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Report of NCSX Milestone Completion

Dear Dr. Blanken:

In this letter we report that the March, 2000 milestone identified in the Program Execution Agreement for the compact stellarator program has been accomplished. This milestone consists of two goals:

- Complete physics tool improvements needed to implement new requirements; and
- Identify candidate machine topology options for evaluation.

The timely accomplishment of these goals keeps the program on a schedule consistent with developing an updated NCSX stellarator configuration by the end of FY-2000 and holding an NCSX Physics Validation Review in December, 2000.

The March milestone involves a set of deliverables that were determined to be needed to begin the next phase of the NCSX design development. Most of these involved a significant R&D component, so in the planning there was uncertainty in predicting the course of the work. It was expected that there would be outstanding issues at this time requiring further work to resolve, and indeed this is the case. Nonetheless, the gains in design capability needed to begin the next design phase have been realized. Now, we will apply these tools to develop an updated design and, in parallel, will work to resolve the holdover issues. The status of the March deliverables and the work planned to resolve open issues are summarized in this report. (The deliverables as originally planned are identified as underlined text.)

Flexibility:

- <u>Startup, flexibility, and robustness requirements (plausible profile sets) are defined and snapshot transport/stability assessments completed</u>.
  - Capability Achieved: Target profile set for use in flexibility targeting.
  - Status: In developing the physics basis for profile flexibility, several approaches were followed in parallel, including experiment-based, theory-based, and simulation-based means of defining and characterizing the needed profile sets.
    - Experiment-based: A set of empirical pressure and temperature profiles was gathered from existing stellarators and similar-sized tokamaks to characterize the range of profiles that might be expected. VMEC input files using these profiles and the C82 boundary shape have been generated and made available for flexibility studies.
    - Theory-based: The MHD stability of a range of parameterized pressure and rotational transform profile shapes in the C82 plasma boundary shape has been assessed. Stability to ballooning and kink modes was found at β=3.8% over a reasonable range of profiles. Instability was found only when the edge shear was decreased significantly or for the very broadest pressure profile. An initial study of C82 startup issues was done by varying the plasma β with fixed rotational transform profile. It was found that MHD stability was maintained at the lower β values, and that quasi-symmetry was not significantly affected.
    - Simulation-based: A new code (THRIFT) was developed to calculate current diffusion in stellarators with externally produced rotational transform, and will be used to simulate the startup evolution of NCSX. A simulation of the NCSX startup temperature evolution is being generated, using the toroidally-averaged C82 shape, with the Tokamak Simulation Code (TSC). This will be used to benchmark THRIFT, and will be used as input to the THRIFT simulation of NCSX current evolution.

- Methodology for evaluation of coil-set flexibility/startup/robustness is developed and tested.
  - Capability Achieved: Ability to evaluate flexibility of candidate coil sets.
  - Status: A new method of operating the physics optimizer has been developed which allows the currents in a specified set of coils to be varied to generate the best plasma equilibrium, according to the specified physics properties (so-called "free boundary optimizer"). This new tool provides the capability needed to assess whether a coil design has sufficient flexibility to produce the range of plasma configurations required for startup and physics exploration. It has been tested on a particular problem and appears to operate correctly. In addition, it should be useful to the larger stellarator community for choosing the coil currents needed to produce desired physics configurations in an existing experiment.
  - Future Plans: The capability to specify a 3D vacuum vessel to restrict the plasma location will be added as an upgrade.

Equilibrium Code Upgrades and Good Magnetic Surfaces.

- Upgrade of VMEC, with the convergence and resolution issues resolved, completed and implemented in the configuration optimizer.
  - Capability Achieved: VMEC with improved convergence, resolution, force balance, and ability to predict islands.
  - Status: The initial stage of the VMEC code upgrade (VMEC2000) has been completed. The new code has improved temporal convergence properties and, therefore, the capability to deal with finer radial meshes and larger numbers of Fourier modes. The new VMEC2000 has been implemented within the configuration optimizer, providing an improvement in optimizer capability over the older VMEC.
  - Future Plans: Further VMEC developments are planned to improve the calculation of certain effects (e.g., parallel currents) which may prove necessary to adequately target island reduction in the optimizer. Further developments are also in progress to improve force balance with increasing number of modes near the edge of the plasma. This is not expected to directly affect the performance of the optimizer.

