**ORNL TNS Program: Plasma Engineering
Considerations and Innovations for a Medium
Field Tokamak Fusion Reactor**

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FUSION ENERGY DIVISION

ORNL TNS PROGRAM: PLASMA ENGINEERING CONSIDERATIONS
AND INNOVATIONS FOR A MEDIUM FIELD TOKAMAK FUSION REACTOR

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ABSTRACT

Recent plasma engineering studies have ascertained a viable concept for The Next Step (TNS) reactor based on medium toroidal fields between 4 T and 7 T at the plasma center, plasma $\bar{\beta}$ values up to 10%, and averaged densities between $0.6 \times 10^{14} \text{ cm}^{-3}$ and $2.5 \times 10^{14} \text{ cm}^{-3}$. Plasma engineering innovations that can substantially reduce the size, cost, and complexity of the TNS reactor have been explored and are summarized in this paper. It is shown that the previously anticipated requirement of high pellet velocities can be substantially reduced; the toroidal field (TF) ripple requirements may be relaxed to reduce the number of TF coils and improve machine access; hybrid equilibrium field (EF) coils have been shown to require building only small interior coils and to reduce the power supply required by the exterior coils; proper approaches of microwave plasma preheating may reduce the peak loop voltage for start-up by an order of magnitude.

The medium-field TNS reactor concepts and the plasma engineering innovations discussed should be applicable to other designs of tokamak reactors; some of the suggested innovations will be tested in upcoming experiments.

1. INTRODUCTION

A major purpose of the plasma engineering studies in the TNS program¹ has been to explore credible ranges of physics parameters for the tokamak fusion plasma core. One of the key requirements is to establish a consistent set of physics assumptions based on recent experimental and theoretical understandings in fusion physics. Section 2 will be devoted to a discussion of the physics concepts that are employed in defining the plasma parameters in the TNS reactor.

Various tokamak reactor design studies based on a credible range of physics parameters have entailed difficult technological requirements. These include the assumed need for high speed of the pellets (~ 10 km/sec) to fuel at the fusion plasma center for long burn,² the poor access due to the relatively small spacings between the TF coils,³ the difficulties in building and remotely maintaining the multiturn EF coils interior to the TF coils,³ and the large, costly pulsed power supplies⁴ to the ohmic heating (OH) coils required to start the reactor plasma in full bore. These engineering and technological difficulties lend themselves to increasing the cost and complexity of the tokamak reactor.

To reduce projected cost and complexity of the reactor, another key role of the TNS plasma engineering studies is to take an innovative look at the plasma physics assumptions and approaches that have led to the technological difficulties, and further to explore new schemes to avoid them. Some of the latest studies related to the reactor problem areas just mentioned are discussed in Sect. 3. As will become clear, some of the innovative solutions explored in the TNS plasma engineering studies have the potential of not only beneficially impacting the TNS reactor, but also suggesting important topics of study in the current and upcoming experimental and theoretical investigations. Although we use the TNS reactor as our focus for the plasma engineering studies, we believe the resulting set of plasma parameters are equally appropriate for use in other tokamak ignition test reactors.

2. TNS PLASMA ENGINEERING CONCEPTS OF A MEDIUM-FIELD D-T REACTOR

In choosing the range of plasma parameters for the TNS reactor, we have taken care to insure a consistent set of physics assumptions. These assumptions include: (1) the approximately linear scaling of plasma density with the heating power density,⁵ (2) the inclusion of local trapped ion mode (TIM) transport coefficients⁶ in the 1-D transport calculations,⁷ (3) the use of D-shaped, high $\bar{\beta}$ (volume-averaged beta), flux-conserving tokamak (FCT) equilibria,^{8,9} (4) the use of the "shell-like" EF coils,¹⁰ (5) the $\bar{\beta}$ limits set by magnetohydrodynamic (MHD) pressure-driven instabilities,^{11,12} (6) the time-dependent evolution of the D-T fusion plasma in an FCT reactor,¹³ and (7) the confinement of α -particle heating that substantially eases the required neutral beam energy.¹⁴ The bases of these concepts are briefly discussed here.

