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Research and Development Technical Report

ECOM-76-1352-F

FORTY KILOVOLT MEGAWATT AVERAGE POWER THYRATRON (MAPS 40)

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Oct[redacted]77

55p.

Final Report [redacted] 20 May [redacted]76 [redacted] 15 Jul[redacted]77

DAAB07-76-C-1352

1L762705AH94

Prepared for:

ECOM

US ARMY ELECTRONICS COMMAND FORT MONMOUTH, NEW JERSEY 07703

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1. REPORT NUMBER: ECOM-76-1352-F	2. GOVT ACCESSION NO.
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle): Forty Kilovolt Megawatt Average Power Thyratron (MAPS 40)	5. TYPE OF REPORT & PERIOD COVERED: Final 20 May 76 thru 15 Jul 77
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s): J. J. Hamilton, D. V. Turnquist	8. CONTRACT OR GRANT NUMBER(s): DAAB07-76-C-1352
9. PERFORMING ORGANIZATION NAME AND ADDRESS: EG&G Incorporated, 35 Congress Street, Salem, Massachusetts 01970	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: 62705, 1L762705.AH.94.E1.05
11. CONTROLLING OFFICE NAME AND ADDRESS: US Army Electronics Command, ATTN: DRSEL-TL-BG, Fort Monmouth, NJ 07703	12. REPORT DATE: October 1977
	13. NUMBER OF PAGES
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	15. SECURITY CLASS. (of this report): Unclassified
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for Public Release; Distribution Unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Thyratron
Switch
Gas-filled device
Hydrogen discharge

20. ABSTRACT (Continue on reverse side if necessary and identify by block number) The purpose of this 12 month program is to develop a 40 kilovolt-megawatt average power thyratron. Electrical objectives are to switch 40 kiloamperes at 40 kilovolts with a pulse width of 10 microseconds and a repetition rate of 125 hertz. A thyratron design to meet these objectives was evolved.

Following extensive development in the areas of electromechanical design, processing and testing, as well as special design and evaluation effort,

20. Abstract (continued)
several thyratrons were fabricated which met the objectives of the program to the extent that it was possible to evaluate them with existing facilities at ECOM.

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1. INTRODUCTION

The purpose of this final report is to provide an overall summary of the work performed on behalf of the U. S. Army Electronics Command, Fort Monmouth, New Jersey, on the development of a 40-Kilovolt, Megawatt Average Power Thyratron (MAPS-40) under Contract No. DAAB07-76-C-1352, between the commencement date of May 20, 1976 and July 15, 1977.

For ease of reference, the principal performance objectives for the required thyratron switch are listed in Table 1.

Following a period of intensive learning and design parameter decision effort (reported in Interim Report ECOM-76-1352-1, May 1977) for the fabrication of a series of developmental and prototype tubes, eight thyratrons were constructed, five of which were delivered to Fort Monmouth for full-scale testing.

Electrical evaluation of the last four prototype thyratron switches furnished sustained evidence of meeting their specified objectives. These switches were tested to the maximum extent possible, without unduly taxing existing facilities at the Fort Monmouth test laboratory.

An external view of the resulting thyratron design is presented in Figure 1. The outline drawing of Figure 1A contains essential envelope dimensions.

Table 1. Major Specification Objectives for MAPS-40 Thyratron.

Parameter (Units)	Rating	Operation (1)	Operation (2)
epy (kV)	40	44	44
ib (ka)	40	44	11
tp (μs)	--	10	20
prr (Hz)	500	125	250
Ib (A dc)	50	50	50
Ip (kA ac)	1.4	1.48	0.74
Pb (10^9 va/s)	400	242	121
dik/dt (ka/μs)	20	20	20
tad (μs)	--	0.2	0.2
Δtad (μs)	--	0.1	0.1
tj (μs)	0.02	--	--
Ef=Eres (Vac)	15 ± 1.5	--	--
If (A ac)	70	--	--
Ires (A ac)	40	--	--
tk (sec)	900	--	--
Life (pulses)	--	5×10^6	5×10^6
egy to be between 1500 and 4000 volts.			

Notes for Table 1:

The conditions listed above describe the on-cycle or burst conditions. The 300-second off-periods in Operations (1) and (2) reduce the average conditions to:

Ib (A dc) = 5

ip (A ac) = 442

Other conditions:

Standby	48 hours – heaters only
Reliability	25 pulses (max) - extra or missing pulses during life
Weight	25 lb (max)
Volume	0.5 cu ft (max)

