COMPACT STELLARATORS AS REACTORS*

J. F. Lyon, L. A. Berry, S. P. Hirshman, D. A. Spong, D. J. Strickler
Oak Ridge National Laboratory

R. Miller, F. Najmabadi, *University of California at San Diego*
P.M. Valanju, *University of Texas at Austin*

Compact stellarators (stellarator-tokamak hybrid configurations with plasma aspect ratios $A_p = R_0/a_p$ = 3-4) could combine the best features of tokamaks (moderate aspect ratio, good confinement, and high β) and currentless stellarators (steady-state operation without external current drive or disruptions, stability against external kinks and vertical displacement events without a close conducting wall or active feedback systems, and low recirculating power in a reactor). Lower A_p leads to reduced size for higher wall loading and lower cost for a given fusion power, which translates into lower cost of electricity. The R_0 = 14 m Stellarator Power Plant Study (SPPS) reactor was calculated to be cost competitive with the R_0 = 6 m ARIES-IV and R_0 = 5.5 m ARIES-RS tokamak reactors with higher wall power density because of SPPS's low recirculated power. A more compact stellarator reactor could retain the cost savings associated with the low recirculated power of the SPPS reactor, but with smaller size (lower cost) and higher wall power density.

Three low-aspect-ratio stellarator-tokamak hybrids (in which the poloidal field is created by both currents in external windings and the plasma bootstrap current, I_{BS}) are examined as reactors: a low-I_{BS} quasi-omnigeneous (QO) case, a medium-I_{BS} quasi-axisymmetric (QA) case which forms the basis for the proposed NCSX experiment, and a higher-I_{BS} QO case. The corresponding reactor configurations are characterized by the ratios $A_\Delta = R_0/\Delta$, A_p, and B_{max}/B_0 where Δ is the minimum distance between the plasma edge and the center of the coils for a given R_0, and B_{max} is the maximum field on the coils. The minimum reactor size is set by $R_0 = A_\Delta(D + ct/2)$ where D is the space needed for scrapeoff, first wall, blanket, shield, dewar, coil case, and assembly gaps, and ct is the radial depth of the modular coils. Values for these distances are obtained from three reactor models: the HSR based on W7-X, ARIES-RS, and an LHD-based reactor. For the reactor systems studies, the NESCOIL code is used to calculate the sheet-current solution at a distance Δ from the plasma that creates the desired plasma boundary for different values of Δ, and B_{max}/B_0 is calculated at a distance ct/2 radially in from the current sheet to choose a maximum value for Δ. Discrete modular coils will be calculated using the NESCOIL and COILOPT codes and the MAGFOR code will be used to calculate B_{max}/B_0 to refine the parameters of the reactors from the MHHOPT cost-minimization reactor systems code [1]. The reference plasma assumptions are volume-averaged $\langle\beta\rangle \leq 5\%$, Lackner-Gottardi confinement multiplier ≤ 2, broad density profiles with $n_e \leq n_{Sudo}$, $n(C)/n_e = 0.01$, and $n(He)/n_e = 0.05$. The reference device parameters are $A_\Delta = 2.22$, $B_{max} \leq 16$ T, ARIES-RS blanket and shield, and $P_{electric}$ = 1 GW (net).

Table 1 compares parameters for SPPS and a medium-I_{BS} QA reactor obtained using the ARIES-IV materials assumptions and costing algorithms and a 0-D model based on Lackner-Gottardi confinement scaling. The A_p = 3.4 QA configuration is closer to ARIES-RS in size than the earlier cost-competitive SPPS [2], resulting in a reduced CoE. Figure 1 shows a POPCON plot of the operating space (volume-averaged density $\langle n\rangle$ and density-averaged temperature $\langle T\rangle$) for a QA reactor. The solid lines indicate constant auxiliary heating power, the heavier solid line indicates ignition, and the orthogonal set of broken lines indicate constant P_{fusion}. The dot marks the 1-GWe

Table 1. Reference Reactor Parameters.

