PLASMA CORE REACTOR SIMULATIONS
USING RF URANIUM SEEDED ARGON DISCHARGES

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Experimental results are described in which pure uranium hexafluoride was injected into an argon-confined, steady-state, rf-heated plasma to investigate characteristics of plasma core nuclear reactors. 80 kW (13.56 MHz) and 1.2 MW (5.51 MHz) rf induction heater facilities were used to determine a test chamber flow scheme which offered best uranium confinement with minimum wall coating. The cylindrical fused-silica test chamber walls were 5.7-cm-ID by 10-cm-long. Test conditions included rf powers of 2-85 kW, chamber pressures of 1-12 atm, and uranium hexafluoride mass-flow rates of 0.005-0.13 g/s. Successful techniques were developed for fluid-mechanical confinement of rf-heated plasmas with pure uranium hexafluoride injection.
### CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>SUMMARY</td>
<td>1</td>
</tr>
<tr>
<td>LIST OF SYMBOLS</td>
<td>2</td>
</tr>
<tr>
<td>INTRODUCTION</td>
<td>3</td>
</tr>
<tr>
<td>DESCRIPTION OF EQUIPMENT</td>
<td>5</td>
</tr>
<tr>
<td>RF Induction Heater Facilities</td>
<td>5</td>
</tr>
<tr>
<td>Test Chamber Flow Configurations</td>
<td>5</td>
</tr>
<tr>
<td>UF&lt;sub&gt;6&lt;/sub&gt; Handling System</td>
<td>7</td>
</tr>
<tr>
<td>Diagnostics</td>
<td>8</td>
</tr>
<tr>
<td>Operating Procedures</td>
<td>10</td>
</tr>
<tr>
<td>DISCUSSION OF RESULTS</td>
<td>10</td>
</tr>
<tr>
<td>Exploratory Tests</td>
<td>10</td>
</tr>
<tr>
<td>Follow-on Tests</td>
<td>13</td>
</tr>
<tr>
<td>REFERENCES</td>
<td>15</td>
</tr>
<tr>
<td>TABLES I Through IV</td>
<td>16</td>
</tr>
<tr>
<td>FIGURES 1 Through 23</td>
<td>20</td>
</tr>
</tbody>
</table>
PLASMA CORE REACTOR SIMULATIONS USING
RF URANIUM SEEDED ARGON DISCHARGES

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United Technologies Research Center

SUMMARY

An experimental investigation was conducted using the United Technologies Research Center (UTRC) 80 kW and 1.2 MW rf induction heater facilities to aid in developing the technology necessary for designing a self-critical fissioning uranium plasma core reactor (PCR). Pure uranium hexafluoride (UF₆) was injected into argon-confined, steady-state, rf-heated plasmas in uranium plasma confinement tests. The objective was to achieve maximum confinement of uranium vapor within the plasma while simultaneously minimizing the uranium compound wall deposition. In all tests, the plasma was a fluid-mechanically confined vortex-type contained within a fused-silica cylindrical test chamber. Exploratory tests were conducted using the 80 kW rf induction heater (f = 13.56 MHz) with the test chamber at approximately atmospheric pressure and discharge power levels on the order of 10 kW. Four different test chamber flow configurations were tested to permit selection of the configuration offering the best confinement characteristics for subsequent tests at higher pressure and power in the 1.2 MW rf induction heater facility.

The exploratory test configuration selected for use in the more extensive rf plasma tests using the 1.2 MW rf induction heater employed a radial-inflow vortex, driven by injectors located on only one of the water-cooled copper endwalls. In addition to thru-flow ducts located at the center of each endwall, an axial bypass annulus was located near the periphery of the endwall opposite the vortex injectors. A concentric set of water-cooled, fused-silica tubes formed the peripheral wall. The cylindrical test chamber was 5.7-cm-ID by 10-cm-long. This test chamber flow configuration was designed to operate at pressures up to approximately 20 atm and rf discharge power levels up to about 100 kW. In the majority of tests, a single UF₆ injector protruded 2.0 cm into the test chamber; the injector was on the centerline axis located concentrically within the thru-flow duct of one endwall. UF₆ was supplied to the injector from a heated cylinder capable of supplying the gaseous UF₆ at temperatures up to 450 K and pressures up to 20 atm. The rf plasma tests in the 1.2 MW rf induction heater were conducted over a range of test chamber pressures from 1 to 12 atm and rf discharge power levels from 10 to 85 kW. The UF₆ mass flow rate ranged from 0.01 to 0.13 g/s.
Diagnostic measurements included: plasma physical and electrical characteristics; calorimetric power losses; radiation intensity in different wavelength bands with and without injection of UF₆; on-axis spectral emission scans between 300-700 nm; side-on absorption measurements using both an argon-ion laser system (514.5 nm) and a cw single-frequency tunable dye laser system (591.5 nm); and, analyses and identification of samples of wall deposits from selected tests using electron diffraction, x-ray diffraction, electron microprobe, and IR spectrophotometer techniques.

The overall test results indicate applicable flow schemes have been developed for fluid mechanical confinement of uranium when pure UF₆ is injected into argon confined, high-temperature, rf-heated plasmas. A typical successful test run had the following operating characteristics: UF₆ flow rate = 0.1 g/s, argon flow rate = 3 g/s, operating pressure = 2 atm, operating discharge power level = 70 kW, total operating time = 10 min, and a total deposition of uranium or uranium compounds on the peripheral wall of 25 mg.

Tests to increase the quantity of uranium confined within the rf-heated plasma, while simultaneously minimizing deposition of the uranium compounds on the peripheral wall of the plasma test chamber combined with additional diagnostic analyses, are in progress.

LIST OF SYMBOLS

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>d</td>
<td>discharge diameter at axial midplane, cm</td>
</tr>
<tr>
<td>f</td>
<td>rf operating frequency, MHz</td>
</tr>
<tr>
<td>I/I₀</td>
<td>transmission, dimensionless</td>
</tr>
<tr>
<td>ℓ</td>
<td>optical path, cm</td>
</tr>
<tr>
<td>Mᵢ</td>
<td>mole fraction, dimensionless</td>
</tr>
<tr>
<td>mᵢAr</td>
<td>argon mass flow rate, g/s</td>
</tr>
<tr>
<td>mᵢUF₆</td>
<td>UF₆ mass flow rate, g/s</td>
</tr>
<tr>
<td>P</td>
<td>chamber pressure, atm</td>
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</tbody>
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Fissioning uranium plasma core reactors (FPCR) could be used as a prime energy source for many space and terrestrial applications. In addition to aerospace propulsion applications, several space power and/or terrestrial options are being considered; these include, direct pumping of lasers, photochemical and thermochemical hydrogen production processes, MHD power conversion, and advanced closed-cycle gas turbine driven electrical generators. Principal features and advantages of these systems include high thermodynamic cycle efficiency, continuous fuel reprocessing, and direct coupling of the radiant energy. Reference 1 discusses the overall status of plasma core reactor technology, the various energy conversion concepts, conceptual designs of various configurations, and a summary of all current research directed toward demonstrating the feasibility of fissioning uranium PCR's.

