nuclear energy from U, Th and LWR waste
Be-Li coolant with U, Th, DU or SNF pebbles
Materials development required for > 99% burn
Technology development required after demonstration LIFE engine


LIFE could provide a bridge to the future
Global Factors
• Population increase
• Developing countries
• Resource depletion
• Climate change
World Electric Demand (TW)
20
15
10
5
0
1950
2000
2050
2100
Year (AD)
Pure Fusion LIFE
World-wide expansion of Fission
LIFE for disposal of Nuclear waste
This challenge must be met and solved in the next 10-15 years ...

We are also exploring advanced LIFE concepts The most promising is Fast Ignition



20 MJ of fusion yield for a Gain of 17

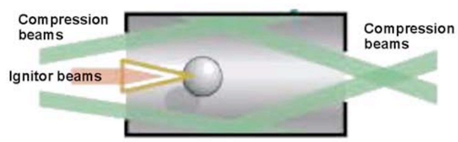


90 MJ of fusion yield for a Gain of 112

Fast ignition targets compress more fuel to ignition conditions with less laser energy, providing higher gain

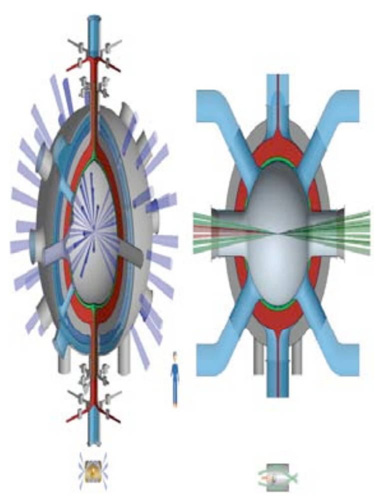
Indirect drive Fast Ignition has the potential of being compatible with low incidence angle illumination

Possible Low Incidence Angle Indirect Drive Fast Ignition Target



- Symmetry requirements relaxed, allows low incidence angle illumination
- Lower drive pressures/Tr, i.e. LPI issues relaxed, allows longer wavelength driver (2ω)

Fast ignition thus offers the possibility of more attractive chamber options and 530 nm compression lasers



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Challenges in Recycling Used Nuclear Fuel

Kathryn A. McCarthy

Deputy Associate Laboratory Director, Nuclear Science & Technology

May 18, 2009

Potential Benefits of Recycling Used Nuclear Fuel

- Expand engineering limits on design of a HLW geologic repository by reducing the long-term radionuclide inventory and heat source term destined for disposal
- Reduce the radiotoxicity of HLW to that of natural uranium ore in hundreds of years rather than thousands
- Resource extension
- Reduce the inventory of commercial plutonium
- Enable U.S. participation in international nuclear material management and reprocessing policy
- Remove used fuel from utility sites

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Challenges in Fuel Cycle Development

- Fuel cycle objectives are technically complex
  - Need a requirement driven process to structure the approach
- Technologies are highly interdependent
  - Need to choose a workable system
- Materials pathways need to be managed
  - Many forms are envisioned; management may need to last for centuries
- Economics and deployment strategies are key issues
  - Need integrated analysis approaches
- Technology risk needs to be managed
  - Need to develop a prioritized technical approach

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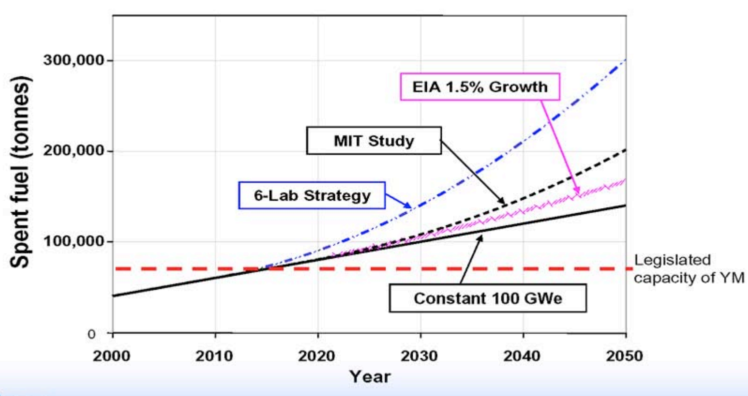
Projected U.S. accumulated spent fuel without recycling



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DOE Advanced Fuel Cycle Initiative

- The Advanced Fuel Cycle Initiative (AFCI) program in the U.S. DOE is investigating advanced nuclear fuel cycles for impact on nuclear energy use, including benefits to waste management
  - Pathways for disposing of used nuclear fuel have not yet been deployed
    - Uncertainties about long-term performance (millions of years)
  - Nuclear energy is expanding worldwide, and is expected to increase in the U.S. in the near future
- Viable approaches for the sustainable use of nuclear energy must be available, and two basic approaches can be envisioned
  - Once-through use of nuclear fuel followed by guaranteed safe disposal of used nuclear fuel (considered as nuclear waste)
  - Recycling of used nuclear fuel to alter the inventory of all nuclear wastes for more favorable behavior in disposal environments
    - Can recycling be used to reduce of the environmental hazards without introducing significant new radiation hazards?
  - Many sub-options exist for separations and recycling of used nuclear fuel
    - Which elements would be recycled and kept out of the waste stream?
    - What are the characteristics of the recycling approaches as far as the ability to achieve reduction in the hazard from all of the nuclear wastes?

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Nuclear Fuel Cycle Options - Drivers

- The evaluation of any particular nuclear fuel cycle depends on the desired goals, and many such goals are possible, depending on the assumptions that are made
  - What disposal environments will be available and what is the potential of the disposal sites to isolate nuclear materials from the environment?
    - Not all elements in used nuclear fuel may have favorable retention characteristics
  - What elements should be recovered or separated in processing?
    - What elements are best kept out of the waste streams?
    - Are there elements that should be separated for targeted disposal?, i.e., some disposal environments may be favorable for some elements and not others, and vice versa
    - What elements are useful in sustaining use of nuclear energy?
  - What can be done with those elements that are recovered and are not desired in the waste streams?
    - Recycle in nuclear reactors can transmute these elements into elements more favorable for disposal, i.e., shorter-lived, less hazardous, more favorable retention in disposal environments, etc., but what are the hazards from recycle?
- The AFCI program is investigating many options for addressing these questions, among others such as mining and enrichment needs, to evaluate potential reductions in environmental impact

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AFCI Historical Options

- AFCI options can be placed in two main categories, with the following examples given that the U.S. uses light water reactors (LWR) today
- Category 1: eventual disposal of used nuclear fuel (and nuclear wastes)
  - Once-through use in LWRs with direct disposal of used nuclear fuel
  - Processing of used LWR fuel to recover one or more elements for limited recycle in thermal neutron reactors (e.g., LWRs) with disposal of nuclear wastes and used recycle nuclear fuel
- Category 2: no disposal of used nuclear fuel, only nuclear wastes
  - Both high- and low-level wastes from processing and fuel fabrication (including losses), operations, maintenance, etc.
  - Processing of used LWR fuel to recover one or more elements for repeated recycle in thermal neutron reactors (e.g., LWRs) with disposal of nuclear wastes only
  - Processing of used LWR fuel to recover one or more elements for repeated recycle in fast neutron reactors (e.g., sodium-cooled fast reactors) with disposal of nuclear wastes only
    - Fast reactors have different fission and capture characteristics, resulting in the isotopic composition of the used fuel being different than that for thermal reactors

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Evaluation of Advanced Fuel Cycles

- The main question in evaluating alternative nuclear fuel cycles is one of establishing the quantitative measures to use as a basis for comparison
  - Many potential repository environments with different engineering requirements and isolation characteristics
    - Different chemical and water characteristics that affect corrosion, degradation, dissolution, and transport
    - Varying level of importance for parameters like decay heat
- Limiting radiation dose in the biosphere is the ultimate goal
  - Predicting peak dose rates from disposal is uncertain for many reasons
    - Fundamental data, site characterization, future climate, future events, etc.
  - Recycling introduces new activities that have radiation exposures
    - Processing and fuel fabrication facilities, new reactor types, waste handling
- What unambiguous measures can be used for evaluation?
  - Radiotoxicity for the radiation hazard from used fuel and nuclear waste
  - Decay heat for effects on the engineered disposal system
  - Exposures from operations and events (e.g., accidents, etc.)

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Radiotoxicity

- The dose rate in the biosphere caused by disposed radionuclides is determined by the radiotoxicity of the disposed inventory modified by the corrosion, degradation, solubility, and transport effects of the disposal environment
- Radiotoxicity is proposed as a useful measure for comparing nuclear fuel cycles in that it represents the 'source term' for any potential health effects from used fuel or nuclear wastes
  - In general, radiotoxicity is the measure of the toxicity due to the radiation from isotopes that are ingested, inhaled, or absorbed
  - Radiotoxicity varies greatly from one isotope to the next
- The radiotoxicity in used fuel depends on the isotopic inventory
  - The longer the fuel has been irradiated, the greater the inventory of hazardous radionuclides and the more hazardous the used fuel
  - On the basis of unit energy generation, higher irradiation is slightly better
    - Greater radionuclide inventory, but greater total power production
- After 100 years, radiotoxicity of used fuel is dominated by isotopes of plutonium and its decay products, followed by the minor actinides
  - One must be careful in the use of radiotoxicity, as this may not be representative of the relative importance of each isotope for repository dose rate estimates (although these estimates have high uncertainties)

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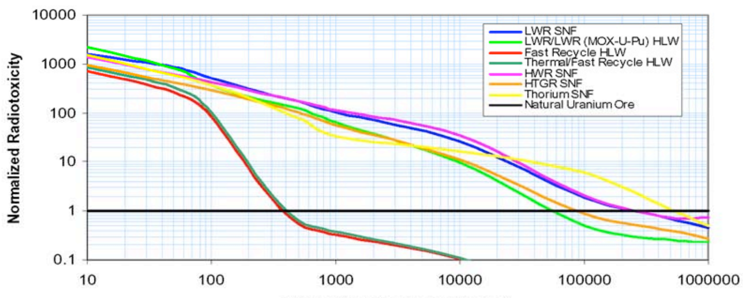
Radiotoxicity of Used Fuel



- Recycle of all actinides in used LWR fuel in fast reactors provides a significant reduction in the time required for radiotoxicity to decrease to that of the original natural uranium ore used for the LWR fuel (i.e., man-made impact is eliminated)
  - From 250,000 years down to about 400 years with 0.1% actinide loss to wastes

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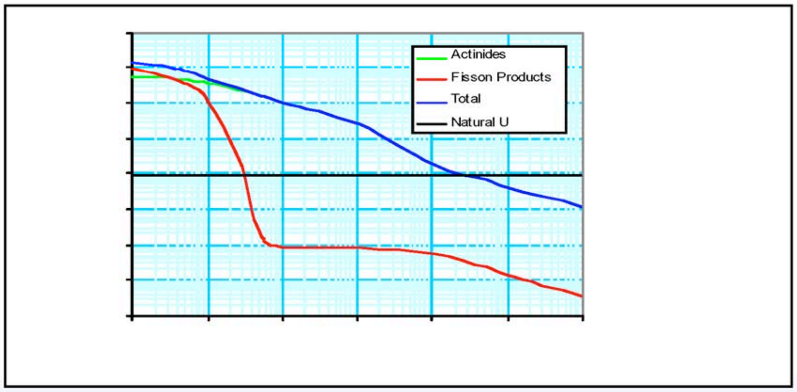
Radiotoxicity of LWR Used Fuel Relative to Uranium



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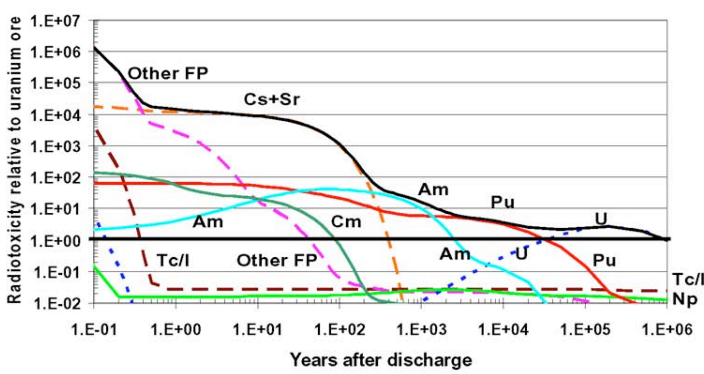
Pu+Am, U, Cs+Sr dominate radiotoxicity



51 MW-day/kg burnup, radioactive daughters included with their parent elements

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Decay Heat and Geologic Disposal

- **Decay heat is important for any engineered geologic disposal since temperature limits are applied to various components of the system to provide confidence in predictions of long-term performance**
  - At Yucca Mountain, the latest design has several requirements, including
    - Peak temperature midway between adjacent drifts must be below boiling
    - Peak temperature of the drift wall (rock) must not be high enough to cause phase alteration of the rock
    - Peak temperature of the surface of the disposal packages must not be higher than that used to measure long-term corrosion behavior
- **These temperature limits constrain the loading of the repository**
  - Maximum allowable loading per meter of drift
  - Determines the size of the repository for a given amount of used fuel
    - Associated with a given amount of total power production
- **With recycle, the waste inventory is reduced, and use of repository space can be improved**
  - Studies have shown that it can be important to manage both actinides (Pu, Am, Cm) and fission products (Cs, Sr), depending on the repository

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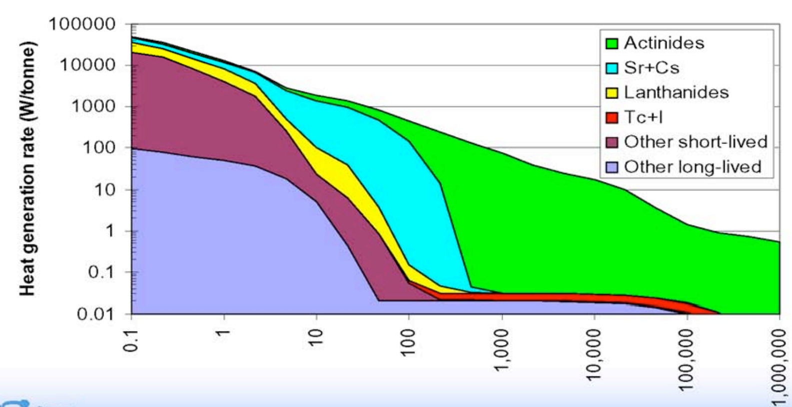
Decay Heat of Used LWR Fuel



Years after discharge

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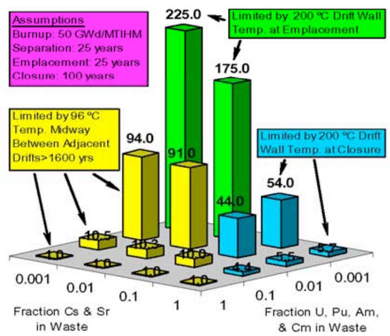
Decay Heat and Yucca Mountain Repository Loading



Potential increase in drift loading on an energy-generated basis

- **The figure shows the potential increase in drift loading as a function of the inventory of actinides and fission products in the waste stream**
  - **Removal of Pu/Am/Cm (decay heat) and U (volume) would permit the waste from about 5.7 times as much used fuel to be placed in the space that used fuel would require**
  - **Removal of Cs & Sr only would have no impact**
  - **Removal of the U/Pu/Am/Cm and Cs & Sr would permit the waste from up to about 225 times as much used fuel to be placed in the space that the used fuel would require**
- **Suitable waste forms would need to be available to fully realize such benefits**
- **Other repository environments could respond differently**

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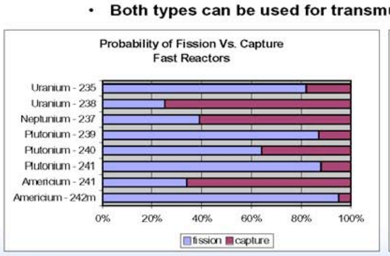
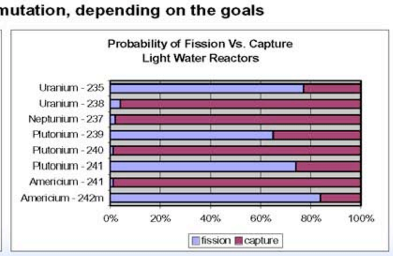
Transmutation – Thermal vs. Fast Reactors

- **Reactors can be used to manage the recovered actinides by transmutation and consumption**
  - **Transmutation depends on the neutron energy spectrum**
  - **Fast neutron reactors have a higher fission to capture ratio than thermal reactors, promoting fission over higher actinide formation**
    - **Fast reactors have much higher probability of U-238 fission and Pu-240 fission, reducing the buildup of higher actinide isotopes during irradiation**
    - **Both types can be used for transmutation, depending on the goals**





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(Traditional) Fuel Cycle Options to Reduce Radiotoxicity

- Fuel cycle options that address the actinide elements are being studied for their effect on radiotoxicity of disposed materials
- Key findings to date:
  - No direct disposal of any used fuel is essential for large reductions
    - Once-through approaches still have large actinide inventories in the used fuel
  - Limited recycle approaches have small effect
    - e.g., U/Pu-MOX in LWRs when not repeatedly recycled is not very effective
  - Repeated recycle is necessary for large reductions in radiotoxicity
    - Actinide losses to the waste streams must be kept as low as possible
- Recycle in fast reactors can manage the transuranic inventory
  - Equilibrium content in the reactor fuel can be achieved so that continued buildup is avoided
    - When fast reactors are used to support the use of LWRs, consumption matches introduction of new transuranics from used LWR fuel
  - May also be possible in thermal reactors, but with cautions
    - Interim storage of higher actinides is likely needed prior to recycle (>40 years)
    - Remote fabrication of thermal reactor fuel needs to be developed
    - Potential consumption rate may not be as favorable

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Advanced Fuel Cycles – Other Considerations

- In addition to radiotoxicity and repository utilization, there are several other important aspects that need to be considered in any evaluation
  - Recycle has a potential impact on the public due to the additional facilities that will be needed
    - Releases from normal operations, within regulatory limits, and possible accidents
    - However, continued use of once-through will mean expanded mining, etc.
  - Implementation of any new approach will require significant investment over an extended time
    - Existing nuclear energy infrastructure is the result of 60 years of deployment and use
    - Systems analysis studies show that it will require decades to make a substantial change from the existing once-through system to any alternative system
    - Total costs are substantial ($100s billions), but the value of the product over the lifetime of the investment is also substantial ($1000s billions or more)
    - Difficult to quantify financial impact of alternative waste management strategies
  - Sustainability of the nuclear energy system
    - Uranium resources are one potential, but highly uncertain, issue that can be addressed with recycle using breeder reactors
    - Adequate disposal capacity for all categories of radioactive wastes needs to be addressed
- There is always the larger question of global non-proliferation goals, the benefits of which are more difficult to quantify

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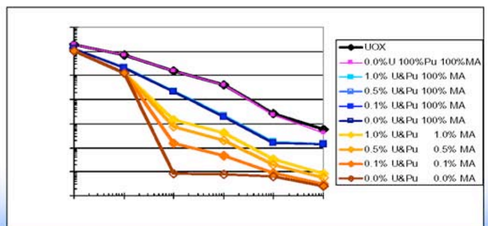
Development of new/expanded metrics is needed to compare options

- Current metrics need reexamination (e.g., comparison to natural uranium, heat load, dose)
  - A science-based development/justification of the metrics is needed
- Metrics are needed both for comparison of fuel cycle options as well as comparison with other energy options
  - Environmental Impact (e.g., greenhouse gas production, land use, mining, etc.)
  - Waste (Isolation time, HLW, LLW….)
  - Resource Use
  - Proliferation Risk
  - Etc.

System requirements will depend on metrics!



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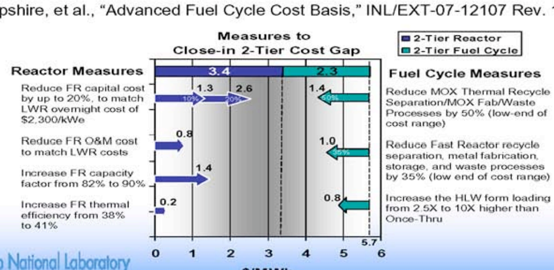
Reducing Cost is a Challenge

- Closed fuel cycles appear to cost ~10% more than Once-Through
  - Nuclear reactor and fuel cycle costs have large uncertainties
  - The cost distributions overlap
- Measures for closing the cost gap were assessed for 1- and 2-tier fast reactor recycle
  - "Advanced Fuel Cycle Economic Tools, Algorithms, and Methodologies," INL/EXT-09-15483, May 2009
  - Shropshire, et al., "Advanced Fuel Cycle Cost Basis," INL/EXT-07-12107 Rev. 1



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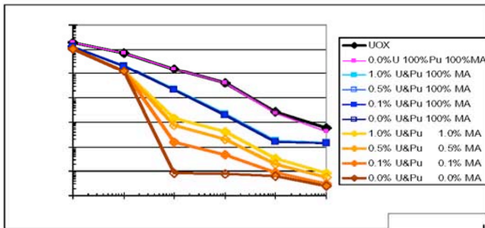
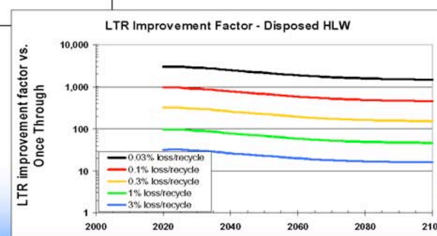
Minimizing System Losses is a Challenge





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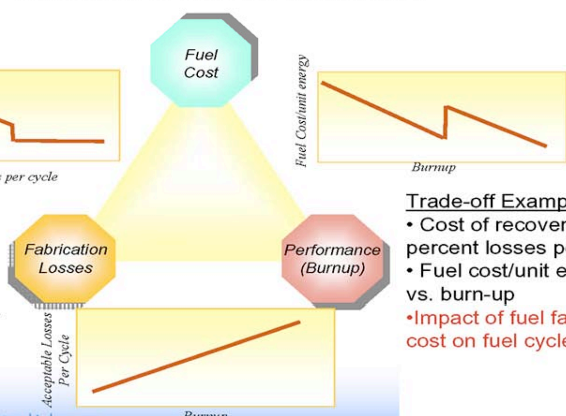
But minimization of losses must be considered relative to cost (and technical feasibility)



Particular attention paid to areas of step-function behavior (e.g., liners in fuel cladding)

Trade-off Examples
- Cost of recovery vs. percent losses per cycle
- Fuel cost/unit energy vs. burn-up
- Impact of fuel fabrication cost on fuel cycle cost

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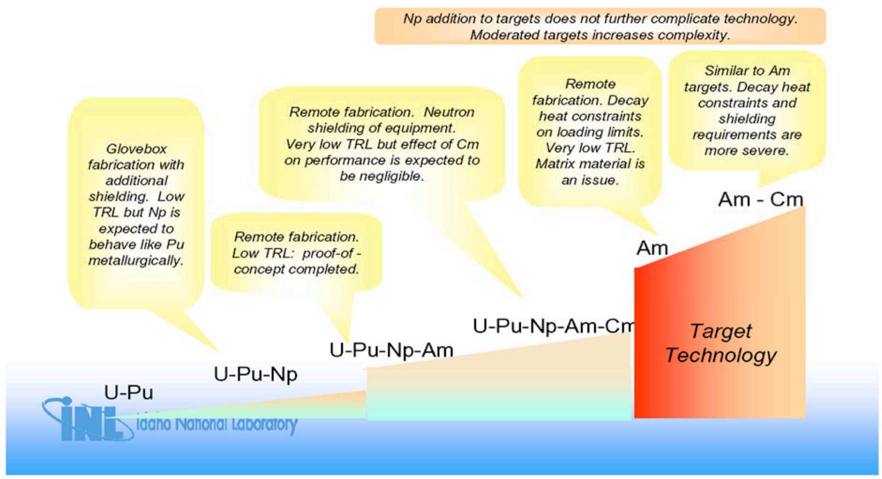
Fabrication of Fuels/Targets is a Challenge