- PIES code modifications to improve physics (implementation of neoclassical effects) and efficiency (speed, usability) are implemented and tested.
  - Capability Achieved: Progress consistent with realization of an efficient surface quality evaluation tool, including all the relevant physical effects, by its need date, June 1.
  - Status: Speed and usability improvements which will benefit the design process immediately have been implemented. A new, robust convergence scheme has been implemented. The speed of the elliptic solver, which previously accounted for 50% of the computer time for a PIES run, has been improved by about a factor of 50. The speed of the field line follower was improved by about a factor of 3. The code has been ported to two new platforms, an SX5 machine in Garching, Germany, where it runs 10 times faster than on the NERSC machines, and to local workstations, where it runs about 2 times faster.
  - Future Plans: Physics improvements will be completed, including implementation of an improved treatment of out-of-phase islands which has been written. and tested. Also, implementation of the neoclassical bootstrap effect, for which a scheme has been devised and coding is being written. The PIES developments are on schedule for completion by June 1.

- Optimizer criteria for obtaining good magnetic surfaces has been implemented and tested in a plasma configuration optimizer.
  - Capability Achieved: Ability to target good surfaces in the plasma configuration design.
  - Status: An analytic criteria and strategy based on the published literature has been developed in collaboration with C. Hegna (Univ. of Wisconsin). The criteria contains four terms ("vacuum", resonant Pfirsch-Schlüter, Glasser or D_R, and neoclassical-tearing), which are evaluated in a modifed version of the JMC code (from MPI-Greifswald), and are in the process of being benchmarked against the PIES three-dimensional equilibrium code. In the course of the testing, it became clear that the published D_R term needed to be re-formulated to exclude resonant currents. The D_R reformulation has been done by Hegna, but the new version of the D_R term has not been implemented. However, it is expected that the design of QA-

stellarators can proceed in the absence of the new D_R evaluation by assuming that reversed shear (rotational transform increasing toward the edge) configuration will ensure that the stabilizing neoclassical-tearing term will dominate D_R, as in similar aspect-ratio tokamaks. The evaluation of the vacuum islands depends critically on VMEC's calculation of resonant currents, which may not yet be accurate enough.

- Future Plans: The new version of the D_R term, applicable to stellarators, requires some further work to determine how to modify JMC to evaluate it. Further VMEC development, which may be needed to improve its calculation of resonant currents, is planned.

Transport Targeting

- Improved transport evaluator has been implemented and tested in a plasma configuration optimizer.
  - Capability Achieved: More accurate transport targeting in configuration design.
  - Status: Four improved methods were investigated for characterizing plasma confinement in the optimizer: DKES calculation of diffusivity, alignment of J surfaces with flux surfaces, calculation of the effective ripple (Kernbichler-Nemov collaboration), and Monte Carlo calculation of ion orbit confinement. All four have been developed to be applicable and compatible with the plasma optimizer, and can be operated in a way which is fast enough for the optimizer (with some approximation in some cases). All have been benchmarked against each other and against the full GTC code simulation of the ion distribution function and Monte Carlo simulations of fast-ion losses. The benchmarking indicates that the effective ripple method best correlates with the GTC simulations of thermal confinement. All of the methods, except the Monte Carlo ion orbit confinement one, have been integrated into the optimizer and tested.
  - Future Plans: The integration and testing of the Monte Carlo method is being completed now.

Heating and Diagnostic Access

- Physics requirements for heating, diagnostics, and pumping access are defined.
  - Capability Achieved: Clear understanding of access requirements.
  - Status: The access requirements for NBI heating, diagnostics, and pumping have been developed and documented in project memoranda. The RF access recommendations have been developed and communicated to engineering; documentation is in progress. While these requirements will need monitoring and revisiting later in the design development, no further development is needed in the near term.
  - Future Plans: Complete documentation of RF access requirements.

- Implementation of access requirements set by physics (e.g., space envelopes, constraints, etc.) are understood well enough to evaluate proposed machine concepts.
  - Capability Achieved: Ability to evaluate the capability of proposed machine concepts to meet access requirements.
  - Status: Access requirements set by physics are sufficient to enable engineering to study how these requirements might be addressed in the design. An access study for a PBX option was initiated. A concept for accommodating neutral beams, RF, and vacuum pumping was developed. Provisions for plasma diagnostics are currently being developed.
  - Future Plans: Complete the access study of the PBX option and evaluate access for machine designs being developed based on other coil topologies.

Requirements Documentation

- An updated Physics Requirements Document (PRD) is issued.
  - Capability Achieved: Clear understanding between physics and engineering as to what requirements must be satisfied in the next phase of the design.
  - Status: Top-level NCSX design requirements have been documented. These requirements represent a clear and mutual understanding between physics and engineering of what is required in the NCSX design. They have been sufficient for the engineering to make significant design progress.

- Future Plans: Requirements for flexibility to be addressed in the design are being developed. The PRD will be a living document and it is expected to be updated as changes occur and as requirements are defined at a more detailed level.

