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RECENT PROGRESS IN STELLARATOR REACTOR CONCEPTUAL DESIGN*

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ABSTRACT

The Stellarator/Torsatron/Heliotron (S/T/H) class of toroidal magnetic fusion reactor designs continues to offer a distinct and in several ways superior approach to eventual commercial competitiveness. Although no major, integrated conceptual reactor design activity is presently underway, a number of international research efforts suggest avenues for the substantial improvement of the S/T/H reactor embodiment, which derive from recent experimental and theoretical progress and are responsive to current trends in fusion-reactor projection to set the stage for a "third generation" of designs. Recent S/T/H reactor design activity is reviewed and the impact of the changing technical and programmatic context on the direction of future S/T/H reactor design studies is outlined.

1. INTRODUCTION

The Stellarator/Torsatron/Heliotron (S/T/H) class of toroidal magnetic fusion devices collectively promises ignited, steady-state, disruption-free operation with reduced recirculating power fractions, natural-magnetic-divertor impurity control, and start-up on existing magnetic surfaces as inherent consequences of the confinement approach. International progress¹ continues on a number of experiments, with the best plasma parameters being similar to those obtained in tokamaks of comparable size (e.g., $n_T = 3-5(10)^{18}$ s/m³, $T_0 = 1$ keV, and $\langle\beta\rangle = 0.02$). The next major US experiment, the Advanced Toroidal Facility (ATF),² is under construction at the Oak Ridge National Laboratory (ORNL) with initial operation anticipated for late 1986. The ATF is designed to demonstrate attractive, second-stability-regime MHD beta limits in excess of 0.08 for moderate aspect ratios (~ 7), thereby opening an important new region of parameter space for eventual S/T/H reactor exploitation. The other major world S/T/H experimental devices, all with major toroidal radius $R_T = 2$ m, include the operational (continuous-helical-coil) Heliotron-E (Japan) and

Wendelstein VII-A (FRG) as well as designs for L-3 (USSR, similar to ATF) and a (modular-coil) Wendelstein VII-AS (FRG), the latter to become operational in 1987. Continuing theoretical progress³ suggests various techniques for optimizing the S/T/H equilibrium configuration⁴ and reducing transport losses⁵⁻⁸ at high beta by appropriate tuning of the number of magnetic-field periods, rotational transform profile, vertical field, magnetic-well depth, and magnetic-field ripple.

Characterized by low beta and large physical size and output, the "first generation" of S/T/H reactor conceptual designs dates from 1954-1970. New information, together with results from "second-generation" S/T/H reactor conceptual-design studies dating to a few years ago based on superconducting continuous-coil⁹⁻¹¹ or modular-coil^{12,13} configurations, sets the stage for a major redefinition and reevaluation of the prospects for a technically and economically competitive "third generation" S/T/H reactor embodiment. Such a reexamination is desirable in view of generic¹⁴ and tokamak-specific¹⁵ suggestions for substantial improvements in the projected performance of commercial magnetic-fusion power reactors based on superconducting coils. The S/T/H approach is responsive to these new design trends. Moreover, advanced non-planar-axis stellarator configurations with projected beta values above 0.20 have been suggested,¹⁶ for which competitive advanced-fuel or high-power-density, compact, resistive-coil embodiments may be possible.¹⁷ In addition to being a viable fusion power core (FPC) in its own right, the S/T/H concept has contributed ideas for disruption-control¹⁸ or impurity-control technology¹⁹ which can benefit the tokamak or other magnetic-fusion concepts. Of course, the ultimate magnetic-fusion reactor may well represent a synthesis or hybrid²⁰ of the several distinct approaches known today, incorporating the known favorable features of the S/T/H.

No major, integrated conceptual S/T/H reactor design activity is presently underway. The collection of second-generation design points of a few years ago, together with more recent suggestions and innovations provides the basis for continued, invigorated interest in

