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**FUSION
RESEARCH
AT
GENERAL
ATOMICS
ANNUAL
REPORT**

**OCTOBER 1, 1992
THROUGH
SEPTEMBER 30, 1993**

FUSION TECHNOLOGY DEVELOPMENT

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FUSION TECHNOLOGY DEVELOPMENT

ANNUAL REPORT TO THE U.S. DEPARTMENT OF ENERGY

OCTOBER 1, 1992 THROUGH SEPTEMBER 30, 1993

**by
PROJECT STAFF**

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Section 1

FUSION TECHNOLOGY DEVELOPMENT OVERVIEW

1. FUSION TECHNOLOGY DEVELOPMENT OVERVIEW

In FY93, the General Atomics (GA) Fusion Group made significant contributions to the technology needs of the controlled fusion power program. The work was supported by the Office of Fusion Energy, Advanced Physics and Technology Division and ITER and Technology Division, of the U.S. Department of Energy. The work is reported in the following sections on Reactor Studies (Section 2), RF Technology (Section 3), and Plasma Facing Components (Section 4). Our report concludes with a listing of FY93 publications resulting from the work (Section 5).

The overall objective of GA's fusion technology research is to develop the technologies necessary for fusion to move successfully from present-day physics experiments to the next-generation fusion reactor experiments, Tokamak Physics Experiment (TPX) and ITER, and ultimately to fusion power reactors. To achieve this overall objective, we carry out fusion systems design studies to evaluate the technologies needed for next-step experiments and power reactors, and we conduct research to develop basic knowledge about these technologies, including plasma technologies, fusion nuclear technologies, and fusion materials. We continue to be committed to the development of fusion power and its commercialization by U.S. industry.

Section 2

REACTOR DESIGN STUDIES

2. REACTOR DESIGN STUDIES

2.1. OVERVIEW

The goal of reactor design studies is to provide critical assessment of the projected performance of fusion experiments, reactors, systems and components; to develop potential solutions to critical issues; and to offer recommendations for an improved fusion system. This activity helps to define the goals and R&D needs of the fusion program, and thus adds focus to near-term activities.

In FY93, GA continued to play a lead role in the Advanced Reactor Innovations Evaluation Study (ARIES) directed by Prof. Robert Conn of UCLA. Within the ARIES project, GA is responsible for the project operation, with Dr. Larry Stewart acting as the Deputy Project Director for Operations. During this period we helped to complete the ARIES II and IV designs; and initiated the work of the PULSAR reactor study. We contributed in the areas of fusion power core components: divertors, first walls, blankets and shields, including materials, neutronics and safety evaluations. We also continued to provide senior plasma physics personnel for analysis of disruption effects and for the design of plasma stabilization shells.

2.2. PROJECT DIRECTIONS

Work in FY93 began with completion of the studies of steady state tokamak reactors represented by ARIES designs. The work then progressed to the pulsed tokamak reactor study represented by PULSAR design. The PULSAR project will be finished in the early part of CY94. Reactor studies will then continue as support of the DEMO evaluation and design study.

2.3. ENGINEERING INNOVATION/FUSION POWER CORE DESIGN

2.3.1. ARIES-IV DESIGN

The ARIES-IV toroidal flow design was completed and documented. U-shaped SiC-composite shells were used to form the blanket module. The helium coolant in the shells was designed to flow in the toroidal direction from the back of the blanket towards the

first wall and then return to the back plenum. When compared to the reference poloidal coolant flow design, this configuration has the advantage of being able to be fabricated from smaller parts. However, due to the need for a poloidal flow plenum at the back of the module, it has the disadvantage of requiring thicker total blanket/shield/plenum.

Detailed thermal and structural analyses were performed on the first toroidal flow shell facing the first wall. Results showed that this shell can meet all the thermal and structural design limits while taking into account the dimensional changes of the module due to thermal expansion during reactor operation. Neutronics design showed that adequate tritium breeding can be achieved with the use of Be as the neutron multiplier. Due to the lower inductance generated by the U-shaped Be shell, it was selected as the kink stabilization shell for the second stability plasma.

Other design areas that were completed for ARIES are: fabrication and costing of Li_2O sphere-pac material, divertor design, and the BOP schematics for the ARIES II and IV designs.

2.3.2. PULSAR REACTOR DESIGN

In parallel with the completion of the ARIES II and IV designs we participated in the initiation and design of the PULSAR reactor. We evaluated different blanket concepts proposed by the PULSAR team, including boiling potassium pool, sodium-cooled liquid metal breeder, and lithium-cooled fiber blanket designs.

