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The Fission-Fusion Hybrid Molten Salt Reactor: A Clean Energy Game Changer

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The Problem:

The world needs more electricity. Net global electricity generation is expected to rise 69% from 21.6 trillion kilowatt hours (kWh) in 2012 to 36.5 trillion kWh in 2040, with most growth coming in developing economies.[1] Even in mature economies, electricity generation is projected to increase, with efficiency gains anticipated to be insufficient to offset demand growth. From 2016 to 2050, total U.S. net generation is expected to increase by over 30% to 5.4 trillion kWh.[2]

The world needs carbon-free electricity. Burning of fossil fuels in energy production has caused a dramatic increase in atmospheric carbon dioxide (CO_2) since the beginning of the Industrial Revolution. This increase has led to growing international concern about the negative effects this concentration of CO_2 has had and will have on Earth's climate. While growth in the rate at which CO_2 is accumulating has plateaued in recent years, the *amount* of this greenhouse gas in the atmosphere continues to rise.[3] Reducing carbon emissions from electricity generation is one key to limiting future atmospheric CO_2 increases.

The world needs safe electricity. Nuclear power is the largest, most reliable source of emission-free electric power in the U.S. While nuclear fission produces only about 20% of U.S. electricity, it provides 57% of current carbon-free generation.[4] However, the nation's ninety-eight nuclear reactors are aging. In recent years, reactor closures have outpaced new reactor start-ups.[5] Nuclear power has nearly inexhaustible potential, but the public has been reluctant to support its increased use due to proliferation, safety and waste concerns.

The world needs more electricity now -- carbon-free, safe electricity -- and much more in the future. It is unlikely that clean energy alternatives to nuclear power (hydro, wind and solar) can satisfy projected world demand on anything approaching the scale required. Nuclear power could provide carbon-free energy on the needed scale; however, proliferation, safety and waste concerns must first be resolved.

The Solution:

This White Paper proposes the Fission-Fusion Hybrid Molten Salt Reactor (FFHMSR) as the solution to the world's growing need for abundant, carbon-free, safe electricity. The FFHMSR combines a *critical* molten salt fission reactor with a fusion source of energetic neutrons in a single connected system, offering advantages that neither has independently. The molten salt reactor provides improved safety and greater efficiency, while the neutron source's high energy neutrons eliminate the need for fuel enrichment and reprocessing and can remove *all* actinides from the waste stream. The dynamic balance between the dual processes capitalizes on their strengths and synergies.

The FFHMSR enables a closed fuel cycle and a 100-fold increase in fuel utilization. The FFHMSR provides greatly increased proliferation resistance and a greatly reduced volume of waste. It can be fueled with spent nuclear fuel, mined uranium, depleted uranium and abundant thorium. This novel concept, an implementation of an idea patented in 2016, relies on technology available today. The FFHMSR combines nuclear fission and nuclear fusion in an integrated system with each doing what it does best.

I. Background

In 2017, commercial U.S. nuclear fission reactors and hydroelectric plants combined generated 78% of the CO_2-free electricity produced by U.S. utilities, with wind contributing another 18%. Solar added only about 4%.[7] Although many developing economies plan to install new hydroelectric facilities, most developed countries have already exploited the economically feasible hydro power sites available to them.[8] While the installed capacity of wind and solar plants will likely continue to increase, these sources produce energy only intermittently. Nuclear power offers the best option for meeting the scale of anticipated demand for reliable, CO_2-free electric power.

A. Light Water Reactors

Fission reactors were developed by the United States during World War II to produce fuel for nuclear weapons. After the war, power reactor designs were developed and tested. Although graphite reactors could use natural uranium without enrichment, the U.S. Navy sponsored development of far more compact light water reactors (LWRs) for submarine propulsion, leading to the USS Nautilus, which first went to sea in 1955. Light water reactors rely on *isotopically enriched* solid uranium fuel with ordinary (light) water serving as the moderator. Although compact size is not necessary on land, LWR designs have been adapted for land-based electricity production, where they predominate worldwide. The LWR's poor fuel economy (due to water's neutron absorption) and its poor thermal conversion efficiency (due to its low temperature operation) have been accepted both to avoid additional development costs and to leverage the operational experience of an existing technology.

Unlike fossil fuel plants, which release energy through combustion, energy from nuclear reactors results from the physical process of fission, the splitting of atoms. Nuclear fuel is energy dense, with *millions* of times the amount of energy contained in a similar mass of chemical fuel. In LWRs, neutrons produced by fission events induce more fissions in a self-sustaining chain reaction, which continues as long as the needed fuel and conditions exist. The heat resulting from the reactions is transferred to a steam generator where it is converted into electricity.

Light Water Reactor Fuel Cycle

LWRs are wasteful in that most of the nuclear energy available from uranium is discarded. The fissile uranium-235 (U-235) isotope constitutes less than 1% of mined uranium. The isotope enrichment process divides mined uranium into two streams, a smaller stream of enriched uranium, which contains more than half of the mined uranium's U-235 content, and a depleted uranium stream, an order of magnitude larger, containing a smaller fraction of the U-235. Depending on enrichment level, enriched uranium typically contains about 60% of the mined uranium's U-235 isotope, but only about 9% of the abundant uranium-238 (U-238) isotope. Although the depleted uranium contains most of the nuclear energy potentially available, it is discarded before the LWR fuel cycle even begins.

Fuel rods fabricated from enriched uranium can be fissioned in an LWR until they become depleted of fissile material, making the LWR incapable of supporting a chain reaction. At that

Actinides
All fission fuel atom types known are from the 15-element actinide series, which ranges from atomic number 89 (actinium) through atomic number 103 (lawrencium). They appear in the bottom row of the periodic table. There are 226 known actinide isotopes. All 226 are unstable with characteristic radioactive decay modes and half-lives. Only the three actinide isotopes with the longest half-lives survive today in Earth's crust: thorium-232 (half-life 14.0 billion years), uranium-238 (half-life 4.47 billion years), and uranium-235 (half-life 0.704 billion years). Natural thorium-232 and the uranium-238 isotope which constitutes 99.3% of natural uranium are not fissile, meaning they cannot be fissioned by slow neutrons.

point, a small fraction of the fuel rods' U-238 will have been converted into plutonium-239 (PU-239), and some of that will have fissioned. The fuel rod will also contain other transmuted actinides. Enough spent (used) nuclear fuel (SNF) must then be removed and replaced with fresh enriched fuel so that reactor operation can resume. Although the removed SNF still contains a small amount of fissile material, together with fission products, it consists mostly of non-fissile actinides. The LWR once-through fuel cycle slates these contents for disposal in long-term radioactive waste repositories. However, the potential nuclear energy content of the non-fissile actinides remaining in SNF is an order of magnitude larger than all of the nuclear energy already released from the fuel, and the potential energy of the depleted uranium discarded in the enrichment process is another order of magnitude larger still. *Thus, the LWR fuel cycle releases only about one percent of the energy content of mined uranium, discarding the other 99%.*

A related issue is that the solid fuels used in most reactor designs are physically disrupted by fission. Disruption occurs because the combined volume of the two daughter fission product atoms in a solid fuel matrix is generally greater than the volume of the original actinide atom before it fissions. The resulting progressive swelling of the solid fuel as fissions accumulate is exacerbated by gaseous fission products, such as the noble elements krypton and xenon, and other fission products, such as iodine, which are gaseous at elevated temperatures. In solid fuel reactors, coolant flows in the narrow spaces between fuel rods or pellets in order to maximize heat transfer area, but the fuel is also surrounded by close-fitting cladding material which keeps fission products out of the adjacent coolant stream. If allowed, fuel swelling and gas pressure buildup would eventually lead to cladding failure.

As a result, solid fuel rod life is determined by its acceptable damage burn-up rating, not by the exhaustion of fuel rod fissile isotope content. For naval propulsion applications, highly enriched uranium fuel retains much fissile content even when the rods reach their burn-up damage limit, a situation that incentivizes reprocessing and recycling of the used fuel. For civilian applications, there have been efforts to restrict uranium enrichment to low levels, e.g., 3% to 5%, so that, by design, the fissile content becomes too low to support a critical chain reaction at about the same time fuel swelling and gas build-up approach fuel rod burn-up damage limits. Thus, an inseparable part of any solid fuel cycle is its outgoing stream of SNF needing reprocessing or disposal or both. This stream is determined by materials damage to solid fuel, not by exhaustion of its fissile content. Typically, about 95% of the contents of SNF remains U-238.

Light Water Reactor Issues

1. Proliferation

Nuclear technology cannot be made proliferation-proof. It is a so-called dual-use technology, one

Fissionable, Fissile and Fertile

All 226 actinide isotopes are fissionable, meaning that they can be fissioned by sufficiently energetic neutrons. All actinides release approximately 200 MeV per fission event with little variation in the energy released regardless of the actinide isotope fissioned.

Only 33 actinide isotopes are fissile, meaning that they can be fissioned by slow neutrons (e.g., neutrons having room temperature thermal energy=0.025 eV). These 33 fissile actinide isotopes can fuel the fission chain reactions used in pure fission reactors. The other 193 actinide isotopes are fissionable, but can only be fissioned by neutrons with kinetic energy greater than a threshold value, different for different isotopes, but *in all cases exceeding typical fission spectrum energies*. Thus, none of the 193 fissionable, but not fissile, actinide isotopes can by themselves support a pure fission chain reaction. However, all can radiatively absorb neutrons and be converted (transmuted) into fissile nuclides, which can subsequently be fissioned by slow neutrons.

Fertile actinide isotopes are isotopes that are not fissile, but that can be transmuted by neutron capture (followed in some instances by beta decay) into other isotopes that are fissile. Generally, all non-fissile actinides are fertile, although some may require multiple captures to become fissile.

It is important to note that for all 226 actinide isotopes, a 14.1 MeV incident neutron is sufficiently energetic to cause fission. Neutrons with energies as high as 14.1 MeV are rarely produced by fission. Almost all neutrons from deuterium-tritium fusion events are 14.1 MeV neutrons.

that can be used for military as well as civilian purposes. A drawback to expanded use of nuclear power is the potential for nuclear proliferation, the spread of nuclear weapons and the material and technology to produce them. Proliferation worries are centered on two separate threats: 1) nations developing weapons programs; and 2) diversion of the material needed to construct nuclear weapons by terrorists or criminal enterprises. The first requires the ability and resources to design, build and operate a nuclear facility, while the second relies on exploitation of weaknesses in procedures used to safeguard nuclear material.

Reactors themselves are not viewed as a significant proliferation risk. However, enrichment facilities and fuel reprocessing plants are seen as particular vulnerabilities in national nuclear programs, where weapons-grade material could be diverted from power production to a weapons program. In addition, the facilities for enrichment and reprocessing, as well as the transportation of materials to and from these facilities, introduce the risk of theft and transfer of nuclear material.[9]

2. Safety

A serious nuclear power plant accident is a prime example of a low-probability, high-risk event. Nuclear plants, which are highly regulated and designed with redundant systems to monitor and control operations, have a long record of operating safely in the U.S. Today's civilian nuclear fission reactors, however, typically contain enormous inventories of highly radioactive material which would pose a dangerous radiation hazard were it to be released. Releases can be large, as in the Chernobyl and eventually the Fukushima accidents, or small but chronic as at some other nuclear plants. In all cases, there is concern about potential harm to the surrounding population from direct exposure to radiation, as well as from indirect exposure through ingestion via the food chain. Accident scenarios have particularly severe implications for densely populated locations, where evacuations could prove difficult. Even the remote possibility of a catastrophic accident has limited public acceptance of nuclear power.

3. Waste

The radioactive fuel rods removed from fission reactor cores are considered high-level nuclear waste requiring special handling. When fuel rods are produced, they generally contain over 95% U-238 enriched with less than 5% fissile U-235. Upon removal from the reactor, contents of fuel rods vary primarily depending on initial enrichment level and the length of time in the reactor. Typically, U-238 comprises about 95% of SNF, with U-235 and plutonium at around 1% each. Fission products and minor actinides make up the balance.[10]

In the U.S., most SNF rods are initially stored in pools near the nuclear reactors in which they were used. Water in the pools both cools the rods and provides radiation shielding. Some long-lived fission products and transuranics (elements with atomic numbers beyond uranium) will remain dangerous for many thousands of years. During this time, they must be kept out of the biosphere. While reprocessing could convert much of this hazardous material into new fuel for reactors, it would concentrate fissile material and thus raise proliferation concerns. The long-term plan being pursued for this waste is storage in geologic repositories, although the facility being constructed at Yucca Mountain in Nevada has encountered political opposition and is currently stalled.

