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## **Evaluation of Target Power Supplies for Krypton Storage in Sputter-Deposited Metals**

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**April 1986**

**Prepared for the U.S. Department of Energy  
under Contract DE-AC06-76RLO 1830**

**Pacific Northwest Laboratory  
Operated for the U.S. Department of Energy  
by Battelle Memorial Institute**



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PACIFIC NORTHWEST LABORATORY  
*operated by*  
BATTELLE  
*for the*  
UNITED STATES DEPARTMENT OF ENERGY  
*under Contract DE-AC06-76RLO 1830*

Printed in the United States of America  
Available from  
National Technical Information Service  
United States Department of Commerce  
5285 Port Royal Road  
Springfield, Virginia 22161

NTIS Price Codes  
Microfiche A01

### Printed Copy

Pages	Price Codes
001-025	A02
026-050	A03
051-075	A04
076-100	A05
101-125	A06
126-150	A07
151-175	A08
176-200	A09
201-225	A010
226-250	A011
251-275	A012
276-300	A013

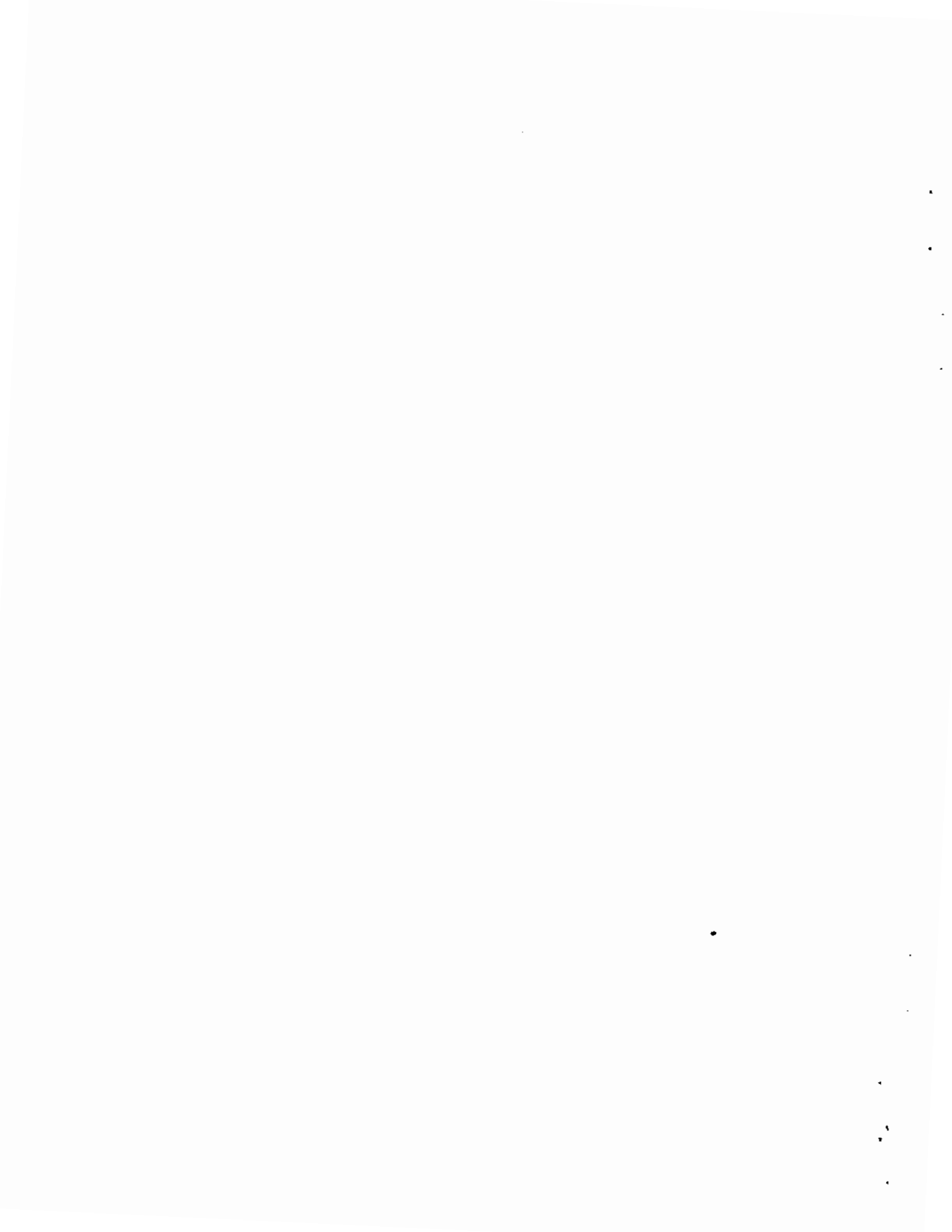
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EVALUATION OF TARGET POWER SUPPLIES FOR KRYPTON  
STORAGE IN SPUTTER-DEPOSITED METALS

1.0 INTRODUCTION

Implantation of  $^{85}\text{Kr}$  in a growing sputtered metal deposit has been studied for the containment of  $^{85}\text{Kr}$  recovered from the reprocessing of spent nuclear fuel.<sup>(1-5)</sup> PNL, as part of DOE's research program for  $^{85}\text{Kr}$  storage, has developed krypton trapping storage devices (KTSDs) in a range of sizes for "cold" and radioactive testing. The KTSD is a stainless steel canister that contains a sputtering target for depositing an amorphous rare-earth transition metal on the inner wall and simultaneously implanting low-energy krypton ions in the growing deposit. Over 90% of the internal area of the KTSD operates at a negative potential of -270 V or -2400 V. The current density of the ions at these surfaces is a nominal  $100 \text{ A/m}^2$ . Cathodic surfaces subject to this level of bombardment are prone to so-called "unipolar" arcs. Arcs are more numerous to metallic surfaces that are contaminated with nonconductive inclusions common in the candidate target materials for the KTSD.<sup>(6)</sup> Uncontrolled arcs not only interrupt the process but can seriously damage the power supplies and the internal structure of the KTSD.

It was recognized early that reliable and easily maintained high- and medium-voltage power supplies, capable of being rapidly switched off without breaking into oscillatory modes, are essential for satisfactory operation of the KTSD. An arc-sensing circuit combined with rapid current interruption can quench undesired arcs. It was also advantageous to remove the implantation voltage applied to the substrate electrode during a target supply off-cycle. This offsets the rapid rise in pressure resulting from the re-emission of krypton by ion bombardment of the sputtered product.

Five power supplies are required to operate the PNL-designed KTSD: 1) a low-voltage, high-current power supply for resistively heating the thermionic electron source for the triode discharge, 2) a keeper or ignitor power supply for initiating the discharge, 3) the plasma or ionization power supply for

maintaining the discharge, 4) the substrate or implantation power supply, and 5) the target power supply to energize the krypton ions to produce the sputtered alloy matrix. Only the last three require the rapid switching current interrupter feature. Since the overall theory behind switching the power supplies was identical in principle, it was assumed that testing several models of the one type most difficult to design and build would demonstrate the general solution for all three types. The target power supply was chosen as the most difficult because the voltage and power are an order of magnitude greater than the next largest supply. The greatest complication for the target power supply current interrupter stems from the need to protect the arc-sensing and timing circuitry from the high working voltage and the higher voltage spikes produced by fast switching.