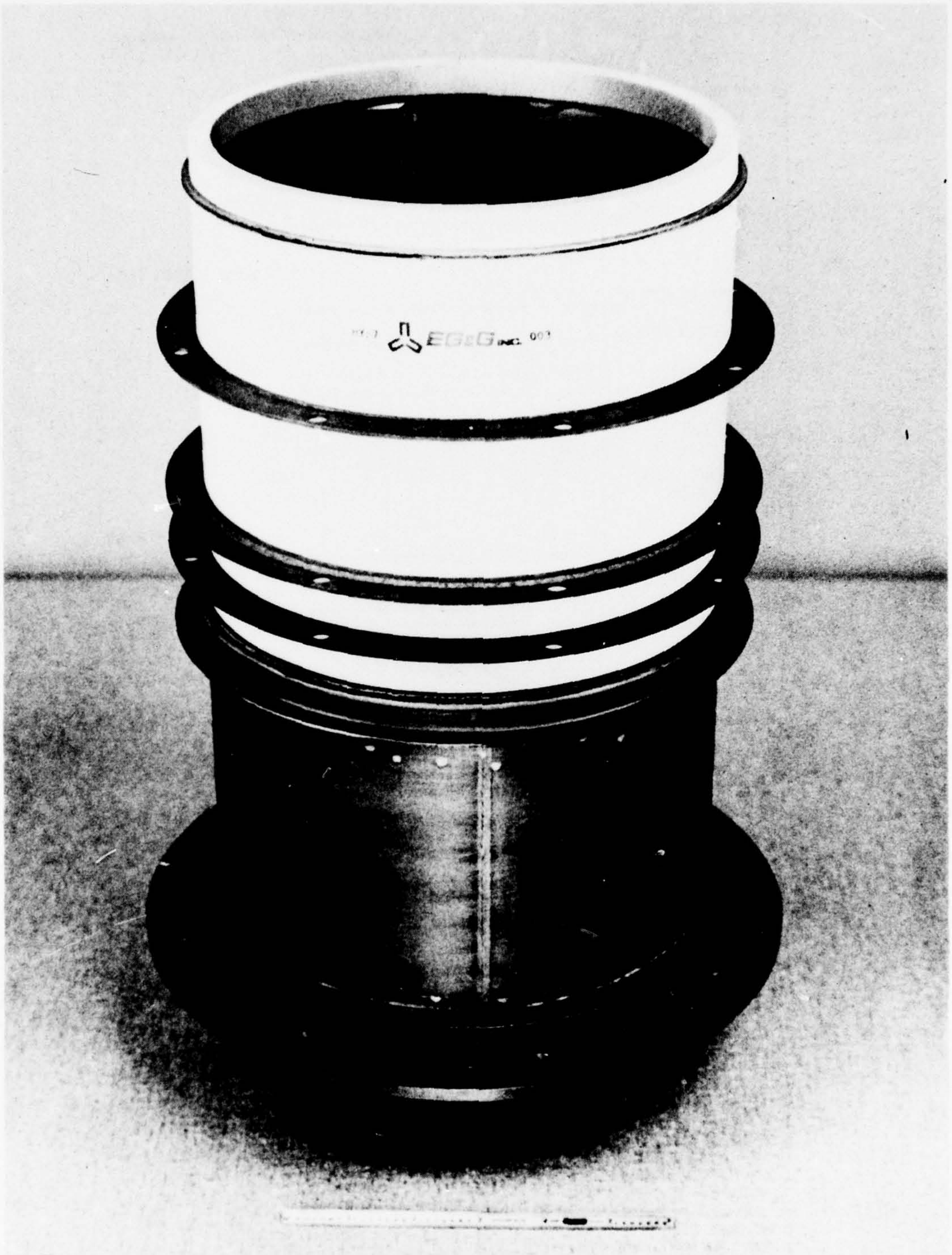
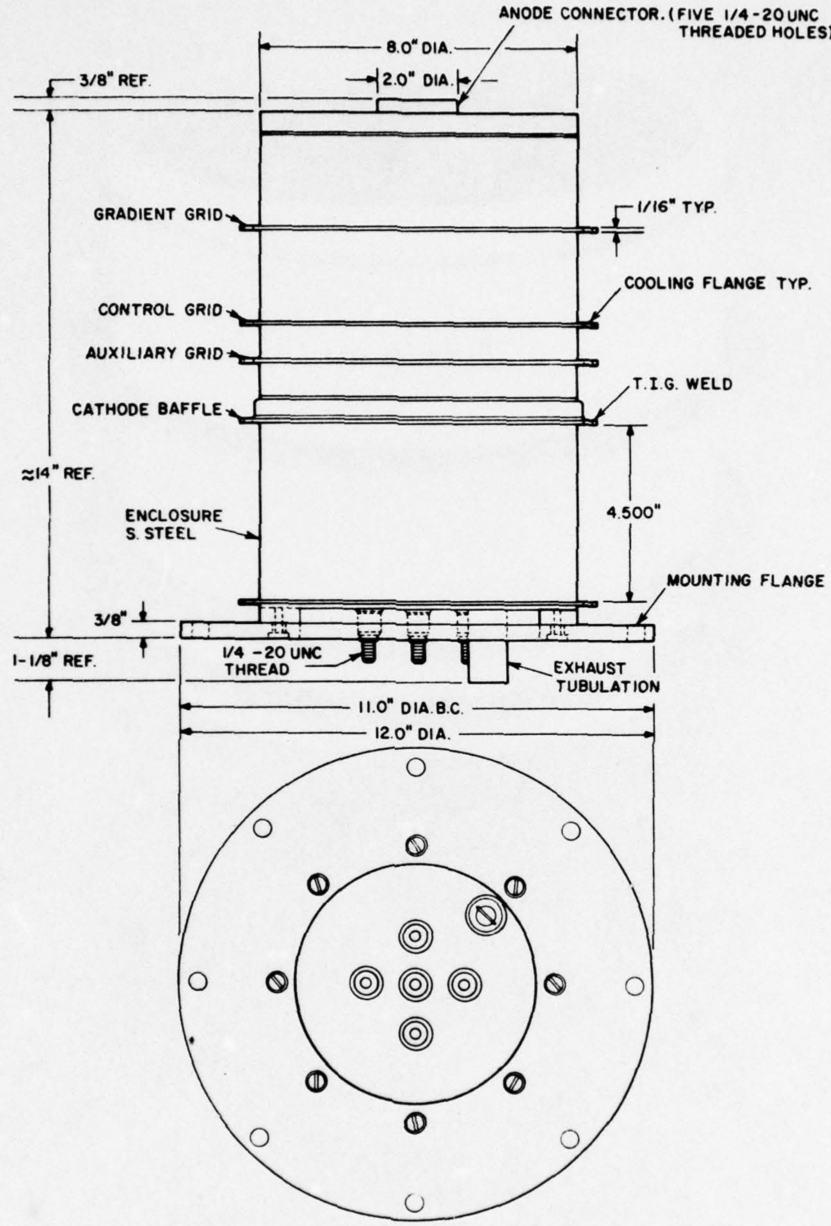


Figure 1. External view of MAPS-40 Thyratron.



NOTES:

1. FOUR FEEDTHRUS 90° APART ARE HEATER CONNECTIONS. CENTER FEEDTHRU IS RESERVOIR CONNECTION
2. CONNECTION LEADS (5) 14" LONG WILL BE SUPPLIED WITH EACH TUBE.
3. SPECIAL 1/4-20 HARDWARE WILL BE SUPPLIED FOR SECURING TO COOLING FLANGES.

Figure 1A. MAPS-40/HY-7 Outline Drawing.

2. DESIGN CONSIDERATIONS

Design goals for the subject development were defined in the Technical Guidelines entitled "40 Kilovolt-Megawatt Average Power Thyratron (MAPS-40)," and are summarized in Table 1.

Distinguishing features of the objective specifications were those addressing the attainment of the following extrapolated performance levels:

1. Operation at an epy level of 40 kilovolts.
2. Discharge into a one-half ohm load, equivalent to 40 kiloamperes of peak current.
3. An rms current of 1400 amperes.
4. Reliable switching under stress conditions imposed by an adiabatic mode of operation.
5. An average power of 1 megawatt.

The design of a hydrogen thyratron capable of meeting these objectives was reviewed in great detail and in the light of recent inputs derived from related MAPS thyratron programs. Principal design factors considered in this analysis are outlined below.

In the grid-anode region, particular attention was given to forward voltage hold-off by introducing a gradient grid and designing a cathode of minimal material migration, optimizing the form factor and the baffling of the control and gradient grid apertures, as well as their individual thicknesses, and filling the tube with deuterium.

Available experimental information indicated that a total grid aperture area of approximately 7-1/2 square inches would be necessary to circumvent the quenching problem. Development of an 8-inch diameter ceramic tube was the direct consequence of this design decision.

Inverse hold-off continued to be a serious problem because of the peak current levels involved. A "virtual anode" approach was introduced to help alleviate this situation.