A principal technology required to establish the feasibility of fissioning uranium plasma core reactors is the fluid mechanical confinement of the hot fissioning uranium plasma with sufficient containment to both sustain nuclear criticality and minimize deposition of uranium or uranium compounds on the confinement chamber peripheral walls. Figure 1 is a sketch of one unit cell configuration of a plasma core reactor. The reactor would consist of one or more such cells imbedded in beryllium oxide and/or heavy-water moderator and surrounded by a pressure vessel. In the central plasma fuel zone, gaseous uranium (injected in the form of UF₆ or other uranium compound) is confined by argon buffer gas injected tangentially at the periphery of the cell. In applications in which it is desired to couple thermal radiation from the fissioning uranium plasma to a separate working fluid, the thermal radiation is transmitted through the argon buffer gas layer and subsequently through internally-cooled transparent walls to a working fluid channel such as shown in figure 1. The mixture of nuclear fuel and argon buffer gas is withdrawn

\[
\begin{align*}
Q_D & \quad \text{total discharge power, kW} \\
Q_R & \quad \text{power radiated, kW} \\
T & \quad \text{temperature, deg K} \\
t & \quad \text{time, min} \\
\Delta \lambda & \quad \text{wavelength band, nm}
\end{align*}
\]
from one or both endwalls at the axial enterline. For other applications in which it is desired to extract power in the form of nonequilibrium, fission-fragment-induced short wavelength radiation emissions, the transparent wall would be removed and a medium such as lasing gas mixtures would be mixed with either the fissioning uranium fuel or the buffer gas. The reason for this distinction is that most transparent wall materials have intrinsic radiation cutoffs at wavelengths longer than those expected to be emitted in the form of fission-fragment-induced nonequilibrium electromagnetic radiation. Typically, for plasma conditions with an edge-of-fuel-region temperature of approximately 5000 K, operating pressures in the fissioning uranium plasma are on the order of 500 atm. This is dependent upon the combined partial pressures of nuclear fuel required for criticality, dissociation products, electrons from ionized species, and some argon buffer gas present in the fuel region. As part of the planned NASA program to determine the feasibility of plasma core reactors, Los Alamos Scientific Laboratory (LASL) is currently performing cavity reactor experiments which employ gaseous UF$_6$.

Plasma core reactor technology studies at UTRC currently consist of several experiments and theoretical investigations directed toward evaluating the feasibility of the PCR concept. Extensive non-nuclear vortex flow and plasma fluid mechanical research has been conducted over the past fifteen years at UTRC.

Previously reported experiments (ref. 2) have been conducted on the confinement of rf plasmas. These tests were directed primarily toward development of a high-intensity, high-power-density plasma energy source (equivalent black-body radiating temperatures $>$ 6000 K). Some of these initial exploratory tests included direct injection of very dilute mixtures of UF$_6$ (typically, 1% UF$_6$ in an argon carrier-gas) into the rf argon plasma. Coating of the fused-silica peripheral wall occurred but sustained plasma operation for several minutes was demonstrated. Particle feeder systems were also developed which permitted steady-state injection of C, W, UO$_2$, and U$_3$O$_8$ into test chambers operating at pressures up to 40 atm. In general, these test results confirmed that high simulated fuel concentrations could be confined fluid-mechanically with steep concentration gradients at the edge-of-fuel location.

The objective of this paper is to present some recent results of the Plasma Core Reactor (PCR) simulation tests conducted at UTRC using pure UF$_6$ injected into steady-state, argon-confined, rf-heated plasmas.
DESCRIPTION OF EQUIPMENT

RF Induction Heater Facilities

The experiments were conducted using both an 80 kW and a 1.2 MW rf induction heater systems. The 80 kW facility was used in the initial set of exploratory tests. Figure 2 is a schematic diagram of the 80 kW rf induction heater electrical system. A photograph of an assembled exploratory test configuration installed under the 2½-turn, 7.5-cm-dia water-cooled rf work coil (0.7 μH) of the 80 kW facility is shown in figure 3. The easily modified work coil is connected to the output of the power amplifier by means of a tunable π-coupling network (see fig. 2). The initial system was modified to operate at 13.56 MHz and low-speed motor drives were installed on the plate and load tuning capacitors to aid in efficiently coupling rf power into plasmas having a relatively wide range of sizes and impedances.

A photograph of the assembled follow-on test configuration installed under the set of 9-cm-dia water-cooled rf work coils within the resonator section of the 1.2 MW rf induction heater is shown in figure 4. Part of the 1.2 MW rf induction heater assembly is shown in figure 4. Figure 5 is a block diagram of the 1.2 MW rf induction heater electrical system. The 1.2 MW rf induction heater was operated at approximately 5.5 MHz. All stages of the 1.2 MW rf system contained controls for tuning the matching circuit at the final power amplifier input, thus aiding in increasing the overall system efficiency. The rf output is supplied by two power amplifier tubes (440 kW output each) which drive a resonant tank circuit of unique design. The output of the two amplifiers is coupled by a push-pull resonator (all stages operated in class C). The entire resonator section consists of two arrays of ten vacuum capacitors, located (as shown in figs. 4 and 5) within a 1.7-m-dia cylindrical aluminum test tank. The front of the test tank is a removable dome (shown removed in fig. 4) containing five windows for observation and/or diagnostic equipment access. A complete description of the rf heater facility is presented in reference 2.