Light Water Reactors Summary

While offering a highly reliable, known technology which generates electricity free of CO_2 emissions, light water reactors require fuel enrichment and incentivize both fuel reprocessing and recycling, all of which raise proliferation concerns. There is also concern that a catastrophic accident or a terrorist attack could release dangerous amounts of radioactivity. Lastly, the problem of a large and growing SNF inventory of long-lived radioactive waste is without consensus solution. These problems have driven the lack of public support for increased use of fission power.

B. Fusion Reactors

Fusion reactions were discovered in accelerator experiments in the 1930s. Their study led to Hans Bethe's 1939 explanation of fusion as the energy source powering the sun and all other stars. Bethe later showed that, by several processes, stars convert groups of four protons into single helium-4 nuclei plus 26.8 MeV of released energy. These combined processes yield almost eight times as much energy per unit mass as uranium fission, their hydrogen fusion fuel is *vastly* more available than uranium, and fusion, unlike fission, does not produce any high-level radioactive waste.

However, such fusion processes involving the protium isotope of hydrogen proceed far too slowly to be useful in machines. The bottleneck is beta decay. Fusion reactions of deuterium avoid protium's beta decay issues, yielding larger effective cross sections. (Nuclear cross sections quantify the probability of a reaction occurring. The larger the cross section, the greater the probability.) Deuterium, which is present worldwide as one out of every 6,700 hydrogen atoms, i.e., $4 * 10^{16}$ kg in Earth's oceans, is vastly more common than uranium or thorium. All fusion reactions with cross sections large enough to consider for energy production involve deuterium or its immediate fusion reaction products. The fusion cross section for the deuterium + tritium (DT) reaction is much larger than other fusion cross sections, larger by about two orders

of magnitude. For this reason, most fusion research has pursued the DT fusion reaction. While deuterium can easily be extracted from seawater, tritium to fuel the reaction must be bred via neutron absorption by lithium-6.

Fusion reactors are inherently different from fission reactors in that they require considerable effort to create and maintain the unearthly conditions needed. Fission systems will react at ambient temperature and pressure if fissile material is simply assembled into a critical geometry. Typical fission engineering concerns are controlling the fission reaction, removing heat for thermal energy conversion, shielding radiations and containing radioactive byproducts. In contrast, fusion fuel must be heated to incredible temperatures, then held together under sufficient pressure and for sufficient time for net fusion energy to be released. Fusion reactors need a substantial power investment for heating and confinement, requiring that some of the electric power produced be fed back to operate the reactor.

An important fusion figure of merit is the energy gain ratio, Q, which is the ratio of fusion energy released divided by external heating energy invested. To date, the best controlled fusion gain performance has been realized with steady magnetic confinement using tokamaks, fusion devices which hold plasmas in torus (doughnut) shaped vacuum vessels at temperatures exceeding 100 million degrees Celsius. Record Q values reached to date are Q=0.3, first achieved during a one-second pulse in 1993 in the Tokamak Fusion Test Reactor, then located at Princeton Plasma Physics Laboratory (PPPL) in New Jersey; and Q=0.67, achieved in 1997 at the Joint European Torus (JET) near Oxford, England.[11] It is hoped that soon after the International Tokamak Experimental Reactor (ITER) is completed and DT operations (now scheduled for 2035) begin, ITER will achieve its goal of demonstrating Q=10 operation for greatly increased pulse times.[12]

Fusion Reactors Summary

While much has been learned about harnessing fusion power, after more than sixty years of research, there are still no controlled thermonuclear fusion reactors able to return more energy than the energy investment required to produce the fusion. *Electrical* energy breakeven, which also addresses real inefficiencies of thermal conversion and plasma heating processes, will be even more difficult, and producing electricity for sale will be more difficult still. Fusion reactors promise a virtually limitless supply of clean energy without the high-level radioactive wastes of today's fission plants. While pure fusion power will likely be a key energy source in the long term, *its practical application is at least many decades away, perhaps much more.*

C. Classic Fission-Fusion Hybrid Reactors

Classic Fission-Fusion Hybrid (FFH) reactors have remained in the conceptual stage, much studied but never built. The lack of any suitable fusion neutron source has so far prevented FFH experiments.

Even at the dawn of the nuclear age in 1942, it was well understood that rare U-235 is the only naturally occurring fissile isotope. U-238 is 138 times more abundant, and thorium-232 (Th-232) is about 500 times more abundant. While neither U-238 nor Th-232 can be used to sustain a chain reaction, they can be transmuted to fissile isotopes (Pu-239 and U-233, respectively), that

Transmutation
Transmutation is the production of isotopes by nuclear processes. It is important for actinide isotopes since most are now missing in Earth's crust. In fission reactors, the most common transmutation processes start with radiative capture of a neutron, i.e., an isotope absorbs an incident neutron while simultaneously emitting a gamma ray. The result is a new isotope of the original element, one nucleon heavier than prior to absorbing the neutron. In many cases, the newly formed isotope is unstable to beta decay. When that is the case, neutron absorption is followed by beta decay emission of an electron from the nucleus, occurring over time according to a characteristic half-life, causing the actinide's atomic number (Z) to increase by one, while its neutron number (N) decreases by one, and its mass number (A=Z+N) stays the same. Other transmutation processes include knocking out neutrons from nuclei by irradiating them with particles having more energy than a characteristic threshold. Usually the irradiating particles are high energy neutrons such as the 14.1 MeV neutrons produced by DT fusion or the even higher energy neutrons produced by spallation.

can sustain a chain reaction. Other actinide isotopes exist, some fissile and some merely fissionable, but are not found in nature above trace amounts.

An obvious question for early researchers was how to make use of these naturally abundant fertile actinide isotopes. Two pathways were envisioned:

- Pathway One – Provide an external source of sufficiently energetic neutrons to induce fissions without sustaining a chain reaction.
- Pathway Two – Transmute fertile isotopes into fissile isotopes.

Every critical nuclear fission reactor incorporating either some U-238 or some Th-232 causes the Pathway Two fissile isotope production reactions to occur. The rate of production of new fissile atoms divided by the rate of fissioning fissile atoms is an important reactor parameter termed the Conversion Ratio (CR). In thermal reactor systems, it is difficult for the CR to exceed one (where it would then be referred to as the breeding ratio), since under many conditions, the average number of neutrons released per fission is insufficient to both maintain the fission chain reaction and also produce a replacement fissile nuclide.

In fission chain reactions of U-235 induced by slow, room temperature, low-energy neutrons, there are two or three daughter neutrons typically emitted by each fission with an average of about two-and-a-half. However, the same U-235 nucleus fissioned by a very high energy 14.1 MeV incident neutron releases on average four-and-a-half daughter neutrons, and a U-238 atom fissioned by a 14.1 MeV neutron releases an average of five neutrons. Thus, the energy of incident neutrons inducing fission is significant in determining how many daughter neutrons are released.

Prior FFH studies have proposed *subcritical* hybrid systems in which a source of energetic neutrons would be surrounded by a subcritical blanket containing fertile actinides. The energetic neutrons striking fertile actinides in the blanket would fission some, thus releasing energy along with copious daughter neutrons, which in turn would transmute other fertile actinides into fissile actinides. The reactions are not self-sustaining. Switch off the source of high energy neutrons, and the subcritical fission reactions cease. Electric power could in principle be produced from the thermal energy released. However, in most such studies the hybrid system served as a fissile fuel factory, which would be periodically shut down in order to harvest batches of bred fissile fuel from the subcritical blanket. The harvested fissile fuel could then be chemically processed

into concentrated form for use as fuel in conventional fission reactors. In most such hybrid studies, DT fusion reactions supplied the energetic neutrons. In DT fusion reactions, essentially all neutrons produced would be 14.1 MeV neutrons adequate for Pathway One. In these schemes, however, the fusion system requires external breeding of tritium, which is only achievable by neutron consuming reactions with lithium. *It is important to note that in previously proposed FFH systems, fissions only occur in a subcritical fission blanket*.

While advocates believe the classic FFH concept is a promising approach for both fuel production and waste elimination, skeptics contend that it combines the drawbacks of both fission and fusion. They argue that the FFH retains the proliferation, safety and waste concerns of fission, while introducing the added complexity, large scale and technical difficulty of fusion.[13]

Classic Fission-Fusion Hybrid Reactors Summary

The classic FFH could enable fuller utilization of the energy content of actinides, greatly increasing the fuel supply, and could transmute some long-lived fission products, thereby reducing waste. However, production and transportation of FFH's concentrated fissile fuel would raise the same proliferation and safety concerns as LWRs. In addition, if the energetic neutron source were a DT tokamak, the system would require tritium breeding to fuel the DT reaction.

D. Molten Salt Reactors

Originally designed in the 1950s for the purpose of aircraft propulsion and later envisioned as a breeder reactor, the molten salt reactor (MSR) is a novel type of nuclear fission reactor with liquid fuel. From 1965 through 1969, the Molten Salt Reactor Experiment (MSRE) was operated for more than 17,000 hours at Oak Ridge National Laboratory in Tennessee. The MSR's 700°C heat transfer temperature offers the potential for greater thermal conversion efficiency than the typical LWR. The MSR also has load-following advantages derived from its liquid fuel. MSRs are not subject to core meltdown accidents since, tautologically, their fuel is already melted. Their salts are chemically stable so they cannot burn or explode.

Active MSR research was abandoned in the early 1970s as research focus shifted to alternative reactor designs intended to address anticipated fuel shortages. The MSR's high temperature, corrosive environment presented challenges for the materials and manufacturing processes of the day. An additional concern was that even if the lithium component of the molten salt were depleted in the lithium-6 isotope, the MSR would still produce radioactive tritium as an unwanted byproduct. Lastly, the argument was made that the U.S. did not need to develop competition for its already deployed LWR technology.

There is renewed interest in the MSR. Advances in high-temperature materials for use in reactor components and fission product removal systems, the introduction of high-temperature additive manufacturing techniques, and the development of new corrosion-resistant materials now offer engineering solutions to challenges identified in earlier research.[14] These advances and the safety benefits of mobile fuel have attracted active investigation of this decades-old idea.

Molten Salt Reactors Summary

The MSR with its flowing liquid fuel is an experimentally proven concept offering greater thermal conversion efficiency and increased safety features when compared with LWRs. However, the MSR posed complex engineering and materials challenges when it operated in the 1960s. Research on the MSR was abandoned in the early 1970s, although there has been renewed interest in the MSR in recent years.

II. Solution: The Fission-Fusion Hybrid Molten Salt Reactor

The question then is how to fully utilize abundant, energy-dense, zero-carbon actinide fuel to produce electricity, while avoiding the proliferation, safety and waste issues of today's LWRs. The solution this White Paper proposes is the Fission-Fusion Hybrid Molten Salt Reactor.

