

Final Report

Development of a 2 MW CW Waterload for Electron Cyclotron Heating Systems

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No confidential or proprietary information is contained in this report

1. Introduction

This program developed an RF load capable of dissipating 2 MW of CW RF power for developing and testing gyrotrons for electron cyclotron heating of tokamak plasmas. Prior to this development, the only load available for dissipating CW RF power exceeding 1 MW was the Calabazas Creek Research, Inc. (CCR) load developed under a previous SBIR program [1]. This load is currently rated at 1.25 MW CW; however, no existing gyrotron has achieved that power and duty. Figure 1 shows a photograph of the 2 MW CW load.

The 2 MW load was developed to support development of 2 MW gyrotrons in the Europe, Japan, and the United States [3, 4]. It is also the specified requirement for loads for the ITER program. The ITER program is an international collaboration to harness fusion energy for production of electrical power. Construction is in progress in France, with major participation from the European countries, Russia, Japan, India, and the United States. An image of the reactor vessel is shown in Figure 2 [2].

The current ITER plan is to provide approximately 20 MW of ECH heating [2]. It is anticipated that this power will be supplied by 24 gyrotrons producing at least 1 MW CW each. An additional three gyrotrons were planned for start-up heating, but recent research indicates these may be used for ECH instead [3]. In any case, a minimum of 23 MW of gyrotron power will be required.

To reduce the number of gyrotrons, the ITER designers are exploring opportunities to use higher power gyrotrons. Research is progressing in Europe and the United States to develop gyrotrons producing 2 MW CW or more. This could reduce the ultimate cost of the ECH system.

The Phase II program initially began with several goals, specifically:

- Develop a load capable of dissipating 2 MW CW of RF power between 100 and 170 GHz,
- Reduce reflected power from the load to less than 1% of the incident power
- Provide robust seals for water cooling and load vacuum,
- Provide a high capacity pumpout port.

As will be described in this report, all these goals were accomplished, though no gyrotron is available to verify the power capability. Following initiation of the Phase II program, however,



Figure 1. 2 MW CW waterload for Gaussian mode gyrotrons

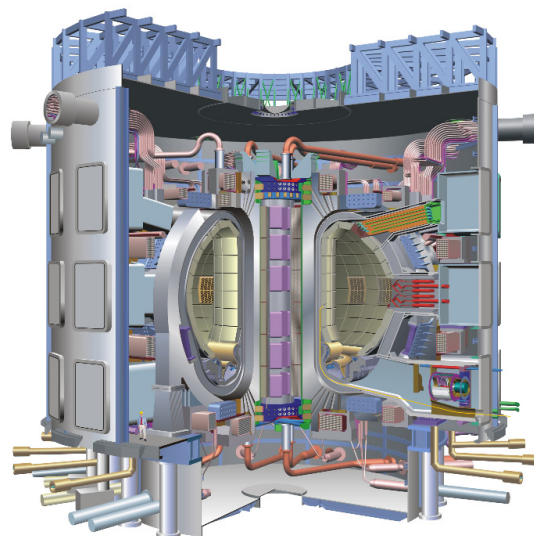


Figure 2. Image of ITER reactor vessel

additional specifications were established for ITER RF loads. These specifications dictated that no corrosive materials could be in contact with cooling water. Unfortunately, this included anodized aluminum, which is the primary material used in the load. Consequently, it became necessary to modify the scope of the program to develop a second version of the load consisting only of copper and stainless steel. This version was completed with Phase III funding from the U.S. Department of Energy and delivered to the US-ITER operation in Oak Ridge, TN.

This report reviews the tasks proposed for the program and the additional tasks added to meet the ITER specification. All tasks were successfully completed, and two version of the 2 MW load are available. CCR sold and delivered an aluminum 2W load to the Japanese Atomic Energy Agency (JAEA) in January 2012 and is scheduled to deliver a second load to JAEA in December 2012.