This report covers the design requirements for the target power supply and the description, testing and evaluation of three basic designs. The designs chosen for evaluation were: 1) a standard commercial power supply with an external PNL-designed current interrupter, 2) a commercially manufactured power supply with an integral series-type interrupter, and 3) a commercially manufactured power supply with an integral shunt-type interrupter. The units were compared on the basis of performance, reliability, and life-cycle cost.

## 2.0 DESIGN REQUIREMENTS

An original task of this program was to design and operate a "cold" full-scale demonstration KTSD. Eight full-size KTSDs were estimated to be required to "solidify" the  $\sim 230 \text{ m}^3$  of krypton released during the reprocessing of 2000 MT of irradiated light-water reactor fuel ( $\sim 6\%$  by volume is  $^{85}\text{Kr}$ ). Reduced operating funds for this PNL program in FY 1983 required revision of the "cold" commercial pilot-scale task. Instead, the demonstration of a smaller scale KTSD was chosen that could handle the krypton product from 15 MT of irradiated heavy metal reprocessed over a 30-day campaign. Calculations, verified by experimentation, showed that this could best be accomplished by using two smaller KTSDs ( $\sim 40\%$  the size of the full-scale size model) operating the target at 10 A and 2400 V. Since the larger power supplies were already on hand for

the commercial-scale KTSD, it was decided that the units would be load bank-tested to the higher power required for the commercial-scale KTSD, but that testing on a sputtering load would be limited to the smaller unit requiring about half as much current.

The basic specifications for a target power supply to meet the needs of the commercial-scale KTSD are as follows:

- voltage output: 0 - 2500 V
- current output: 25 A
- voltage ripple: less than 10 V + 2% RMS of output
- voltage regulation: less than 1% change in output for 1% change in input; less than 20 V change for 1 A output current change.

The power supply needs to be equipped with an arc-detection and current-interruption circuit to prevent damage to the power supply and the internal electrode structures of the KTSD during electrical arcing. This circuit must interrupt the current that feeds the arc in less than 1 msec after the arc is sensed. Moreover, the power supply/current interrupter must be able to return the operating voltage to the KTSD as soon as the fault clears. It was desirable that off-time and turn-on rate be adjustable internally. The "over-current" setpoint should be externally adjustable.

The response to current changes and arcs is very important since the target power supply affects the system's stability by affecting the target sputtering rate, either through changing output voltage or interrupting the output entirely during arc suppression. For example, consider this sequence:

1. The target voltage rises, raising the sputtering rate.
2. The increased rate raises both the gas-trapping rate and the emission from the filament.
3. The increased emission increases the plasma current and hence the target current, causing a further rise in the pumping rate.
4. The increased pumping rate traps krypton faster than the pressure controller can add krypton, causing the pressure to decrease.

5. The decreasing pressure tends to lower the plasma and target currents, thus reducing the trapping rate.
6. The more slowly responding pressure controller is still reacting to the initial sharp decline in pressure, and so begins to let far too much gas into the chamber.
7. The high pressure causes sharply increased sputtering, again leading to increased trapping, and so the cycle tends to repeat.

The output voltage of a power supply with poor load regulation will decrease as the current increases. This can further complicate the above sequence because even though some changes seem to be compensatory, all have different response times. The problem is most pronounced at a target voltage below 500 V, where the percentage changes in sputtering rate with voltage are greatest. Both the series interrupter and shunt interrupter units have sufficient load regulation to avoid any interaction; the external interrupter unit does not. The problem is avoided by using lower currents until the target voltage is above 500 V, the usual practice regardless of the power supply in use.

Ripple is not a problem because its frequency is much higher than any of the other response times. Line regulation is not a factor either, as it simply changes the output voltage but does not interact with the other variables.

Potentially more drastic is the complete interruption of the target output during arc suppression. The comparatively long reaction time of the chamber pressure controller allows the pressure to build rapidly while no trapping is taking place. Interrupting the trapping for too long allows such a large pressure rise that the current will exceed the supply's current setpoint and, when it does turn back on, it causes another current interruption cycle. This situation requires a lengthy recovery procedure; therefore, the quicker the target output is restored, the better.

Although cost considerations were not part of the design requirements, they would be important in the final choice for production units. Consequently, factors affecting cost were considered in the evaluation. The basic design of the power supply is the primary factor in the unit's capital cost.

Other design factors affecting the "cost of ownership" but not the actual operation include the unit's electrical efficiency, reliability, and ease of repair. Based on a preconceptual design prepared for the DOE,<sup>(7)</sup> the electrical energy consumed by the target electrode for the commercial-scale process amounts to about 5% of the life-cycle costs (30-year cycle). Power consumed in the power supply itself would add to this cost, making efficiencies close to 100% desirable. The reliability of a particular unit affects the cost through downtime (lost production), repair costs, and any additional power supplies or major assemblies required as backup to ensure availability.

### 3.0 DESCRIPTION OF UNITS

A PNL-developed current interrupter used with a commercial power supply and two commercially obtained power supplies (each with integral current interrupting of a different design) were evaluated.

1. The PNL current interrupter and commercial power supply are shown as a diagram in Figure 1 and as a photograph in Figure 2.