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TABLE I
CONTINUOUS-COIL TORSATRON/HELIOTRON REACTORS

	MIT	JAPAN	USSR	ORNL	ORNL
	T-2	HELIOTRON-H	TNPP	ATF-R	ATFSR
Pooidal periodicity	$l = 2$	$l = 2$	$l = 3$	$l = 2$	$l = 2$
Toroidal periodicity	$n = 19$	$n = 15$	$n = 7$	$n = 12$ $N = 24$	$n = 12$
Edge rotational transform	1.9	2.2	--	0.7	0.9
Plasma radius (m)	1.5	1.7	2.1	1.8	1.0
Coil radius (m)	4.0	3.2	--	3.5	(3.7)
Major toroidal radius (m)	24.0	21.0	36.8	12.25	7.0
Plasma volume (m ³)	1070	1200	3200	785	~140
Average density (10 ²⁰ /m ³)	2.5	1.17	2.5	--	(1.2)
Plasma temperature (keV)	15	10.3	9.4	--	(15)
Lawson parameter (10 ²⁰ s/m ³)	--	3.0	7.25	--	--
Average beta	0.065	0.06	0.1	0.08	(0.07)
DT plasma power density (MW/m ³)	--	2.4	--	4.7	(4.3)
On-axis magnetic field (T)	5.0	4.0	4.4	6.0	5.0
Peak field at coil (T)	~9	9	--	12.0	--
Stored magnetic energy (GJ)	--	115	--	--	--
First-wall neutron current (MW/m ²)	2.2	1.3	4.0	2.7	(3.3)
Thermal power (MWt)	3600	3400	9300	4000	(700)
Net electric power (MWe)	(1170)	~1200	(3250)	1302	(230)
System power density (MWt/m ³)	(0.35)	0.41	--	1.5	--
Mass utilization (tonne/MWt)	--	9	--	2.5	--
Specific net power (kWe/tonne)	--	39	--	130	--
Recirculating power fraction	(0.07)	(0)	0.10	0.07	(0.07)
Net plant efficiency ($\eta_{TH} = 0.35$)	(0.33)	(0.31)	0.36 ^(a)	0.33	(0.33)

^(a) here, $\eta_{TH} = 0.39$

Fig. 1. a) elevation and b) plan views of the $l = 2$ Heliotron-H reactor.²² The vertical-field coil set is not shown.

he S/T/H. Available S/T/H conceptual reactor design activity is summarized in Sec. II. Technical and economic assessment issues for the S/T/H approach are considered in Sec. III. The conclusions of this review are summarized in Sec. IV. Unless otherwise noted, all of the T/H designs discussed here assume superconducting coils and the D/T/Li fuel cycle, consistent with beta values less than .10.

I. S/T/H REACTOR DESIGN ACTIVITY

A. Continuous-Helical Coil Systems

Because of superior magnetic performance i.e., higher values of rotational transform and shear), continuous-helical-coil T/H configurations project favorable reactor embodiments. Second-generation examples include the US T-2,^{9,21} the Japanese Heliotron-H,^{10,11,22} and several designs from the USSR.²³⁻²⁵ Because life-of-plant coil reliability cannot be credibly defended for these systems, the inclusion of rarely-remountable resistive joints in the helical coils doubtlessly will be required.^{21,26} Such joints also facilitate initial off-site fabrication and on-site assembly and therefore reduce construction time and risk. Schemes for routine access to and replacement of underlying first-wall/blanket/shield modules without decoupling the coil joints or otherwise disturbing the coils have been identified in preconceptual studies.

Design points for representative second-generation T/H reactor systems are summarized in Table I. Not included are two toratron coil configurations with generally similar parameters generated by the Los Alamos/Westinghouse/Stone & Webster study.^{13,27} The second-generation systems tended to have large aspect ratios and major radii > 20 m, because of unfavorable neoclassical-transport-scaling considerations. Figure 1 illustrates the $l=2$ (high transform, high shear) Heliotron-H, the best elaborated of these systems. Coil support rings are provided at every half period to react the outward radial force of ~ 40 MN/m. The blanket modules (~ 3 tonnes) are removed through the ports indicated in Fig. 1. Impurity control is provided by a helical magnetic divertor. As originally introduced, the Heliotron-H postulated life-of-plant continuous helical coils. Beyond more recent consideration of the demountable coil joints, Heliotron-H design activity is largely confined to neutronics analyses^{28,29} of the water-cooled Li_2O (natural Li) blanket and tungsten shield. Activity in this area is coordinated by the University of Kyoto, site of the Heliotron-E experiment, with contributions from several other Japanese university/industrial groups. The level of effort is reduced from that of a few years ago.

Work on the T-2 design at the Massachusetts Institute of Technology (MIT) has been largely suspended since late 1983.

Considerable recent activity regarding S/T/H reactor conceptual design in the USSR has been reported,²³ activity being centered at the Physico-Technical Institute in Kharkov. The base design is a second-generation $l=3$ toratron (designated TNPP) with magnetic-divertor impurity control. A module of the TNPP system is illustrated in Fig. 2. As is generally the case for commercial fusion reactor designs in the USSR, hybrid blanket systems for fissile-fuel production are being actively pursued.²⁴

Fig. 2. Diagram of a module of the $l=3$ TNPP reactor:²⁴ 1) plasma, 2) helical winding, 3) vertical-field (compensating) coil, 4) case, 5) blanket, 6) cryostat covering, 7) radiation shield, 8) divertor system.

