GA-C24360

DIII-D UPGRADE PROJECT

**FINAL REPORT FOR THE PERIOD
OCTOBER 1, 1993 THROUGH MAY 31, 2003**

**by
R.D. STAMBAUGH**

**Prepared under
Contract No. DE-AC03-99ER54463
for the U.S. Department of Energy**

JUNE 2003

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**GENERAL ATOMICS PROJECT 30033
JUNE 2003**

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1. INTRODUCTION

Under DOE Contracts DE-AC03-89ER51114 and DE-AC03-99ER54463 to General Atomics (GA), three “capital project” upgrade projects were accomplished on DIII-D from FY93 to FY03 at a total GA cost of \$27.2M. These projects included the Fast Wave Current Drive (FWCD) Upgrade (\$8.2M), the Radiative Divertor Upgrade (\$7.2M) and the Electron Cyclotron Heating (ECH) Upgrade (\$11.8M).

The ECH and FWCD upgrades provided DIII-D rf and microwave power for electron heating, driving plasma current, controlling the plasma current profile, controlling tearing mode instabilities, and modulated transport studies. The divertor provided adequate density and impurity control for high triangularity single null plasmas in the Advanced Tokamak (AT) Program and information for International Thermonuclear Experimental Reactor (ITER) divertor design. These upgrades provide the power and density control required to initiate the active control of advanced tokamak discharges, which is the key element in the DIII-D program.

2. FAST WAVE SYSTEM UPGRADE

The DIII-D Fast Wave Current Drive (FWCD) system was upgraded with the addition of 4 MW of generator power capability to the existing 2 MW system (FMIT). DIII-D Advanced Tokamak scenarios typically call for fast wave power to be combined with the ECH gyrotron capability. The fast wave power is used principally for electron heating and current drive to control the central current density. This upgrade to 6 MW provided a significant capability for DIII-D research.

The scope of this project included the two 2 MW, 30–120 MHz generators from Asea Brown Boveri (ABB), the transmission system, some DIII-D vacuum vessel modifications, the control system, support hardware, interface with DIII-D operations, and antenna manufacture.

This program was a collaborative effort between GA and Oak Ridge National Laboratory (ORNL), with ORNL providing two new modular four strap fast wave antennas.

The project was accomplished from October 1993 to September 1995. Direct project costs were \$8.2M compared to a management plan budget estimate of \$9.0M. See Attachment A "DIII-D Fast Wave Current Drive 4 MW Upgrade Project," GA-C22429 Rev-1.

3. RADIATIVE DIVERTOR UPGRADE

The original objective of the Radiative Divertor Project (RDP) was to "demonstrate dispersal of divertor power by a factor of ten with sufficient diagnostics and modeling to extend the results to ITER and TPX." The divertor was also needed by the DIII-D Advanced Tokamak Program for density and impurity control and power dispersal for long pulse operation. The design supported the then current TPX project since it was of a similar shape and for a similar mission within the project. This design was also intended to test physics features of the ITER divertor design and to allow geometry variations (divertor slot length and width). The proposed program would address issues that were unlikely to be resolved anywhere in the world except in DIII-D: double versus single null, the necessity of pumping the inner leg, variation of slot length, variation of slot width, and divertor biasing effects.

The project, which was authorized in 1994, had a series of scope changes and especially after the severe reduction to the Fusion budget in FY96 was descoped and rebaselined finally to \$8.1M in July 1996, the final scope including only the installation of the upper half of the originally proposed RDP.

This upper radiative divertor upgrade, was divided into two phases. The first was to design, install, and operate a divertor and cryopump in the upper outer radius of DIII-D. Installation of this equipment (outer baffle, cryopump, external cryostat and cryogen service) was completed in January 1997. The second phase was to design, install, and operate a divertor and cryopump in the upper inner radius of DIII-D. The physical installation of the pump and divertor (inner private flux baffle) was completed in December 1999. Operation of the pump commenced in January 2000. This divertor has provided adequate density and impurity control for high triangularity single null plasmas in the AT Program and information for ITER divertor design.

The RDP was a joint effort between GA and several collaborators. General Atomics had the lead responsibility for the design and engineering of the Radiative Divertor Project. Lawrence Livermore National Laboratory (LLNL) had the senior management responsibility for the Radiative Divertor Project and the lead in divertor physics, modeling and diagnostics. Divertor diagnostics contributions (not part of upgrade project

funding) were made by GA, LLNL, ORNL, University of California, San Diego (UCSD), University of California, Los Angeles (UCLA) and Sandia National Laboratories (SNL). Low activation materials (vanadium) activities were authorized and carried out by GA, Argonne National Laboratory (ANL) and ORNL from within their existing research operations and technology program budgets.

The Project was started in October 1994 and completed in December 1999. The total GA cost of the RDP was \$7.2M, within the management plan estimated cost of \$8.1M. See Attachment B, "Final Report for the DIII-D Radiative Divertor Project," GA-C23380.

4. ECH UPGRADE

Heating and Current Drive Power at the electron cyclotron frequency (110 GHz) is used in DIII-D for electron heating, driving plasma current, controlling the plasma current profile, controlling tearing mode instabilities, and modulated transport studies. Two separate upgrade projects and operating funds have provided DIII-D with its current system of six gyrotrons of the 1 MW class.

4.1. Initial Three Gyrotron System

Initial scope of this ECH upgrade plan was to meet a 2 MW objective using two 1 MW 110 GHz gyrotrons, one from the Department of Energy (DOE) Gyrotron Development Program, CPI-D1, delivered to GA in January 1997, and the second from GYCOM (Russia), delivered to GA in July 1995. CPI-D1 was provided from the U.S. I&T gyrotron development program at Varian. It was a 1 MW, short pulse gyrotron with an internal converter similar to a successful Russian design. The pulse length of this gyrotron was limited to about 1.3 seconds by thermal stresses in the sapphire output window. The GYCOM-1 gyrotron was capable of 0.8 MW with 2 second pulses limited by its boron nitride output window. The project scope included acquisition of these two gyrotrons and adapting for them existing tanks, controls, transmission lines, and cooling systems. In March of 1997 the CPI tube was operated in conjunction with the GYCOM gyrotron. GYCOM-1 is still in service on DIII-D. CPI-D1 was used in experiments until April, 1999 when it developed a cathode short. Since it had been through so many bake cycles, it was decided that after it was repaired not to put it into service but to replace it with a spare Russian gyrotron GA had acquired with operating funds from the Tokamak de Varennes (TdeV) when that program was terminated; that spare GYCOM-2 is still in service on DIII-D. Total cost of this phase of the upgrade was \$3.35M.

In 1996, the DOE Gyrotron Development Program also made available to GA an older 1 MW prototype tube. The project scope included the rebuild of this tube as an internal mode converter gyrotron with a new launcher and output mirrors, as well as adding the first chemical vapor deposition (CVD) diamond output window. This gyrotron CPI-D2 was successfully rebuilt in May 1998. Testing at CPI was completed by the middle of July 1998. This gyrotron was used for experiments until July 2000 when its window failed. Since it had been through even more bake cycles than CPI-D1, it was decided to replace it with GYCOM-3, the second spare gyrotron that had been acquired from TdeV. GYCOM-3 is still in service on DIII-D. The associated cost of modifying CPI-D2, its controls and installation was \$0.77 M.

4.2. Upgrade From Three to Six Gyrotrons

The scope of this project was to upgrade the ECH system from the initial three-gyrotron system to a six-gyrotron system by adding 1 MW-level 110 GHz long pulse gyrotrons to reach a level of near 6 MW of installed ECH system power. This upgrade to six gyrotrons will provide the ECH and ECCD power required to initiate the active control of advanced tokamak discharges, which is a key element in the five-year plan for the DIII-D program.

The upgrade provided three-single disc chemical vapor deposition (CVD) diamond window 1 MW gyrotrons developed by Communication & Power Industries (CPI), gyrotron magnets and their power supplies, gyrotron tanks, low-loss-windowless evacuated transmission lines to connect the gyrotrons to the tokamak, water manifolds, and control systems.

The project began with an external project review held on July 22, 1998. The conceptual design and program review for the DIII-D six gyrotron upgrade project was held at CPI on October 9, 1998. On April 10, 2003, the last of the new gyrotrons passed its final acceptance test producing 1 MW for 5 seconds and completing the project. The full six gyrotron system was scheduled to be ready for service on DIII-D in January 2001; actual completion was April 2003. The total cost of this phase of the EC project was \$7.7M, compared to the Project Management Plan cost estimate of \$8.2M. See Attachment C, "DIII-D Electron Cyclotron Heating System Upgrade to 6 MW Project," GA-C24315.

4.3. Present System

The 110 GHz ECH system for the DIII-D tokamak now consists of six assemblies. Each assembly consists of a gyrotron, a gyrotron superconducting magnet, a gyrotron/magnet supporting tank, a low-loss-windowless evacuated transmission line

using circular corrugated waveguide for propagation in the HE_{11} mode, a two-mirror launcher which can steer the rf beam poloidally from the center to the outer edge of the plasma and toroidally for either co- or counter-current drive, high voltage and magnet power systems, and associated controls and water cooling systems. Three of the gyrotrons were manufactured by GYCOM and have a nominal output of 800 kW 2 s. The three long-pulse gyrotrons were manufactured by CPI and have a nominal rating of 1 MW, 10 s.

LIST OF ATTACHMENTS

- A. "DIII-D Fast Wave Current Drive 4 MW Upgrade Project," General Atomics Report GA-C22429 Rev-1.
- B. "Final Report for the DIII-D Radiative Divertor Project," General Atomics Report GA-C23380.
- C. "DIII-D Electron Cyclotron Heating System Upgrade to 6 MW Project," General Atomics Report GA-C24315.

DIII-D FAST WAVE CURRENT DRIVE 4 MW UPGRADE PROJECT

FINAL REPORT

**for the period
1 October 1993 through 30 September 1995**

**by
RICHARD W. CALLIS**

CAUTION

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1. EXECUTIVE SUMMARY

In FY92 the decision was made to upgrade the DIII-D Fast Wave Current Drive (FWCD) system by adding 4 MW of generator power capability beyond the existing 2 MW. Long range DIII-D Advanced Tokamak (AT) scenarios typically call for a total of 8 MW of fast wave power to be combined with the ECH gyrotron capability. This upgrade to 6 MW makes a significant step toward the final goal.

A novel feature of the DIII-D system is the configuration chosen to control the phasing of each strap of the antennas. It deviated from the standard approach of using one transmitter per strap, and controlling the phasing of each transmitter; instead a system of power splitters and decouplers were assembled, which gives complete control over the phasing at a reduced cost. This concept was validated during the first plasma coupling experiments using the new equipment, when the new systems were operated at 3.6 MW in current drive phasing. The system has now been successfully used to support the DIII-D physics program and good electron heating has been demonstrated.

Several of the vendors had difficulties in meeting the technical requirements of their contracts, see Section 2 for details, thus the project was delayed in its completion by over a year. The project final cost was \$8,236K.

FWCD on DIII-D is a collaborative program between General Atomics (GA) and Oak Ridge National Laboratory (ORNL). To define the collaboration in relation to this upgrade project, a Memorandum of Understanding (MOU) was established between GA and ORNL, with representatives from DOE also cosigning. The MOU defined a Work Breakdown Schedule (WBS), the technical scope of the project, the responsibilities of each party, the project management organization for each party, and established the schedule, budgets, milestones, and reporting requirements. The direct GA support of ORNL to meet the antenna fabrication needs was defined by a separate written agreement between GA, ORNL, and DOE.

For the upgrade ORNL provided two new modular four-strap fast wave antennas which were installed in FY94 on midplane ports at 0° and 180° toroidally in DIII-D. GA was responsible for the necessary preparation of the DIII-D vacuum vessel for the antennas, the high power rf generators, the transmission system, the control system, and all aspects of interface with DIII-D operations. Subsequent physics experiments will also be a collaborative effort. Also, GA helped accelerate the fabrication of the two antennas by providing capital funds to ORNL in FY93, and by assuming financial responsibility for the manufacturing of the antenna components in outside machine shops. GA also performed engineering liaison with the shops as necessary.

The project completion delay was caused by several vendors failing to meet the technical requirements of their contracts. Appendix A provides a lessons learned evaluation of what went wrong with those procurements.

2. PROJECT SCOPE AND OBJECTIVES

The Fast Wave Current Drive 4 MW Upgrade Project on the DIII-D tokamak is a collaborative effort between GA and ORNL), with ORNL providing the design and fabrication of the FWCD antennas and GA providing the technology to generate, transmit, and couple the high power rf to the antenna. Both parties participate in the experimental activities.

The work breakdown structure between GA and ORNL was defined in the DIII-D Fast Wave Current Drive 4 MW Upgrade Management Plan, which defined the technical, cost, and schedule requirements necessary to achieve the program objectives. GA and ORNL were assigned specific scopes of work. GA and ORNL established within their own project organization, a system for controlling and accomplishing the work assigned. In addition GA and ORNL also developed a MOU covering the Fabrication of DIII-D Fast Wave Current Drive Antennas.

2.1. OVERALL PROGRAM MANAGEMENT

The technical, cost, and schedule baselines at GA and ORNL were the basis for control of the Fast Wave Current Drive 4 MW Upgrade Project. Once these baselines were established to meet the program objectives each organization proceeded to complete their respective scopes of work within the approved baselines. GA utilized a system of breaking the baselines down to identifiable subtasks and developing an Approved Task Authorization for each subtask, with an appointed subtask manager held responsible for cost and schedule control. A monthly assessment of the progress of each subtasks was held and a project cost-to-complete re-estimate was performed every six months.

2.2. TECHNICAL DESCRIPTION

An overall schematic of the new FWCD system is shown in Fig. 1. There will be two identical 2 MW systems, like the one described in Fig. 1. The primary elements of each system are the antenna, the transmitter, the transmission system, and the control system. The transmission system must perform an impedance match of the transmitter to the antenna under varying plasma conditions and allow flexibility in the intrastap phase shift for various experiments.

2.2.1. WBS ELEMENT 1 - TRANSMITTER

A lengthy competitive bid and technical evaluation cycle held in FY92 resulted in the selection of transmitters from Asea Brown Boveri (ABB). These units are of the type used on the ASDEX-Upgrade tokamak in Germany, and have proven very reliable in operation there.

Fig. 1. Schematic for one of the 2 MW, 30 to 120 MHz Fast Wave Current Drive Systems.

The transmitter consists of four stages of rf amplification, as shown in Fig. 2. The input signal is fed to the 50 W rf preamplifier by way of an attenuator and the PIN regulator. The 5 kW predriver stage is of a straightforward design and uses a water-cooled Siemens type RS10S4 transmitting tetrode. The input and output tuning circuits of this grounded-cathode stage are motor driven. The 100 kW high-power driver stage is a grounded-grid configuration using a type 4CW 150000 tetrode made by Eimac. The output circuit is design as a coaxial 1/4 circuit with a 50 W output impedance adjusted by a motor-driven variable coupling. The 2 MW high power final stage is entirely a coaxial design. It is fitted with an ABB type CQK 650-2 tube, operated in a grounded-grid configuration. The output circuit is made up of coaxial line sections with tuning achieved by motor-driven sliding elements. The control system can store the position of the tuning elements for up to 12 different frequencies, so that when the operator wants to change frequency settings a recall of the stored tuning element locations is all that is required. The specifications for the transmitter are given in Table 1.