A 20 MPa helium-cooled, V-alloy SiC-fiber metal matrix, Li breeder and Closed Cycle Gas Turbine (CCGT) concept was evaluated. Due to the generation of after heat from the V-alloy and the presence of Li, a LSA-1 rating could not be achieved. At a helium outlet temperature of 850°C, a direct cycle efficiency of ~50% was projected.

Neutronics calculations were performed to determine tritium breeding ratio and shielding characteristics of the blanket concepts. The most promising concepts were helium-cooled SiC-composite/ Li_2O and V-alloy-SiC-fiber metal matrix/Li options. Both concepts can potentially achieve adequate tritium breeding without the need of beryllium neutron multiplier. To meet the tight schedule of the PULSAR effort, work on these high performance designs was deferred in order to compare the steady state and pulse operation responses of the selected ARIES II and IV designs.

2.3.3. PULSAR SHIELD AND THERMAL STORAGE DESIGN

We supported the investigation of the design implications of operating the tokamak in a pulse mode. We began by quantifying the effect of interrupting the blanket surface heating and nuclear heating on the balance-of-plant power conversion equipment. It was observed that for the steam-cycle, limits on the transient operation of the steam generator is likely to constrain the down time to under one minute. This is probably not achievable for a pulsed tokamak operating in a regime of interest for power production. This motivated a survey of energy storage options.

Several possibilities for sensible and latent heat storage were identified and some basic economics (material costs) were quantified. We then analyzed the use of the shield for thermal energy storage in PULSAR concepts which incorporated an ARIES-IV-like blanket (PULSAR I) and an ARIES-II-like blanket (PULSAR II). We found that the shields can be used as the thermal storage medium. For both cases, we used a poloidal flow nested shell configuration. For the PULSAR I design, we used the helium-cooled shield, utilizing a packed bed of SiC micro-spheres for thermal storage. For the PULSAR II design, we used the lithium-cooled shield, utilizing a packed bed of tenelon spheres immersed in NaK liquid metal as the thermal storage medium. Time-dependent, 2-D heat transfer analyses were performed to confirm the feasibility and performance of both designs. We found that high thermal performance of both designs can be maintained with a dwell time of 2 to 3 minutes.

2.4. PHYSICS INNOVATIONS

The plasma vertical stability analysis for the ARIES IV second stability plasma was performed. The specific location and configuration of the stabilizing shells and active feedback control coils were identified. To reduce the TF ripple, a study was performed on including iron in the TF magnet system.

2.5. UTILITY ADVISORY COMMITTEE

GA assembled a team of five utility contacts. A set of questions was drafted and submitted to the contacts with the objective of understanding the utility viewpoint on various embodiments of a tokamak-based pulsed power plant. Responses were reviewed,

documented and summarized for PULSAR group discussion. The utility contacts advised avoiding pulse operation.

Support was provided for extending and formalizing the utility contacts as a Utility Advisory Committee. Potential Committee members were contacted at TVA, PG&E, Southern California Edison, Duke, PSE&G, Wisconsin Power and Light, Ontario Hydro and Northeast Utilities.

2.6. MEETINGS

We participated and contributed papers to the following reactor design relevant meetings in FY93:

1. International Workshop For Fusion Nuclear Data, May 3-6, 1993, Del Mar, California.
2. 15th IEEE/NPSS Symposium on Fusion Engineering, October 11-15, 1993, Hyannis, Massachusetts.
3. IAEA meeting on Fusion Reactor Design and Technology, September 13-17, 1993, University of California, Los Angeles, Los Angeles, California.

Section 3

RF TECHNOLOGY

3. RF TECHNOLOGY

3.1. U.S./JAPAN COLLABORATION ON RF VACUUM FEED-THROUGH TESTING

The testing of the feed-throughs at Naka, Japan was completed and a final report was written. The feed-throughs show short pulse hold-off voltages of over 70 kV, but it drops as the pulse is extended beyond 1 second. The cause of this deterioration is unknown. JAERI is willing to continue the testing at Naka to investigate this phenomenon, and it appears that further testing is justified.

3.2. GYROTRON AC SWEEPING COIL

In FY92 GA designed an ac sweeping coil system to spread the heat load over a greater area of the gyrotron collector assembly, in order to eliminate the hotspots and allow long pulse operation of the gyrotron. In FY93 this beam spreading system was used on a gyrotron under test at Varian and produced dramatic improvement: a reduction of power in the hot spots by a factor of approximately 2.5 was obtained.

3.3. COORDINATION OF INTERNATIONAL ACTIVITIES

The U.S./Japan RF Technology Exchange meeting was held at the JT-60U site in Naka, Japan, November 4-6, 1992 with approximately 40 people in attendance. Seven Americans represented the U.S. effort and 30-35 persons represented the Japanese effort.

