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Progress Report: Fusion Reactor Design Studies

for the Period 11/1/89 to 10/31/90

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1 Introduction

Personnel of the Fusion Technology Institute played an active role in the ARIES project during the present contract period. This role was reflected in numerous presentations at project meetings and in a great many communications, both by electronic and regular mail. Because of ARIES Executive Committee decisions, however, publications related to this work will be forthcoming only in the upcoming contract year.

In light of the shifting objectives of the ARIES project during the present contract year, a brief review is in order. In August, 1989, before the present contract year began (November 1, 1989), the original plan to follow the in-progress, D-T, first-stability ARIES-I tokamak reactor design with the D-³He ARIES-II design (now renamed ARIES-III and hereafter called by that name) was changed, and it was decided to study a D-T, second-stability tokamak to be called ARIES-II. The rationale for this change of course was that input would be needed for the Fusion Power Advisory Committee (FPAC). In May, 1990, it became obvious that sufficient work would not be done on the D-T ARIES-II in time for significant impact on the FPAC recommendations, and the need for timely information on the attractiveness of a D-³He tokamak reactor was becoming apparent. Therefore, the ARIES Executive Committee decided to postpone work on the D-T ARIES-II tokamak until 1991, and to begin immediate study of the D-³He ARIES-III tokamak.

Both decisions mentioned in the previous paragraph had major ramifications for the work to be done by Fusion Technology Institute personnel. In particular, when the major FY90 focus was to be upon the D-T ARIES-II tokamak, the main Fusion Technology Institute task was to continue a very low-level scoping of a D-³He tokamak in order to provide at least minimal input to the evaluation by the U.S. administration and by NASA of the lunar ³He resource and its implications. This task was to be implemented by learning the use of the ARIES systems code, generating strawmen, and accomplishing as much technical analysis as a very low level of funding would allow. Then, in May, 1990, when the whole ARIES project shifted to again examining D-³He, the role of Fusion Technology Institute increased greatly, continuing input to the systems area, but including major input to plasma physics, energy conversion, disruptions, materials, neutronics, shielding, first wall, fuel cycle, fuel cost, and fuel resources. At that time, the ARIES Executive Committee decided to focus ARIES project publication effort on the ARIES-I design for FY90, deferring papers and presentations on ARIES-III until FY91.

The remaining sections of this progress report will give a detailed breakdown of the work being accomplished for ARIES-III during the second phase of FY90, after the shift in ARIES project emphasis back to the D-³He ARIES-III tokamak. Work accomplished during the first phase of FY90, for which only Fusion Technology Institute was pursuing D-³He, was primarily in the systems area up to that point, and will be discussed in the systems section.

2 Participation in ARIES Meetings

Table 1 summarizes attendance and presentations by Fusion Technology Institute personnel at ARIES meetings and reflects the level of Fusion Technology Institute activity in the project.

Table 1: *Activities of Fusion Technology Institute personnel at FY90 ARIES meetings.*

PERSON ATTENDING	PRESENTATION
January 22-24, 1990	
Santarius	
March 12-14, 1990	
Santarius	Ergodic magnetic limiters
May 7-9, 1990	
Kulcinski	D- ³ He timing
Santarius	Engineering task planning
July 10-12, 1990	
Blanchard	Observations on materials choice
Emmert	Power balance and ash accumulation
Kulcinski	Materials issues
Santarius	Energy conversion
	Ripple loss issues
Sawan	Neutronics
Sviatoslavsky	Power cycle
Wittenberg	Fuel cycle
August 27-29, 1990	
Blanchard	Materials
Emmert	Power balance considerations
Kulcinski	Design considerations
Santarius	Ripple loss
	Synchrotron radiation conversion
	Energy conversion group summary
Sviatoslavsky	Metallic FW/shield design ideas
US-Japan Tokamak Reactor Workshop	
October 15-17, 1990	
Santarius	D- ³ He rationale
	ARIES-III energy conversion

3 Systems

This was a very active area for the Fusion Technology Institute during FY90, and it included a three-day working meeting at the University of Wisconsin with Dr. Ronald L. Miller, of LANL, on July 30–August 1, 1990. The working agenda for this meeting listed the following questions and issues:

- Magnet coil algorithms
- N-stamp costing
- Availability
- $\tau_p^{ash} / \tau_E^{bulk}$
- Density, temperature, and current profiles
- Current drive algorithms
- Thermal/direct conversion algorithms
- Tritium cycle
- First wall/'blanket'/shield dimensions
- τ_E scaling laws
- Fuel/ash/impurity concentrations
- Parameter space boundaries
- Systems code future directions
- Benchmarking

These issues were attacked partly by benchmarking the ARIES systems code, written by Miller, against the RAGE systems code, written by Gilbert A. Emmert of the Fusion Technology Institute. Considerable progress was made at that time, and subsequent work has brought the two codes essentially into agreement. The benefit of this is that, while the ARIES systems code contains more sophisticated algorithms for engineering systems, the much smaller RAGE code is better suited for scoping out parameter space and is providing guidance for systems code runs.