2.1 SCALING OF PLASMA DENSITY WITH HEATING POWER DENSITY

A recent study by Murakami et al.⁵ shows that the maximum densities for various ohmically heated tokamaks scale linearly with B_T/R_O , which in turn is roughly proportional to the plasma heating power density. In tokamaks with auxiliary heating by substantial amounts of neutral beams, higher maximum densities beyond those achievable in ohmic discharges have been obtained.¹⁵ As Fig. 1 indicates, increasing the heating power from 420 kW (point A) by a factor of 1.6 (point B) in the Oak Ridge Tokamak (ORMAK) raises the density limit from $4.6 \times 10^{13} \text{ cm}^{-3}$ (point A) to $7.1 \times 10^{13} \text{ cm}^{-3}$ (point B), i.e., by a factor of roughly 1.6. For the same higher density to be achieved only ohmically in ORMAK, the value of B_T/R_O would have to be increased from 3 T/m (point A) to 5 T/m (point C), i.e., by a factor of roughly 1.7.

Although values of B_T/R_O above 5 T/m in a high-field tokamak (such as Alcator¹⁶) can assure high densities, increased plasma heating power in a medium field tokamak with $0.5 \text{ T/m} \lesssim B_T/R_O \lesssim 2 \text{ T/m}$ has similar capabilities of reaching high density. For TNS, B_T/R_O is assumed to be in the medium-field range with a neutral injection power (P_{inj}) of $\sim 75 \text{ MW}$. By also using effective plasma purity control mechanisms to

Fig. 1. Scaling of maximum line averaged densities with and without gas puffing for ORMAK and other tokamaks. Neutral beam injection allowed an increase of the density limit in ORMAK. Point A corresponds to ohmic heating power (P_{OH}) of 420 kW only. Point B corresponds to an addition of neutral injection power (P_{inj}) of 240 kW. Point C corresponds to the higher density value of the B_T/R_0 than point A produced ohmically.

insure $Z_{\text{eff}} \lesssim 1.5$, the assumption of achieving a plasma density of at least a few times 10^{14} cm^{-3} in TNS is reasonable.

2.2 1-D MULTIFLUID TRANSPORT ESTIMATES

In a zero-dimensional (0-D) study¹⁷ based on the empirical energy confinement scaling derived from experiments in ATC, ORMAK, and Alcator, a set of reference parameters has been obtained and is shown in Table 1. For the case with $R_0 = 5 \text{ m}$, $a = 1.25 \text{ m}$, $b/a \approx 1.6$, and $B_T = 4.3 \text{ T}$, the D-T plasma is found to ignite at $\beta = 11\%$ using 15 MW neutral beam injection and to burn at $\beta = 15\%$ producing 1500 MW fusion power. When the global TIM loss rate, D_{TIM} , is considered, it is found that a value of $D_{\text{TIM}}/10$ is equivalent to the empirical scaling.

Although the use of a full D_{TIM} loss rate may result in pessimistic estimates of the plasma performance in TNS, the use of $D_{\text{TIM}}/10$ in the 0-D calculations needs justification. Such a justification can be found in a recent study using a 1-D analytic model that describes the energy and particle transport in a tokamak reactor dominated by the TIM instability.¹⁸ It is shown that the density profile solution of the transport equations leads to an equivalent global loss rate, $\langle D_{\text{TIM}} \rangle$, no larger than $D_{\text{TIM}}/10$.

The effects of the density profile on $\langle D_{\text{TIM}} \rangle$ are also investigated using 1-D multifluid transport codes with pellet fueling.⁷ It is shown that fueling profiles peaked toward the plasma edge tend to flatten the density profile, which in turn reduces the trapped ion loss rate.¹⁹

2.3 HIGH $\bar{\beta}$ FCT EQUILIBRIA

With large neutral beam power, the plasma is expected to heat up in a time scale much shorter than the plasma skin time. The resulting sequence of plasma equilibria then forms a family of flux-conserving equilibria.⁸ Calculations in a D-shaped FCT⁹ have produced equilibria of $\bar{\beta}$ above 20% and a safety factor up to five in TNS. Values of $\bar{\beta}$ substantially above a few percent are expected to result in high fusion power density, to permit the use of medium field, and to reduce the reactor size.

Table 1. Typical parameters for a D-shaped, medium field TNS
 $[R_0 = 5 \text{ m}, a = 1.25 \text{ m}, (b/a) = 1.6, B_T(\text{max}) = 8 \text{ T}, B_T(R_0) = 4.3 \text{ T},$
 $q_a = 4$; higher B_T (up to 7 T at $R = R_0$) results in increased
margin of flexibility or reduced device size.]