Also included in Table I are preliminary ORNL parameters for third-generation toratron reactors based on ATF physics studies. Integrated conceptual designs have not been performed to date. The ATFR²⁷ retains the nominal $P_{TH} = 4000$ MWt of the second-generation systems but at lower aspect ratio (~ 7) and higher beta (~ 0.08). More recent preliminary calculations including radial electric field ($e\phi/T = 4$, electron regime) effects on neoclassical transport (thermal diffusivity, $\chi = v$ rather than $1/v$) result in the ATF SR,³⁰ a much smaller fusion-power-core (FPC) size and power output, which could be multiplexed ($N = 5$) with a shared central-station balance of plant to avoid adverse economies of scale. The ATF SR could also serve a valuable role as a convenient individual pilot plant.

TABLE II
MODULAR-COIL STELLARATOR REACTORS

	UW UWTOR-M	LA MSR-IIB	IPP ASR25T7	ORNL/UW SYMMOTRON	UW RARSR
Poloidal periodicity	$l = 3$	$l = 2$	$l = 2$		$l = 2$
Toroidal periodicity	$m = 6$	$m = 4$	$m = 5$		$p = 3$
Number of modular coils	$N = 18$	$N = 36$	$N = 50$	$N = 24$	$N = 12$
Edge rotational transform	1.13	0.80	0.6		0.40
Plasma radius (m)	1.72	0.81	1.65		2.1
Coil radius (m)	4.8	3.3	5.2	4.0	5.55
Major toroidal radius (m)	24.1	23.0	25.5	16.0	13.6
Plasma volume (m ³)	1410	298	1370		1180
Average density (10 ²⁰ /m ³)	1.46	3.64	1.4		--
Plasma temperature (keV)	9.8	8.0	~11		--
Lawson parameter (10 ²⁰ s/m ³)	5.4	3.43	2.4		--
Average beta	0.06	0.08	0.053		0.044
DT plasma power density (MW/m ³)	3.0	12.4	2.6		--
On-axis magnetic field (T)	4.5	6.56	5.3	4.5	5.7
Peak field at coil (T)	11.6	11.6	8.7		--
Stored magnetic energy (GJ)	171	109	170		--
First-wall neutron current (MW/m ²)	1.41	2.0	(~2)		2.0
Thermal power (MWt)	4820	4000	2600		3600
Net electric power (MWe)	1836	1302			1200
System power density (MWt/m ³)	0.34	0.60	--		--
Mass utilization (tonne/MWt)	11.4	6.6	--		--
Specific net power (kWe/tonne)	33	49	--		--
Recirculating power fraction	0.033	0.07	--		0.08
Net plant efficiency ($\eta_{TH} = 0.35$)	0.38 ^(a)	0.33	--		0.33

(a) here, $\eta_{TH} = 0.39$

Fig. 3. Elevation view of the $l = 3$ UWTOR-M modular stellarator reactor, 12

Fig. 4. Elevation view of the 1 - 2 Modular Stellarator Reactor.¹³

Fig. 5. Plan and elevation views of the W-VII-AS-based ASR coils.³⁴

Fig. 6. Views of a reactor-scale SYMMOTRON coil configuration.³⁶

B. Modular-Coil Systems

Modular-coil stellarator configurations³¹ obtain helical magnetic-field components from periodic lateral deformations of a discreet set of nominally toroidal-field coils, as in the Interchangeable Modular Stellarator (IMS) experiment at the University of Wisconsin (UW). Several second-generation reactor designs based on such coils have been generated, including the $l = 3$ UWTOR-M¹² of the UW group, the $l = 2$ Modular Stellarator Reactor (MSR) from the Los Alamos/Westinghouse/Stone & Webster study,^{13,32} and a reactor extrapolation of the $l = 2$ Wendelstein-VII-AS (W-VII-AS) configuration.³³⁻³⁵ These reactors are illustrated in Figs. 3-5. Parameters are summarized in Table II. Also included are parameters for a third-generation-reactor coil set based on the Symmetric Modular Toratron (SYMMOTRON)³⁶ configuration, as illustrated in Fig. 6, and the Reduced-Aspect-Ratio Stellarator Reactor (RARSR).³⁷ A coil modularization scheme for the TNPP toratron reactor has also been proposed.²⁴