The first half of FY90 was spent learning the use of the ARIES systems code, with the expectation that Fusion Technology Institute personnel, working with Ron Miller, would have to do various modifications to the code to properly model a D-³He tokamak reactor. When the Executive Committee decided to switch the order of study for ARIES-II and ARIES-III, Ron Miller made those modifications, and the Fusion Technology Institute role was changed to providing observations and suggestions to him, and to helping run the code for some parametric studies.

At present, because it appears to the full ARIES team that a second-stability D-³He tokamak reactor will be more attractive than a first-stability D-³He tokamak reactor, the major ARIES-III effort, including almost all of Miller's effort, is concentrated upon second-stability. There remains a task, however, of generating the best strawman possible in the first stability regime, and Fusion Technology Institute has taken the lead role in that effort in collaboration with Miller.

4 Plasma Power Balance

Fusion Technology Institute personnel have contributed and will continue to contribute to an ongoing discussion of D-³He plasma power balance issues for ARIES-III. These issues include energy confinement scaling relations, particle confinement scaling, edge plasma effects, plasma profiles, synchrotron radiation calculation, and bremsstrahlung radiation calculation. Besides Miller's ARIES systems code and Emmert's RAGE tokamak systems code, this discussion includes Ibrahim's systems code—also a code primarily useful for scoping studies.

There has been a very active flow of electronic mail (E-mail) regarding plasma power balance and the related questions of the proper calculation of synchrotron and bremsstrahlung radiation. Examples of Fusion Technology Institute contributions include pointing out that the Ibrahim code needed to use relativistic effects in calculating bremsstrahlung radiation power losses and correcting the neoclassical energy loss time used in that code. For the ARIES systems code, the interactions between Ron Miller and Fusion Technology Institute personnel have been numerous—examples include refining shield thicknesses and various costs, and correcting calculations of neutron production and first-wall surface heat load.

5 Impurity Control and Fusion Ash Removal

The ergodic magnetic limiter (EML) is an important option for ARIES-III. The Fusion Technology Institute ergodic magnetic limiter computer code **ergo** was used to calculate EML parameters for the scoping phase of ARIES-III. Although preliminary indications looked positive, the decision has been made by the ARIES team to use a divertor unless a no-go issue is found.

A critical area for many fusion reactors, including both D-T and D-³He tokamaks, is that of fusion ash accumulation. Especially in the first stability regime, where achievable β values appear to be very low, a high energy confinement time is required. To avoid choking the plasma with fusion ash, the particle confinement time for the ash must be low compared to present experimental values for the bulk plasma. Fusion Technology Institute personnel have contributed to the question of what ratio of $\tau_p^{ash}/\tau_E^{bulk}$ is required for a viable D-³He tokamak, and whether active ash pumping can be accomplished at reasonable input power levels. Fusion Technology Institute has been a major contributor to the analysis of this question, which will be important for ARIES-II D-T operation as well.

A literature search for active fusion ash-pumping ideas was accomplished, and some new ideas were suggested. These include:

- Using the Doppler-shifted ICRF resonance;
- ICRF resonance effects on banana orbits;
- Ponderomotive force-induced $\mathbf{F} \times \mathbf{B}$ diffusion; and
- Ponderomotive force effects on orbits.

None of these have been experimentally verified, and preliminary estimates indicate that it will be difficult to access the proper regions of the plasma without undue losses to parasitic effects such as electron Landau resonances. However, the ash-pumping problem has so far received only a small amount of study, and the swiftly developing state of knowledge in the fields of ICRF-plasma interactions and stochasticity theory lead to some confidence that the problem can be resolved favorably.