Challenges in Separations

- Minimize losses
- Minimize/optimize waste generation (all types)
- Minimize cost
- Minimize radioactive off-gas emissions
- Lesson learned: Need to simplify separations
  - Fewer separation processes
  - Fewer waste form processes and
  - Fewer waste form handling/storage facilities

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Example Scenario - Recycle in Fast Reactors Only

- Nuclear energy increases 2.25%/year (results in ~33% nuclear energy market share by the end of the century)
  - The electricity market grows at a rate of 1.5%
- Yucca Mountain accepts LWR SNF from 2017 to 2039 (63,000 MT total).
- ABRs
  - Start-up requires fuel for a spare core
  - 1st ABR in 2021 (1000 MWt)
  - Restricted construction from 2030-2044 (learning)
    - 1 GWe/yr 2030-2034
    - 2 GWe/yr 2035-2044
  - ABRs after 2044 built based on TRU availability
- ABR Separations and TRU fabrication Built as needed (co-located with ABRs)
- LWR SNF cooling time = 10 yrs
- Fast Reactor SNF cooling time = 2 years
- TRU fuel is metal
- TRU Conversion ratio is 0.5
- LWRs/ALWRs
  - First ALWR on-line in 2015
  - Retired after 60 year life (only one license renewal)
  - ALWRs built to maintain nuclear growth rate
  - ALWR and LWR fuel burnup increases slowly to 80 MWd/kgHM
- LWR Separations Plants start up in 2020, 2050, 2080
  - Each separations plant processes 2000 MT/yr at maximum expected capacity.
  - First plant ramp-up rate: year 1: 5%, year 2: 10%, year 3: 20%, year 4: 40%, year 5: 60%, year 6: 100%
  - Subsequent plants: year 1: 10%, year 2: 30%, year 3: 60%, year 4: 100%
- TRU bank provides material for fuel fabrication plant in case of unavailability of LWR SNF separations plant
  - Inventory equal to 2 yrs of capacity of first separations plant

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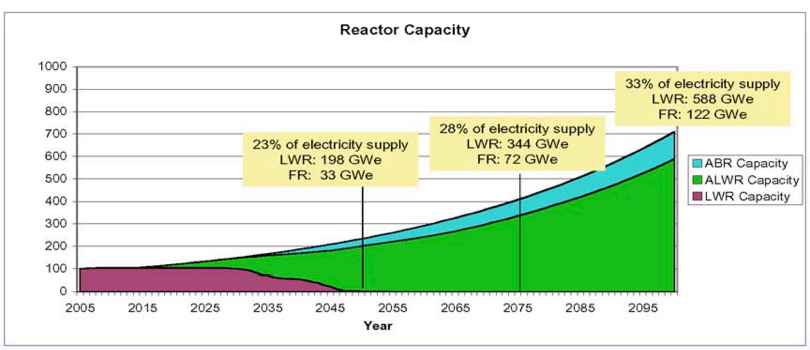
Example Scenario - Nuclear energy provides 33% of electricity by the end of the century



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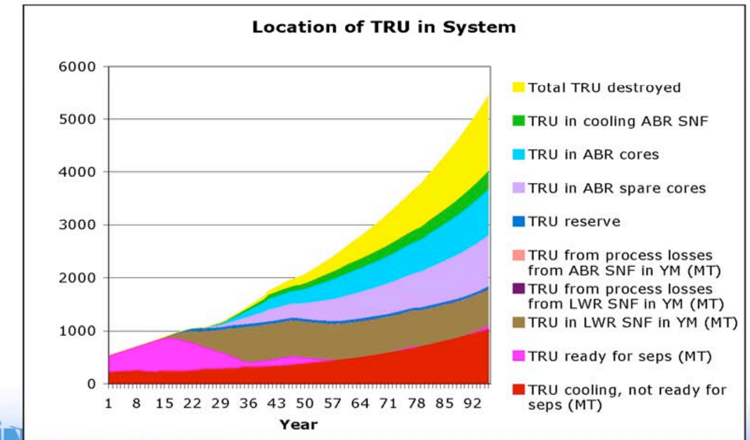
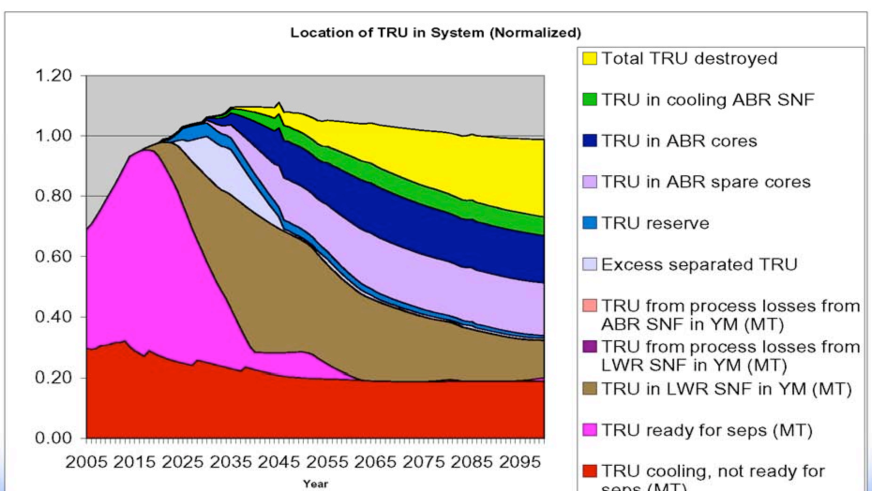
Location of TRU for Baseline Scenario





Summary

- Challenges can include
  - Cost of facilities
  - Proliferation risk
  - Potential release of gaseous or dissolved (liquid) radionuclides
  - Growth of secondary wastes
  - Poor historical precedent of reprocessing under different priorities, regulations, and societal values
- Consider the entire system*
  - Separations
  - Fuel/target fabrication
  - Transmutation
  - Transportation
- A strong systems analysis activity is needed!
- Technology scale-up can introduce new challenges

*Example: B. Dixon, et al., Dynamic Systems Analysis Report for Nuclear Fuel Recycle, INL/EXT-08-15201, Idaho National Laboratory, 2008.

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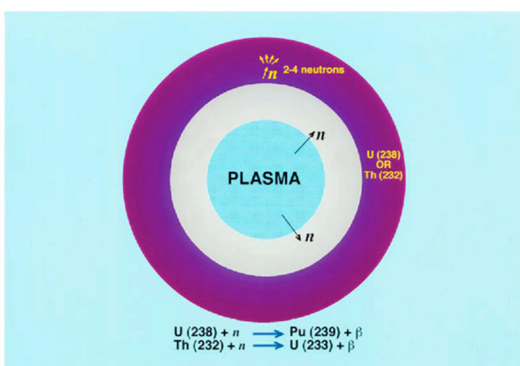
Hybrid fusion and energy parks, the justification, cost, and schedule

Wallace Manheimer
Retired from the U.S. Naval Research Laboratory
Washington D.C.

Talk at Brookings Institute

May 19, 2009

The fusion hybrid: From Hans Bethe, Phys. Today, May 1979



Wall must contain Neutron multiplier so To breed both T and ^{233}U

But each 233U releases ~200 MeV when burned. Q is effectively raised by at least an order of magnitude

Fission is energy rich and neutron poor, while fusion is energy poor and neutron rich. A perfect match!

This is a very old idea

- Andrei Sakharov, Memoirs, p142: “An important proposal of mine (in 1951 or late 1950) was that neutrons from thermonuclear reactions be used for breeding purposes”.
- Hans Bethe, Physics Today, May, 1979: “It seems important to me to have an achievable goal in the not too distant future in order to encourage continued work, and continued progress toward the larger goal, in this case pure fusion”
- Others: L. Lidsky, R. Moir, W. Stacy, D. Jassby, etc

NAS Review ~ 1984

- Recommended against separate program for hybrid fusion:
- Envisioned rapid development of pure fusion. Report was at a time of large and increasing fusion budgets.
- Saw conventional and hybrid fusion as following the same path so hybrid could ride coattails. One could always switch to hybrid fusion at an appropriate time.

What has changed?

- Fusion's disappearing coattails
- Much faster world development, especially in China and India than NAS envisioned
- China now world's largest carbon emitter
- Africa, Latin America and rest of Asia will most likely follow
- Energy supplies are extremely stressed
- Possibility that tokamaks, magnetic fusion's best hope may stop short of reaching pure fusion (9)
- From 1992-2008 I seemed to be about the only one, at least in USA, advocating hybrid fusion (1-10)

Energy cost of a neutron

- Fission reactors (thermal or fast neutron): E~200MeV, ~2.3 neutrons (thermal a little less, fast neutron a little more), 1 to continue reaction, so 1.3 neutrons for other purposes, or ~150Mev/n
- Accelerators: Electricity (η~33%) →Accelerator (η~50%) →1Gev proton →~30 spallation neutrons, or 200 MeV/n
- Fusion: E~20MeV →2-4 neutrons (Bethe), one to produce T, so 1-3 for other purposes, or 6-20MeV/n
- FUSION HAS A LOWER ENERGY COST/N BY MORE THAN AN ORDER OF MAGNITUDE

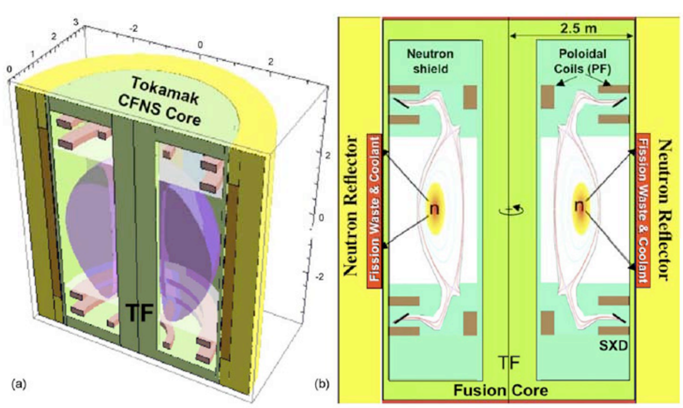
What to do with these neutrons?

- Boil water i.e pure fusion, (Maybe in 22nd century)*
- Burn actinide Waste (No)*
- Fast Fission, i.e. combine fission and fusion in a single power plant (No)*
- Fission Suppressed, i.e. use fusion to produce nuclear fuel for use in conventional nuclear plants (yes)*
- Transmute long lived radio isotopes, i.e ^{99}Tc (maybe)* [see ref 6]

* Author's opinion

Conference seems to be focusing on waste treatment, but I'd like to take a few slides to give a dissenting view

From Kotschenreuther et al, Fusion Engineering and Design, 84, p83, 2009



Fusion reactor surrounded by subcritical fission reactor

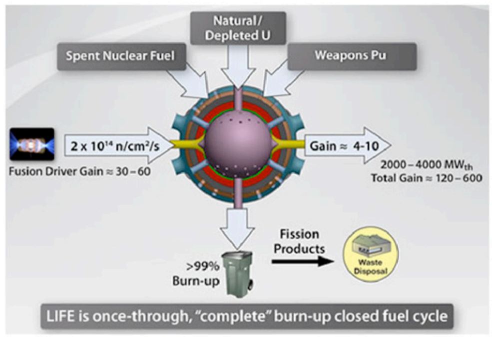
- Neither a subcritical fission reactor nor fusion reactor has ever been built, but they have to work together seamlessly.
- Google search on subcritical reactors emphasize accelerators to provide neutrons, accelerators at least have standoff; 100 MW fusion reactor sits right in the middle of a 3 GW nuclear reactor, k apparently~0.5- 0.7.
- Plasma which we do not understand very well, and which might disrupt, is just a thin wall away from a ton or so of plutonium. Significant safety issue.

Subcritical reactor con't

- Uses copper magnets. Power drain not given, but in GA FDF proposal seemed to require 500 MW, but for a larger system
- Beams, rf, lots of wires, etc, must pass through a 3GW nuclear reactor to reach the plasma deep inside. Can this really be done? Has anything like this ever been done?
- Can the thin center post really absorb the neutron flux and the current from all the toroidal field coils and remain viable? How would one cool it?
- In places walls seem thinner than conventional designs. Neutron leakage?

What about Livermore's LIFE?

•



Being sold principally as a way to burn up nuclear wastes. Proposes an indirect drive pellet (gain~30-50) being injected 10-15 times a second.

MORE ON LIFE

- Indirect drive requires the dropped pellet to be properly oriented on three axes, rather than a sphere as in direct drive pellets.
- Cost of the hohlraums: Denise Hinkel told me that current hohlraums cost ~$10,000 and have expensive metal, i.e. gold, etc.
- LLNL portrays LIFE as environmentally benign, but how do they think Greenpeace and NRDC will react when they learn that they plan to blow up the equivalent of 50-100 lbs of TNT, 10 times a second in a chamber surrounded by a ton or so of plutonium?
- A solution to the waste actinide problem already exists, fast neutron reactors like the IFR and AFR. These have been built, tested and they work.
- One could argue that LIFE or its MFE analog is an expensive, and technically risky, and indeed dangerous solution to a problem which has already been solved.

Is fusion better than fast neutron fission (i.e. Integral fast reactor (IFR))?

- Kotschenreuther: "The transuranic 'sludge' is extremely unfavorable as a fuel for any critical system"
- But:
- Charles Till in PBS frontline interview (Leader of IFR project): ".. But {the waste contains} none of the long lived toxic elements like plutonium, americium or curium, the so called man made elements."
- Wikipedia article on IFR: "The reactor was an unmoderated design running on fast neutrons, designed to allow any transuranic isotope to be consumed."

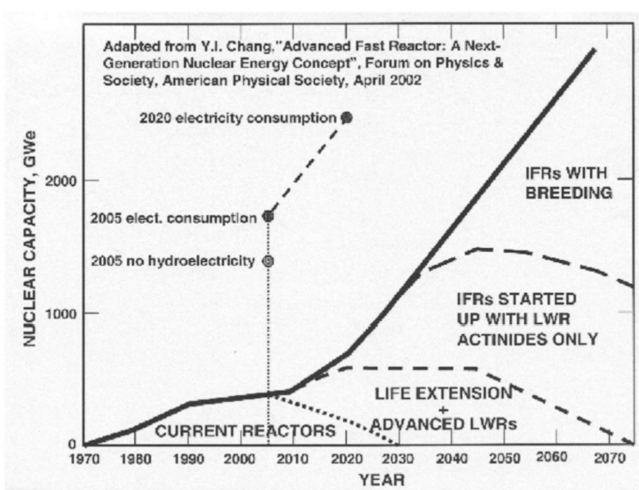
The IFR

- Was built and worked well for several years.
- Claimed it burns all transuranic elements, and does so in reactor mode which is passively safe.
- Can run as a breeder, burner, or in a breakeven mode.
- Molten salt breeder reactors, using the thorium cycle make the same claim.
- Also there are years of experience with superphenix
- Why not use fusion for something breeder reactors admit they cannot do, namely produce large, and necessary amounts of nuclear fuel?

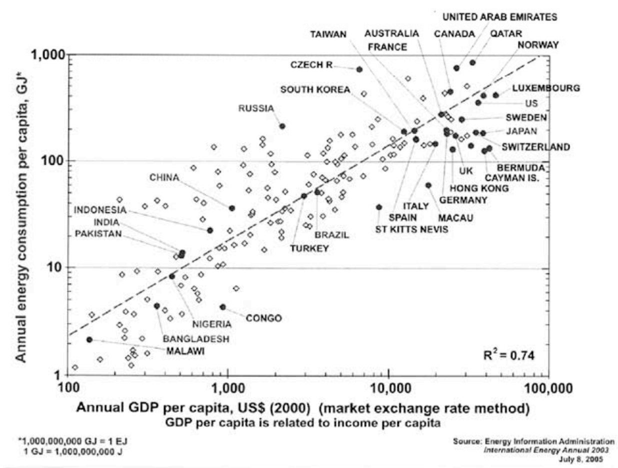
Two emails from Dan Meneley (former head of Canadian nuclear society)

- I've nearly finished prepping my talk for the CNS on June 13th (2006) -- from what I can see now, we will need A LOT of fissile isotopes if we want to fill in the petroleum-energy deficit that is coming upon us. Breeders cannot do it -- your competition will be enrichment of expensive uranium, electro-breeding. Good luck.
- We (I'm on the Executive of the Environmental Sciences Division of ANS) held a "Sustainable Nuclear" double session at the ANS Annual in Reno a couple of weeks ago. I have copies of all the presentations. ………… The result was an interesting mixture of "we have lots", just put the price up and we'll deliver (we've heard the same from Saudi recently) and "better be sure you have a long-term fuel supply contract before you build a new thermal reactor".

From Yoon Chang, also a strong advocate of breeders, claiming they cannot breed fast enough for what he sees as the growth of demand



Country's energy use vs per capita GNP



What about Kyoto and CO_2

	1990	2005	%increase
Non Warsaw Eur.	2166	2516	16
Warsaw Eur.	2621	2129	-19
USA	4747	5289	11
Japan	935	1075	15
China	1454	2844	96
India	288	862	199
Egypt	42	98	133
Malawi	0.53	0.85	62

The world needs energy, where from?

Oil and Gas? We will run out of economical supply certainly in our children's lifetime.

Coal? Environmental problems, and we will run out in our grandchildren's lifetime anyway.

Solar, wind and biofuel? Most likely bit players (<10%)

Nuclear? Once through cycle with high grade ore will not supply us for long. Expensive low grade ore may be an option, seawater is much too dilute in uranium.

Breeding by fusion or fission seem like about only other choices.

The options are few, time to start is now; it takes decades to make major changes in energy infrastructure.

The dilemma of fusion

- One might think that we go to hybrid fusion instead of pure fusion, great new vistas open up.
- But if pure fusion is next to impossible, then hybrid fusion is very difficult.
- In my opinion this means the best pure fusion device will be the best hybrid fusion device
- This leaves only tokamaks and laser fusion left standing. Only these have the worldwide infrastructure and sufficient head start to continue the race.
- USA has already abandoned partially constructed mirrors and stellarators.

THE NRL KrF LASER FUSION PROGRAM

Three linked experimental programs

•NIKE: 3 kJ single shot laser: planar target studies and laser development (Google NRL NIKE laser)

•ELECTRA: A reprated laser, 5Hz, 750 Joules, >50,000 shots so far (Google NRL Electra laser)

•HAPL (NRL Led/Multi institution): Development of the technologies needed for laser fusion. (Google NRL HAPL high average power laser)

Where is MFE in all this?

- 3 Large tokamaks have had good success
- TFTR (decommissioned in 1998), JET and JT-60U
- In good shots TFTR and JET they produced 10^{19} neutrons in a DT plasma in a 1 sec shot, powered by 40 MW of neutral beams for $Q \leq 1$.
- JT-60U got similar results in DD plasmas.

But now it's all ITER

- World effort focused on ITER now.
- ~$10B Machine, 10 year construction, 1 year decommission for $5B, 10 years operating, $0.5B/yr.
- Hopes to generate ~400 MW neutron power or 140 MW electric power in 1 or 2, 5-10 minute shots per day.
- Stipulate that it operates 24/7 and is connected to grid, all for cost of isolated machine and capital and decommission spread over 30 year life, $0.55/kwhr.
- Original Large ITER, $20B, 1.6 GW neutron power reduces cost a factor of 2

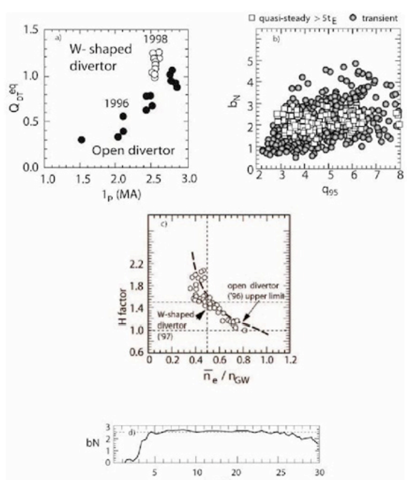
ITER's Dilemma as a Power source

- ITER and LARGE ITER are both Q~10 machines.
- 33%of neutron power produces electricity
- tokamak power supply (neutral beams, rf, whatever) are ~ 33% efficient.
- ITER JUST POWERS ITSELF.

Conservative Design Rules

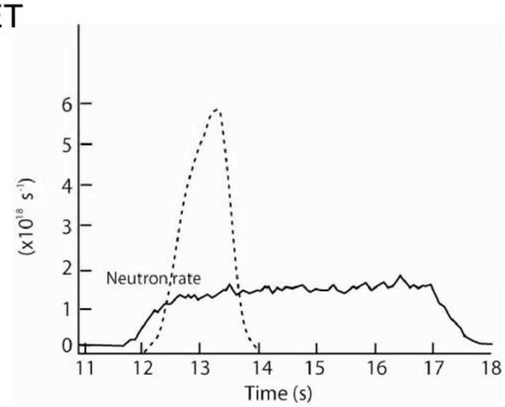
- Even with Q=∞, the tokamak is restricted in the current, pressure and density it can contain.
- Conservative design rules (CDR) (9):
- Current: q(a)<3
- Pressure: β_N <2.5
- Density <3/4 Greenwald Density
- Best neutron shots on JET and TFTR ~ factor of 2 below CDR.
- Estimates of ITER also factor of 2-3 below CDR
- I claim conservative design rules prevent economic power from tokamaks (9).

Are conservative design rules valid? Example from JT-60U



But the best neutron shot were transient

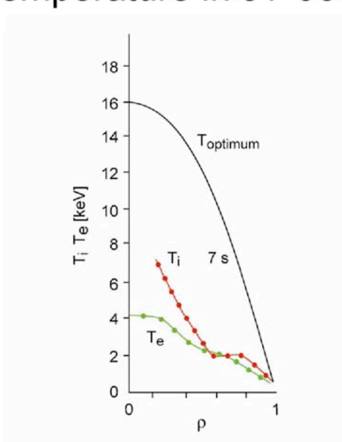
Example from JET



Best long lived shots ~ factor of 5-10 below CDR for JET and JT-60

Why don't steady state shots on JT-60 give CDR results?

Temperature in JT-60U



- For a $ß_n$=2.5, and parabolic profile, optimum maximum temperature for a beta limited plasma is 16keV.
- JT-60 results have half max T_i and probably less than 1/3 average T_i

As regards pure fusion, to Quote James Lovell: "Houston we have a problem!"

Let's take another look at hybrid fusion

Fate of a 14 MeV fusion Neutron

- Calculated by Monte Carlo codes used to follow path of a neutron and all its progeny.
- Typical result by Moir considering an 'engineered blanket (i.e. with appropriate structural material):

14 MeV neutron → 0.73 ^{233}U + 1.1 T + 35 MeV

I have always focused on producing ^{233}U instead of ^{239}Pu because raw fuel has less proliferation potential. It could even be exported.

Indeed, why shouldn't the USA, using its brains, scientific and engineering smarts become the Saudi Arabia of the Mid to late century?

