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Produced by the NASA Center for Aerospace Information (CASI)
PROGRESS REPORT

NASA Grant NSG 1547

An Experimental Investigation of \( ^{235}\text{UF}_6 \)
Fission Nuclear-Pumped Lasers

March 1979

(NASA-CR-158162) AN EXPERIMENTAL INVESTIGATION OF (UF-235)6 FISSION NUCLEAR-PUMPED LASERS Progress Report (Illinois Univ. at Urbana-Champaign) 28 p
HC A03/MF A01 CSCL 20E G3/36 16340

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UF₆ HANDLING SYSTEM

FOR

NUCLEAR-PUMPED LASER EXPERIMENTS

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December 1978
I. Introduction

A. Background:

Considerable interest exists in pumping nuclear-pumped lasers (NPLs) with the energetic fragments produced by fission of $^{235}$U distributed throughout the laser gas as UF$_6$ vapor[1]. The quenching effect of UF$_6$ on gas lasers is unknown but is expected to be considerable. We are preparing to perform the first controlled nuclear pumping experiments with UF$_6$ vapor contained in the laser cell[2].

On a hardware level, the gas fill system currently used for NPL experiments at the Nuclear Reactor Lab must be evacuated after each pulse because it is also the vacuum line. Filling the long, relatively large diameter (for reasonable conductance) vacuum line each pulse is very wasteful of the expensive, ultra-pure rare gases (such as Xenon) that are used for these experiments.

B. Objectives:

The main objective was to design a UF$_6$ handling system that could be used in conjunction with the existing NPL Group vacuum system at the Nuclear Reactor Laboratory to perform the experiments described above. A secondary objective was to separate the gas fill system from the vacuum system and thus greatly reduce its volume.

C. Design Considerations:

Figure 1 is a phase diagram for UF$_6$. As can be seen, UF$_6$ is a solid at room temperature. Additionally UF$_6$ contains copious amounts of F which is very corrosive. Finally, U (esp. $^{235}$U) possession and usage is regulated by the NRC. For these reasons UF$_6$ presents special problems for the gas laser experimentalist.
Our usual gas handling method involves connecting high pressure bottles of the gases of interest to a manifold, through copper lines, and then through another copper, brass, or SS line to the laser, which is also connected to a vacuum system. The laser, manifold, and copper lines are pumped down to the residual gas pressure desired, then the desired amounts of laser and buffer gases are added. This method is not satisfactory for UF₆, obviously, since it is a solid at pressures above a couple hundred torr (at room temperature) and very corrosive.

Mercury and other metal vapor lasers face a somewhat similar problem. However, there are major differences. Nuclear-pumped lasers at the TRIGA reactor are >.4 m from any possible location for an oven vapor source and the vapor densities required are much greater, 10 - 100 torr vs. m torr. For Hg lasers, the oven problem was solved by putting small amounts of Hg in reservoirs within the laser envelope and the laser, which must be heated anyway, became the oven. This is unsatisfactory for UF₆ because the excess UF₆ would still react with neutrons if enriched. Also, the UF₆ could be cracked, producing UFₓ(x<6) solids, or react with the fluorine bearing laser gases, contaminating all of the UF₆ in the laser. Only the precise amount of UF₆ required as vapor may be present in the laser at any given time. Therefore, in addition to heating and temperature control of the laser cell, a method is required to transport the UF₆ vapor over a distance of several meters from the UF₆ vapor source to the laser cell.

A method that has been used successfully for UF₆ transport relies on the vapor pressure-temperature relationship shown in Figure 1. By imposing a temperature differential one also imposes a pressure differential causing the UF₆ vapor to be transported from the region of higher temperature and thus pressure to the region of lower temperature.[3] Such a transport system is practical only for a material which goes from solid to vapor (and back)
Figure 1 State Diagram for UF₆
with the attendant large changes in specific volume. Thus the laser gases must be transported by the usual methods: filling the laser cell from a high pressure reservoir and evacuating the laser cell with a vacuum pump to the atmosphere. Since the UF$_6$ is to be returned to a spent UF$_6$ cylinder, rather than vented to the atmosphere, and because it would most likely badly mess up the vacuum system, the UF$_6$ must be separated from the laser gases.