2.2.2. WBS ELEMENT 2 - DIII-D VESSEL MODIFICATION

The two ports which will house the two new antennas required extensive modification. A pumped limiter was installed on the 180° port and a moveable limiter blade was installed on the 0° port. Removal of the pumped limiter and preparation of the 180° port was completed in early 1993, during the last major vent before the 1993 experimental campaign. The other location was prepared in the vent in the fall 1993.

Fig 2. Block diagram of the rf transmitter amplifier stages.

Table 1

Specifications of the ABB Type VU 62 B 1 Transmitter

Frequency Range	30 MHz to 120 MHz	
Bandwidth	$\pm 0.25\%$ -1 dB	
	± 75 kHz to ± 300 kHz - 1 dB	
Output Power	from 30 MHz to 80 MHz	2.0 MW
	at 100 MHz	1.5 MW
	at 120 MHz	1.0 MW
	into 50 ohms, VSWR 1:1.5	
Pulse Duration	20 sec max.	
Duty Cycle	10% max	

2.2.3. WBS ELEMENT 3 - SUPPORT HARDWARE

This WBS element includes the dummy loads, rf exciters, test equipment, and instrumentation and control systems. The dummy loads, exciters, and test equipment were specified in FY93 and ordered to arrive in FY94. A microcomputer was acquired for the control of the two systems.

2.2.4. WBS ELEMENT 4 - TRANSMISSION SYSTEM

Each of the two transmission line consist of 9 3/16 and 6 1/8 inch diameter coaxes, a switch, a splitter, a dummy load, phase shifters, stub tuners, gas barriers, test sections, and diagnostic equipment as depicted in Fig. 1. All the transmission line and components have ceramic

insulators. Each of the transmission lines to the two antennas have the same equipment, but due to the DIII-D building layout, one line is approximately 200 feet longer than the other. For the sake of discussion, only one transmission line will be referenced in the discussion of the two systems.

The transmission line system is straightforward. The generator power is split into two feedlines with a 3 dB hybrid junction, optimized for the primary 60 to 120 MHz band of operation. A four-port, two-way switch is used to direct any power reflected through the hybrid to the dummy load.

Each feedline contain a standard line-stretcher/stub-tuner pair for impedance matching, and one feedline has the main 360° phase shifter. There is a five-way junction at the end of each feedline where the line transforms down to a pair of 6 1/8" 25 ohm lines forming a resonant loop with a pair of current straps on the antenna. A decoupler/nuller system connects the two five-way junctions in order to compensates for the circulating power that is created by the mutual coupling between resonant loops.

2.2.5. WBS ELEMENT 5 - FACILITY MODIFICATIONS

The facility modifications required: new outdoor concrete pads for the transmitter power supplies, indoor site preparation for the transmitters which included a rearrangement of the FWCD control room, and the tie in of an additional water cooling system to the overall DIII-D system.

Major rework of the area just outside of the torus hall was required for the construction of two new mezzanines for the large transmission system tuning elements for the 180° system, and the preparation of the area just outside of the hall at 0° which was formerly occupied by the 60 GHz gyrotron systems, which were removed at the beginning of FY94.

2.2.6. WBS ELEMENT 6 - ANTENNA MANUFACTURE

The design, manufacture, assembly, and initial check-out of the two new antennas is the responsibility of ORNL, with close interaction with the DIII-D RF Physics and Operations groups. The final design review was held in Oak Ridge in January 1993. Title II engineering was completed at the end of March with the approval and issuance of drawings.

The FWCD antenna for DIII-D was designed to be modular in nature with each antenna consisting of four modules mounted side by side in one of the larger DIII-D midplane ports. The two ports large enough to support an antenna are located at 0° and 180°, respectively. Each module of an antenna is capable of handling 1 MW for pulses up to 10 sec which means that each antenna could support a total power of 4 W with appropriate antenna/plasma impedance loading. Each module is fed by its own vacuum feedthrough and then external to the vacuum vessel are interconnected and by coaxial transmission line are connected to the high power rf transmitter.

Each module, as shown in Fig. 3, consists of a cavity box, Faraday shield, current strap, and vacuum coax. The cavity box, Faraday shield, and current strap are tilted to match the magnetic field lines at the surface of the plasma for optimum rf coupling. Cooling channels are fabricated into the modules to remove heat caused by rf and plasma heating. The Faraday shield rods specifically do not have water flowing through them so that if a rod was melted by wayward plasma particles, the vacuum integrity of the vessel would not be spoiled by a water leak. The Faraday shield rods are only edge-cooled and are thus the limiting factor for experimental pulse length applications.

Fig. 3. ORNL modular Fast Wave Current Drive Antenna, coaxial feed NOT shown.

The current straps are grounded at two locations, one end of the strap is grounded at the bottom of the cavity, while the other end is grounded to the side wall of the cavity midway up the wall. The feed to the strap is attached to back of the strap as the folded strap comes closest to the cavity wall. The folded strap design allows the antenna to have effective performance at the high frequency end ($f \approx 80$ MHz) while being effective at lower frequencies as well. The cavity walls are recessed to increase directionality and was achieved by wrapping the Faraday shield rods over like a croquet wicket and then connecting them to the cavity box. All parts have been nickel plated to reduce sputtering and thus maximize voltage standoff capability.

2.3. COST SUMMARY

The breakdown of the final total capital project cost of \$8,236K by WBS and year is given in Table 2. The original management plan estimate was \$9,009K, but included some cost items allocated to the DIII-D RO budget and some cost items completed before the overall DIII-D upgrade project was defined and approved on October 1, 1993. The DIII-D RO budget covered \$981K for various modifications to the existing DIII-D facility to accommodate the Fast Wave System.

2.4. SCHEDULE BASELINE

A Project Schedule (Fig. 4) was developed, which identified the major activities for the entire project. This schedule was used during DOE reviews to report the progress of the project. Milestones from this schedule were selected and are shown in Table 3 for both DOE and GA. The DOE milestones depicted the major events which must occur in order that the project be completed on time. They formed the Schedule Baseline. The GA milestones supplemented the DOE milestones, and provided additional reference points for denoting the progress of the project.

Table 2
DIII-D Fast Wave Currnet Drive 4 mw Upgrade Project
Final Costs by WBS Level
(K\$)

WBS ELEMENT	FY92	FY93	FY94	FY95	FY96	TOTAL
WBS 1						
Transmitter						
ODC Sub-Total	\$0	\$0	\$18	\$60	\$0	\$78
Labor Sub-Total	\$0	\$0	\$173	\$25	\$0	\$198
Total	\$0	\$0	\$191	\$85	\$0	\$276
Procurement (Capital)	\$0	\$1,487	\$1,916	\$161	\$271	
Total Transmitter	\$0	\$1,487	\$2,107	\$246	\$271	\$4,111
WBS 2						
Asset Modification						
ODC Sub-Total	\$0	\$0	\$41	\$0	\$0	\$41
Labor Sub-Total	\$0	\$0	\$115	\$2	\$0	\$118
Total	\$0	\$0	\$156	\$2	\$0	\$158
WBS 3						
Support Hardware						
ODC Sub-Total	\$0	\$0	\$257	\$2	\$0	\$259
Labor Sub-Total	\$0	\$0	\$144	\$10	\$0	\$154
Total	\$0	\$0	\$401	\$12	\$0	\$413
WBS 4						
Transmission System						
ODC Sub-Total	\$0	\$0	\$1,184	\$136	\$0	\$1,320
Labor Sub-Total	\$0	\$0	\$328	\$139	\$0	\$467
Total	\$0	\$0	\$1,512	\$275	\$0	\$1,787
WBS 5						
Facility Modifications						
ODC Sub-Total	\$0	\$0	\$1	\$0	\$0	\$1
Labor Sub-Total	\$0	\$0	\$1	\$0	\$0	\$1
Total	\$0	\$0	\$2	\$0	\$0	\$2
Sub-Total WBS 1 thru WBS 5	\$0	\$1,487	\$4,178	\$534	\$271	\$6,471
WBS 6						
Antenna Manufacture						
ORNL	\$300	\$965	\$500	\$0	\$0	\$1,765
TOTAL 4 MW PROJECT	\$300	\$2,452	\$4,678	\$534	\$271	\$8,236

Figure 4 Project Summary Schedule

Table 3
DIHI-D Fast Wave Current Drive
4 MW Upgrade Project

	Schedule Baseline	
	<u>Original</u>	<u>Completion</u>
<u>DOE</u>	<u>Date</u>	<u>Date</u>
#83 Install ORNL FWCD antennas	Mar 94	Apr 94
#84B Complete transmitter construction	Sep 93	Sep 93
#96B Complete transmitter check-out	Feb 94	Jul 95
#97B Report initial results	Oct 94	Oct 95
<u>Internal</u>		
1. Complete prep of 180° port	Dec 94	Dec 92
2. Hold transmitter FDR	Jan 93	Jan 93
3. Hold antenna FDR	Jan 93	Jan 93
4. Release order for transmission system	Jun 93	Aug 93
5. Release order for dummy load	May 93	Aug 93
6. Release order for exciter, test equip., and I&C	Jul 93	Jul 93
7. Pour power supply pads	May 93	May 93
8. Complete transmitter site prep	Jul 93	Jun 93
9. Complete new tuner mezzanine	Sep 93	Aug 93
10. Install power supplies	Sep 93	Oct 93
11. Install transmitters	Oct 93	Aug 93
12. Install dummy loads	Oct 93	Jun 94 0°
13. Install transmission system	Dec 93	Jul 94 180°
	Dec 93	Jan 95
14. Complete prep of 0° port	Dec 93	Feb 94

3. LESSONS LEARNED

LESSONS LEARNED DURING ICRF UPGRADE PROJECT

(sent to Dr. Mark Foster DOE-OAK, Sept. 30, 1994.)

You produced an excellent summary of our discussion of vendor problems encountered in the ICRF Upgrade project in your Record of Meeting: DIII-D Research Operations FY94 3rd Quarter Review dated September 1, 1994. As you are aware, additional problems have been encountered since the last Quarterly Review, so we wanted to document the most recent problems and provide additional information on the previous problems, including discussions with principals at other labs doing ICRF work. Since FWCD is expected to be employed on TPX, many of the issues we have encountered will be of concern to them as well.

As you pointed out in the summary, perhaps a common element of our vendor difficulties was our misinformed belief that these were basically "off-the-shelf" components including the transmitter. All of the components had been used elsewhere in similar circumstances with reasonable success, and we had discussed our intended purchases with the key user personnel. For example, the ABB transmitters were virtually the same systems supplied to ASDEX, the stub tuners and phase shifters from RF Technologies were similar to those supplied to MIT, and straight coax pieces from Dielectric had been used previously at DIII-D. This approach followed our "fast-track" philosophy that to maintain schedule validity we had to avoid lengthy developmental activities and go with proven designs.

We carefully wrote the specifications for the transmission components to avoid the difficulties we had encountered with our old transmission lines, namely the irreversible damage done to Teflon due to arcing and our inability to pressurize the system with insulating gases. Therefore, we attempted to insure the quality from all vendors would be acceptable by requiring ceramic insulators instead of Teflon and a requirement that all components be pressure tested before shipment. All of these features were known to be incorporated into the components of the European company, Spinner, with a reputation for supplying high quality, reliable components; as we expected they were unable to offer a cost competitive bid on most components. U.S. procurement regulations make it nearly impossible to select the foreign bidder based on technical know-how when we had two U.S. companies which appeared qualified. In contrast the ABB bid for the transmitters was very cost competitive.

Our belief that the components purchased were not particularly challenging, supported by our discussions with other users, led us to require only minimal supervision at the vendor facilities. The fact that the vendors in the U.S. were located in Maine and the transmitters were built in Switzerland made frequent supervisory visits a costly endeavor. Even then we did have project

staff visit the Maine transmission line vendors before the procurement was placed and an engineering liaison visit was scheduled early in the project to work out any problems in the design. On-site liaison during the fabrication phase was not scheduled at any significant level until the severity of the schedule problems at RF Technologies was apparent.

Given these general remarks, let us examine the problems encountered in some detail by looking at the three prime subcontracts.

ABB/TRANSMITTERS

Before the transmitters were procured from ABB, several GA staff, both engineers and scientists, had on site visits and discussions with the key personnel at ASDEX to confirm their satisfaction with the equipment and identify problems encountered. The ASDEX staff were uniformly enthusiastic about the ABB systems; problems with power tube failures were reported, but appeared to be resolved in their replacement tubes.

The problems associated with this section of the Upgrade Project are:

- Excessive number of miswiring, incorrect settings, and broken hardware.
- Shipping damage to high voltage power supply hardware.
- Incomplete assembly of the high voltage power supplies.
- Leaky or blocked water cooling circuits.
- Regulator circuit for the high voltage power supplies provided by an ABB subcontractor did not meet ABB requirements for tube operation.
- All three Final Power Amplifier tubes have failed, one after only two weeks of operation.
- The step-down transformer for the high voltage power supplies provided by an ABB subcontractor developed a short, rebuild also failed; analysis indicated that transformer design was faulty.
- Not all German markings were converted to English and few detailed procedures were provided.

Recommendations:

- Early design reviews should be held to evaluate any deviation from proven designs and to validate that field changes have been incorporated.
- Engineering visits during fabrication to assess progress.
- Subsystem tests should be developed and required to the extent possible, particularly with incentive contract. Integrated systems tests should be required to the power level consistent with the factory capability.
- Full performance operation should be demonstrated before final payment.

TRANSMISSION LINES

The transmission line configuration was intended to be similar to the one proven on the first 2 MW DIII-D Fast Wave Current Drive System, with design improvements to increase the voltage standoff capabilities. Each vender of a component was chosen because the component had a proven track record at DIII-D or another fusion laboratory, *e.g.*, MIT, PPPL, ASDEX, JET, etc.

The problems associated with this section of the Upgrade Project are:

- All vendors were late in delivery.
- RF voltage stand off requirements were not achieved even though parts passed the dc hipot tests.
- Component cleanliness is questionable.
- Mechanical and electrical design of some parts was poor and required reworking.
- One vender, RFF, is on the verge of bankruptcy causing creative efforts to get parts out the door.

Recommendations:

- The fusion lab rf experts are knowledgeable about ii high power designs and should review and approve new hardware/designs. Vendors do not have rf breakdown experts on their staff.
- Vendors' financial viability must be taken into account before awarding a contract.
- More emphasis on reviewing a vendors ability to fabricate the parts within the schedule constraints. This should include independent verification of the vendors subcontractor schedules.
- Whenever possible full power rf testing should be required before acceptance.

ANTENNAS

Antenna design was done by ORNL under the DIII-D collaboration effort and the fabrication was jointly completed between ORNL and GA staff to accelerate the schedule completion. Design reviews included key staff from MIT and PPPL. Overall this effort went as planned, but not without problems nor without ways in which it could have been done better.

The problems associated with this section of the Upgrade Project are:

- Weld warpage lead to extended reworking of parts.
- Antenna cooling circuits interfered with port box requiring field reworking of the antenna modules

- Faraday shield rod elements could only be brazed in small batches
- Faraday shield assemblies got hung up in France because of transportation and custom problems
- Brazing tests beyond simple coupons were not pursued to save money -Brazing of the real parts took more braze material than anticipated and the development of special tooling, and temperature control requirements dictated a small batch process only.
- ORNL did not make a port mockup to save money ó the interference of the water cooling lines with the port boxes would have been caught during assembly.

Recommendations:

- In joint efforts like the antenna fabrications, constructability reviews should be held jointly.
- A second, and preferably a U.S., vender should be found who can coat B4C.