The Phase II Project

2. Technical Objectives of the Phase II Program

The Phase II program included the following tasks:

- Extend RF analysis of rotating reflector design to estimate escape of RF power from the load
- Perform complete mechanical design, including thermomechanical analysis, of rotating reflector assembly
- Construct prototype rotating reflector assembly and test water and vacuum seals
- Perform thermomechanical analysis of wobble load configuration
- Construct prototype wobble reflector assembly and perform mechanical tests
- Test reflector assemblies at high power
- Finalize load design
- Update the control and diagnostic electronics
- Generate Final Report

The change in scope required by the ITER specification resulted in cancellation of several of these tasks. Specifically, work on the wobble load was deleted from the program. This is unfortunate, as this version of the load would have met more recent ITER specifications. The high power test of the reflector assembly was also dropped, because it was no longer necessary. Operation of the load delivered to JAEA in January 2012 confirmed the ability of the reflector up to approximately 1 MW. This is the highest RF power currently available for load testing.

The ITER specification required development of a new load design consisting of parts fabricated primarily of stainless steel and copper. This additional task will be described in this report.

The additional ITER specification preventing use of anodized aluminum required a redesign of the primary load cylinder and the end plates. The aluminum load consists of an internal cylinder with grooves on the outer surface and an outer cylinder to contain the water coolant and direct flow through the channels. The load meeting the ITER specification consisted of a single cooper cylinder with axial holes for the coolant flow. This was constructed by brazing two shorter cylin-

ders together. It was necessary to define fabrication processes to fabricate and drill these cylinders to form a single cylinder of the required length of approximately one meter. Gun drilling the coolant channels introduced significant complexity to the fabrication.

The end plates were fabricated from stainless steel components welded together. This eliminated many O-ring joints present in the aluminum load, but introduced greater assembly complexity due to the welding of large plates subject to warping and distortion.

3. Phase II Work Plan

3.1. Extend RF analysis of rotating reflector design

This task was to insure that power reflected from the downstream end of the load would not escape from the load and be transmitted back toward the gyrotron. The program analyzed the path of RF power following impact with the downstream endplate and compared the direction of propagation with the position of the rotating launcher at the load input. The analysis indicated that RF power should not couple into the waveguide.

These results were confirmed experimentally with the RF load delivered to JAEA. Japanese scientist measured the RF power dissipated in the first section of corrugated waveguide connected to load. Because reflected power from the load would not couple into the HE_{11} mode, it would be absorbed in this first section. Measurements made by JAEA and calculations performed by Joan Doan at General Atomics, manufacturer of the waveguide, confirmed that reflected power was less than 0.5% of the input power. This significantly exceeded the goal a reflected power being less than 1%.

3.2. Perform complete mechanical design, including thermomechanical analysis, of rotating reflector assembly

The Phase I program examined the steady state and transient performance of the load using the simulation data for the first two bounces. CCR used this information to specify the loss coating thickness on the inner surface of the load.

The Phase II proposal described preliminary design of a water seal generated by Trelleborg Sealing Solutions [14]. Phase II tests of this seal, however, indicated that leaking could occur if the coolant water pressure was low. This routinely occurs when the coolant flow is stopped and back pressure is removed. Consequently, CCR explored several alternate approaches. It was determined that a double seal would provide the required performance. With the double seal, one provides a firm seal when the water pressure is high and the thinner seal prevents leakage when the pressure is low.

Three double seal versions were tested in a test configuration. One seal was manufactured by Trelleborg and two were from American High Performance Seals, Inc. All the double seals provided the performance required; however, one was rejected because it presented excessive drag and could not be removed from the assembly without damage. The two loads delivered to customers during the program used the Trelleborg seal.

Vacuum seals were provided by ferromagnetic seals from FerroTec, Inc. [13]. These are the same type seals successfully tested in the Phase I program. These seals also provide the bearings for the rotating assembly.

The 2 MW load uses the same drive motor for rotation as the 1 MW load. None of these motors have caused any problems since the original load was built in 1999. Initial attempts to use a belt drive failed due to high drag. The design was modified to use a chain drive instead. It was subsequently determined that one of the ferromagnetic seals was defective, causing the excessive drag. Never the less, it was determine that the chain drive was more robust than the belt drive, so all loads now use this approach.

The complete drawing package was generated and parts ordered for the prototype load. At the same time, parts were ordered for the JAEA load that was delivered in January 2012. Due to scheduling requirements, the JAEA load was assembled first. The load was assembled with little difficulty, validating the mechanical design.

3.3. Construct prototype rotating reflector assembly and test water and vacuum seals

Figure 3 shows the setup for bench testing water and vacuum seals. The assembly uses the same parts as the launcher assembly installed on the load with the exception of the central waveguide. The test setup allows testing of both the water and vacuum seals while rotating the central structure as in the load.