Table 1 compares the boiling or sublimation temperatures for the laser gases of interest with that of UF$_6$ and CO$_2$. It can be seen that a dry ice trap can be used to separate UF$_6$ from XeF* laser gases. (But not from any byproduct HF that is formed. This can be removed in a separate operation at room temperature.)

Table 1

<table>
<thead>
<tr>
<th>Substance</th>
<th>Temp (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N$_2$</td>
<td>77</td>
</tr>
<tr>
<td>Ar</td>
<td>84</td>
</tr>
<tr>
<td>F$_2$</td>
<td>85</td>
</tr>
<tr>
<td>NF$_3$</td>
<td>144</td>
</tr>
<tr>
<td>Xe</td>
<td>166</td>
</tr>
<tr>
<td>CO$_2$</td>
<td>195</td>
</tr>
<tr>
<td>HF</td>
<td>293</td>
</tr>
<tr>
<td>UF$_6$</td>
<td>329</td>
</tr>
</tbody>
</table>
Figure 2 is a block diagram of the gas and UF₆ handling systems. The arrows indicate flow direction. A typical experiment would be run as follows (a detailed operating procedure is given in section three):

1. the laser cell is evacuated to the desired residual gas pressure (determined by allowed impurity concentration,
2. the laser is filled with the desired mixture of laser gases and UF₆,
3. the reactor is pulsed and data taken,
4. the "used" UF₆ is returned to the UF₆ supply system and the contaminated (with chemical reaction products) laser gas exhausted.
5. If it is desired to change the laser gas mixture for the next pulse, the gas fill line and manifold are evacuated.
Figure 2 Block Diagram of Apparatus for UF₆-NPL Experiments
II. System Design

The re-design of the gas fill system was basically trivial. The modified system design is shown in Figure 3. The modification required is the addition of the components to the left of the dotted line. A new valve will be connected to the existing gas fill manifold. From this valve the laser gases will pass through a dry ice trap and a long, small diameter (1/8" + 1/4" OD) SS tube to the laser cell.

The UF₆ Supply System design problem was somewhat more demanding. It was divided into two parts. The first part was the design of the vacuum envelope, which assumes the presence of a temperature control system; the second part was the design of the temperature control system.

II.A. Vacuum Envelope

Figure 4 is a schematic of the vacuum envelope of the UF₆ supply system. In this section, the details of the vacuum envelope will be considered. In the next section we will consider temperature control, shown cross-hatched in Figure 4.

Laser Cell

The most critical part of the vacuum envelope design is the laser cell where the actual experiment takes place and which is exposed to nuclear radiation. The internal details of the laser cell are set by laser physics considerations and will be discussed here only as they effect the vacuum envelope. One of these considerations is that, in addition to being compatible with fluorine compounds (NF₃, UF₆) and neutron radiation, to permit the inclusion of electrical pumping the laser cell materials must be insulators. Teflon (TFE) and poly-vinyl chloride (PVC) were identified as suitable materials. As designed the cell uses PVC for tubing and TFE for parts machined from rod because they are most available in these forms. "Torrseal" low vapor pressure epoxy is used for attaching the PVC to the TFE. Fused silica, which maintains
Figure 3 Gas Fill System
Figure 4: UF₆ Handling System Schematic

- Fill Line to Fill System
- Solenoid Valves
- Transfer Line to Reservoir
- Vacuum System
- Dry Ice Trap
- Pressure Gauge
- New UF₆ Supply Cylinder
- Used UF₆ Return Cylinder
- LN₂ Coils
- Insulation and Hot N₂ Plus Heater Tapes
- Laser Cell
- To Laser
its >99% transmissivity under irradiation (because of its high purity) is used for windows, and Viton is utilized for the gaskets. Figure 5 shows various views of the laser cell. A prototype cell has been constructed using acrylic in place of TFE.

Transfer Line

For a very long vacuum line (such as is required at the TRIGA) the ultimate pressure obtained at the end of the vacuum line (i.e. the laser cell) is dependent on the inverse of the cube of the diameter of the vacuum line \( \left( \frac{1}{d^3} \right) \) and independent of the pump capability (unless the pumping speed is very low).\(^4\)

Thus it is desirable to make the effective diameter of the vacuum line as large as possible. However, limited space in the throughport makes a very large diameter line into the laser cell impossible. The diameter of the throughport is 6". A 1" ID cylindrical volume, concentric with the centerline of the throughport, is reserved for the output from the laser cell. Thus a 2 1/2" thick annular cross-sectional area is available for the laser cell envelope and the hardware for connecting the laser cell to the gas fill, vacuum, and UF₆ handling systems. As shown in Figure 6, the largest diameter circular cross-section transfer line that can be accommodated is 1"-1 1/4." Any geometry other than circular would probably be too expensive to fabricate and would not have a much more favorable surface area to volume ratio. The vacuum line currently used is 1" in dia. and residual gas concentrations have been found to be satisfactory.