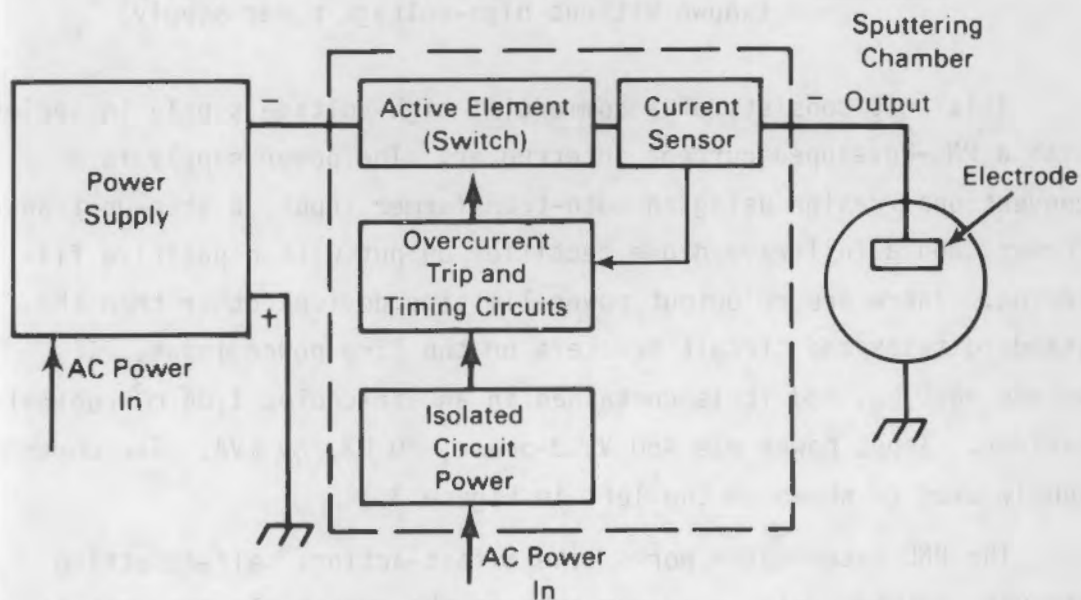


FIGURE 1. Power Supply with External Interrupter

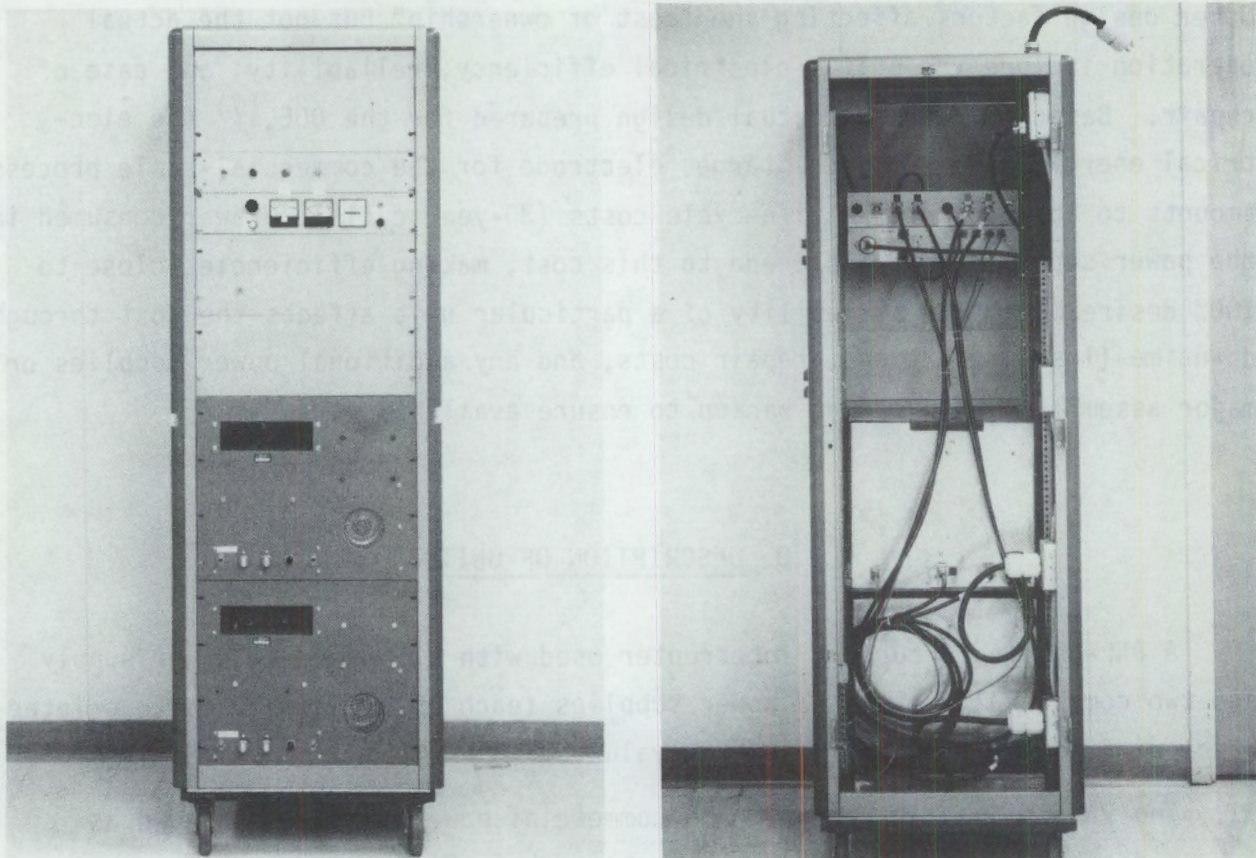


FIGURE 2. Separate Series-Type Current Interrupter (shown without high-voltage power supply)

This unit consists of a commercial high-voltage supply in series with a PNL-developed current interrupter. The power supply is a conventional design using an auto-transformer input, a step-up transformer, and a full-wave diode rectifier output with capacitive filtering. There are no output power-limiting devices other than the standard fuses and circuit breakers on the line power input. It weighs ~860 kg, and it is contained in an air-cooled 1.06 m<sup>3</sup> cubical cabinet. Input power was 460 V, 3-phase, 60 Hz, 80 kVA. The power supply used is shown on the left in Figure 3.

The PNL interrupter works like a fast-acting, self-resetting circuit breaker, using a vacuum tube as the switch element. It is connected in series between the negative output of the high-voltage

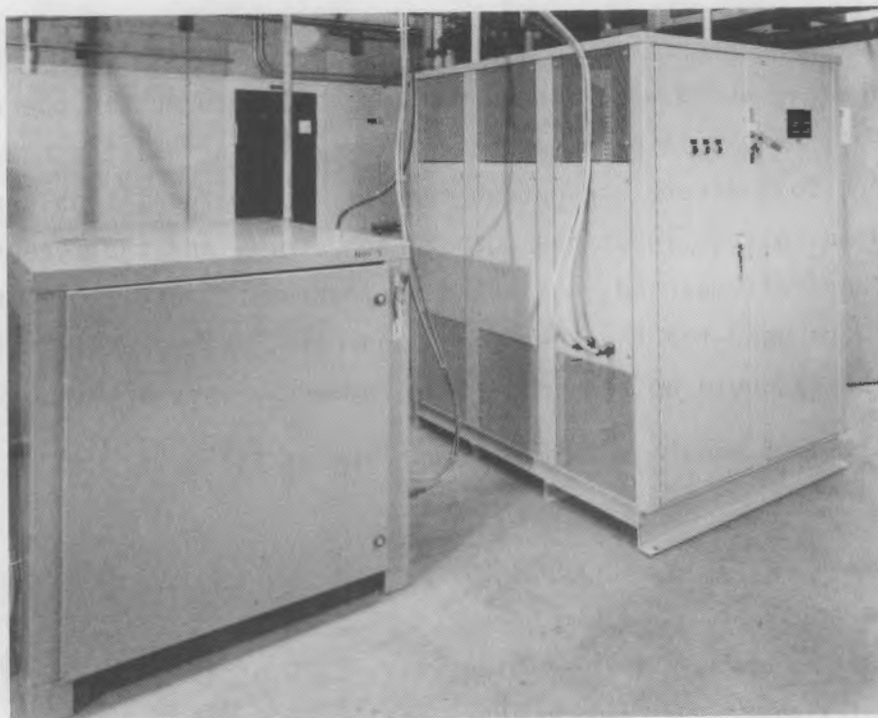


FIGURE 3. Conventional 3 kV, 20 A Power Supply (left) and 3 kV, 25 A Power Supply with Shunt Interrupter (right)

power supply and the target electrode in the sputtering system. During normal operation, it presents a low impedance to the current through it; however, when the output current exceeds the overcurrent setpoint, it switches to a very high impedance, blocking the current to the target. After a predetermined time, it returns to the normal low impedance mode. If the overcurrent persists, the cycle is repeated. This feature protects both the target and the load from damaging overcurrents. The overall electrical efficiency varies with output voltage and current, and would be about 80% at normal operating levels for a commercial-scale KTSD.

The basic commercial power supply unit can be placed up to 100 m from the current interrupter. The interrupter itself should be placed near the sputtering chamber to reduce the generation of voltage spikes caused by inductance and capacitance in the cable.

The interrupter (Figure 2) was built with modules rated at 7-A capacity each, which were connected in parallel to obtain the capacity needed. A single panel contained controls for all the modules and meters to indicate the output current and voltage. The control panel, high-voltage input and output connectors, and the interrupter modules were all mounted in a standard instrument rack. Only two modules were used for the tests reported here. Four modules with a 28-A capacity would be required for a commercial-scale KTSD.