APPENDIX A

4 MW Upgrade to DIII-D FWCD System: System Commissioning and Initial Operation

presented at the 16th Symposium on Fusion Engineering,
Urbana, Illinois, 1995

4 MW Upgrade to DIII-D FWCD System: System Commissioning and Initial Operation^{*}W.P. Cary,^a F.W. Baity,^b G.C. Barber,^b R.W. Callis,^a J.S. deGrassie,^a S.W. Ferguson,^c T.E. Harris,^a
R.C. O'Neill,^a R.I. Pinsker^a^aGeneral Atomics, P.O. Box 85608, San Diego, California 92186-9784^bOak Ridge National Laboratory, P.O. Box 2009, Oak Ridge, Tennessee 37831^cLawrence Livermore National Laboratory, P.O. Box 808, Livermore California 94551-9900**ABSTRACT**

The initial installation of the 4 MW fast wave current drive (FWCD) upgrade started in 1992 with the purchase of two ABB/Thomcast AG rf power amplifiers. These amplifiers cover the frequency range 30 MHz to 120 MHz. A maximum output power of over 2 MW between 30 MHz and 80 MHz and 1 MW at 120 MHz were the specification requirements. The system as installed is comprised of the two mentioned rf amplifiers, coaxial transmission and matching components, rf phase and amplitude monitoring, and a SUN SparcStation 10 control system.

Due to various reasons almost every major component in the system required redesign and engineering in order to meet the system requirements. The failures, probable cause and the final redesigns will be discussed as well as some thoughts on how better to specify system requirements for future systems.

INTRODUCTION

The DIII-D 4 MW ICH upgrade can be thought of as being comprised of three major categories: the rf sources, the transmission and matching system, and the controlling software and electronics (Fig. 1). The philosophy from the onset of the project was to minimize the risks inherent with development programs and stay with components having a proven track record. The vendor choices were to be judged not only on a competitive cost basis but also on their perceived capabilities and expertise. This meant that we would be looking at mostly "off the shelf" type components. It was felt that this would eliminate the time consuming task of development and have the added advantage of proven reliability; unfortunately this did not prove to be the case. Initially, we assumed that our vendors had the expertise and experience to design a system which would meet our specifications, but in retrospect in some cases the tasks

Fig. 1. Simplified diagram of one of the new fast wave current drive systems.

^{*}Work supported by the U.S. Department of Energy under Contract Nos. DE-AC03-89ER51114, DE-AC05-84OR21400 and W-7405-ENG-48.

proved beyond the experience base and technical expertise of the vendor staff. The major problem areas and their resolutions will be presented in the following sections.

RF SOURCES

The sources can be further subdivided into the three general areas of control, rf amplifiers, and High Voltage Power Supplies (HVPS). Owing to schedule constraints it was determined early in the procurement phase that a complete system test could not be performed anywhere except after installation at DIII-D. Because of this, only limited testing of the various subsystems could be completed at the various manufacturing facilities. This was felt to be a low risk plan since there had already been six of the rf sources already built [1], so these two could be considered to be production units.

Installation of the two amplifiers, and their associated HVPS went smoothly. It was not until checkout was started that the deficiencies were identified. Many control functions failed to work properly. In some cases there were problems with the traces on the circuit boards. There were also a number of logic and voltage level interfacing problems.

The rf amplifiers have not been immune to failure either. To date there have been three tube failures in the final stage. All three tubes have been analyzed by the factory and found to have similar control grid to cathode shorts. The cause of these failures has not yet been determined; however, these failures have led the tube manufacturer to impose more conservative operating limits which in turn have made it more difficult for the rf amplifiers to meet their design specifications. The most troublesome problem to date has been an oscillation occurring in the final stage at approximately 750 MHz that occurs when the rf absorber is removed from around the tube or when degraded due to overheating. The transmitter specifications call for removal of rf absorber material above 80 MHz but due to the parasitic oscillations the rf absorber was required for high power operation. This would not present a problem, except that due to excessive heating of the rf absorber by the fundamental power we have been forced to operate at reduced pulse length. Testing of the material showed that temperatures in excess of 300°C would easily be exceeded while not exceeding the original transmitter specifications. Furthermore, these high temperatures have been observed to degrade the absorptivity of the material which eventually caused the material to fail as an absorber (manufacturer's maximum operating temperature is 200°C). A water cooled version of the rf absorber has been furnished by Thomcast but not yet tested as of this writing.

With full power (>2 MW) and long pulses (>3 s) we are starting to see signs of tube problems. There is a gradual increase in anode current after removal of rf drive and there is also a negative screen grid current transient seen at the beginning of this anomaly (Fig. 2). This may be due to secondary heating effects. Owing to lack of a tube vacuum pump it is not known if there is an increase in tube pressure. The tube manufacturer has been made aware of the problem and we are awaiting their response.

Fig. 2. Anode voltage droop.

The HVPS has also been a source of several problems. Early rf testing revealed only minor problems, but as the power levels and pulse lengths were increased several new problems were encountered. The first of the major problems was with the voltage regulation of the anode voltages for the final power amplifier and driver tubes. Several attempts were made by the manufacturer and a continuing effort by us has yielded only marginal improvement. The major problem occurs in the beginning of the pulse where the voltage sags more than 5 kV (specification calls for less than 2.5 kV) in 25 ms before responding and another 25 ms to return to the nominal operating voltage (see Fig. 3). This loss of voltage causes an excess amount of screen grid current in the beginning of the pulse, resulting in a loss of transmitter output power, and potential shutdown on a screen overcurrent fault. This voltage droop can be compensated for by increasing the requested voltage, but at the risk of running into anode dissipation problems when the voltage returns to the requested voltage level.

Inadequate regulation has not been the only problem with the HVPS. During testing at DIII-D the main step-down transformer (12.47 kV to 570 V) had a failure of the insulation at the winding margin. The repair of this unit required return to the vendor and took over three months to complete. Even the vacuum circuit breakers have been a source of problems. The breakers have failed several times with parts either fracturing or becoming disconnected.

The rf source manufacturer has been very responsive to our problems, and have provided engineering support on several occasions. Unfortunately, the problems encountered did impact the timely completion of the upgrade system.

TRANSMISSION AND MATCHING SYSTEM

After determining the actual components desired (i.e., phase shifters elbow, etc.) the component design responsibility was given to the two selected vendors. One manufacturer was chosen to supply the standard 6 in. and 9 in. transmission line

Fig. 3. Secondary emissions.

components while the other was chosen to supply the special components such as the hybrid and the tuning elements.

In order to improve the high voltage capability of the transmission line components, a decision was made to disallow any organic material from being used inside the transmission lines. This was based on our experience with Teflon (the industry standard) in a previous system, because of its degrading after an arc had occurred, and our positive experience with 6 in. coaxial line using ceramic standoffs. The ceramic material selected was unable to support the specified rf voltages. A poor design of the triple point interface (insulator/gas/conductor) required considerable time and effort at GA to develop a workable solution [2].

The vendor's choice of insulating materials for the tuning elements proved problematic. An epoxy glass material (G-7), with continuous fibers running along the length of the shaft, was chosen to be the push rod for the center conductor. When the tuning elements were positioned near the minimum length position and this coincided with the rf voltage being near maximum at the rod-to-conductor junction, a failure occurred. Repeated pulses with this condition caused a short to develop between the center and the outer conductor with a path along the insulating rod. The correction for this failure was the replacement of the fiberglass rod with a homogenous plastic rod (Delrin), which caused us much lost time due to the difficulty in effecting a repair to the units. Testing in our rf high potter [2] revealed <47 kV peak rf voltage for breakdown in 15 lbs., SF6 for the G-7 rod and >72 kV peak for the Delrin rod. Our design goal was to have all 50Ω components capable of holding off >70 kV peak rf voltage. Several mechanical aspects of the moveable tuning elements have proven troublesome. Several failures of the mechanical drive system in the tuning elements have occurred. The

motor to worm gear couplings has been a continuing source of problems.

SOFTWARE AND COMPUTER CONTROL

Of the three major categories, the software and computer control system seemed to be the least troublesome. A Sun SparcStation 10 was chosen as the computer platform, due to its UNIX environment and supposed ease of integration with the existing DIII-D computer systems. Lab View and VXI were chosen as the software-hardware configuration due to the strong industry support of both. The Sun was not as easy to set up and connect to the other computers as was first thought. At the beginning of this program National Instruments had just started to introduce a new version of Lab View for the Sun, so what was first envisioned as a six month effort turned into an 18 month task. The VXI hardware and the vendor support was not up to speed in the beginning compared with our old tried and true CAMAC equipment. This caused some delays in the implementation of the VXI based control. If we were looking at doing this again, CAMAC would probably be the hardware of choice [3].

CONCLUSION

Several observations can be made after this two year effort. The first and probably the most significant to the fusion community is that there is currently no such thing as an "off-the-shelf" 2 MW rf system. Second, vendor experience and expertise with high power long pulsed rf systems is rather limited. Our experience indicates that the end users must take an active and possibly leading role in the solution of these engineering problems. Lastly, when a new system is specified strong consideration should be given to spending the up front money to have the systems demonstrated and acceptance testing performed at the factory or at the site as part of a fixed price contract.

All things considered, there have been many successes with the introduction of the upgrade. The problems with the various components have been mostly resolved and the transmitters have operated into DIII-D plasmas with a combined rf source output power in excess of 3.6 MW. This is 90% of the rated power and we expect to achieve full power in the near future.

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- [3] T.E. Harris, "System control and data acquisition of the two new FWCD rf systems at DIII-D," this conference.

GA-C23380

**FINAL REPORT FOR THE
DIII-D RADIATIVE DIVERTOR PROJECT**

**by
R.C. O'NEILL AND R.D. STAMBAUGH**

**Prepared under
Contract No. DE-AC03-99ER54463
for the U.S. Department of Energy**

JUNE 2003

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**GENERAL ATOMICS PROJECT 30040
JUNE 2003**

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BACKGROUND AND HISTORY, PROJECT EVOLUTION

DIII-D FIVE YEAR PLAN FOR 1994-1998

The Radiative Divertor Project originated in 1993 when the DIII-D Five Year Plan for the period 1994-1998 was prepared. The Project Information Sheet described the objective of the project as "to demonstrate dispersal of divertor power by a factor of ten with sufficient diagnostics and modeling to extend the results to ITER and TPX." Key divertor components identified were:

1. Carbon-carbon and graphite armor tiles
2. The divertor structure providing a gas baffle and cooling
3. The divertor cryopumps to pump fuel and impurities.

A conceptual design target was set for February, 1994. The Project was envisioned to take place in the years 1994-1996 with the following expenditure profile for each year.

Cost Summary (\$000)			
<u>FY94</u>	<u>FY95</u>	<u>FY96</u>	<u>Total</u>
3,360	8,796	3,919	16,075

RADIATIVE DIVERTOR PROJECT REVIEW — JUNE 15-16, 1994

The Department of Energy convened a formal review of the proposed Radiative Divertor Project at General Atomics, June 15-16, 1994. Presentations at that review were:

Opening Remarks	R.D. Stambaugh
DIII-D Program Overview	T.C. Simonen
Overview of the Radiative Divertor Program	S.L. Allen (LLNL)
Divertor Requirments for the AT Program	T.S. Taylor
Modeling Applied to the RDP	G.D. Porter (LLNL)
Physics Review of Biasing	G.M. Staebler (GA)
Engineering Conceptual Design	J.P. Smith (GA)
Management Plan: Cost and Schedule	J.P. Smith/S.L. Allen
Diagnostics and Physics Measurements	D.N. Hill (LLNL)

The divertor configuration presented (Fig. 1) was a double-null divertor with a short but reasonably baffled design to be relevant to the ITER slot divertor. Cryopumps were provided to

separately pump both the inner and outer strikepoints of both ends of the double null. The lower, outer pump was a carry-over from a previous installation.

Fig. 1. Features of the DIII-D Radiative Divertor Design.

This divertor was needed by the DIII-D Advanced Tokamak Program for density and impurity control and power dispersal for long pulse operation. The design supported the then current TPX project since it was of a similar shape and for a similar mission within the project. This design was also intended to test physics features of the ITER divertor design and to allow geometry variations (divertor slot length and width). The proposed program would address issues that were unlikely to be resolved anywhere in the world except in DIII-D:

1. Double versus single null
2. The necessity of pumping the inner leg
3. Variation of slot length
4. Variation of slot width
5. Divertor biasing effects.

The overall Divertor Development Plan for DIII-D is shown in Fig. 2. The design requirements were:

1. Provide power exhaust for 38 MW for 10 seconds
2. Use proven existing technology — ADP biasing, ADP baffle, ADP cryopump, first wall and divertor armor.
3. Maintain conditioning capabilities — vent recovery time of 1–3 weeks and use of the then current inductive baking system.
4. Satisfy the intent of the ASME code.

Important changes had been made in the Project concept since the 1993 description. The Project was now separated into a Phase I and a Phase II. Phase I included the first construction and operation of the 23 cm slot divertor as shown in Fig. 3, providing high triangularity, double-null operation with cryopumping of all strike points. Phase II covered various future options such as variations in slot length (33 and 43 cm, Fig. 3), unipolar biasing, the gas bag divertor, and long pulse operation.

The total cost of Phase I was \$9.5M and the total cost of Phase II was \$6.6M for an overall total of \$16.1M. While the total cost was kept in the same envelope as in the 1993 planning, the configuration of the project had changed considerably to provide more physics investigation flexibility in the new Phase II. To hold the Project cost, careful analysis had shown that expensive carbon-carbon composite materials could be deleted in favor of much more economical graphite tiles. The cost layout over years was:

RDP Upgrade Costs					
Costs (\$M)	<u>FY95</u>	<u>FY96</u>	<u>FY97</u>	<u>FY97-01</u>	<u>Total</u>
Phase I	2.9	5.0	1.6		9.5
Phase II				6.6	<u>6.6</u>
					16.1

The Review Committee strongly endorsed proceeding with the Plan as outlined.

MANAGEMENT PLAN FOR THE DIII-D RADIATIVE DIVERTOR PROJECT — OCTOBER 1, 1994

After the successful review, a Project Management Plan was issued in October, 1994. Refined cost estimates and engineering innovations had reduced the overall Project cost to \$14.6M, with Phase I at \$8.7M and Phase II at \$5.9M. This plan identified General Atomics as having lead responsibility for the design and engineering of the Radiative Divertor Project. Lawrence Livermore National Laboratory had the senior management responsibility for the Radiative Divertor

Fig. 2. DIII-D Divertor Development Plan.

Fig. 3. Modular radiative divertor hardware provides flexibility.

Project and the lead in divertor physics and modeling. Divertor diagnostics would involve contributions from GA, LLNL, ORNL, UCSD, UCLA, and Sandia National Laboratory.

AUTHORIZING LETTER — NOVEMBER 17, 1994

On November 17, the RDP Project was authorized by a letter from Erol Oktay, Group Leader, Base and Advanced Toroidal Program, Division of Confinement Systems, Office of Fusion Energy, Office of Energy Research to Tom Simonen, DIII-D Program Director. This letter gave formal approval to Phase I with an estimated total cost of \$8.7M and a funding profile of \$2.7M in FY1995, \$4.6M in FY1996, and \$1.4M in FY1997. The Project start date was October 1994 and the end date was December 1996. The diagnostics were not included in the Project budget.

DIAGNOSTIC PLAN FOR THE RADIATIVE DIVERTOR — JANUARY, 1995

A Diagnostic Plan for the Radiative Divertor was created in January, 1995. This multi-institutional work was to be funded from Research Operations budgets.