The transfer line vacuum envelope will be made of SS tube because of its availability (relative to Aluminum and Monel).
Figure 6 Diagram of Laser Carriage for TRIGA Reactor
Thru-port with Maximum Diameter Transfer
Lines Indicated (Full Scale)
As can be seen from Figure 1, any reasonable $\Delta p$ desired can be achieved (by heating) for transporting UF$_6$ to the laser cell. This is not true for the reverse process. Also only a small fraction of the UF$_6$ contained in the supply cylinder must be transported to the laser cell. However, we wish to return essentially all of the UF$_6$ from the cell to the return cylinder. It is not obvious that cryopumping the UF$_6$ will work or what size to make the system.

Reference 3 used four 1-ℓ monel cylinders. The only "cryopumping rate" that they report is the return of 20(±.5)g of 25(±.5)g of UF$_6$ in one hour. However, their "canister" is 85ℓ in volume vs. 1/2 ℓ for our laser cell (-2 1/2 ℓ for the transfer line) and the most UF$_6$ anticipated to be in the laser cell at one time is -1 g. Thus, our pumpdown rate should be somewhat better.

The maximum cryopumping speed can be estimated by assuming that all UF$_6$ molecules impinging on the cold UF$_6$ in the return cylinder are trapped. The impingement rate is given by[4]

$$\gamma = \frac{1}{4} n \bar{v} = 3.5 \times 10^{22} \frac{p}{\sqrt{MT}}.$$  (1)

The inside diameter of the cylinder can be taken as 6 cm. Thus, the pumping speed of the cylinder can be calculated from[4]

$$S_{\text{max}} = \frac{Q}{P} = \frac{\gamma \cdot A \cdot kT}{p} = 3.6 \sqrt{\frac{T}{M \cdot A}}.$$  (2)

Substituting the M value for UF$_6$, 350 K, and the area corresponding to a 6 cm diameter gives
This is a pumping speed comparable to a small diffusion pump.

Estimation of the pumpdown time to a given UF₆ density (or partial pressure) is more difficult because it requires knowledge of the surface properties of the various materials involved for UF₆. However, several simplified approximations can be made.

The crudest approximation is to neglect surface effects (and the finite conductance of the transfer line) altogether. Thus we are essentially considering a 3l volume with an ~30² cyropumping area. From reference 4,

\[
\frac{dN_{\text{UF}}}{N_{\text{UF}}} = -36.4 \frac{N_{\text{UF}}}{V_{\text{system}}} \cdot A_{\text{cyl}} \cdot \frac{T}{M_{\text{UF}}} \cdot \sqrt{\frac{kT}{2\pi}} \\
\text{or} \\
\frac{dN_{\text{UF}}}{dt} = -\gamma A = -\sqrt{\frac{8kT}{\pi IM_{\text{UF}}}} \cdot \frac{N_{\text{UF}}}{V_{\text{system}}} \cdot A_{\text{cyl}}
\]

For \( T = 350K \),

\[
\frac{dN_{\text{UF}}}{N_{\text{UF}}} = -36.4 \frac{dt}{N_{\text{UF}}}
\]

so that
\[ \frac{N_{\text{UF}_6}}{N_{\text{UF}_6}^{(0)}} = e^{-36.4t} \]  \hspace{1cm} (5)

For \( \frac{N}{N_0} = 10^{-8} \), \( t \) is about .5 sec.

While this result is very crude, pumpdown times more than three orders of magnitude greater would be acceptable.

Another crude approximation is to treat the system as a normal vacuum system made of materials with high outgassing rates.