GA hosted the 2nd Bi-annual International ECH Transmission Line workshop in San Diego, California, December 9-11, 1992.

Planning was performed for the U.S./Japan RF Technology workshop which was held October 28-29, 1993 at Inn at Grand Glaize, Osage Beach Mo.

3.4. TE_{22,6} MODE GENERATORS

Two TE_{22,6} mode generators for testing the internal launchers for the MW gyrotron development program were fabricated. One unit was assembled, tested and shipped to the University of Wisconsin in September. This unit had over 98% mode purity. The second

unit was assembled and will be shipped to the University of Wisconsin for testing in October.

3.5. GYROTRON DISTRIBUTED WINDOW

A conceptual design for a 2" X 8" gyrotron window based on the General Atomics "distributed window" concept was completed. The long lead materials were ordered and fabrication of the window frame and vacuum bellows will start in early October.

Section 4

PLASMA FACING COMPONENTS

4. PLASMA FACING COMPONENTS

4.1. OVERVIEW

The most challenging conditions to be dealt with by fusion technology occur at the interface between the fusion plasma and the first material wall. Erosion of the divertor target materials by physical and chemical sputtering processes and from disruption events are critical issues for high-power, long-pulse divertor tokamaks such as ITER. An ITER R&D program was initiated in response to the need to understand the interaction between the plasma and different divertor surface materials. Material erosion, tritium retention, disruption effects and material transport are very important topics for the design of ITER. For the DiMES program, we are using DIII-D as a test bed to directly measure and model the erosion/redeposition characteristics of different materials at the divertor plate. The DiMES sample changer system was fully operational in the latter part of 1993. Piggyback and dedicated erosion and redeposition experiments were performed. Excellent agreement was obtained between the measured net erosion of the coated material and the results obtained by modeling of specific plasma shots and conditions.

4.2. PROJECT DIRECTIONS

The plasma facing components project has been carried out as a cooperative effort by Sandia National Laboratory (SNL), responsible for program planning, DiMES sample supply and preparation, pre-and-post material surface characterization and disruption simulation, and GA, responsible for project planning and coordination, experimental operations, plasma and divertor diagnostics and analysis. Erosion/redeposition analysis is being done in conjunction with SNL and Argonne National Laboratory (ANL). Disruption analysis is being organized in conjunction with the University of New Mexico, North Carolina State University, SNL and ANL. Piggyback and dedicated erosion and redeposition experiments were performed in 1993. More erosion and redeposition experiments will be performed on ITER-relevant plasma facing materials in 1994 to further confirm the results. Dedicated disruptions experiments will also be introduced in 1994.

4.3. DiMES SAMPLE CHANGER SYSTEM ON DIII-D

The complete DiMES sample changer system was installed to DIII-D in early January of 1993. The system passed initial mechanical and vacuum operation design requirements. It functioned properly under high vacuum of 10^{-8} torr. Installation of the control system was completed by mid-January. The work of leveling the sample with the divertor tiles to about 0.25 mm was completed shortly after. Initial sample exposure experiments were then initiated.

In the next two months and during the DIII-D maintenance period, extensive modification was made on the sample changer system to resolve problems of system alignment and vacuum control. A new primary vacuum isolation valve and an upper guide tube with a nitride coated surface were installed. The nitride coating is needed to ensure minimum metal surface contact resistance while operating in vacuum. The bottom support was re-designed, fabricated and installed to make sure that the moving parts will self-align during insertion and lowering of the sample. Tests of these changes were made during early June. All sample changer critical operation difficulties were resolved and initial experiments resumed in mid-July.

4.4. SAMPLE EXPOSURE EXPERIMENTS

In coordination with the DIII-D schedule, we focused on erosion/redeposition experiments in FY93. However, while we were learning about the DiMES system, preparing the dedicated plasma exposure experiments and the necessary diagnostics, we were able to perform other material exposure experiments in DIII-D. For example, we evaluated effects of vessel bakeout and He glow discharges, and the effects of boronization of the first wall surface.

Two working group meetings were held in FY93 to plan the first series of DiMES experiments. Three experiments were identified and executed. The first experiment was a study of the deposition of material on a Si-chip sample during vessel bake-out and glow discharge cleaning to determine the effect of bakeout conditioning on first wall materials. Post-exposure examination indicated significant deposition of carbonaceous material, with some metallic contamination. The coating on the sample that experienced only bakeout was significantly different than the coating produced by bakeout with He glow

discharge. The second experiment was a study of ATJ graphite net erosion during plasma operation. We performed piggyback integrated exposure and dedicated exposure experiments on implanted Si-chip and the ^{29}Si isotope implant samples, and the results are reported below. The third experiment was a study of the boron coating thickness from boronization of the vessel. Exposed samples were sent to SNL for analysis. A list of DiMES sample exposure experiments performed in DIII-D is presented in Table 1.

