

Memo: ARIES-26 **Blue font items have been modified or added**
Date: 28 February 2006
Subject: ARIES Project Meeting Minutes, 23 January 2006, University of California, San Diego
To: ARIES Team
From: L. Waganer

Organization	ARIES Compact Stellarator
ANL	
Boeing	Waganer
DOE	
FZK	Ihli
General Atomics	Turnbull
Georgia Tech	Abdel-Khalik
INL	
LLNL	
MIT	Bromberg
NYU	
ORNL	Lyon
PPPL	Ku, Zarnstorff (phone)
RPI	
UCSD	Mau, Najmabadi, Raffray, Tillack, Wang (X.)
U of Wisc	El-Guebaly

Ref: Agenda and Links to Presentations: <http://aries.ucsd.edu/ARIES/MEETINGS/0601/>

Administrative

Welcome – Rene Raffray welcomed the ARIES Team to the University of California – San Diego that graciously provided the refreshments. He also informed the team of the facilities and the building safety instructions.

Status of ARIES Program – Farrokh Najmabadi affirmed the good project teamwork to converge to a baseline design point suitable to enter the more detailed design phase. He expects the conceptual design to be completed by the end of 2006. He also mentioned that the team is considering future assessment candidates for future years.

The date and location for the next ARIES **meeting** was not discussed and finalized. Farrokh mentioned that following this current meeting, the US/Japan/EU Fusion **Power Plant** Workshop will be conducted for 2 days with updates on the current US, Japan, and EU **power plant and demonstration designs**.

[Order of discussions below are grouped according to topic areas and do not reflect agenda sequence.]

Compact Stellarator Physics Basis

New Results for Plasma and Configuration Studies – Long Poe Ku discussed the surface quality of the NCSX-class plasma configurations ranging from low aspect ratio (3.5) up to higher aspect ratio (5.6). Low effective ripples have been predicted for $A > 4$ with favorable MHD stability properties and ballooning conditions. N3ARE has been predicted to be stable at $A = 4.5$. The rotational transform profile and quality of the equilibrium flux surfaces are predicted to be similar to NCSX. The latter equilibrium flux surfaces were shown by PIES calculations.

Collisionality (ν), beta, and R scaling are very important to the alpha loss. Long Poe showed the strong dependence for N3ARE on ν , β , and R. He provided a graph of density and temperature profiles for N3ARE to be consistent with the systems code results at $\beta = 5\%$. The resulting pressure profile using density and temperature is consistent with the systems code results. The bootstrap current profile is broader and shifted inward. More convergence studies are needed. Because of the larger $n_0 R / T_0^2$ of the new profiles, the bootstrap current will be smaller. At $\beta = 5\%$, the bootstrap current is similar to NCSX levels at corresponding $\beta = 4\%$ with similar MHD properties. Moreover, a small modification of the plasma shape can provide kink stability. The ripple and alpha loss are nearly the same due to changes in the pressure and current profiles.

Update on Beta Limits for ARIES-CS – Alan Turnbull has initiated application of the equilibrium and stability tools to the plasma geometry variations. He can also evaluate the sensitivity to iota and pressure profiles for the ARE and MHH2 configurations. The new ARE cases are baselined back to the scaled NCSX cases. He found that the larger, but similar wall geometries, resulted in the ARE plasma tips approaching the calculated wall positions, which caused code difficulties. He is working to construct a revised wall that will relieve the close approach of the plasma tips. This wall is not representative of the actual physical wall and is only used in the code as a construct.

An Update on Divertor Heat Load Analysis and Derived Geometry – T.K. Mau summarized the code usage to determine the alpha and heat load distribution to establish the divertor geometry. It is desired to have a low heat flux peaking factor for the divertor (<10 and preferably around 2), but also to keep the divertor surface area less than 10% of the wall area. It was also suggested the divertor should provide a geometry suitable for pumping neutrals out of the scrape-off region, but that has not yet been considered so far. TK suggested a systematic optimization approach in that the divertor surface will be nearly conformal and somewhat inwardly convex to LCMS to provide grazing incidence together with large field line interception, with the aim to spread out the heat load. Suggested geometry plots were provided, but more code analysis work will be needed. The related action items address additional areas of concerns.