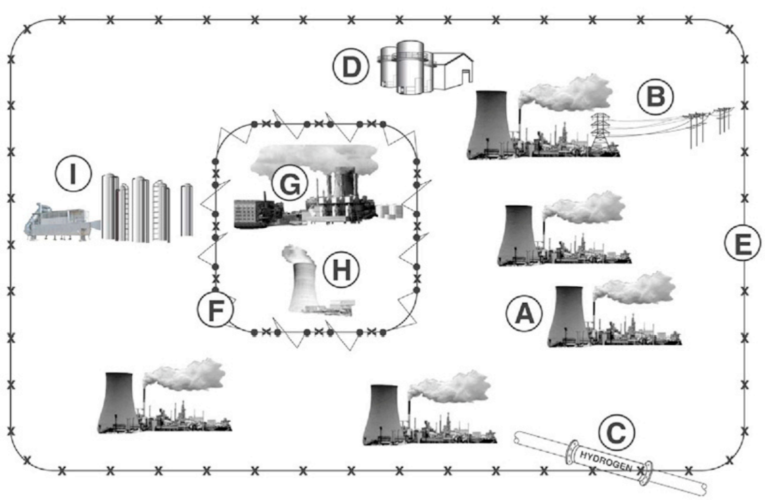
- Fission Suppressed (Ralph Moir and others)
  - Use a liquid or flowing blanket and reprocess the ^{233}U or ^{239}P on the fly and burn these in a reactor designed to do this and only this.
  - Proliferation considerations, $^{232}Th/^{233}U$ cycle
  - One calculation [Moir] shows that in a 'engineered blanket', one fusion neutron produces 1.1 triton, 0.73 ^{233}U and 35 MeV.
  - But the 0.73 ^{233}U when burned produce ~150MeV!
- Fusion is neutron rich and energy poor, fission is neutron poor and energy rich, a perfect marriage.

- Question: Doesn't breeding both T and ^{233}U make the blanket much more complicated than just breeding T as in pure fusion?
- Answer: Absolutely not! If it is too complicated to breed both in a single blanket, and hybrids pervade the economy, some can breed T and others ^{233}U.
- Also an overwhelming advantage of the hybrid, the wall flux is only ~10% of what it would be for pure fusion.

ITER as a breeder

- The 1.5 GW of Large ITER's neutron power was ~$.25/kwhr. 1.5 GW of neutron power→15GW of fuel.
- At the same price we produce 15 GW of nuclear fuel and Large ITER is itself a 3.5 GW power plant. Fuel cost from this calculation <2¢/kWhr.
- Added cost from breeding and cw operation probably increases the cost to 3-4 ¢/kWhr.
- Gasoline at $1/gallon is 2.5¢/kwhr as raw fuel, or 7.5¢/kwhr when powering a 33% efficient generator.
- LARGE ITER can produce nuclear fuel at a reasonable cost.
- ITER can produce fuel at a higher cost but could be a valuable prototype.

This led to the fusion-fission energy park; more than a dream, much less than a careful plan.



Everything shown in the same location, but of course they do not have to be.

The Energy Park (or What Marty Snyder calls 'The Manhattan Project')

More than a dream, certainly less than a careful plan

A. A Nuclear reactor, perhaps of today's design. Each year takes in 1000 kg of ^{233}U (mixed with 24,000 kg of ^{238}U) and discharges, among other things, 200 kg of ^{239}Pu, 750 kg of highly radioactive intermediate Z isotopes, and 50 kg of lower activity isotopes, e.g. ^{99}Tc with 200,000 year half life.

B. Output electricity

C. Output hydrogen

D. Cooling pool where waste is taken and low Z highly radioactive isotopes cool for perhaps 300-500 years. We have already stored in cooling pools for 40 years, or more than one half life if Pu and long lived actinides and radioisotopes are separated out.

E. Low Security fence

F. High security fence

The Energy Park, con't

G. Separation plant where actinides (mostly plutonium), highly radioactive elements, and less active elements are separated. Highly radioactive elements go back to cooling pool, plutonium to a plutonium burner, and low active waste perhaps back to fusion reactor for transmutation.

H. Plutonium burner. Separated plutonium from all 5 reactors are burned here. Most likely to be a fast neutron reactor, but might be a thermal neutron reactor if the fertile material is ^{232}Th.

I. The fusion reactor. Produces 1.5 GW of neutron power (like the large ITER), 3.5 GW thermal power and 15 GW of ^{233}U, enough to feed the 5 thermal reactors. 5% of wall area might be used to transmute all the low activity elements produced in park if one neutron for 1 transmutation.

The Energy Park, conclusion

- Produces 7 GWe
- No long time storage or long distance travel of material with proliferation potential.
- Treats all of its own wastes.
- Waste treated with a combination of fission, fusion and patience.
- Only ^{232}Th comes in, only electricity and hydrogen go out!

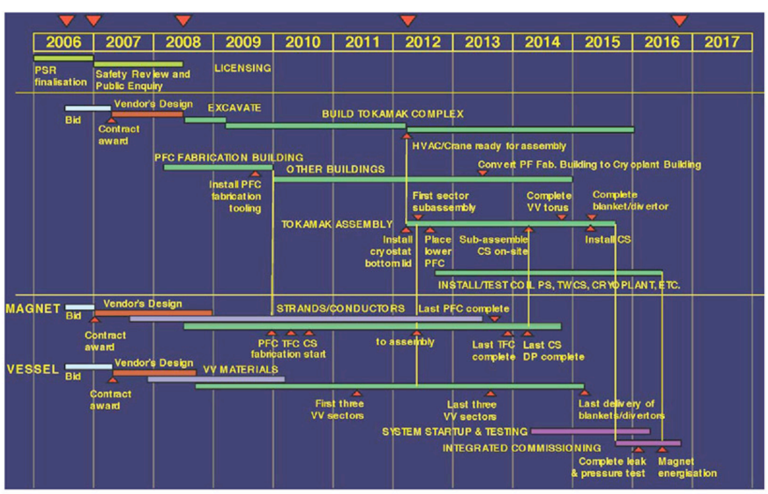
Original proposed schedule for energy park

- Hoffert (4) spoke of 10-30 GW needed by midcentury.
- First build scientific prototype, tokamak like JT-60 (Q~1) but running cw in DT and breeding both T and ^{233}U. (15 years)
- When we have results on CW operation in DT, ITER would be getting results on large tokamak with Q~10.
- Then build Large ITER as a fuel producer (15 years)
- If this works, then begin to mass produce, so that large scale power is produced by mid century.
- 15 years for a large tokamak experiment is aggressive, but not unreasonable.

Can this schedule be accelerated?

- Support work in JET and JT-60 to see if they can achieve long lived Q~1 plasma.
- Start building our own ITER right away, but as a cw machine to breed ^{233}U and T. It would not supply the entire energy park, but could supply one its reactors.
- How fast could we build our own ITER

ITER Construction Schedule



ITER Schedule and Cost con't

- ITER thinks of a 10 year construction time for $~5B.
- This is with international consortium, much time for international negotiations.
- Building an ITER in a national program might go faster.
- But it would have to breed ^{233}U and T. Cost would almost certainly be more.
- We have the advantage of having the entire design of a non breeding ITER, we would only have to add the breeding part.
- Construction cost would probably double to $10B due to necessity to engineer high average power and breeding.

An 'Energy Park' or 'Manhattan Project' in 15 years?

- The 5 LWR's we could build today. Since they would be of same design and in same place, licensing would as simple as possible.
- The separation plant we could build today.
- The actinide burner, using the experience of the IFR and superphenix, we could almost certainly build today with some technical risk. As this is both a power producer (industry) and waste disposal (government) the cost would be shared.
- An attractive alternative is to build an thorium-U^{233} breeder as the actinide burner. It fits in better with the architecture of the energy park.

An 'Energy Park' or 'Manhattan Project' in 15 years? Con't

- The ITER sized reactor is obviously the most technically risky part.
- Using ITER rather than Large ITER minimizes the risk, but it will not supply the entire park as Large ITER would.
- But Uranium would be available in the commercial market for the 4 reactors, and for the fifth in a worst case scenario.
- This would be a multi billion $$ operation paid for almost entirely by the private sector, bringing together a large and powerful consortium of advocates for thermal reactors, breeders, and recyclers.
- The private sector might even be willing to pay a portion of the fusion part so as to play in such a large project

An 'Energy Park' or 'Manhattan Project' in 15 years? Con't

- An energy park exists today. It is the Kashiwazaki-Kariwa nuclear plant complex in North Western Japan. It is a suite of 7 LWR's, producing a total of 8 GW.
- To build the 'Manhattan Project' we would have to replace two of the reactors with an ITER breeder and an actinide burner and add a separation facility.
- The LWR's could be run in a tritium producing mode (See TVA Watts Barr Nuclear plant). This would increase the T produced by each fusion neutron from about 1.1 to about 1.25. This could be an important reserve.
- The energy park is then truly symbiotic, fusion produces fuel for the LWR's, the LWR's produce an additional tritium reserve for fusion.

An 'Energy Park' or 'Manhattan Project' in 15 years? Con't

- To me it seems like a much more intelligent, less technically risky, and indeed much less dangerous course of action than building say an ST tokamak as a part of a subcritical reactor for actinide burning.
- It is a much smaller departure from the fusion main stream effort.
- If successful, it would be of tremendous value, a sustainable energy source forever.
- Even if the fusion part fails or delivers less ^{233}U than planned, the energy park will still be a vast pollution free, carbon free energy source..
- Very likely could be done in 15 years.

If insufficient resources to build energy park:

- Build only the scientific prototype. This is a steady state, Q~1 tokamak roughly the size of JT-60, but built to run steady state with a DT plasma and facility to breed both T and ^{233}U. The latter would be immediately mixed with ^{238}U and used as nuclear fuel. Expected neutron power ~40MW, expected ^{233}U power ~ 400 MW. If resources are small, this would be earliest fusion hybrid nuclear facility.

Published papers, available from author, contact wallymanheimer@yahoo.com,

- 1. W. Manheimer, *The Transition of Plasma and Beam Research at NRL, from Death Rays to Doo dads*, Plenary talk on winning IEEE PSAC Award, IEEE Plasma Science Conference, Boston, June 1996
- 2. W. Manheimer, *Back to the Future, the Historical, Scientific, Naval and Environmental Case for Fission Fusion,* Fusion Tech. 36, 1, (1999);
- 3. W. Manheimer, *Can a Return to the Fusion Hybrid Help both the Fission and Fusion Programs?* Physics and Society, v29, #3, July 2000
- 4. M. Hoffert el al, *Advanced Technology Paths to Global Climate Stability: Energy for a Greenhouse Planet*, Science 298, 981, (2002)
- 5. W. Manheimer, *An Alternate Development Path for Magnetic Fusion,* J. Fusion Energy, 20, #4, 131, (2001, cc2003);
- 6. W. Manheimer, *The Fusion Hybrid as a Key to Sustainable Development,* J. Fusion Energy, 23, #4, 2004 (cc2005)
- 7. W. Manheimer, *Hybrid Fusion*, Physics and Society, vol25, #2, April 2006
- 8. W. Manheiemr, [note journal accidentally misspelled name] *Can Fusion and Fission Breeding Help Civilization Survive?* J. Fusion Energy, vol. 25, p 121, 2006
- 9. W. Manheimer, *Hybrid Fusion, the Only Viable Development Path for Tokamaks?*, J. Fusion Energy, vol 28, #1, p. 60, 2009
- 10. W. Manheimer, *Hybrid Fusion and Energy Parks for Sustainable Development*, accepted for Asian Journal of Physics, special issue on renewable and sustainable energy, Vol 18, #1, Jan-March 2009

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Non-fusion Solutions to Waste Disposal & Fuel Production

Conference of the Center for Hydrogen Fusion Power and the Brookings Institution
Hybrid Fusion Systems

May 19-20, 2009
Washington DC

Albert J Machiels
Senior Technical Executive

Topics

1. Sustainability Considerations
2. Natural Resources Utilization
3. Fuel Cycles
4. Impact on Wastes
5. Summary

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EPRI's Findings (EPRI Report 1013442)

- Near-term US adoption of spent fuel processing would incur a cost penalty. To reap the major benefit possible to uranium conservation and/or the major reduction possible to required repository capacity, processing would have to be accompanied by deployment of fast reactor plants.
- The nation needs a broad consensus on which processing/fast-reactor technology combination is the best choice to take through as far as a demonstration. Developing and demonstrating an acceptable, affordable and reliable fast reactor appears likely to control the overall schedule and should receive appropriate development program emphasis.
- Whether the US adopts processing or not, if an expansion of US nuclear power is to be part of a global expansion, substantially improved international agreements and safeguards provisions will be necessary.
- Decisions on a possible second repository will not really be necessary until at least mid-century, so there are decades available to see whether an escalating uranium ore price will create an incentive to adopt processing and/or whether engineering development can reduce the costs of the processing scenario. All the existing spent fuel will still, of course, be accessible for processing should that be the decision.

The Sustainability Argument

- Drivers
  - Effective utilization of natural resources
    - U_{nat} (99.28%U-238/0.71%U-235) and Th (Th-232)
  - Protection of environment
    - Used (spent) fuel/high-level wastes
  - Non-proliferation
    - Diversion resistance
- Attributes
  - Safety
    - Licensing
    - Operations
  - Economic competitiveness
    - Reliability of goods/services
  - Institutional and societal aspects
    - Public acceptance

Interim Dry Storage (60-year license)

 5

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Fuel Cycle Costs vs. Electricity Cost

Comparison of Equilibrium Total Generation Costs for Alternative Fuel Cycles Assuming Nominal Value Unit Costs (Mills/kWhe)

Cost Indicators	Fuel Cycle 1	Fuel Cycle 2	Fuel Cycle 3
Reactor Cost	43.51	43.51	46.71
Fuel Cycle Cost	9.82	10.55	8.99
Cost of Electricity	53.33	54.06	55.70
Relative Cost to Fuel Cycle 1	1.00	1.01	1.04
The Cost of Electricity equals the Reactor Cost plus Fuel Cycle Cost.			

1. Fuel cycle cost typically less than 20% of cost of electricity
2. Impediment: Who is going to take the risks?

 6

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Natural Resources

U-238: 0.99284

►**U-235: 0.00711**◄

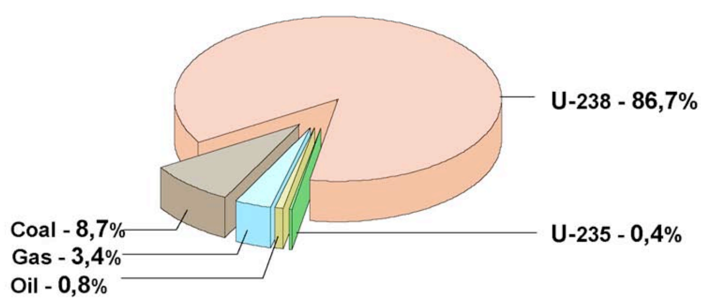
U-234: 0.00005

Th-232

U-238 + n → U-239 → Pu-239

Th-232 + n → Th-233 → U-233

Relative Energy Potential of Natural Resources of Russia

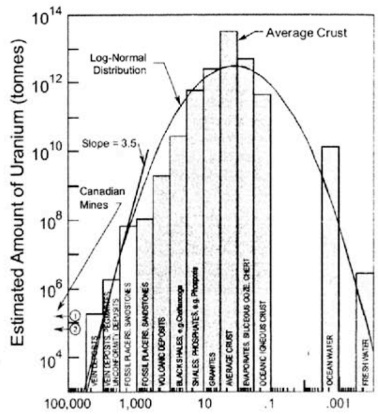


Data sources:

For proven resources of fossil fuel – British Petroleum «Statistic review of world energy 2005»: oil – 9,9 billion tons, gas – 48 trillion m3, coal – 157 billion tons ;

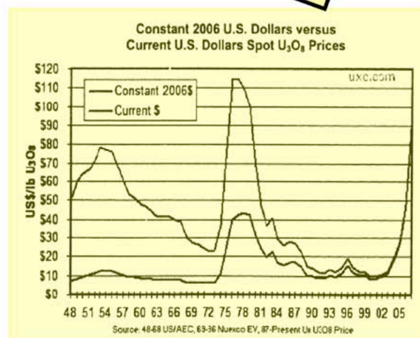
For proven resources of natural U – Federal Subsoil Resource Use Agency – 615 thousand tons

Natural Uranium in the Earth



Source: I.A. Matthews and M.J. Driscoll

"Security of fuel supply is what keeps me awake at night" (Kevin Houston, Duke Energy)



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Uranium from Seawater

- Uranium concentration in seawater: 3.3 mg/m^3
- ~700 times known terrestrial resources recoverable at <\$100/kgU (\$40/lbU_3O_8)
- ~100 Mega tons in uppermost few hundred meters
- Major challenges
  - Need for concentration factor in excess of 10^6
  - Acceptable ratio between energy resources (1) to be extracted from separated uranium and (2) devoted to the U recovery process
- State-of-the-Art: "Adsorptive recovery of uranium" (Japan)
  - Report of recovery of >1 kgU_3O_8 by immersion of 350 kg of uranium-specific adsorbent in the Pacific Ocean at a depth of 20 m (67 ft) 7 km (4.4 miles) offshore of Japan
  - Unconfirmed cost estimate: ~up to \$1,500/kgU (\$577/lbU_3O_8) assuming very significant improvements (adsorbent capacity & cycling frequency) in existing technology

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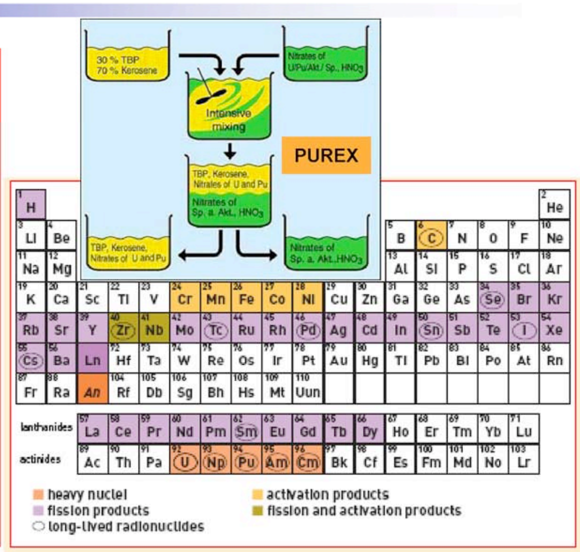
Used LWR Fuel Make-up

- Uranium (U) ~94%
  - *U-235* *~0.7%*
  - *U-238* *~93%*
- Plutonium (Pu) ~1%
  - *Pu-238* *0.04%*
  - *Pu-239* *0.7%*
  - *Pu-240* *0.3%*
  - *Pu-241* *0.2%*
  - *Pu-242* *0.1%*
- Minor Actinides (MA) ~0.1%
  - *Np-237* *0.07%*
  - *Am-241* *0.03%*
  - *Cm-244* *0.01%*
- Fission Products (FPs) ~4-5%
  - *Sr-90* *0.1%*
  - *Cs-137* *0.2%*
  - *I-129* *0.03%*
  - *Tc-99* *0.1%*



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Past (10), Current (9), Planned (6) Reprocessing Plants [From IAEA-TECDOC-1587 (August 2008)]

I-2. CUMULATIVE AMOUNTS OF CIVIL REPROCESSED SPENT FUEL (tHM, the end of 2006)

Country	Site	Plant	Fuel Type				
			GCR	LWR	FBR	MOX	TOTAL
Belgium	Mol	Eurochemic[a]	19[b]	86			105
France	Marcoule	UP1	18 000[c]				18 000
	La Hague	UP2/UP3		22 450	100	150	22 700
Germany	Karlsruhe	WAK[a]		180			180
India	Trombay	PP					
	Tarapur	Prefre-1					
Japan	Tokai-mura	TRP		1 000		18	1 018
Russian Fed.	Chelyabinsk	RT-1		3 550	450		4 000
UK	Sellafield	B205	42 000[e]				42 000
	Sellafield	Thorp		5 800[f]			5 800
	Dounreay	UKAEA RP			14		14
USA	West Valley	NFS[a]		194			194
TOTAL			60 019	33 260	564	168	94 011

[a] Closed facility [b] CANDU, GCR and other [c] UNGG [d] Spent fuel from Fugen [e] Magnox [f] LWR/AGR

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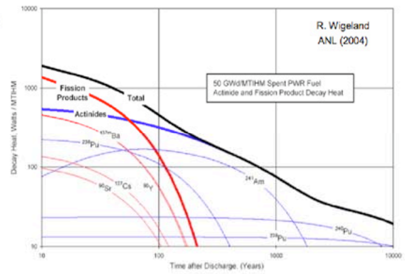
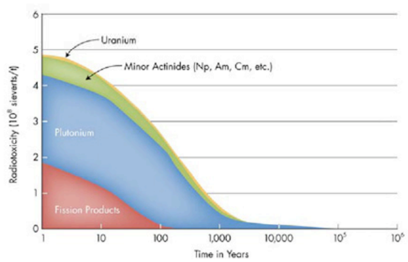
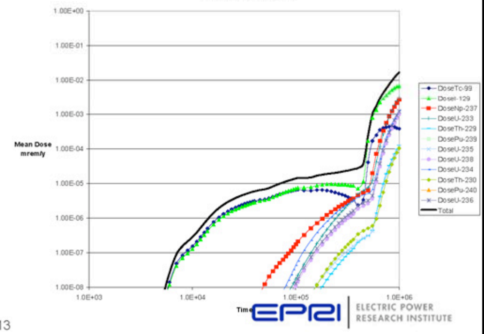
Waste Management Perspective

- Actinides are primary long-term risk drivers for disposal of HLW and SNF
- Transmutation of actinides would simplify disposal
  - Pu
  - Minor actinides: Np, Am, Cm







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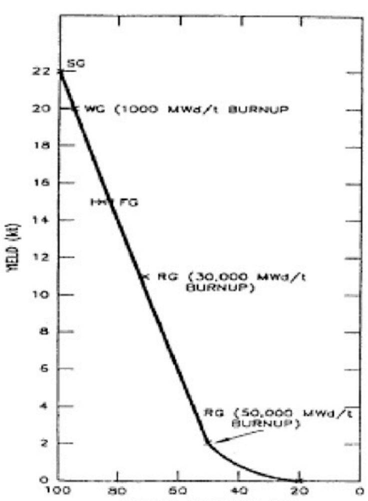
Non-proliferation



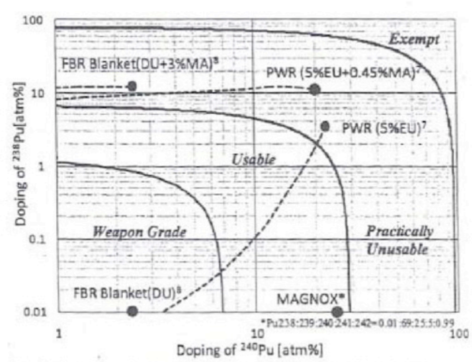


Fig.1 Example of plutonium categorization based on the present methodology

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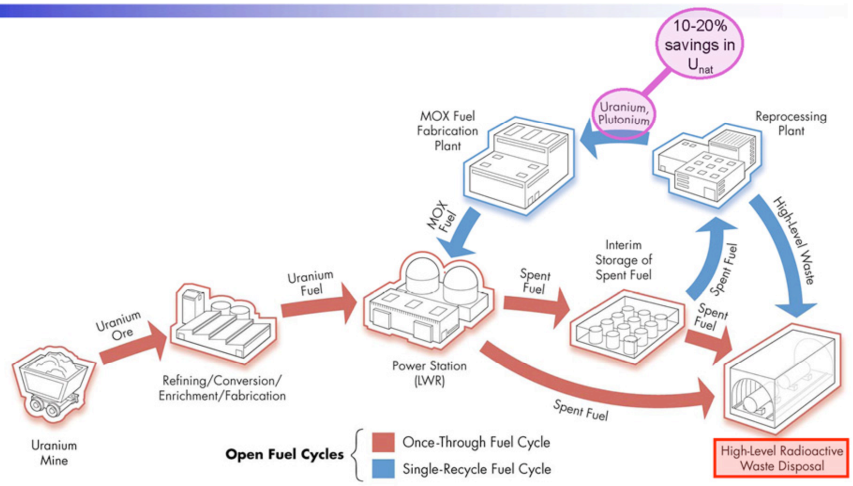
"Open" Fuel Cycles