Test Chamber Flow Configurations

Figure 6 contains schematic diagrams of the various test chamber flow configurations employed in the exploratory tests conducted in the 80 kW rf facility. Different configurations were tested to permit selection of the flow geometry with the best confinement characteristics. A gas-cooled 5.7-cm-ID x 6.1-cm-OD fused-silica tube formed the peripheral boundary of the test
chamber. A symmetrically-arranged set of water-cooled endwalls spaced 10 cm apart formed the axial boundary of the test chamber. Argon was injected through a set of 1.7-mm-ID vortex injectors equally-spaced around the periphery of one or both endwalls to provide the confining flow. As shown in figure 6(d), some tests were conducted with the argon gas injected tangentially through hypo-sized injectors located within the fused-silica peripheral wall. The exhaust gases were removed through one or both endwalls with thru-flow ducts on the centerline and/or off-axis annular exhaust ducts. To permit steady-state injection of pure UF₆ into the plasma, several types of concentric-tube, water-cooled copper injectors were fabricated and located concentrically within the on-axis thru-flow duct. UF₆ was selected as the form of uranium bearing compound for injection into the plasma because it could be supplied in a gaseous form. Earlier tests in previous programs had indicated that injection of uranium in the form of small particulates was a more difficult technology. However, UF₆ is very reactive chemically and must be heated to be sure that it remains in the gaseous state and does not condense on the injector walls prior to entering the plasma test chamber. Therefore special cleaning procedures, operating procedures, and heating and feeding techniques had to be employed. These included the use of steam augmentation and electrical heater assemblies throughout the UF₆ injector and feed systems to eliminate the possible condensation and subsequent plugging of the UF₆ feeder lines. As shown in figures 6(a) and 6(d), the UF₆ injector could be extended into the test chamber/plasma region to eliminate some of the end effects. The various test chamber flow geometries and combinations thereof, permitted a wide variation in the types of flow conditions obtainable with UF₆ injection. Based on the exploratory test results, the test chamber flow configuration shown in figure 6(a) was selected for the continued tests employing the 1.2 MW rf induction heater system. This geometry has several attractive features: ability to vary the distribution of exhaust gas flow (axial bypass); ease of change in the injection area of the argon vortex injectors; and, ease of change in the location of the on-axis UF₆ injector.

Figure 7 is a sketch of the test chamber configuration employed in the 1.2 MW rf induction heater using pure UF₆ injection. For simplicity, only half the chamber is shown. As in the exploratory tests, the axial length between endwalls was 10 cm. Because of the higher power, higher pressure, and associated radiation levels involved, a concentric set of water-cooled fused-silica tubes were used as the peripheral wall. The inner tube was 5.7-cm-ID x 6.1-cm-OD; the outer tube was 6.5-cm-ID x 7.3-cm-OD. An alternate outer fused-silica tube was also prepared, having a 9-mm wall thickness (see fig. 7) to permit safe operation, if required, at relatively high chamber pressures (≈ 40 atm). The water-cooled copper endwalls incorporate provisions for driving the vortex from one (or symmetrically from both) endwalls. The other endwall (not shown in fig. 7) has provision for removing the exhaust gas.
through an axial bypass on the periphery of the endwall. Both endwalls have the option for removing varying amounts of the exhaust gas through the on-axis thru-flow ducts. As shown in figure 7, the UF₆ injector, located on-axis and concentrically within the right endwall, was fabricated from a 50-cm-long three concentric copper tube assembly. In the majority of tests, the injector tip extended 2 cm into the test chamber. High pressure water (20 atm) heated to approximately 350 K via a steam heat exchanger flowed at 0.14 l/s between the concentric tubes of the UF₆ injector. This provided cooling relative to the hot plasma environment while still maintaining a high enough temperature in the injector to permit flow of the pressurized gaseous UF₆ without solidification and subsequent plugging in the UF₆ transfer line.

UF₆ Handling System

In support of the rf plasma experiments, a UF₆ handling and feeder system to provide a controlled and steady flow of heated UF₆ at temperatures up to 500 K was developed. Figure 8 is a schematic diagram of the UF₆ system. The system was designed to provide UF₆ mass flow rates up to about 5 g/s and subsequent possible injection of UF₆ into test chambers operating at pressures up to 20 atm. Figure 9 shows the vapor pressure curve for UF₆ for the operating ranges of interest. The principal components of the system are the UF₆ boiler, the boiler heat supply system, and the UF₆ condenser (exhaust) system. The boiler is a 2 l monel cylinder rated at 200 atm working pressure. Monel was selected because of its resistance to chemical attack by hot, pressurized UF₆. A heat exchanger to provide internal heating is located in the bottom of the boiler and thermocouples are located at both the top and bottom of the boiler. The thermocouple wells, heat exchangers, and UF₆ flow lines were all fabricated from 6.4-mm-OD monel tubing. A 3.5 kW electrical heater surrounds the boiler and is used to reach the desired equilibrium temperature and pressure prior to flowing the UF₆. In the tests reported herein, use of the electrical heater assembly alone was sufficient to provide the required flow rates; in future tests employing higher UF₆ flow rates for longer time periods, electrically-heated gaseous N₂ can be supplied to the UF₆ boiler heat exchanger. Control on the rate of UF₆ evaporation is accomplished by using a bypass loop, as shown in figure 8. During operation of the system, the gaseous UF₆ flows from the boiler through a metering valve and a linear mass flow meter (calibrated for UF₆ operation) prior to entering the UF₆ injector located within the rf plasma test chamber. The exhaust from the test chamber, comprised of argon, UF₆ and other volatile uranium compounds is collected in the UF₆ condenser system located downstream of the test chamber. The condenser system consists of two 0.5 l stainless-steel tanks (connected in parallel) immersed in liquid N₂. All valves throughout the system are welded-bellows type. A neutralizing trap (NaOH + H₂O) is located downstream.
of the condenser system to remove any residual uranium or uranium compounds which pass through the flow trap, shown in figure 8. To provide additional safety, a high flow capacity exhaust vent and gas scrubber system is installed on the Laboratory roof above the test apparatus.

Diagnostics

The total power deposited into the plasma was obtained from an overall test chamber heat balance by summing the power lost by radiation, power deposited into the annular coolant of the peripheral wall, power deposited into the endwall assemblies, power convected out the exhaust ducts, as well as, power deposited into the effluent gas heat exchanger and UF₆ injector assemblies.

The power radiated from the plasma was measured using a radiometer and chopper wheel assembly. A thermopile detector with a quartz window was used as the radiometer sensing element. Its output was connected to an operational amplifier and displayed on a strip chart recorder. Radiation within different wavelength bands was measured using various filters. The response of the thermopile with filters was calibrated using a standard source of spectral irradiance. The total power radiated from the plasma and in each wavelength band was calculated assuming isotropic radiation including allowance for blockage due to the rf work coils.

The physical size and shape of the plasma was determined from photographs taken using various neutral density filters. Continuous observation of the plasma was accomplished using a lens-projection-screen system. During all tests, the voltage, current and power of various stages of the rf systems, were monitored by meters. In addition, strip chart recorders were also used to continuously monitor the rf plate voltage, plate current, and resonator voltage.

