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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 a 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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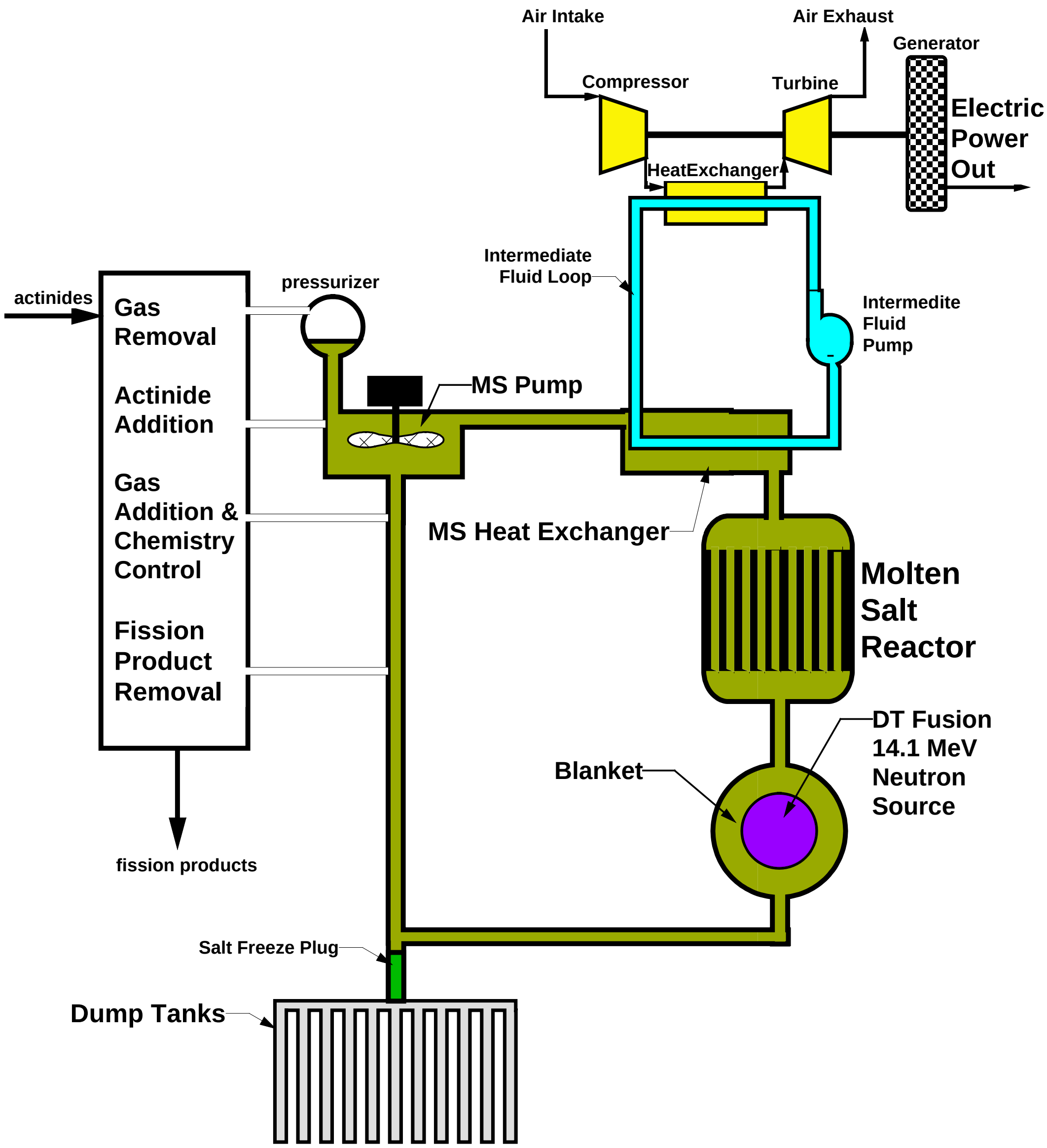

Fig. 1. Hybrid Molten Salt Reactor (HMSR) Configuration

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.

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

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.

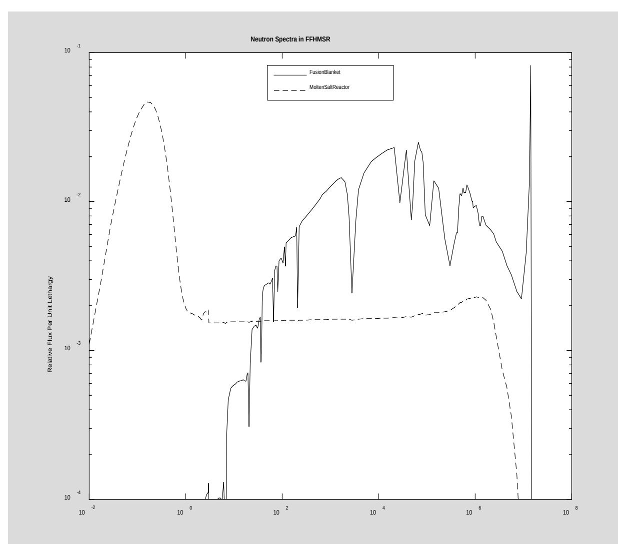

Fig. 2. Lethargy Plot of Neutron Spectra in HMSR

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]. 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[4] (Rare Earth-Ba-Cu-O) high temperature superconducting (HTS) tapes, such as YBCO[5,6], 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[7], 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.