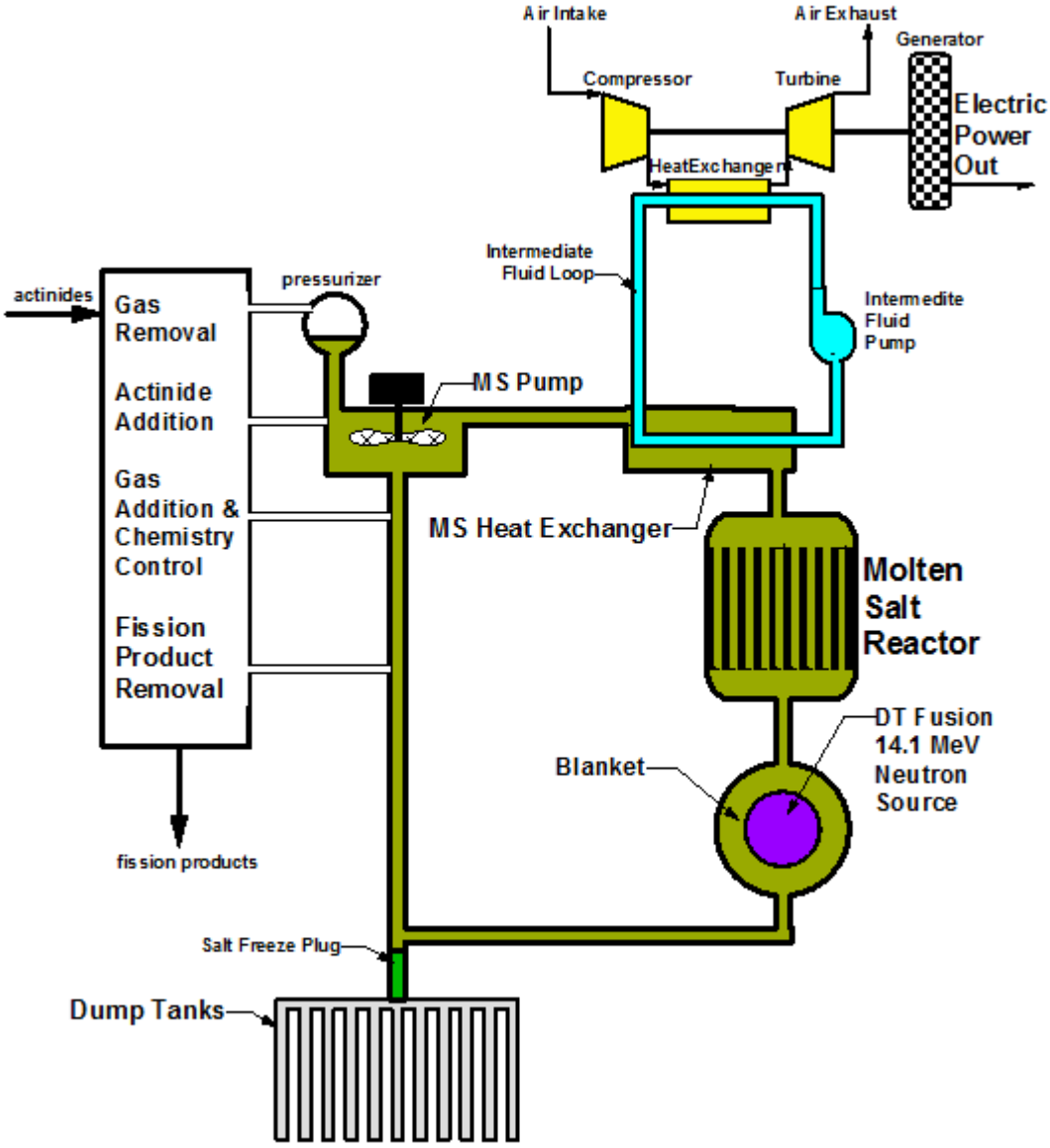
The Fission-Fusion Hybrid Molten Salt Reactor (FFHMSR) is a unique combination of a *critical* fission MSR and an energetic (≥14MeV) neutron source into a single connected system. (Although this concept could utilize spallation, the discussion here is of a DT fusion reactor as the source of energetic neutrons.) The combination confers advantages that neither has independently. The essential concept is to maintain a dynamic balance between nuclear reactions occurring in the molten salt as it flows through the critical MSR and as it flows outside the MSR, where it is irradiated by energetic neutrons. Although some fertile actinides are converted into fissile actinides within the critical MSR, fissile actinide atoms there are fissioned at a faster rate than the MSR can internally breed replacements. Outside of the MSR, irradiation of the molten salt by energetic neutrons causes nuclear reactions that produce new fissile atoms, with the rate of production adjusted to counter the net consumption of fissile atoms within the critical MSR, giving the FFHMSR a breeding ratio of one. The primary advantage is the closing of the nuclear fuel cycle marked by a greatly increased fuel supply and a greatly decreased waste stream, while avoiding the proliferation concerns of both the LWR and the FFH.

A. FFHMSR Configuration

A conventional MSR system includes three of the four components depicted in the diagram of the molten salt flow loop, i.e., the reactor, the heat exchanger and the pump. It becomes an FFHMSR with the addition to the loop of a fourth component, the DT Fusion Reactor, surrounded by a molten salt blanket irradiated by the produced DT neutrons.

The important feature is that fission fuels and products dissolved in a molten salt carrier can flow into and out of a blanket of tanks almost completely surrounding the fusion reaction zone, and that the molten salt is irradiated there by an unmoderated hard spectrum of 14.1 MeV neutrons generated by DT fusion. To balance fissile isotope production with consumption, fertile isotopes such as U-238 or Th-232 would be present in greater concentration than fissile isotopes. The fusion blanket tanks remain deeply subcritical so little fissile fuel will fission there. The fast fission of non-fissile actinides that does occur there releases fission daughter neutrons to be absorbed, thus eventually producing more fissile actinides. Molten salt blanket heating will be determined by the fusion power level and the blanket's subcritical power multiplier, so blanket power may fluctuate over time if the DT fusion reactor device relies on a pulsed design.

Fission-Fusion Hybrid Molten Salt Reactor (FFHMSR)



Molten salt exiting the fusion blanket and flowing into the critical molten salt fission reactor may have a fluctuating temperature. However, most of the plant's thermal power will be generated by fission in this MSR core zone which will have a critical geometry and graphite moderator, giving it a soft epithermal or thermal neutron energy spectrum. Since molten salt density decreases with increasing temperature, the quantity of fissile fuel present in the core zone also changes with temperature, thus causing fission power to naturally increase or decrease as needed to regulate the MSR core salt temperature at an approximately constant value. This reduces temperature fluctuations in the salt as it flows out of the MSR core into the heat exchanger. Thus, fusion and fission power levels are *not instantaneously coupled* as they would unavoidably be in an entirely subcritical hybrid scheme. Their power levels can vary independently over the short term. The

molten salt reactor portion of the plant compensates for time-varying fusion power production in addition to naturally following any fluctuations in load demand. Over longer time intervals, average fission and fusion power levels must be coordinated to maintain the inventory of fissile fuel bred from fertile fuel and also maintain progress on transmutation of long-lived fission wastes.

The MSR uses a low absorption moderator to achieve a thermalized neutron energy spectrum criticality with a low fissile inventory and a high CR. Graphite can satisfy these moderator requirements, hence the MSR is shown in the diagram with black bands. The heat exchanger transferring heat from the molten salt to an intermediate heat transfer fluid not containing actinides is essential, as is the molten salt loop's circulating pump. In the depicted configuration with heat removal shown at the top right corner of the molten salt loop, natural convection would circulate the molten salt at some rate even if the molten salt circulating pump were to fail, provided the intermediate fluid were kept colder than the molten salt. With proper choice of loop dimensions, this natural convection rate could safely accommodate decay afterheat in the event of pump failure.

The diagram depicts subcritical molten salt dump tanks at the bottom. These function as an additional MSR safety feature. In an emergency, all molten salt would drain into the dump tanks, where criticality is impossible and where passive features (not shown) would cool the salts by transferring afterheat from fission product decays to external air. If the temperature were to exceed a safety threshold, the salt freeze plug would initiate flow to the dump tanks simply by melting.

The diagram also depicts a gas volume in a pressurizer structure located at the highest point in the molten salt loop. This gas volume is necessary to avoid pressure spikes as the volume of the molten salt liquid contracts or expands due to transient temperature changes. It also provides a single location for gas bubbles to collect for extraction.

With any MSR, there must be subsystems that measure and control the chemistry of the liquid mixture and allow for the addition and removal of gases. In the FFHMSR, chemistry control features also include the continuous removal of *accumulating* fission products and the addition of fresh actinides to replace fissioned actinides. Special separation equipment must continually remove selected fission products and other elements from the primary molten salt loop. For different species, separations may function based on principles of sparging with gas bubbles, centrifugal separation by density, filtration, pressure changes, temperature changes, chemical reactions, electrochemical reactions, or by combinations of these or other techniques.

Tritium must be bred from neutrons reacting with lithium in order to fuel the DT fusion reactor. This may best be accomplished by making lithium a component of the molten salt, in which case, the tritium breeding rate can be adjusted by changing the isotopic ratio of lithium-6 to lithium-7. Bred tritium would be recovered from the molten salt along with other hydrogen gases, then separated from the other isotopes by cryogenic distillation. Since hydrogen isotopes diffuse through hot metal walls, tritium containment may require use of double walls with helium flowing between them, with the helium continuously scrubbed to limit tritium partial pressure.

Fission Products
Fission products referred to are those fragments emerging directly from fissions of fuel atom nuclei that become new atoms. Neutrons and gamma rays also emerge directly from fissions, but are not referred to as fission products because they do not become new atoms. Fission events split fuel nuclei in many different ways, randomly distributed in accordance with an empirical fission yield curve. This fission yield curve is slightly different for different isotopes, but in all cases is bimodal. The yield curve is nonzero for fission product elements ranging from the lower atomic number Z=28 (nickel, as in the nickel-72 isotope) to the higher atomic number Z=68 (erbium, as in the erbium-167 isotope). There are also very small fission yields of atomic numbers Z=1 (tritium) and Z=2 (helium-3 and helium-4) which result from the 0.3% of fissions that are ternary. These fission products, (atomic numbers 1, 2, and 28 through 68 inclusive) are the chemical elements that could be continuously removed from the molten salt in this proposed hybrid reactor. None of these fission products can be used to fuel either fission reactors or explosives.

There are several different options for the thermal conversion system which accepts heat from the intermediate fluid, converts a fraction (the efficiency) into mechanical work driving an electrical generator and transfers the remaining waste heat into the atmosphere. The particular thermal conversion subsystem depicted uses the Open Brayton Cycle. This is the simplest and lowest cost scheme, requiring only a turbine and compressor mounted on a single rotating shaft along with an electrical generator. It also does not require a water cooling tower for heat rejection and can obtain acceptable conversion efficiency by using the high temperature heat produced by an MSR. Higher conversion efficiencies could be obtained using Closed Brayton Cycle systems, albeit with more complexity and higher capital cost.

For simplicity, the diagram omits certain subsystems that would be included as part of the design. For instance, electrical heaters must be distributed around salt loops for initial heating and for recovering from any freeze-up events. There must be electrical heaters on dump tanks and also pumps and plumbing to return molten salt from the dump tanks to the molten salt loop for restart. There must also be means to add or remove molten salt within the loop and provisions for its external storage

B. Source of Energetic Neutrons

An energetic neutron source suitable for the FFHMSR has never been built. A pure fusion energy reactor producing more electricity than it consumes may be very far in the future. However, current knowledge of fusion science could be applied to energy production in the relatively near future with the FFHMSR. Construction of an energetic neutron source would be an extension of current designs and technology.

A DT fusion neutron source for the FFHMSR would have more relaxed requirements than would a pure fusion energy reactor, including:

1) The DT fusion neutron source may be pulsed or intermittent without affecting production of output electricity, compared with the steady or rapidly pulsed operations required for pure fusion electricity production.

2) The DT fusion neutron source need not internally achieve tritium-breeding self-sufficiency. Most of the tritium-breeding neutron captures would occur in the critical fission MSR.

3) The DT fusion neutron source need only produce a fraction of the electric power that it consumes. The Q=0.65 energy gains achieved at JET in 1997 would be sufficient for the FFHMSR, although a higher gain would be better. The MSR would subsidize neutron source energy requirements. *The contribution of the neutron source to the FFHMSR is not to the increase of system power. The contribution of the neutron source is to the increase of system neutrons.*

C. Benefits of the FFHMSR

Proliferation Benefits

The FFHMSR's combination of an MSR with an energetic neutron source provides a complete shift in the basis for considering proliferation issues. Fuel enrichment facilities would be *entirely eliminated* for civilian nuclear power. The FFHMSR accepts actinide fuel having fissile content that is either extremely low or nonexistent. Adequate fissile material for criticality is maintained by irradiation of the molten salt with DT fusion neutrons, while actinides with low or zero fissile content are added at the same rate that actinides are fissioned.

Whereas solid SNF is primarily composed of unfissioned actinides, actinides are never extracted from the FFHMSR's molten fuel since they are completely fissioned. Thus, the FFHMSR would also eliminate fuel reprocessing plants, another major proliferation concern. The SNF theft hazard arises because solid SNF contains actinides, such as plutonium, which might be used to fuel weapons if the fissile-to-nonfissile ratio of actinides in it were sufficiently high. The FFHMSR waste stream, however, contains no actinides. Without fuel reprocessing and fabrication facilities, the risk of fuel diversion during transportation would also be eliminated.

Since FFHMSR actinides would never be removed, there would be no need for actinide removal equipment on site. The presence of such equipment could be discovered during careful inspections by international observers. In addition, if an FFHMSR were operated steadily for long periods without actinide removal, fissile isotopes would be denatured by larger quantities of non-fissile isotopes of the same chemical element. Nuclear explosives could not be made without further isotopic separation. It would be far simpler for a proliferator to isotopically separate natural uranium than to separate the extremely radioactive mixture taken from an FFHMSR, since natural uranium's radioactivity is low enough to avoid the complexities of remote handling equipment.

Safety Benefits

The FFHMSR would inherit the MSR's many safety features. The most striking characteristic of MSRs is that their fuels are liquid and thus can be made to flow. This confers several safety advantages:

1) A strongly negative temperature coefficient resulting from thermal expansion of mobile liquid fuel enhances stability and safety. Thermal expansion of the liquid fuel as power and temperature increase can force liquid to leave the moderated reaction chamber, carrying out fissile material, thereby reducing reactivity and slowing the chain reaction.

2) Liquid fuel can be moved by gravity from the reactor core to passively cooled dump tanks in an emergency.

3) External cooling becomes possible because of fuel flow. Heat can be removed in heat exchangers located outside the critical core region – away from where the fission chain reaction occurs – instead of using space within the reactor core for heat transfer to a coolant, as is required for all solid fuel designs.

4) No solid fuel fabrication is needed, simplifying the fuel cycle and improving proliferation resistance.