Figure 3. Setup for testing water and vacuum seals

Seals were installed and the motor energized for several hundred hours to verify the performance. As indicated above, the setup identified a problem with leakage from the initial seal when the water flow was stopped and pressure was removed. This was a very small leak that occurred following approximately 40 hours of operation. Never the less, it was not acceptable, motivating testing of the double seals which provided the performance required.

Additional testing was performed by assembling a complete launcher assembly and mounting it on an load endplate. This is shown in Figure 4. The end plate was elevated above the load cylinder and white, gridded poster paper placed against the inner diameter of the cylinder. Using a light directed into the input end of the launcher assembly, CCR mapped the distribution of the light beam on the gridded paper. A photograph is shown in Figure 5. This confirmed that the incoming beam was well distributed, both axially and azimuthally, over the inner surface of the load cylinder. Movies were also taken with the launcher motor energized and the reflector mirror rotating.

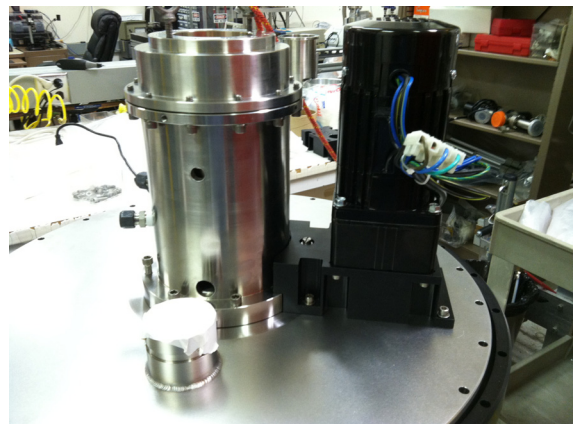


Figure 4. Launcher assembly mounted on load end plate for testing

3.4. Perform thermomechanical analysis of wobble load configuration

This task was dropped following receipt of the revised ITER load specifications.

3.5. Construct prototype wobble reflector assembly and perform mechanical testing

This task was dropped following receipt of the revised ITER load specifications.

3.6. Test reflector assemblies at high power

It was anticipated that high power testing would be performed at General Atomics; however, testing during actual use became possible with the load shipped to JAEA. The JAEA load was installed into their transmission line for testing of a 1.5 MW, long pulse gyrotron at 170 GHz.

High power testing began in May, 2012, and Table 1 presents the performance. JAEA indicated that the load performed well and they intend to extend the pulse length to 100 seconds and increase the power to 1.5 MW. They subsequently ordered a second load, which is scheduled for shipment in December 2012.

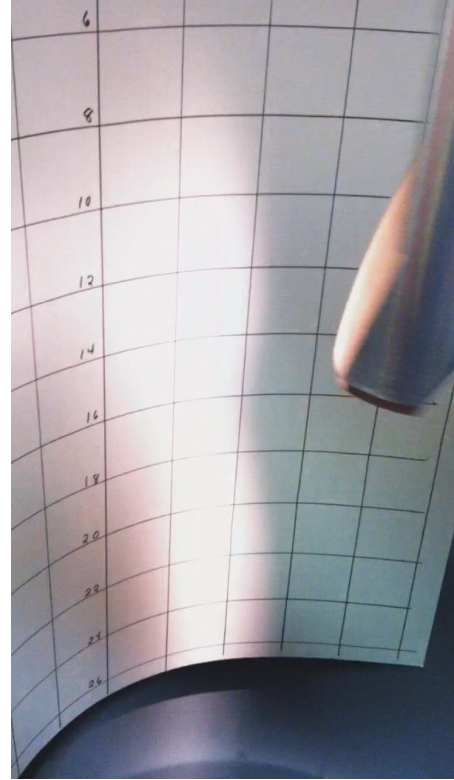


Figure 5. Image of launched light beam on inner surface of load

Table 1: High power test performance at JAEA

Date	Power (kW)	Pulse Width (seconds)
May 28	400	40
May 30	600	5
June 1	850	5
June 4	1000	5
June 7	900	30
June 14	900	60

The requirement to develop a second load using copper and stainless steel delayed the high power tests planned at General Atomics. Those tests will use the cylinder from the prototype 1 MW load containing resistance thermal devices (RTDs) to measure the deposited RF power distribution. This load is shown in Figure 6. CCR will remove the existing endplates and reflector assembly and install the new endplates, launcher assembly, and vacuum pumpout. Unfortunately, it was not practical to schedule this tests before the end of the Phase II program. Consequently this test will be performed following the Phase III program at a time when test facilities are available at General Atomics. The results will be submitted to an appropriate journal for publication, along with other information about the load.