	0-D estimates	Self-consistent parameters
I_P (ohmic) (MA)	4.0	4.0
I_P (burn) (MA)	6.0	4.5-5.5
$\bar{n}$ (ohmic) (cm^{-3})	0.5×10^{14}	$0.3-0.5 \times 10^{14}$
$\bar{n}$ (burn) (cm^{-3})	2.2×10^{14}	$0.6-2.5 \times 10^{14}$
$\bar{T}$ (ohmic) (keV)	2	1.0-2.0
$\bar{T}$ (ign) (keV)	11	4.0-7.0
$\bar{T}$ (burn) (keV)	13	5.0-10
$\bar{\beta}$ (ign) (%)	11	3.0-5.0
$\bar{\beta}$ (burn) (%)	15	3.5-10
C (ohmic)	0.5	0.14-0.96
C (burn)	0.02	0.01-0.15
$\bar{n}\tau$ (burn) ($\text{cm}^{-3} \text{ sec}$)	3×10^{14}	$0.6-2.5 \times 10^{14}$
P_{D-T}/V (MW/m^3)	6	0.4-8.0
W_L (MW/m^2)	3.7	0.3-5.0
P_{D-T} (MW)	1500	100-2000

2.4 HIGH $\bar{\beta}$ SHELL-LIKE EF COILS

The characteristic configurations of the proper EF coil have been determined. It has been shown that the proper coil arrangements can either be interior¹⁰ or exterior²⁰ to the TF coils. As indicated in Fig. 2, either the interior or the exterior coils are divided into three groups, the coils in each group being connected in series and requiring a single power supply. It has also been demonstrated²⁰ that either option of the coils can maintain the plasma position and D-shape over a wide range of $\bar{\beta}$ values.

2.5 LIMITS ON $\bar{\beta}$ BY MHD BALLOONING MODES

Although MHD equilibrium $\bar{\beta}$ above 20% with $q_a \lesssim 5$ in TNS has been obtained based on the FCT approach, pressure-driven MHD instabilities are expected to limit $\bar{\beta}$ to lower values. Recent calculations¹¹ have revealed D-shaped equilibria which are stable with respect to the internal ballooning modes at $\bar{\beta}$ values of $\sim 5\%$ for TNS-like tokamaks. For a tokamak with aspect ratio equal to 2.4, stable $\bar{\beta}$ values up to 12% have been found.¹² With shaping and profile optimizations, current estimates of stable $\bar{\beta}$ are between 5% and 10% for TNS.

Recent analytic²¹ and numerical²² ballooning modes have provided further indications that a D-shaped plasma with modest elongation and realistic current profiles provides a factor of two to three increase in stable $\bar{\beta}$ values from the circular plasmas.²³ However, the 0-D scaling calculation has indicated that ignition and burn occur at $\bar{\beta} = 11\%$ and 15%, respectively (see Table 1), above the estimated $\bar{\beta}$ limit for MHD stability.

2.6 1-1/2-D EVOLUTION OF D-T PLASMA IN A FLUX-CONSERVING TNS TOKAMAK

The resolution of this apparent discrepancy in $\bar{\beta}$ requirements lies in the effects of the density (n) and temperature (T) profiles on the fusion power output. Since the D-T fusion power density is proportional to $n_D n_T \propto n^2$ and is significant only when the local $T \gtrsim 6$ keV, one finds

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Fig. 2. Generic EF coils that are interior (II, ID, IO) or exterior (EI, ED, EO) to the TF coils. Either the interior or the exterior coils can be used alone to maintain high- β , D-shaped equilibria. The dotted lines indicate a group of coils that are connected in series and use a single power supply. Only three power supplies are needed for either the interior or the exterior set.

that $\int dV n_D n_T \langle \sigma v(T) \rangle \gg V \bar{n}_D \bar{n}_T \langle \sigma v(\bar{T}) \rangle$ near ignition. The 0-D model is thus inadequate in estimating the ignition and burn requirements of TNS plasma.