PLAN FOR THE USE OF VANADIUM IN THE RDP, MARCH 22, 1995

In order for the Fusion Program generally to begin making progress in serious use of low activation material in fusion systems, General Atomics proposed in 1995 to fabricate the upper half of the Radiative Divertor out of a low activation alloy of Vanadium (V-4Cr-4Ti). The Plan for Use of Vanadium Alloys in the Radiative Divertor, was created as Appendix B to the Management Plan for the DIII-D Radiative Divertor Project. A cost of \$1.396M was identified for procuring the Vanadium material and using it in the RDP fabrication. These costs were not incorporated in the RDP Project; they were to be born by the DIII-D RO budget and the technology program budgets of GA's partners in this effort, ANL and ORNL.

In this effort, GA procured the largest heat (800 kg) of the low activation alloy V-4Cr-4Ti which has ever been made. Small samples tests were made in DIII-D and in later years in the JFT-2M tokamak in Japan. Test plates were made for the lower divertor region of DIII-D and exposed in the DIII-D plasma chamber. Funding limitations on the RO budget starting in 1996 caused a descopeing of the ambitions of this effort to first just installing the upper private flux baffle made of Vanadium and finally to a cancellation of the entire Vanadium effort.

MANAGEMENT PLAN FOR THE RADIATIVE DIVERTOR PROJECT, REVISION 1, JULY 22, 1996

FY96 saw a very large reduction in the overall budget of the Fusion Energy Sciences Program nationally. The DIII-D Program saw a \$12M reduction, about 25%. This severe reduction necessitated reexamination of all expenditures and projects in the DIII-D Program.

For the Radiative Divertor Program, the necessary changes were captured in Revision One of the Management Plan, July 22, 1996. The cancellation of the TPX Project removed that motivating element for the RDP. Faced with necessary Project descopeing, the decision was made to only install the upper half of the RDP. Extensive physics assessments led to the conclusion that it would be desirable for DIII-D to spend some years with the flexibility to study a highly baffled divertor in the upper half and to compare that operation with the open divertor in the lower half. Also, an extensive investment had been made in the diagnostic set for the lower divertor, including a novel Thomson scattering system that could make unique 2-D maps of the divertor plasma by sweeping the divertor in the open lower divertor geometry. These diagnostic capabilities would have been severely compromised by the highly baffled lower divertor geometry proposed in the RDP. The Phase I effort, the only part of the RDP that had been approved, was rebaselined to \$8.1M.

Reviews of the Project were completed by the Fusion Energy Advisory Panel (FEAC, now FESAC) in December 95, by the DIII-D Executive Committee in January 96, and by the Facilities Subpanel of FEAC in March of 1996. In the course of all these reviews, the Project was revised and a staged installation was developed. Specifically, the Phase I installation was broken into two parts, Phase IA and Phase IB. Phase IA was just the upper outer baffle and cryopump. Phase IB was the

inner private flux baffle and cryopump. Completion of Phase IB would be equivalent to the original Phase I. These phases are shown in Fig. 4.

Fig. 4. DIII-D Divertor Configurations Planned. Phase 1A in 1997 and Phase 1B in 2000.

Phase 1B was to include construction of the upper inner private flux baffle out of Vanadium. A separate management plan was written for that. But as discussed above, this Vanadium plan was eventually discarded for cost reasons.

Phase 1A was scheduled for completion December 31, 1996 and Phase 1B December 31, 1998. The cost of Phase 1A was to be \$4.168M and for Phase 1B \$3.924M for a Project total cost of \$8.091M. Phases 1A and 1B are now complete and the remainder of this report concerns the details of those installations.

The July 22, 1996 Management Plan budgets are in Table I up to 1999. For 1999 that plan envisioned \$804K to reach a total of \$8091K. In April 1999, looking toward project completion, a further revision of the Management Plan was made. The total of those estimates for 1999 and 2000 plus actuals for 1998 and prior years was \$7215K. The final project cost of \$7223K hit that target within 0.1%.

1. EXECUTIVE SUMMARY

The radiative divertor is a major element of the DIII-D program. The divertors were designed to provide particle control for highly triangular advanced tokamak operations. In the divertors, the power and particles are exhausted over a very narrow spatial region, resulting in very high power and particle fluxes per unit area. The challenge has been to simultaneously control the heat and particle flow and to minimize the adverse influence on the core plasma. High heat fluxes can be handled with thin materials but divertor materials erode quickly in the presence of energetic particle fluxes. Erosion can be minimized with thick materials or the use of high-Z materials, but it is difficult to transport the heat through thick structures and high-Z materials may induce plasma impurities.

The major goals of the divertor project have been to simultaneously control the heat and particle fluxes so that "conventional" (and ultimately low activation) materials can be used. In addition, the divertor must provide some control of particle and impurity content of the core plasma. The design for the DIII-D divertors addresses these issues in an advanced tokamak (i.e., double-null plasma with high triangularity plasma shape). The design has included the basic ingredients of an efficient and effective divertor, and further research is aimed at demonstrating: simultaneous heat flux control, erosion control, and core particle and impurity (including He or α -particle) control.

The RDP or upper radiative divertor upgrade was divided into two phases. The first, Phase 1A, was to design, install, and operate a divertor and cryopump in the upper outer radius of DIII-D (Fig. 4). Installation of the Phase 1A divertor and cryopump was completed in January 1997 and the system has been operational since. The second phase, Phase 1B, was to design, install, and operate a divertor and cryopump in the upper inner radius of DIII-D. The physical installation of the pump and divertor was completed in December 1999. Operation of the pump commenced in January of 2000.

The total cost of the RDP was \$7,223K, a cost reduction of \$1,500K relative to the original 1994 plan. With the 25% reduction in DIII-D funding in FY96 it was necessary to re-plan the RDP budget, schedule, and scope relative to the October 1, 1994, \$8,723K plan. A \$8,091K, 1996 plan developed cost savings by simplifications in the engineering design of the baffle structure [1] and eliminating the modification of the lower divertor (maintaining excellent diagnostic access for divertor physics research but giving up close baffling of high-triangularity advanced tokamak shaped double-null plasmas). That original three-year project was divided into two three-year phases. A 1999 plan [2] identified further cost savings, among them, eliminating a second external cryostat. (Tests had shown one cryostat could supply enough helium flow for both upper cryopumps.)

The RDP was a collaborative effort between General Atomics (GA) and several collaborators. While GA led the design and engineering of the RDP, each party participated as a team in all

phases of the project. Moreover, the project depended heavily on significant contributions from several collaborators, particularly in the area of new diagnostics, diagnostic modifications, and modeling. Lawrence Livermore had the diagnostic program management responsibility for the RDP.

2. PROJECT SCOPE AND OBJECTIVES

The objective of both phases of the RDP (Phases 1A and 1B) was to design, fabricate, assemble, and install divertors and cryopumps in the upper quadrants of the DIII-D vacuum vessel. The systems were to be operational by February 2000 with a cost of \$7.2 million. The purpose of the divertor(s) was to implement and investigate the following:

- Reduce divertor heat flux by a localized radiation source (~10 cm, with a halo region for neon).
- Reduce the plasma pressure along the separatrix, with an increase away from the separatrix.
- Provide density control, helium exhaust, and impurity control by a more-closed divertor geometry and active pumping. This geometry is consistent with advanced tokamak (high plasma triangularity) operation.
- Reduce the divertor heat flux with less influence on the core plasma, (i.e., reduce the density rise with a more closed slot divertor configuration).
- Evaluate the effect of the divertor geometry on the divertor and plasma performance. We are implementing a very flexible design in which we can readily change the slot width and slot height.

The work breakdown structure was defined in the Management Plans for the DIII-D Radiative Divertor Project (GA-C23340), which defined the technical, cost, and schedule requirements necessary to achieve the program objectives. GA established within its own project organization, a system for controlling and accomplishing the work segments.

2.1. OVERALL PROGRAM MANAGEMENT

The technical, cost, and schedule baselines were the basis for control of the DIII-D Radiative Divertor Project. GA utilized a system of reducing the baselines down to identifiable subtasks and developing an Approved Task Authorization for each subtask, with an appointed subtask manager held responsible for cost and schedule control. A monthly assessment of the progress of each subtask was held and a project cost-to-complete re-estimate was performed every six months.

2.2. TECHNICAL DESCRIPTION OF RDP

The overall sketch of the RDP, Phase 1A and 1B is shown in Fig. 5 with its major components.

Fig. 5. Sketch of RDP, Phase 1A and 1B.

2.2.1. Baffles — WBS Element 1.0

This element was comprised of the design, fabrication, and installation of the two upper baffles. The baffles are the major divertor slot structures and consist of graphite tiles mounted on the conical and flat support rings. The rings are water-cooled in the areas near the slot, keeping the structure at a constant starting temperature with a ten minute DIII-D plasma repetition rate. The structure was designed to be flexible so that the height of the slot can be varied from an X-point to target plate distance of 23 cm up to 43 cm.

To facilitate tracking of the components and assembly for this portion of the project, two WBS sub-elements were instituted: 1.1 (structure) and 1.2 (tiles and hold-down hardware). Element 1.1 included the design, fabrication, assembly, and installation of the water-cooled rings, supports, feedlines, and feedthroughs. Element 1.2 contained the design, fabrication, cleaning, and installation of the graphite tiles and hold-down hardware. In Phase 1A, the budget for Elements 1.1 and 1.2 was exceeded slightly (\$2,308K actual costs versus \$2,300K budgeted, see Table 1). Though this is small for the budget of the phase overall, it should be noted in FY97, the budget was over run by \$307K. This occurred for two reasons. The first was failure of the manufacturer of the cooling

rings to complete the machining of the rings. The manufacturer machined only half of the rings prior to dropping the job. This required GA to bring the job in-house and complete machining with labor and materials that were not budgeted. The second reason for the over run was the development of information on halo currents and loads created by them. The new information required significant engineering analysis to verify the structure could handle the load. The lessons learned from these two problems were carried forward into Phase 1B of Element 1.0 which permitted the successful completion of the installation of upper inner baffle structure and tiles on time.

In Phase 1B, Element 1.0, the budget was under run (\$1,524K actual costs versus \$2,637 budgeted) but during this phase, the overall scope of the project was changed. Cost savings were realized by simplifications in the engineering design of the baffle structure. The change in scope was reflected in the new Management Plan, revised April 1999, which was written in the later part of this phase.

Also in the later part of this phase, the budgets for the structure, tiles and hardware was over spent. This was due to tasks being added to the project as components and systems were assembled, and further analysis were performed. Analysis in four areas revealed that enhanced pumping and plasma performance could be achieved and further protection of the divertor structure would be prudent. These four areas were: reduction of plasma carbon contamination and improvement of tile performance, increased protection of structures, improved pumping capabilities, and improved tile hold-down nut bars. None of these tasks were included in the original scope of work. The focus of reduction of plasma carbon contamination was to reduce the temperature of critical tile areas. Generally, this meant reducing the surface area of exposed edges in high heat flux regions: rows 1 and 2 on the centerpost, and the tiles on the ceiling. This was accomplished by rounding the plasma facing surfaces (centerpost tiles), reducing the poloidal gaps between adjacent tiles from 0.1 in. to 0.025 in., and by contouring the tiles in order to remove any steps. Locally, the tile performance was improved at the Thomson dump location where the dump was removed and replaced by high conductivity carbon composite tiles. Increased structure protection dealt with insuring that the structure was not exposed to plasma field lines for any and all plasma configurations. This led to the addition of protective tile assemblies on the ligaments and inner supports of the inboard baffle. The third area was concerned with increasing the pumping performance. Analysis revealed a leak path through the archway of the ceiling tiles. A seal was designed, fabricated, and installed in order to rectify this problem. The final area involved the tile hold-down nut bars. During previous vents, it was observed that a few tiles had lost some of their pre-load during operations. An investigation was conducted and it was determined that the pre-load system of three belville washers per stud was extremely sensitive to creep in the compliant layer of graphoil (located between the nutbar and tile and the tile and vacuum vessel). A less sensitive configuration of four washers per stud was installed on all new tiles as well as any old tile that was temporarily removed and replaced.

2.2.2. In-Vessel Cryosystems (Divertor Cryopumps) — WBS Element 2.0

As shown in Fig. 4, there are two additional divertor cryopumps based on the current successful advanced divertor DIII-D design, located in the outer, lower quadrant of DIII-D. The upper cryopumps use the same concept as the advanced divertor cryopump which was installed in the early 1990s.

The DIII-D cryopumps consist of liquid-helium cooled tubes that are thermally shielded by a liquid-nitrogen cooled shell. The pumps are toroidally continuous structures that have been designed to handle the induced disruption loads. This WBS covered the design, fabrication, and installation of the upper cryopumps and feedthroughs. In-house fabrication and assembly was also included in this element. For Element 2.0, Phase 1A, the budget was exceeded by \$12K (\$1052K actual costs versus \$1044K budgeted). This over run was due to manufacturing, welding, and processing the liquid nitrogen shells and tubes, and the liquid helium tubes. The costs of these tasks were simply under estimated during the development of the budget.

For Phase 1B of Element 2.0, the budget was under spent. As stated before, the scope of the overall project was changed and the Management Plan and budget were changed accordingly in the latter part of this phase. In the last year of this phase, FY00, budget was overspent due to the addition of an out-of-scope task. Additional analysis of the proximity of the private flux baffle to the plasma separatrix, revealed electrons could orbit around the centerpost under the baffle structure which could damage the cryopump, diagnostics or the structure itself. To eliminate this concern, electron avalanche shields were designed, fabricated and installed at 90° intervals.

2.2.3. Ex-Vessel Support Systems — WBS Element 3.0

This element consists of mainly the ex-vessel support systems for the cryopumps. These systems supply the liquid nitrogen and liquid helium to the cryopumps. The upgrade for the system was essentially duplicated from the system that operates the advanced divertor cryopump. A new transfer line was installed to supply liquid nitrogen and helium to both of the upper cryopumps. This new line was spliced into the existing line and system, thus eliminating the need for a new cryostat. Modifications to the liquid helium distribution box were also necessary.

During Phase 1A, the budget for this element was exceeded by \$310K (\$959K actual cost versus \$649K budgeted). This was due to an error in the July 1996 Management Plan numbers. Due to different options being considered including not completing the installation of the ex-vessel system, approximately \$100K of installation was not included in the estimates. The other \$210K over run can be attributed to three things:

1. Budget limitations required stopping and starting some procurement contracts. There were termination fees as well as higher costs when restarted.
2. Added complexity of upper platform design and installation to meet the requirements of all DIII-D users rather than just supporting the cryostat.
3. Additional labor cost on the assembly and installation of the ex-vessel system.

In Phase 1B, the budget was significantly under spent (\$304K actual cost versus \$1176K budgeted). The planned second cryostat was removed from the project scope when tests of the first cryostat showed it could probably handle both upper pumps. Even with the adjustments due to other change of scope of the project, this element proceeded well, meeting the schedule and under running the budget.

2.2.4. Diagnostic Integration/Project Management — WBS Element 4.0

This WBS element provided the engineering interface support for diagnostic installation and modification efforts, and overall management of the project. The design, fabrication, and installation of the diagnostics was completed by various collaborating institutions and was not part of this WBS or of the project as a whole. For Phase 1A and 1B, the budgets for this element were over spent by \$28K and \$52K respectively. In Phase 1A, the budget was exceeded due to under estimating the labor required to install thermocouples and various probes. For Phase 1B, the cost of updating/correcting drawings was under estimated.

2.3. COST BASELINE

The total cost of the RDP was \$7,223K. This is a cost reduction of \$1,500K relative to the original 1994 plan and an underrun of \$868K relative to the Management Team, Revision 1, dated July 22, 1996. The baseline budget profile for (FY95–FY00) the RDP is shown in Table 1 according to the WBS elements.