Grid dissipation was considered in its multifarious aspects and in light of the adiabatic mode of operation. Adequate thermal mass and conductivity were incorporated in the design to offset potential instabilities. Refractory metal was applied to areas of maximum thermal stress. Extensive use was made of molybdenum to resist and attenuate the more damaging end-products of arcing.

Design of the auxiliary grid and cathode baffle adhered to standard thyratron practice. The hydrogen reservoir was studied from the standpoints of adequate storage capacity and response time, as compared to the enormous amount of gas clean-up anticipated during the long "on" cycles of operation.

While a number of areas of mild to serious uncertainty existed at the time of tube design, no physical limitation of a magnitude which might preclude the feasibility of achieving the specified performance became evident in the course of the foregoing analysis.

Cathode design considerations were especially intricate in view of the severe stresses imposed by the burst mode and the high rms current conditions of operation. Cathode surface emissivity and utilization were analyzed conservatively. Careful attention was paid to the problem of adequately supporting and current feeding the vane structure. The thermal properties of the structure were examined under full operating conditions in order to prevent the occurrence of potential thermal vane-tip runaway effects.

During the course of the MAPS-40 development several of these design considerations were partially or fully evaluated.

Current quenching was averted, by the design provisions, to a level of approximately twice the objective maximum peak current specified.

Inverse hold-off was as serious a problem as anticipated, and in fact was virtually non-existent. The use of inverse clippers in parallel with the tube became mandatory.

While secondary thermal analysis of the grid region is incomplete as of this writing, visual examination of the condition of these electrodes in dissected tubes provided ample evidence of the adequacy of the thermal design. Monitoring the individual cooling ring or connector temperatures during high power testing, as well as the operating stability of these tubes, supplied data corroborating the visual tests.

The design of the reservoir received considerable scrutiny; as a result, three separate areas in need of attention were identified:

1) A heater open-circuit problem, which was rectified by incorporating proper stress relief to the input turns of the convoluted reservoir heater as shown in Figure 2.

2) A point of inversion, believed to be due to thermal variations in the reservoir itself, was observed in the voltage-pressure characteristic of the reservoir, as evident from Figure 3. Whereas this deviation does not hamper the performance of the tube per se and, in fact, under the right circumstances might be considered stability-wise as an asset, the phenomenon is under study and will be addressed in the near future.

3) The thyratron's preference to operate at two different settings of the reservoir voltage under cold start-up and hot running

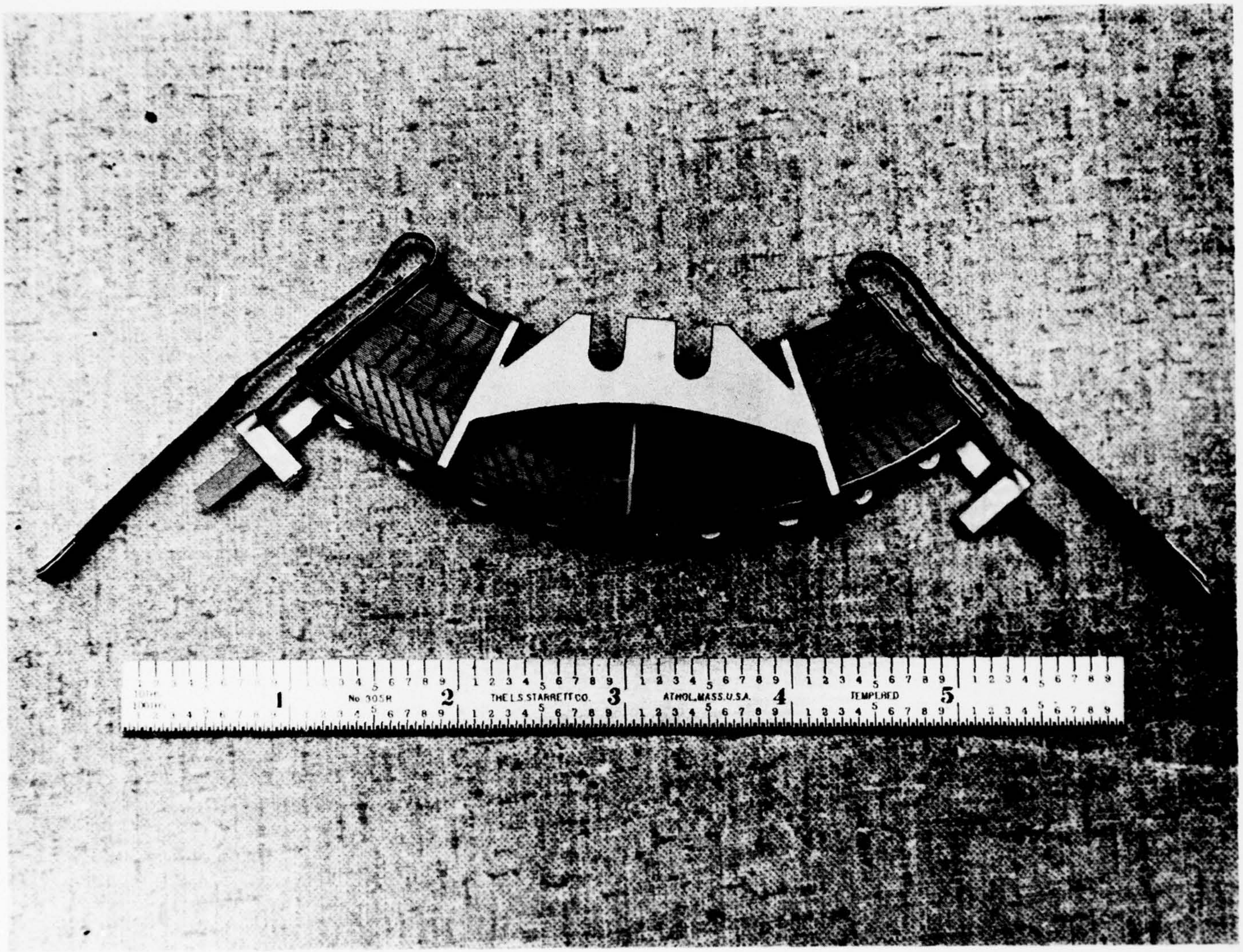


Figure 2. Stress-relieved MAPS reservoir design.