Compact Stellarator Reactor Integrated Systems Assessment

Assessment of Power Core Parameters and Related Costs – Laila El-Guebaly reported her results of analyzing the costing algorithms for several major power core systems and normalizing them to recent ARIES reactor assessments. The CS Reactor Building cost compared favorably with the

RS but the AT was lower (LSA=1 as compared to 2 for the others). This same trend was observed for the primary structure. [Les Waganer will verify the costing algorithms for the reactor and hot cell buildings.](#) Laila considered a dual coolant option for the Main Heat Transfer and Transport System. She raised the question about the number and the complexity of the heat exchangers. Additional investigation of this system still remains as some details remain to be finalized. The miscellaneous power for the reactor building and BOP should remain at a 50 MW (5% of net electric power), as this is a generic value for this size of power plants. Laila showed the costs for the Turbine Plant Equipment for [single and dual coolant/turbine](#) systems with a Brayton cycle conversion. [The single turbine system will be adopted for ARIES-CS.](#) The Heat Rejection System costs seemed reasonable, but as the system becomes more defined so will the costing. The advanced LiPb/SiC, higher performance system remains an [attractive](#) option.

Systems Code Refinements and Updated Information – Jim Lyon summarized his action items from the last meeting and then provided the new or revised data. He showed the current power flow used in the systems code along with the revised thermal conversion efficiencies and pumping power assumptions and algorithms. It was recommended the Balance of Plant (Miscellaneous) would be reset to 5% of the net electric power. Jim and Laila have been collaborating on the definition of the other plant costing algorithms with convergence on reasonable values. The cost of the helium has been provided by Les Waganer, but not in time for inclusion in the current presentation. Jim highlighted how he was modeling the bucking element and its impact on the overall nuclear island masses and costs.

Jim then summarized the code output data (masses, costs, physics data, and power flows) for the ARE case. In order to examine the specific cost items, Jim provided in-depth cost data sheets for each cost category. He also provided several parametric scans for neutron wall load. He compared the cost of the Compact Stellarator to the AT, RS, and SPPS power plant costs.

Jim closed with a list of remaining items to incorporate into the systems code, including startup coils, more definition of manifold design, divertor definition, [replacement cost](#), and a better understanding of the underlying physics.

Compact Stellarator Reactor Engineering Assessment

Status of Coil Structural Design and Magnetic-Structural Analysis – At the last meeting, it was proposed to modify the coil cross-section to better reflect the current coil geometry. Xueren Wang modified his CAD model accordingly and illustrated the new geometry as compared to the previous model. More radial space is provided at the expense of toroidal and poloidal open space. Some coils are physically touching each other, but not interfering. He presented the results of the ANSYS EM FEM analyses. Lots of discussion was required to understand the force diagrams. Again, TK showed that the forces on the field periods were balanced with no net forces except for a net inward force that is resisted by a bucking surface (shell and/or strong-back). A bucking cylinder is not [required if 85 cm thick strong-back supports the inboard side of the coils.](#) Again, a lot of discussion is required to understand the geometry and the supporting analysis. Suggestions were made on how to illustrate the strong-back and supporting shell. The coil structure is Incoloy 908 and the calculated stresses are well below the design allowables. However, displacements ([1.5-1.8 cm](#)) under load exceeded design allowables. The solution might

be to position the coils so that when they are under load, the displacement brings the coils into the correct position. Another solution might be to add more local structure in regions of maximum displacement and reduce structure where displacement is significantly below displacement allowables. [It was suggested to include open areas in the outer regions of the coil structure to represent cutouts for maintenance ports.](#)

Updated of the ARIES-CS Power Core Configuration and Maintenance – As mentioned previously, some coils are in intimate contact but not interfering. Leslie Bromberg suggested a small separation of the coils (~ 0.5 cm) [is needed for electric insulation and](#) to insert a separating coil structure to facilitate coil winding. [Xueren mentioned that the rectangular coil cross-section has the effect of reducing the maintenance port envelope by](#) adding small triangular region at the top and bottom. Pending final coil geometry, radial build, coil configurations and blanket module geometry, these ports may have to be further modified.

The shield-only region still is being examined for manifold capability and access, plumbing provisions for cutting, removal and rewelding. An alternative transition and shield-only region was proposed for consideration.

Magnets for ARIES-CS: Magnet Protection and Cooling of Magnet Structure – The cooling of the low temperature superconducting magnets for the Compact Stellarator has the challenge of a large complex coil structure that is nearly continuous and very massive. Can somewhat higher temperatures (e.g. 20K) be used to cool the [inter-coil structure](#) while cooling the [winding pack](#) to a lower temperature? Leslie Bromberg conducted a 2D thermal analysis using the 0.1 m-thick steel structure and a 2 mm insulation layer between structure and coil and the nominal coil geometry and a 5 MW/m² peak wall load. His analysis showed that the structure could be adequately cooled (0.1 W/cm³ and greater) with the heat being removed at 20K.