Figure 10 is a schematic of the diagnostic systems used in the exploratory rf plasma tests. A 0.25-m monochromator and a S-20 response photomultiplier detector were used to obtain spectral emission data between 300-700 nm. Twenty-five μm-wide entrance and exit slits were employed. These measurements were taken on-axis at the midplane of the test chamber. The scanning rate was 100 nm/min and the data were recorded on a strip chart recorder; measurements were obtained for both argon only and argon plus UF₆ plasmas.
Measurements also included side-on absorption measurements using a cw, single-frequency, tunable dye laser system. The feasibility of this technique was investigated as a possible means for determining the number density and spatial distribution of uranium vapor contained within the discharge boundary in future UF\textsubscript{6}/rf plasma tests containing uranium vapor of heavy concentrations. A argon-ion laser (10 W) was used for the pump power and was operated at 514.5 nm. The unit was used with a methanol and water solution containing rhodamine 6G dye. Rhodamine 6G absorbs in the band 480-530 nm and provides laser gain from 540 to 630 nm. This particular Model dye laser system permits synchronizing the three possible tuning mechanisms: cavity length, etalon length, and cavity prism. The unit employed a single high-finesse, low-loss piezo-scanned tunable etalon, automatic scanning electronics, a low f-m jitter dye circulation system, and a temperature-controlled oven assembly to aid in stability. For high resolution scans, the cavity length is tuned while the etalon is tracked in synchronism with the cavity scan. For large bandwidth scans, the etalon is scanned while the cavity length tracks. The cavity prism is tracked in synchronism with the etalon to keep the laser power constant. For the majority of the exploratory tests reported herein, 1 W of pump power was used. Typical dye laser output powers (narrow line operation at 591.5 nm) were 100 mW. As shown in figure 10, a hollow-cathode uranium lamp was used to select the reference uranium line (591.5 nm) used in these tests. A Fabry-Perot spectrum analyzer was used to define and calibrate the tuning frequency spectrum. A 0.5-m spectrometer with a photomultiplier was used in conjunction with a set of beam splitters and two front surface mirrors, as shown in figure 10. The laser beam (≈ 1.5-mm-dia) traversed the test chamber on the major axis at a distance 1 cm away from the tip of the UF\textsubscript{6} injector. In these tests the UF\textsubscript{6} injector extended 1 cm into the test chamber. This position was selected since prior rf plasma tests (argon only) included chordal scans at this location from which temperature profiles were determined.

UF\textsubscript{6}/rf plasma tests conducted in the 1.2 MW induction heater facility did not include the dye laser system, but the argon-ion laser system operating at 514.5 nm was used for additional side-on absorption measurements taken on-axis at the axial midplane of the test chamber. The test setup was similar to that shown in figure 10.

To permit a detailed analysis of the quantity and composition of the wall deposition incurred after several selected UF\textsubscript{6}/rf plasma tests, samples of the wall residue were collected and analyzed by means of electron diffraction, x-ray diffraction, electron microprobe, and IR spectrophotometric techniques.
Operating Procedures

In general, the tests (80 kW and 1.2 MW) were first conducted with only argon injected into the test chamber. After sufficient time to establish equilibrium, pure UF₆ was injected for various time periods. Normally, a series of UF₆ tests were conducted with the same fused-silica tube prior to shutdown for post-test examination. In all tests the discharge was ignited using a vacuum start technique at a chamber pressure of approximately 10 mm Hg. This technique had the advantage of eliminating the introduction of foreign materials into the test chamber which would be present with dc arc rod starting techniques and also, in conjunction with the argon feed and the exhaust trap system, permitted a partial purge between tests.

DISCUSSION OF RESULTS

Exploratory Tests

TABLE I is a summary of the exploratory tests conducted, including a brief description of the test chamber configuration and flow control scheme, range of test conditions, number of tests conducted, and pertinent comments applicable to each. A direct one-to-one comparison between each of the various configurations was difficult because of the different operating characteristics associated with each test. Also, due to time and cost constraints, each configuration by no means represents the optimum in design and sizing of the various components.

Based on the overall test results, the test chamber flow configuration shown in figure 6(a) was selected as the one best-suited for use in the follow-on rf plasma tests employing the 1.2 MW rf induction heater system. With this configuration, a relative maximum mass flow rate of pure UF₆ (0.04 g/s) injected directly into the argon plasma was achieved with corresponding minimum wall coating, thus offering potentially the best confinement characteristics. In addition, this test chamber flow configuration possesses significant flexibility in the control of the flow field and exhaust gas distribution.

To illustrate the effect of the pure UF₆ injection on the plasma discharge, figure 11 shows the operating conditions and results of corresponding radiation measurements for a typical exploratory test. In the majority of tests, attempts were made to maintain constant as many of the independent variables as possible during the injection of UF₆. However, changes in the
rf power and/or tuning and associated flow rates were sometimes required to prevent discharge extinguishment or plasma oscillations. In general, the introduction of pure UF₆ into the discharge significantly altered the impedance of the plasma which, in turn, determined the plasma size and electrical conductivity. This was manifested principally as a significant increase in the radiation emitted from the plasma; correspondingly, a moderate increase in the total power deposited into the plasma was also observed. The table and bar graph of figure 11 illustrates both these effects. Note that a significant amount of the increase in radiation occurred in the visible and near-UV wavelength bands. At the relatively low discharge power and pressure levels of these exploratory tests, the discharge was quite sensitive to changes in both the argon mass flow rate and the UF₆ mass flow rate. Occasionally, when the UF₆ injection mass flow rate exceeded a certain level, corresponding to a given set of test conditions, distortion occurred (plasma unsteadiness) in the central region of the plasma; this was sometimes followed by extinguishment of the discharge.

Periodically throughout the exploratory rf plasma tests, spectral emission measurements throughout the wavelength band from 300-700 nm were taken on-axis at the axial midplane using the 0.25-m monochromator system shown in figure 10. Figure 12 illustrates some results obtained for the wavelength band between 400 to 1,600 nm. Many of the strong argon, uranium, and fluorine lines present in the wavelength range from 300-700 nm have been identified, cataloged, and compared with those documented in the literature. Also to aid in the analyses of the present and future tests, UF₆ equilibrium composition data were calculated for total pressures from 10⁻⁴ to 1 atm and over a range of temperatures from 300 to 10,000 K. Figure 13 is an example of this UF₆ equilibrium composition data. For all practical purposes, at a pressure of approximately 1 atm complete thermal decomposition of UF₆ has occurred at a temperature of about 4700 K.