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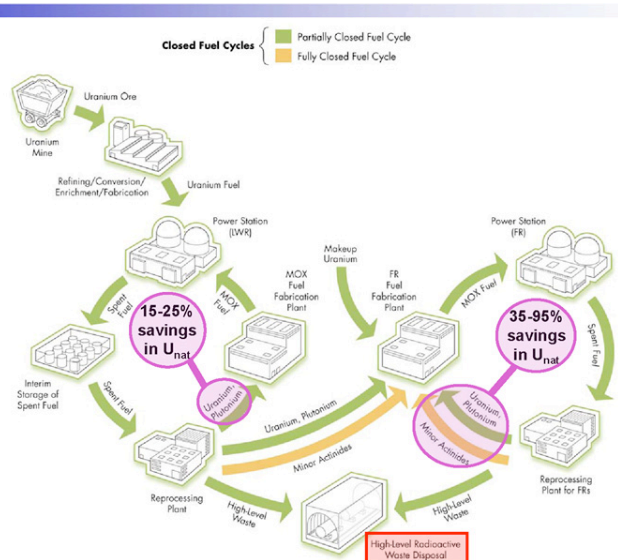
"Closed" Fuel Cycles



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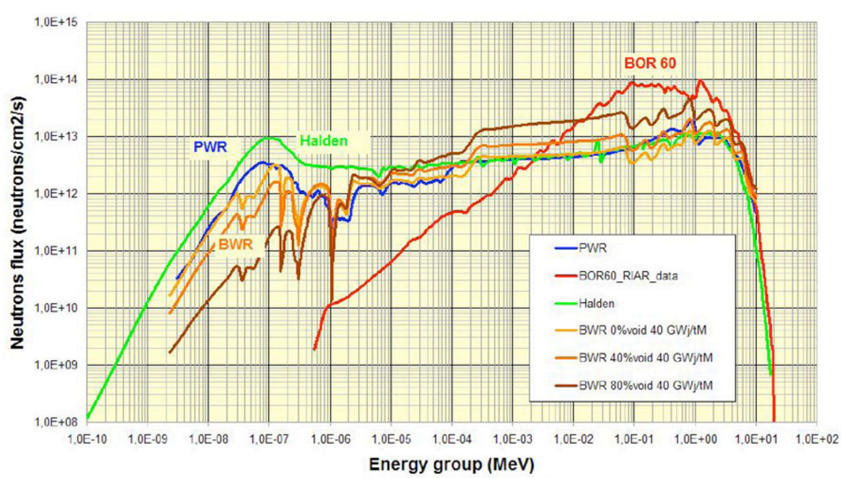
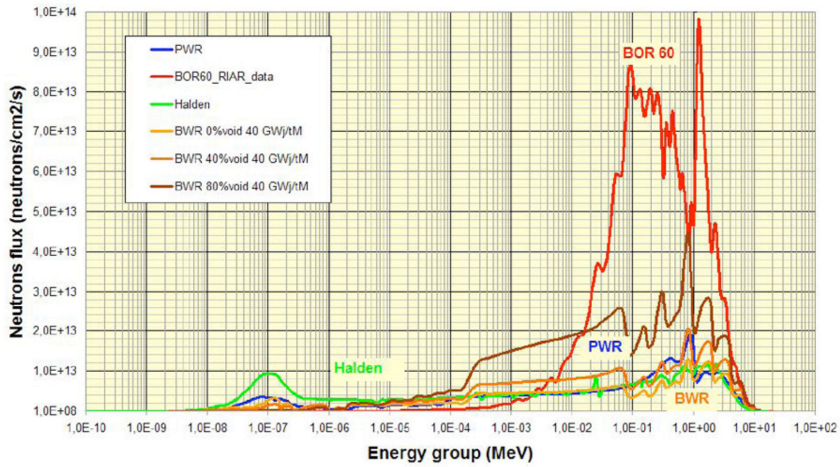
Sources of Neutrons

- Fast Reactors
  - Liquid Metal Reactors
  - Molten Salt Reactors
  - …
  - HITACHI's Resource-renewable BWR (RBWR)
  - Traveling-wave Reactor
  - …
- Thermal Reactors
  - Multi-recycling
  - Inert Matrix Fuel, CONFU
  - Deep Burn
  - …
- ADS/ATW

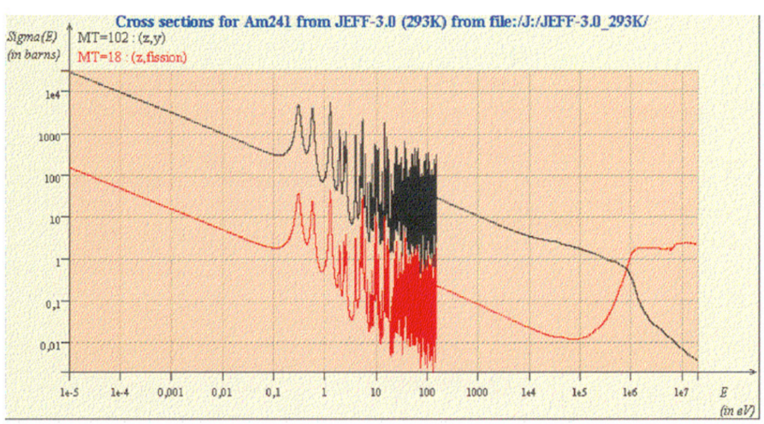
Comparison of Neutron Spectra for Several Reactors (Log-log)



Comparison of Neutron Spectra for Several Reactors (Semi-log)



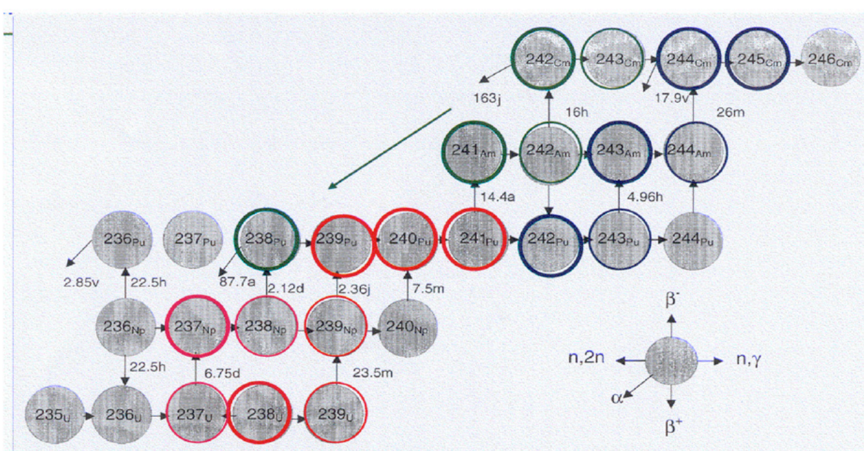
Americium 241



Fission vs. Capture

Isotope	Thermal spectrum			Fast spectrum		
	σ_f	σ_c	α	σ_f	σ_c	α
^{235}U	38,8	8,7	0,22	1,98	0,57	0,29
^{238}U	0,103	0,86	8,3	0,04	0,30	7,5
^{239}Pu	102	58,7	0,58	1,86	0,56	0,3
^{240}Pu	0,53	210,2	396,6	0,36	0,57	1,6
^{241}Pu	102,2	40,9	0,40	2,49	0,47	0,19
^{242}Pu	0,44	28,8	65,5	0,24	0,44	1,8
^{237}Np	0,52	33	63	0,32	1,7	5,3
^{241}Am	1,1	110	100	0,27	2,0	7,4
^{243}Am	0,44	49	111	0,21	1,8	8,6
^{244}Cm	1,0	16	16	0,42	0,6	1,4
^{245}Cm	116	17	0,15	5,1	0,9	0,18

Uranium and Transuranium (TRU) Nuclides



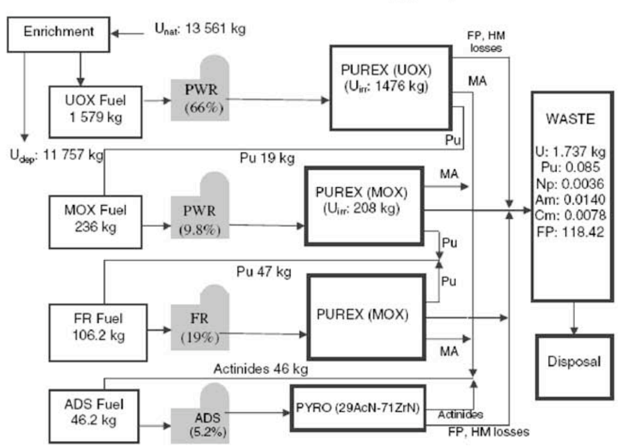
Advanced Nuclear Fuel Cycles and Radioactive Waste Management (OECD 2006 NEA No. 5990)

1a Once-through fuel cycle
1b Mono-recycling of Pu in LWRs
1c Mono-recycling of Pu+Np in LWRs
1d DUPIC Fuel Cycle
2a Burning of Pu in LWRs
2b Burning of Pu+Am in LWRs
2c Recycling of Pu and heterogeneous burning of Am in FRs
3a TRU burning in FRs
3b Double strata fuel cycle with FR and ADS
3bV Double strata fuel cycle with ADS
3c All-FR strategy

Scheme 3b "Double Strata"

Scheme 3b "Double Strata"
UOX, MOX and FR(MOX) reprocessed (PUREX) – Pu once recycling in PWR (MOX) – Pu multi recycling in FR(MOX) – Pu and MA partitioning and homogeneous transmutation – ADS (nitride) Fuel reprocessed (PYRO)

Fuel Characteristics and Mass Flows (kg/TWhe)



Utilization of Natural Uranium Resources

Fuel Cycle	PWR	FR	Natural U Consumption	Recovered REPU
Once-through	100%	0	100%	0%
Mono-recycling of Pu	100%	0	89.0%	9.1%
Mono-recycling of Pu+Np	100%	0	89.5%	9.3%
Multi-recycling of Pu	100%	0	86.6%	10.3%
Multi-recycling of Pu+Am	100%	0	99.4%	8.9%
Multi-recycling of Pu in FBR	44%	56%	44.1%	11.9%
TRU Burning in F(burner)R	63%	37%	62.7%	10.9%
TRU Burning in F(Breeder)R	0%	100%	3.57% (Depleted U)	86.6%

Source: NEA No. 5990 (2006)

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Equilibrium Fuel Cycle Scenarios Simulation “Synthèse des Résultats des Recherches sur l’Axe 1” [Amounts Normalized to 8.76 TWhr]

Fuel Cycle →	LWR: Once-through	LWR: Single Pu Recycling	LWR: Multi Pu Recycling	LWR: Multi (Pu/MA) Recycling	LWR + FR Multi (Pu/Np) & Single (Am/Cm) Recycling	LWR + FR Burner (CR = 0.5)	FR: Multi (MOX + MA) Recycling
TRU Content Going to HLW Repository Assuming 0.1% Loss In Separation Processes [kg/year]							
Pu	230	153	0.37	0.50	2.10	0.682	1.25
Np	16.2	16.6	14.45	0.022	0.017	0.020	0.0066
Am	**6.35**	16.2	39.4	0.057	0.35	**0.059**	0.055
Cm	3.3	8.1	19.7	0.079	2.06	0.031	0.013
Σ TRU	256	194	74	0.66	4.53	0.792	1.32
Relative Reduction Factor in Potential Radiotoxicity of HLW Going to Geologic Formation							
1,000 y	1	1.2	3	390	70	-	210
10,000 y	1	1.5	3	350	50	-	150
Cycle Inventory (reactors + fabrication + reprocessing) [kg]							
Pu	767	3,285	4,818	6,570	10,293	9,094	17,520
Np	53	131	116	285	241	256	88
Am	**22**	88	307	745	438	**803**	701
Cm	11	44	158	1,029	263	413	175

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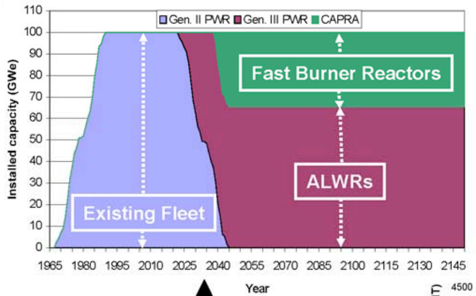
Cooperation with EDF R&D – Nuclear Fuel Cycle Simulation Tools

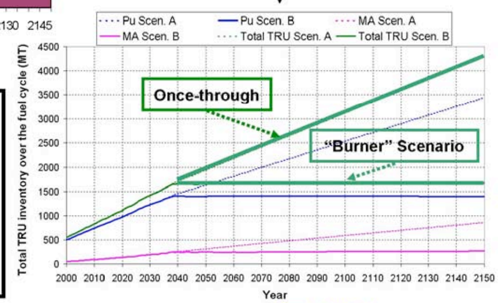


From ~2040 on:

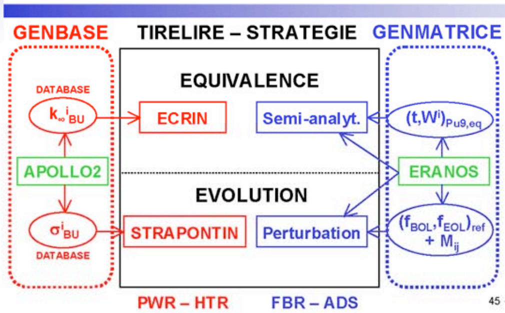
- "Once-through" fuel cycle continues build-up of spent fuel (→ repository)
- "Burner" scenario results in a stabilization of the TRU inventory that is continuously recycled

"Burner" Scenario: Assume constant 100 GWe

- After 55 years of operation, existing reactors are first replaced by ALWRs
- When capacity of ALWRs reaches 65 GWe, existing reactors are then replaced by fast burners reactors with a conversion ratio of 0.5 (or CR = 0.5)

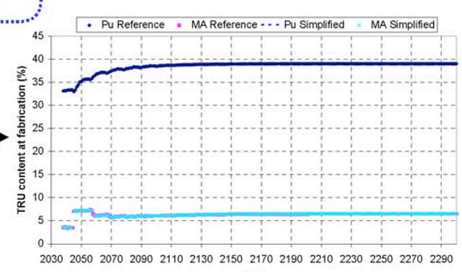


1. Nuclear Fuel Cycle Simulation Code (continued)

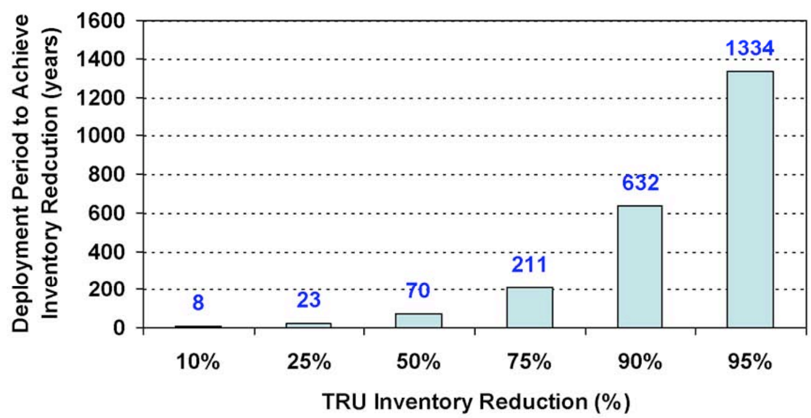


Required: Neutronic codes

TRU mass content at the time of fresh fuel fabrication based on the physical models for calculating the evolution in fresh fuel composition for the burner reactors



Time Required to Achieve Specified TRU Inventory Reduction Gains



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In-reactor TRU Inventory

TRU Nuclide	Once-through [MT of TRU]	PWRs +Fast burner Reactors [MT of TRU]
Np-237	4.0	5.6
Pu-238	2.3	15
Pu-239	28	75
Pu-240	13.5	87
Pu-241	8.8	16.6
Pu-242	4.6	29.3
Am-241	0.32	11.6
Am-243	1.2	8.3
Cm-244	0.66	8.4
Cm-245	0.05	2.1
Total TRU	**~63**	**~259**

Compared to once-through cycle:

- Greater TRU inventories are maintained in advanced fuel cycle facilities
- Short-term exposure risks (advanced fuel cycles) need to be weighted against long-term exposure risks (once-through)

Impact of Minor Actinide Content		+1% Np	+1% Am	+1% Cm
Fast Reactor Fuel Fabrication	Heat Release	x 1	+30%	x 10
	γ Dose	x 2	x 30	x 200
	Neutron Source Term	x 1	+15%	x 700

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Summary

- Substantial benefits in terms of extracting energy from existing natural resources
  - Assuming that U is a finite commodity
  - Fast reactors are typically considered the most promising option
  - But geo-political stability is highly desirable
- Synergy from more efficient use of natural resources and high-level waste disposal issues
- Simplicity is a virtue

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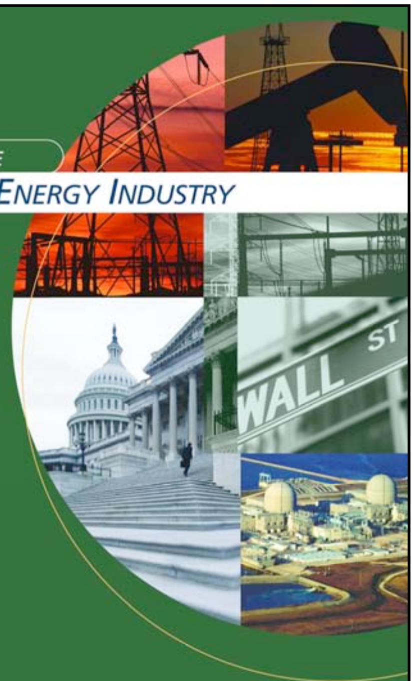
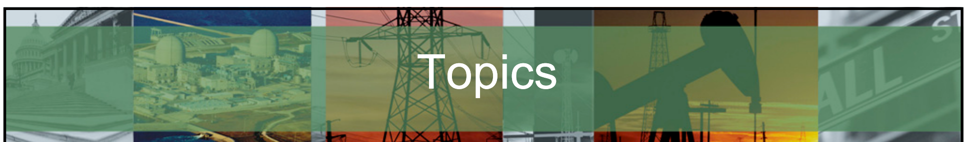


Statutory and Regulatory Provisions Governing Fusion Power

Steve Frantz

Morgan, Lewis & Bockius LLP



Topics

- Provisions in the Atomic Energy Act (AEA)
- Provisions in Regulations of Nuclear Regulatory Commission (NRC)
- Jurisdiction of NRC over Fusion Reactors
- Steps Needed for NRC to Regulate Fusion Reactors

2

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Provisions in Atomic Energy Act

- An agency's jurisdiction is limited by its organic statute
  - Agency cannot act outside of its jurisdiction, regardless of importance of the matter
- Atomic Energy Act provides NRC with jurisdiction over:
  - Certain types of Radioactive Material
    - Source Material
    - Byproduct Material
    - Special Nuclear Material
  - Certain types of Facilities
    - Production Facilities
    - Utilization Facilities
    - Enrichment Facilities

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Definitions in the Atomic Energy Act

- Special nuclear material - - Plutonium or enriched Uranium 233 or 235
- Source material - - Uranium or thorium
- Byproduct material - - Material made radioactive during production or utilization of special nuclear material
  - Now includes material made radioactive by a particle accelerator

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Definitions in the Atomic Energy Act

- Production facility - - Facility that produces special nuclear material
- Utilization facility means device "determined by rule of the Commission to be"
  - capable of making use of special nuclear material; or
  - "peculiarly adapted for making use of atomic energy"
- AEA (and legislative history of the Act) do not mention "fusion"

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NRC Regulations

- NRC regulations further define production and utilization facilities in terms of "nuclear reactors" that use fission
- NRC regulations do not mention fusion power

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Is Fusion Power Subject to NRC Jurisdiction?

- Fusion Reactor, without hybrid function
  - Not a production facility under AEA, *because it doesn't* produce plutonium or enriched U-233 or U-235
  - Not a utilization facility under AEA, because it:
    - does not utilize special nuclear material; and
    - has not yet been defined by NRC regulations as "peculiarly adapted for making use of atomic energy"
  - Not a production or utilization facility under NRC regulations, because it is not a nuclear fission reactor
  - Existing fusion test facilities (e.g., Princeton, MIT)
    - Not licensed by NRC as utilization facilities
    - DOE sponsored facilities

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Is Fusion Power Subject to NRC Jurisdiction?

- Fusion Reactor, without hybrid function
  - Conclusions –
    - Fusion reactors are not currently subject to NRC regulations as a utilization facility
      - May need a materials license
    - Fusion reactors probably would qualify under AEA as devices "peculiarly adapted for making use of atomic energy"
    - NRC would need to issue regulations defining fusion reactors as "utilization facilities"

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Is Fusion Power Subject to NRC Jurisdiction?