3.7. Finalize load design

Results of the high power testing at JAEA provided sufficient information to validate the design, up to the 1 MW power level. The 5 second pulse was sufficient for two rotations of the RF beam around the load. The 60 second pulse was sufficient for approximately 30 rotations. This is sufficient for the load surfaces to reach equilibrium operation. Thermal analysis indicates that equilibrium performance is achieved after two rotations.

Further optimization of the load performance will follow the thermal tests at General Atomics. The measurements will show the uniformity of the power deposition as a function of axial position in the load. If appropriate the loss coating profile will be modified.

3.8. Update the control and diagnostic electronics

The controller provides a single point of operation for controlling all required interlocks and accessing diagnostic sensors for determining the RF power dissipated in the load. The controller includes the following features:

- On/Off control for the rotating mirror motor
- Measurement of the reflector rotation rate
- Measurement of the reflector assembly coolant flow rate
- Measurement of the main load coolant flow rate
- Monitoring of inlet and outlet coolant temperatures
- Determination of average RF power for short pulse or CW operation
- Determination of peak RF power for short pulse or long pulse operation
- Interlock for main coolant flow
- Interlock for reflector rotation
- Interlock for reflector coolant flow
- RS-232 output of all signals for remote processing or control

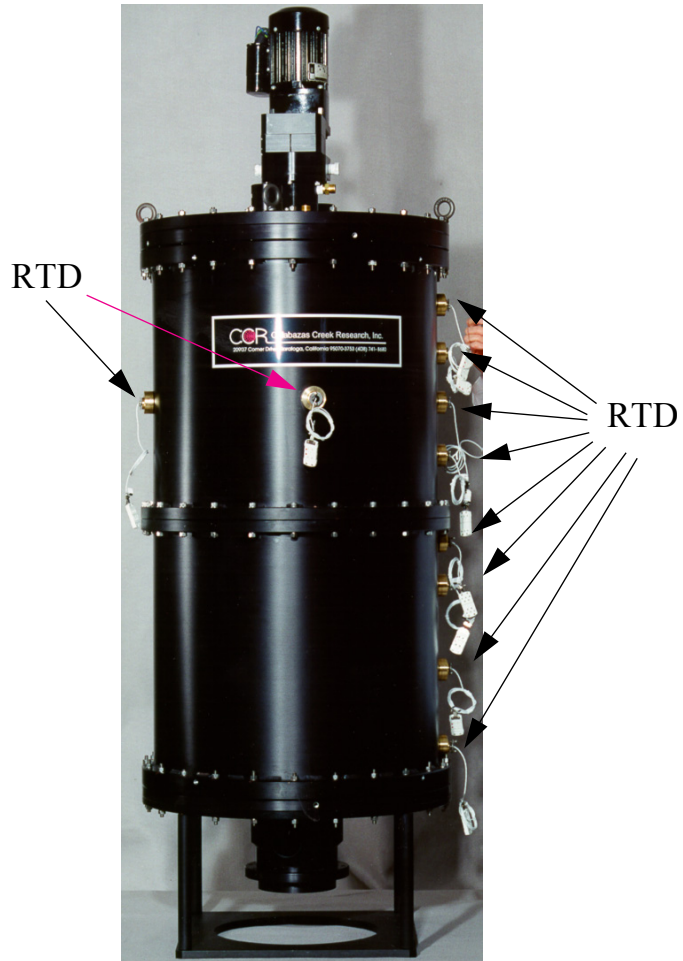


Figure 6. Prototype RF load showing location of RTDs

The controller includes the following components:

- Rack mounted central control chassis with diagnostic monitoring and waterload interlocks
- Remote mounted NEMA chassis for signal conditioning and transmission to the rack-mounted control unit
- Fiber optic cable to connect the NEMA chassis to the rack-mounted controller. The system is designed for transmission over fiber optic cable up to 100 meters in length.
- Flow meter for monitoring mirror/reflector coolant flow
- Flow Technology, Inc. turbine flow meter for main coolant flow monitoring
- Omega Resistance Temperature Devices (RTDs) with victaulic elbow assemblies
- Auxiliary plumbing for main flow system
- Precision encoder for monitoring reflector rotation
- Rack-mounted control chassis that includes an on-board, programmable, central processing unit (CPU). Additional functionality can be programmed into the unit as requested.