5) Delicate solid fission fuel and cladding structures, vulnerable to meltdown damage in LWRs, are eliminated.

6) Damage to solid fuel is eliminated, since ionic liquids have no structure to damage.

7) Accumulating fission products can be continuously removed and make-up fuel added while operating, eliminating the need for the refueling outages of batch-fueled LWRs.

8) A low radioactivity source term for accident releases can be achieved by the continuous removal of fission products from the molten salt, thus maintaining a low fission product inventory in the MSR. This safety feature is impossible with solid fuels.

9) Low reactivity margins for criticality optimized designs are feasible, thus reducing the extent of worst-case criticality excursions. This safety feature, made possible by continuous refueling, is impossible with solid fuels that must carry enough excess initial reactivity to maintain criticality throughout the intervals between refueling outages.

10. While the benefit of the increased cost would require evaluation, undergrounding of the reactor with above-ground heat exchange could be adopted to provide an additional barrier to slow radioactivity release in the event of an accident.

Waste Benefits

Due to its energetic neutron source, the FFHMSR represents a paradigm shift for radioactive fission waste since much of what has been considered waste becomes fuel. All actinides supplied to an FFHMSR can be fissioned within it, leaving only fission products as waste. Spent nuclear fuel from LWRs, which primarily consists of unfissioned actinides, can be processed to molten salt form and then fed into an FFHMSR as its fuel feedstock. Since actinides typically comprise over 95% of SNF, elimination of actinides from the waste stream would greatly reduce the amount and long-term radioactivity of civilian reactor waste.

In addition to actinides, SNF contains a much smaller quantity of radioactive fission products. Unlike actinides, most fission product isotopes decay to stable states too rapidly to constitute any long-term waste problem. Only seven fission product isotopes are truly long-term issues with half-lives ranging from 0.2 million years to 15.7 million years. All other fission products have half-lives shorter than a century. The remaining medium-lived fission products' steady inventories are all small except for strontium-90 and cesium-137. Some of the seven very long half-life fission product isotopes, e.g., technetium-99 and iodine-129, are transmuted easily by

neutron reactions in the thermal spectrum portion of the FFHMSR. If the DT fusion power portion were increased and some isotopic separation were selectively used, it *may* also be feasible to transmute the remaining long-lived fission products together with strontium-90 and cesium-137. Although that has not been demonstrated, this approach could potentially eliminate remaining long-term radioactive waste disposal issues.

Energy Utilization Benefits

The energetic neutron source also enables the consumption of all uranium and its transmutation products by fission instead of the approximately 1% now fissioned in LWRs, thus increasing energy utilization by two orders of magnitude. Thorium, present in Earth's crust at 3.5 times the abundance of uranium, can, along with its transmutation products, also be fully consumed by fission in an FFHMSR.

Fission-Fusion Hybrid Molten Salt Reactor Summary

The FFHMSR is a combination of a critical fission MSR and an energetic (≥14MeV) DT fusion neutron source into a single connected system. The MSR would rely on prior experimental designs updated with new materials and methods. The energetic neutron source would build upon knowledge gained over decades of fusion experimentation. DT fusion system requirements would be relaxed from those needed for pure fusion, with already-demonstrated energy gains sufficient for this application. The FFHMSR would inherit the MSR's improved safety features, with the source of energetic neutrons adding waste elimination and fuel utilization benefits along with improved proliferation resistance.

III. Steps to FFHMSR Deployment

Although the FFHMSR is currently a conceptual design, the technical capability needed to implement it is almost within reach. No fundamental scientific research is needed, as is the case with pure fusion. All that remains could be accomplished as part of an aggressive engineering development program. Its five components, which could be pursued simultaneously, are as follows:

1. Develop a suitable DT fusion neutron source of either frequently pulsed or steady state operation with the focus on reliability and cost.
2. Develop extraction systems for all *accumulating* fission products.
3. Develop robotic replacement of the fusion chamber's solid first-wall components and recycling/manufacturing facilities for first-wall molten salt tanks and plumbing.
4. Upgrade engineering analysis tools and data.
5. Complete all systems studies and optimize the FFHMSR design.

First, it is necessary to develop a reliable DT fusion neutron source operating at plasma Q levels and total power levels that have already been transiently created in fusion experiments with tokamaks. Study results indicate that the *fusion power* required could be well less than one percent of *fission power* produced.[15] It is only necessary to reduce the total electrical energy consumption by the fusion neutron source to be about ten times the *fusion* power produced, although less would be better. In addition, it is not essential that the fusion neutron source operate steadily, although it is necessary that the time intervals between pulsed fusion operations

be short enough that the molten salt's fissile inventory remains sufficient to maintain MSR criticality. The permissible fusion intermittency time is design-dependent, but would be measured in days. It is not necessary that tritium for the DT fusion neutron source be bred within the fusion subsystem. Tritium would be bred throughout the FFHMSR from neutron absorption by lithium in the molten salt, with most occurring within the critical MSR where most neutrons are released. Also, unlike with pure fusion, it is not necessary for the fusion power density to be high, since most system power is produced in the MSR portion of the FFHMSR.

Minimizing cost is a major neutron source design goal. This constraint likely dictates a small physical size. The neutron source may match some of the characteristics of the neutral-beam-driven Spherical Torus (ST) magnetic confinement concept. An ST is a tokamak that appears almost spherical due to its low aspect ratio. The main attraction of the ST configuration is that its plasma pressure can stably be an order of magnitude larger fraction of its magnetic pressure than that of a tokamak with a conventional aspect ratio. PPPL has done work to develop DT fusion neutron source designs for a materials testing device in support of the pure fusion program. This work may have useful application for the FFHMSR's fusion neutron source.[16]

A conceptual design layout for a DT fusion neutron source in which novel synergistic features are combined to reduce device size and to simplify maintenance, thus limiting cost, is presented in the attached Appendix. Special features proposed include:

a. low aspect ratio plasma
b. structural optimization, including constant-tension straps connected to structural rings
c. high-radiation resistant all-metal magnet windings, which also provide radiation shielding
d. high temperature superconductor magnet windings
e. demountable winding joints.

Second, it is necessary to further develop chemical separation technologies for continuous online removal of each type of *accumulating* fission product, while leaving all actinides in the molten salt. Techniques already developed in conjunction with the MSRE can be refined and extended using advances in high-temperature materials, corrosion-resistant materials, and high-temperature additive manufacturing developed since the MSRE project ended, and new techniques can be explored. Development of fission product removal systems could proceed in engineering laboratories apart from the fission or fusion subsystems. These systems could be fully tested without using highly radioactive isotopes.

Third, instead of waiting for the unlikely discovery of new solid materials able to withstand years of continuous first-wall bombardment by 14.1 MeV DT fusion neutrons, engineers should develop designs for rapid, remote-handling replacement of fusion blanket tanks and pipes made of a molten-salt-compatible alloy.

The fields of additive and robotic manufacturing, as well as remote handling, have advanced greatly since the MSRE was designed in the early 1960s. The FFHMSR design should take advantage of these advances by periodically replacing damage-prone components and doing so quickly using robotics. If a metal alloy is used to contain the DT fusion blanket, engineering designs should be developed to melt the activated, neutron-damaged blanket tanks, thus entirely

erasing their accumulated materials damage. The molten metal would be robotically re-manufactured into new tanks and pipes that would then be installed during the next brief maintenance interval. Graphite could be superior as a molten salt container material because of its chemical compatibility and higher temperature capability, however, issues of brittleness and of leak-proof assembly would need to be fully resolved. The robotic replacement scheme has the additional benefit that, if and when improved materials were developed, they could easily be introduced into the system.

Fourth, the upgrading of engineering information and tools would be helpful in at least two areas. It would be useful to develop modified versions of SCALE (Standardized Computer Analyses for Licensing Evaluations) codes, such as ORIGEN (Oak Ridge Isotope Generation code) that are better suited for nuclear engineering studies of FFHMSR operations. It would also be useful to complete the phase diagram characterization of mixtures of the fluoride salts for the actinides important for this application, as well as for lithium fluoride and sodium fluoride. Although the equilibrium inventories of fission products that are dissolved in the molten salt will be kept small by the continuously operating fission product removal systems, it is important to measure the solubility limits for each fission product element over the operating temperature range.

Fifth, there should be a full complement of systems studies followed by the development of an optimized design that would then be extended into a detailed design. The systems studies should begin by varying design parameters to quantify their effects. Details not yet examined should be studied – such as the effects of liquid fuel circulation rate on delayed neutrons, on feedback control (in which control rods are modeled), and on isotope transmutation. Safety issues should also be studied, with postulated off-normal events simulated to identify the adequacy of engineered safety features. These are standard activities done for every new reactor system.

IV. Fission-Fusion Hybrid Molten Salt Reactor - Conclusion

The FFHMSR is an advanced unconventional nuclear reactor concept whose single, liquid-fuel loop combines critical fission in a thermal spectrum MSR with a driven source of fusion neutrons having energies an order of magnitude above the fission spectrum. Its resulting bimodal effective spectrum allows a low fissile inventory while fissioning any actinide mix, including spent nuclear fuel, depleted uranium, natural uranium or thorium. When further combined with continuous fission product removal and fuel addition, resource utilization rises to 100%, while actinides are entirely eliminated from the waste stream. Fuel enrichment and recycling become unnecessary, enhancing proliferation resistance and safety. Key to the FFHMSR is its DT fusion source of energetic neutrons, which could function with already-demonstrated fusion performance. *By combining fission and fusion, with each doing what it does best, the Fission-Fusion Hybrid Molten Salt Reactor can be developed now for near term deployment.*

List of Abbreviations

A	Atomic mass; number of nucleons – the total number of protons and neutrons in the nucleus of an atom
CO_2	Carbon dioxide
CR	Conversion Ratio
DT	Deuterium + Tritium
eV	Electron volt
FFH	Fission-Fusion Hybrid
FFHMSR	Fission-Fusion Hybrid Molten Salt Reactor
ITER	International Tokamak Experimental Reactor
JET	Joint European Torus
kWh	Kilowatt hour
LWR	Light water reactor
MeV	Mega (million) electron-volts
MSR	Molten salt reactor
MSRE	Molten Salt Reactor Experiment
N	Number of neutrons in an atom
PPPL	Princeton Plasma Physics Laboratory
PU-239	Plutonium-239
Q	Energy gain ration; Ratio of fusion energy released divided by external heat invested
SNF	Spent nuclear fuel
ST	Spherical Torus
Th-232	Thorium -232
U-235	Uranium-235
U-238	Uranium-238
Z	Atomic number (also known as the proton number); the atomic number uniquely identifies a chemical element

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About the Originator of the Fission-Fusion Hybrid Molten Salt Reactor Concept

Robert D. Woolley recognized the potential of combining two existing concepts into the Fission-Fusion Hybrid Molten Salt Reactor due in part to his unconventional background. A lifelong student, he earned a Bachelor of Science degree in Electrical Engineering; Masters of Science degrees in Electrical Engineering, Applied Mathematics, and Nuclear Engineering; and a Ph.D. in Nuclear Engineering. In addition to his degree work, his transcript boasts more than 60 graduate-level course credits in physics, mathematics and engineering earned at Princeton University while he was employed there.

His early engineering career included developing military avionics and spacecraft controls, providing spacecraft attitude and orbit control services for NASA, as well as designing reactor controls for nuclear steam supply systems. From 1976 to 2016, he was employed by the Princeton Plasma Physics Laboratory, a national laboratory engaged in thermonuclear fusion research operated by Princeton University for the Department of Energy. He was named a Distinguished Engineering Fellow in June 1996 for work that enabled the Tokamak Fusion Test Reactor to safely operate beyond original design specifications, thereby recording its best experimental results.

He was granted three fusion-related U.S. patents during the course of his work at PPPL:

1. Patent No. 5,804,965 – Method and apparatus for steady-state magnetic measurement of poloidal magnetic field near a tokamak plasma.
2. Patent No. 5,991,351 – Method and system to directly produce electrical power within the lithium blanket region of a magnetically confined, deuterium-tritium (DT) fueled, thermonuclear fusion reactor.
3. Patent No. 6,411,666 – Method and apparatus to produce and maintain a thick, flowing, liquid lithium first wall for toroidal magnetic confinement DT fusion reactors.

Dr. Woolley was granted a fourth U.S. patent, Patent No. 9,368,244 – Hybrid Molten Salt Reactor with Energetic Neutron Source, on June 14, 2016, for the independent work described in this White Paper.