To demonstrate the feasibility and practicality of using a cw single-frequency tunable dye laser system for making uranium plasma absorption measurements, several tests were conducted using the dye laser system illustrated in figure 10. Significant effort had to be devoted to properly shielding the entire dye laser and associated diagnostic equipment from the rf fields. As shown in figure 10, the dye laser beam traversed the test chamber on the major axis at a distance of 1 cm away from the tip of the UF₆ injector. Based on prior spectral emission chordal scans taken under similar test conditions (argon only), the temperature profiles determined (based on both absolute line and continuum radiation) indicated centerline temperatures of approximately 8000 K exist with a slight off-axis peak at a radius ratio of about 0.5.
Figure 14 shows an example of the absorption measurements obtained from the actual strip chart recorder output in the exploratory rf plasma experiments with pure UF₆ injection. The 591.54 nm uranium line was selected as it is a relatively strong uranium I line and appeared well-defined in the earlier spectral emission scans. The lower state for the 591.54 nm line is the uranium I ground state. The half-width of the laser line at the 591.54 nm wavelength was approximately 10⁻⁴ nm. To obtain the measurements shown in figure 14, the scanning generator of the dye laser system was activated to an automatic continuous scan mode as shown by the output data in the left portion of figure 14. Only argon was present in the rf plasma discharge during these initial scans. The 8 GHz range (free spectral range of the confocal Fabry-Perot spectrum analyzer) translates to approximately 10⁻² nm on the wavelength scale. Many such scans at different operating test conditions were completed with only several (at fixed test conditions) shown in figure 14 for simplicity. The test conditions for the argon-only case were similar to those shown in the table in figure 11. The zero reference line (zero transmission) is shown at the top of figure 14. As noted, no absorption was detected for any of the argon-only test conditions. When pure UF₆ was injected into the discharge, sufficient time was allowed for all conditions to come to equilibrium (~10 seconds); additional scans were then completed. Results from tests at two different UF₆ mass flow rates are shown at the right of figure 14. The first case corresponds to a UF₆ mass flow rate of approximately 0.02 g/s. The measurements indicate an absorption of approximately 25% (corresponding to an \( I/I_0 = 0.75 \)). Doubling the mass flow rate of UF₆ to approximately 0.04 g/s increased the relative absorption to about 55% (\( I/I_0 = 0.45 \)) for the second case. Based on an assumed 50-50 occupancy (ground state/excited state), a temperature of ~8000 K, an optical path length of 2 cm (relatively small core due to close proximity of the UF₆ injector), and including a factor for ionization reduction, the ground state uranium I atom number density based on the absorption measurements were estimated to be approximately \( 8 \times 10^{12} \) atoms/cm³ and \( 2 \times 10^{13} \) atoms/cm³, respectively, for the two cases. This compares with approximately \( 10^{14} \) atoms/cm³ based on temperature and pressure calculations. These results are encouraging and demonstrated that a dye laser system combined with optical scanning and tracking may be employed in future rf plasma UF₆ confinement tests to permit mapping of the spatial absorption distribution; from this and other measurements the total number density and spatial distribution of uranium vapor contained both within the discharge boundary and in trace quantities in the buffer layer may be determined.

Periodically throughout the exploratory test series, portions of the fused-silica peripheral tubes were examined for thermal stresses and wall deposition. Figure 15 is a photograph of two of the tubes used in the exploratory tests with pure UF₆ injection. The analysis indicated some degree of thermal stress was present in the central region of the fused-silica
tube, generally following the outline of the rf work coil. This was as expected due to the limited air jet cooling supplied to the fused-silica tube and the close proximity of the rf plasma to the wall during the majority of tests. The fused-silica tube numbered 8 in figure 15 is representative of the type of wall coating obtained after about two minutes of operation in the relatively high UF₆ mass flow rate range.

Follow-on Tests

TABLE II is a summary of the tests conducted in the 1.2 MW rf induction heater using the test chamber flow configuration shown in figure 7. Over 140 tests were conducted over the range of test conditions shown in TABLE II. The pure UF₆ was injected on-axis from one endwall. Results similar to those shown in figure 11 were obtained and additional spectral measurements in the 300-700 nm range were taken. The effect of the 2-mm-thick passage of annular water coolant was noted in the upper wavelength cutoff of about 1300 nm as compared to the exploratory tests which employed only gas cooling. In general, the higher power, higher pressure argon rf plasma discharge employed in the 1.2 MW rf induction heater tests was less susceptible to perturbations due to the injection of pure UF₆. Thus, a greater mass flow rate of UF₆ could be injected while still maintaining a well-confined, stable discharge. Occasionally, under certain extreme combinations of test conditions, indications of plasma unsteadiness were also observed to occur.

The maximum mass flow rate of pure UF₆ employed was 0.13 g/s. This corresponded to a chamber pressure of 1.7 atm, argon plasma power level of 71 kW, argon buffer gas mass flow rate of 3.2 g/s. The test at maximum UF₆ flow rate extended over a time interval of ten minutes.

During the latter part of the tests using the 1.2 MW rf induction heater, ten tubes were selected for analysis of wall deposits by several techniques, including electron diffraction, x-ray diffraction, electron microprobe, and IR spectrophotometry. TABLE III is a summary of the results and shows the types of compounds deposited on the peripheral wall. To assist in analyzing the wall deposition samples, a detailed cataloging of the possible uranium compounds that may form with the associated diffraction pattern lines and physical characteristics was also completed and is shown in TABLE IV. Figure 16 is a photograph showing four of the ten tubes which were analyzed. Only one complete test was conducted prior to the removal of these tubes from the test section. Note that greater than an order of magnitude reduction in the deposition of uranium compounds was achieved in these tests. It should be pointed out that a relatively uniform deposition of approximately 10 mg is difficult to detect visually. The SiO₂ detected using the IR
spectrophotometer, was believed to be from the fused-silica tube itself and partly due to the silicone grease used in the O-rings for sealing the fused-silica tube to the endwall assembly. The agreement between the different analysis techniques is reasonable considering the statistical nature of sampling the residue and partial exposure to the atmosphere in the preparation of the small samples. In addition to the results shown in TABLE III for the fused-silica peripheral tube, some UF$_4$ was found to be present on the surface of the endwalls, UF$_6$ injector, and within the exhaust thru-flow duct. Figures 17 through 21 show examples of the results obtained from the various analysis techniques. Figure 17 illustrates the type of electron diffraction patterns obtained. For the particular sample shown, the primary compound was UO$_2$ with a trace amount of UF$_4$. The tabular data to the right of the actual diffraction pattern photograph gives additional details on the compounds characteristics. Photomicrographs of the residue wall coating (800X magnification) and corresponding to the three principal color samples analyzed are shown in figure 18. The distinctly different crystalline structure of each is clearly evident in the photographs. Figure 19 contains four photographs showing the different x-ray diffraction patterns obtained from post-test analysis of the fused-silica tube residue. In all cases, the samples were subjected to copper K$_\alpha$ radiation in a Debye camera. In addition to the three color powders obtained (black, rust, green), a black chip sample was also included for comparison. The distinctly different x-ray diffraction patterns from each sample is evident from the photographs. Figure 20 contains three photographs of the distribution of U, F, and O from samples of the black powder residue wall coating from a post-test x-ray analysis. The magnification was approximately 350X. Figure 21 is an example of the recorder output trace obtained from the IR spectrophotometry absorption measurements of a post-test analysis of the residue wall coating. At the bottom of the trace is noted the particular compounds associated with the peaks.