- Fusion Reactor, with hybrid function for burning actinides or generating U-233
  - Would not be a production or utilization facility under NRC regulations, because it is not a nuclear fission reactor
  - A hybrid facility that produces enriched U-233 would be a production facility under the AEA and would be subject to NRC jurisdiction
  - A hybrid facility that burns actinides:
    - Might be a utilization facility under AEA, to the extent it utilizes plutonium, U-233, or U-235;
    - Would require a license for source, byproduct and special nuclear material

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Regulation of Fusion Reactors

- Uniform national regulation would be desirable
- Logical choice is DOE or NRC
  - DOE is probably best choice for pilot or test facilities
  - NRC is probably best choice for multiple commercial facilities

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Steps Needed for NRC to Regulate Fusion Reactors

- Step 1 - - Clearly give NRC jurisdiction
  - NRC amends its regulations to define fusion reactor as a utilization facility; or
  - Amend the Atomic Energy Act to give NRC jurisdiction
    - Given significantly lower risk of fusion reactors, there would be advantages to not treating a fusion reactor as a utilization facility

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Steps Needed for NRC to Regulate Fusion Reactors

- Step 2 - - Establish NRC regulations governing fusion reactors
  - 10 CFR Part 50 only applies to fission reactors
  - In general, the design criteria in Part 50 are not suitable for regulation of anything except large light water reactors
  - Issue a new Part in 10 CFR for fusion reactors
    - Technology neutral regulation for fission reactors may not be practicable for fusion reactors
  - Other NRC regulations could be applied or adapted; e.g.
    - Part 20 on radiation protection

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Steps Needed for NRC to Regulate Fusion Reactors

- Step 3 - - Establish NRC guidance for fusion reactors
  - NRC has bookshelves of guidance documents
    - They don't mention fusion reactors
    - In general, guidance applies to fission reactors and is not adaptable to fusion reactors
  - NRC would need a new set of guidance documents for fusion reactors

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Conclusions

- There is no regulatory framework for fusion reactors
- Regulation and guidance for fission reactors are not readily adaptable for fusion reactors
- Advantages to:
  - not treating fusion reactors as utilization facilities, and
  - establishing an entirely new regulatory framework for fusion reactors
- A new regulatory framework will take time to develop, and will likely be an iterative process

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Breakout Session A

Breakout Session A

LLNL-PRES-413144

Axisymmetric Mirror as an Engine for the Hybrid System: a Modest-Q Version*

D.D. Ryutov

Lawrence Livermore National Laboratory, Livermore, CA 94550

Presented at the Conference "Hybrid Fusion Systems," May 19-20, 2009 Washington DC

* Prepared by LLNL under Contract DE-AC52-07NA27344

Motivation

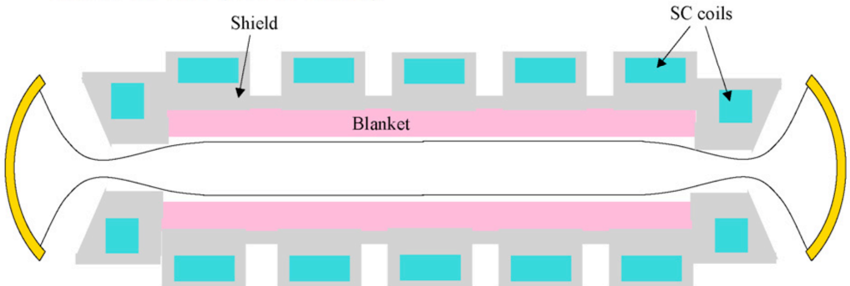
For some versions of hybrid/waste-burning systems, relatively low-Q plasma engines may be of interest.

A relatively simple mirror machine can reach Q ~ 1. It will offer all the advantages of mirror-based fusion devices and will have a reasonable "engineering" Q, Q_{eng}~0.2-0.3.

This modest-Q system will be directly based on the experimental results obtained during the last 20 years in the studies of axisymmetric mirrors with sloshing ions (especially with the Gas Dynamic Trap at Novosibirsk)

This fusion "engine" can be built and tested within a few years from now

Schematic of a fusion “engine” based on the axisymmetric mirror device (not to scale)



Fusion power 100 MW

Q_{fus}=0.5, $\eta_{heating}$=0.4 (plug-to-plasma)

Required power amplification in the blanket ~ 10-15 (power to the grid ~ 200 - 500 MW)

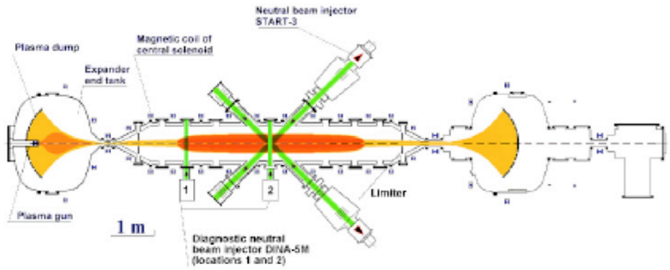
Length 50 m (mirror-to-mirror 30 m)

Plasma diameter 1 m

B_0=2.5 T, B_{mir}=15 T (SC)

GDT at the Budker Institute of Nuclear Physics, Novosibirsk, July 1988: working together with the LLNL team

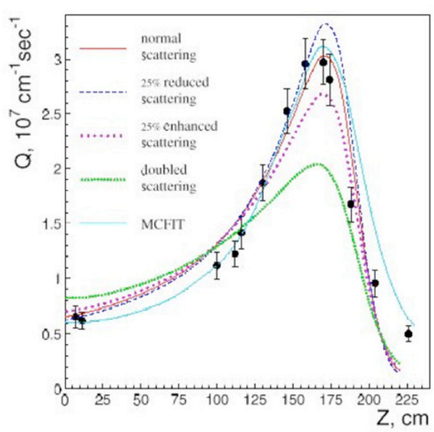
GDT Experimental Results



Fully axisymmetric plasma, MHD stable for beta 0.6 (60%), average ion energy 10 keV, average ion density 5×10^{13} cm^{-3}, no signs of the ion microinstabilities, electron temperature 230 eV, classical energy and particle confinement.

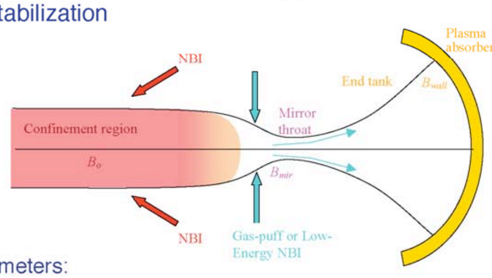
MHD stability by favorable curvature in the expansion tanks; can be enhanced by sheared rotation

Measured profile of DD-reaction intensity



General concept of the engine

Axisymmetric mirror with sloshing ions, artificially cooled electrons, and line-tying stabilization



Device parameters:

Injection energy W_0=70 keV; absorbed beam power 200 MW; plasma radius a=0.5 m; mirror-to-mirror length L=30 m; plasma density n=10^{14} cm^{-3}; plasma beta = 0.25; neutron wall load 1 MW/m^2; electron temperature T_e=3 keV; cold plasma outflow 3 kA (Eq) per end. Magnetic field (superconducting) B_0= 2.5 T, B_{mir}= 15 T, B_{wall}=0.08T.

We want to keep the electron temperature low in order to make the system more stable for both velocity-space modes and MHD modes

Without gas-puff near the ends, we would approach a standard simple-mirror power and particle balance, with electrons heated to ~ 0.3 T_i and a large "hole" formed in the ion velocity space

Most probably, the system without gas-puff near the ends would "fall apart" due to both velocity-space and micro-instabilities

One has to pay for the good plasma stability by a relatively low Q value of 0.5

SLOSHING IONS ARE REMARKABLY STABLE WITH RESPECT TO THE MICROINSTABILITIES

This general observation has been made in 1980s, during experiments with TMX-U

It served as a basis for the GDT neutron source proposal at Novosibirsk, where the sloshing ions are one of key ingredients for making the neutron source attractive

Sloshing ions in GDT are remarkably stable (no “anomalous” scattering)

Overall energy balance in the system

For the 50-70-keV DT beams, one can expect the plug-to-plasma efficiency of 50%

As the magnetic system is superconducting, the engineering Q ($Q_{eng}=\eta_{inj}Q$) of our system is Q_{eng}~0.2-0.3

The condition for the net power output:

$\eta_{inj}QA\eta_{thermal}>1$ (A = blanket power amplification)

Assuming $\eta_{inj}=0.5$, $Q=0.5$, $\eta_{thermal}=0.4$, one sees that the blanket power amplification A has to be 10 - 15, to make the system a net energy producer

Summary

A version of an axisymmetric mirror machine that can serve as an engine for the hybrid fusion reactor/waste burner has been considered

The system is based on the sloshing ion injection at <45 degrees, artificial electron cooling by the gas puff outside the turning points of the sloshing ions, and line-tying stabilization

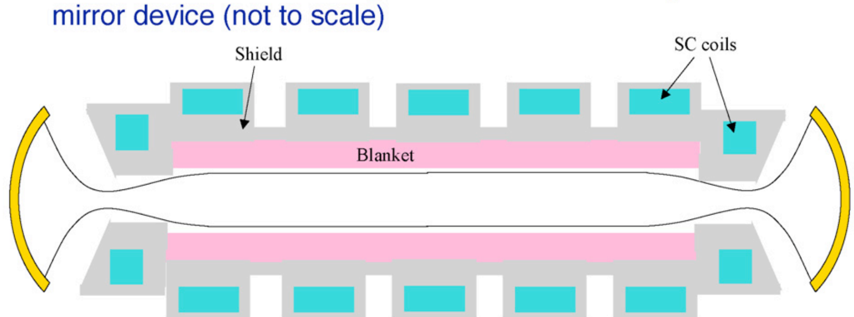
The engineering Q of this system can be 0.2-0.3

The system has a number of attractive features:

- naturally steady-state
- no plasma current and disruptions
- natural divertors with a low heat load
- easy access to the blanket (no interlinking coils)
- very simple magnets
- flexibility in the power output (30 MW – 1 GW neutron power)

Some aspects of this system performance can be tested with minor modifications of the existing GDT facility

Schematic of a fusion "engine" based on the axisymmetric mirror device (not to scale)



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SUMMARY (Continued)

Required technology developments

- Demonstration of the steady-state operation of heating and vacuum systems
- Tritium handling
- Existence of materials suitable for years of operation in the 14-Mev neutron environment.

SUMMARY (Continued)

Required technology developments

- Demonstration of the steady-state operation of heating and vacuum systems
- Tritium handling

- Existence of materials suitable for years of operation in the 14-Mev neutron environment. Neutron source!!!

Final quotation:

"The tremendous importance of the ultimate goal and the enormous difficulties that lie in the way combine to stamp the problem of thermonuclear fusion with a quite distinctive character. For the time being we find ourselves as it were on the dividing line between dream and reality…"

L. A. Artsimovich
20th September 1962

Fusion Drivers for hybrids

M. Kotschenreuther, S. Mahajan, P. Valanju

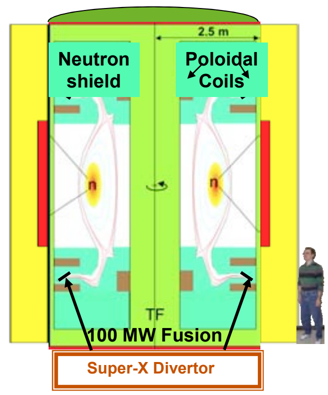
Institute for Fusion Studies

E. Schneider, C. van der Hoven

Dept. of Nuclear Engineering

The University of Texas at Austin

Washington DC, May 19, 2009



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UT-devised fusion drivers: to enable a near term hybrid

- Conservative *experimentally supported* physics basis for credibility, near term implementation
  - Credibility demands modest physics extrapolations to Q ~ 1, 100 MW fusion
- High power density
  - So fusion driver is small,low cost - *cost of fusion is always an issue*
  - High power density fusion is needed to couple to a high power density fission blanket
- Replaceable module to tremendously reduce technological development
  - Reduce material development, time and risk to reach a system with high availability/ reliability
- Greatly minimizes negative impacts of fusion on the fission assembly
  - Don't want to add failure modes to fission assembly- *safety is always an issue*
  - Doesn't interfere with cooling the high power desnity fission blanket- MHD problems minimized
  - Rare off-normal plasma events (disruptions) *MUST NOT* be able to strongly affect the fission blanket- otherwise likely unlicensable

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Physics basis (MFE): Q ~ 1 requires *BOTH T_i ~ 10 keV and T_e ~ 10 keV* (or more)

- Perpendicular turbulent transport *must be small enough*
- Complexity of transport has been repeatedly under-estimated over decades
  - Alcator scaling -> Goldston scaling -> H-mode, super shot, ITB
  - 30 years to go from T_e~1 keV to T_e~ 10 keV
- ITER design experience: multi-machine experimental basis required to confidently build a high power DT device
- A credible hybrid will require this as well
  - tokamaks, spherical tokamak (tokamak variant), stellarator

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Neutron source credibility

- **Major issue for hybrid credibility is the credibility of the fusion driver**
- **JET in 1997**: 16 MW attained for ~ 1 sec, ~4 MW for 5 sec (~ 22 MJ/pulse)
  - TFTR 8-11 MW for < 1 sec, ~ 5 MJ/pulse
- Devices under construction in coming decade:
  - JET upgrades -possibly several times better ~10's MJ?
  - Long pulse K-STAR DT equivalent (several MW, 300 sec) > 10^3 MJ
  - ITER: (several 100s MW for > 500 sec) > 10^5 MJ
  - NIF 20-30 MJ
  - Perhaps Wendelstein 7X might come in range of K-STAR for MJ
- For the next decade (or two with ITER), tokamak fusion sources will be far ahead of others for demonstrated performance

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4

High power density:
required for an attractive concept

- Economic fission blankets require a minimum fusion neutron flux of ~ 0.5-1 MW/m^2 to meaningfully impact the fission neutron balance
- With typical fission energy gains for waste destruction, and reasonable fission plant sizes: fusion source ~ 20-200 MW
- **Tokamaks and STs with ordinary H-mode operation (no wall stable, only H mode confinement) can give such parameters**
- Conventional stellarator reactor designs give ~ 1 MW/m^2 only for much larger systems (fusion power > 1000 MW)- **inadequate power density**
  - Compact stellarators are **much closer**, but alpha loss might be severe at high α ρ_*
  - No near term experimental basis for compact stellarators, much less multi-machine
- Mirrors would give adequate power density, but Q based on experimental Te is few percent: much too low, and little data on scaling of perpendicular losses

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High power density implies
a new power exhaust solution is needed

- Exhaust power for hybrid relevant toroidal device appears substantially higher than ITER (which appears at the limit of conventional divertor)
- Saving the divertor by using extremely high radiation has not been found to work well in tokamaks-
  - Either inadequate confinement (H-mode, L-mode)
  - Or very low beta limit (RI mode, some ITB)
- A better divertor is needed
- **UT has developed the Super-X divertor for tokamaks**
  - Relies on robust properties of magnetic geometry to solve the problem
  - Indeed works very well with ITER divertor simulation codes
  - Works for both steady state power exhaust and ELMs
- Stellarators are still in need of a divertor solution for high power density

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UT hybrid has found a way to reduce serious generic problems of a hybrid

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Generic problems with hybrid- I

- Fusion driver is **far** more complex than a fission fast reactor

Fusion driver technology issues:

- Complexity- a long time to develop to be reliable
- Internal maintenance, with TF coils and vacuum vessel-"Like disassembling a ship in a bottle"
- So complex components must reside in reactor a long time, accumulating high radiation damage
- Damage from 14 MeV neutrons has unique unquantified degradation that is worse than fission neutrons

How to attain adequate reliability and availability in such a device with acceptable time/risk/effort?

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Generic problems with hybrid- II

- Fission devices: safety issues can be show stoppers- a device might be un-licensable

The fusion driver can potentially impact the integrity of the fission assembly (FA) unfavorably

- ***Mechanically*** => FA is an integral part of the mechanically very complex fusion driver =>new coupled failure modes
- ***Electro-magnetically*** => plasma disruptions cause large mechanical EM loads: a deformed FA could lead to prompt criticality, impeded coolant flow or coolant loss
- ***Magnetically*** => coolant flow strongly impeded by MHD effects, leading to inadequate or unreliable coolant flow

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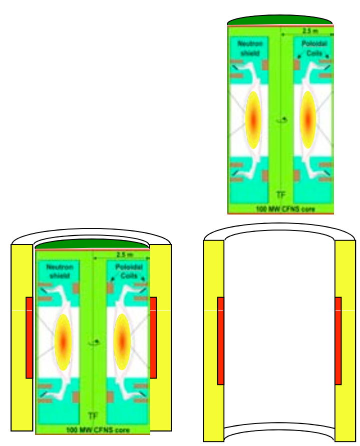
A new design concept to address all these issues

Replaceable fusion driver

- Driver replaced up to yearly while fuel rods reshuffled **(development time, neutron damage)**
- Damaged driver refurbished in remote maintenance bay **(maintenance)**
- Fission assembly is physically separate from fusion driver **(failure interactions minimized)**
- Fission assembly is electro-magnetically shielded from plasma transients by TF coils **(disruption effects greatly reduced)**
- Fission blanket is outside TF coils **(coolant MHD drastically reduced)**



We shall now spell these out

10

CFNS: easier than Component Test Facility (CTF)

- Driver is exposed to as little as **one** year of damage:

  ~ 1 Mwyr/m^2

- CTF requirement for DEMO components

  ~ 6 MWyr/m^2

- **CFNS mission could be much easier than CTF mission because**
  - Components are much less damaged
  - A testing cycle is 6 times shorter, so development to obtain high reliability is faster

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Physical separation of Driver and fission blanket

Failures that arise inside the complex fusion driver have much less affect on the fission assembly where safety is paramount

- The fission assembly can consist of conventional fission technology and fuel rods
- Licensing safety analysis is substantially simplified

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Electromagnetic disruption effects on blanket

- The L/R time of the fairly thick, highly conducting TF is

~ 1 second

(even with substantial holes to let neutrons through)

- Disruptions: as fast as

~ 1 ms

- TF slows down EM transients in the fission blanket by orders of magnitude

Eddy currents and forces in fission assembly are reduced orders of magnitude

MHD coolant effects

- **Fission blanket power density is ~ 1 1/2 orders of magnitude higher than pure fusion-** MHD coolant problems could be very severe for a hybrid cooled by liquid metals
- Inadequate or unreliable coolant flow for sodium, lead ???
- Magnetic field outside the TF coils is only from PF, and is almost exactly vertical- **aligns almost perfectly with the coolant flow direction**

MHD drag effects reduced by orders of magnitude from previous tokamak hybrids

Reduce Hybrid Complexity and Technology Development

- A hybrid is more complex than to pure fission technology
- Pure fission technology is already complex enough so that reliability/availability and the licensing barrier are substantial issues

UT Concept:

The demands (both physics and technology)

for initial operation of an hybrid

***must* be reduced to as low as possible**

to make the hybrid

an attractive, credible and practical endeavor

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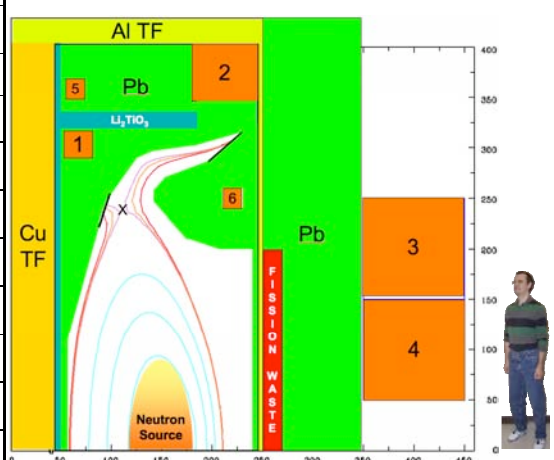
CFNS gross parameters

R (m)	1.35
A	1.8
κ	3
P_{CD} (MW)	50
n_e (m^{-3})	1.3-2 x 10^{20}
$\Gamma_{neutron}$	1.1 MW/m^2
n_e (m^{-3})	1.2-2 x 10^{20}
n/n_G	0.14-0.3
β	15-18%
I_p (MA)	10-14
B_{coil}	7 T
B_{plasma}	2.9 T



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Back-up slides

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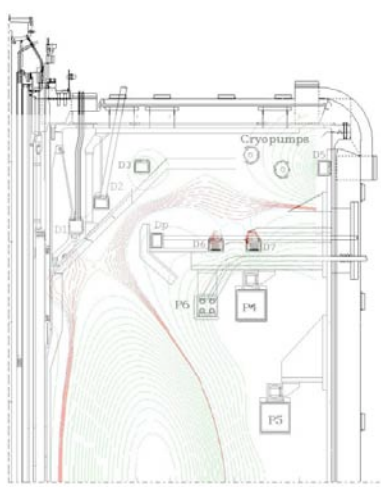
SXD-from theory to experiment

- **Worldwide plans are in motion to test SXD**
  - MAST upgrade now includes SXD
  - NSTX: XD and future SXD?
  - DIII-D SXD test experiments, possibly next year
  - Long-pulse superconducting tokamak SST in India designing SXD
- **SXD: enables power exhaust into much lower neutron damage region**
  - Much of ITER divertor technology be used (H_2O cooled Cu substrate- steady Q < 10MW/m^2, 20 MW/m^2 transient)



SXD for MAST Upgrade

18

Conservative Core Physics Demands

- **CFNS** can use operating modes and **dimensionless performance parameters** where experiments operate reliably on present tokamaks

  - **only because SXD allows high power density without degrading the core**

Device	Normalized confinement H	Gross stability β_N	Poloidal ρ / minor radius
Today's experiments-Routine operation	1	< 3	~ 0.05-0.1
Today's experiments-Advanced operation	< 1.5	< 4.5	~ 0.05-0.1
Hybrid - CFNS	**1**	**2-3**	**~0.05**
ITER- basic	1	2	~0.02
ITER-advanced	1.5	< 3.5	~0.03
"Economic" pure fusion reactor	1.2 -1.5	4-6	~0.02

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Hybrid closer to Today's experimental achievements than ITER or a pure fusion reactor

Device	Outer radius (R + a)	Fusion Power	Q = Fusion power/ Heating power
JET, JT-60U (exist)	**4 m**	**16 MW** (achieved)	**Close to 1** (achieved)
Fusion driver for Hybrid (Transmutation)	**2.5 m** Fits inside fission blanket	**100 MW** (~3000 MW fission)	**1-2**
ITER (being built)	**8 m**	**400 MW** (expected ~ 2020)	**10** (expected ~ 2020)
Pure fusion reactor	**7-10 m**	**2000-3500 MW**	**10-30**

The Hybrid fusion source has a higher *power density* compared to current experiments and ITER - need SXD

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20

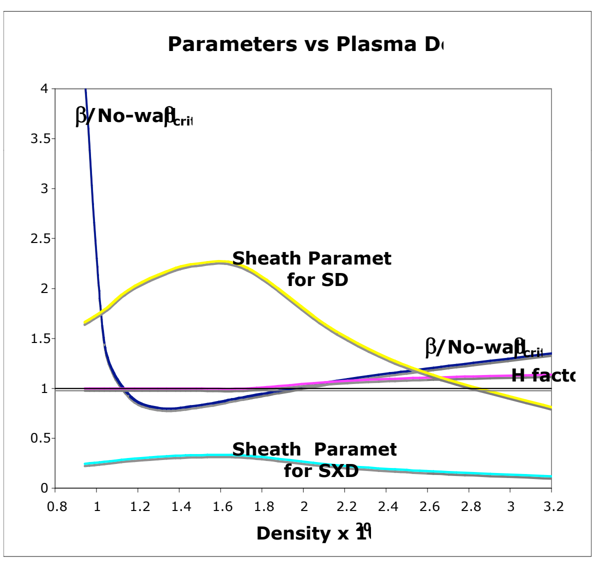
The CFNS divertor is implausible without the Super-X divertor

- Divertor must avoid so called "sheath limited" regime
  - Unacceptable erosion sputtering
  - Negligible radiation/high heat flux
  - Low neutral pressure and very likely unacceptable He exhaust
- Use Sheath limited parameter from Stangeby- **S** - but normalized to SOLPS simulations
- Benchmark and renormalize **S** with SOLPS runs:

S > 1 => sheath limited: unacceptable divertor conditions

S < 1 => high recycling: acceptable (radiative operation possible)

CFNS: SXD allows conservative core physics



CD power = 50MW

P_{fus} = 100 MW

- **At moderate density, no wall stable regime**
- **At very low density:**
  - ***too much* current =>**
  - **poor MHD stability**
- **Add core radiation to make H = 1 and "save" divertor when possible**

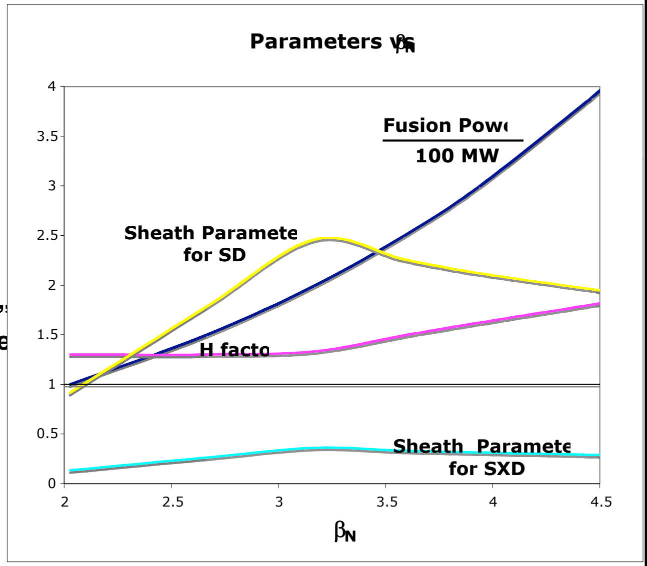
Only SXD has

S ~ 1/3 <<1

CFNS: SXD enables more advanced scenarios

CD power= 50MW

- **Only SXD has S<1**
- **400 MW fusion at $<\beta_N> \sim 4.5$**
- **Assume H = 1.3 attainable**
  - **More core radiation to "save" divertor if possible**
- **Advanced operation H ~ 1.5 enables**
- **~ 300 MW fusion**



CFNS Unknowns - Plasma wall interaction

- SXD is promising, but needs *testing*
- Success of SXD still leaves further PMI issues
  - Tritium retention
  - Effect of loss of wall conditioning on plasma performance?
  - Will material surfaces evolve acceptably at long times (e.g., will erosion / re-deposition lead to wall flaking & plasma disruptions?)
  - Will surfaces survive a rare disruption without unacceptable damage?
- Liquid metal on porous substrate looks like a promising potential solution to all of these
  - NSTX might be able to test it sometime in the future?