Appendix A:

A Fusion-Fission Implementation of the Hybrid Molten Salt Reactor (HMSR)

January 2016

A Fusion-Fission Implementation of the Hybrid Molten Salt Reactor (HMSR) *

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The Hybrid Molten Salt Reactor (HMSR) is an advanced unconventional nuclear reactor concept whose single liquid fuel loop combines critical fission in a thermal spectrum molten salt reactor (MSR) with a driven source of fusion or spallation neutrons having energies an order of magnitude above the fission spectrum. Its resulting bimodal effective spectrum allows a low fissile inventory, while fissioning any actinide mix including spent nuclear fuel, depleted uranium, natural uranium or thorium. When further combined with continuous fission product removal and fuel addition, resource utilization rises to 100%, while actinides are entirely eliminated from the radioactive waste stream and both fuel enrichment and fuel recycling become unnecessary. Key to the HMSR is its energetic neutron source. Simulations show that average energetic neutron power for steady fixed-point system operation, in which the entire blend of dissolved isotopes remains constant over time, can be less than 1% of total plant power. This fact may allow near-term HMSR deployment using already-demonstrated fusion performance. This paper proposes an implementation of the energetic neutron source tailored to the HMSR application using presently existing fusion technology. It is a tokamak which repetitively and with high duty cycle generates pulsed DT plasmas heated to thermonuclear fusion temperatures by neutral beams.

I. INTRODUCTION TO THE HMSR

The HMSR configuration[1,2] is depicted in Fig.1. It differs from other hybrid concepts in that it contains a critical fission reactor. This includes the conventional features of an MSR such as the vessel in which the critical fission reaction occurs, a loop of pipes in which the fuel circulates, a heat exchanger removing heat from the circulating liquid fuel for transfer to an energy conversion system, a fuel circulating pump, and equipment for chemically processing, pressurizing, and safely removing the fuel in the event of an emergency. In addition, the HMSR also includes a region in which the fuel, circulating through a blanket of tanks, is irradiated by an enclosed non-fission source of very energetic neutrons.

Benefits of the HMSR include its consuming all actinides and some long-lived fission products (FPs) such that waste issues are ameliorated, while available fission energy is increased by two orders of magnitude. Proliferation resistance is enhanced by eliminating the need for fuel enrichment, by the absence of fuel reprocessing and related transportation, by low fissile inventories and by the HMSR's inherent denaturing of fissile by non-fissile isotopes. Safety is enhanced by liquid fuel characteristics allowing emergency draining of fuel to a passively cooled safe location and by providing a stronger negative power coefficient than feasible with solid fuel.

The HMSR concept differs from existing fission reactors in two major ways. First, it implements its critical fission reactor as a continuous flow process instead of as a batch process. Second, it incorporates a driven source of non-fission neutrons having a mean energy well above the fission spectrum. Each of these departures from current fission reactor practice carries profound implications. Although their synergies are best when combined, it is useful to introduce and discuss them separately.

I.A. Transition from Batch to Continuous Flow

Switching from batch process to continuous flow fission reactors is a major paradigm shift. To date, all fission reactors have operated in batch mode between refueling outages. Continuous flow reactors will operate steadily without refueling outages, generating no "spent fuel" to be reprocessed into both a fuel recycle component and a geological repository waste component.

I.A.1. Batch Mode

The familiar batch mode refueling cycle is paced by two phenomena. Fission causes swelling and material damage to the solid fuel matrix by increasing the number of atoms while introducing some gaseous atoms, thus eventually compromising physical integrity. Second, the depletion of fissile isotopes and the accumulation of neutron absorbing fission product isotopes in the solid fuel eventually cause loss of reactor criticality. Both phenomena are acceptably limited by restricting the operating time between batch refueling intervals.

A familiar aspect of conventional batch mode reactor operation is that sufficient surplus reactivity must be provided initially after a refueling shutdown to provide criticality throughout the subsequent reactor operating period. That excess reactivity must also be compensated by providing additional neutron absorption to cancel it.[1]

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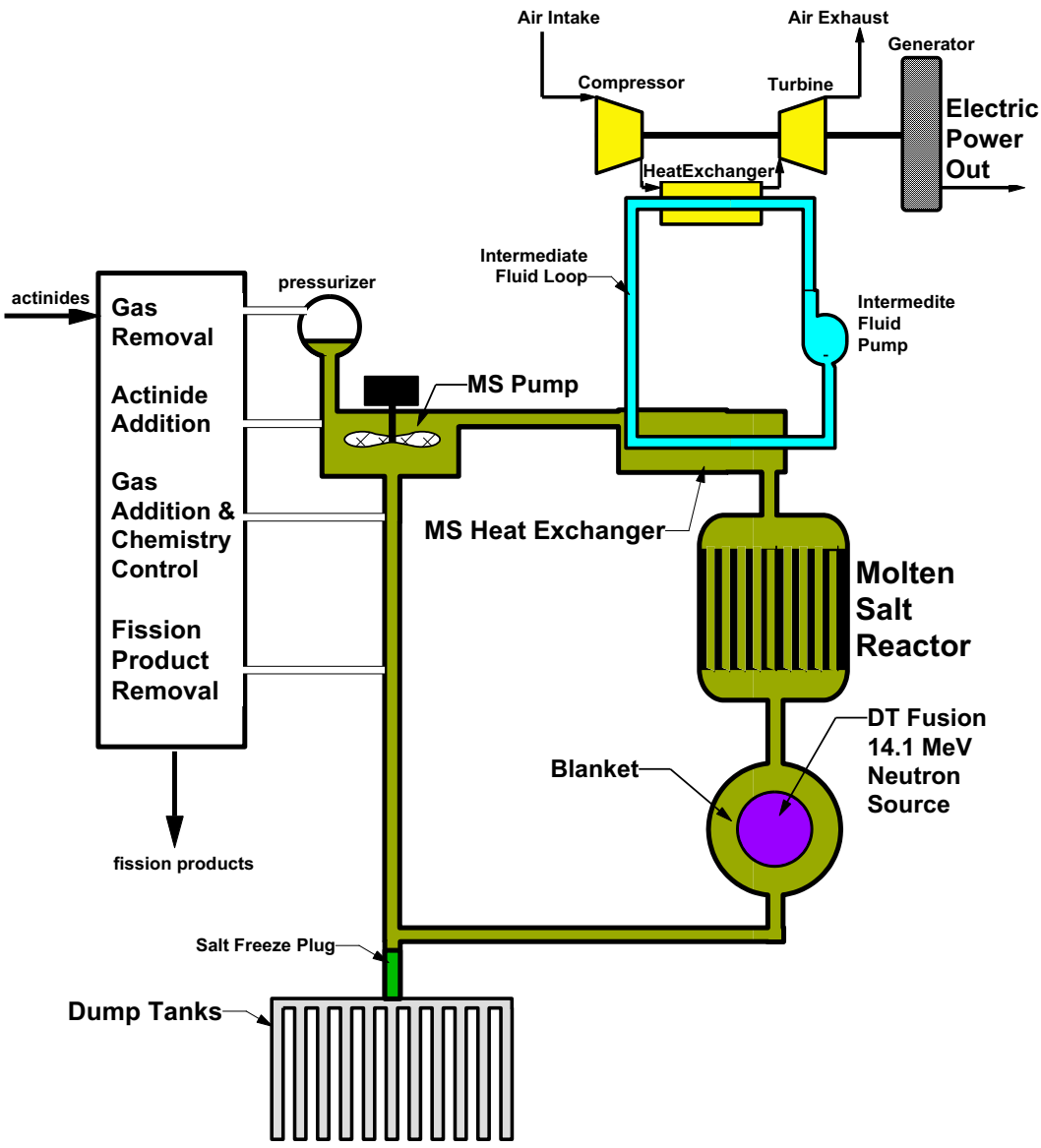

Fig. 1. Hybrid Molten Salt Reactor (HMSR) Configuration

Spent solid fuel removed in batch operations contains a variety of isotopes, both actinides and fission products in addition to transmuted isotopes from other ingredients such as cladding structures. The spent fuel contents are uncontrolled in that whatever isotopes happen to be present in the spent fuel are removed together from the reactor. The actinides in spent fuel are different from the fission products in that all actinides can, in principle, still be fissioned, thus releasing substantial additional energy. Fission products cannot be fissioned again and carry relatively little additional energy in their radioactivity. They are also different in that most unfissioned actinides will remain radioactive far longer than most fission products. Both must be isolated until no longer dangerous, but most fission products have relatively short half-lives, so secure isolation storage for a few centuries, which clearly is feasible using existing technology, would be adequate.

It can be economical to improve energy utilization by separating some actinides from the batch mode's spent fuel for recycling into fresh solid fuel, especially those actinides with a substantial fissile isotope fraction. Other actinides cannot be economically recycled so must be securely isolated as hazardous radioactive waste. Since most have very long half-lives, their isolation requires a geological repository secure on the multi-million year time-scale. However, it should be understood that the need for such a geologic repository for actinides is a consequence of the present batch mode operation of fission reactors, and that this need disappears with the switch to continuous flow reactors.

There are also proliferation concerns that spent fuel from batch operations might be a source of fissile actinides suitable for constructing a fission explosive weapon. If any actinide in spent fuel has a high ratio of fissile to non-fissile isotopes, then it may be a potential proliferation vulnerability. This concern further extends to recycled fuel, which if diverted and chemically separated might provide concentrated fissile materials.

I.A.2 Conversion Ratio (CR):

Critical fission reactors which include both fissile and non-fissile actinide isotopes transmute non-fissile to fissile isotopes by radiative neutron capture. For example, capture of a neutron by non-fissile thorium-232 results in fissile uranium-233, or capture of a neutron by non-fissile uranium-238 results in fissile plutonium-239. These processes are characterized by the Conversion Ratio, (CR), the ratio of the reactor's total net rate of fissile atom production to its total net rate of fissile atom consumption. The (CR) value reflects the extra neutrons released per fission beyond those needed to maintain the critical chain reaction. It is traditional to rename this as the Breeding Ratio (BR) if it equals or exceeds unity. Typical (CR) values are 0.6 for light water reactors and 0.8 for high temperature gas-cooled reactors.

It is easy to show that for values of (CR) <1, adding a quantity of fissile material, f, supports reactor fissioning of the larger quantity of material, f/[1-(CR)]. For instance, a (CR) value of 0.9 extends added fissile fuel material tenfold. However, some of the advantage of this potentially large factor is lost in batch operated reactors without recycling, since refueling entirely removes the fissile isotopes accumulated in spent fuel from the reactor.

The (CR) value is affected by neutron losses through leakage and absorption, so it depends on reactor geometry and composition. The (CR) value is maximized by choosing a large physical reactor size minimizing neutron leakage and choosing low absorption structural and moderator materials such as graphite or a compound containing deuterium.

In batch-operated reactors, the (CR) value typically changes over time, but in continuously operating reactors operating at a steady fixed-point, the (CR) value will remain constant.

1.A.3 Continuous flow fission reactors

MSRs can in principle operate in a continuous flow mode instead of batch mode. Ionic liquids have no internal solid structure to damage so are impervious to radiation and to fission. Therefore, molten salt liquid fuel never requires refueling replacement to limit any materials damage to it.

Concerning the loss of criticality that also paces batch operations, it is straight-forward that a feedstock of fresh actinide fuel can be continuously added to a circulating molten salt liquid. This capability of continuous fueling, not available with solid fuel reactors, becomes possible by using circulating liquid fuel.

A less trivial advance is that fission products can be continuously removed from liquid fuel by special engineered removal systems so that they never build up past fixed steady equilibrium concentrations. Noble gas fission products such as xenon-135 simply bubble out of the liquid fuel instead of accumulating, as was observed in historical experiments with molten salt reactors. Continuous removal of other fission products will require more sophisticated removal systems which appear feasible but have not yet been demonstrated. For continuous flow reactors, fission product concentrations in the liquid fuel must be kept low enough that reactor criticality is not compromised. Steady fission product concentrations clearly depend on the intensity with which the engineered removal systems are operated, so trade-off studies will be needed to optimize their designs.

Continuous operation implies never removing an uncontrolled "spent fuel" mix of radioactive wastes. Continuous material removals are all deliberate and controlled. Actinides go in but never come out, so actinides requiring geologic repository disposal can be entirely eliminated from the waste stream. Since the actinide fuel feedstock is entirely fissioned, its energy utilization becomes 100%. With no actinides in the waste stream, fuel recycling and weapons proliferation concerns associated with fuel recycling are eliminated.

Consider a large uranium-fueled MSR with a (CR) value of 0.9 operated with a continuously added fuel feedstock enriched to 10% uranium-235, 90% uranium-238, and with continuous removal of all fission products fast enough to keep FP concentrations low. Then the factor, f/[1-(CR)], ensures that all of the uranium-238 content would be internally converted through neutron captures before being fully consumed through fission, along with the uranium-235. There would be no actinide wastes from this continuous flow reactor system.

On the other hand, the isotopic separation enrichment operation producing the 10% enriched uranium fuel feedstock would still leave most of the mined uranium content unused, as depleted uranium.