Figure 22 shows an example of some of the absorption measurements obtained in the 1.2 MW rf plasma experiments with pure UF$_6$ injection. Refer to figure 10 for the basic diagnostic setup. In these tests, an argon-ion laser beam of approximately 300 mW power and operating at 514.5 nm was used. Figure 22 shows the change in transmission ($I/I_0$) which occurred for various changes in the UF$_6$ mass flow rate. A semi-log plot was used to give an indication of the possible exponential dependence of the transmission on the UF$_6$ mass flow rate. In this case the UF$_6$ mass flow rate would be related to the concentration. The product of absorption coefficient, concentration, and optical path length forms the exponent in the relationship with transmission. Post-test calibration indicated the transmission returned to approximately the initial value, thus confirming the observation of minimum wall coating. Figure 23 is a photograph showing the rf plasma with pure UF$_6$ injection within the 1.2 MW rf induction heater.
The test results indicate successful techniques have been developed for fluid mechanical confinement of uranium in argon-confined high-temperature, high-pressure, rf-heated plasmas with pure UF₆ injection. Included, has been the development of the associated handling and feeder techniques for steady-state injection of pure UF₆ into the rf plasma discharge. Various diagnostic techniques have also been developed and applied to determine some of the uranium plasma characteristics and composition of the uranium compound wall deposition.

Continuing tests to further increase the quantity of uranium confined within the rf-heated argon plasma, while simultaneously minimizing deposition of the uranium compounds on the peripheral walls of the plasma test chamber, are in progress. Included is the development and application of x-ray absorption methods for determining contained uranium mass.

REFERENCES


### TABLE I

**SUMMARY OF EXPLORATORY TESTS CONDUCTED IN 80-kW RF INDUCTION HEATER USING ARGON BUFFER GAS AND PURE UF₆ INJECTION**

Test Chamber 5.7-cm-ID x 10-cm-long
On-axis UF₆ injection (flush to 3 cm into chamber)

<table>
<thead>
<tr>
<th>Test Chamber Configuration and Flow Control Scheme</th>
<th>Range of Test Conditions (all tests conducted at operating frequency of 13.56 MHz)</th>
<th>Tests</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single endwall driven vortex injection. Combination of on-axis thru-flow (both ends) and single axial bypass exhaust.*</td>
<td>Argon mass flow rate 0.15-1.5 g/s UF₆ mass flow rate 0.005-0.040 g/s Chamber pressure 1-1.2 atm Axial bypass flow 0-100% On-axis thru-flow 0-100% RF discharge power 2-15 kW Discharge diameter 3.8-5.5 cm</td>
<td>16</td>
<td>Relatively high UF₆ flow rates obtained with light coating on central region of peripheral wall. Well confined, stable discharge over wide range of test conditions.</td>
</tr>
<tr>
<td>Coaxial flow endwall argon injection, bluff body stabilization. Combination of on-axis thru-flow (both ends) and single axial bypass exhaust. See Fig. 4a.</td>
<td>Argon mass flow rate 0.010-0.2 g/s UF₆ mass flow rate 0.005-0.03 g/s Chamber pressure 1 atm Axial bypass flow 0-100% On-axis thru-flow 0-100% RF discharge power 2-11 kW Discharge diameter 4.5-5.5 cm</td>
<td>8</td>
<td>Central region and extremities of peripheral wall became heavily coated in all tests. Ellipsoidally-shaped discharge extending close to peripheral wall. Discharge sensitive to changes in argon/UF₆ mass flow rate. Difficult to tune rf load during UF₆ injection.</td>
</tr>
<tr>
<td>Symmetrical endwall driven vortex injection. No on-axis thru-flow. Symmetrical large radius exhaust annuli. See Fig. 4c.</td>
<td>Argon mass flow rate 0.10-1.5 g/s UF₆ mass flow rate 0.005-0.035 g/s Chamber pressure 1 atm RF discharge power 2-15 kW Discharge diameter 4.5-5.5 cm</td>
<td>10</td>
<td>Central region became moderately coated in all tests. Discharge sensitive to changes in argon/UF₆ mass flow rate. Retuning load required during UF₆ injection to eliminate extinguishment. Occasional discharge oscillation noted.</td>
</tr>
<tr>
<td>Peripheral wall driven vortex injection** (endwall augmentation used in some tests). See Fig. 4d.</td>
<td>Argon mass flow rate 0.08-0.2 g/s UF₆ mass flow rate 0.005-0.03 g/s Chamber pressure 1 atm Axial bypass flow 0-100% On-axis thru-flow 0-100% RF discharge power 2-8 kW Discharge diameter 4.5-5.5 cm</td>
<td>5</td>
<td>Entire peripheral wall became heavily coated. Apparent turbulence noted along discharge boundary. Flow control limited due to fixed vortex injector area. Excessive heating of peripheral wall occurred.</td>
</tr>
</tbody>
</table>

*Test configuration and flow control scheme selected for follow-on tests in 1.2 MW rf induction heater system.