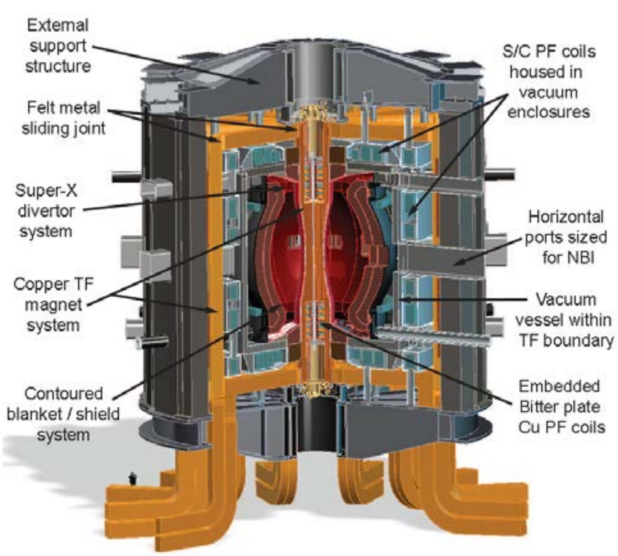

Fig. 3. FNSF with 1-turn Copper TF, No Solenoid

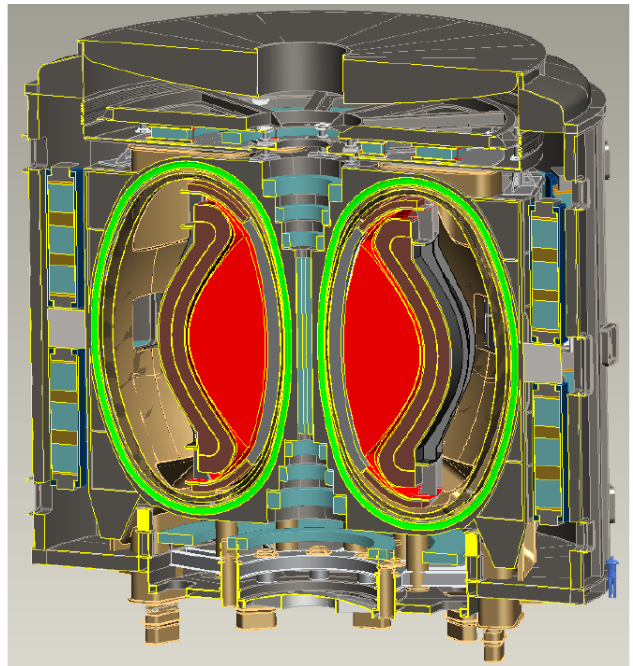

Fig. 4. FNSF with HTS TF and Small Solenoid

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[8]. 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.

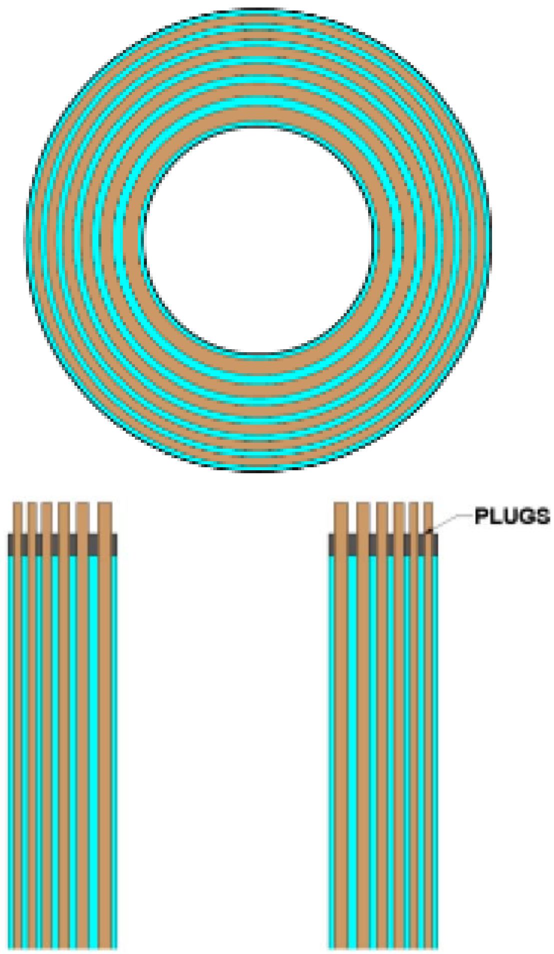

Fig. 5. Central TF; Plan and Section Elevation Views

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.

$$B_{TF} = \frac{\mu_0 NI}{2\pi R} \tag{2}$$

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.