Individual module specifications were as follows:

- high-voltage input: 3000 V
- maximum operating current: 7 A
- turn-off time: about 8  $\mu$ sec
- cooling requirements: ambient air, 30°C or less at 130 cfm
- input power: 240 VAC, 60 Hz, 1-phase, 1.4 kVA.

The cost of a PNL unit with four modules and a commercial power supply is estimated at ~\$65K in 1985 dollars.

2. The series interrupter power supply (Figures 4 and 5) has an unregulated, constant-output, high-voltage power supply in series with vacuum tubes used as linear regulators to provide output voltage regulation and control from 0 to 3000 V. Other circuitry monitors the output current, turning the tubes off for an adjustable period to allow an arc or short circuit to clear. Because it is linearly regulated with a constant-voltage basic supply, the unit's efficiency decreases more rapidly at lower output voltages than does that of the other two units, which vary the basic supply voltage. The efficiency at the normal operating level is 60%.

An important difference between this unit and the PNL unit is that the output impedance of the power supply varies with the speed of the load changes; therefore, ripple currents and slow load changes see a low impedance (reducing voltage variations), while rapid load changes due to arcs see a high impedance, limiting the rate at which

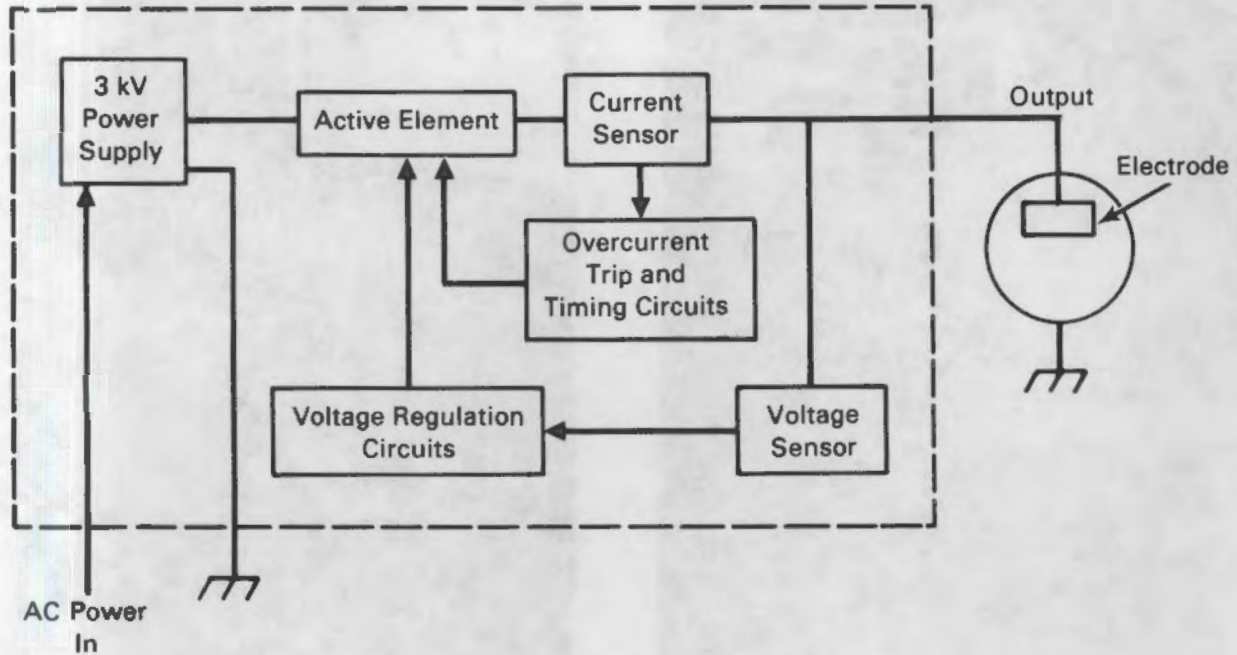
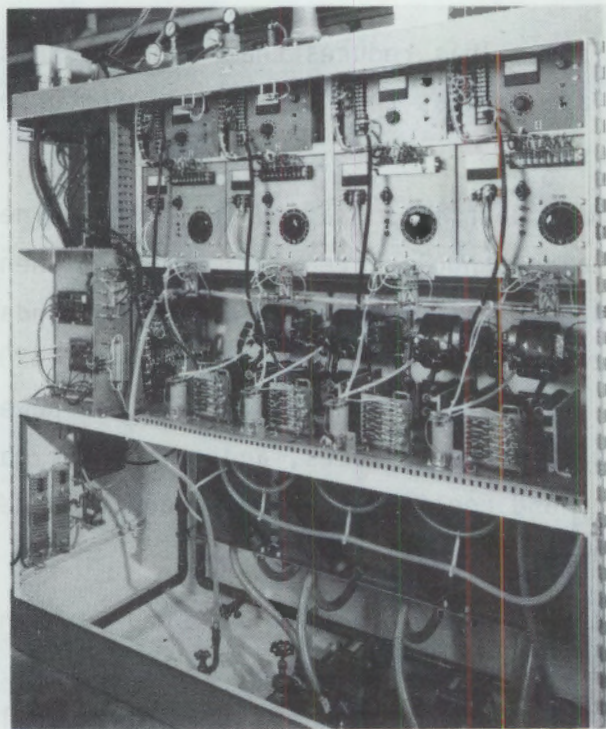
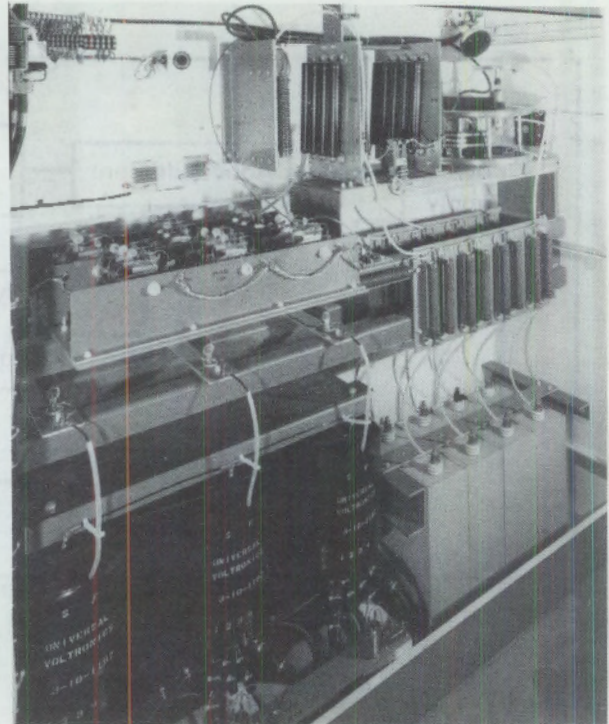
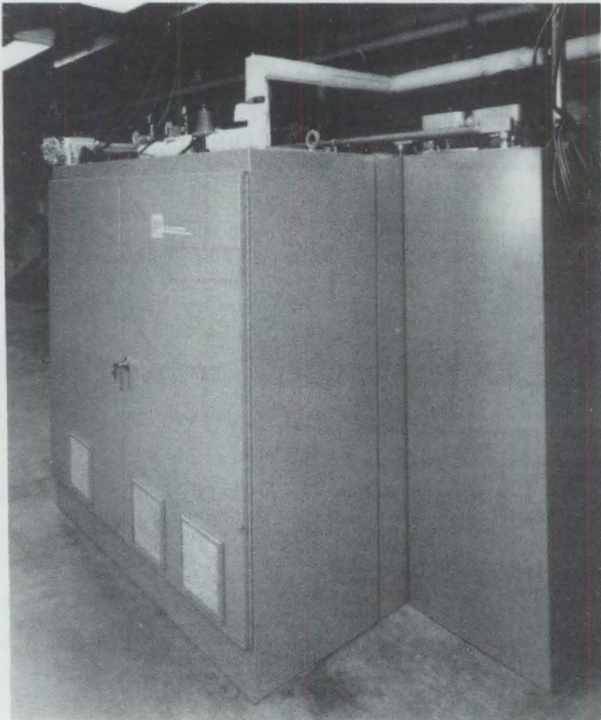


FIGURE 4. Integral Power Supply - Series-Type Interrupter

the arc current rises. This reduces the overshoot in the output current during an arc to less than 10% of the overcurrent setpoint value.