For the high T_c case (high temperature superconductor YBCO, generation 2), the coil design must include large heat capacities to ensure no quench can occur (quench cannot be monitored). The design provided to the systems code is designed to allow a 2-second energy dump, probably external dump. An internal dump capability was also quantified and seemed to be attractive. Following a coil energy dump (which heats up the coils), Leslie discussed the recool (down) issues. Approximately 10 kW of cooling would be required at 4K that would occur over a time period of 200,000 seconds (55 hrs). Other design enhancements might speed up this process.

Status of Engineering Effort on ARIES-CS Power Core – Rene Raffray also discussed the reactor power flow [diagram](#) and highlighted the salient issues. The divertor definition has a significant influence on the power flow from various core components. Rene then amplified on the impact of the separate and combined divertor and alpha [heat load](#), and [baffle](#) modules to highlight divertor coverage, heat flux peaking factor, and fractional radiation in divertor region. He is also concerned about helium implantation in the tungsten armor from the prompt alpha losses. One question is how high should the tungsten surface temperature be to limit exfoliation, tritium retention, and defect annealing.

Rene showed a refined optimization of the selected Brayton cycle for the dual coolant case. With high efficiency recuperators, the net cycle efficiency would be around 0.41 to 0.44 (nominally an

efficiency of 42%, a helium pressure of 10 MPa, and a blanket pumping power of 97 MW). There is some net efficiency variation due to the neutron wall load (from 1.5 to 5.0 MW/m²). Coolant (Pb-17Li) temperatures are limited to around 500° due to the compatibility limit with advanced ferritic steel. Detailed flow diagram was provided along with the thermal power levels on the diagram. Detailed parameters for the dual coolant case were provided.

Rene discussed the divertor study that highlighted the 10 MW/m² peak surface heat load divertor design approach by Thomas Ihli. This design has been integrated into a blanket module and plumbing system. Georgia Tech is providing experimental testing of this cooling concept.

Rene provided cycle efficiency and pumping power data versus neutron wall load for both the dual coolant and self-cooled Pb-17Li thermal conversion cycles.

A web search revealed existing cutting and welding tools are available for the plumbing sizes and configurations being proposed. The ITER cryostat provides the experience basis for the ARIES-CS cryostat. Rene provided the CAD visualization of the cryostat for the port-based maintenance approach. To be conservative, the thickness of the cryostat was chosen to be equivalent to 5 cm.

Revised Radial Build Data: Breeding and Streaming Concerns – Laila El-Guebaly reviewed the previous radial build cross-sections and the plasma-coil separation toroidal and poloidal plots for the R = 8.25 m case for reference. She then discussed the major design impact areas and the plasma-coil separation area results for the new 7-m radius design. The nominal blanket region now covers only 65% of the wall area (UW estimate), which causes concern about the ability to adequately breed sufficient tritium. UCSD should verify predicted coverage fraction with CAD.

Laila reviewed her previous breeding assumptions regarding blanket/divertor/penetration coverage. Based on the new 7-m design, the TBR with sufficient margin is inadequate for either a design approach with a shield-only + transition (Option I; TBR ≈ 1.00) or transition only (Option II; TBR ≈ 1.07). Even with Option II, approximately 10% of the VV is not reweldable after 28 FPY. An additional 3 cm of WC shielding would provide full VV reweldability. Increasing the TBR to 1.10 requires increasing full blanket thickness by 10 cm or increase machine major radius to achieve a full breeding coverage area (> 65%).

Additional local shielding of approximately 25-30 cm thick is required to protect the magnet against neutrons streaming through the helium access tubes, as shown in a cross-section diagram. UCSD should verify if this is possible in the region needed.

Experimental Verification of Gas-Cooled T-Tube Divertor Performance – Said Abdel-Khalik summarized 2-D and 3-D analyses to assess the thermal performance of the helium cooled T-tube divertors at nominal design and operating conditions. Particular emphasis was on the robustness of the design and fabrication of the tubes on the thermal performance. The results indicated that for heat fluxes up to 10 MW/m², local temperatures were within material property allowables. The design is robust with respect to manufacturing tolerances and flow inconsistencies within the divertor. Very high heat transfer coefficients (> 40 kW/m² K) were predicted at the stagnation point opposite the slot. This very high heat transfer coefficient is outside the experience base for helium cooling. Therefore, it is necessary to experimentally validate these predicted values. Said

then described the experimental program initiated at Georgia Tech to validate the predicted thermal performance of gas-cooled divertors. The experimental flow loop and the test section simulating the T-tube divertor design were described. The test section geometry matched the slotted inlet tube and concentric outer tube geometry used in the T-tube divertor. Instrumentation is included to allow the azimuthal and axial variations of the local heat transfer coefficient to be measured. The experimental setup was also analytically modeled to predict the thermal and flow-field performance prior to the conduct of the experiments. These analyses would be used to predict heat transfer coefficients and compared with the experimentally measured values. Laila suggested including in the analytical model the effect of neutron irradiation on the thermal conductivity of W and steel.