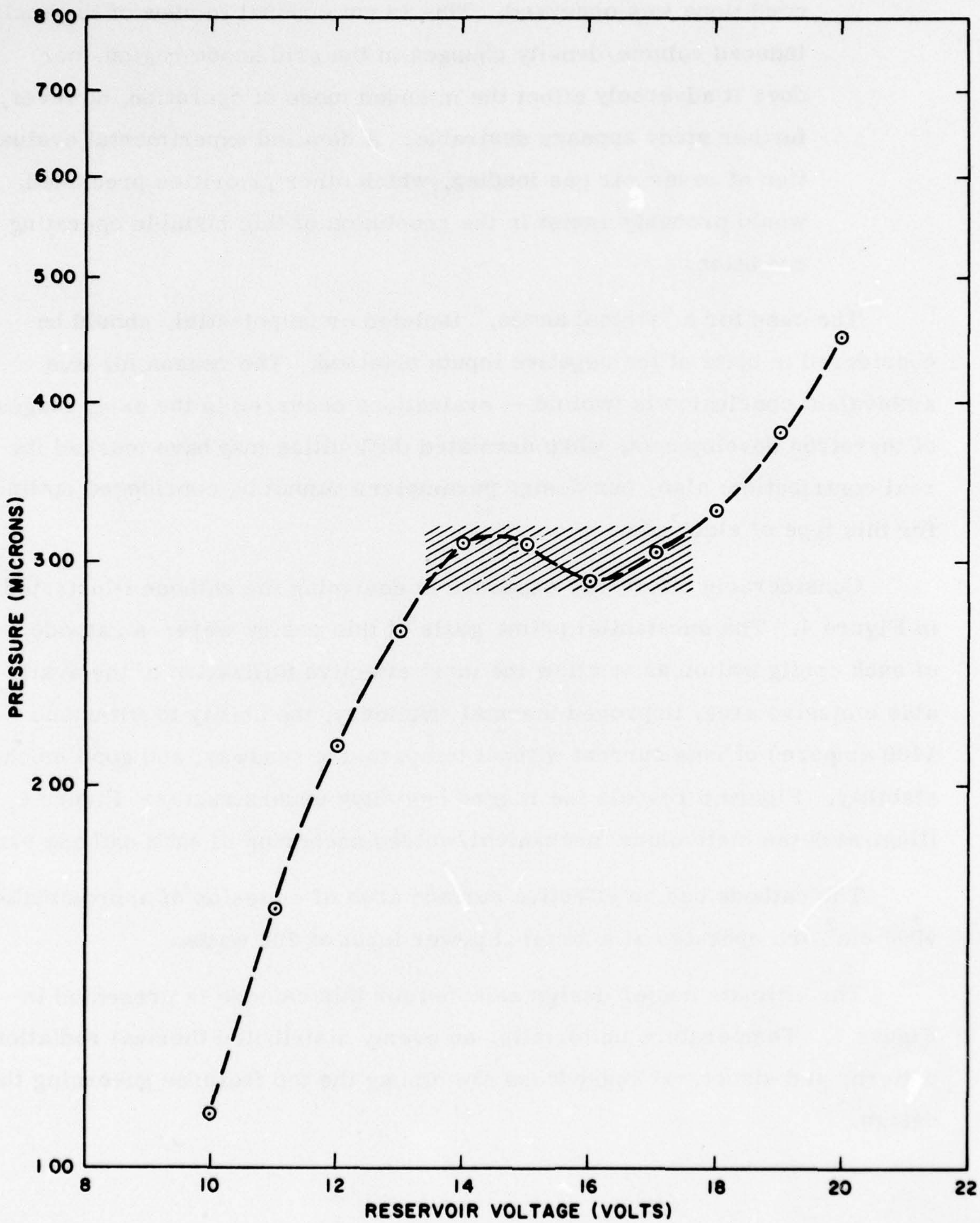


Figure 3. MAPS-40 reservoir voltage versus deuterium pressure characteristic.

conditions was observed. This is not unusual in view of thermally induced volume/density changes in the grid anode region, nor does it adversely affect the intended mode of operation; however, further study appears desirable. A detailed experimental evaluation of reservoir gas loading, which other priorities precluded, would probably assist in the resolution of this bistable operating condition.

The case for a "virtual anode," isolated or unipotential, should be considered in spite of the negative inputs obtained. The reason for this ambivalent conclusion is twofold — evaluations occurred in the early stages of thyratron development, when unrelated difficulties may have masked its real contribution; also, our design parameters cannot be considered optimized for this type of electrode.

Considerable effort was expended in designing the cathode illustrated in Figure 4. The substantial prime goals of this design were: a cathode of such configuration as to allow the most effective utilization of the available emissive area; improved thermal efficiency; the ability to withstand 1400 amperes of rms current without temperature runaway; and good mechanical stability. Figure 5 reveals the rugged hastelloy understructure; Figure 6 illustrates the meticulous mechanical/welded anchoring of each cathode vane.

The cathode has an effective surface area of emission of approximately 4000 cm^2 and operates at a nominal power input of 900 watts.

The ultimate heater design selected for this cathode is presented in Figure 7. Temperature uniformity, an evenly distributed thermal radiation pattern, and structural ruggedness are among the top features governing this design.