As indicated in Table 1, we performed a piggyback integral exposure experiment on sample number 9, which was an ATJ graphite sample with ^{29}Si implant. The net erosion distribution measured by SNL matches well with the model results generated by ANL, as shown in Fig. 1.

Our first dedicated experiment was the exposure of sample number 8 on October 21. A DiMES sample with implanted ^{29}Si and a coating of W was exposed to six shots of ELM-free H-mode plasma. The sample was exposed to divertor scrape-off-layer fluxes during the current flat-top from two long ELM-free periods (lower single-null). Measurements of carbon and tungsten erosion have been made by Sandia. Significant carbon erosion was observed, but the tungsten erosion was below the detection limit (5 nm). However, redistribution of tungsten onto the surrounding carbon was measured. IR TV and CCD camera data were analyzed for this experiment. Detailed plasma parameters were provided to ANL for modeling analysis. The results will provide inputs to validate the REDEP and other erosion/redeposition modeling codes.

DIMES Sample Insertion

DIMES Experiment (July 22, 1993)

Comparison of Net Erosion with REDEP Model

Fig. 1. Material Evaluation Experiments in DIII-D Divertor.

Table 1
1993 DIMES samples exposure experiments in DIII-D

Date	Sample	Materials	Comments
March 2	16	ATJ graphite	Exposed to 2 pre-shots
March 3, 16-18	22, 21	ATJ graphite with Si Chip insert	Bakeout and conditioning
March 29 & 30	15	ATJ graphite	Piggy back on 13 & 23 shots
July 14	36	ATJ graphite	Piggyback on 16 shots
July 19	27	ATJ graphite with Si chip insert	12 He glow discharge cleaning shots
July 22	9	ATJ graphite with ²⁹ Si implant	13 plasma shots with last second strike point on DiMES
August September 11	23, 30, 24	ATJ graphite with Si chip insert	Boronized in DIII-D
September 13	TRINITI sample	MPG8/B ₄ C sample	Exposed to 15 shots
October 1-20	SNL probes	Sheath physics	Testing of 3 different Langmuir probes
October 21	8	ATJ graphite W- coating with ²⁹ Si implant	Dedicated experiment, sample exposed to 6 plasma shots

4.5. SHEATH PHYSICS STUDIES

A DiMES probe with three embedded langmuir probes was inserted into DIII-D for testing during plasma operations. Although two of the probes failed due to problems with

electrical connections, we did demonstrate the ability to do active experiments using DiMES.

4.6. BILATERAL EXCHANGES

Dr. Irina Opimach was at GA to perform DiMES sample exposure experiments. During her stay she assisted in the optical diagnostic measurement of the Russian B₄C coated tiles, and the examination of a DiMES sample exposed to disruption simulation experiments. She also spent one week at SNL to perform an Auger measurement on the DiMES sample that was exposed to a few DIII-D plasma shots.

Russian B₄C coated MPG-8 and RGT graphite DiMES samples were sent to the University of New Mexico for disruption simulation tests using electron and plasma guns. These samples were returned to GA and detailed examination was performed by Dr. Phil West and Dr. Opimach. The exposed surfaces were examined using SEM, EDAX and X-ray crystallography measurements. A large number of cracks were seen on the exposed sample surfaces, and some of the B₄C coating was detached. However, all the exposed surfaces were covered by boron. No exposed bare graphite surface was found. Further examinations are continuing at TRINITI laboratory, Russia.

4.7. MEETINGS

Dr. Clement Wong presented the DiMES program status at the following meetings:

1. U.S./Japan Workshop on Plasma Facing Components, November, 1993, Kyushu University, Japan.
2. U.S./Russian Workshop on High Heat Flux Components, June, 1993, St. Petersburg, Russia.

Section 5

FY93 PUBLICATIONS

5. FY93 PUBLICATIONS

Sager, G.T., et al., "Limitations of Power Conversion Systems Under Transient Loads and Impact on the Pulsed Tokamak Power Reactor," to be published in Proc. 15th Symp. on Fusion Engineering, IEEE (Hyannis, Massachusetts, October 11-15, 1993); General Atomics Report GA-A21474 (1993).

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Wong, C.P.C., "Helium Cooling of Fusion Reactor," IAEA meeting and workshop on Fusion Reactor Design and Technology, September 13-17, 1993; University of California, Los Angeles, Los Angeles, California.

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Wong, C.P.C., et. al., "Safety Design and Radioactive-Waste-Disposal Analysis for the TITAN-I Reversed-Field-Pinch Reactor Design," Fusion Engineering and Design, **23** (1993) 133-156.

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