The evolution of TNS plasma heated by neutral injection to ignition and burn is studied with the flux-surface averages of the particle and energy balance equations together with FCT MHD equilibria.¹³ It is found that the centrally peaked density and temperature profiles result in centrally localized α -particle heating, which can exceed the injection heating when a relatively low value of $\bar{\beta}$ ($\sim 2.5\%$) is reached. When $\bar{\beta} > 3.0\%$, the plasma can be considered ignited near the center to bring about an overall steady-state burn. As indicated in Fig. 3, the steady-state burn can occur (assuming the empirical confinement law) with $3.5\% \lesssim \bar{\beta} \lesssim 15\%$ and giving $100 \text{ MW} \lesssim P_{D-T} \lesssim 3000 \text{ MW}$ by controlling the density over the range of $0.6 \times 10^{14} \text{ cm}^{-3} \lesssim \bar{n} \lesssim 3 \times 10^{14} \text{ cm}^{-3}$.

It is seen that the ignition and burn processes in TNS can be controlled over a wide range of $\bar{\beta}$ and P_{D-T} values by adjusting $\bar{n}$.

2.7 NEUTRAL BEAM INJECTION HEATING SCENARIOS

Because of the centralized α -particle heating, the need for full neutral beam penetration beyond $\bar{\beta} \sim 2.5\%$ is eliminated (see Fig. 4). An attractive injection procedure¹⁴ emerges that starts with low density, ohmically heated plasma to facilitate initial penetration. Plasma density is increased in conjunction with the increased $\bar{\beta}$ to reduce beam penetration away from the plasma center, where significant α -particle heating occurs. It is found that beam energy from 150 keV to 200 keV may be sufficient for perpendicular injection at $Z_{\text{eff}} \lesssim 1.5$ in TNS.

2.8 SELF-CONSISTENT TNS PLASMA PARAMETERS

Based on the physics concepts discussed above, we have arrived at a set of self-consistent plasma parameters for the TNS reactor with $B_T = 4.3 \text{ T}$, medium-to-high density ($0.6 \times 10^{14} \text{ cm}^{-3} \leq n \leq 2.5 \times 10^{14} \text{ cm}^{-3}$), and high beta tokamak ($\bar{\beta}$ up to 10%) (see Table 1). Upcoming

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Fig. 3. The density dependence of the $\bar{\beta}$ values and fusion power P_{D-T} at the steady-state burn in TNS, assuming empirical energy confinement scaling with a plasma heat conductivity profile similar to those deduced from ORMAK observations.

ALPHA HEATING POWER CAN RELAX BEAM PENETRATION REQUIREMENTS

Fig. 4. Alpha-particle heating and the required neutral injection heating profiles in a sequence of FCT equilibrium in TNS form $\beta = 0.7\%$ to 3.7% . Meanwhile, the peak plasma density (n_0) is assumed to increase from $1.2 \times 10^{14} \text{ cm}^{-3}$ to $2.1 \times 10^{14} \text{ cm}^{-3}$ in a linear fashion with β .

tokamak experiments will refine stability limits of $\bar{\beta}$ and plasma confinement scaling laws. Since $B_T = 4.3$ T is near the lower end of the medium-field strength (see Fig. 1), a large margin of reliability can be achieved in TNS by using $B_T = 6-7$ T with a similar device size. If the experiments indicate $\bar{\beta}$ limits and confinement scalings comparable to or more favorable than those used in this discussion, smaller TNS sizes can be considered in the future.

3. PLASMA ENGINEERING INNOVATIONS

The TNS reactor based on the physics parameters shown in Table 1 assumes a number of significant technological developments. Here we briefly discuss four such areas in which innovations in the plasma engineering studies have a high potential of circumventing or avoiding the advanced technological requirements. These areas cover: (1) the high speed of the pellets anticipated for fueling at the plasma center for long burn,² (2) the relatively poor access due to the anticipated number of TF coils³ for a TF ripple less than a few percent at the outer plasma edge, (3) the difficulties in building and remotely maintaining the multiturn EF coils interior to the TF coils,⁴ and (4) the relatively large, costly pulsed power supplies⁴ to the OH coils required to start up the plasma current in full bore.

3.1 1-D TRANSPORT EVALUATIONS OF PELLET FUELING REQUIREMENTS²⁴ — REDUCED PELLET VELOCITY

Pellet injection simulations using a discrete pellet ablation model²⁵ based on observations in ORMAK have been carried out self-consistently with a 1-D multifluid transport code. The code uses the six-regime anomalous transport model⁶ together with the full neoclassical transport matrix as a reference level of losses.