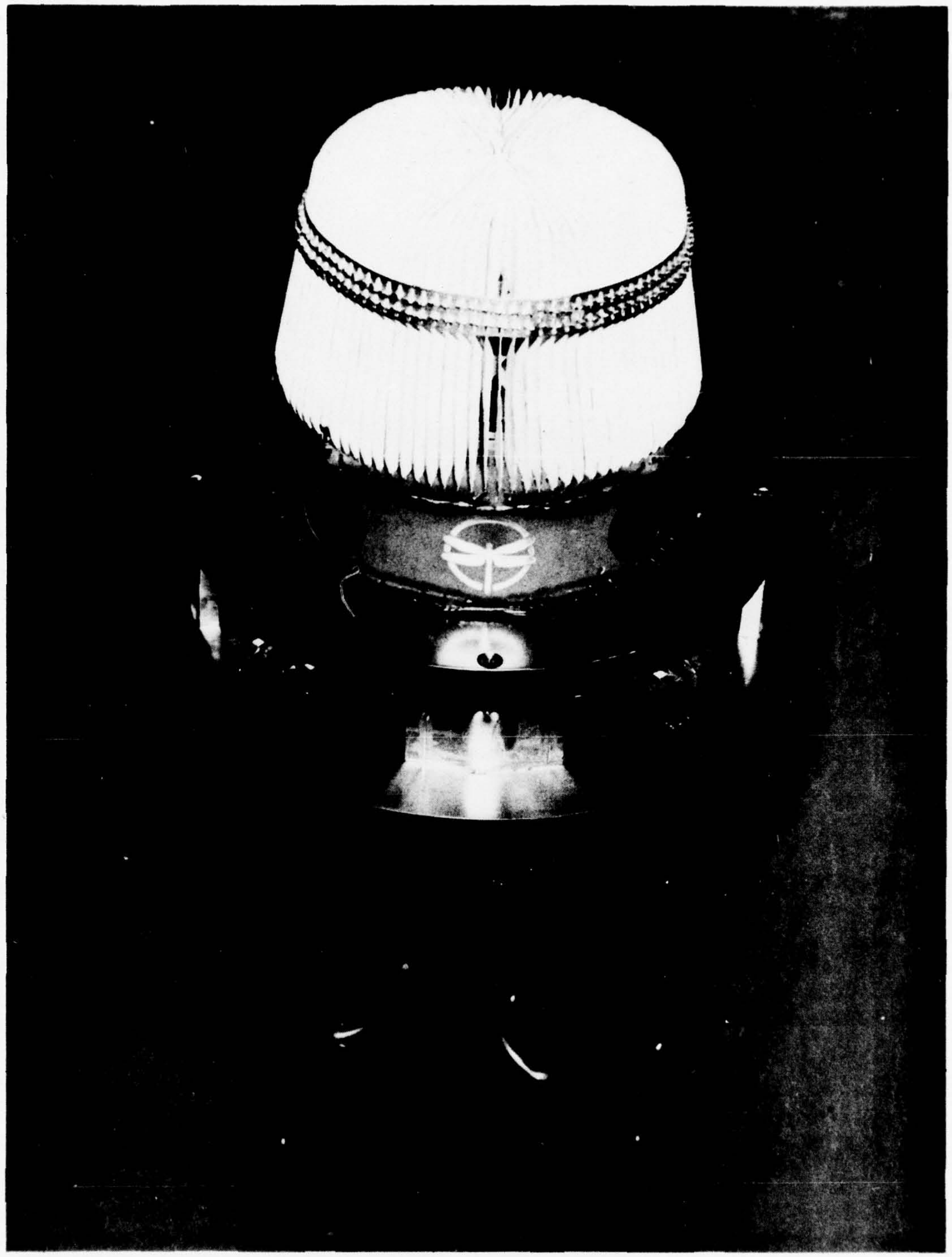


Figure 4. New MAPS-40 cathode configuration.

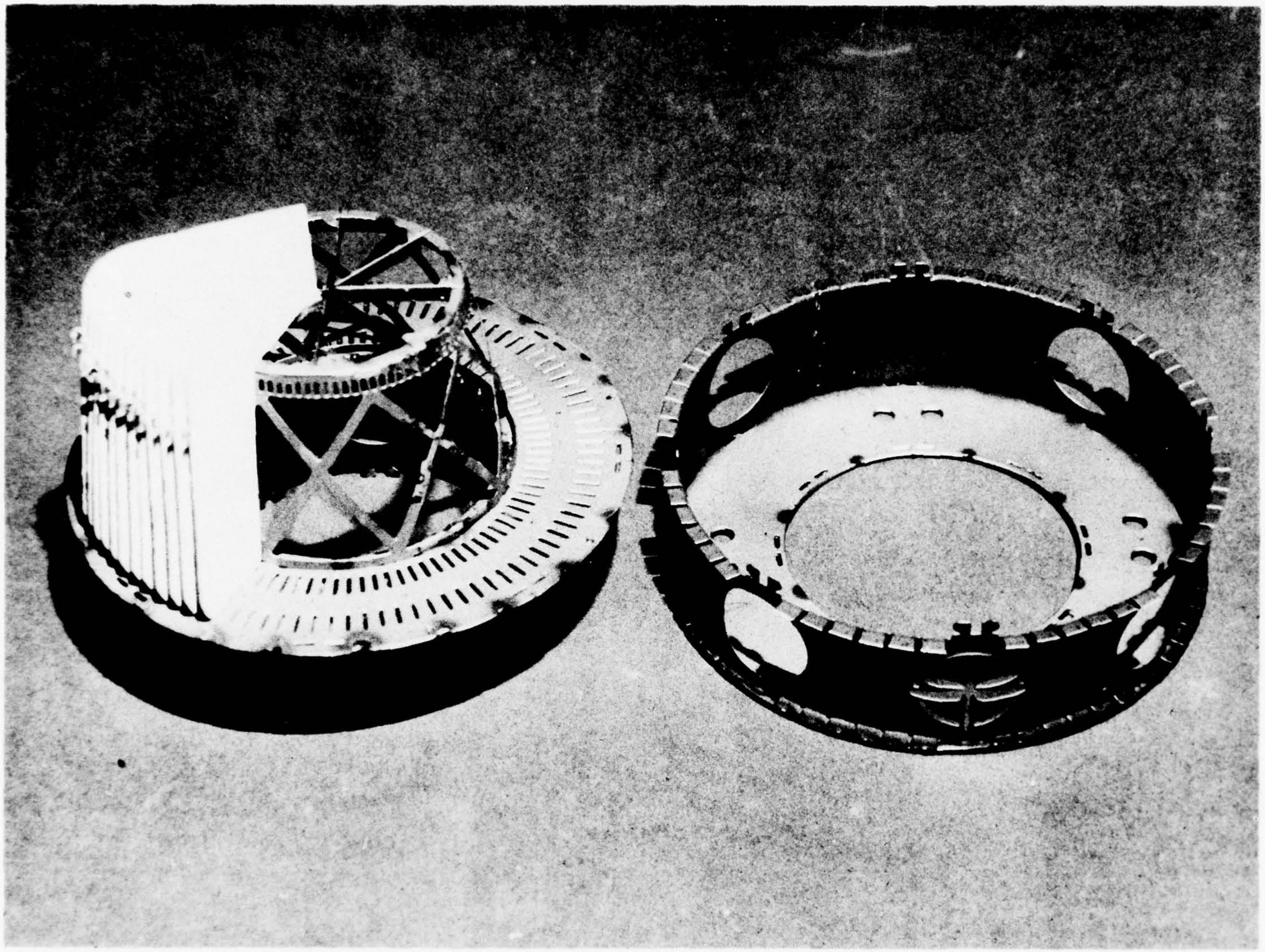


Figure 5. New MAPS-40 cathode understructure.