**The peripheral wall injection flow control scheme was used with both the first and third test chamber configurations.
TABLE II

SUMMARY OF RF PLASMA TESTS CONDUCTED IN 1.2 MW RF INDUCTION HEATER USING ARGON BUFFER GAS AND PURE UF₆ INJECTION

See Fig. 7 for Sketch of Test Configuration
On-Axis UF₆ Injection from One Endwall Only

<table>
<thead>
<tr>
<th>Test Chamber Configuration and Flow Control Scheme</th>
<th>Range of Test Conditions</th>
<th>No. of Tests</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Dual Endwall Driven Vortex Injection</strong>&lt;br&gt;On-Axis Thru-Flow (Both Endwalls)&lt;br&gt;No Axial Bypass</td>
<td>Argon Mass Flow Rate 1.8 - 3.4 g/s&lt;br&gt;On-Axis Thru-Flow Through One Endwall&lt;br&gt;RF Discharge Power 20 - 60 kW&lt;br&gt;Range of RF Operating Frequency 5.4700 - 5.5000 MHz&lt;br&gt;Discharge Diameter 2.5 - 3.1 cm&lt;br&gt;Chamber Pressure 2 - 12 atm&lt;br&gt;UF₆ Mass Flow Rate 0.008 - 0.13 g/s&lt;br&gt;Test Time 0.17 - 10 min</td>
<td>86</td>
</tr>
<tr>
<td><strong>Single Endwall Driven Vortex Injection</strong>&lt;br&gt;On-Axis Thru-Flow (One Endwall Only&lt;br&gt;Opposite Vortex Drive)&lt;br&gt;Single Axial Bypass (Endwall Opposite Vortex Drive)</td>
<td>Argon Mass Flow Rate 2.2 - 3.85 g/s&lt;br&gt;Axial Bypass Flow 0 - 52 %&lt;br&gt;RF Discharge Power 30 - 85 kW&lt;br&gt;Range of RF Operating Frequency 5.4776 - 5.4878 MHz&lt;br&gt;Discharge Diameter 2.3 - 3.3 cm&lt;br&gt;Chamber Pressure 1.7 - 5 atm&lt;br&gt;UF₆ Mass Flow Rate 0.013 - 0.131 g/s&lt;br&gt;Test Time 0.25 - 10 min</td>
<td>97</td>
</tr>
<tr>
<td>Analysis Technique</td>
<td>Primary Compound or Element Present in Residue Sample</td>
<td></td>
</tr>
<tr>
<td>------------------------</td>
<td>-------------------------------------------------------</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Green Color Sample</td>
<td>Rust Color Sample</td>
</tr>
<tr>
<td>Electron Diffraction</td>
<td>UF₄</td>
<td>UF₄</td>
</tr>
<tr>
<td>X-Ray Diffraction</td>
<td>UF₄</td>
<td>UO₂, U₄O₉</td>
</tr>
<tr>
<td>Electron Microprobe</td>
<td>U, F, Trace amount of O</td>
<td>U, O, F</td>
</tr>
<tr>
<td>IR Spectrophotometry</td>
<td>UF₄, UO₂F₂, SiO₂</td>
<td>UO₂F₂, SiO₂, UO₂</td>
</tr>
</tbody>
</table>

Summary of Analysis of Residue Samples Taken from Inside of Fused-Silica Tubes After RF Plasma Tests with Pure UF₆ Injection

Total of 10 Tubes Analyzed
See Fig. 16 For Photograph Showing Examples of Wall Coating
### TABLE IV

CATALOGED LIST OF (EIGHT) STRONGEST LINES OF POSSIBLE
REACTANTS/COMPOUNDS AND ASSOCIATED LINE SPACINGS

Data Taken From American Society of Testing Materials X-ray Card File

<table>
<thead>
<tr>
<th>Compound</th>
<th>ASTM X-ray Card File No.</th>
<th>d-spacing, Å</th>
</tr>
</thead>
<tbody>
<tr>
<td>U</td>
<td>11-625</td>
<td>2.93</td>
</tr>
<tr>
<td>UO</td>
<td>17-659</td>
<td>2.83</td>
</tr>
<tr>
<td>UO₂</td>
<td>5-0550</td>
<td>3.157</td>
</tr>
<tr>
<td>αUO₃</td>
<td>12-43</td>
<td>4.17</td>
</tr>
<tr>
<td>UO₃</td>
<td>15-201</td>
<td>4.98</td>
</tr>
<tr>
<td>αUO₃₂₈</td>
<td>8-244</td>
<td>4.10</td>
</tr>
<tr>
<td>U₂O₈</td>
<td>23-1460</td>
<td>4.15</td>
</tr>
<tr>
<td>U₄O⁹</td>
<td>20-1344</td>
<td>3.14</td>
</tr>
<tr>
<td>UF₃</td>
<td>9-339</td>
<td>3.67</td>
</tr>
<tr>
<td>UF₄</td>
<td>12-701</td>
<td>7.52</td>
</tr>
<tr>
<td>UF₅</td>
<td>4-447</td>
<td>5.06</td>
</tr>
<tr>
<td>UF₆</td>
<td>9-166</td>
<td>5.20</td>
</tr>
<tr>
<td>U₂F₉</td>
<td>4-860</td>
<td>4.15</td>
</tr>
<tr>
<td>U₂OF₂</td>
<td>4-633</td>
<td>5.22</td>
</tr>
<tr>
<td>*U₂OF₂₂</td>
<td>4-230</td>
<td>5.18</td>
</tr>
<tr>
<td>UC</td>
<td>9-214</td>
<td>2.87</td>
</tr>
<tr>
<td>UC₂</td>
<td>6-372</td>
<td>3.04</td>
</tr>
<tr>
<td>U₂C₃</td>
<td>6-709</td>
<td>3.29</td>
</tr>
<tr>
<td>UN</td>
<td>11-315</td>
<td>2.61</td>
</tr>
<tr>
<td>UN₂</td>
<td>10-93</td>
<td>3.02</td>
</tr>
<tr>
<td>UN₃N₃</td>
<td>15-426</td>
<td>4.34</td>
</tr>
<tr>
<td>CU</td>
<td>4-0836</td>
<td>2.08</td>
</tr>
</tbody>
</table>

α - Hexagonal
* - Rhombohedral
FIG. 1 DETAILS OF PLASMA CORE REACTOR UNIT CELL
FIG. 2 SCHEMATIC DIAGRAM OF 80 KW RF INDUCTION HEATER
FIG. 3 PHOTOGRAPH OF TEST CHAMBER EMPLOYED IN EXPLORATORY TESTS IN 80 KW RF INDUCTION HEATER
FIG. 4 PHOTOGRAPH OF TEST CHAMBER CONFIGURATION INSTALLED IN 1.2 MW RF INDUCTION HEATER
OPERATING FREQUENCY = 5.5 MHz
POWER LEVELS SHOWN ARE MAXIMUM DESIGN VALUES