The $l = 3$ UWTOR-M study at UW emphasized engineering aspects and concentrated on establishing a credible coil design and overall system integration. Poloidal stepping of the successive modules accommodates the helical precession of the plasma column without helical mechanical components. The coil configuration consists of $N = 18$ wedged coils with $l = 3$ and lateral deformation $d/r_c = 0.5$. The design physics basis includes detailed one-dimensional radial transport computations and an assumed $\langle B \rangle = 0.06$. Engineering aspects of the design were concluded to be within reasonable extrapolation of present technology. Radial coil forces (~ 70 MN/m) are reacted by structural rings at the coil midplanes. Lateral coil forces (~ 80 MN/m) are supported by contacting the neighboring coils at the points of maximum coil lateral deformation. Impurity control is provided by magnetic divertors which take advantage of discrete, localized flux bundles emerging between the bands of the coils. Divertor targets, consisting of rotating graphite-coated cylinders, are located outside the shield.¹⁹ Because access is diminished by the coil support rings, the routine maintenance scheme requires radially outward translation without lifting of a decoupled coil/blanket/shield module (~ 900 tonnes). To avoid vacuum seals between modules, the entire reactor torus is housed in a vacuum enclosure, as shown in Fig. 3. The blanket uses a static PbLi eutectic as the breeder material with embedded steam tubes for heat removal.

The $l = 2$ MSR¹³ coil configuration consists of $N = 36$ modified Rehker-Wobig modular coils with modest lateral deformation, $d/r_c = 0.28$ in order to reduce individual coil

mass, the ratio of peak coil field and on-axis field, the toroidal-field ripple, and lateral force components. Higher beta (0.08) allows higher plasma power density, higher system power density and better mass utilization, and consequently lower unit costs. Relatively few MSR toroidal-field periods ($m = 4$) allows radial rotational transform profiles, $\iota(r)$, in the range 0.7-0.9, providing significant non-zero transform on-axis, avoiding rational surfaces within the plasma, and, with the addition of appropriate higher-harmonics into the coil winding law providing significant positive shear at the plasma edge. To improve the plasma filling fraction, impurity control is assumed to be provided by a pumped limiter, although divertors are also compatible with the design. Each of the 36 coils is associated with 3 blanket/shield modules. The rotation cross section of the plasma is tracked toroidally by stepped rotations of the blanket/plenum zones between successive modules. No helical mechanical components are required. The blanket uses a Li_2O solid breeder with pressurized water coolant. A nonbreeding beryllium multiplier/reflector zone is used at the extreme ends of the elliptical plasma cross section, where the coil/plasma standoff distance is small. The MSR module configuration is shown in Fig. 7. The blanket and movable shield are subdivided into convenient modules, which can be removed without disturbing the coil set. All connections to the modules are made in the shielded region above a port in the permanent vacuum boundary. Routine maintenance and replacement of limiter/first-wall/blanket components would be accomplished without moving modular coils in order to promote high plant availability. Integrated blanket and movable shield modules are inserted/removed through ports between the fixed modular coils and above the reactor midplane.

Fig. 7. Typical MSR module configurations.¹³

While not an integrated reactor study, the IPP-Garching group has performed an extrapolation of the proposed W-VII-AS (modular) experimental coil configuration to reactor dimensions for the Advanced Stellarator Reactor (ASR).^{33, 34} A conservative blanket/shield standoff distance of 1.8 m is assumed between the plasma ($\langle\beta\rangle = 0.053$) and coils, leading to a major radius of 25 m at an aspect ratio $A = 16$, consistent with other second-generation S/T/H reactor designs. Unlike the UWTOR-M and MSR designs which invoke identical modular coils, the ASR requires several distinct coil types having different lateral distortions and coil radii to achieve the desired plasma behavior. The larger number of coils (50) results in reduced lateral forces on the coils and lower field ripple but inhibits access to underlying first-wall/blanket/shield components. Coil designs for non-planar-axis systems³³ and a 15-m major radius, ~500 MWt burn experiment have also been reported,^{34, 35} which could serve as a multiplexed FPC or a useful pilot reactor.

In a similar spirit to the ASR design activity, the UW group in collaboration with the ATF group at ORNL has extrapolated a SYMMOTRON coil set to third-generation reactor dimensions ($R_T = 16$ m).³⁶ Detailed coil structural-analysis calculations are in progress, but other reactor parameters have not been reported. The relatively sharp corners of SYMMOTRON outboard coil return legs act to concentrate stresses to relatively high values (~400 MPa) for the present reference reactor coil set. Modifications to improve performance are under investigation.