I.B. Addition of Non-fission neutrons

An external source of neutrons irradiating the circulating liquid fuel can cause additional radiative captures transmuting non-fissile actinide isotopes to fissile isotopes. Continuing to consider the case of a (CR)=0.9 continuous flow MSR, if such captures by non-fissile actinides proceeded at a rate 10% of the MSR's total fission rate, then the feedstock of fresh fuel could be pure uranium-238 having no fissile content whatsoever. In effect, the additional source neutrons would have

boosted the continuous flow reactor system to the threshold of breeding.

With fresh actinide fuel from a specified fuel feedstock mixture continuously added to the circulating liquid fuel and with fission products continuously removed, the mix of dissolved isotopes in the liquid evolves over time according to a nonlinear vector differential equation modeling reactor neutronics, nuclear reaction rates, fission product removal rates and actinide addition rates.

$$\frac{d}{dt}\underline{N}(t) = \underline{f}(\underline{N}) = P_{fusion}\underline{f}_{fusion}(\underline{N}) + P_{MSR}\underline{f}_{MSR}(\underline{N}) + \underline{f}_{decay}(\underline{N}) + \underline{B}(t) - \underline{\underline{R}}\underline{N}(t) \quad (1)$$

Here, $\underline{N}(t)$ is the generally time-varying vector of isotope concentrations in the liquid fuel. Concentration rates of change, $\underline{f}$, are further decomposed into terms proportional to fusion and MSR power levels, to decay rates, to material addition rates, $\underline{B}(t)$, and to material removal rates modeled as proportional to concentrations.

Of special interest are any fixed-points of Eq. (1), since each fixed-point represents a steady operating condition of a continuous flow reactor system. If a continuous flow reactor is started with its initial set of dissolved isotope concentrations matching such a fixed-point, then all dissolved isotope concentrations will remain constant along with all other aspects of reactor operation, such as criticality, while the reactor continuously generates power. The key point is that equilibrium fixed-point solutions do exist for which:

1. fission products are steadily removed,
2. no actinides are ever removed,
3. actinides are continuously added,
4. fission product concentrations remain steady,
5. actinide concentrations remain steady,
6. criticality is steadily maintained at keff=1, and
7. MSR fission power is continuously produced.

Operating the MSR without fusion power consumes fissile isotopes, so the $\underline{f}_{MSR}$ term in Eq. (1) slowly reduces the MSR's critical keff value. It turns out that if the molten salt has sufficiently low fissile concentrations then operating the fusion subsystem has the opposite effect, adding neutron captures which convert from non-fissile to fissile material, so that the $\underline{f}_{fusion}$ term increases the MSR's critical keff value. Therefore, adjusting the ratio of MSR power to fusion power causes keff to increase or decrease, so the MSR can be feedback controlled to stay at its criticality threshold. Since fixed-point continuous operation implies constant criticality, it is not necessary to provide excess initial reactivity along with burnable poisons. A constant reactivity is sufficient.

It also turns out that steady fixed-point solutions tend to have all fissile isotopes in solution heavily denatured by non-fissile isotopes of the same actinide elements. This reduces proliferation concerns about withdrawing liquid from the reactor since subsequent isotopic enrichment would be required to concentrate its fissile material.

I.B.1 Fission-Fusion Hybrid MSR System Study Results

HMSR neutronic and isotope evolutions were simulated using the ORIGEN code along with other neutronic modules from the SCALE 6.1 code system, and custom software to implement Eq. (1) with keff controlled to unity. The MSR's graphite moderator was modeled as a matrix of 15 cm/side prismatic hexagonal blocks with 3.5 cm diameter molten salt channels. Cylindrical MSR diameter and height were set to 8.8 m. The fusion blanket thickness was set to 0.8 m, which guaranteed that over 99% of fusion and fission daughter neutrons were absorbed there. Molten salt mixtures investigated were 44.5 mole% lithium fluoride (LiF), 24.1 mole% sodium fluoride (NaF) and 31.4 mole% total (HM)Fx where HM (Heavy Metal) represents actinide species and where x ranges from 4 for thorium through uranium to 3 for plutonium and higher. Fuel feedstocks included uranium-238, spent nuclear fuel (SNF) from light water reactors, and thorium-232.

Simulations were continued until concentrations in the molten salt converged to steady fixed-point solutions. Fig. 2 shows typical lethargy plots of the neutron energy spectra. The 14 MeV component in the fusion blanket is clearly visible while the MSR's neutrons are mainly in the thermal energy range.

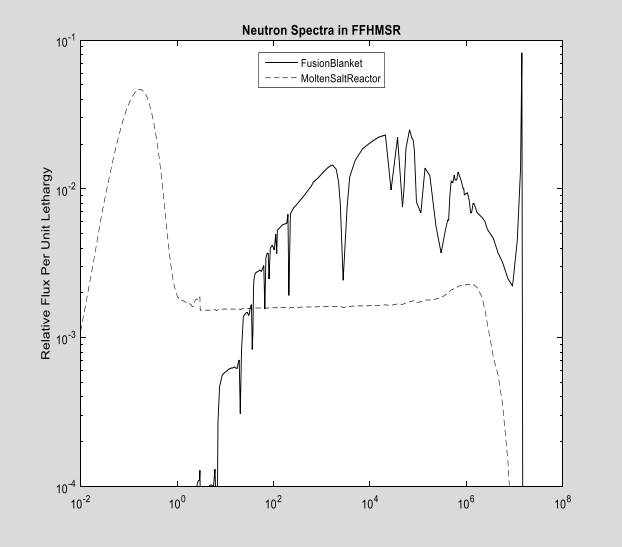

Fig. 2. Lethargy Plot of Neutron Spectra in HMSR

I.B.2 Energetic Neutron Source Effects on Reaction Rates

For SNF and uranium-238 fueling cases, simulations showed that for each incident 14 MeV DT fusion source neutron, 0.22 fissions of uranum-238 occur in the fusion blanket releasing daughter neutrons and about 44 MeV of fission energy, while 1.663 neutrons are captured by other uranium-238 nuclides converting them into uranium-239 which eventually decay into fissile atoms. Thus, for any (CR)=0.9 continuous flow MSR, irradiation of the molten salt by DT fusion neutrons at the rate of 10%/1.663 = 6.0% of the MSR's total fission rate would be adequate to support continuous operation using an actinide feedstock of pure uranium-238.

I.B.3 Energetic Neutron Source Effects on Power Levels

The ratio between the power levels of the continuous flow MSR and the DT fusion neutron source is different from the ratio of their reaction rates. Each DT fusion neutron results from a fusion event releasing 17.6 MeV of fusion energy, while each fission event releases about 200 MeV of fission energy. The ratio of the energy releases per event is thus 200 MeV/17.6 MeV = 11.4.

Continuing to address the example of a hypothetical (CR)=0.9 continuous flow MSR, irradiation of the molten salt by DT fusion neutrons at a fusion power level only 6.0%/11.4 = 0.53% of the MSR's total fission power level would be adequate to support continuous flow operation using an actinide feedstock of pure uranium-238. Uranium utilization would then reach 100%, there would be no actinide wastes, fuel recycling would be eliminated, and isotopic enrichment of uranium would no longer be needed.

Fixed-point fusion power found necessary by the HMSR simulations to maintain MSR criticality were in some cases less than 0.53% of MSR power, signaling that their modeled MSR's (CR) values exceeded 0.9.

II. HMSR Energetic Neutron Source Characteristics

Assuming that a single HMSR will produce 5 GW thermal power at 700 C, thermal conversion systems should be able to generate 2.1 GW gross electricity. For comparison, the largest PWR's now under construction will convert the same thermal power to 1.6 GW of electricity, i.e., 500 MW less. One could consider using a portion of the extra 500 MW of electrical power resulting from the greater thermal conversion efficiency to operate the HMSR's driven DT fusion source of energetic neutrons.

Because simulations showed that less than 1% of the MSR power is adequate for the HMSR, no more than 50 MW of average DT fusion power is needed for a 5 GWth HMSR if all fusion neutrons are absorbed in the molten salt. Equivalently, no more than $1.77*10^{19}$ fusions/s on average are needed for $1.56*10^{20}$ MSR fissions/s. Therefore, one could consider implementing an HMSR in which 50 MW of DT fusion is driven by up to 500 MW of electric power, corresponding to a fusion energy multiplication ratio of only 50/500 = 0.10. Such fusion performance less than energy breakeven can be obtained today using available technology. This is in contrast with the problem faced by pure fusion which must develop a large energy gain factor considerably greater than one in order to generate any net electricity to sell.

It is not necessary that the fusion neutron source operate continuously. The critical MSR naturally adjusts its power production to follow load demand via its strong temperature coefficient, so pulsed operation of the fusion neutron source is acceptable. This is in contrast to the situation faced by pure fusion in which any interruption to the fusion process interrupts the heat powering its electricity production.

It is not necessary that tritium for the DT fusion neutron source be bred within the fusion subsystem itself. Tritium is bred from neutron absorption by lithium in the molten salt, but the breeding process occurs throughout the HMSR. In particular, tritium breeding mostly occurs within the critical MSR where most neutrons are released. This is in contrast to the situation faced by pure fusion in which an adequate tritium breeding ratio must be accomplished based on the fusion neutrons.

It is not necessary that the fusion power density be high, since most HMSR power is not produced in the fusion subsystem. In contrast, if power density were low in a pure fusion reactor then its economics would be difficult.

If fusion is pulsed and intermittent, then the peak fusion power may need to exceed 50 MW in order to achieve the average. If fusion neutron losses are significant or if the MSR's conversion ratio is low due to neutron leakage or absorption then it may be necessary to provide more than 50 MW of fusion on average. Also, it clearly would be preferable to produce the 50 MW of fusion using much less than 500 MW of electricity and to do so inexpensively.

II.A Fusion Neutron Source Options

Pure fusion research has investigated many alternative schemes. Most have demonstrated energy gain factors that are far too small to be useful in an HMSR and even less useful in pure fusion concepts. At the present time, the only scheme that can generate DT fusion neutrons with an overall fusion energy "gain" greater than 0.1 is the tokamak.

Plasma energy gain is the ratio of DT fusion power to the auxiliary heating power reaching the plasma. It thus is greater than the overall fusion energy gain which must account for energy losses and inefficiencies outside the plasma. More than two decades ago the TFTR tokamak demonstrated a plasma energy gain of 0.28, then the JET

tokamak demonstrated 0.65. If heating system efficiency were 30% and the use of superconducting magnets eliminated magnet power losses, these would correspond to overall energy gain factors of respectively 0.1 and 0.22. However, research progress has continued to raise expectations. The ITER tokamak's goal is to demonstrate a plasma energy gain of 10, a performance far exceeding efficiency needs for the HMSR's fusion neutron source but likely inadequate for pure fusion.

A DT fusion neutron source for the HMSR can certainly be built. However, its economy is uncertain. It is crucially important that the cost of the fusion neutron source not be too large in comparison to the cost of the MSR which it augments. Minimizing cost is thus a major design goal. At present, the details are unknown of how costs depend on design choices, so the focus for now is to instead minimize overall device size and simplify maintenance operations.

Special design features proposed in combination for the DT fusion neutron source include (1) low aspect ratio plasma, (2) structural optimization including use of constant-tension straps connected to structural rings, (3) high-radiation resistant all-metal magnet windings which also provide radiation shielding, (4) high temperature superconductor magnet windings, and (5) demountable winding joints. These are discussed further below.

A tokamak magnetically confines an axisymmetric ring of ionized plasma. Confinement is based partly on a toroidal magnetic field (TF) component directed around the ring's major circumference, generated by poloidal electrical currents flowing in TF winding conductors which link the ring and surround its minor circumference. The other aspect of tokamak plasma confinement is based on a toroidally directed electric current, which flows through the plasma ring along its major circumference and on poloidal magnetic field components generated by toroidal currents in poloidal field coil windings parallel to the plasma ring. The plasma current is conventionally initiated by inductive transformer coupling from a time-varying current in a solenoid winding located in the middle of the plasma ring. Steady plasma current sustainment by less efficient non-inductive means can be obtained by specialized injection of neutral beams or radio frequency energy into the plasma.

Currents in the poloidal field coils control the position and shape of the plasma cross section. Plasma shaping is important because energy confinement is sensitive to plasma operating modes, such as whether a poloidal divertor plasma magnetic structure exists.

It is conventional to refer to the ratio of the plasma's major and minor radii measured on the horizontal midplane as the plasma's aspect ratio. Many tokamaks in fusion research have aspect ratios of three or more, for instance the Joint European Torus (JET) tokamak near Oxford, or the much larger ITER tokamak now under construction at Cadarache, France. However, there is some recent evidence indicating that tokamak plasmas with lower aspect ratios near two may perform better in terms of higher plasma pressure and the resulting fusion power density. Their lower aspect ratio also makes them more compact, which may tend to reduce their cost. As a result, the fusion neutron system discussed here for the HMSR selects a lower aspect ratio design in pursuit of better economics.