The 1800-kg main unit is contained in three cabinets, 1.8 m high, that occupy a rectangular area 1.2 m x 2.4 m when assembled. The main control panel was mounted in a separate standard instrument rack. Services required are 460 V, 3-phase, 60 Hz, 320 kVA electrical power, and 100 L/min of cooling water. The power cabinet contains the circuit breakers, fuses, and relays for managing the input power, safety and cooling interlocks, and time delays for the regulator and high-voltage cabinets.

The high-voltage cabinet contains the step-up transformers, rectifiers, and filters that produce the unregulated high voltage. Also included are 1) safety circuits such as spark gaps to limit damage from high-voltage transients and 2) a "crowbar" circuit to protect



**FIGURE 5.** 3 kV, 25 A Power Supply with Integral Series-Type Current Interrupter

the output circuitry and the load from a short circuit in the regulator section. The output from this section is fed to the regulator cabinet.

The regulator cabinet contains four large vacuum tubes, filament, bias, and grid power supplies, grid regulators, and the output regulator logic. There are also the output shorting solenoid, fans, and cooling-water flow meters and valves.

The remote control panel containing the operator controls, output meters, status lights, and connections for remote operation is connected to the other units by a 15-m cable, allowing its placement in a more convenient location.

The cost of the commercial series-type interrupter is estimated to be ~\$130K in 1985 dollars.

3. The shunt interrupter power supply (Figures 6 and 7) is basically an auto-transformer/rectifier supply similar to the one used with the PNL current interrupter, although the interrupting function is achieved differently than with either of the other two units. A set of high-voltage silicon-controlled rectifiers (SCRs) are in parallel (shunt) with the output. When an overcurrent is detected, the SCRs

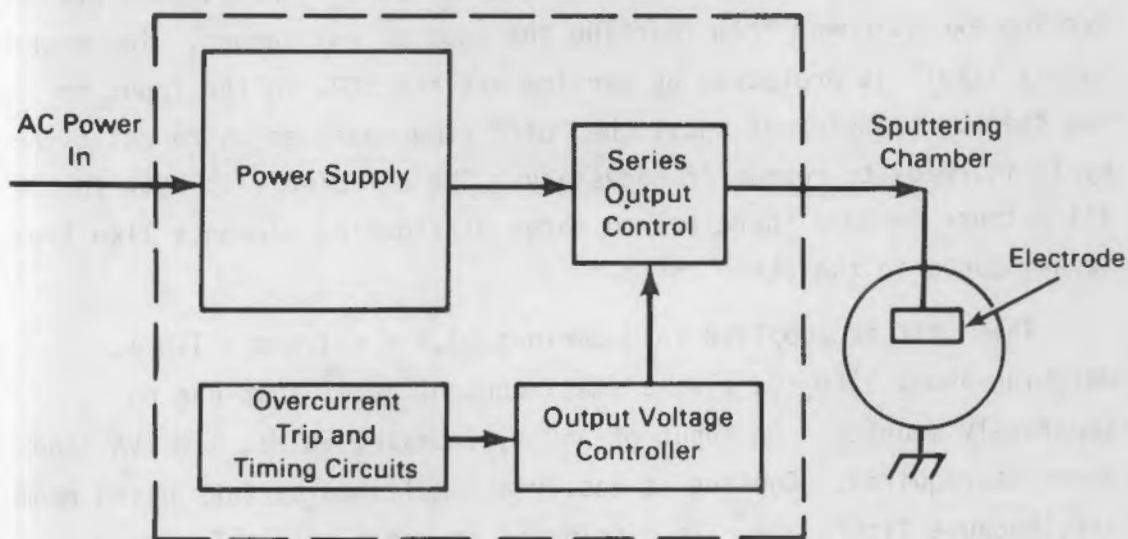
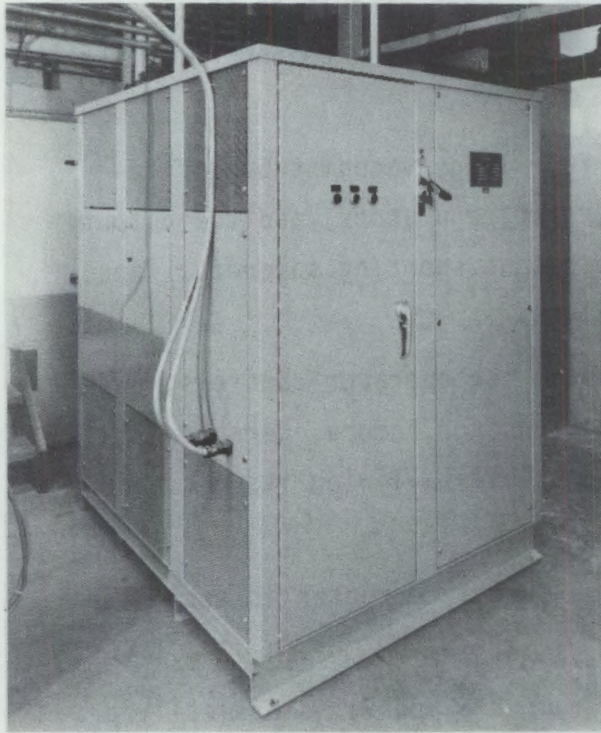
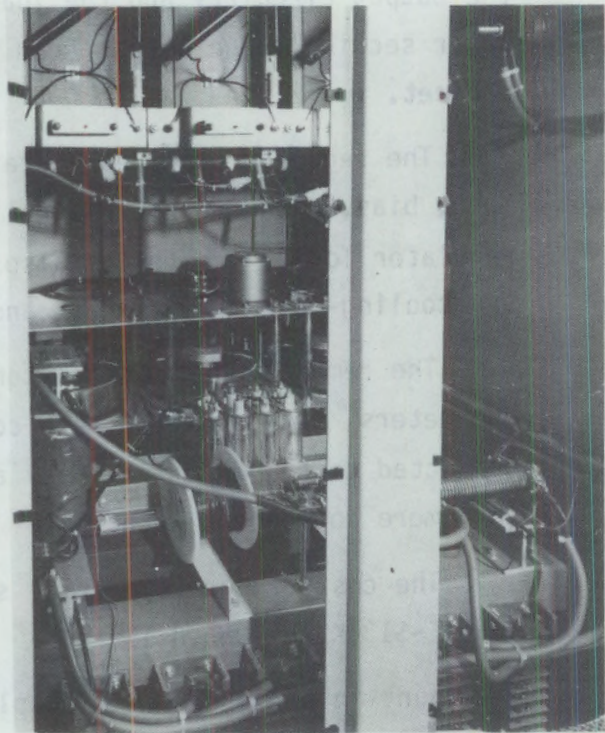


FIGURE 6. Integral Power Supply - Shunt-Type Interrupter



(a)



(b)

**FIGURE 7.** a) 3 kV, 25 A Power Supply with Integral Shunt-Type Current Interrupter and b) Partial Interior View of the Supply

are switched on, shunting the output at the power supply, thus preventing excess power from reaching the sputtering chamber. The power supply itself is protected by turning off the SCRs in the input to the step-up transformer until the "off" time ends, at which point the cycle is ready to repeat if necessary. The efficiency is ~95% for all outputs because there are no large dissipating elements like the vacuum tubes in the other units.