Coil Design

- Capability to handle alternative background and conformal coil topologies of interest is available.
  - Capability Achieved: Ability to design optimized background coil systems as alternatives to using the existing PBX-M coils.
  - Status: A new code has been developed to design background coils, which work in conjunction with closer-fitting conformal coils, optimized on physics and cost objectives. The genetic algorithm (GA) coil discretization code has been upgraded to deal with general background coil sets. The capability to run with either fixed currents in these background coils or to allow these currents to be determined as part of the GA optimization has been completed and is being tested on the L=3 background coil set envisioned for the C82 reference plasma configuration.

- Several machine topology options have been explored and are defined for comparative evaluation in the next phase.
  - Capability Achieved: Promising options identified for comparative evaluation in the next phase.
  - Status: Three classes of machine topology options have been scoped:
    1) Re-use PBX TF and PF coils in conjunction with (new) conformal coils. For this first class of options, different conformal coil helicities were explored. It was concluded that none of the alternatives was clearly better than the saddle coil topology (with 0/0 helicity) used in design studies to date. The 4064 reference coil design represents a reasonable point of departure for continued study using the newly developed free boundary optimizer.
    2) Provide new background coils used in conjunction with conformal coils. For this second class of options, two types of new background coils were investigated: tilted TF coils and planar L=3 coils. Both result in substantial reductions in conformal coil current density, which provides substantial design benefits, and are candidates for continued study.
    3) Provide new background coils that do not require conformal coils. Topology studies for this third class of options is underway and should be completed later in March.
  - Future Plans: The evaluation of the third class of options is expected to be completed later in March.

- Improved methodology for finding the optimum conformal coil configuration for a given plasma and background coil set has been implemented and tested.
  - Capability Achieved: Improved optimization capability, e.g. reduce current density or complexity for fixed physics performance.
  - Status: A new three-dimensional optimization code, COILOPT, has been developed. This code allows near-conformal coil configurations to be generated by directly manipulating the coil geometry to minimze the normal B-field on the plasma surface, instead of post-processing a NESCOIL current sheet solution. A coil parametrization based on linearizing the 2D Hamiltonian coil "trajectories" around the NESCOIL current potential was introduced in this period. This code is being benchmarked for C82 against NESCOIL results to determine whether a small degree of non-conformality can be exploited to improve (i.e., achieve lower current density) the saddle coil solutions for C82.

    A penalty function, based on the Hessian Matrix (or Quality Matrix) method, has been added to the plasma configuration optimizer to constrain the plasma to solutions which have smooth conformal coils. Initial indications are that this method produces smoother conformal coils, as it was intended to do. For a C82 test case, quasi-symmetry is well-preserved when the new constraint is added; however preservation of kink stability has yet to be demonstrated.
  - Future Plans: Efforts are continuing to benchmark the Quality Matrix and to benchmark COILOPT for c82 against the NESCOIL results.

- Cabled conductor design criteria are defined.
  - Capability Achieved: Understanding of engineering limits for cable conductor in order to include the proper constraints in coil optimization codes.
  - Status: Draft design criteria have been developed to provide provisional recommendations for the various limits as well as a brief explanation of how the limits were derived. Test results from R&D activities played a major role in establishing these criteria. For assumed pulse length, magnetic field, and a current variation allowance for flexibility, criteria were developed for maximum current density in copper, nominal current density in copper, minimum bend radius, minimum shell groove width, minimum separation of windings, and other parameters. The design criteria will be refined as additional R&D results become available.

Reactors

- First stage of study of quasi-axisymmetric (QA) stellarator reactor parameter sensitivities based on scoping using available QA plasma and modular-coil solutions has been completed.
  - Capability Achieved: Adaptation and first application of existing analysis tools needed to improve future QA reactor projections.
  - Status: First stage deliverables completed. A model for a QA reactor was constructed based on NESCOIL current sheet calculations of the plasma-coil spacing vs B_{max}/B_0 for C82 and the ARIES-RS blanket and shield dimensions. A multi-parameter constrained nonlinear optimization systems code was tested that uses different 0-D and 1-D stellarator transport models (with and without electric fields) and with the ARIES materials assumptions, constraints, and costing algorithms. A code to calculate the POPCON operational space for a QA reactor based on the same 0-D and 1-D transport models and a time-dependent 0-D transport code to follow the evolution to ignition were also tested. The reactor systems optimization code and the POPCON code are being used to generate a reference cost-minimized QA reactor case and to test the sensitivity to different physics and reactor component assumptions. In the remainder of FY 2000, the sensitivity to various assumptions will be explored using the current QA stellarator model. As better coil and plasma configurations become available, the model will be updated.

Technical discussions and supporting analyses for these deliverables are documented in Project memoranda and publications which are available from the Physics and Engineering files-share areas on the NCSX web site (http://www.pppl.gov/ncsx/ncsxfss/file_share.html) or upon request. If you have any questions, please contact me.

Sincerely,

G. H. Neilson
NCSX Project Manager