Although the tokamak plasma current itself heats the plasma, it is necessary to use auxiliary heating systems to reach and sustain the high thermonuclear plasma temperatures at which fusion reactions between hydrogen isotopes occur. Auxiliary heating systems successfully producing thermonuclear plasma temperatures include various radio frequency schemes, which couple to resonances within the plasma, and neutralized ion beams (i.e., neutral beams), which can penetrate the magnetic fields and are injected directly into the plasma. Neutral beams come in two flavors, the older technology of neutralized positive ion beams suffers from poor neutralization efficiency at high energy. The newer negative ion beams can be accelerated to considerably higher energies, then efficiently neutralized. In the present proposed system, negative ion neutral beams are favored for reasons of reliability and efficiency.

II.B Fusion Nuclear Science Facility Findings

Design studies of fission-fusion hybrid concepts have not been explicitly funded. However, there have been extensive efforts, conducted under the rubric of a Fusion Nuclear Science Facility (FNSF), to develop designs for a DT fusion neutron source to perform the materials testing needed for the pure fusion program[3,4]. Some FNSF results may have useful hybrid applications, so it is appropriate to consider them here. Much of the FNSF efforts have focused on tokamak designs having aspect ratios of two or smaller. For compact devices, such designs have very limited space inboard from the plasma, far too limited for effective radiation shielding. Without radiation shielding for the center of the tokamak, it is not feasible to use superconducting windings there due to the large radiation heat loads that would be deposited in the windings at cryogenic temperatures, thus exacerbating cryogenic cooling requirements.

Abandoning superconductors forces TF system designs to use normal water-cooled resistive copper conductors operating near room temperature. Worse, it is not feasible to use electrical insulation in the tokamak's center since ionizing radiation would cause the insulation to conduct. As a result, some FNSR efforts have focused on designing single turn TF systems so that TF magnet insulation could be avoided. However, all solenoid windings have relied on electrical insulation between turns, so it has appeared necessary to also find non-inductive ways to achieve initial plasma ionization and

current ramp-up. Non-inductive plasma start-up research in support of such designs is ongoing.

The Fig. 3 layout depicts a low aspect ratio tokamak concept showing TF and PF magnets, structure, blanket and vacuum vessel. To produce a 3 Tesla toroidal field at the plasma's 1.7 meter major radius, the TF magnet's central single turn copper conductor must carry a steady DC current of 25.5 million amperes. Such high current low voltage power supplies would need to be developed and integrated with the tokamak to avoid excessive transmission losses. Heat dissipated in the TF conductor must be removed by cooling water flowing in channels within the copper, not shown.

New REBCO[5] (Rare Earth-Ba-Cu-O) high temperature superconducting (HTS) tapes, such as YBCO[6,7], with superior properties have been developed during recent decades. Their development is continuing along with discovery of new applications for them. As identified by D. Whyte and students in the ARC design[8], HTS permits operation at higher temperatures and stronger magnetic fields and with larger critical currents than conventional low temperature superconductors. Two potential advantages may result. Since fusion power density scales proportional to plasma pressure squared, while the maximum stable plasma pressure is proportional to magnetic field strength squared, the resulting fourth power dependence implies the stronger magnetic fields enabled by HTS may allow more compact fusion devices. Second, the fact that HTS can operate at higher temperatures at which material specific heats better absorb quench dissipation may allow demountable superconducting joints to be engineered, thus greatly improving access to fusion device internals.

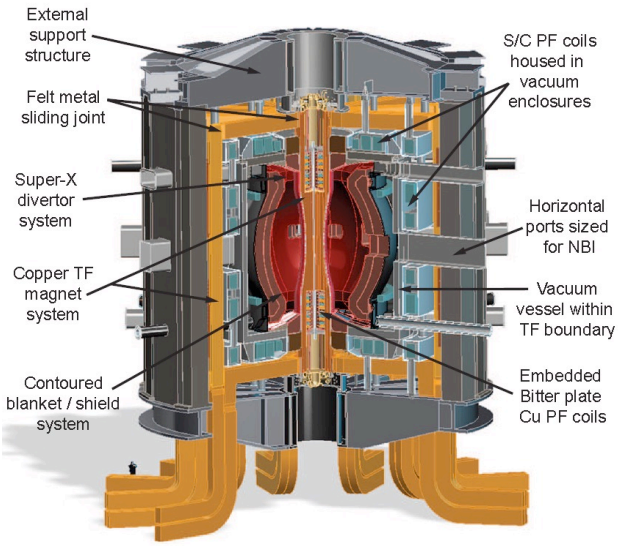

Fig. 3. FNSF with 1-turn Copper TF, No Solenoid[4]

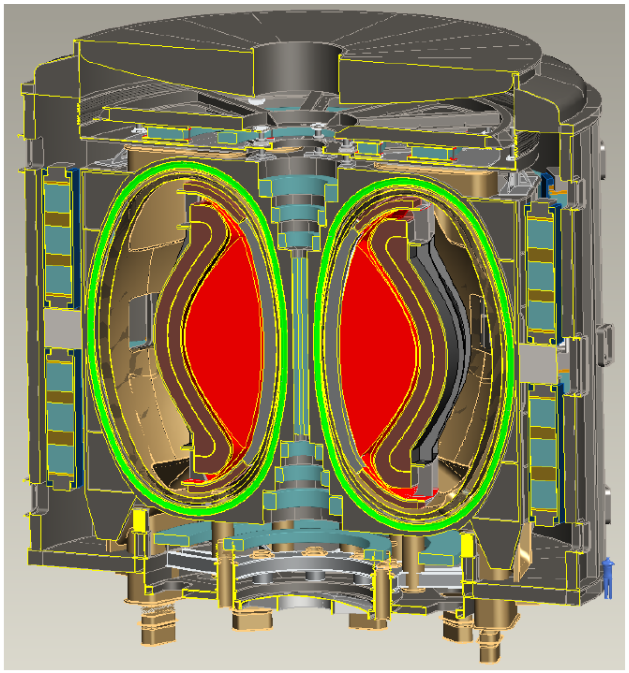

Fig. 4. FNSF with HTS TF and Small Solenoid[4]

FNSF efforts have begun to consider adapting HTS for use in low aspect ratio tokamaks. In aspect ratio two devices by increasing the plasma's major radius to 3 m, enough space then becomes available for HTS radiation shielding inboard from the plasma, predominantly using tungsten carbide. The Fig. 4 layout depicts such a plasma surrounded by inboard shielding and an outboard neutron-absorbing blanket, all within the bore of integral HTS TF coils. A small central HTS solenoid is also provided to help with plasma start-up. The toroidal field at the 3 m major radius is 4 Tesla. There is no significant dissipative power loss in the TF system. Physics calculations predict the total DT fusion power exceeds 500 MW.

Although the benefits of HTS are obvious, the volume of material in the Fig. 4 layout is an order of magnitude greater than in the Fig. 3 layout. Since the HMSR does not need 500 MW of fusion power, attention was given to finding a more compact approach.

II.C High Radiation All-Metal Coil Designs

In locations where there is not enough space for shielding, it may still be possible to use normal resistive metal conductors since they need no cryogenic cooling, they conduct current well during irradiation, and they function until badly damaged by atomic displacements[9]. On the other hand, the solid insulation materials conventionally used in resistive magnet windings are vulnerable to radiation.

Solid insulation performs two different functions in magnet windings. It blocks leakage currents between conductors, and it transmits forces without significant

deformation. Ionizing radiation creates free ion and electron charges causing temporary loss of an insulator's high resistivity. If leakage current then flows in solid insulation, damage can occur quickly with heating. Even without heating, damage still occurs gradually as chemical and microstructure changes accumulate. Either way, the solid insulator eventually fails.

The situation with fluids is different. With no solid structure to damage, many fluids are compatible with intense radiation. For instance, helium is chemically unaffected, while water slightly dissociates into hydrogen and oxygen but these are easily recombined so that no permanent damage results. Their resistivities are high enough to serve as good insulators in many applications, although the resistivities decline when irradiation is producing charge carriers in the fluids. However, charge recombination also occurs and becomes complete as the coolant fluid flows outside the radiation zone to be cooled in a heat exchanger. It is expected that either rapidly flowing helium or water coolant would retain a minimum electrical resistivity considerably greater than the resistivity of any metal while being irradiated anywhere in a DT fusion reactor.

Therefore, either of these two coolant fluids or some other candidates could be used as lossy insulators in fusion reactors. Lossy implies that some leakage current would flow, so it is essential that adverse effects remain small. The electric field must be small enough and the flow fast enough to avoid electrical breakdown. Electric fields driving the fluid's leakage currents should be nearly axisymmetric in order to avoid departures from magnetic axisymmetry in the plasma.

However, fluids cannot resist sustained mechanical stresses so a different approach involving structural bracing using radiation-resistant solid materials is needed to accommodate the forces. The strategy starts with rearranging and reshaping the conductor layout to reduce the net force on each conductor so that a minimal amount of solid bracing can be used. Since bracing material will bridge between different conductor voltages, it is important to limit the leakage current flowing through bracing. The bracing cross section should be limited consistent with net forces and any other mission constraints. Thus it is important to choose bracing material that is strong and has a high resistivity. Candidate resistive bracing materials include type 316 stainless steel with 44 times copper's resistivity, inconel-718 with 73 times copper's resistivity, and alloy Ti-6Al-4V with 100 times copper's resistivity. It may alternatively be possible to brace using graphite whose resistivity is strongly anisotropic, varying from approximately 150 to 300 times copper's resistivity in directions parallel to the graphite's basal plane and to orders of magnitude more resistivity in the direction perpendicular to that plane.

II.C.1 Multiturn All-Metal Central TF System

Low aspect ratio tokamak TF systems are frequently implemented without using integral TF coils, for instance in the NSTX and MAST devices. Instead, there are vertical inner leg conductors in a center stack region, horizontal radial conductors in rigid upper and lower umbrella structure regions, and outer leg vertical conductors running between upper and lower umbrella regions. The lack of sufficient space for radiation shielding applies mainly to the center stack region near the tokamak's horizontal midplane. There is more room for shielding in the umbrellas and outer legs.

The multiturn central TF magnet conductor system for low aspect ratio tokamaks as proposed here does not use solid insulation in high radiation portions of its turns. Instead, each of the multiple central TF conductor turns is shaped as a vertically oriented pipe. Multiple turns are configured as pipes of different diameters nested inside each other and aligned concentrically about the tokamak's symmetry axis. Flowing coolant fills the space between the nested conductors and in addition fills volumes beyond the innermost and the outermost turns. Inter-turn voltages appear across the flowing coolant separating the nested conductors.

This configuration is chosen so that magnetic TF self-forces are balanced within each conductor turn by hoop compression in the metal, without involving solid insulation. The net magnetic force vector on each central TF turn is identically zero, while net torques, which depend on the radial field profile, are typically small.

This configuration requires engineering development of annular plug assemblies located in the reduced radiation field at the central TF's top and bottom where they serve three purposes. They structurally connect pipes together as bracing, they contain the pressurized coolant, and they provide a mounting location for external coolant hose fittings. Because the net magnetic force on each TF turn is zero the plug assembly's required strength is limited. However, the plug assembly material should have high resistivity to limit leakage currents.

Electrical return currents from each central TF pipe are split among multiple outer legs connected electrically in parallel, in order to avoid magnetic field ripple. Current through each central pipe-shaped TF turn flows vertically through demountable joints into conducting rings in upper and lower umbrella structures, then to connected insulated conductors which run radially within the umbrellas and are associated with each outer leg. Each outer leg interconnects turns between upper and lower umbrellas, but their connections are advanced between top and bottom in order to connect the central TF pipe-shaped turns in series.

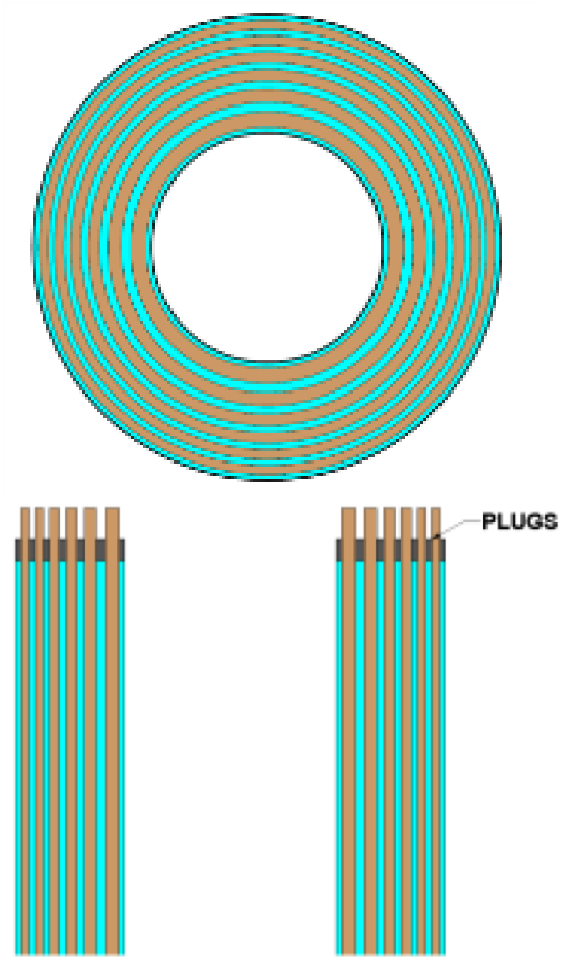

Fig. 5. Central TF; Plan and Section Elevation Views

II.C.2 All-Metal Barberpole Solenoid

A second high radiation magnet concept is the all-metal solenoid without any solid insulation. The design motivation is the lack of space within low aspect ratio tokamaks for adequate radiation shielding. The all-metal solenoid proposed here may provide some help from induction for plasma startup and may also provide an ability to better regulate fast variations in plasma current.