UT-Hybrid vs Fission-only Cycle

Required Reactor fleets for zero net transuranic nuclear waste production from the current ~100 US utility reactors

	Hybrid Route	Fission-only (AFCI)
US Light Water Reactors	100	100
Fast-spectrum waste destruction reactors	4-6	37-56

<u>Under our proposal</u>

4-6 new utility-scale hybrid reactors would suffice

Waste reprocessing for fast-spectrum reactors will also be reduced by roughly an order of magnitude

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Reactor Requirements for Waste Transmutation for different schemes

Reactors needed to destroy waste from 100 LWRs

	Fast Reactors BR= 0.5	Fast Reactors BR= 0.25	Hybrids burning all TRU	Hybrids burning only Np & Am	IMF pre-burn followed by hybrids
Number of FRs	39-56	37	0	20	0
Number of Hybrids			28	5	4-6
Total # of Fast systems	39-56	37	28	25	4-6
"Excess" Cost above all LWRs (LWR equivalents)	19-28	19	28	15	4-6

FR cost = 1.5 LWR, Hybrid = 2 LWR

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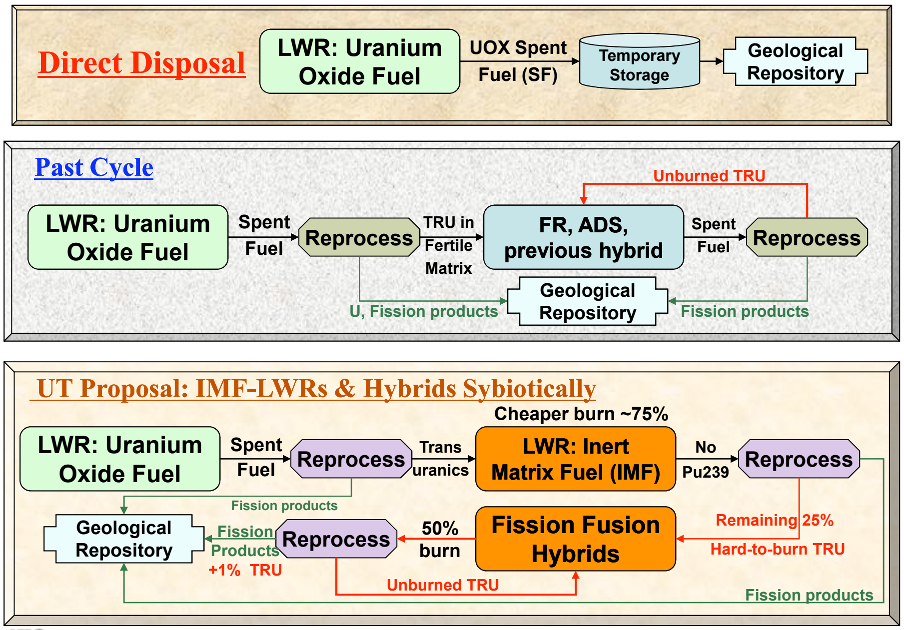
New hybrid transmutation scheme



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This hybrid based scheme has a major *system cost advantage* over other schemes

- First hybrid based scheme with this advantage
  - (to our knowledge)--- perhaps several times cheaper?
  - The advantage appears easily more than enough to overcome the cost disadvantage of *individual* hybrid vs an *individual* FR
- **The system cost advantage may be enough to overcome the other disadvantages of the hybrid:**
  - Complexity, stage of development, novel failure modes
  - We turn to these **technological drawbacks** momentarily
- First, consider the **physics feasibility** of the fusion driver

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Scientist and Businessman - A rare meeting of minds

Jim Hansen - Tell Obama the Truth-The Whole Truth:

- However, the greatest threat to the planet may be the potential gap between that presumption (100% "soft"energy) and reality, with the gap filled by continued use of coal-fired power. Therefore it is important to undertake urgent focused R&D programs in both next generation nuclear power and ---
- However, it would be exceedingly dangerous to make the presumption today that we will soon have all-renewable electric power. Also it would be inappropriate to impose a similar presumption on China and India.

Exelon CEO John Rowe Interview - Bulletin of American Scientists:

- We cannot imagine the US dealing with the climate issue, let alone the climate and international security issues without a substantial increment to the nation's nuclear fleet
- I think you have to have some federal solution to the waste problem ---- If it (the Federal Government) ultimately cannot, I do not see this technology fulfilling a major role

Renaissance of Fission Energy is emerging as a global imperative - everyone is talking!

A believable technical solution to the nuclear waste problem- a scientific imperative

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Core physics operation assumed to be conservative at this point

- **Below No-wall limit**
  - estimates by Jon Menard quoted in Jeff Freidberg's book:
  - use TROYON definition $<\beta>_N$ with correction for q*
- **H-mode confinement (H ~ 1)**
- **$T_e = T_i$ (no enhancements to reactivity for hotter ions)**
- **Densities far below Greenwald limit (< 0.3)**
- **Minimum q above 2 (avoids worst NTMs)**
- **CD efficiency: $I\, n_e R/P_h = 0.2 \times 10^{20}$ ($<T_e>$/10kev) A/Wm^2**
  - Most uncertain core physics parameter?- to be investigated by NSTX

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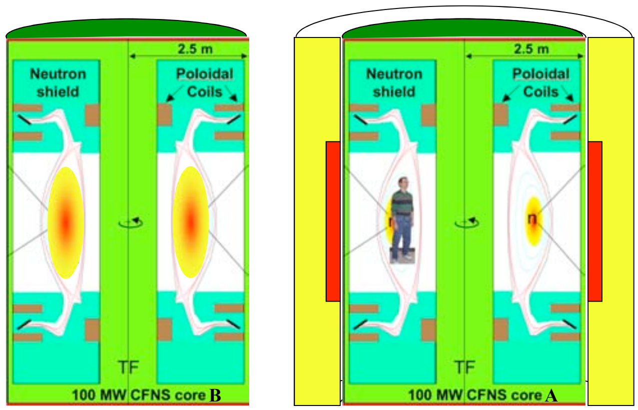
Replaceable Fusion Driver Concept

- **Due to SXD, the whole CFNS is small enough to fit inside fission blanket**
- CFNS driver to last about 1-2 full power years
- It can be replaced by another CFNS driver and refurbished away from hybrid
- **CFNS driver itself is small fraction of cost, so a spare is affordable**



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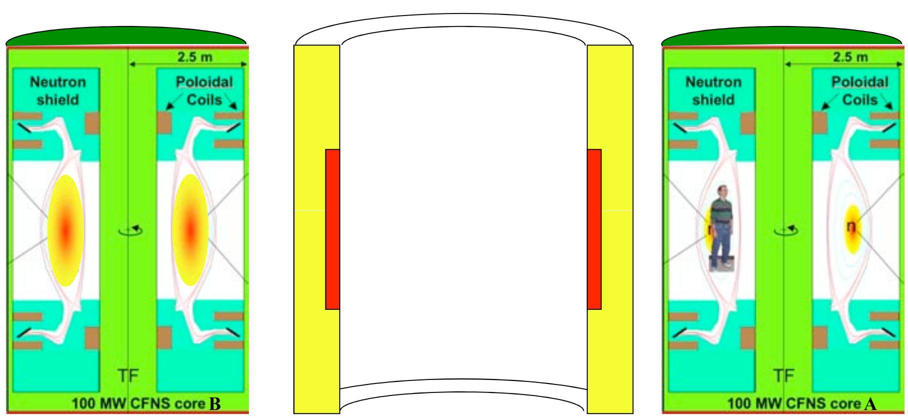
Replaceable Fusion Driver Concept

- **Pull CFNS driver A out to service bay once every 1-2 years or so - at the same time when fission blanket maintenance is usually done**
- Refurbish driver A in service bay - much easier than in-situ repairs



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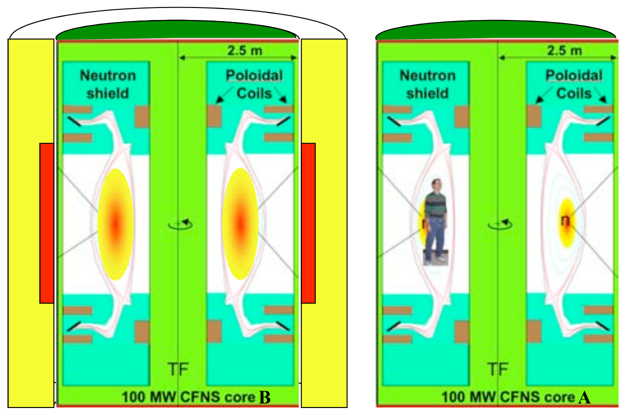
Replaceable Fusion Driver Concept

- **Put driver B into fission blanket**
- This can coincide with fission blanket maintenance
- Use driver B while driver A is being repaired



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Issue: Maintenance of highly radioactive driver

- Driver is removed as a unit relatively quickly
- Refurbishment of a “spent” driver is done relatively slowly in a remote maintenance bay
- Rapid inspection/replacement of components of the “ship in a bottle” method- which we don’t know how to do- is avoided

Credible inspection/maintenance improves the credibility of high availability

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New Hybrid versus Generic Hybrid

- The new hybrid is **technologically much more credible**

Together with the advantages of the IMF-hybrid fuel cycle,

the new hybrid emerges as a potentially attractive and credible endeavor

Google:[Leonid Zakharov] → http://w3.pppl.gov/~zakharov

FirstFFH as a reference device for hybrids

(First Superconducting Tokamak Fission-Fusion Hybrids)

Leonid E. Zakharov[1], *Jiangang Li*[2], *Yican Wu*[2]

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Presented by Leonid E. Zakharov

Hybrid Fusion Systems

May 19, 2009, Brookings Institution, Washington DC

[1]This work is supported by US DoE contract No. DE–AC020–76–CHO–3073.

PPPL

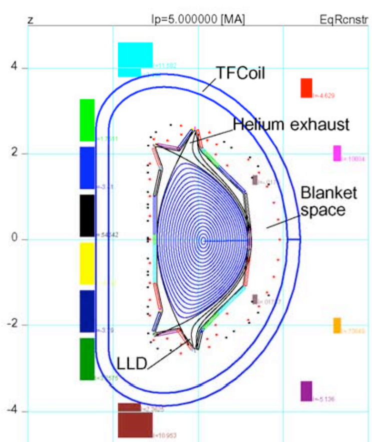
Contents

Abstract

The talk gives the introduction to a project, called FirstFFH, standing for the First superconducting tokamak Fusion-Fission Hybrid, (R/a=4/1 m/m, Ipl=5 MA, Btor=4 T, PDT=50 MW, Pfission=80-4000 MW) with launching the machine in China in 12-15 years.

Reliance on the LiWF plasma regime with high plasma temperature (Ti 26 keV, Te=20 keV) and low density (ne=0.6 1020/m3) makes realistic a device, which would be a next step in Chinese development of stationary superconducting tokamaks. The device will have sufficient space for the fission blanket (1 m thick) in order to explore different fusion driven blanket regimes with variety of nuclear fuels.

1 Parameters of FirstFFH



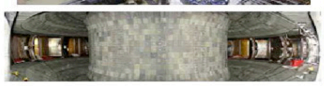
Parameter	FirstFFH
$d_{blanket,m}$	1
a_m	1.0
R_m	4.0
n_{20}	0.4
E^{NBI}_{keV}	120
$\frac{T_i+T_e}{2}\|_{keV}$	24
$B_{t,T}$	4
$I_{pl,MA}$	5.16
P^{DT}_{MW}	50
$W_{th,MJ}$	42
$\tau_{E,sec}$	21.4-8.5
P^{NBI}_{MW}	2-5
Q^{DT}	25-10

Active core power 80-4000 MW. Only thermal neutron regimes have been analyzed so far. He cooling is possible.

With cooperation of the US, China (and RF), the machine can be launched in 12 years, certainly before ITER will get its 15 MA

From EAST to FirstFFH

EAST Update



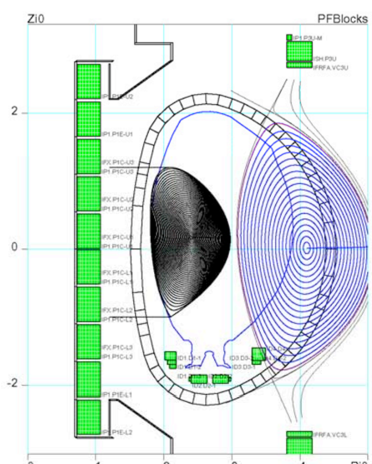
Full performance commissioning
Plasma
$Ip=0.6MA \quad B_T=2\text{-}3T$
$Ne=1\text{-}5\times10^{19}m^{-3}$, $Te=1\text{-}2keV$
LHCD:0.8MW(2MW)
ICRF:0.2MW(4.5MW)
Internal structures Active cooled C PFC
Fast IV coils
Cry-pump >10^5 l/s
2 Active cooled C movable Limiters
20 diagnostics
Reliable safety and interlock system

(taken from Director of ASIPP Jiangang Li talk "EAST current status and its short-term and long-term plans". Hefei. Dec. 24. 2008)

B=3.5-4 T, Ipl=1-1.5 MA, R=1.8, a=0.5, k=1.8

A month ago the regime Ipl=0.25 MA for 63 sec has been demonstrated.

A series of EAST1-FFFH



Scaling between different configurations is straightforward

Parameter	EAST1	$\propto$	FDS-EM
a_m	0.6	$\rightarrow$	1.0
R_m	2.4	$\propto a$	4.0
n_{20}	0.67	$\propto \frac{1}{a}$	0.4
E^{NBI}_{keV}	120	$=$	120
$\frac{T_i+T_e}{2}\|_{keV}$	24	$=$	24
$B_{t,T}$	5	$\propto \frac{1}{\sqrt{a}}$	3.87
$I_{pl,MA}$	4	$\propto \sqrt{a}$	5.16
P^{DT}_{MW}	30	$\propto a$	50
$W_{th,MJ}$	15.2	$\propto a^2$	42
$\tau_{E,sec}$	7.7	$\propto a^2$	21.4
P^{NBI}_{MW}	1.95	$=$	1.95
Q^{DT}	15.3	$\propto a$	25.5

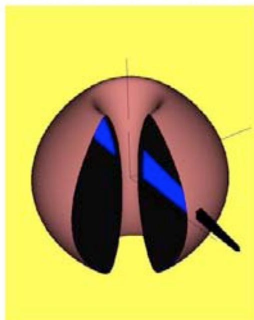
EAST1 has higher neutron flux density, FFFH has more space for a blanket

2 Plasma physics regime of FFFH

Approach 2: What will happen, if

1. Neutral Beam Injection (NBI) supplies particles into the plasma core, while
2. a layer of Lithium on the Plasma Facing Surface (PFC) absorbs all particles coming from the plasma ?

(Assume that maxwellization is much faster than the particle diffusion.)

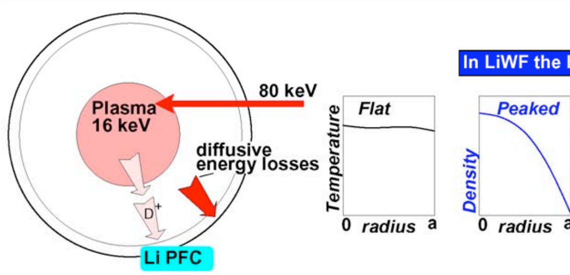


LiWF relies on "Let my plasma go" approach

Only particle diffusion matters

LiWF is the best possible confinement regime. Also, the entire plasma volume will produce fusion.

In LiWF the high edge T is OK



No "gifts" from plasma physics (ITG/ETG, sawteeth, ELMs) are expected or accepted.

Stability is excellent. LiWF relies only on external control.

Independent of anomalous electrons, rate of losses is determined by neo-classical ions.

$$\vec{\Gamma} = -\chi_i^{neo}\nabla n, \quad \vec{q}_i = -n\chi_i^{neo}\nabla T_i, \quad \vec{q}_e = -n\chi_i^{neo}\nabla T_i$$

Such a Reference Transport Model* (RTM) *can be used for predictions of transport properties.

LiWF is a new concept of magnetic fusion

LiWF introduces (a) core fueling and (b) the right plasma-wall interaction when plasma particles are absorbed by the wall.

This combination multiplies by 0 the value for fusion (if ever existed) of ongoing ITG, ETG turbulence studies

The right plasma contact with the wall, rather than the transport properties of the core, determines the plasma regime for controlled magnetic fusion.

It is much more efficient to prevent plasma cooling rather than the confronting cooling by extra heating

2.1 The "know-how" of the LiWF regime

The simple formula

$$\frac{T_i^{edge}+T_e^{edge}}{2} \geq \frac{1-R_{ei}}{1+(\Gamma^{gasI}/\Gamma^{NBI})} \cdot \frac{\left\langle E^{NBI}+E^{aux}\right\rangle}{5}$$

$$\left(\text{where} \quad R_{ei} \equiv max\{R_e, R_i\}, \quad E^{aux} \equiv \frac{P^{aux}}{I^{NBI}}\right)$$

encodes the "know-how" of the LiWF regime.

Trapped Electron Modes (TEM) are frequently mentioned as a blame that LiWF replaces one turbulence by another.

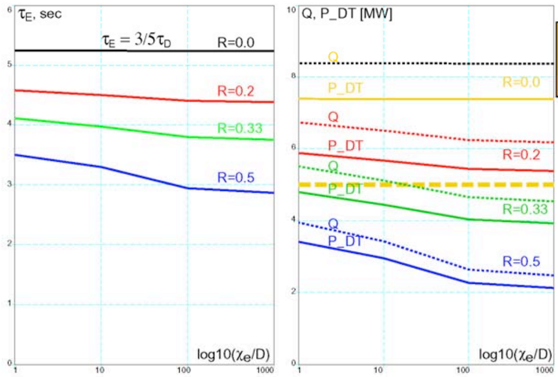
There is no TEM turbulence in the formula. LiWF regime is not sensitive to TEM.

Increase in NBI current can confront TEM without involvement of plasma physicists.

In order to obtain the LiWF regime the recycling and external gas sources should be eliminated

2.2 Breaking with anomalous electrons

LiWF boundary automatically leads to a diffusion controlled confinement regime, where nothing depends on anomalous electron heat conduction.



Reference Transport Model:

$D = \chi_i = \chi_i^{neo}$, $\chi_e = f \cdot \chi_i^{neo}$, $1 \leq f \leq 10^3$

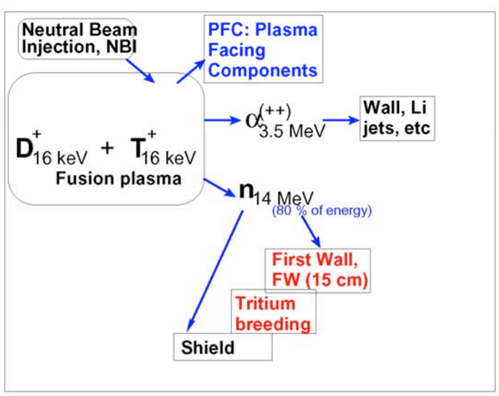
ST1:

$$
\begin{aligned}
R_{max} &= 1.65 \text{ m},\\
R_0/a &= 5/3,\\
R_0 &= 1.05 \text{ m},\\
a &= 0.63 \text{ m},\\
B &= 1.5 \text{ T},\\
I_{pl} &= 4 \text{ MA},\\
\beta &\simeq 0.2,\\
P_{NBI} &= \text{1-3 MW}\\
P_{DT}^{equiv} &= \text{10-20 MW}\\
Q_{DT}^{equiv} &= \text{5-8}
\end{aligned}
$$

Instead of "NSTX upgrade", PPPL should target ST1 as a facility with a real value for fusion

LiWF has a clean path to a Reactor Devel. Facility

Reactor issues rather than plasma physics are the focus of LiWF



LiWall concept has a clean pattern of flow of fusion energy

α-particles are free to go out of plasma

NBI controls both the temperature and the density

$$P_{NBI} = \frac{3}{2}\frac{\langle p\rangle V_{pl}}{\tau_E},$$
$$\frac{dN_{NBI}}{dt} = \Gamma^{ions}_{core\rightarrow\ edge}$$

Super-Critical Ignition (SCI) confinement is necessary to make NBI work this way

$$\tau_E >> \tau_E^*$$

LiWF is very consistent with Fusion-Fission ideas

The target plasma regime can be develop without use of tritium

LiWF vs Main Stream Fusion (MSF)

Issue	LiWF	MSF concept of "fusion"
The target	RDF as a useful tool	Political "burning" plasma
Operational point:	$P_{NBI} = E/\tau_E$	ignition criterion $f_{pk} p \tau_E = 1$
Hot-α, 3.5 MeV	"let them go as they want"	"confine them"
He ash, mixed with plasma	residual, flashed out by core fueling	"politely expect it to disappear"
$P_\alpha = 1/5 P_{DT}$	goes to walls, Li jets	dumped to SOL
Power extraction from SOL	conventional technology	no idea except to radiate 90 % of P_α by impurities
Plasma heating	"hot-ion" mode: NBI $\rightarrow i \rightarrow e$	to heat first useless electrons, then ions: $\alpha \rightarrow e \rightarrow i$
Use of plasma volume	100 %	25-30 %
Tritium control	pumping by Li	tritium in all channels and in dust
Tritium burn-up	>10%	fundamentally limited to 2-3 %
Plasma contamination	no Z^2 thermo-force, core fueling	junk from walls goes to the plasma
He pumping	Li jets, as ionized gas, $p_{in} < p_{out}$	gas dynamic, $p_{in} > p_{out}$
Fusion producing β_{DT}	$\beta_{DT} > 0.5\beta$	diluted: $\beta_{DT} < 0.5\beta$
Fusion power control	Existing NBI technology	no idea

For both Fission-Fusion Hybrids (FFH) and Non-Fission Fusion (NFF) there is no alternative to LiWF

LiWF and plasma physics issues

LiWF relies on existing plasma physics rather than on empirical scalings

Physics issues	LiWF	MSF concept of "fusion"
Confinement	diffusive, RTM$\equiv \chi_= \chi_e = D = \chi_i^{neo}$	turbulent thermo-conduction
Anomalous electrons	play no role	is in unbreakable 40 year old marriage with anomalous electrons
Transport database	easyly scalable by RTM (Reference Transp. Model)	beliefs on applicability of scalings to "hot e"-mode
Sawteeth, IREs	absent	unpredictable and uncontrollable
ELMs, $n_{Greenwald}$-limit	absent	intrinsic for low T_{edge}
p'_{edge} control	by RMP through n_{edge}	through T_{edge} and reduced performance
Fueling	existing NBI technology	no clean idea yet
Fusion power control	existing NBI technology	no clean idea yet
Current drive	efficient at low n_e, high T_e	inefficient
Stationary plasma	straightforward external control, no thermo-force driving impurities	unresolvable issue
Operational DT regime	identical to DD plasma	needs DT power for its development
Time scale for RDF:	$\Delta t \simeq 15$ years	$\Delta t \simeq \infty$
Cost:	$\simeq$ $2-2.5 B for RDF program	$\simeq$ $20 B with no RDF strategy

So far, the LiWF never failed in predictions (not interpretations!!!) of relevant tokamak experiments

NSTX in PPPL is unique and crucial for fusion

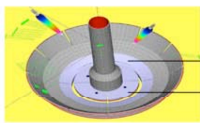
PPPL and NSTX team have everything to demonstrate the LiWF regime: people, experience with Li handling, NBI, and understanding of necessary steps.