Recent preliminary parametric studies by W.N.G. Hitchon³⁷ have identified attractive low-aspect-ratio, $\langle\beta\rangle = 0.04$, $l = 2$ modular-coil ($N = 12$) reactor configurations. Cost estimates suggest direct costs comparable to that of the 1980 STARFIRE tokamak design. High rotational transform is maintained by having few (2-3) toroidal field periods. At higher third-generation beta values, truly superior performance can be anticipated for S/T/H reactors in this size range.

III. S/T/H REACTOR ASSESSMENT

The collection of second-generation S/T/H reactor conceptual design studies summarized in the previous section have identified generally competitive fusion systems based on conservative physics assumption and engineering design constraints. The larger physical size and capital cost of the typical second-reactor generation S/T/H FPC is offset by significantly reduced recirculating power requirements to give comparable electric power costs. The greater level of attention devoted to the S/T/H concept in recent years has produced important innovations and refinements in the S/T/H

concept, which set the stage for a dramatic improvement in third-generation S/T/H reactor extrapolations. Those improvements include higher beta values (> 0.08) and reduced radial transport at lower aspect ratio ($A < 10$). Such fundamental improvement is consistent with the theme of ongoing improvement in superconducting-coil tokamak and tandem-mirror reactor conceptual designs, against which the S/T/H concept must inevitably compete. No integrated S/T/H reactor conceptual design has been initiated to date that takes full advantage of these third-generation features to identify the crucial advantages/limitations of the relevant physics, technology, or economics.

Critical engineering/technology issues for the S/T/H can be categorized as related to Plasma Engineering Systems, Nuclear Systems, Magnet Systems, and Maintenance Systems. These issues are summarized in Table III. Other issues, generic to magnetic fusion, also exist.

TABLE III
S/T/H REACTOR CRITICAL ISSUES

Plasma Engineering Systems

- Better resolution/optimization of the S/T/H magnetic topology required to maximize equilibrium/stability limits on beta.
- Tuning of the magnetic topology to reduce radial transport in the presence of self-consistent electric fields.
- Better assessment of alternative impurity control schemes on plasma performance and reactor operation/cost.
- Minimum-grid-power plasma start-up and approach to ignition.
- Adequate fusion-product alpha particle retention to offset transport losses and achieve thermally-stable ignition at attractive plasma power densities.
- Hybrids with other confinement approaches.

Nuclear Systems

- Thin blankets and high-albedo shields near coils to improve the coil/plasma coupling.
- Neutron streaming in helical-magnetic-divertor configurations.
- Reduced nuclear envelope as the FPC size is reduced in third-generation embodiments.
- Safety implications of increased afterheat power density in blankets and high-heat-flux components in third-generation embodiments.

Magnet Systems

- Factory fabrication of modular-coils or segmented helical coils to reduce cost/risk.
- Problems associated with the inability to wind modular coils under tension, as is done with Yin-Yang mirror coils.
- Tradeoffs and options for resistive-coil, compact or non-planar-axis systems.

Maintenance Systems

- Provision of rapid removal replacement of first-wall/blanket/shield modules without disturbing the coils to improve availability.
- Removeable modular coils or demountable helical-coil segments in the (rare) event of coil failure/damage.
- Integration and subsystem design of helically arrayed FPC components for reduced-accessibility, third-generation embodiments.
- Multiplexing of low-output third-generation FPCs in a ~1000-MWe-class plant.
- Cost/operating advantages deriving from the absence of a current-drive subsystem.

IV. CONCLUSIONS

Recent international S/T/H theoretical and experimental activity has produced favorable results, inspiring renewed interest in S/T/H reactor extrapolations. Global conceptual reactor design activity has subsided somewhat from the level of a few years ago, at which time several second-generation conceptual design studies were carried out. Recent progress has identified important options for reduced S/T/H FPC physical size at sufficiently high beta values (> 0.08) to allow competitive commercial performance of third-generation superconducting-coil designs, should they be commissioned. Appropriate technical issues (e.g., demountable joints) are being addressed in focussed studies. Advanced, non-planar-axis systems have been introduced, which at even higher beta values, may allow advanced-fuel or compact, resistive-coil reactors. The S/T/H approach contributes to an integrated toroidal-confinement program for magnetic-fusion development and eventual commercialization.

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