2.4. SCHEDULE BASELINE

The project schedule is shown in Fig. 6.

TABLE 1
Radiative Divertor Project Costs (\$K)

	PHASE 1A						PHASE 1B								Total of Actuals
	FY95		FY96		FY97		FY97		FY98		FY99		FY00		
	Actual	Mgmt. Plan Rev. 1	Actual	Mgmt. Plan Rev. 1	Actual	Mgmt. Plan Rev. 1	Actual	Mgmt. Plan Rev. 1	Actual	Mgmt. Plan Rev. 1	Actual	Mgmt. Plan Rev. 4/99	Actual	Mgmt. Plan Rev. 4/99	
1.0 Baffles	606	616	1,095	1,384	607	300	157	276	344	1,476	863	885	160	0	3,832
1.1 Structure	557	549	757	927	553	280	157	172	280	1,115	464	591	79	0	
1.2 Tiles and Hardware	49	67	338	457	54	20	0	104	64	361	399	294	81	0	
2.0 In-Vessel Cryosystems	430	430	524	513	98	101	31	93	146	476	382	399	34	0	1,645
3.0 Ex-Vessel Support	105	105	387	320	467	224	0	99	0	552	214	270	90	255	1,263
4.0 Diagnostic Integration/Project Management	71	71	108	104	24	0	43	55	82	92	84	81	71	0	483
TOTALS	1,212	1,222	2,114	2,321	1,196	625	231	523	572	2,596	1,543	1,635	355	255	7,223

Fig. 6. Radiative divertor schedule.

3. LESSONS LEARNED

During Phase 1A, despite having a well defined plan to qualify and select machining vendors, problems with vendor's capabilities and willingness to complete the job can arise. In selecting a machining vendor for the manufacturing of the water cooled panels, two vendors were selected to make prototypes based on their capabilities and past histories. The vendor who provided the best quality and on-time prototype panel was selected. The contract for the panels was let, but the vendor did not start the task until three weeks after receiving the job which was scheduled to be completed in fourteen weeks. The vendor was then unwilling to apply any more resources to make up the schedule and to resolve technical machining issues. Potentially, tracking more closely and being more aggressive early on may have helped in this situation, but it is not clear. To further aggravate this situation, the machining vendor upper management was switched half way through the task which caused further delays due to bringing the new management team up to speed.

In the ex-vessel support task, Element 3.0, an accountability issue arose during Phase 1A. The responsibility and authority of the task was not clearly defined between DIII-D operations and project staff. A clear and precise understanding at the beginning of the undertaking of the task by the responsible/assigned personnel would have alleviated the budget and schedule issue. This lesson learned as well as proper vendor selection and control were carried forth into Phase 1B of the project.

In Phase 1B, the most critical aspect of the project was the manufacturing and assembly of large quantities of parts and components, and the dimensional control and tolerance management. Small deviations can arise at any point during the fabrication and assembly process and without proper control they can quickly grow and propagate. The experience with the inner RDP only reinforces this statement, dimensional and tolerance control is paramount. Specific examples during Phase 1B of the project; design, fabrication, and assembly illustrate the importance of this statement.

During the design phase of this portion of the project, early establishment of hard pre-existing reference points was crucial as was integration of the new geometry with pre-existing geometry. Validation and verification of the critical dimensions and interfaces, as well as avoiding interferences, with pre-existing hardware helped insure that the assembly would proceed accurately and quickly. The importance of references internal to the new geometry also became apparent. The inclusion of hard registration features in the design of the cryopump, for example, would have provided more accurate dimensional control during the assembly process and would have reduce the assembly time as well.

During fabrication, the qualification and capability of the vendor to produce the parts as designed, meeting the tolerances, as well as achieving the schedule milestones proved to have importance as demonstrated earlier during Phase 1A. The lesson learned in this case was to more critically question and screen more thoroughly potential vendors. More aggressive tracking may

have improved the situation with certain vendors, but it may have just as easily made it worse. Another component of error that appeared during the fabrication phase was distortion caused by welding. Though it is difficult to accurately predict, it was found to be useful to have means to compensate for welding distortion.

The lesson learned during the assembly phase was that extra time and effort placed into careful tool design and pre-assembly more than made up for itself during final assembly inside the vacuum in both time and tolerance. Errors were identified and corrected in advance, dimensional control of the final assembly was both verified and controlled, the assembly procedure was fine tuned and validated, and the technicians gained valuable experience in handling and assembling components and systems. Development of a stud grinding tool saved a substantial amount technician labor and radiation exposure in the vessel.

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Radiative Divertor Project Review, June 15-16, 1994

DIII-D Radiative Divertor Conceptual Design Review Report, August 17, 1994

Management Plan for the Radiative Divertor Project, October 1, 1994

RDP Project Authorizing Letter, November 17, 1994.

Diagnostic Plan for the Radiative Divertor, January, 1995.

Appendix B to the Management Plan, Plan for the Use of Vanadium Alloys in the Radiative Divertor, March 22, 1995.

Management Plan for the DIII-D Radiative Divertor Project , Revision One, July 22, 1996

[1] Management Plan for the DIII-D Radiative Divertor Project, Revision 1, July 1996.

[2] Management Plan for the DIII-D Radiative Divertor Project, Revised April 1999.

GA-C24315

DIII-D ELECTRON CYCLOTRON HEATING SYSTEM UPGRADE TO 6 MW PROJECT

**FINAL REPORT FOR THE PERIOD
FY98 THROUGH FY03**

**by
R.W. CALLIS**

**Prepared under
Contract No. DE-AC03-99ER54463
for the U.S. Department of Energy**

JUNE 2003

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**GENERAL ATOMICS PROJECT 30033
JUNE 2003**

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1. EXECUTIVE SUMMARY

The scope of this project was to upgrade the ECH system from the existing three-gyrotron system to a six-gyrotron system. The upgrade was to add three additional 1 MW-level gyrotron systems at a frequency of 110 GHz to reach a level of near 6 MW of installed ECH system power. This upgrade to 6 MW will provide the ECH and electron cyclotron current drive (ECCD) power required to initiate the active control of advanced tokamak discharges, which is a key element in the five-year plan for the DIII-D program. The upgrade provided three single disc chemical vapor deposition (CVD) diamond window 1 MW gyrotrons developed by Communication & Power Industries (CPI), gyrotron magnets and their power supplies, gyrotron tanks, low-loss-windowless evacuated transmission lines to connect the gyrotrons to the tokamak, water manifolds, and control systems. The project was initiated by a letter from John Willis (Director OFES Research Division) to Tom Simonen (DIII-D Program Director), which authorized an expenditure not to exceed \$8,243k. Shortly thereafter, an external project review was held on July 22, 1998. The conceptual design and program review for the DIII-D 6 MW upgrade project was held at CPI on October 9, 1998. On April 10, 2003, the last of the new gyrotrons passed its final acceptance test producing 1 MW for 5 seconds and completing the project. The final project cost was \$7.668M.

The 110 GHz ECH system for the DIII-D tokamak now consists of six assemblies. Each assembly consists of a gyrotron, a gyrotron superconducting magnet, a gyrotron/magnet supporting tank, a low-loss-windowless evacuated transmission line using circular corrugated waveguide for propagation in the HE_{11} mode, a two-mirror launcher which can steer the rf beam poloidally from the center to the outer edge of the plasma and toroidally for either co- or counter-current, high voltage and magnet power systems, and associated controls and water cooling systems. Three of the gyrotrons were manufactured by GYCOM and have a nominal output of 800 kW 2 s, with the pulse length limit resulting from the peak temperature allowed on the boron nitride output window. The three long-pulse gyrotrons added by this project were manufactured by CPI and have a nominal rating of 1 MW, 10 s. These three new CPI gyrotrons for the 6 MW upgrade project were based upon the SN 3R2 1 MW development gyrotron with the same design for the beam tunnel, cavity, launcher, and collector. A 30-day hold superconducting magnet design was chosen, to be manufactured by Oxford Instruments.

2. PROJECT OVERVIEW

The work for FY99 was adjusted to meet the available funding with the primary objective of getting the first gyrotron system installed and checked out before assembly and installation of the next two systems. The need for project staff to support current operations slowed progress.

Near the end of the first year Oxford Instruments failed to deliver the first magnet to CPI, thus preventing the testing of CPI-P1. A work-around to this roadblock was developed which required the DIII-D Program to loan CPI a magnet from one of the development gyrotrons which was being repaired. The problems with the magnets from Oxford Instruments continued throughout the project; they did not meet the liquid He hold time nor the transverse field error requirements. Eventually, the contract with Oxford was descoped to two magnets and the price of the magnets was reduced to compensate for the lack of performance.

There were several activities outside the project that contributed to its success. In order to house the new equipment, a new two-story addition was added onto the DIII-D building (paid for by GA). The second level floor was designed to take the large localized floor loads created by the gyrotrons as well as minimizing the concentration of magnetic material. High voltage power supplies at GA were modified to meet the gyrotron requirements. Water support systems were provided. PPPL provided new, upgraded steerable launchers from their DOE funding as part of their DIII-D support activity.

In 1999 the project hardware started to come together. The building addition was completed, the transmission lines were installed and the support structure, gyrotron tanks, water manifolds, and control electronics were installed. The first gyrotron, CPI-P1, arrived at the end of December 99 and was quickly put into service. After two months of testing, this gyrotron developed a vacuum leak at the window seal which was eventually traced to corrosion of the aluminum bond between the window and the seal ring. This problem was solved by CPI employing a Gold-Copper high temperature braze which they had developed.

However, the CVD diamond window on CPI-P3 (with the new AuCu braze technology) cracked when the tube was being tested at 550 kW and pulse lengths of 5.6 s. This window failure put gyrotron production on hold and an intensive R&D program, supported by the DOE gyrotron development program, was initiated to find the root cause of this and other similar window failures internationally. After several months and extensive help from the FZK institutes in Karlsruhe, Germany, the cause of the failure was identified as a graphite film that had been deposited on the window during the vacuum seal brazing procedure. It was determined that this film could be removed by grit

blasting the window, after the braze procedure, with 3 micron alumina powder. This same grit blasting process was performed on the outside of the CPI-P2 gyrotron window already installed at GA, with significant improvement as measured with an infrared (IR) camera. After the window cleaning process, the power level and pulse length were increased to 1 MW and 5 s, successfully completing the gyrotron acceptance test on CPI-P2.

With the loan of two CVD diamond window discs from the Wendelstein VII-X program, the repair of the two gyrotrons, CPI-P3 and CPI-P1, was initiated. These two gyrotrons were then delivered to the DIII-D Program in September 2001, and February 2002, respectively. The CPI-P3 gyrotron was installed and promptly conditioned to 800 kW, 2 s, which was the level needed to support experiments. When experiments were completed in June 2002, the tube was extended to 1 MW 5 s, meeting the acceptance criteria.

Near the end of the FY02 operating period, CPI-P1 was installed and started commissioning. However, at the 1 MW level, a leak developed between the collector cooling passages and the tube vacuum. The gyrotron was returned to the vendor for evaluation and repair. It was found that the copper used to make the outer section of the collector had excessively large grain structure and, at the site of the leak, a crack along one of these grains extended between a cooling passage and the collector face. Etching of the copper revealed many more crack locations, requiring the rejection of the outer collector and the requirement to build a new section using better copper. The gyrotron was returned to GA at the end of 2002. On April 10, 2003, CPI-P1 passed its final acceptance test, producing 1 MW for 5 seconds, and the project was declared completed.

3. PROJECT SCOPE AND OBJECTIVES

The scope of this project was to upgrade the ECH system from the previous three-gyrotron system to a six-gyrotron system. The upgrade was to add an additional three 1 MW-level gyrotron systems at a frequency of 110 GHz to reach a level near 6 MW of installed ECH system power. The full six gyrotron system was scheduled to be ready for service on DIII-D in January 2001 at a cost not to exceed \$8.2 M. These objectives were considered the Level-1 objectives. It was anticipated that this upgrade project was to be the second phase of a 10 MW, 110 GHz ECH program.

The work breakdown structure was defined in the DIII-D 110 GHz ECH System Upgrade to 6 MW Project Management Plan, which defined the technical, cost, and schedule requirements necessary to achieve the program objectives. The DIII-D Program established a project organization, for controlling and accomplishing the work assignments.

The project was completed on April 10, 2003 at a cost of \$7.668 M.

3.1. OVERALL PROGRAM MANAGEMENT

The technical, cost, and schedule baselines were the basis for control of the DIII-D 110 GHz ECH System Upgrade to 6 MW Project. The DIII-D Program utilized a system of breaking the baselines down to identifiable subtasks and developing an Approved Task Authorization for each subtask, with an appointed subtask manager held responsible for technical, cost, and schedule control. A bi-monthly assessment of the progress of each subtask was held and a project cost-to-complete re-estimate was performed every six months.

3.2. TECHNICAL DESCRIPTION

The 110 GHz ECH system for the DIII-D tokamak now consists of six assemblies (Fig. 1). Each assembly consists of a gyrotron, a gyrotron superconducting magnet, a gyrotron/magnet supporting tank, a low loss transmission line, a launcher and associated controls. Three of the gyrotrons (not part of the upgrade project) were manufactured by GYCOM and have a nominal output of 800 kW 2 s, with the pulse length limit resulting from the peak temperature allowed on the boron nitride output window. The three long pulse gyrotrons provided by this project are manufactured by CPI and have a nominal rating of 1 MW, 10 s. All sub-elements of these gyrotrons are expected to be in thermal equilibrium at 10 seconds, therefore a cw rating is possible for these units.

Fig 1. Layout of the DIII-D 110 GHz ECH system showing the location of the three CPI 1 MW gyrotrons, the three Gycom par spec gyrotrons, the six transmission lines, and the location of the launchers on the DIII-D vacuum vessel.

3.2.1. WBS Element 1 — RF Sources

The gyrotrons used in this project are the culmination of years of DOE-funded development of gyrotrons lead by MIT. In this development program the University of Maryland developed the codes used to design the cavities, MIT developed the codes used for designing the launchers and internal mirrors, the University of Wisconsin developed the codes for the exit mirrors, and CPI integrated these designs into a functioning gyrotron.

The three long pulse 110 GHz gyrotrons used in the DIII-D ECH system are an internal-mode-converter design (Fig. 2) with a Gaussian output rf beam. Each gyrotron has a hollow annular electron beam produced by a magnetron injection type electron gun with a single anode (diode) which can operate up to 45 A. The hollow electron beam is compressed by the 44 kG field from the gyrotron super-conducting magnet with the field maximum designed to occur at the center of the gyrotron cavity. At this location, the beam diameter (~ 1 cm) and thickness (~ 1 mm) are adjusted such that only the $TEM_{22,6,1}$ cavity eigenmode is excited. The beam thickness is critical to pure mode operation since the over-moded cavity has a large number of modes spaced closely together. If any of the nearby modes are excited, they can rob power from the desired mode.

The rf power generated in the cavity has a complex structure that does not lend itself to low loss propagation. To achieve the desired low loss propagation, the rf wave must be

formed into a Gaussian-like rf beam. The first step of this process is to make small perturbations in the launcher tube that bunch the rf energy together as the wave bounces along the spiral path as it exits the launcher. Since the cavity and launcher are deep inside the magnet bore, a series of relay mirrors is used to direct the rf beam out of the gyrotron. These mirrors can also be used to make final corrections to the phase and profile of the beam such that at the output window, the beam has good Gaussian qualities. The use of mirrors also allows the rf beam to be decoupled from the electron beam with the rf exiting out the side of the gyrotron, while the spent electron beam is deposited on a water cooled collector mounted above the output mirror/window assembly. All the sub-elements that may intercept either the rf beam or electrons are made from copper and are water cooled with a cw rating at full power. The gyrotron is vacuum pumped by dual 20 ℓ/s vac-ion pumps and the collector is electrically isolated from the gyrotron body by a ceramic break. The isolation allows for a convenient method of centering the beam inside the cavity by monitoring the low level body current signal.