We find that fueling with 2-mm, 1-km/sec pellets tends to flatten the density profile over the bulk of the plasma and thus dramatically reduces the trapped particle loss rates in a fashion consistent with the analytic estimates.¹⁸ As a result, the inclusion of the full trapped

particle losses increases the heating power required for ignition only by a factor of two to three from the neoclassical estimates. An optimal fueling depth up to one-half the plasma minor radius also emerges⁵ (see Fig. 5). It appears that full penetration by pellets into the plasma may not be desirable due to the associated enhancement of the gradient-driven, trapped particle loss rates.

The requirement of high pellet velocities around 10 km/sec as anticipated previously² could be eased considerably. Assuming that the required depth of pellet penetration can be reduced to roughly a quarter of the minor radius, pellet velocities in the vicinity of 3 km/sec may be more desirable.

3.2 REASSESSMENT OF THE TOROIDAL FIELD RIPPLE REQUIREMENTS — IMPROVED MACHINE ACCESS

In many tokamak designs, it is assumed that the TF ripples near the plasma edge should be lower than one percent or so to avoid any potentially deleterious effects on the plasma confinement. The implied number of TF coils in a reactor is usually around 20, which in turn has strongly limited the access³ to the plasma, the vacuum vessel, the shield, and the interior EF coils. There is strong engineering incentive to carry out a more detailed study of the ripple-induced plasma transport.

We have studied the magnetic field ripple effects with the inclusion of noncircular cross sections of the TF coils and the plasma.²⁶ It is found that, for the typical TNS plasma shown in Table 1 and using 20 nearly pure-tension TF coils with a bore of roughly $7.7 \text{ m} \times 5.4 \text{ m}$, the ripple at the D-shaped plasma edge is below one percent.²⁷ The estimated heat conductivity due to the ripple-trapped ions is then somewhat less than the pseudoclassical electron conduction and also the neoclassical ion conduction (see Fig. 6).

In regions where $r > a/2$, this ripple conduction loss rate is one order of magnitude less than the empirical loss rate, which in turn is another order of magnitude less than the trapped particle loss rates. A reduced number of TF coils will then allow a ripple-induced loss rate comparable to the empirical or the trapped particle loss rates. As

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FUELING PROFILES MAY HAVE A STRONG BEARING ON HEATING
POWER REQUIREMENTS (A. T. MENSE, ET AL)

Fig. 5. The dependence of the minimum heating power (required for ignition) on the depth of fueling for various levels of trapped particle loss rates assumed in the 1-D transport calculations for TNS.

THE ACCEPTABLE MINIMUM NUMBER OF TF COILS DEPENDS
ON THE DOMINATING TRANSPORT PROCESS

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Fig. 6. Heat conduction due to ripple trapping of the ions for 20 and 16 TF coils in TNS in comparison with the pseudoclassical, neoclassical Alcator empirical, and trapped particle coefficients.

indicated in Fig. 6, the use of 16 TF coils with the same bore would result in a ripple conduction coefficient that is roughly five times above the empirical coefficient and roughly six times below the TIM coefficient. Inclusion of the ripple-induced heat loss rate into the 1-D transport calculations will provide an improved assessment of the tolerable reductions in the number of TF coils.

3.3 HYBRID EQUILIBRIUM FIELD COILS — REDUCED ENGINEERING DIFFICULTY AND POWER SUPPLY²⁸

The interior EF coils shown in Fig. 2 are closely coupled to the plasma. If they are also arranged to mimic a conducting shell,¹⁰ they have the advantages of requiring a relatively small power supply and minimizing the OH power supply during plasma start-up and rapid heating; they also contribute to stabilizing the axisymmetric modes.²⁹ However, being about 0.5 m away from the plasma, they are necessarily copper coils due to the anticipated neutron heating load. Because each coil bundle carries an average ampere-turn of about 0.4 MA, multiturn coils must be used; these make them difficult to build and remotely maintain under radioactive environments.

The exterior EF coils shown in Fig. 2 largely avoid these engineering difficulties; however, they require a total power supply which is an order of magnitude above the interior coil requirements. During start-up, the exterior coils require a total of 1.2 GW in addition to an OH requirement of 2.4 GW; the latter is twice the OH requirement when the interior coils are used.