This unit is supplied in a cabinet, 1.4 m x 1.5 m x 1.8 m, weighing about 1250 kg, plus a small control panel that can be separately mounted. An input of 460 V, 3-phase, 60 Hz, 110 kVA line power is required. Cooling is easily accomplished by fans using room air, because little power is dissipated in the supply. Figure 3 shows a comparison of sizes for the shunt style supply and the power

supply used for the external interrupter. The remote control panel contains the operator controls, output meters, status indicator lights, and connections for remote operation. A 15-m cable to the power cabinet allows locating it conveniently for the operator.

The power cabinet contains the circuit breakers and relays for switching the input power; the auto-transformer, step-up transformer, and rectifiers to produce the high-voltage output; and the SCRs and their trigger circuitry for current interruption and protection against short circuits.

There are two sets of SCRs, one on the input to the high-voltage step-up transformer and one on the output of the supply. The input set is composed of standard modules incorporating circuitry to turn off the input and to automatically limit the line current input to a preset amount. Turning off the input allows the output SCRs to recover from their shunting action; the current-limiting feature provides backup protection to the supply and load if the trigger or output shunt circuitry fails.

The shunt set of SCRs are specifically selected to withstand the rigors of routinely shorting a high-voltage, high-power supply. The shunt SCR trigger circuitry is a modified standard SCR power supply circuit board. This type of unit is estimated to cost less than \$40K in 1985 dollars.

## 4.0 TEST METHODS

### 4.1 EQUIPMENT USED--METERS, SCOPES, LOAD BANK

Standard voltage and current meters were used to make the DC measurements on the supplies. A high-current, high-frequency, noncontacting current probe and a 20-MHz bandwidth digital storage oscilloscope were used together to measure the response to arcs and short circuits. The noncontacting probe could easily and safely be placed around a high-voltage lead to examine the currents flowing in it. The digital storage oscilloscope made it easy to record and examine the arc currents, despite their random and transient nature.

The three units were initially tested using the special "load bank" described below to simulate a sputtering system target load, including the arcs. This method is much simpler, quicker, and cheaper than using an actual sputtering system because "arcs" can be simulated on demand, rather than occurring at random (or not at all) as with a sputtering system. The load bank consisted of banks of high-wattage resistors that could be connected in series/parallel arrangements for testing at several voltage and current levels. A high-current, vacuum-insulated relay connected across the inputs was used to short-circuit the resistors, simulating the low impedance of the target load during an arc.

#### 4.2 POWER-OUTPUT TESTING

Each unit's voltage and current output, regulation, ripple, and efficiency were determined by using both the load bank and a sputtering system to apply known loads to their outputs and then measuring the values needed.

#### 4.3 CURRENT-INTERRUPTER TESTING

The first phase of testing each unit's current-interrupting capability used the load bank as shown in Figure 8. During testing, the voltage was raised to the test value and the shorting relay was activated. The unit's response was measured using the current probe and digital storage oscilloscope and then was recorded on film with a camera.

The second phase of testing was done on a sputtering system, with the target electrode connected in place of the load bank shown in Figure 8. The response of each unit was measured as described above. The measurements made on the sputtering system were comparable to those made on the load bank. It was not necessary to use a gas implantation system for these measurements, as the target arcs are not affected by what is happening on the substrate.

#### 4.4 SYSTEM-INTERACTION TESTING

The effect of interruptions of the target power supply current on a sputtering system's operation during gas-trapping can be substantial;<sup>(8)</sup> because the interactions with the system's other elements are complicated and hard to

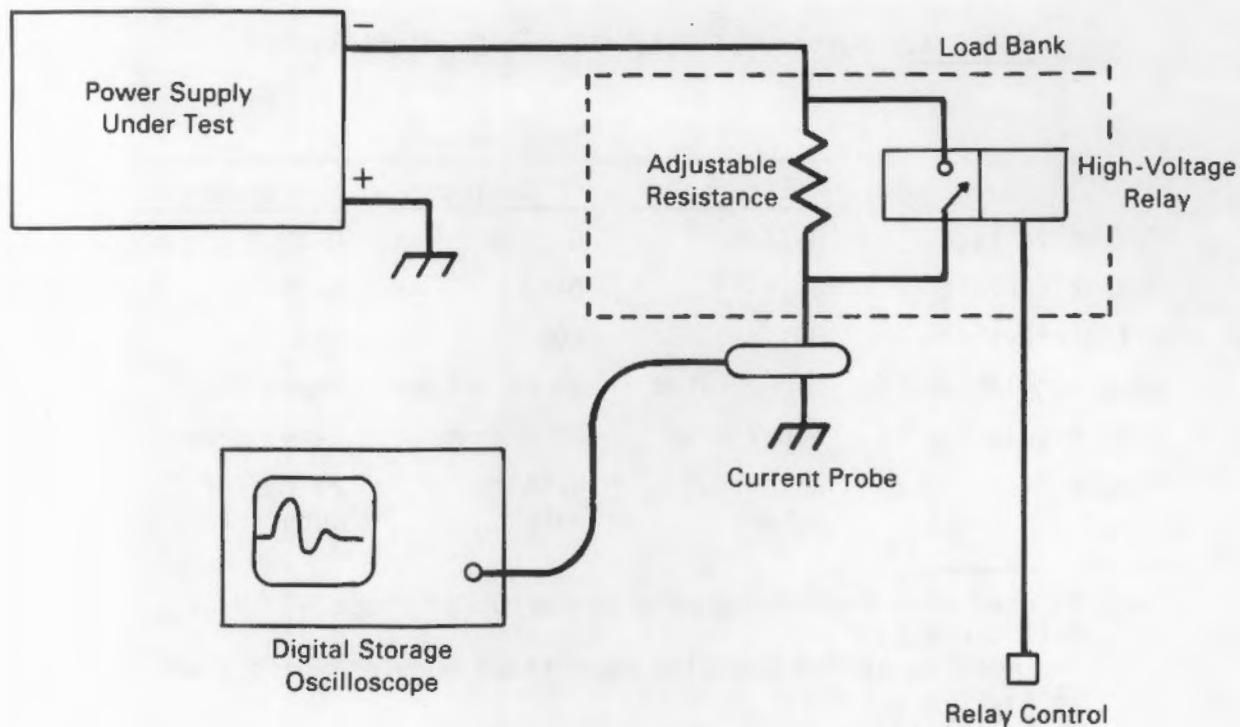


FIGURE 8. Testing on the Load Bank

simulate, this testing must be done on a sputtering system while it is actually trapping gas. The power supply parameter with an overriding effect is the length of time the current interruption lasts; normally the shorter it is, the quicker the system recovers; nevertheless, it must be long enough to quench the arc. Each unit was tested by using it to power the target on KTSDs with target areas of 545 to 980 cm<sup>2</sup>. During the target arcs, the system's response was noted as the length of the current interruption was varied.