Fig. 2. Schematic diagram of 110 GHz, 1 MW gyrotron and CVD diamond output.

3.2.1.1. CVD Diamond Window.

The advent of large-size CVD synthetic diamond windows with low rf loss has ushered in the feasibility of truly high power cw gyrotrons. Previous gyrotron output window material had either relatively high loss, 4% for boron nitride, or poor thermal conductivity (sapphire), that limited the pulse length at 1 MW to a few seconds at best. These windows also required spreading the rf beam in a non-Gaussian profile which needed to be converted back to Gaussian external to the gyrotron, resulting in, at minimum, a loss of 10% of the rf power. CVD diamond also has the beneficial characteristic of a high thermal conductivity of $6.5 \text{ kW/m}^2\text{K}$, about four times that of copper, which allows simple edge cooling to extract all the energy absorbed ($\sim 0.2\%$) as the rf beam passes through.

The application of CVD diamond as an output window did not come without several technical challenges. Diamond by its nature has a very low thermal expansion coefficient, much lower than any of the metals one would propose using in making a vacuum seal. Thus, the first vacuum seals attempted relied on a low temperature diffusion

bond using pure aluminum. The diffusion bond allowed the seal processing temperature to be low and the softness of the aluminum reduced any stresses caused by differential thermal expansion. The use of aluminum had three significant problems. First, the aluminum was subject to aggressive water corrosion which, even with corrosion inhibitors in the water, led to several vacuum failures, two at General Atomics and several worldwide. Second, the tube could not be processed after assembly at the normal 500°C , but had to be kept below 450°C , otherwise the aluminum bond would soften leading to a seal failure. Third, some windows cracked at low power levels due to a lossy hydrogen film, believed to be created on the surface of the window during the diffusion bonding process.

An anticipated solution to the above issues was the development of a AuCu high temperature braze between the diamond and a copper seal ring. It was shown that such a braze could be made to a 63.5 mm diameter 1.14 mm thick CVD disk, giving a 50 mm clear aperture for the rf beam. Two gyrotrons with this design were built for the DIII-D program, with the first unit passing a 600 kW, 10 s factory test before being delivered to the DIII-D program. However, during the testing of the second gyrotron at CPI, the window failed when a 20 mm crack developed from the center to the edge. The failure had the characteristics of a thermally induced stress crack which was unexpected since even at 1 MW the thermal stress level should have been a factor of two lower than the expected 350 MPa yield stress for CVD diamond.

Following the failure, an investigation was mounted to determine the root cause of the failure and to validate the brazing process before any more gyrotrons were assembled. The failed window, along with the windows that had been brazed but not installed and unbrazed window blanks, were re-measured to determine if the loss tangent had changed. It should be noted that by this time the high losses caused by the hydrogen contamination of the aluminum bonded windows had become known. Loss tangent measurements indicated that the losses in AuCu brazed windows had increased during brazing, with the worst case being a factor of 8 higher than the blank disk of $\leq 1 \times 10^{-4}$. The power lost in the failed window assembly was consistent with a loss factor of 3.8×10^{-4} and the window disk then would have a thermal stress level of 350 MPa at ~600 kW transmitted power.

In evaluating the cause of the enhanced loss factor, the window disks were measured for impurities using a 514 μm laser Raman scattering system. This investigation revealed a thin ($\leq 1 \mu\text{m}$) layer of graphite on the surface of the window but no bulk contamination. It was also shown that this graphite layer could be removed by grit blasting with 3 μm alumina powder as shown in Fig. 3. The DIII-D program had one of the AuCu brazed window gyrotrons, CPI-P2, in acceptance testing when this enhanced loss issue was discovered. In order to minimize the risk of failure, the gyrotron was initially limited to maximum operating conditions of 800 kW, 2 s. Once the cause of the enhanced loss was

identified to be a graphite film, the window was grit blasted in-situ and then tested by pulsing the gyrotron and observing the window temperature with an IR camera. Before and after IR images of the window are shown in Fig. 4.

Following the cleaning, the gyrotron was able to run at close to 1 MW for 5 seconds without the window temperature exceeding 150°C. Comparing the window temperature measurements to those calculated for 1 MW shows that the effective loss tangent is well below the required 1×10^{-4} , (Fig. 5). Figure 6 shows that the window comes into thermal equilibrium in about 3 seconds.

Fig. 3. In-situ Raman spectra of the CPI-P2 gyrotron CVD diamond window near the graphite wave number of $\approx 1600 \text{ cm}^{-1}$. Measurements of the surface before and after cleaning with $3 \mu\text{m}$ alumina powder, and a measurement of the bulk diamond is shown.

Fig. 4. IR images of the CVD diamond window before and after cleaning with $3 \mu\text{m}$ alumina grit. Note the removal of localized hot spots believed to be caused by local graphite inclusions. The hot spots at the bottom of the "after" image are thought to be the fluorescence of dust by low power rf, since there is no substantial power in the rf beam at this location.

Using diamond disks borrowed from the Wendelstein VII-X, the two gyrotrons with damaged windows were rebuilt. This time the loss tangent of each window was measured before and after brazing and no film was detected on the windows. The improvement in window loss can be clearly seen in a lower peak window temperature of only 90°C as shown in Fig. 5.

Fig. 5. Temperature profile, measured and calculated for a 50 mm clear aperture CVD diamond gyrotron output window for three CPI gyrotrons at the end of a ~1 MW, 5 s pulse, cooling water 22°C.

Fig. 6. Peak window temperature for CPI-P2 for a ~1 MW, 5 s pulse, cooling water temperature 22°C.

3.2.2. WBS Element 2 — Gyrotron Support Systems

The gyrotron support systems are the set of subsystems required to make the gyrotrons operate. They include the gyrotron tank, gyrotron heater power supply, gyrotron instrumentation and control, gun coil power supply, collector coil power supply and sweep signal generator, high voltage power supply, and vac-ion power supply. The gyrotron is supported on an oil tank which, contains the insulating and coolant oil for the cathode assembly (components and circuits associated with the cathode heater, and cathode). As part of the PPPL/DIII-D collaboration, and not part of the project, PPPL provided engineering support for the new gyrotron tanks shown in Fig. 7. All of the

hardware costs and the assembly of the tanks were the responsibility of the DIII-D Program. The three new gyrotron tanks are located in the new addition at the north end of the DIII-D building. The gun coil power supply, the collector coil power supply and sweep signal generator, and the vacuum power supply are placed in equipment racks located near the gyrotron tank area. All communication with the gyrotron and its auxiliaries and diagnostics is from the control room via fiber optics cables. All important signals and waveforms will be digitized and stored for recall and analysis on a shot-by-shot basis. In addition, control and interlock functions are hardwired in order that the system can be operated and protected independent of the status of the computer, which will operate as a backup to the primary control system. The important signals and wave-shapes also have analog displays on the control console and are interfaced with the DIII-D control room.

Fig. 7. Photo of the gyrotron support tank design by PPPL under the DIII-D collaboration, and built by the project.

3.2.3. WBS Element 3 — RF Transmission

3.2.3.1. RF Transmission Line System. The transmission line system connects the gyrotron to the launcher on the DIII-D tokamak using evacuated corrugated waveguide with a 31.75 mm inside diameter. To couple the Gaussian rf beam exiting the gyrotron 65 mm diameter output window to the 31.75 mm waveguide only requires one mirror that is placed about one meter from the output window, as shown in Fig. 8. The mirror is a simple focusing mirror cut using Gaussian optics criteria to match the beam at the entrance to the waveguide. Micrometer positioners on the mirror mounts allow for fine tuning the location of the beam waist at the wave guide entrance. An accuracy of less than 1 mm is required. The tee holding the mirror provides a convenient location for vacuum pumping for the evacuated waveguide and to have viewing ports for observing the gyrotron window during operation.

Fig. 8. The rf beam exiting the CVD diamond gyrotron window is focused into the 31.75 mm evacuated corrugated waveguide using only a single ellipsoidal mirror. This assembly is referred to as the L-box Mirror Optics Unit (MOU).

In order to tune and assess the performance of the gyrotron before injecting power into the tokamak, the rf power is directed into a dummy load placed as close to the gyrotron as practical. The redirection of the rf beam is performed by a waveguide switch that inserts a 45 degree mirror in the transmission line. It is important that any dummy load used to test high power gyrotrons have a very low reflection coefficient, i.e. the load must look very black. The evacuated dummy load developed to handle the 1 MW, 10 s pulses with no reflections, was based on converting the low loss HE_{11} rf beam, which has small to non-existent wall currents, to a TM mode with wall currents that dissipate their energy on a water cooled section of lossy waveguide. The final design uses a 2 m section of a specially machined Glidcop[®] copper waveguide with the interior corrugations plated with nickel to increase the losses. This load, shown in Fig. 9, absorbs 800 kW cw, or 80% of the input power. The remainder of the power is absorbed in a normal open-tank dummy load made from Inconel.

3.2.3.2. Launcher. Each transmission line uses a dual-mirror launcher to direct the rf beam to the desired location within the plasma. The launchers, located on the outer upper ports of the DIII-D vacuum vessel, must have the ability to scan the rf beam, both poloidally and toroidally, in order to locate the beam on- and off-axis; and to support both co- and counter-current drive. An additional challenge is that two launchers and their mirror steering mechanisms must reside inside a port box approximately 300x400 mm, which is 1 m in length.

The launchers used for the six gyrotrons systems were supplied by PPPL outside of the project scope, but are described here for completeness. Each launcher has a fixed

Fig. 9. Compact dummy load made from a lossy copper waveguide section inserted into a water jacket. A 2 meter load can remove 800 kW cw, with little or no reflection.

focussing mirror and a flat steering mirror. Owing to concerns over water leaks these mirrors are not water-cooled, but depend on radiation cooling between shots to keep the mirrors within operating temperatures. The design, features a butcher block copper/stainless steel laminated structure where the copper acts as a thermal heat sink and the stainless provides strength and reduces the eddy currents which caused unwanted torque on the steering mechanism. The back surface of the mirror is blackened to raise its emissivity to over 90% to enhance radiation cooling. A fork connected to a hollow shaft holds the flat butcher-block mirror. Rotation of the fork causes the rf beam to scan toroidally. A push rod through the hollow shaft is used to tilt the mirror up and down. This action steers the rf beam poloidally. Each adjustment has a $\pm 20^\circ$ range of motion. Presently there are three dual launchers on DIII-D and there is one more port with the dimensions for a possible fourth launcher. Figure 10 shows a picture of the newest dual launcher, which was built by Princeton Plasma Physics Laboratory (PPPL), and incorporates the butcher block mirror design.

3.2.4. WBS Element 4 — Cooling Systems

3.2.4.1. Low Conductivity Water. Each gyrotron requires 450 gpm at various pressures up to 150 psig of low conductivity cooling water. To provide this, a pair of

12-in., 200 psig stainless steel distribution lines were connected to the existing 2 Meg-ohm, deoxygenated, deionized high pressure water system with a pressure reducing station located near the gyrotrons. Each gyrotron has its own dedicated water distribution manifold incorporating all the water flow/pressure/temperature safety interlocks and water flow calorimetry instrumentation to support operation of the gyrotron. The project paid for additional pumps, piping, manifolds and instrumentation to support the three gyrotron systems.

3.2.4.2. Cryogenics. Originally the magnets to be supplied with the gyrotrons were to be 30-day hold magnets which incorporated a cryocooler on the leads and heat shield, thus eliminating the need for liquid nitrogen, LN_2 . Also the 30-day hold time for liquid helium, LHe , eliminated the need for a LHe autofill system. However when Oxford Instruments failed to produce the desired magnets a 3-day hold magnet with LN_2 -cooled shields was substituted. This required the addition of a LN_2 autofill system as well as associated instrumentation. Eventually Oxford delivered two magnets with the lead cryo-cooler capability, however these had only a 7-day hold time, not the 30 contracted for. Therefore the contract price was negotiated down to reflect the reduced hold time.

3.2.5. WBS Element 5 — Facility Modifications

There was not sufficient space in the DIII-D building to add any additional gyrotrons. General Atomics therefore built a 30 ft x 115 ft addition to the north end of the DIII-D experimental building, as shown in Fig. 11. This space houses the gyrotrons and electrical instrumentation equipment needed for the three new gyrotron systems. The equipment location is shown in Fig. 12.

Fig. 10. Photo of a dual steerable ECH launcher designed and built by PPPL. Each launcher incorporates a fixed focusing mirror and a flat steering mirror. The steering mirror can rotate over a range of ± 20 degrees poloidally and toroidally.

The floor plan of the 1st floor of the FBI Laboratory is shown on a grid. The layout includes the following labeled areas and equipment:

- Top Left:** Three small rectangular units, each labeled "NET FLOOR BOARDING UNIT IN USE".
- Top Center:** A large rectangular area labeled "PL-1 PL-2 PL-3" with "NET FLOOR BOARDING UNIT IN USE" written below it.
- Top Right:** Two large rectangular areas labeled "TdeW #1" and "TdeW #2", each containing a "PUMP SYSTEM" and a "CL" label. To their right is a vertical rectangular area labeled "Storage Transfer Unit".
- Far Right:** A large rectangular area labeled "CA-P3" containing a large circle with a cross inside.
- Center:** A long, dark horizontal rectangular area.
- Bottom Left:** A small rectangular area labeled "NET FLOOR BOARDING UNIT IN USE".
- Bottom Center:** Two large rectangular areas labeled "CP-P2" and "CP-P1", each containing a large circle with a cross inside.
- Far Right Edge:** A vertical label "6000" with a series of small circles next to it.

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Although GA paid for the construction of the building shell the project covered the cost of the gyrotron room including a copper ground floor, shielded walls, electrical power, electrical cable trays, water manifolds, safety systems, and other supporting infrastructure.

3.3. COST BASELINE

The original budget established for the 110 GHz ECH System Upgrade to 6 MW Project is shown in Table I with the final budget expenditures shown by task. The Project was originally started in FY98 with an approved budget of \$8,243k, in FY99 the total Project budget was reduced to \$7,749. The final expended funds for the 110 GHz ECH System Upgrade to 6 MW Project was \$7,668.

TABLE I
DIII-D 110 GHz ECH UPGRADE COST BASELINE

Work Breakdown Structure	July 1998 Management Plan	April 1999 Management Plan	July 2002 Actual
1. RF Sources 1.1 Gyrotrons 1.2 Gyrotron magnets and power supply 1.3 Gyrotron test and checkout 1.4 Gyrotron contract management	\$2,948	\$3,065	\$3,017
2. Gyrotron Support Systems 2.1 Gyrotron controls 2.2 Gyrotron tanks 2.3 Gyrotron instrumentation	\$1,956	\$1,957	\$1,763
3. RF Transmission 3.1 Mirror optic unit 3.2 Transmission line components 3.3 Transmission line installation	\$1,533	\$1,504	\$1,442
4. Cooling Systems 4.1 Low conductivity water 4.2 Cryogenics	\$821	\$332	\$478
5. Facility Modifications.	\$654	\$564	\$604
6. Project Management 6.1 Project control 6.2 Quality assurance	\$331	\$327	\$365
Totals	\$8,243	\$7,749	\$7,668

3.4. SCHEDULE BASELINE

The project schedule was primarily driven by the delivery and checkout of the gyrotrons. A list of the milestones used for the Project is given in Table II.