Taking \( S_{\text{eff}} \approx S_{\text{th}} = S_{\text{max}} \), assuming that \( \frac{S_{\text{max}}}{L} \ll l_e \) and molecular flow regime, and neglecting \( p_{\text{ult.}} \); the pumpdown time is given by [4]

\[
t = V \frac{S_{\text{max}}}{Q_g} \left( \begin{array}{c}
p_i - \frac{Q_g}{S_{\text{max}}} \\
p_f - \frac{Q_g}{S_{\text{max}}} \\
-1
\end{array} \right) \]  \hspace{1cm} (6)

It has previously been determined that \( V \) is \( \sim 3 \text{ L} \) and \( S_{\text{max}} \) is \( \sim 100 \text{ L/s} \).

\( Q_g = q_g A_{\text{system}} \) and \( q_g \) can be approximated by taking a high value of \( 10^{-5} \) (torr-liter)/(S-cm\(^2\))[4]. Then

\[
Q_g = 10^{-5} \frac{\text{torr-liter}}{\text{sec-cm}} \cdot 4 \times 10^3 \text{ cm}^2 = 4 \times 10^{-2} \frac{\text{torr-liter}}{\text{sec}} \cdot 
\]

This says that the lowest attainable pressure is

\[
P_{\text{lowest}} = \frac{Q_g}{S_{\text{max}}} = 4 \times 10^{-2} \frac{\text{torr-liter}}{\text{sec}} \cdot \frac{100}{\text{Liter/sec}} = 4 \times 10^{-4} \text{ torr}. \]

An infinite amount of time would be required to achieve this pressure. Using equation (6), the time to pump down from 100 torr to \( 5 \times 10^{-4} \) torr would be
\[ t = \frac{3 \ell}{100 \text{ s}} \ln \frac{100}{5 \times 10^{-4} - 4 \times 10^{-4}} = .4 \text{ sec} \]

Again it appears that pumpdown times will be very satisfactory. And, while a UF₆ pressure of \(-5 \times 10^{-4}\) torr is not ideal, it represents about 10 μg for our system volume -- a negligible amount, even for NPLs or the NRC.

The result of these crude calculations and the comparison to reference 3 is that it appears that cryopumping using a single 1-ℓ UF₆ cylinder wall satisfy the needs of the experiment quite well.
II.B. Temperature Control

Since the UF₆ transfer system utilizes a vapor pressure pumping scheme (the return portion of the cycle being the well known cryopumping process), accurate control of temperature is important. Additionally, uniformity of temperature is important since having the temperature drop below the sublimating temperature at any point would result in the deposition of UF₆ at that point. This is of special concern for the sealing surface of the valves.

We have designed a temperature control system that attempts to provide maximum performance at minimum cost. Factors included in performance include accuracy of temperature control at a point, uniformity of temperatures, flexibility, and minimum of manual intervention. The temperature control system can be divided into two basic subgroups:

1. Heating and Cooling
2. Temperature sensing and control electronics

1. Heating and Cooling

Four different types of hardware must be heated. These are: (a) the laser cell, (b) the transfer line, (c) the UF₆ cylinders, and (d) valves.

(a) Laser Cell Heating and Insulation

The laser cell, Figure 5, it is not very conducive to the use of heater tapes since they would have to be applied to the outside of the capacitor. The capacitor and the "air" gap between the capacitor and the laser cell provide a considerable thermal resistance. As will be explained in the temperature sensing section, thermistors are the desired method of temperature sensing. However, the lifetime of thermistors in the severe radiation environment of the reactor is unknown and probably very short. Both of these problems can be solved by the use of flowing hot nitrogen
heating. The hot nitrogen can fill the gap between the capacitor and the laser cell and by flowing it, temperature sensing can be moved outside the reactor. Nitrogen is chosen over air because it is not reactive with UF₆ or any of the laser gases. By maintaining an N₂ pressure higher than the pressure in the laser, any leakage will be of N₂ into the laser.

(b) The transfer line could be heated by either the hot N₂ used for the laser cell or by heater tapes as with the valves. Both methods have advantages. Heater tapes are very easy to install, one simply wraps them around the transfer lines, and occupy a minimum volume (if no further insulation is used), which can enable the maximization of the cross-sectional area of the transfer line (the importance of which was discussed earlier). On the other hand, with heater tapes, one controls the heating rate rather than the temperature so one must accurately measure the temperature. However since one end of the transfer line is in a high radiation environment thermistors cannot be used. Thermocouples are much less accurate. Heating and temperature measurement would probably be required in a minimum of three regions, the middle and the two ends, making the control problem slightly more complex than it could be. Similarly, six pairs of wires would be required.