6 Fusion Product Ripple Loss

In a D-³He tokamak, ripple loss of fusion products is expected to lead to more stringent constraints than in a D-T tokamak, due to the larger gyroradius of fusion-product protons at their birth energy and because almost all of the fusion power is produced as charged particles. Fusion Technology Institute is analyzing ripple loss for ARIES-III and pointed out the potential problem. The methodology will be applied throughout the ARIES-III effort and is applicable to ARIES-II as well. Preliminary estimates of ripple losses indicate that the allowable ripple limits will be approximately a factor of two more severe than for a D-T tokamak.

Work is in progress to run the computer code EFFI to generate ripple contours and to run the PPPL code RIPLOS to assess ripple losses for the actual ARIES-III toroidal field magnet set. This is expected to be accomplished by the end of the present contract period.

7 Energy Conversion

Fusion Technology Institute coordinated the effort to select and design energy conversion systems for ARIES-III. This involved the assessment of both conventional thermal conversion cycles and of non-conventional cycles such as liquid metal MHD, plasma MHD, and synchrotron radiation conversion. A major focus of Fusion Technology Institute effort in the energy conversion group was coordinating the choice of a single non-conventional energy conversion system to compete with a conventional thermal energy conversion system for the ARIES-III reference design. This choice was made at the August, 1990 ARIES project meeting, and synchrotron radiation conversion by rectennas was selected. Much of the background work for this decision was accomplished in FY89, but there was effort in FY90 in more detailed design of rectennas for the conversion of synchrotron radiation to electricity.

The work on synchrotron radiation conversion included analyzing the direct conversion of synchrotron radiation using either rectennas or distributed parameter power rectifiers (DPPR's). This analysis has so far supported Grant Logan's initial estimate of 80% conversion efficiency of synchrotron radiation to electricity. Areas investigated have included antenna design, circuit design, quantum mechanical effects on components, fabrication, large-scale integrated circuit costs, chamber design, and synchrotron radiation production.

Fusion Technology Institute personnel have also contributed to the effort to define attractive thermal energy conversion cycles, including detailed design work. Parameters for a steel first wall and shield, using organic coolant for the thermal cycle have been scoped out, and a detailed presentation is being prepared for the next ARIES project meeting.

8 Fueling

Fusion Technology Institute personnel have investigated both pellet fueling and compact toroid fueling, and are taking an active role in the ARIES fuel cycle group. Pellet work has identified an innovative method for fabricating a D-³He pellet: condensing ³He within a lithium or beryllium shell and coating the shell with frozen deuterium. The examination of compact toroid fueling has just begun, but the concept looks very promising for fueling all the way to the axis.

9 First Wall Design

Scoping designs of the ARIES-III first wall have been performed, and much more detailed designs will be required for the next phase of the ARIES-III study. Fusion Technology Institute is presently analyzing metal first wall designs, but is providing some input to the design of ceramic first walls. Structural design, neutron damage, activation, thermal hydraulics, and coating properties are all included in the analysis. A key accomplishment has been the design of a steel first wall and shield that preliminary calculations indicate is sufficiently robust to survive the current quench phase of a disruption without damage.

10 Shield Design

Fusion Technology Institute has performed the design of an ARIES-III shield optimized for the low neutron wall-loading of the D-³He fuel cycle. Parameters for metal, SiC/SiC-composite, and C/C-composite shields have been scoped out. Corresponding algorithms for shield thickness have been given to the ARIES systems code group. Optimizing the shield will be an ongoing effort throughout the course of the ARIES-III design. Structural design, and thermal hydraulics, and neutronics calculations are in progress; they will be presented at the November ARIES project meeting.

11 Safety

Fusion Technology Institute personnel are heavily involved in the analysis of ARIES-III safety, which is a critical issue for D-³He tokamaks. Present activities include providing background material and commenting upon preliminary safety judgements. Initial studies of loss of coolant accidents (LOCA) indicate that a steel first wall and shield will suffer no damage. Analysis of activation, waste disposal ratings, afterheat, LOCA, loss of flow accidents (LOFA), and other safety issues are presently under investigation.

12 Fuel Cost and Resources

The present cost of ³He fuel for ARIES-III is estimated to be \$1000/g. The effect of ³He fuel cost will be assessed by parametric variation using the ARIES systems code. Cost estimates will also be further refined in a "bottoms up" manner during the course of the ARIES-III study.

Fusion Technology Institute personnel have done extensive analysis of the availability and procurement of ³He resources, for both terrestrial and lunar resources. These will be summarized for the ARIES-III project and included in appropriate reports. Information from ongoing JW analysis of these resources within the Fusion Technology Institute and the Wisconsin Center for Space Automation and Robotics (WCSAR) will also be included.

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