TABLE II
DIII-D 110 GHz ECH UPGRADE CONSTRUCTION MILESTONES

	Milestone	Original Date	Revised Date	Achieved Date
1	OFES initiation of project	Jul-98	Jul-98	Jul-98
2	Decision on gyrotron vender and placement of an order	Aug-98	Aug-98	Aug-98
3	Delivery of gyrotron CPI-P1 to GA	Sept-99	Sept-99	Dec-99
4	Complete installation of first gyrotron tank system	Sept-99	Sept-99	Dec-99
5	Complete installation of first transmission line	Sept-99	Sept-99	Apr-00
6	Complete test of gyrotron CPI-P1 (1 MW/5 s)	Feb-00	Mar-03	Apr-03
7	Delivery of gyrotron CPI-P3 to GA	Mar-00	Mar-00	Sept-01
8a	Complete test of gyrotron CPI-P2 (800 kW/2 s)		Sept-00	Dec-00
8b	Test gyrotron CPI-P2 (1 MW/5 s)	Sept-00	Nov-01	Oct-01
9	Complete test of gyrotron CPI-P3 (1 MW/5 s)	Dec-00	Feb-02	Jun-02
	DOE Milestone 129 4 th gyrotron into DIII-D		Apr-00	Jun-00
10	CVD diamond window loss validation		Apr-01	Jun-01
	DOE Milestone 130 6 th gyrotron into DIII-D	Jan-01	May-02	Jun-02

4. LESSONS LEARNED

4.1. 2 MW 110 GHz ECH PROJECT

For the project that preceded this project, there were several recommendations made, which were to be imposed on the next phase of the ECH system improvements. These suggestions and actions taken are listed below. New lessons learned from executing the present project follow after.

4.1.1. Gyrotrons

4.1.1.1. Recommendations.

1. Do not buy gyrotrons that have not been fully developed. Contracts with the manufacture should be payment on demonstration of performance not cost plus fixed fee.
2. Gyrotron manufactures concerns seem to end at the output window; therefore the acceptance tests should demonstrate coupling into a section of waveguide.
3. Manufacturers are not forth coming on production problems, several fact finding trips to the factory should be scheduled.
4. All systems should be hardened to EMI radiation, either from sparkdowns or parasitic oscillations of the tube.

4.1.1.2. Actions Taken.

1. Prototype gyrotron (CPI-D2), with aluminum brazed CVD diamond window, using Gaussian output beam was tested at GA before project started.
2. Final acceptance test was to be performed at GA into a dummy load connected to the gyrotron via a standard section of waveguide.
3. Several trips were taken, even one to the magnet vender when delivery schedules were not met.
4. The gyrotron room walls were constructed with rf screening to reduce EMI propagation.

4.1.2. Magnets

4.1.2.1. Recommendations.

1. Insist that the gyrotron be tested with its mated magnet at the final acceptance test.
2. Properly inform the magnet manufacturer what the required cryogenic hold times are.
3. Procure magnets with external magnet alignment capabilities.

3.1.2.2. Actions Taken.

1. This was in the contract, but when gyrotrons started to fail not all gyrotrons got tested in their respective magnets.
2. This was in the contract specification, the vender did not meet spec.
3. This was in the spec.

4.1.3. Gyrotron Tanks

4.1.3.1. Recommendations.

1. The need for maintenance should be factored in during the design phase.
2. More protection from voltage transients during spark-downs should be included in the electronics design.

4.1.3.2. Actions Taken.

1. The design of the tanks and the layout of the room incorporated these issues.
2. Incorporated.

4.1.4. Transmission Line System

4.1.4.1. Recommendations.

1. The DIII-D Program should have its own experts on phase correcting mirror design. The gyrotron venders are not very responsive to issues in this area.

4.1.3.2. Actions Taken.

1. Nothing done in this area. We used MIT as in the past for all mirror correction calculations.

4.2. THE ECH SYSTEM UPGRADE TO 6 MW

There were two primary issues that impacted the completion of the ECH System Upgrade to 6 MW Project. These were the failure of the superconducting magnet vendor to deliver a product meeting specs and on time, and the loss of two CVD diamond windows owing to failures of the braze material/process control. Both issues suffered from applying a technological improvement before it was fully tested in a developmental article.

4.2.1. Recommendations

- Procurement should have been phased with a first article proof of performance before producing the follow on units.
- Since schedule was the only free parameter under the control of the project, more time should have been allocated in the project schedule to find and workout design/fabrication issues.

APPENDIX A BASE LINE CHANGE NOTICES

Baseline Change Notice: ECH-01

DATE OF NOTICE: October 20, 2000

WBS ELEMENT No. 1.1

WBS ELEMENT TITLE: RF Sources-Gyrotrons

DESCRIPTION OF CHANGE:

The expected completion date for the 6 MW ECH upgrade project will be delayed by approximately 2 months, from January 2001 to March 2001.

REASON FOR CHANGE:

There are two key factors, which attributed to the delay. The first factor was the continued delay in the delivery of the Oxford superconducting magnets. The original delivery of the first unit had been scheduled for March 1999 while it was not delivered until April 2000. Even though an alternate magnet was used for the initial testing of the first gyrotron, the late delivery had and continues to impact the project. The second factor affecting the completion date was the failure of the gyrotron window seal on the first production gyrotron. This failure has meant that the gyrotron had to be returned to CPI for repair using a superior braze technique which has been used on the two other production tubes. The delivery of this tube, to GA, is now scheduled for middle of December 2000. With the late delivery of the final gyrotron and the projected installation and commissioning time, we are now looking at a project completion date of mid to late March 2001.

EFFECT OF CHANGE:

This delay may require the rescheduling of any experiments needing the entire six gyrotrons until after the March 2001 operating period. There should not be significant impact on the proposed experimental plan as it is still in the initial formulation stage. It is projected that there will be no significant change in the total project cost caused by this delay.

Baseline Change Notice: ECH-02**DATE OF NOTICE:** Feb 21, 2001**WBS ELEMENT No. 1.1****WBS ELEMENT TITLE:** RF Sources-Gyrotrons**DESCRIPTION OF CHANGE:**

The expected completion date for the 6 MW ECH upgrade project will be delayed by approximately 12 months, from March 2001 to March 2002. However, the three high power gyrotrons should be available to support physics operations at reduced parameters by December 2001.

REASON FOR CHANGE:

There has been a failure in a single key area associated with the gyrotron that has further delayed the program, that area being the gyrotron output window. Failures in the windows (CPI-P1 and CPI-P3) have resulted in a lengthy delay, not only to procure replacement windows but also to develop a testing process that will identify and prevent any of the suspected causes for the prior failures. A failure of the gyrotron window seal on the first production gyrotron (CPI-P1) was our first major setback followed by the cracking and subsequent loss of vacuum on the third production tube (CPI-P3). These failures have resulted in an aggressive investigation into identifying potential changes in the loss tangent of the windows that may occur during the manufacture process. Current analysis indicates that a resistive surface may have developed on the surface of the windows during the brazing process. This surface may have increased the microwave power absorption of the window by as much as a factor of four (4), thereby increasing the stress in the windows beyond their limits.

We have been able to borrow two windows from the European ECH Fusion community and have a plan in place to measure the loss tangent of the windows after each step of the window assembly manufacturing process. Upon detecting any significant increase in the loss tangent of the window a surface cleaning process will be used take to remove the surface contaminate and the loss tangent will then be re-measured to validate acceptable performance. Validation of the original specifications of the windows after assembly should be completed by April 2001.

EFFECT OF CHANGE:

This delay may require the rescheduling of any experiments needing the entire six gyrotrons until after the January 2002 operating period. There should not be significant

impact on the proposed experimental plan as it is still in the initial implementation stage. It is projected that there will be no significant change in the total project cost. The cost of a replacement window for the first production tube, which had originally been provided by the DIII-D Program, will be offset by the transfer of the cost for an unused Mirror Optical Unit out of the project.

Baseline Change Notice: ECH-03

DATE OF NOTICE: Feb 25, 2002

WBS ELEMENT No. 1.1

WBS ELEMENT TITLE: RF Sources-Gyrotrons

DESCRIPTION OF CHANGE:

The expected completion date for the 6 MW ECH upgrade project will be delayed by approximately 2 months, from March 2002 to May 2002.

REASON FOR CHANGE:

Repair and delivery of the CPI-P1 gyrotron (which is needed for completion of the upgrade project) was delayed due to scheduling problems at CPI associated with the failure of their test facility (Mod-Reg.). In an effort to minimize the impact caused by this failure on the gyrotron schedule, the DIII-D Program loaned one of its spare tetrodes to CPI. The delay in delivery has meant that the installation of CPI-P1 now has to be accomplished while resources are being used to supporting both DIII-D physics operations and conducting the final acceptance testing (to full parameters) of the CPI-P3 gyrotron. This sharing of resources and the later than planned delivery of the gyrotron, combined, are expected to delay completion of the project until May 2002.

EFFECT OF CHANGE:

This delay may require the rescheduling of any experiments needing the entire six gyrotrons until after the April 2002 operating period. There should not be significant impact on the proposed experimental plan as it is still in the initial formulation stage. It is projected that there will be no significant change in the total project cost.

Baseline Change Notice: **ECH-04**

DATE OF NOTICE: June 11, 2002

WBS ELEMENT No. 1.1 & 1.3

WBS ELEMENT TITLE: RF Sources-Gyrotrons

DESCRIPTION OF CHANGE:

The ECH Project requirement on pulse length for the gyrotrons is changed from 10 seconds to 5 seconds at full operating specifications (–80 kV, 40 A cathode current, 1 MW through the output window).

The expected completion date for the 6 MW ECH Upgrade Project will be July 2002.

REASON FOR CHANGE:

There is a pressing need for the use of the upgrade gyrotrons in the DIII-D research program. However research requirements for the next two years only require 5 second pulses. This change better aligns the project goals with the research requirements.

EFFECT OF CHANGE:

This change will complete the project and release the 6 MW ECH Upgrade systems to the research program sooner. It is projected that there will be no significant change in the total project cost.

Baseline Change Notice: **ECH-05**

DATE OF NOTICE: January 17, 2003

WBS ELEMENT No. 1.1 & 1.3

WBS ELEMENT TITLE: RF Sources-Gyrotrons

DESCRIPTION OF CHANGE:

The expected completion date for Milestone 6a (Test First Gyrotron) and the completion of the 6 MW ECH Upgrade Project is moved from July 2002 to March 31, 2003.

REASON FOR CHANGE:

This gyrotron developed a water-to-vacuum leak in the collector during conditioning due to defective copper. This necessitated replacement of the collector.

EFFECT OF CHANGE:

This change will complete the project and release the last of the 6 MW ECH Upgrade gyrotrons to the research program in time to support the planned 2003 operations. It is projected that there will be no change in the total project cost.

APPENDIX B PUBLICATIONS

1. W.P. Cary, et al., "Performance of the 1 MW, 110 GHz, 10 s Gyrotrons Recently Installed in the DIII-D ECH System," in the Proc. of 21st Symposium on Fusion Technology, Madrid, Spain, 2000, to be published in Fusion Eng. and Design.
2. W.P. Cary, "The Upgrade of the DIII-D 110 GHz ECH System to 6 MW," in the Proc. of the 18th IEEE/NPSS Symp. on Fusion Engineering, Albuquerque, New Mexico (Institute of Electrical and Electronics Engineers, Inc., Piscataway, 1999) p. 190.
3. I. Gorelov, et al., "Calorimetric Power Measurements of the DIII-D Gyrotron System," Bull. Am. Phys. Soc. **46**, 302 (2001).
4. I. Gorelov, et al., "Infrared Measurements of the Synthetic Diamond Window of a 110 GHz High Power Gyrotron," in the Proc. of the 14th Top. Conf. on Radio Frequency Power in Plasmas, Oxnard, California, 2001, to be published.
5. H.J. Grunloh, et al., "Design and Analyses of Transmission Lines for the 110 GHz ECH Upgrade to 6 MW for DIII-D," in the Proc. of the 18th IEEE/NPSS Symp. on Fusion Engineering, Albuquerque, New Mexico (Institute of Electrical and Electronics Engineers, Inc., Piscataway, 1999) p. 499; and General Atomics Report GA-A23288 (1999).
6. J. Lohr, et al., "High Power Performance of the DIII-D Gyrotron System," Bull. Am. Phys. Soc. **46**, 302 (2001).
7. J. Lohr, et al., "Performance of the 110 GHz System on the DIII-D Tokamak," in the Proc. of the 14th Top. Conf. on Radio Frequency Power in Plasmas, Oxnard, California, 2001, to be published.
8. J. Lohr, et al., "Commissioning of the 110 GHz ECH System on DIII-D for Physics Applications," Bull. Am. Phys. Soc. **45**, 220 (2000).
9. D. Ponce, et al., "Design and Performance of the 110 GHz Electron Cyclotron Heating Installation of the DIII-D Tokamak," in the Proc. of 14th Top. Meeting on Technology of Fusion Energy, Park City, Utah, 2000, and to be published in Fusion Technology abstract (pdf).

APPENDIX C GYROTRON PROJECT HISTORY

	Project Related Activities	Non-Project Activities
1998		
Jul	<ul style="list-style-type: none"> Project initiated via letter from John Willis to Tom Simonen – estimated cost to complete \$8,243k. Initial Project Management Plan addresses the upgrade of the existing 3MW system to a 6MW system with the addition of 3 more 1 MW-level gyrotrons (with matching optics units, waveguides, HV tanks, magnets, and control systems) at a frequency of 110 GHz. The power is to be contained within a 10-s-long pulse. Gyrotrons to be delivered from as yet undetermined vendor by August '99, November '99, and February '00 – to be ready for operations respectively by February '00, June '00, and September '00 (initial project end date). 	
Aug	<ul style="list-style-type: none"> The DIII-D Program completed a competitive acquisition for three 1-MW diode gyrotrons (and magnets) capable of 10-second pulses, to be provided on a firm-fixed-price basis. CPI was selected as the gyrotron vendor and a contract was executed with early delivery incentives and late delivery penalties. Contract with CPI is for 3 gyrotrons and 3 superconducting magnets. 	
Oct	<ul style="list-style-type: none"> Upgrade gyrotron design review with MIT, GA, CPI, and OFES participating. 	
Dec	<ul style="list-style-type: none"> Formal project kickoff meeting at GA 	
1999		
Feb		<ul style="list-style-type: none"> 3 systems used at GA (2-Dev. Tubes, 1 Russian)
Apr	<ul style="list-style-type: none"> Revised Project Management Plan approved – baseline cost reduced to \$7,749k. Gyrotrons to be delivered from CPI by September '99, December '99, and March '00 – to be ready for operations respectively by February '00, September '00, and December '00 (revised project end date). 	<ul style="list-style-type: none"> CPI-D1 cathode short – sent to CPI for repair CPI-D2 vented; sent to CPI for repair
May	<ul style="list-style-type: none"> Meeting at GA to discuss recent failure of development tubes. 1st Oxford magnet originally scheduled for delivery to CPI this month – there is a delay at Oxford, but no indication yet that it should affect the schedule. 	
Jul	<ul style="list-style-type: none"> The first upgrade tube (CPI-P1) completed cold testing and is ready for final assembly at CPI. The CPI-P1 tube was assembled using a diamond disk window assembly with an aluminum diffusion bond vacuum seal. 	<ul style="list-style-type: none"> Two TdeV GYCOM tube systems purchased as spares