The machine should be converted into **ST0** *device which would provide*

$$R < 0.5, \quad \Gamma^{gasI} < \Gamma^{NBI} \qquad (2.1)$$

and then target the mailestone

Reproduce the CDX-U results in 3-4 fold confinement enhancement (tauE$\simeq$200 ms)

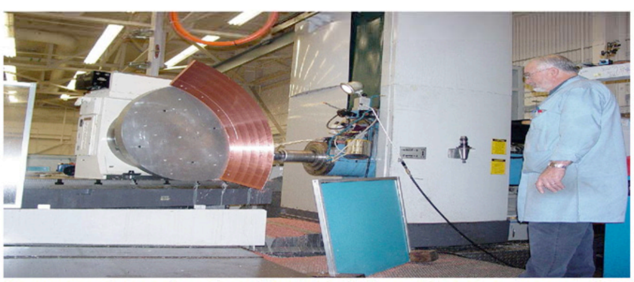


New plasma regimes require plasma contact with Li on the target plates.

LLD on NSTX should include the entire surface of the low divertor.

Instalaltion of full LLD would be a real step of NSTX toward relevance to ITER and consistency with Orbach's letter on future of PPPL

Liquid Lithium Divertor for NSTX



Copper plates for the Liquid Lithium Divertor to put NSTX on the LiWF track.

3 FirstFFH is ready for a conceptual design phase

The plasma physics concept has been chosen and relies on our best understanding of fusion. It eliminates fundamental problems which has stagnated fusion.

With well specified remaining fusion technology issues, such as
(a) stationary 120 keV NBI,
(b) Liquid Lithium Divertor,
(c) pumping of the low density He,

the major unknown are related to merging fission blanket with the toroidal plasma, fast neutron regime, tritium cycle, remote maintenance of nuclear components inside the toroidal device, etc.

The plasma physics issues are, finally, in the schedules of research programs (US, Europe, China). Blanket techology can be developed in parallel with designing the machine.

4 Summary

It is necessary to realize that the present concept of magnetic fusion (originated in the 60-70s) has been exhausted at the end of the 80s.

Switching the program to a new concept is necessary. The emphasis should be shifted from heating the core to prevention of cooling the plasma edge.

The LiWF gives the reliable scientific basis for the First Fission-Fusion Hybrid

FirstFFH gives an excellent topic for collaboration between the US and China (and potentially RF) starting with the conceptual design of FFFH

Even without US, with a delay of 5-10 years, China is capable (and motivated) to develop and build FirstFFH. It is in strategic US interests to be involved from the early stage.

Stellarators as fusion-fission reactor candidates

Jeffrey H. Harris
Donald A. Spong
Fusion Energy Division
Oak Ridge National Laboratory

Hybrid Fusion Systems
Washington, DC

Managed by UT-Battelle
for the Department of Energy

OAK RIDGE National Laboratory

Topics

- **Magnetic fusion systems all feature compromises**
- **Characteristics of stellarators**
- **What we (really) know about stellarator performance**
- **Key issues for stellarator development for fusion**
- **Use a stellarator as driver in a fusion-fission hybrid?**

2

OAK RIDGE National Laboratory

Magnetic fusion systems all have compromises

"Ideal" MFE system

- Nested toroidal flux surfaces
- Composed of simple planar, unlinked coils
- Low magnetic fields (ideally could use copper coils)
- Steady-state without recirculating power
- Inherently stable
- Simple divertor and maintenance concepts
- Straightforward development path, scaleability

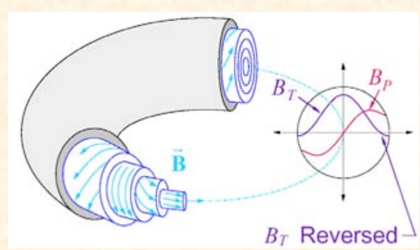
Configurations show to confine plasmas well are all non-ideal

- Tokamak: good geometry (for a torus), but challenges in sustainment & stability
- ST: compact, simpler tokamak, copper coils, but shares tokamak challenges
- RFP: mostly self-generated fields, copper coils, challenge is sustainment
- Stellarator: stable, steady-state, but complex coils, divertor & maintenance

Reversed Field Pinch configuration for fusion-fission hybrid

RFP strengths for hybrid application:

- **Low field at the magnets, Cu if desired**
- **High beta, compactness**
- **Ohmic heating, using axisymmetric coils**
- **No known constraint on aspect ratio, larger could be advantageous for a hybrid**
- **Nearly classical energetic ion particle confinement, helpful for NBI-driven fusion**



Reversed Field Pinch

Challenges to overcome:

- **Transient tokamak-like confinement; scaling not established**
- **Current drive is required, possibly steady-state using OFCD (i.e, AC induction)**
- **Active feedback of resistive wall modes now routine; needs to become robust**
- **Control strategy for the plasma-boundary interface needs to be developed**

J. Sarff, University of Wisconsin

Distinguishing characteristics of stellarators

Flux surfaces & rotational transform (ɫ) from external windings

- Non-axisymmetric magnetic configuration
  - Great design flexibility
- Avoid (or minimize need) for plasma current
- Steady-state without disruptions
  - Potential for real fusion ignition ($P_{ext} \sim 0$)

Torsatron/ Heliotron — Advanced Stellarator

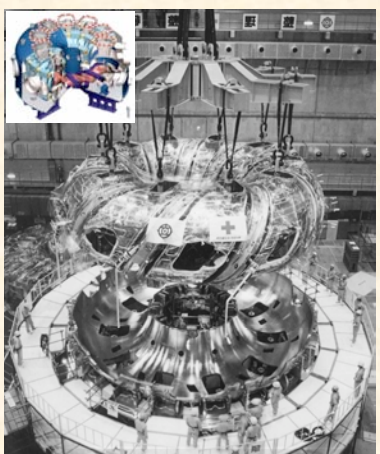
Broad and deep experience base

- 1970-present: 30 stellarator devices successfully built & operated in 7 countries
  - R: 0.12 m → 3.9 m
  - B: 0.05 T → 3 T (including superconducting)
  - P: 0.005 MW → 18 MW

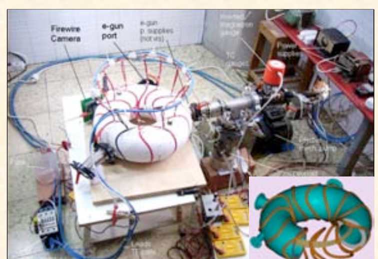
Harder to build than tokamaks . . . but easier to operate

- 3-D construction with challenging coil shapes
- Accuracy in construction: ~1 part in 5×10^4 (resonant components)
- Improved construction strategies are developing: metrology, etc.

Stellarators from large to small have been succesfully constructed



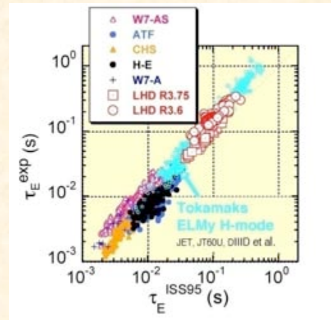
LHD, **Japan**; 1997-present
R = 3.9 m, a = 0.6 m, B = 4 T
superconducting coils
1500 tonnes

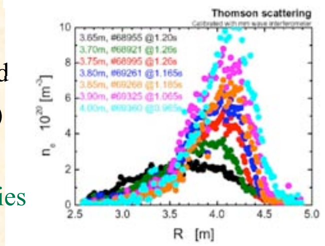


UST-1, Spain; 2006-present
R = 0.12 m, a = 0.02 m
B = 0.1 T; auto batteries
V. M. Queral; self funded
Capital cost ~ $5000
www.fusionvic.org

Stellarators are achieving outstanding results

- **Quiescent high beta plasmas**
  - Limited by heating power & confinement
  - LHD β = 5.2% transiently; 4.8% sustained
  - W7AS β > 3.2% for 120 τ_E
- **τ_E similar to ELMy H-mode**
  - ELMs occur in narrow parameter ranges
- **Improved confinement with orbit optimization**
  - W7AS, HSX
- **High density operation**
  - Limited only by heating power and magnetic field
  - Up to 3 × equivalent Greenwald density (W7AS)
  - LHD $n_e(0) \sim 10^{21}$ m^{-3} at B=2.7T with pellets
  - 3-D divertor controls recycling, excludes impurities
- **Steady-state operation**
  - LHD ~0.7 MW pulse lengths ~1 hr (utility limit)





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Useful stellarator performance predictor tools developed

- **Energy confinement: International Stellarator Scaling 2004 [1]**

$$\tau_E^{ISS04} / f_{ren} = 0.134 a^{2.28} R^{0.64} P^{-0.61} \overline{n}_e^{0.54} B^{0.84} \iota_{2/3}^{0.41} \quad [\text{s, m, m, MW, } 10^{19}\text{ m}^{-3}]$$

f_{ren} = configuration factor ~ 1; correlates with degree of orbit optimization

- **Maximum density limited by radiative collapse (power/volume) [2-4]:**

$$n_c = 14.6 \left(\frac{P}{V_p} \right)^{0.48} B^{0.54} \quad [10^{19}\text{ m}^{-3}\text{, MW, m}^{-3}]$$

Large stellarators easily attain n > 10^{20} m^{-3};
LHD has reached n(0) > 10^{21} m^{-3};
Reduces α slowing down time & instability drive;
Reduces wall damage from escaping α's

- **Maximum normalized pressure [5-6]:** $\beta \le 5\%$ *Easily stated, but immensely important.*

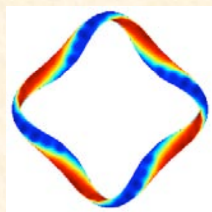
References [. . .] on the last slide.

OAK RIDGE National Laboratory

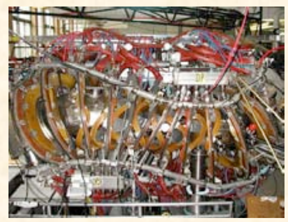
Configuration optimization is major goal of stellarator program

- Goal: make stellarator fusion reactor smaller. (Would also help hybrid).
- Reduce "effective" helical ripple to improve orbits of thermal & α particles
- US: quasi-symmetry (helical, axi- (toroidal), or poloidal)
- Other goals/trade-offs include tailoring of bootstrap current, flows, etc.
- New configurations developed numerically: W7X, HSX, NCSX, QPS . . .
- HSX (U. Wisconsin) already showing improved confinement in exp'ts

Helically
Symmetric
E**X**periment



quasi-helical
symmetry



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9

US compact stellarator research program is developing basis for attractive reactor concepts, e.g. ARIES-CS

Ref. baseline parameters:

NCSX-like (QA): 3 periods

$\langle R \rangle$ = 7.75 m

$\langle a \rangle$ = 1.72 m $\langle R \rangle / \langle a \rangle \sim 4.5$

$\langle n \rangle$ = 4.0 x 10^{20} m^{-3}

$\langle T \rangle$ = 6.6 keV

$\langle B \rangle_{axis}$ = 5.7 T

$\langle \beta \rangle$ = 6.4%

H(ISS04) = 1.1

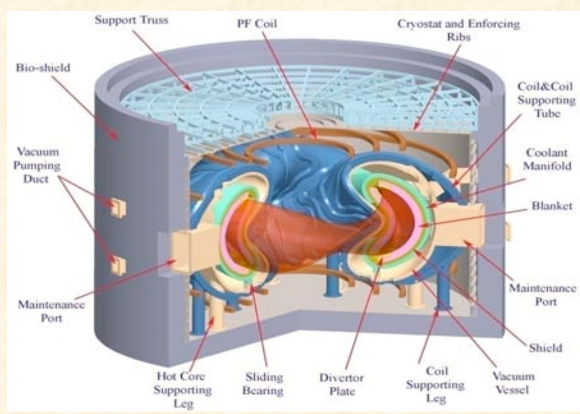
I_{plasma} = 3.5 MA (bootstrap)

25% of rotational transform

P(fusion) = 2.364 GW

P(electric) = 1 GW

Fully ignited (P_{ext} = 0)



Aries-	-I	-RS	-CS	-AT	-CS
Blanket			LiPb/FS	LiPb/SiC	LiPb/SiC
COE(92)	99.7	75.8	61.3	47.5	48.

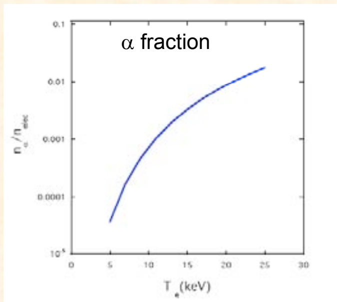
alpha loss ≈ 5% ⇒ divertor heat load ~ 5-18 MW/m^2

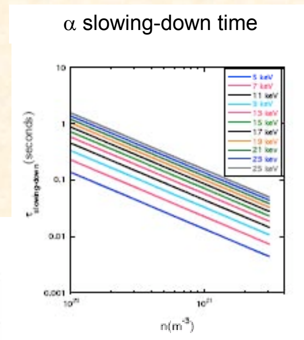
(core radiation fraction ~75% as in ARIES tokamaks)

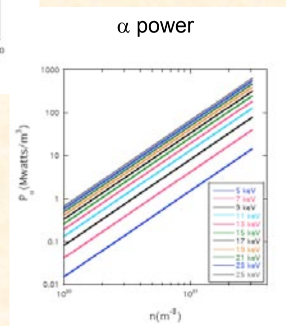
10

Need to integrate stellarator into a fusion-fission hybrid scenario

Operation with 10-100 MW of α power & corresponding output of fusion neutrons looks feasible.



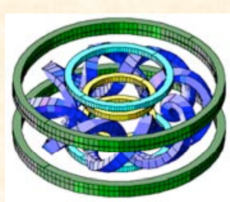




Stellarator optimization path will take time to follow

- Modular "advanced" stellarators have a large number of complex parts that must be assembled to high accuracy.
- Complex projects do *not* play well with risk-averse funding agencies.
- Start of W7X (R = 5.5 m) delayed to 2014; NCSX and QPS canceled.
- Older designs "simpler," if not optimal for "pure" fusion.

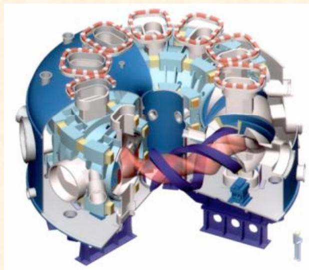
Torsatron/ Heliotron



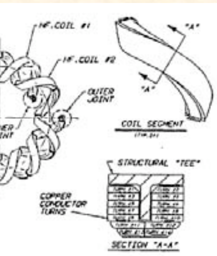
Advanced Stellarator

- ***Could a less-optimized stellarator drive a steady-state hybrid while we sort out the more complex designs for fusion use?***

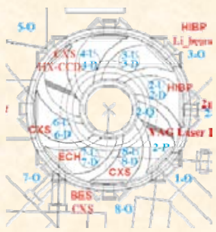
If there is a real rush . . . we have a lot of experience with LHD-like configurations. But need optimization.



LHD
(NIFS)



ATF
(ORNL)



CHS
(NIFS)

Heliotron-E
(Kyoto Univ.)

Conclusions

- **Characteristics of stellarators**
  Gains may outweigh complexity to yield an elegant fusion reactor.
  Steady-state ignited operation
  Passive stability ⇒ reliability ⇒ passive safety

- **What we (really) know about stellarator performance**
  Good international database from which to extrapolate, & tools to do it with.

- **Key issues for stellarator development for fusion**
  How well does configuration optimization work in practice?
  Must make construction more predictable.
  Divertor and wall: manage fueling, particle & heat flux

- **Use a stellarator as driver in a fusion-fission hybrid?**
  Demonstrated stable operation at high density is key.
  Reculer pour mieux sauter:
  Use partially optimized configuration, not most advanced?
  Need viable development scheme.

Stellarator Performance Estimator Toolkit

[1] H. Yamada, J. H. Harris, A. Dinklage et al, Nucl. Fusion **45** (2005) 1684.

[2] L Giannone, J Baldzuhn, R Burhenn, et al, Plasma Phys. Control. Fusion **42** (2000) 603.

[3] M. Greenwald, Plasma Phys. Control. Fusion **44** (2002) R27.

[4] K. Itoh, S-I. Itoh, L. Giannone, J. Phys. Soc. Japan **70** (2001) 3274.

[5] S Sakakibara, K Y Watanabe, Y Suzuki, et al, Plasma Phys. Control. Fusion **50** (2008) 124014.

[6] A Weller, K Y Watanabe, S Sakakibara, et Nucl. Fusion 49 (2009) 065016.

OAK RIDGE National Laboratory

Breakout Session B

Breakout Session B

High Support Ratio fuel cycle Must for a Hybrid

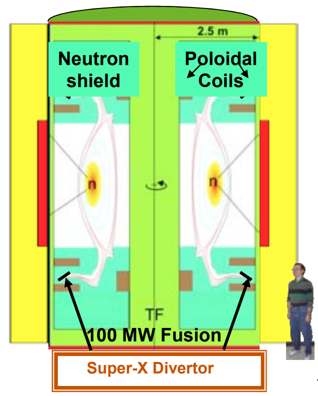
S. Mahajan, M. Kotschenreuther

P. Valanju E. Schneider, and

C. van der Hoven

The University of Texas at Austin

NYU-Brookings May 19, 2009



★IFS

1

Transmutation schemes (non-fusion)-recent history

- National Academy of Sciences (NAS) review of transmutation schemes and - recent public congressional testimony (2005-2006) on Fission only (FR) approaches **(to thoroughly destroy waste)**
  - **all too costly**
  - all take too long (~ 2 centuries to reduce 99%)
  - Proliferation concerns due to reprocessing

Why so expensive? - More expensive tools

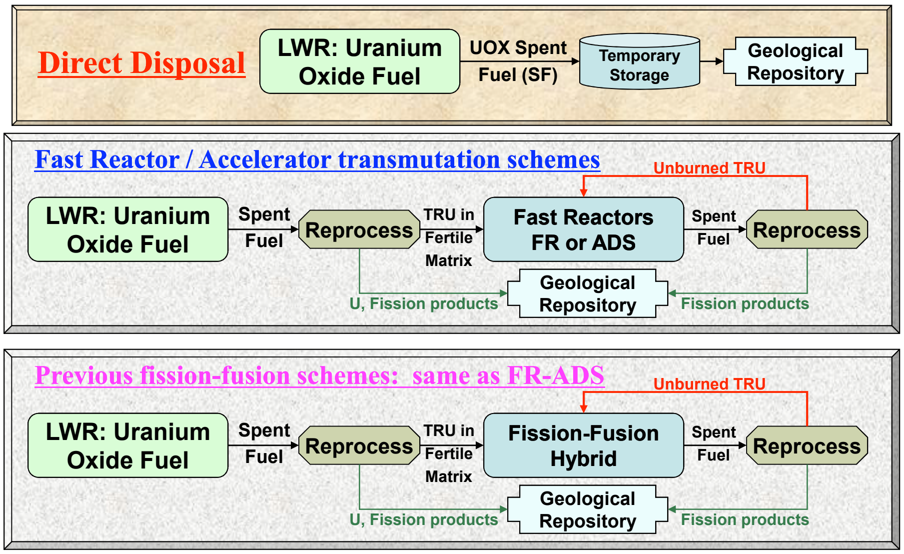
FRs and ADS (advanced reactors,AR)-more expensive than LWRs

- And far too many ARs were needed-relatively low support ratio
- Total excess cost > $100 billion dollars, perhaps $100's billion

★IFS

2

Generic Nuclear Waste Management Schemes



Simply substituting a more expensive Hybrid does not help same problems as FR & ADS schemes

IFS

What does it take to make an attractive Hybrid-system

- Aforementioned hybrid schemes have little advantage over proposed FR schemes in **cost, proliferation (and possibly time)**
- The fusion driver, of course, comes with obvious “disadvantages”
  - extra cost, complexity, new technology development, new coupled failure modes--
- There is, however, a **fundamental *technical* advantage** that a fusion neutron source driven sub-critical fission assembly (Hybrid) brings to the scene **- it can safely burn much lower quality nuclear fuel**

The Texas ref. Hybrid turns precisely this unique technical capability of a hybrid into money- a transmutation scheme with a large advantage in cost
(and in time and in “proliferation”)

IFS

Burning very low quality fuel-Harnessing the Hybrid

- We constructed "an" **optimal** two-step fuel cycle to exploit hybrid's uniqueness
- **The LWR-IMF "deep pre-burn" first step Minimize total system cost:**
  - Burn *as much TRU as possible* in *least expensive* reactors - the medium to high quality TRU (~75% of the total) is readily burnt in existing cheap LWRs
    - This would entail little extra cost- no new reactors!
    - The 25% TRU residue which isn't burned is *very low quality fuel*
- **Use hybrid reactors only for the residual (~25%) TRU- the Hybrid-step**
    - Consensus: such residual **cannot be burned safely in FRs to 99% destruction**
    - Only a **small number of hybrids** needed to destroy this small residual
- **A symbiotic relationship - each reactor type does what it does best**
  - LWR- burns majority of "high quality" TRU cheaply and quickly
  - Hybrid- burns low quality TRU, but is only used only for the minority of TRU that really need it, so few are needed

IFS

Why is the hybrid needed for the residue?