VARIABLE FREQUENCY OSCILLATOR 0.5 W

105 V 2 W

DIGITAL FREQUENCY COUNTER

40 W OUTPUT

600 V 60 W

NEUTRON CONSOLE POWER SUPPLY

2 KW OUTPUT

5 KV 5 KW

BUFFER

80 KW OUTPUT

15 KV 120 KW

DRIVER

40 KW OUTPUT

15 KV 60 KW

POWER AMPLIFIER

440 KW OUTPUT

23 KV 600 KW

POWER AMPLIFIER NO. 1

440 KW OUTPUT

23 KV 600 KW

1.2 MW DC POWER SUPPLY

SATURABLE REACTOR

POWER CONTROL

23 KV

RESONATOR SECTION — —

880 KW INPUT:

ARRAY OF 10 PARALLEL

CAPACITORS IN EACH HALF

OF RESONATOR SECTION

9 - CM DIA RF WORK COILS

LOAD

FIG. 5 BLOCK DIAGRAM OF UTRC 1.2 MW RF INDUCTION HEATER
a) END WALL INJECTION WITH ON–AXIS THRU FLOW EXHAUST AND PROVISION FOR AXIAL BYPASS

b) END WALL INJECTION WITH BLUFF BODY STABILIZATION AND ON–AXIS THRU FLOW EXHAUST

c) END WALL INJECTION WITH OFF–AXIAL ANNULAR EXHAUST

d) PERIPHERAL WALL INJECTION

FIG. 6 SKETCH OF TEST CHAMBERS EMPLOYED IN 80 KW EXPLORATORY RF PLASMA TESTS WITH PURE UF₆ INJECTION
9-CM DIA RF WORK COIL
OPERATING FREQUENCY = 5.5 MHz

ARGON BUFFER GAS
VORTEX INJECTORS

EXHAUST GAS
HEAT EXCHANGER

ADJUSTABLE
COMPRESSION ROD (3)
FOR HIGH PRESSURE OPERATION

INNER PERIPHERAL WALL
FUSED SILICA TUBE 5.7-CM-IDx1.1-CM-OD

OUTER WALL FUSED SILICA TUBE 6.5-CM-IDx8.3-CM-OD

AXIAL MID-PLANE

OPERATING RANGE:
CHAMBER PRESSURE 1—12 ATM
RF DISCHARGE POWER 10—85 KW
ARGON BUFFER GAS FLOW RATE 1—10 G/S
DISCHARGE DIAMETER AT AXIAL MID-PLANE 1.5—3.5 CM.

FIG. 7 SKETCH OF TEST CHAMBER CONFIGURATION USED IN TESTS IN 1.2 MW RF INDUCTION HEATER USING PURE UF₆ INJECTION
FIG. 8 SCHEMATIC DIAGRAM OF UF₆ TRANSFER SYSTEM
FIG. 9  VAPOR PRESSURE CURVE FOR URANIUM HEXAFLUORIDE
FIG. 10 SCHEMATIC OF DIAGNOSTIC SYSTEMS USED IN EXPLORATORY RF PLASMA TESTS
FIG. 11 TYPICAL OPERATING CONDITIONS AND RESULTS OF CORRESPONDING RADIATION MEASUREMENTS IN EXPLORATORY RF PLASMA TESTS WITH PURE UF₆ INJECTION
FIG. 12 RESULTS OF SPECTRAL EMISSION MEASUREMENTS FROM EXPLORATORY TESTS WITH PURE UF₆ INJECTION
FIG. 13 EXAMPLE OF UF₆ EQUILIBRIUM COMPOSITION DATA
FIG. 14 EXAMPLE OF ABSORPTION MEASUREMENTS OBTAINED IN EXPLORATORY RF PLASMA TESTS
FIG. 15 PHOTOGRAPH OF FUSED-SILICA TUBES USED IN EXPLORATORY RF PLASMA TESTS WITH PURE UF₆ INJECTION
SEE FIG. 7 FOR DETAILS OF TEST CONFIGURATION AND OPERATING RANGE

232.3 MG RESIDUE  61.3 MG RESIDUE  52.1 MG RESIDUE  19.1 MG RESIDUE

FIG. 16 PHOTOGRAPH OF FUSED – SILICA TUBES USED IN 1.2 MW RF PLASMA TESTS WITH PURE UF₆ INJECTION
FIG. 17 EXAMPLE OF ELECTRON DIFFRACTION ANALYSIS
FIG. 18 PHOTOGRAPHS OF RESIDUE WALL COATING FROM 1.2 MW RF PLASMA TESTS WITH PURE UF₆ INJECTION
ALL SAMPLES SUBJECT TO COPPER kα RADIATION IN A DEBYE CAMERA

FIG. 19 EXAMPLE OF X-RAY DIFFRACTION PATTERNS OBTAINED FROM POST TEST ANALYSIS OF RESIDUE WALL COATING
FIG. 20 PHOTOGRAPH OF X-RAY DISTRIBUTION FOR U, F, AND O ON SAMPLE OF RESIDUE WALL COATING FROM POST TEST ANALYSIS
INSTRUMENT USED: IR SPECTROPHOTOMETER USED IN CONJUNCTION WITH 3x-BEAM CONDENSER AND SPECULAR REFLECTANCE ACCESSORY

PREPARATION: THIN WAFER KBr MATRIX

FIG. 21 EXAMPLE OF IR SPECTROPHOTOMETRY ABSORPTION MEASUREMENTS OBTAINED FROM POST TEST ANALYSIS OF RESIDUE WALL COATING
SEE FIG. 7 FOR SKETCH OF TEST CONFIGURATION USED IN TESTS
(LASER BEAM TRAVERSED ON-AXIS AT AXIAL MID-PLANE)
SEE FIG. 10 FOR SCHEMATIC OF DIAGNOSTIC SYSTEM
(DYE LASER HEAD NOT USED IN THESE TESTS)

ARGON ION LASER
514.5 NM LINE
300 mW OUTPUT POWER

RANGE OF TEST CONDITIONS
35 \leq \dot{Q}_D \leq 55 \text{ kW}
5.4758 \leq f \leq 5.4778 \text{ MHz}
2 \leq P \leq 2.5 \text{ ATM}
1.9 \leq \dot{m}_A \leq 2.7 \text{ G/S}
0.5 \leq t \leq 2 \text{ MIN}

FIG. 22 EXAMPLE OF ABSORPTION MEASUREMENTS OBTAINED IN 1.2 MW RF PLASMA TEST WITH PURE UF\textsubscript{6} INJECTION
P = 24 ATM  Q_D = 52 KW  f = 5.4778 MHz  d = 2.9 CM

\[ \dot{m}_{\text{Ar}} = 2.2 \text{ G/S} \quad \dot{m}_{\text{UF}_6} = 0.09 \text{ G/S} \]

FIG. 23 PHOTOGRAPH OF RF ARGON PLASMA IN 1.2 MW RF INDUCTION HEATER TEST CHAMBER WITH PURE UF\(_6\) INJECTION