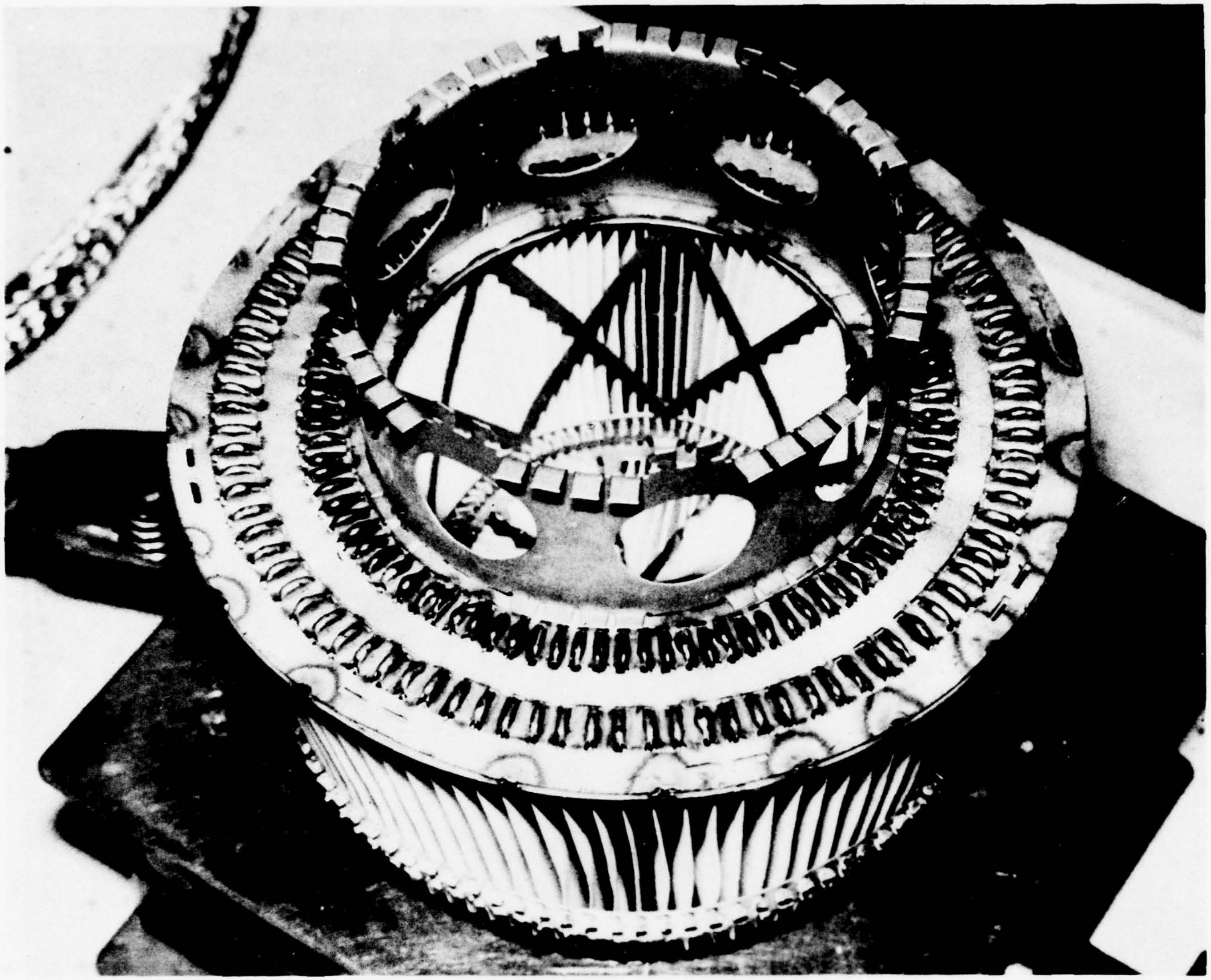


Figure 6. New MAPS-40 cathode: vane anchoring detail.

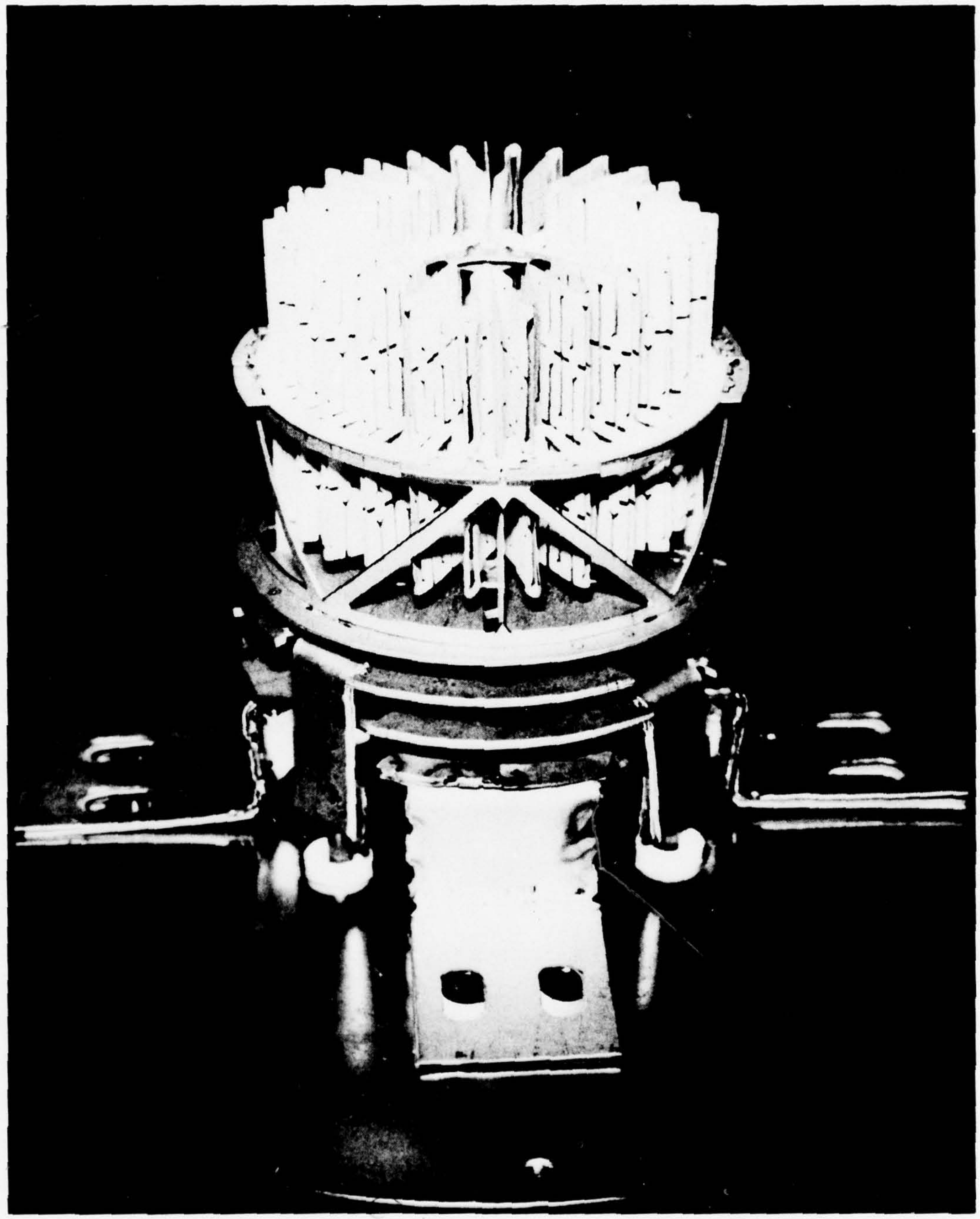


Figure 7. New MAPS-40 cathode heater design: final version.