## 5.0 RESULTS AND DISCUSSION

Table 1 summarizes the operational characteristics of the three types of units.

TABLE 1. Summary of Output Power Characteristics

	Type of Unit		
	External	Series	Shunt
Output voltage	0-2500 <sup>(a)</sup>	0-3000	0-3000
Output current	0-14 <sup>(b)</sup>	0-24	0-24
Efficiency <sup>(c)</sup>	80%	60%	95%
Line regulation <sup>(d)</sup>	Unregulated	1% of output	Unregulated
Load regulation <sup>(c)</sup>	500-V drop	10-V drop	240-V drop
Ripple	2% rms of output	0.5% rms of output	2% rms of output

- (a) As used with 0-3000 V supply (interrupter drops 500 V at full current).  
 (b) Two modules at 7-A capacity each (four modules would give 28 A).  
 (c) At full load.  
 (d) For 10% line input variation.

### 5.1 ARC RESPONSE

Figure 9 shows a comparison of the typical arc responses of the three units, using a common time and current scale.

#### PNL External Unit (curve 1)

The low impedance of an arc causes the current from the supply to increase until the current capacity of the interrupter is reached. When the modules can no longer pass any more current (about 9 A per module at outputs above 1500 V), the output voltage falls to a few volts. Within a few microseconds of the start of the arc, the interrupter controller has sensed the overcurrent and commands the modules to shut off. By 25  $\mu$ sec, the current is off, then is held off for a given period.

The charge delivered to the arc is about  $2.1 \times 10^{-4}$  sA (9 A for 20-25  $\mu$ sec) per module. For the two-module system tested, it would be  $4.2 \times 10^{-4}$  sA. The energy delivered is not well known because it is difficult to determine the arc voltage, due to the large difference between the 2500-V

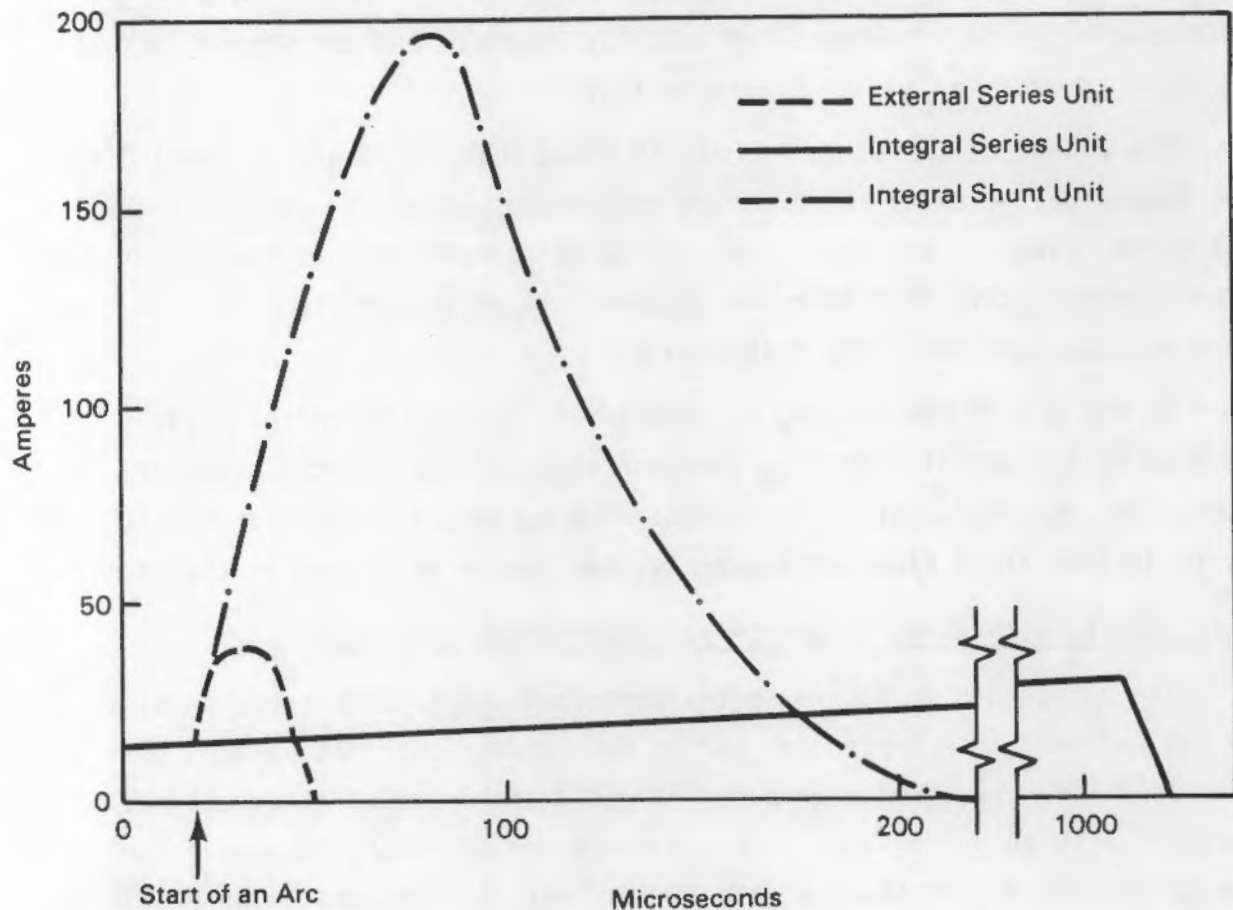


FIGURE 9. Comparison of Arc Responses of the Three Different Units

operating level and the less than 50-V arc level, the rapid change in voltages, and the electrical (rf) noise from the arc. The arc voltage appears to be about 20 to 40 V.

At the end of the interruption cycle time, the current is turned back on. If a low impedance still exists, the current exceeds the controller setpoint, restarting the interrupt cycle. In this case, the current does not rise to the module's peak capacity, but only to the setpoint. The charge delivered in this case would be about  $0.5 \times 10^{-4}$  sA per module, because of the lower peak currents, shorter "on" cycle, and triangular wave form.

#### Power Supply with Integral Series-Type Interrupter (curve 2)

Unlike the external interrupter unit, the output current does not rise rapidly when there is an arc. The output voltage still goes to a low value

immediately, but the regulator circuitry will let the current rise only at a 20 A/msec rate; once the setpoint value is reached, the current is interrupted in about 20  $\mu$ sec for an adjustable period.

The charge delivered to the arc is about  $300 \times 10^{-4}$  sA, or about 100 times the amount delivered by the external interrupter unit. Again, the actual energy delivered is not known, but should be proportional to the charge delivered; consequently, much more energy goes into an arc before it is extinguished than with the external interrupter unit.

At the end of the period, the current is allowed to increase again until it reaches the normal operating level or it again reaches the setpoint; in that case, the interrupt cycle is repeated. The current increases at the same rate as it did the first time; consequently, the charge delivered is the same.