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

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[9.10] 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).

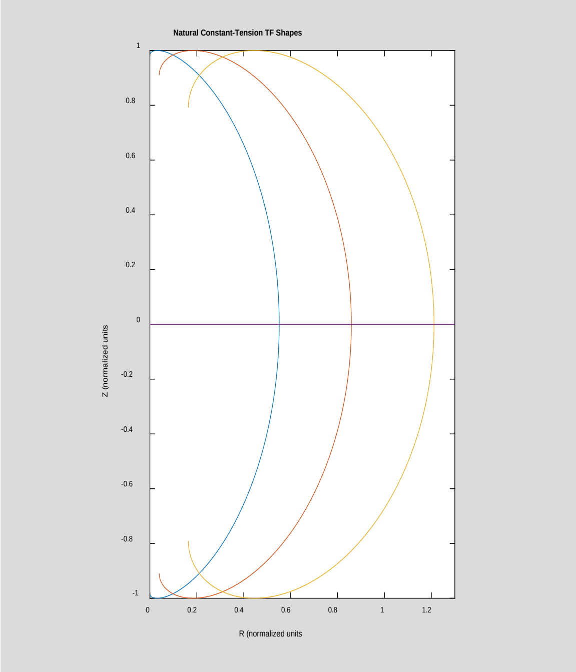

Fig. 7. Constant-Tension TF Shapes

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[11]. 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.

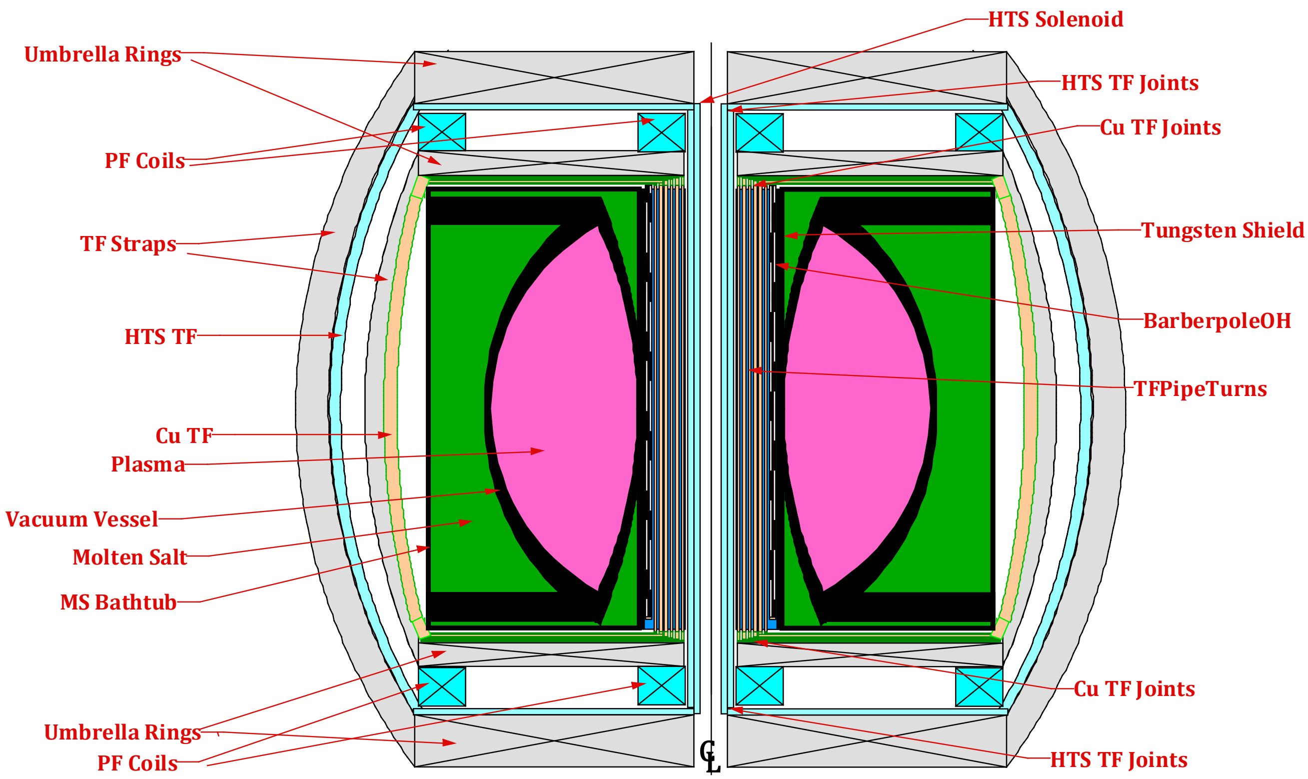

Fig. 8. DT Fusion Neutron Source for HMSR

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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