- Safety issue for the FR: stability of the fission chain reaction
- Consensus of many previous analysis of FRs:

Only a smallish minority fraction of minor actinides is tolerable in FRs

- The residue from the LWR step: about half minor actinides
- Even the isotopes which aren't minor actinides, but are left after the 75% LWR burn, behave like minor actinides for an FR- threshold fissioners

Fuel quality of residue is really poor

Safety requires that such fuel must be burned "subcritically",

with the help of non-fission neutrons

Fusion may be the cheapest available source of external neutrons for burning this low quality fuel

IFS

UT-Hybrid vs Fission-only Cycle

Required Reactor fleets for zero net transuranic nuclear waste production from the current ~100 US utility reactors

	Hybrid Route	Fission-only (AFCI)
US Light Water Reactors	100	100
Fast-spectrum waste destruction reactors	4-6	37-56

Under our proposal

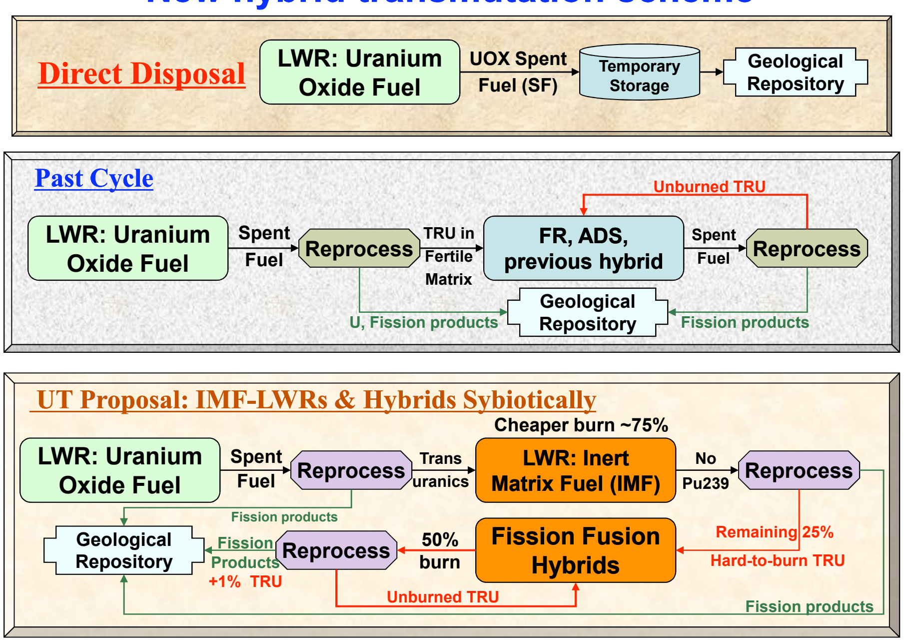
4-6 new utility-scale hybrid reactors would suffice-a support

Support ratio: Hybrid S~16-25, FR S~3

Total waste reprocessing for fast-spectrum systems will also be reduced by roughly an order of magnitude

IFS 7

New hybrid transmutation scheme



IFS 8

Reactor Requirements for Waste Transmutation for different schemes

Reactors needed to destroy waste from 100 LWRs

	Fast Reactors BR= 0.5	Fast Reactors BR= 0.25	Hybrids burning all TRU	Hybrids burning only Np & Am	IMF pre-burn followed by hybrids
Number of FRs	39-56	37	0	20	0
Number of Hybrids			28	5	4-6
Total # of Fast systems	39-56	37	28	25	4-6
"Excess" Cost above all LWRs (LWR equivalents)	19-28	19	28	15	4-6

FR cost = 1.5 LWR, Hybrid = 2 LWR

IFS

9

LWR-IMF + Hybrid system => High support ratio=> major *cost advantage* over other systems

- UT system - the first hybrid based scheme with high support ratio S
  - High S implies that the total Hybrid system may be considerably cheaper even when the *individual* hybrid is more expensive than an *individual* FR
- **The system cost advantage may be enough to overcome the other disadvantages of the hybrid:**
  - Complexity, stage of development, novel failure modes
  - These **technological drawbacks** can be greatly reduced by the replaceable compact fusion module design presented in a companion paper.

High S => constituency for a Hybrid-based waste Destruction system => =>The Hybrids should be thoroughly investigated.

IFS

10

Hybrid Fusion Systems
Why combine fusion and fission?

Gregory Moses
Department of Engineering Physics
University of Wisconsin

Ford Fusion
Hybrid 2010

Conference of The Center for Hydrogen Fusion Power
And
The Brookings Institution
Washington DC, May 19, 2009

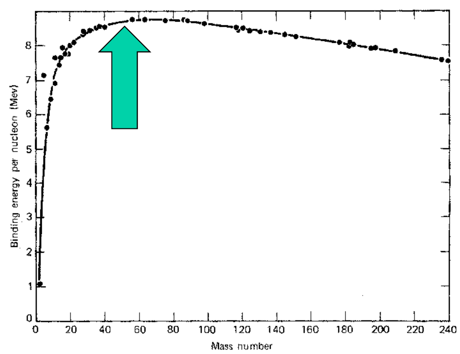
Energy = Force x Distance

- What forces do we have available?
- Gravity— -infinity→1960
- Electromagnetic—cavemen→2010
- Nuclear—1950→future

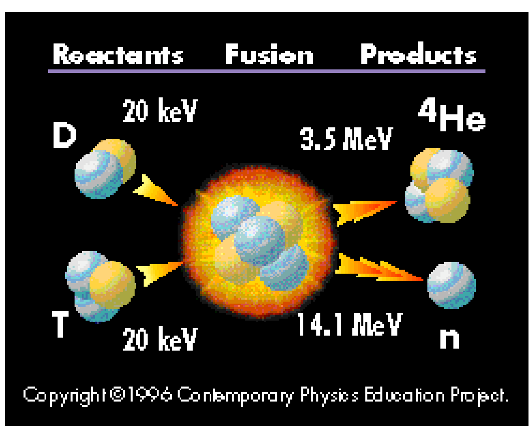
Fusion and Fission Physics

The binding energy per nucleon peaks at 8.7 MeV for nuclear mass numbers of about 50.

More tightly bound nuclei can be produced by either combining lighter nuclei or inducing heavier nuclei to fission. Spontaneous fission does not occur because of short range nuclear forces. Fission barrier is 6-9 MeV.

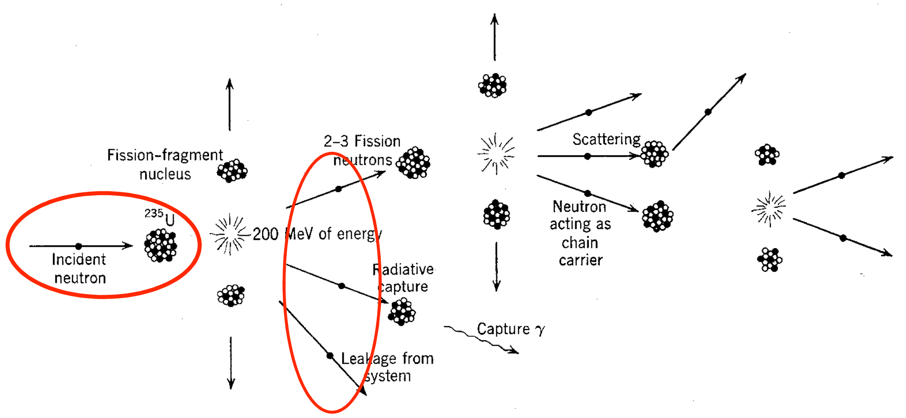


Energy release from DT fusion



Only D is found in nature at 0.02% of hydrogen.

Fission chain reaction



$$k \equiv \text{multiplication factor} \equiv \frac{\text{number of neutrons in one generation}}{\text{number of neutrons in preceding generation}}$$

Fission fuel energy release (MeV)

- Fissile fuels
  - ^{233}U 190.0+/-0.5
  - ^{235}U 192.9+/-0.5
  - ^{239}Pu 198.5+/-0.8
  - ^{241}Pu 200.3+/-0.8

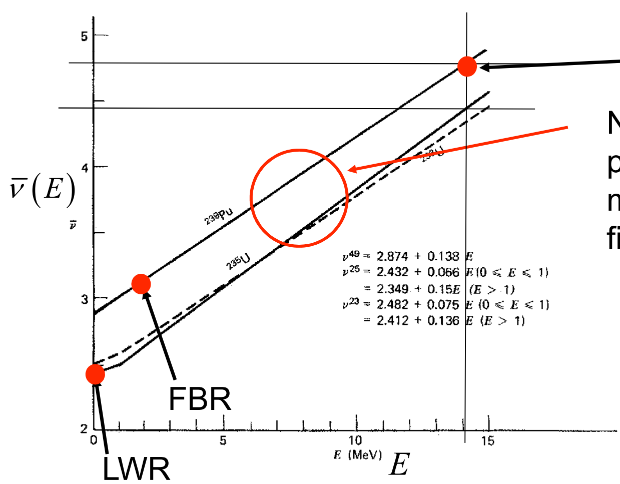
Only ^{235}U is found in nature at 0.7% with remaining being 99.3% ^{238}U.

- Fissionable fuels
  - ^{232}Th 184.2+/-0.9
  - ^{234}U 188.9+/-1.0
  - ^{236}U 191.4+/-0.9
  - ^{238}U 193.9+/-0.8
  - ^{237}Np 193.6+/-1.0
  - ^{238}Pu 196.9+/-0.8
  - ^{240}Pu 196.9+/-1.0
  - ^{242}Pu 200.0+/-1.9

Fusion vs. fission

- Fission is energy rich
- Fusion is neutron rich
- Is this the right measure?
- Coin of the realm is neutrons

Number of neutrons produced vs inducing neutron energy



Fusion-Fission

Note that ^{239}Pu produces about 0.5 more neutrons per fission than ^{235}U.

$\nu(E)$=average number of neutrons produced per fission

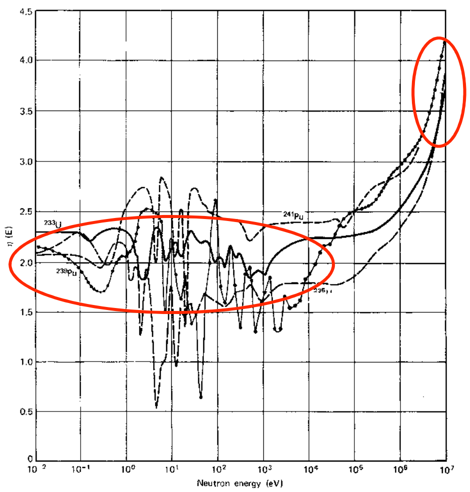
η–– key parameter in fission chain reaction

$\eta \equiv$ Average number of neutrons produced per neutron absorbed in fuel.

$$\eta = \nu\sigma_f / \sigma_a = \nu/(1+\alpha)$$

$$\eta = \frac{\sum_j \nu_j \Sigma_f^j}{\sum_j \Sigma_a^j}$$

Fuel mixtures

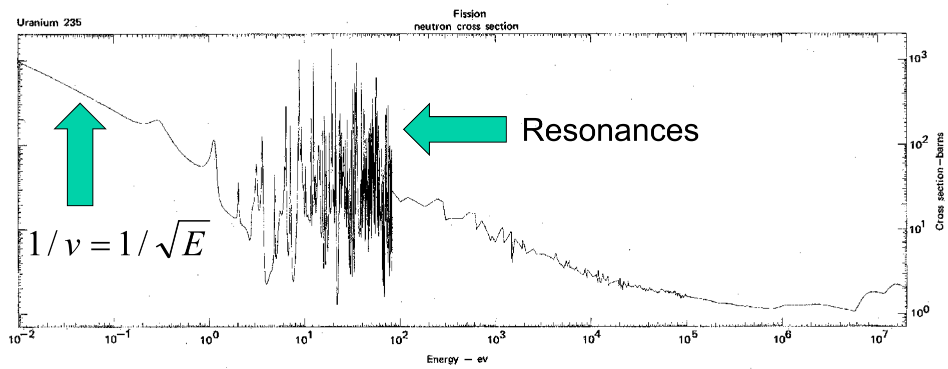


Summary

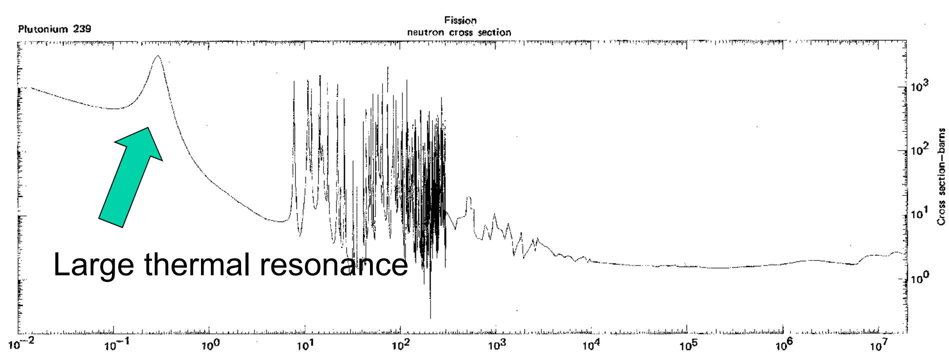
- Fission and fusion come from nuclear forces
- Fission and fusion produce radioactive isotopes
- Fission and fusion both produce neutrons
- Fusion produces harder working neutrons to put to work for beneficial purposes

- Neither fission nor fusion produce CO_2
- Don't circle the wagons and shoot inward, nuclear forces are the force of the 21st Century

Fission cross section for ^{235}U



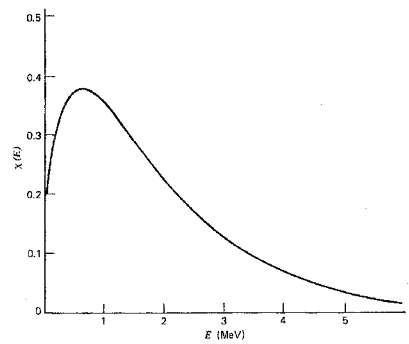
Fission cross section for ^{239}Pu



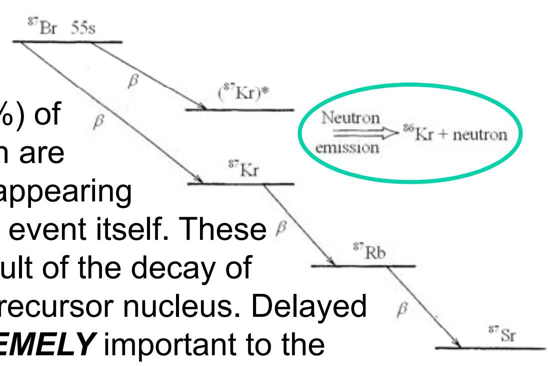
Fission prompt neutron energy spectrum

$$\chi(E) = 0.453e^{-1.036E}\sinh\sqrt{2.29E}$$

$\chi(E)dE \equiv$
Average number of fission neutrons emitted with energy in E to $E + dE$ per fission neutron.



Delayed fission neutrons



A small fraction (<1%) of neutrons from fission are delayed neutrons—appearing long after the fission event itself. These neutrons are the result of the decay of a delayed neutron precursor nucleus. Delayed neutrons are ***EXTREMELY*** important to the control of the fission chain reaction. Delayed neutron precursors are grouped together into six groups with six average radioactive half lives.

Fertile isotopes

$$^{238}U(n,\gamma)^{239}U \underset{23\text{ min}}{\overset{\beta^-}{\rightarrow}} {}^{239}Np \underset{2.3\text{ d}}{\overset{\beta^-}{\rightarrow}} {}^{239}Pu$$

$$^{232}Th(n,\gamma)^{233}Th \underset{22\text{ min}}{\overset{\beta^-}{\rightarrow}} {}^{233}Pa \underset{27\text{ d}}{\overset{\beta^-}{\rightarrow}} {}^{233}U$$

Isotopes that can be transmuted into fissile isotopes are called fertile isotopes. “Extra” fission neutrons can be used to convert fertile fuel into fissile fuel.

U.S. DEPARTMENT OF ENERGY | Nuclear Energy

AFCI Options Study – Nuclear Energy R&D Issues

Roald Wigeland, Idaho National Laboratory

Temi Taiwo, Argonne National Laboratory
Michael Todosow, Brookhaven National Laboratory
Bill Halsey, Lawrence Livermore National Laboratory
Jess Gehin, Oak Ridge National Laboratory

May 19, 2009

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Nuclear Energy R&D

- **The AFCI Options Study supported by DOE-NE was started earlier this year to take a broad look at nuclear power and issues**
  - The goal is to identify and analyze potential options for their ability to resolve the issues with nuclear power
    - ***What are the issues and concerns?***
    - *Account for all of the previous studies looking at nuclear power*
    - *Can we continue with the current 'once-through' approach followed by disposal of used fuel?*
- **The results are intended to inform decisions on the future directions of nuclear energy R&D**
  - How far can existing or evolutionary technologies go in addressing the issues?
  - What technological breakthroughs are needed to be able to succeed?

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Scope of the AFCI Options Study

- Identify the issues with nuclear energy
  What's wrong with it today?
- Identify the underlying cause(s)
  What causes the problems?
- Develop evaluation measures and goals based on underlying causes
  What does an option need to be able to do?
- Develop and / or review nuclear energy options
  What are the options?
- Evaluate the impact on the evaluation measures
  How well does an option do?
- Identify where R&D results in superior options
  Are there unsolved problems or does no suitable option exist yet?

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Nuclear Energy Concerns

- **Nuclear waste, the top-level concern**
  - In general, HLW and LLW, hazardous for a very long time
- **Proliferation risk, and the spread of weapons-usable technologies**
  - Both weapons-usable materials and the ability to produce them
- **Safety, and public concerns about accidents**
  - TMI and Chernobyl, but 25 years of safe operation since then
- **Security in a post-9/11 world**
  - Terrorist attack and sabotage resulting in radioactive release
- **Economics and affordability**
- **Sustainability for the future**

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Science and Engineering: Nuclear High-Level Waste Example

	Direct HLW Disposal	*Reduced HLW Disposal Needs*	*Very Low HLW Disposal*	*No Geologic Repository*
Existing Industrial Capabilities	*UOX/MOX Fuel, Yucca Mtn. (today)*			
Improved Technologies		*UREX, Pyro, TRU Recycle (tomorrow)*		
Evolutionary Changes			*New Separations, Fission Product Treatment (likely with R&D)*	
Revolutionary Developments				*Science and Engineering Breakthroughs (possible?)*

How aggressive should the goal be for an advanced fuel cycle?

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Examples of Underlying Causes

- **Nuclear waste**
  - Uncertainty about isolating waste from the biosphere ‘forever’
- **Proliferation risk**
  - Availability of weapons-usable materials (Pu, etc.)
  - Use technologies and facilities for weapons-usable materials
- **Safety**
  - Potential for accidents that could disperse radioactive materials
- **Security**
  - Risk from terrorist attack that disperse radioactive materials
- **Economics**
  - Uncertainty about licensing, cost recovery, …
- **Sustainability**
  - No solution for the current, difficult, waste management problem

May 19, 2009 Nuclear Energy R&D Options 6

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Nuclear Energy Options

- **Few or no constraints on the types of potential systems**
  - No presumption of technical viability, but identification of desirable technical capabilities that warrant development effort
- **A broad range of options is being considered**
  - 'Once-through,' in which nuclear fuel is irradiated and disposed
  - 'Recycle,' in which used fuel is not disposed, but processed instead for further irradiation of recovered elements
    - *Separations processes for recovery*
    - *Irradiation environments for power production, transmutation (Options for fuels, storage, …)*
    - *Disposal options for wastes (Options for disposal environments, waste forms, …)*
- **How much better can we make a nuclear energy system?**

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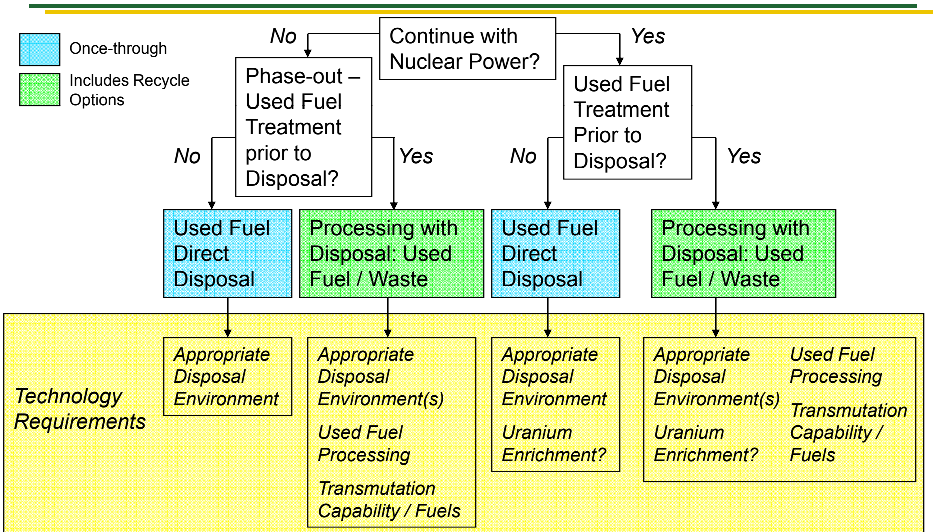
Logic for Options Identification and Development



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Technology Area Questions

- **Identification of storage and disposal environment characteristics**
  - For nuclear fuel cycle options that produce wastes requiring deep geologic disposal, many environments can be considered
    - *Different isotopes are important depending on the environment*
  - Can the need for deep geologic disposal be avoided (no HLW)?
  - What can be done about LLW?
- **If required, identification of used fuel processing requirements**
  - Waste stream content objectives (No TRU, long-lived fission products, …)
  - Is it possible to separate and recover everything of concern, and with very little or no losses?
  - Can technologies be developed that remove proliferation concerns?
- **If required, identification of transmutation requirements**
  - Elements that need to be transmuted – Is complete transmutation possible?

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Current Activities

- **AFCI Campaigns are supporting the Options Study**
  - Identify and characterize options in each technology area
    - *Irradiation, Processing, Transmutation, and Storage / Disposal*
  - The largest possible range should be covered for both 'once-through' and 'recycle' systems
  - Potential integrated systems are built from the technology pieces
- **For transmutation, this can include**
  - Thermal, epithermal, and fast reactors
  - Designs with fuel pins or with fuel in the coolant
  - Accelerators, fission/fusion hybrids, laser-induced, …
- **The real question is if there are separation and transmutation options for every element (isotope) of potential concern**
  - Fission product transmutation or 'perfect disposal' for isotopes: Cs-135, Tc-99, I-129, Sn-126, Zr-93, Se-79, Cl-36, C-14, …?
  - What about chemically toxic (stable) materials?

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Goals of the Study

- **The study is designed to collect information about potential nuclear fuel cycle options**
  - Options will be assessed for their impact on the issues for nuclear power (wastes, proliferation risk, …)
  - What distinguishes one option or set of options from others?
- **No selection of option(s) will be made**
  - R&D directions will depend on what goals are selected
    - *Decisions made by policy-makers*
- **It is possible that a range of options will be studied further**
  - High technical risk, potentially high payoff options
  - Moderate / low technical risk, substantial payoff

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Evaluation Criteria

- **Nuclear Waste Management - Characteristics and Disposal Requirements**
  - Radiotoxicity, waste forms and amounts, heat load, compatibility with geologic disposal options
- **Proliferation Risk**
  - Inventory of weapons-usable materials, material attractiveness, intrinsic features of technologies and facilities, safeguardability, etc.
- **Safety**
  - Level of difficulty of designing licensable systems, transportation risks
- **Security**
  - Response to potential terrorist acts and sabotage
- **Economics of fuel cycle options**
  - Cost of options development (time/effort to bring to maturity) and cost of implementation, compatibility with existing infrastructure and the ability to transition, replacement for other energy sources
- **Sustainability, i.e., is the option a long-term solution?**
  - Resource utilization (fuel and commodities), environmental impacts