Since hot N₂ is already required for the laser cell, no additional hardware is required for its use with the transfer line other than the co-axial envelope around the transfer line required to contain the temperature can be maintained more accurately and uniformly than with heater tapes. The two disadvantages are 1) that any co-axial flow design will be bulkier than heater tapes without insulation and 2) a 4-5 m co-axial flow line will be relatively complex and expensive to build.
In summary, a heater tape system is simpler to construct but more complicated to operate and allows a greater conductance (and thus vacuum system) performance) but gives poorer temperature control performance than a co-axial flow system. Figure 7 depicts the hot N₂ approach which we have chosen.

(c) The UF₆ cylinders require both heating and cooling: heating for vaporizing the UF₆ and generating the desired pressure to transport it ~5 m to the laser cell and cooling, with liquid nitrogen, to cryopump the UF₆ back. In fact, for the cryopumping phase, heating and cooling will be required simultaneously - the inlet to the cylinder will be heated to prevent plugging. As shown in Figures 3 and 7, copper cooling coils will be soldered to the bottom half of the monel UF₆ cylinders. For cooling, LN₂ will be run through the copper coils. Heating will be provided by a combination of heater tapes and hot N₂. The cylinders and valves will be wrapped with heater tapes, in two regions, and inserted in an airtight, insulated enclosure connected to the hot N₂ flow system. Any UF₆ leaks will be into this enclosure.

(d) Five valves require heating. These are the two UF₆ cylinder valves, the laser cell to transfer line valves, the transfer line to transfer line trap valve, and the transferline trap to vacuum system valve. All of these will be heated using heater tapes. The heater tapes will be wrapped around the valves and fiberglass insulation will be wrapped around the heater tapes.
Figure 7: Temperature Control System for UF6 Handling System
2. Temperature Sensing and Control Electronics

The temperature of greatest interest is that in the laser cell. This will be measured using one or both of two methods. The preferable method depends on the effectiveness of a shielding material called flex boron which has recently come to our attention (the NPL Group) but which we have yet to test in the reactor. If effective, we will be able to use it to shield a number of neutron radiation sensitive components (the unknown is the fraction of current damage caused by $\gamma$'s), including thermistors, one of which will be located in a shielded portion of the laser cell. In either case, the inlet and outlet $N_2$ temperatures will be measured using thermistors and the cell temperature inferred from these $N_2$ temperatures. Similar thermistors will be used to measure the temperature in the UF$_6$ supply enclosure.

The electronics for the thermistor temperature measuring system are shown in block diagram form in Figure 8. Such systems are highly accurate even though relatively inexpensive. A similar system is used by the Combustion Engineering Boronometer$^\text{TM}$ (designed by the author). With a 10 KHz V/F and a 1 second counting time, resolution was .01°C and error was <.1°C. For this system an ~1 second counting period will be used producing a resolution of .1°C and an error of ~.1°C. The thermistor that will be used is a unique dual thermistor (manufactured by Yellow Springs Inst.) that has an output that changes linearly with temperature. A monolithic instrument amp (such as the Analog Devices 521) raises the voltage level of the thermistor output so that the maximum design temperature equals the full scale voltage of the voltage to frequency convertor (V/F), which functions as an analog to serial-digital converter. The serial-digital data is transmitted to a microcomputer where it can be converted to temperature units and displayed or used for control.
Figure 8 Temperature Sensing and Control Electronics for UF₆ Handling System
Items that will be controlled include the temperature and flow rate of the hot \( \text{N}_2 \), the flow of the LN\(_2\), and the various system solenoid valves.

The solenoid valves are the easiest to control. The \( \mu \)-computer address is decoded to drive a transistor which drives the solenoid directly or through a relay. The LN\(_2\) flow is controlled in a similar manner using air pressure controlled by a solenoid to propel the LN\(_2\). (This method is used for keeping the diffusion pump cold trap filled in the vacuum system currently in use at the reactor.)