During the Phase II program, critical controller components were modified to accommodate the changes in the load design. This included integration of a proximity detector for monitoring the launcher rotation rate and upgrade of the software to accommodate the increased 2 MW power capability and increased maximum coolant flow rate to 250 gpm. Component of the electronics package are shown in Figure 7.



Figure 7. Photograph of waterload electronics, including rack mounted controller, RTDs, flow sensor, fiber optic cables, launcher motor, and remote sensor controller.

4. Additional Task

Revised specifications for the ITER loads required development of a second version of the load consisting of only stainless steel and copper in contact with coolant water. An additional specification was static pressure testing to 200 psi. The subsequent modification of major subassemblies are described below.

4.1. Launcher Assembly

Fortunately, the launcher assembly already consisted only of the metals copper and stainless steel in contact with the coolant water. No modification of this assembly was required. The water seals use teflon as the sealing surface. Figure 8 shows a photograph of the launcher assembly.

4.2. Load cylinder

The load cylinder fabrication provided the greatest challenge. Because of the limited depth of gun drilling, it was necessary to make the cylinder from two smaller cylinders. These were then brazed together to form the one meter cylinder for the load. The program explored two methods for making the cylinder. One method used centrifugal spinning, similar to the aluminum cylinders. Based on the vendors recommendation, the material was changed from pure copper to copper chromium. This was more compatible with the spinning process and resulted in stronger material. The other technique consisted of rolling and electron beam welding copper plate.

CCR procured copper cylinders fabricated using both techniques. While the rolled and welded cylinders were fabricated first, they were damaged by the carrier when shipped from the gun drilling vendor to CCR's facilities. This required procurement of new cylinders, delaying availability for several months. Consequently, the centrifugally spun cylinders were used in the load.

Brazing the large and heavy cylinders presented several problems. Not only were special lifting fixtures required, but stainless steel support rings were necessary to insure the copper material would support the static forces imposed by the coolant water pressure and the inter-



Figure 8. Launcher assembly

nal vacuum. It was also necessary to braze stainless steel O-ring surfaces on the inner diameter and flanges on the ends for mounting the endplates.

CCR attempted to braze the copper cylinders, support rings, O-ring rings, and flanges in a single braze. While most joints were successfully brazed, the lower O-ring ring was not adequately supported at temperature when the alloy melted. It required several additional brazes of the very heavy assembly to completely braze the joints. Figure 9 shows the brazed cylinder assembly.

The assembly procedure was changed based on this experience. In the future, the stainless steel rings and flanges will be brazed into each copper cylinder first where they can be properly supported. The copper subassemblies will be brazed together in a subsequent braze.