Parameter	QA	SPPS
Ave. major radius R (m)	9.0	14.0
Ave. plasma radius (m)	2.5	1.6
Field on axis, B_0 (T)	5	5
B_{max} (T) on coil	13.5	14.5
Vol. ave. $\langle n \rangle$ 10^{20}m^{-3})	1.1	2.3
n-ave.Temp. $\langle T \rangle$(keV)	10.7	6.7
Vol. ave. beta $\langle \beta \rangle$ (%)	3.5	4.7
L-G Confinement mult.	2	1.25
Wall power (MW/m^2)	4.7	1.2

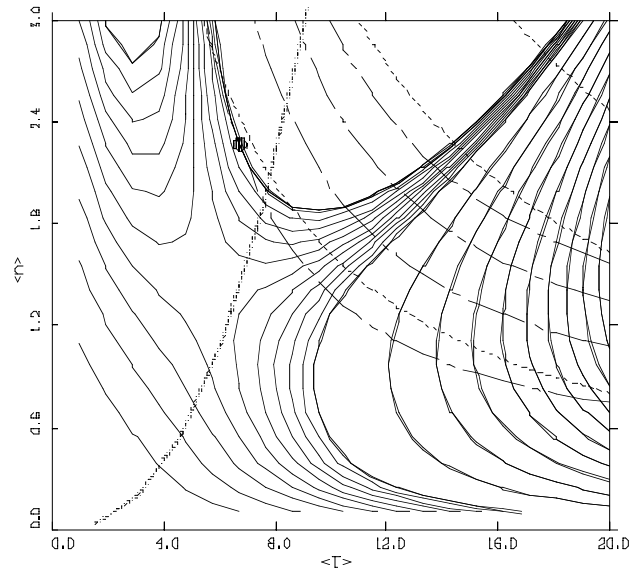

Fig.1. Operating space for a QA reactor.

operating point. Other transport models used in the study are: (1) a 1-D transport model that solves the electron and ion heat flux equations for $T_e(r)$ and $T_i(r)$ with anomalous and electric-field-dependent $\chi_{e,i}(r)$ for different fixed $n_e(r)$ and electric potential $\phi(r)$ profiles; and (2) a self-consistent 1-D transport model that solves for $T_e(r)$, $T_i(r)$, $n_e(r)$, $n_i(r)$, and $\phi(r)$ assuming only heat (alpha-particles) and particle source (pellets or gas) terms [3].

The study examines sensitivity to various assumptions and constraints in the optimization: different 0-D and 1-D transport models, level of the ambipolar electric field, degree of alpha-particle losses, beta limits, impurity levels, B_{max}, j_{coil}, electric power output, blanket and shield models, materials and costing assumptions, etc. The table below indicates the sensitivities to some of these assumptions as they are varied one at a time for reactors with R_0 = 9 m and R_0 = 13.3 m. The value of R_0 is set by the blanket and shield thickness, or equivalently the minimum distance between the plasma edge and the coils. The updated costing algorithms and blanket/shield models being developed for the ARIES-AT study will be applied to these cases.

R_0 = 9 m			R_0 = 13.3 m		
Parameter	**B, T**	$\langle\beta\rangle$ (%)	**Parameter**	**B, T**	$\langle\beta\rangle$ (%)
base case, P_{elect} = 1 GW	5.0	3.5	$P_{electric}$ = 1 GW	5.0	2.6
Reduced field on coil	4.4	4.6	Reduced field on coil	3.8	4.4
$P_{electric}$ = 1.5 GW	5.0	4.4	$P_{electric}$ = 1.5 GW	5.0	3.3
$P_{electric}$ = 2 GW	5.0	5.2	$P_{electric}$ = 2 GW	5.0	3.9

References

[1] J. F. Lyon et al., *Fusion Engineering and Design* **25** (1994) 85.
[2] Stellarator Power Plant Study, UCSD-ENG-004 (1997).
[3] J. F. Lyon et al., 21st EPS Conf. on Controlled Fusion and Plasma Phys., Montpellier, 1994, Vol. 18B, Part I, p. 380.

* Research supported by the USDOE under contract DE-AC05-96OR22464 with Lockheed Martin Energy Research Corp.