January 23 ARIES Meeting Action Items:

ALL

Continue the verification process as design changes are incorporated into the systems code.

Jim Lyon

1. Use 50 MWe for Miscellaneous Reactor Plant and BOP Power
2. Adopt 5 cm for cryostat thickness
3. Use 76% plant availability for now to compare with previous ARIES designs until a detailed availability assessment is conducted.
4. Research and correct replacement cost
5. Estimate COE for full blanket coverage as a reference point to justify complexity of a shield only zone.
6. Try to increase radiated power fraction with the goal of >70%.
7. Add 0.5 cm to coil-coil distance.
8. Use cheaper FW heating approach instead of ECH for plasma startup.
9. Update coverage fractions for full blanket, transition, and shield-only zones.
10. Increase FS shield thickness from 18 cm to 28 cm

Future action items from Jim Lyon to be added when appropriate

1. Add ν^* , B, R, and beta corrections to alpha-particle loss when available from Long-Poe Ku.
2. Near end of study, vary P_{electric} up to 1.5 GW or more and look at NbTi at higher beta.
3. Vary shield thickness with p_{wall} , blanket coverage, radial build, etc. when numbers available from Laila.
4. Change coil support structure when better model available from Xueren/Les.
5. Generate parameters for advanced LiPb/SiC design with 58% thermal conversion efficiency (check with Laila).
6. Generate parameters for 2 PF configurations (get radial build from Laila).

Laila El-Guebaly

1. Check blanket coverage and TBR for $R = 7.5$ and 8 m. Need plasma-midcoil separation contours from PPPL
2. Optimize local shield behind helium access tubes
3. Provide radial build at cross-section through He access tube near delta-min
4. Update shield vs. NWL scaling law
5. Update power fraction to blanket Pb-17Li coolant, blanket and shield He, shield-only zone He and divertor He
6. Update He:LiPb power split using 28 MWe pumping power for div He and 97 MWe for blanket He.
7. Check magnet activation for candidate structures (get composition from Leslie)
8. Provide heat load to 35-cm thick inter coil structure

9. Provide radial build for 2 field period configuration. Need plasma-midcoil separation contours from PPPL
10. Provide radial build for advanced LiPb/SiC system
11. Provide radial build for full blanket coverage
12. [Redefine reference radial build and post it on UW website](#)

Long Poe Ku

1. Provide plasma-midcoil separation contours to Laila for 3 FP, $R = 7.5$ and 8 m
2. Provide plasma-midcoil separation contours to Laila for 2 FP configuration
3. Examine the 3-FP cases with regard to $A=4$ to determine if there are positive benefits.
4. Try to reduce alpha losses for all configurations

Alan Turnbull

1. Improve wall modeling approach to be more “conformal” to eliminate or reduce Terpsichore difficulties

TK Mau

1. Provide divertor and baffle coverage fractions to Laila to estimate overall TBR
2. Provide optimized divertor plate geometry and heat load distribution for ARE configuration, to Rene (divertor) and Jim (system).
3. Provide alpha particle strike points on first wall and divertor plates (if time allows)

Xueren Wang

1. Check VV-magnet space behind He access tubes
2. Provide CAD input file to UW for reference design with blanket variation, divertor system, and penetrations.
3. Update the power core layout based on Laila’s Baseline Design Option for $R=7$ m
4. Update the power core layout based on Laila’s Baseline Design Option for $R>7$ m
5. Perform a 3D ANSYS magnetic-structural solid modeling to confirm the results obtained by ANSYS shell modeling
6. [Verify UW prediction for blanket coverage fraction for \$R=7\$ m](#)

Les Waganer

1. Verify volume of reactor building (V_{RB}) [and hot cell building](#) as influenced by maintenance access (with Xueren Wang’s help)
2. Develop timeline for maintenance scheme and determine availability.
3. Develop new coil support structure to reduce mass and cost
4. Obtain firm data on helium contamination levels and constituents

Said Abdel-Khalik

1. Conduct "Shakedown tests" to verify the operational range of the gas-cooled divertor test facility.

2. Calibrate all instruments (flow, pressure and temperature) in the test facility.
3. Conduct "a-priori" calculations to predict the temperature distribution within the test facility for different operating conditions.
4. If time permits, begin collecting data for the local heat transfer coefficient in the simulated gas-cooled divertor using air as the working fluid.
5. Include in analytical model effect of irradiation on thermal conductivity of W and steel

Leslie Bromberg

Estimate cryogenic heat load to 35 cm thick inter-coil structure. Get nuclear heating from Laila.