Hybrid EF coils using both the interior and the exterior coils are proposed.²⁸ In this system, the interior currents are permitted to respond to changes in the plasma in a fast time scale and then to decay in a slow time scale. The exterior currents can now respond in the slow time scale. The interior, time-averaged currents are reduced by an order of magnitude below the case when the interior coils are used alone. This permits the use of small, single-turn coils and substantially improves their engineering properties, while the power supply required by the exterior coils can be reduced by an order of magnitude.

3.4 MICROWAVE START-UP — REDUCED COST OF OH POWER SUPPLY³⁰

Assuming the benefit of the hybrid EF coils, the power requirement of the OH coils in TNS is shown to be ~ 1.4 GW.²⁸ The estimated cost of the OH power supply is between 150–250 M\$.⁴ These large power and cost requirements stem primarily from the high and pulsed loop voltage ($V_L > 300$ V for a duration of about 0.2 sec) estimated for plasma start-up in full bore.³¹ The value of V_L could be reduced if a method can be found to preheat the electrons to a few hundred eV in a small volume.

The scenario of toroidal plasma start-up with microwave initiation and heating near the upper hybrid frequency is examined.³⁰ We assume microwave irradiation in the extraordinary mode from the high field side and large absorptions of the extraordinary wave near the upper hybrid resonance. Electron energy losses are due to magnetic field curvature and parallel drifts, ionization of neutrals, cooling by ions, and radiation by oxygen. It is shown by particle and energy balance considerations that electron temperatures around 250 eV and densities of 10^{12} – 10^{13} cm⁻³ can be maintained, at least in a narrow region near the upper hybrid resonance. The corresponding microwave power requirements are estimated to be < 0.6 MW at a frequency of 120 GHz.

The loop voltage and duration required for start-up from this initial plasma in TNS are estimated to be 33 V and 1.8 sec, respectively, to reach a full current of 4.2 MA. These lowered V_L and smoothed voltage pulses, each by an order of magnitude from the unassisted start-up, are expected to reduce the OH power supplies substantially; verification of this start-up method can be carried out in the ISX experiment.³²

4. CONCLUSION

The consistent set of reactor plasma parameters exemplified in Table 1 for the TNS tokamak is arrived at based on reasonable fusion physics assumptions. These include the scaling of the plasma density with the heating power, the inclusion of the trapped particle loss rates into 1-D multifluid transport calculations, the FCT nature of the plasma

evolution during rapid plasma heating, the "shell-like" EF coils appropriate for D-shaped high beta plasmas, the latest estimates of $\bar{\beta}$ limits by the pressure-driven MHD ballooning modes, the coupled equilibrium evolution and transport calculations in a D-shaped FCT, and the centrally localized α -particle heating profile that lowers the neutral beam energy requirements.

Our calculations have identified that a D-shaped TNS reactor with medium fields ($B_T = 4-7$ T), medium-to-high densities ($0.6 \times 10^{14} \text{ cm}^{-3} \leq n \leq 2.5 \times 10^{14} \text{ cm}^{-3}$), high betas ($\bar{\beta}$ up to about 10%), a major radius of 5 m, a vertical elongation of 1.6, and an aspect ratio of four, encompasses a viable tokamak reactor concept. We also showed that the ignition and burn process in the TNS reactor can occur over wide ranges of fusion power output and plasma density below the maxima set by the stability $\bar{\beta}$ limits. This is in contrast to the sharp thresholds in density and power output indicated by the 0-D calculations. Although we have used the TNS reactor as a focus, the result of these studies should be equally applicable to the plasma cores in short pulse ignition test reactors and long pulse power demonstration plants.

To further improve the attractiveness of our medium-field reactor concept for TNS, we have derived improved understandings and explored innovative approaches in the plasma engineering studies that have high potentials of reducing the size, cost, and complexity of the reactor. Here we have discussed the examples related to four areas of anticipated technological difficulties: the high fueling pellet velocity, the limited access between the TF coils, the difficulties of building and maintaining large, multiturn EF coils interior to the TF coils, and the large and costly pulsed OH power supply.

The proposed solutions to these difficulties are expected to impact the TNS reactor in a very beneficial fashion, although detailed engineering evaluations of these innovations are needed to quantify the benefits. Each of these exploratory results for the TNS reactor, if verified by upcoming theoretical and experimental studies, should equally benefit many other tokamaks.

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