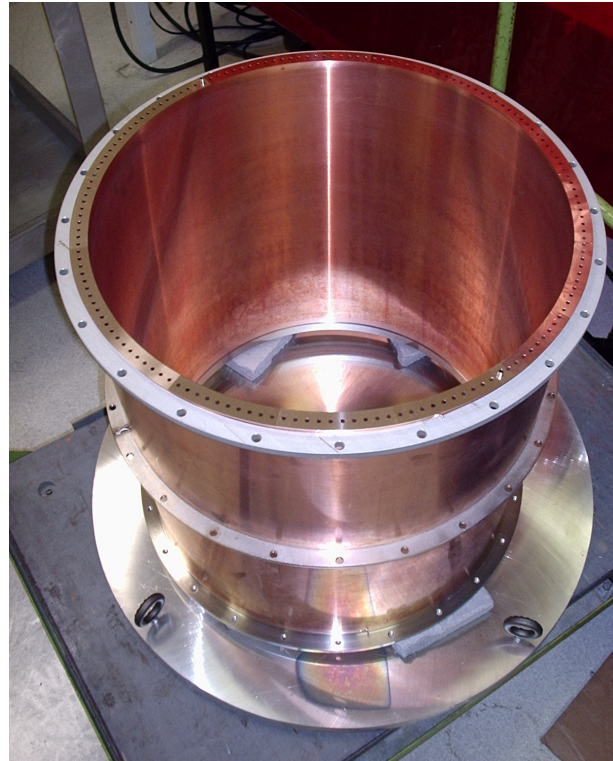


Figure 9. Photograph of brazed copper cylinder

4.3. Endplates

Replacement of the aluminum endplates with ones fabricated from stainless steel presented the opportunity to eliminate many O-ring joints. Consequently, the parts of the endplates were welded instead of bolted together. This required careful consideration of warpage due to the non-uniform application of heat during welding. All major weld joints on the large plates included grooves to

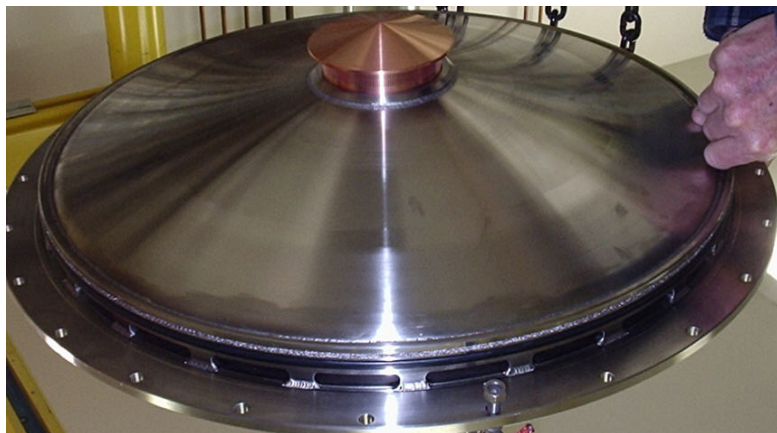


Figure 10. Stainless steel endplate with copper sieve for vacuum pumpout

relieve stresses that would distort the plates. Even so, some distortion did occur. This was anticipated, however, so sufficient material was provided for subassembly machining to true up mating surfaces for the copper cylinder and the launcher assembly. Figure 10 shows the stainless steel endplate containing the vacuum pumpout.

4.4. Final Assembly

The load was successfully assembled and pressure tested. This load, shown in Figure 11, was shipped to the U.S. ITER organization at Oak Ridge, TN, for high power testing.

5. Future Plans

CCR will pursue thermal measurement of the load using the configuration shown in Figure 6. All parts to perform these measurements are in stock; however, testing must be coordinated with General Atomics to insure a gyrotron is available. This requires coordination with use of the gyrotrons with the DIII-D reactor.

The design of the copper cylinder will be modified based on experience with assembly of the load for Oak Ridge. Future load cylinders will be fabricated from three shorter cylinders instead of two. This will reduce the difficulty of gun drilling the cooling channels. It will also simplify handling and assembly.

The brazing schedule will also be modified so that the flanges and support rings are brazed separately from brazing of the cylinders. This will simplify the assembly and allow verification of bond integrity at an earlier stage in the process.

6. Summary

Calabazas Creek Research, Inc. successfully developed a load designed to dissipate 2 MW of continuous power from ECH gyrotrons. Tests at the highest available power demonstrated the load is performing as designed. Measurement of reflected power indicated the design exceeded the goal of less than 1%. JAEA measurements indicate reflected power is less than 0.5%.

The program developed two designs for the load. The first design uses anodized aluminum for the principal components, including the load cylinders and the end plates. The second uses copper chromium for the cylinder and stainless steel for the remaining parts. While both loads achieve the goals of the program, the copper/stainless steel load is considerably heavier and more expensive. This is primarily due to the weight and cost of the gun-drilled copper cylinder. The stainless steel endplates are also heavier than the aluminum endplates. Welding of the stainless steel endplate components also adds to the expense.

CCR will implement additional refinements to both designs as experience and feedback are provided from users. JAEA indicated that the load was working well in their facility, and they are



Figure 11. 2 MW CW copper and stainless steel load

pleased with the performance. They ordered a second load scheduled for delivery in December 2012. It is anticipated that the copper/stainless steel load will be tested at Oak Ridge in late fall 2012. If the tests at Oak Ridge also are successful, it is hoped that CCR will receive an order for the twenty four loads required for ITER.

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