Alternating strips of dissimilar metals are helically wound between single-metal end-rings, then rigidly joined together forming a "barberpole" cylindrical conducting assembly as in Fig. 6. The principle of solenoid operation without insulation is the barberpole's tilted resistive anisotropy, which causes some current to flow azimuthally around the cylinder in response to a purely axial applied voltage. As with conventional solenoids, magnetic flux is produced, but the barberpole dissipates more power for the same flux.

Fig. 6. Barberpole All-Metal Solenoid

Two such barberpole windings with opposite helicities and different radii are co-located with the smaller nested inside the larger, separated by a radial gap of cooling water. A conducting metal ring bridges the gap at one end, connecting the two windings electrically in series. A voltage applied radially between the other ends of the two windings thus generates poloidal magnetic flux without coupling to the toroidal field.

II.D TF Winding Shaping

A tokamak's toroidal field is generated by toroidal solenoid windings, which surround and link the plasma ring. The TF strength varies inversely with radial distance, R, from the cylindrical symmetry axis.

$$B_{TF} = \frac{\mu_0 NI}{2\pi R} \qquad (2)$$

Here, N is the number of TF turns linking the plasma ring and I is the current per turn. Vertical force on an upper half-turn depends on its radial extent.

$$F_{Z-halfturn} = \frac{\mu_0 NI^2}{4\pi} \ln\left(\frac{R_{\max}}{R_{\min}}\right) \qquad (3)$$

Although Eq. (3) sets the sum of vertical tensions on inboard and outboard TF legs, it does not determine how tensile stresses divide between them. However, a TF winding conductor locally supported by its internal

tension assumes a natural shape[10, 11] in its (R,Z) poloidal plane, as governed by the following differential equations.

$$\frac{d\theta}{ds} = \frac{\mu_0 N I^2}{4\pi R T}$$
$$\frac{dR}{ds} = \cos\theta \qquad (4)$$
$$\frac{dz}{ds} = \sin\theta$$

Here, T is the tension force in each turn. Fig. (7) graphs TF winding shapes satisfying Eqs.(4).

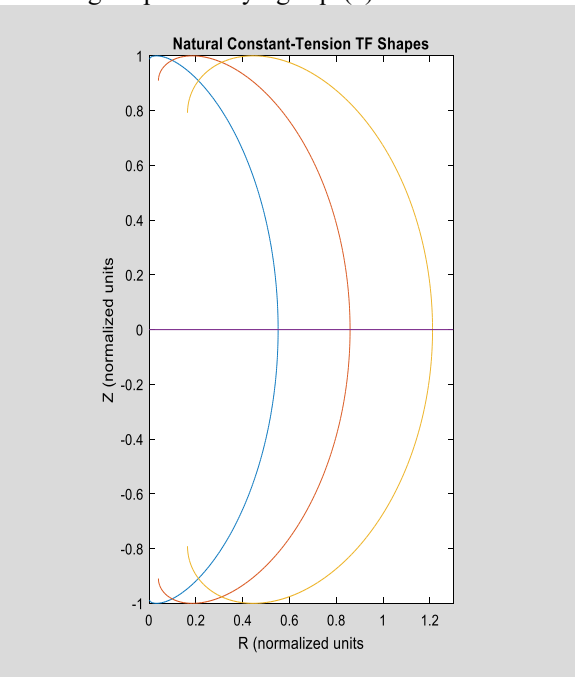

Fig. 7. Constant-Tension TF Shapes

Since these constant-tension curves do not close on themselves, their use in a TF winding system design requires adding a portion of each turn not supported by its own tension. D-shaped coils achieve this by connecting together the upper and lower vertically sloped ends of the Fig. 7 curves, using a vertically oriented straight line. With no slope discontinuity where the vertical line joins the curve, the straight portion smoothly transmits the tension. Thus in D-shaped coils the total tension of Eq. (3) divides equally between inboard and outboard legs. However, the radially inward magnetic centering force on each straight section must be supported by other means, either wedging together the system of different TF coils or by providing a bucking cylinder which the TF coils lean against. Either way the inboard leg is in lateral compression, which increases its Tresca or Von Mises stress beyond corresponding outer leg stress.

A different TF design approach is to terminate the constant-tension shape either where its direction becomes horizontal or slightly outboard from the horizontal slope locations. As with the D-shaped coils, a straight vertically oriented conductor connects between lower and upper ends of the curved outer legs to complete each turn. The resulting coils have been termed "Bow-Coils" due to their shapes, which include abrupt changes in TF conductor direction at top and bottom[12]. The advantage of Bow Coils is that their outer legs place no vertical tension whatsoever on their inner legs. Furthermore, if the straight inner leg is located slightly outboard from the horizontally sloped locations, then the natural outer leg tension can vertically squeeze the inner leg, causing compression. Either way, the Bow Coil scheme reduces limiting stresses in the inner legs. Slight magnetic compression may also simplify the engineering of demountable joints in a TF system.

In the Bow Coil scheme, the radial tensions in structural straps supporting outer leg conductors are transferred to upper and lower toroidally continuous ring structures. With symmetrical outer legs, the vector sum of outward forces on each structural ring can only have a vertical resultant. The radial rings can also have a large radial extent along which radially oriented straight conductors run, without compromising the Bow Coil scheme, and this allows a vertically shorter TF implementation than is possible with D-shaped coils.

II.E Combining HTS With Copper

A set of nested water-cooled central copper TF turns can also act as a neutron shield, slowing and absorbing neutrons released by fusion reactions in the plasma. This leads to the concept of a 2-stage TF winding system. Winding turns closest to the plasma are configured as high radiation water-cooled copper which boost field strength while shielding HTS turns in the other TF stage.

Figure 8 depicts a fusion neutron source to be used in an HMSR incorporating design features discussed herein. A 8 MA plasma is confined by a 4 Tesla TF at its 2 m major radius, heated by negative ion neutral beams (not shown) to produce 165 MW of DT fusion power. A thin-walled axisymmetric vacuum vessel closely surrounding the plasma is immersed in an axisymmetric bath of the same molten salt, which also flows in a loop through the critical fission MSR. Non-axisymmetric ducts through the molten salt provide vacuum vessel access for neutral beam heating and vacuum pumping systems.

This molten salt contains various dissolved fissile and fertile actinide fuels and equilibrium fission products in addition to lithium, sodium, and fluorine. With little inboard molten salt blanket, with losses in neutral beam duct streaming and in absorption by plasma-facing hardware not shown, it is expected that about half of fusion neutrons will be absorbed in the molten salt. This is adequate for HMSR needs. If fewer DT fusion neutrons are required, then the neutron source will be operated with longer time intervals between fusion pulses.

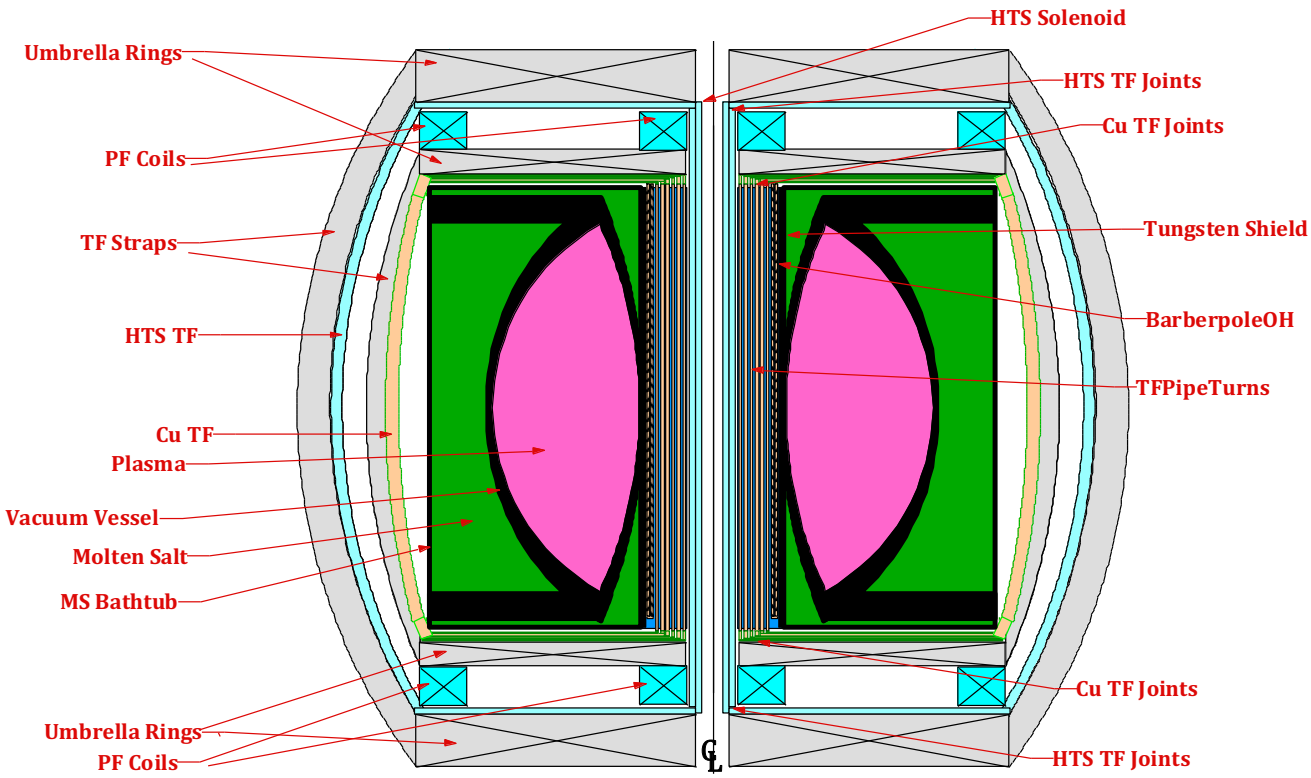

Fig. 8. DT Fusion Neutron Source for HMSR

A 2-stage TF system is used including six high radiation water-cooled pipe turns connected in series with ten HTS cable turns, with each turn carrying 2.5 MA electrical current. The central HTS-stage TF's ten cable turns have demountable joints at top and bottom and are bucked against a small diameter HTS solenoid to generate 15 Tesla at R= 0.33 m. The six pipe turns' radial thicknesses are each 42 mm, which for each avoids lateral buckling at full field without additional bracing. Demountable copper joints are provided for each pipe turn. Each pipe turn current is split in parallel between 10 outer legs, with each normal outer leg driven by a single 250 kA power supply. The series-connected HTS stage is driven through the same power supplies.

Because of TF system demountable joints, it is feasible to access the vacuum vessel using an overhead crane. The bathtub containing the molten salt surrounding the vacuum vessel therefore has a removable upper lid.

Umbrella rings appearing in Fig.8 are rather wide. This is necessary to implement the Bow Coil scheme, compressing TF inner legs without requiring the machine to be much taller than the plasma. Although these umbrella rings could be implemented as forgings, they can alternatively be implemented as space trusses providing 3D rigidity.

It is noteworthy that vertical forces on straight radial umbrella conductors are supported through the rings by tension in the TF outer legs. As shown in Fig.8, most of that tension is developed in structural straps against which the outer leg TF conductors lean, not in the conductors themselves. The straps of all outer legs are structurally connected to the rings so that radial force components cancel out.

Shielded HTS PF Coils for plasma equilibrium and divertor shaping are located between the TF stages.

III. CONCLUSIONS

A conceptual design layout for a DT fusion neutron source has been presented in which novel synergistic design features are combined to reduce device size and to simplify maintenance, thus limiting costs. After further development of this conceptual energetic neutron source design, it may be feasible to deploy fusion-fission HMSR systems in the near-term using fusion energy gain factors that have already been demonstrated, without waiting for additional pure fusion research progress.

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