A somewhat more complex system is used to control the \( \text{N}_2 \) heater and the heater tapes. According to the heating rate desired, the \( \mu \)-computer outputs an eight bit digital word, corresponding to the fraction of the 60 Hz power frequency phase required to produce that heating rate, to a latch. At the start of each 60 Hz half-cycle a counter is reset from the latch and counted down to zero at which point it produces a pulse which turns on the triac and allows power to flow in the heater circuit for the remainder of the half cycle. If the word is 0 power starts flowing immediately. If the word is 256 the triac will never turn on. Precision of control will be better than 1 part in 100.
III. Operating Procedures for UF₆ and Gas Handling Systems for NPL-UF₆ Pumping Experiments

A. System Preparation (1-5 performed only at the beginning of each series of experiments)
1. Open gas and UF₆ handling systems and laser cell to vacuum system, pump down and bake out (with diffusion pump).
2. Valve-off diffusion pump, chill UF₆ cyl. and transfer line trap to 0°C (ice bath, after initial cooling with LN₂), fill with inert gas, and open UF₆ valves. Allow accumulated HF to be pumped out (note: forepump is exhausted through reactor stack).
3. Close valve between transfer line trap and vacuum system. Chill UF₆ supply cyl. with LN₂ and then the heat trap with a heat gun, thereby cryopumping UF₆ from trap into cylinder.
4. Cool transfer line trap end gas fill line trap with dry ice.
5. Close-off cylinders from transfer line and open transfer line trap - vacuum system valve.
6. Open diffusion pump valves and pump down system to desired background pressure.

B. Transfer UF₆ from supply cyl. to laser cell.
1. Heat supply cyl., transfer line, and laser cell to desired temps.: laser cell and transfer line to T[subl] + 25K (for desired n UF₆), supply cyl. to temp. which will provide a P_sat which, when expanded into laser cell, will provide the desired n UF₆. Start cooling UF₆ return cyl. with LN₂.
2. When desired temps. are achieved, close laser cell to gas fill line valve and transfer line to transfer line trap valve (thus valving UF₆ system and laser cell off from vacuum system).
3. (a) Set temp. control on supply cyl. to provide temp. for sat. pressure for desired n UF₆ , then
(b) open UF₆ supply cyl. valve. \[ \text{Expansion of } UF₆ \text{ into transfer line and laser will cool } UF₆, T = T₀ \frac{V₀}{V}, q = \frac{p}{C_v}. \]
4. Once pressures and temperatures stabilize: (a) close transfer line valve to laser, (b) start cooling supply cyl. in order to cryopump extra uncontaminated UF₆ in transfer line back into supply cyl. and, (c) start cooling transfer line trap with dry ice.
While supply cyl. is cooling and pumping go on to...
C. Fill laser cell with laser and buffer gases
   1. (a) Close gas fill manifold valve to vacuum system.
      (b) For laser systems with small atom fraction constituents (\textless{}0.1\%) also close manifold - gas fill line valve.
   2. (a) Add gases to manifold or gas fill line in order of increasing atom fraction (add to desired pressure times volume factor).
      (b) If small atom fraction constituents, add these plus portion of buffer gas first to manifold only (using volume factor of manifold to manifold + fill line + laser cell) then expand into manifold plus fill line and add remainder of buffer gas to desired pressure (taking into account volume factor).
   3. Open valve between gas fill line and laser cell and, as soon as pressure fluctuations subside, close valve again. [Since UF$_6$ pressures will be <20\% of total pressure in laser cell and since volume factors should be 2 or greater, pressure in the fill line should be 10-100 times greater than the UF$_6$ pressure in the laser cell so that UF$_6$ loss from the laser cell into the gas fill line should be minimal - hopefully negligible.]
   4. After allowing time for temperatures to stabilize and for gas mixing by diffusion, the laser cell is ready for pulsing.

D. Pulse reactor and take data (covered by separate procedure)

E. Evacuate gases and return UF$_6$ to return cyl.
   1. Check to see that transfer line trap is cold (dry ice cooling)
   2. Shut UF$_6$ supply cylinder valve and diffusion pump valve
   3. Open transfer line - transfer line trap valve and pump out gases [UF$_6$ is caught in trap] to best pressure available with forepump.
   4. Close transfer line trap - vacuum system valve and open UF$_6$ return cylinder valve.
   5. Remove cooling from transfer line trap and heat with heat gun until all UF$_6$ and other cryopumpable residuals are returned to return cylinder.
   System is now ready to return to A.6 and recycle.
References