#### Power Supply with Integral Shunt-Type Interrupter (curve 3)

The output has no active series-connected current interrupting element as do the external interrupter and series interrupter supplies, but it does have some filtering capacitance in parallel and a small amount of inductance in series. When an arc or short circuit occurs in the load, the capacitor's energy is dumped into it at a rate limited only by the power supply's inductance and any external inductance that exists. SCRs shunting the output are turned on as the output current exceeds the setpoint, shorting the output and thus diverting the current around the load. Simultaneously, the SCRs on the input side of the output transformer are turned off to remove power from the supply output. This protects the supply components from high currents due to the shorting SCRs and allows the SCRs to recover to their "off" state. Actual time to shut off the current is about 200  $\mu$ sec.

The charge delivered to the arc is about  $110 \times 10^{-4}$  sA, intermediate between the other two units. The peak currents, however, are so much higher (150 A versus about 25 to 30 A) that the charge delivered may not be a good measure of the relative arc energy into the target. Because of the very high peak currents, the voltage on the target at the onset of an arc is more difficult to determine than for the other two units.

At the end of the interruption, the SCRs on the input side of the output transformer are turned on, allowing the output voltage to return to its former value. If the load is still shorted, the output shunt SCRs are switched on as before, again diverting the current around the load. A major difference in the second and subsequent cycles is the reduction in energy dumped into the load by the output filter capacitors, because the voltage has built up to only a few volts before the interruption cycle repeats.

## 5.2 OPERATING STABILITY DURING GAS-TRAPPING

The process responded identically to the external interrupter and series interrupter units for the same current interruption period. Both units could be adjusted for a current interruption of 10 to 120 msec. At 120 msec, system operation was severely affected by pressure fluctuations whenever a target arc occurred. Reducing the interruption time reduced the process upset; below 15 msec essentially no upset would occur. Because the shunt interrupter supply uses SCRs operating at line frequency (60 Hz) to restore the output, it could not recover as quickly. The shortest off-time it could tolerate was about 60 msec. With this length of interruption, the process would still suffer significant upset.

## 5.3 COSTS

The differences in complexity of the three units are reflected in their purchase cost. Table 2 shows the cost of each unit and its effect on the cost of a commercial implantation facility, based on the preconceptual design documentation by the Ralph M. Parsons Company.<sup>(7)</sup> The table shows the purchase costs (estimated in 1985 dollars) and the percent values as based on the cost figures from the preconceptual design for the DOE:<sup>(7)</sup> the estimated 1985 dollar costs were adjusted by multiplying by 0.78 to match the 1981 figures used in the study. While the values are only estimates based on the acquisition of the prototypes during 1982-3, it is believed that the relative costs are representative.

Target power electricity costs for the process are about 5% of the life-cycle costs of a production facility, based on a supply with 100% efficiency.

TABLE 2. Costs of Eight Required Units Related to Total Plant Capital and Life-Cycle Costs

	<u>Capital Cost (a)</u>	<u>Capital Cost, % (b)</u>	<u>Overall Cost, % (c)</u>
External series unit	65,000	4	7.2
Internal series unit	130,000	8	10.7
Internal shunt unit	40,000	2.4	5.7

(a) Estimated in 1985 dollars.

(b) Capital cost as percent of total capital cost. (7)

(c) Capital plus operating cost as percent of total life-cycle costs. (7)

The increase in power costs that each of the tested supplies would cause, due to their varying efficiencies, would be: external series unit, 25%; internal series unit, 65%; and internal shunt unit, 5%.

All three units are expected to be reliable enough in production versions that maintenance costs would be a small fraction of capital and operating costs. The greater complexity and use of life-limited vacuum tubes in the two series units (particularly the internal series unit) would probably entail more maintenance costs than the shunt unit and longer to repair when a failure occurred. Nonetheless, the reliability is dependent on the specific production design and cannot be evaluated from the prototype units.

#### 5.4 POTENTIAL IMPROVEMENTS

There appear to be no changes that would significantly improve the external interrupter unit's functions or cost.

For the series interrupter unit, "preregulating" the high-voltage supply with SCRs would reduce the power dissipated in the output regulator at voltages less than full output. Even though the cost of the high-voltage portion would increase somewhat, this improvement would reduce the cost of the output regulator and would slightly lower the overall cost. While the partial load efficiency would also increase, the electrical savings would be very small due to the high percentage of full output during a trapping run.

A useful functional improvement would be a considerable decrease in the charge delivered to an arc. This could be achieved by beginning the current interruption at the sudden drop in output voltage caused by an arc, rather than waiting for the current to increase to the setpoint. The charge delivered would decrease from  $300 \times 10^{-4}$  to  $2 \times 10^{-4}$  sA, or about the same as with the external interrupter unit.

With the shunt interrupter unit, there is little leeway for cost reduction, as it already has the lowest cost and highest efficiency of the three units evaluated. Several functional improvements, however, must be made before it can be used on a production system.

Both the peak current and the total charge delivered could be reduced considerably by eliminating the filter capacitor in the output. This would require some small changes in the gating circuitry for the shunt SCRs. Further improvement might come from a small increase in the output inductance, as this would also reduce the peak currents.

The major problem, however, is the slow recovery of the output voltage after an arc-suppression cycle. The use of SCRs at the 60-Hz line frequency imposes a fundamental limit of about 20 to 30 msec on the recovery speed. Even with the careful design and component selection needed to approach this limit, this time may still be too long. Using a higher line frequency of, say, 400 kHz, would perhaps allow a design that was fast enough. The extra cost of the 60 Hz to 400 Hz input power converter plus its losses of efficiency, however, would reduce and possibly eliminate the advantage of this concept.

Changes in the other components of the sputtering system might make the recovery time less critical. For example, improving the response of the pressure control system to transients, permitting continuous, high-volume pumping with a recirculating pump, or using a "ballast" volume to diminish the pressure rise are possible methods for reducing process upsets caused by long interruptions of current.

## 6.0 SUMMARY AND CONCLUSIONS

The implantation of  $^{85}\text{Kr}$  in a growing sputtered metal deposit requires a high-voltage power supply to power the target of the krypton trapping storage device (KTSD). The most important aspect of the supply is its ability to quickly suppress arcs occurring in the KTSD without disturbing the implantation process.

The method used to suppress arcs in the KTSD greatly affects the process stability, the capital cost of the equipment, and the operating cost (primarily electricity). Three power supplies were evaluated, each of which used a different method. They were: 1) power supply with an external series interrupter; 2) power supply with an integral output controller/interrupter; 3) power supply with a shunt interrupter. The effect of the combined capital cost and the electrical efficiencies of the three power supply/current interrupters changed the life-cycle costs, based on the Ralph M. Parsons study,<sup>(7)</sup> only 5%.

The external and internal series units, with suppression periods of ~10 msec, both performed satisfactorily with the KTSDs used. The shunt-type interrupter's longer suppression period (~60 msec) was not fast enough to avoid upsetting the sputtering process, but was otherwise satisfactory. Because this unit had the lowest costs, it may be worthwhile to further develop it (to improve its recovery after an arc-suppression cycle) or the KTSD and its pressure-control system (to mitigate the effects of the slow recovery).

The reliability of each power supply tested was not evaluated in this study because each unit was considered, at most, only a prototype of the units that would be used in a production facility. It appeared that all three methods could be implemented with sufficient reliability for a production facility.

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