Aug	<ul style="list-style-type: none"> • CPI-P1 underwent successful bakeout at CPI. • Oxford magnet for CPI-P1 not delivered on time – magnet borrowed from development tube CPI-D1 for testing at CPI. • The Oxford magnet to be used for the upgrade gyrotrons is a “reduced cryogen” model with an extended liquid helium hold time (30 days) between required refills. This is the first indication that Oxford was having trouble actually making this magnet. 	<ul style="list-style-type: none"> • CPI-D2 repaired and tested at CPI
Sep	<ul style="list-style-type: none"> • CPI-P1 ready for testing at CPI • High voltage tanks received from PPPL and installation begun at GA. • First Oxford magnet not expected to be ready until February 2000. 	<ul style="list-style-type: none"> • Building addition completed • CPI-D2 returned to GA • TdeV equipment shipped to GA
Oct	<ul style="list-style-type: none"> • CPI-P1 achieves 1 MW for short pulses during testing at CPI. 	<ul style="list-style-type: none"> • CPI-D2 conditioning at GA • Two TdeV tubes being installed • PPPL99 launcher at GA
Nov	<ul style="list-style-type: none"> • Oxford commits to supply one magnet with required magnetic properties, but not extended He hold time, by the end of November. • CPI-P1 enters pulse extension phase of testing at CPI. 	<ul style="list-style-type: none"> • CPI-D1 (repaired) returned to GA • 900 kW short pulse achieved on CPI-D2
Dec	<ul style="list-style-type: none"> • CPI-P1 passes factory acceptance tests at CPI. • Among other things this involves a reliability test of 10 consecutive 10 second long pulses at 25 A (corresponding to generated power >500 kW) and a full power (1 MW) test for short pulses (~5 ms) with an rf generation efficiency of 32%. • CPI-P1 delivered to GA (three months late with respect to the initial project baseline). 	<ul style="list-style-type: none"> • PPPL99 launcher installed • CPI-D2 600 kW/450 ms • TdeV tube installation complete
2000		
Jan	<ul style="list-style-type: none"> • CPI-P1 installed at GA. • CPI-P2 underwent successful bakeout at CPI and is waiting for a magnet. This tube has the first successful high-temperature (Au/Cu) brazed diamond window vacuum seal. 	<ul style="list-style-type: none"> • CPI-D2 500 kW/950 ms • PPPL99 launcher used for first time
Feb	<ul style="list-style-type: none"> • First Oxford magnet delivered to CPI. Meets magnetic requirements of gyrotron (barely — has 0.3% transverse field error, twice the specification), but not long liquid He hold time specification (1 week vs. 4 weeks specified). Contract will be credited for failure to meet full specification. 	<ul style="list-style-type: none"> • CPI-D2 650 kW/2.5 s – used for experiments with PPPL99 launcher • TdeV magnets aligned
Mar	<ul style="list-style-type: none"> • CPI-P2 testing begun at CPI. • New system of quarterly project reports initiated by DOE – Quarterly report #1 this month covers last quarter of CY99. 	<ul style="list-style-type: none"> • First low power operation of two TdeV tubes – measurements made for phase correcting mirrors
April	<ul style="list-style-type: none"> • Quarterly project report #2, covering 1st quarter of CY00. • ECH project funding schedule adjusted to take into account gyrotron payments being delayed into next FY. Total estimated cost to complete actually decreased due to credit anticipated for late gyrotron delivery penalty. • CPI-P1 installation at GA complete and testing begun (roughly 3 months behind schedule). • CPI-P2 up to 1 MW/5 ms and 500 kW/50 ms at CPI. • Transmission line fabrication and installation completed. • ECH control equipment being installed. • CPI-P3 subassemblies completed at CPI. 	

May	<ul style="list-style-type: none"> • CPI-P2 passes factory acceptance tests at CPI. 	<ul style="list-style-type: none"> • Phase correcting mirrors for TdeV Russian tubes completed and installed • First indication of PS-1 crowbar problems (thyatron failures) • Failure of diamond window on 95 GHz gyrotron at CPI.
Jun	<ul style="list-style-type: none"> • CPI-P2 delivered to GA with 1st Oxford magnet (5 months late with respect to initial project baseline – largely due to delay in delivery of Oxford magnet). • Oxford decides not to provide 3rd magnet to CPI, but will provide 2nd magnet since parts have already been manufactured. Project will continue to use magnet from the development tube that is currently being held as a potential spare and will take credit (\$280k) on CPI contract for magnet not supplied and failure to meet He hold time on two other magnets. • CPI-P1 injected short pulses (100 ms) into DIII-D for first time • CPI-P1 develops a vacuum leak in the diamond window seal (Al diffusion bond) – attempts are made to repair it in-situ. 	<ul style="list-style-type: none"> • Two TdeV tubes and CPI-D2 ready for operations – these three used to support experiments for the first time.
July	<ul style="list-style-type: none"> • CPI-P1 was pulled from its high voltage socket and shipped back to CPI for repair. Analysis of the window after removal indicated that the leak was caused by corrosion of the aluminum seal. • CPI-P2 conditioned up to 400 kW/1 s and 500 kW/650 ms pulses to support experiments. • Quarterly project report #3. 	<ul style="list-style-type: none"> • CPI-D2 shows signs of diamond window (Al diffusion bond) vacuum leak – operated to support experiments with modified cooling scheme • First use of 4 systems to support experiments (2 TdeV tubes, CPI-D2, CPI-P2) • First complete suppression of 3/2 NTM on DIII-D
Aug	<ul style="list-style-type: none"> • CPI-P2 achieves 500 kW/5 s and 700 kW/200 ms pulses but longer, higher power pulses not obtained prior to summer shutdown of 138 kV system for required maintenance. 	
Oct	<ul style="list-style-type: none"> • Baseline change notice ECH-01 was completed to extend project end date by three months to March '01 due to delays in magnet delivery and failure of CPI-P1 window vacuum seal. • CPI-P3 being conditioned at CPI – up to 1 MW/5 ms and 600 kW/40 ms pulses. • CPI-P3 window with Au/Cu braze cracks at a moderate power conditioning pulse (613 kW/5.6 s). 	
Nov	<ul style="list-style-type: none"> • Technology Division diverts funds and begins R&D effort into the cause and prevention of window failure. • Quarterly project report #4. 	

Dec	<ul style="list-style-type: none"> The diamond disk from CPI-P1 could not be reused in its repair, so this requires the procurement of two new diamond disks for the repair of CPI-P1 and 3. This long-lead time item will extend the project end date significantly. Initial indications point to some type of contamination of the window during the brazing process, leading to an increase in loss tangent leading to increased power absorption and cracking due to the increased stress. 2nd Oxford magnet was delivered to CPI. CPI-P2 achieves 800 kW/2 s pulses (1 MW for short pulses ~5 ms). Further performance extension is deferred (as questions arise about the diamond windows) so that this tube can support 2001 research campaign with a high probability of success. Improved infrared measurements of the diamond window on this tube are implemented. 	
2001		
Jan	<ul style="list-style-type: none"> Arrangements were made to borrow 2 diamond disks already manufactured for W7-X and replace them later. This will speed up the repair process for CPI-P3 and 1, once it can be determined what caused the disk failures and how to avoid it. These disks will have to be cut to size and the thickness ground down slightly to work with the DIII-D 110 GHz tubes. Even taking into account the earlier availability of the diamond disks, initial estimates indicate that the CPI-P1 and 3 systems would not be ready for operation until December '01, thus the project completion date will slip at least until then. Quarterly project report #5. 	<ul style="list-style-type: none"> PS-2 begins testing
Feb	<ul style="list-style-type: none"> CPI-P2 began routine use to support experiments at the 800 kW/2 s performance levels. Tests at Sandia confirms that a carbon film forms on the diamond disk during the high temperature braze process. A process (bead blasting) was developed that removes most of the film and achieving original value of loss tangent. 	
Mar	<ul style="list-style-type: none"> Baseline change notice ECH-02 was completed to extend the project end date by 12 months to March '02 due to the need to replace the diamond disk windows on the CPI-P1 and CPI-P3 gyrotrons. The two borrowed diamond disks for CPI-P1 and CPI-P3 have been received. Loss tangent measurements to be made at each manufacturing stage by KFK, Germany. 	<ul style="list-style-type: none"> Thyrotrons in PS-1 and PS-2 still not performing well – PS-1 then PS-2 changed to thyrotron + ignitron design
Apr	Quarterly project report #6.	
May	<ul style="list-style-type: none"> Infrared measurements of the CPI-P2 window during operations do indicate the presence of localized hot spots. 	<ul style="list-style-type: none"> PPPL99 launcher damaged – replaced with fixed launcher for last research period
Jun	<ul style="list-style-type: none"> Extensive characterization and testing was performed during the fabrication of the new diamond window assembly for the CPI-P3 gyrotron. CPI made some modifications to the brazing setup and all indications are that no resistive film was formed on the diamond disk during manufacturing, and that the required loss tangent was maintained throughout the process. The CPI-P3 tube bake-out completed at CPI. The second diamond disk is being prepared for the repair of the CPI-P1 tube. 	<ul style="list-style-type: none"> 3/2 NTM suppression with feedback and increasing beta

July	<ul style="list-style-type: none"> Quarterly project report #7 Interim project "lessons learned" developed and discussed. Repaired CPI-P3 begins conditioning at CPI – power supply problems and scheduling cause this to take longer than usual. 	
Aug	<ul style="list-style-type: none"> Raman scattering system rented from Renishaw to do in-situ characterization of the CPI-P2 window in preparation for power and pulse-length extension effort on this tube. The DIII-D Program loans spare tetrode to CPI in order to finish final conditioning & testing of CPI-P3. 	
Sept	<ul style="list-style-type: none"> CPI-P3 passes factory acceptance tests at CPI and is delivered to GA (18 months late with respect to initial project baseline). In-situ Raman scattering measurements of the CPI-P2 window did showed some evidence of graphite contamination. The outer face of the window was grit blasted with fine alumina powder to remove surface contamination on the outer surface. Data indicated that the grit blasting might have removed some contamination. Rebuild of CPI-P1 begun at CPI 	
Oct	<ul style="list-style-type: none"> CPI-P2 achieves 1MW/5 s pulses, all data (including infrared data from the diamond window) indicated that 10-s full parameter operation would probably be possible with just several more hours of conditioning. However, due to the value of this gyrotron to the planned 2002 research program, and the fact that CPI-P3 would not be available for several months, a decision was made to administratively limit this tube to parameters under 1MW/5 s until the completion of the 2002 research campaign. Partial final payment to CPI was authorized, but the warranty at full parameters was maintained. Quarterly project report #8 Installation of CPI-P3 begun at GA. 	
Nov		<ul style="list-style-type: none"> Repaired PPPL99 launcher and new PPPL01 launcher received and installed on DIII-D
Dec	<ul style="list-style-type: none"> Installation of CPI-P3 complete and testing begun at GA. Rebuilt CPI-P1 begins conditioning/testing at CPI. 	
2002		
Jan	<ul style="list-style-type: none"> Quarterly project report #9 Measurements taken for CPI-P3 focusing mirror. CPI-P1 finishes factory conditioning (up to 500 kW/ 9.5 s pulses) and is shipped to GA (the project funded an extra two weeks of conditioning at CPI for this tube). 	
Feb	<ul style="list-style-type: none"> Baseline change notice ECH-03 completed extending project end date by two months, to May 2002, due to delays in testing CPI-P1 at CPI (power supply problems/scheduling conflicts) and an extra two weeks of conditioning for this tube once testing had begun. CPI-P3 focusing mirror received and installed. CPI-P1 installed in high voltage tank and magnet at GA. 	
Mar	<ul style="list-style-type: none"> Testing/conditioning of CPI-P3 begun. Power supply crowbar problems necessitate second redesign and rebuild (to remove thyrotrons completely). CPI-P3 up to 750 kW/250 ms pulses. 	<ul style="list-style-type: none"> First use of both PPPL launchers (99 and 01) in experiments. First use of ECH in feedback mode – controlled by the PCS.

DIII-D ELECTRON CYCLOTRON HEATING SYSTEM UPGRADE
TO 6 MW PROJECT

R.W. Callis

Apr	<ul style="list-style-type: none"> Quarterly project report #10 Request made for final project funding of \$22k in FY02, bringing total project cost to complete to \$7,753k, only \$4k over baseline. CPI-P3 used for the first time to support experiments (at intermediate parameters ~750 kW/2 s). Infrared measurements on the CPI-P3 diamond window show a significantly lower bulk temperature during high power, extended pulses than that displayed by the CPI-P2 window. First use of 5, 1MW-class gyrotrons to support DIII-D experiments – 2 CPI systems from the upgrade project (CPI-P2 and 3) and 3 short pulses GYCOM gyrotrons from the initial prototype/development system. 	<ul style="list-style-type: none"> PS1 converted to SCR/ignitron crowbar circuit design. First use of 5, 1 MW-class gyrotrons to support DIII-D experiments.
June	<ul style="list-style-type: none"> Quarterly project report #11 The CPI-P3 gyrotron achieved 1MW/ 5 s operating parameters. Installation of the repaired CPI-P1 tube was completed in June and testing/conditioning was initiated. All six systems were operational, marking completion of the DIII-D contract Milestone 130. System capability of 4.1 MW source power for pulse lengths just over 2 s was demonstrated to match the OMB Exhibit 300 DIII-D upgrade project description. Baseline change notice ECH-04 was submitted and approved to change the required pulse length for the gyrotrons to 5 s for project completion, and extend the project end date by two months, to July 2002. CPI's warranty for tube operation to 10-s pulse lengths is maintained. Final FY02 project funding of \$22k was provided by OFES, bringing the total project funding to \$7,753, only \$4k over the baseline TEC. 	
July	<ul style="list-style-type: none"> Quarterly project report #12 In mid-July the CPI-P1 tube suffered a vacuum leak at the 1MW/ 800 ms operating regime while being conditioned up to full parameters. The tube was shipped back to CPI for diagnosis and repair 	
Sept	<ul style="list-style-type: none"> An initial attempt to repair the leak by brazing failed when a leak reopened during bakeout in mid-September. Since CPI had sufficient spare components on site, it was decided to replace the entire outer collector assembly. The repaired superconducting magnet power supply was received back from Oxford. Concerns about the thermal performance of the CPI-P1 window were also raised during the testing at GA (from IR measurements), so additional tests are being done during the repair at CPI. 	
Oct	<ul style="list-style-type: none"> The leaking segment of the collector assembly was cut apart and examined after being removed from CPI-P1. Additional cracks and flaws in the copper were observed. CPI is currently attempting to determine (nondestructively) how best to insure the replacement parts (and one reused conical section) are not flawed. 	

Nov	<ul style="list-style-type: none"> • CPI replaced the outer collector assembly on CPI-P1 with available spare components after metallurgical flaws were discovered in the leaking assembly. • A test piece of scrap diamond window was put through the bakeout cycle with CPI-P1 to determine if a film was being deposited on the diamond surface during this process. There were no indications of any film deposition on either the test piece or the outside of the CPI-P1 window. 	<ul style="list-style-type: none"> • The third PPPL launcher PPPL 2002 was installed in the 270 degree port.
Dec	<ul style="list-style-type: none"> • A vacuum leak during the bakeout cycle caused this process to take about two weeks longer than usual, but the repaired tube was delivered to GA in December. Installation was completed just prior to the GA December holiday shutdown. 	
2003		
April	<ul style="list-style-type: none"> • CPI-P1 completed commissioning on April 10, 2003 by producing 1 MW for 5 s into dummy load. This is the last miles stone for the project and marks the completion of all activities covered by the project management plan.

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