3. TUBE DEVELOPMENT

To conserve valuable developmental effort, and simultaneously acquire vital information concerning prime areas of functional uncertainty, it was decided to conduct preliminary development in thyratron vehicles wherein the parameters under investigation would be modified to simulate operating conditions pertaining to the final MAPS-40 tube.

With this in mind, developmental tubes Q-001 through Q-004 and a special HY-5, all of which have a cylindrical ceramic diameter of 4-1/2 inches, were constructed for the specific reasons outlined in Section 4.

It was similarly agreed to build the earlier 8-inch diameter developmental MAPS-40 samples with a somewhat modified, existing 5000 cm^2 cathode, judged adequate for the intended service, prior to the development of a new, totally compatible cathode structure, so as to identify, diagnose, and rectify unforeseen problems in the remaining portion of the device at an early stage. Several other pertinent factors of lesser impact could also be checked, with the help of existing thyratrons, at the Salem laboratory.

The first two 8-inch diameter tubes were fabricated in accordance with initial paper design considerations, one with a regular and one with a virtual anode. As anticipated, in view of the massive nature of the electrodes as well as the overall body, dictated by the high average power level and mode of operation involved, several problems were encountered during the construction and subsequent testing of these two tubes. It was, in retrospect, fortunate that most of the crucial technological problems surfaced in these tubes, signaling areas of mandatory revision during the initial stage of development.

Improvements which led to the successful development of the MAPS-40 thyratron stemmed from three complementary directions:

1. Design refinement and tolerance control.
2. Processing improvements.
3. Improvements in aging and test techniques.

The following paragraphs highlight some of the essential steps taken in the course of the MAPS-40 hydrogen thyratron development work.

Brazing Refinements

Areas of marginal ceramic-to-metal sealing were buttressed and/or further compensated by the application of orthodox techniques to ensure survival of the 8-inch diameter interface through severe thermal cycling. Every effort was exerted to preserve the traditional structural simplicity of EG&G thyratron seals.

Incompatibilities arising from the brazing of electrodes consisting of dissimilar metallic elements, as in the anode, gradient grid, and control grid regions, were similarly resolved by the use of buffering or stress relieving techniques.

Electrode Configuration

A review of data obtained from testing two "virtual anode" tubes of different parameters shows that the negative influence of other factors present in those vehicles may have masked any beneficial contributions by the virtual anodes themselves. While the final tube design utilizes a regular anode, no hard evidence exists to assess the potential impact of introducing a virtual anode in the future.

Vernier control of interelectrode spacings was instituted with considerable advantage, together with enhanced concentricity of the stacked grids. A tightening of the anode-to-gradient grid spacing (to 0.120 inch) is also believed to have been of some benefit.

A heat choke introduced in the area of the circular auxiliary grid connector, in addition to enhanced, more uniformly distributed, forced-air cooling of the cathode enclosure, helped to reduce the maximum temperature reached by the auxiliary grid-cathode envelope ceramic spacer during high average power operation to a level consistent with accepted criteria for stable and reliable performance, as well as reasonable life expectancy.

Reservoir

The standard MAPS-40 reservoir heater exhibited a tendency to short at a point, a few turns away from the entrance of the hot-side lead into the reservoir structure. This failure was corrected through moderate redesign by fastening the reservoir heater head and tail securely, relative to the frame of the structure. Expansion differentials and other possible transmitted movements were taken up by yielding auxiliary leads, as shown in Figure 2. These modifications were introduced without compromising the proven features of the reservoir design.

Careful study of the fine grain voltage/pressure characteristic of the MAPS-40 titanium reservoir disclosed an atypical inversion between 14 and 17 volts. This phenomenon was studied further, and future heater design modifications are planned to restore it to a normal, approximately straight line, log-linear relationship.

Cathode

The 5000 cm^2 cathode heater was modified for nominal operation at 15 volts. Two clusters, seven individual heaters each, were introduced to obtain the proper V-I characteristic coupled with uniform heating of the cylindrical surface area of the cathode. This provisional arrangement worked out satisfactorily.

Development of the new MAPS-40 cathode design ran into unexpected delays. While the cathode structure itself translated into a first-class prototype requiring only slight refinement, the heater design proved more problematic. Two redesigns were necessary to satisfy stringent electrical and mechanical criteria.

However, this cathode design was subjected to vigorous tests prior to its introduction into the last MAPS-40 developmental sample. The final heater was subjected to operation at twice its nominal voltage and some 70 cycles at 15% overvoltage without evidence of degradation. The cathode structure underwent a simulated 1400-ampere, rms current, test without discernible signs of stress. Two marginal hot spots on the cathode mount were easily rectified.

The new cathode structure was also subjected to vibration testing, as shown in Figure 8, in the axial and orthogonal (worst) planes between 50 and 2000 Hz to an acceleration level of 10g without problem. The circular box-girder base proved to be resonance-free and while the vaned portion exhibited a number of resonances at 65, 110, 180, 270, 550, 625 and 800 Hz, the latter were quite controlled and innocuous. The structure thus exhibited mechanical endurance greatly superior to its 5000 cm^2 predecessor which, under similar vibration testing, experienced severe mechanical degradation.

The advanced design features of the new cathode withstood realistic trials satisfactorily and demonstrated potential for superior performance. Early test results on the first developmental sample incorporating the design were very encouraging.

Processing Improvements

Special attention was paid to the processing of the tubes fabricated during the program, which was essentially governed by the following broad guidelines:

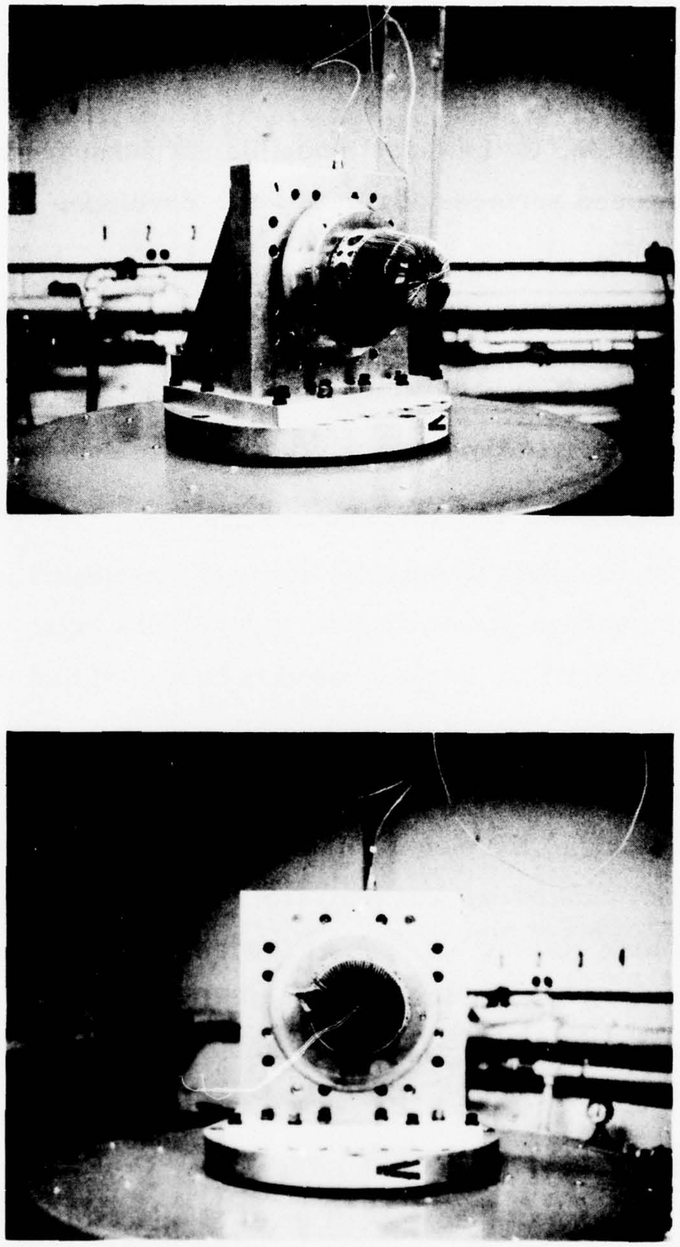


Figure 8. Vibration set-up for the new MAPS-40 cathode.

1. Control of adequate purity of raw materials.

2. Meticulous cleaning of all internal parts.

3. Prevention, to the extent possible, of subsequent contamination of exposed surfaces within the tube envelope.

4. Refinements in cathode breakdown and activation intended to leave the latter in a state of high and uniform electron emissivity.

The contribution of processing improvements toward the achievement of tube performance objectives is believed to be significant.

Improvements in Aging and Test Techniques

Meticulous attention to specific demands, peculiarities, and consequences of high average power switching during the aging and early test phases of the MAPS-40 thyratron proved to be a vital and indispensable link in the successful development of the tube.

From the relatively unsophisticated steps adopted — adequate and symmetrical cooling of the envelope, and the reentrant portion of the anode, continuous monitoring of critical temperatures, and gradual and systematic aging — to the less obvious but crucial procedures instituted, such as symmetric current feed, thyrite protection, and the provision of inverse clippers, each contributed measurably toward the achievement of the required performance.

Under these carefully controlled test conditions, five developmental type thyratrons reached the megawatt level of operation at ECOM. While preliminary low-power testing, to ascertain the absence of basic flaws in the delivered samples, was conducted at EG&G's switch tube facilities in Salem, all high-power aging and testing of the tubes was performed at the Fort Monmouth test laboratories, with the close assistance and cooperation of ECOM personnel. Pertinent test conditions are summarized in Table 2.

Table 2. MAPS-40 Typical Test Conditions and Operating Parameters at ECOM.

Test Conditions

1. Auxiliary grid biased positive with respect to cathode for ≥ 20 mA.
2. Gradient grid connected to anode and cathode by means of 20-megohm dividing resistors.
3. Thyrites inserted in the auxiliary and control grid circuits.
4. End of line inverse clippers installed.
5. Fans installed to provide symmetric cooling of the tube's envelope and anode.
6. Circular hoop connector attached to the anode stud to provide symmetric current flow.
7. Anode temperature thermometers installed.

Operating Parameters

1. Cathode heater voltage = 15.0 volts
2. Reservoir heater voltage = 11-1/2 volts.
3. Auxiliary grid current = 50 mA
4. Control grid drive voltage = 1500 volts.
5. Control grid drive impedance = 500 ohms.
6. Tube load = 1/2 ohm.

Start-Up

1. Pulse width: 10 microseconds.
2. Pulse rise time: 1 microsecond.
3. Repetition Rate: 10 pps, continuous.
4. Increase anode voltage in suitable increments to 40 kV.
5. Turn over to burst mode operation: 5 seconds on, 30 seconds off, and raise anode voltage gradually to 40 kV.
6. Increase number of pulses per second until the megawatt average power level is reached.
7. Increase burst mode "on" and "off" times as required.

The fact that all thyratrons which achieved the megawatt average power level were operable at the close of the program, with the exception of the MAPS-40, No. 003 sample which was accidentally sprayed with copper sulphate solution while undergoing extended evaluation tests, may be largely attributed to the special care exercised over testing.

In the process of applying maximum thrust in the direction of operable hardware fabrication, two valuable evaluations, in terms of calorimetry measurements on grids and reservoir capacity and transient/long-term clean-up, were not carried out as planned.

4. THYRATRON CONSTRUCTION

The following developmental and prototype thyratron samples were constructed during the course of the project:

<u>Q-001</u>

Design Parameters:	A 4-1/2-inch diameter experimental triode, having a normal anode.
Purpose:	To acquire pertinent current quenching data.

<u>Q-002</u>

Design Parameters:	A triode similar to Q-001, but incorporating a virtual anode.
Purpose:	To assess current quenching behavior in the presence of a virtual anode.

<u>Q-003</u>

Design Parameters:	A tube similar to Q-002, containing a thick, gradient grid of the "box" type (grid thickness = 3/4 inch).
Purpose:	To evaluate the influence of a thick grid on triggering and forward hold-off voltage in the presence of a virtual anode.

<u>Q-004</u>

Design Parameters:	Built identically to Q-003, but had a regular anode in place of the virtual type.
Purpose:	To evaluate the effect of a thick grid on triggering and forward hold-off voltage in the absence of a virtual anode.

Special HY-5

Design Parameters: A special narrow-slotted close grid-anode spaced HY-5 thyratron sample.

Purpose: To assess possible benefits in terms of recovery time.

MAPS-40, No. 001

Design Parameters: The first 8-inch diameter, gradient grid, developmental MAPS-40 model, incorporating a virtual anode, is shown in the layout drawing of Figure 9.

Purpose: To test initial MAPS-40 thyratron design assumptions.

MAPS-40, No. 002

Design Parameters: The second 8-inch diameter tube, similar in all respects to No. 001, but incorporating an anode of regular design, as shown in the cross sectional drawing of Figure 10.

Purpose: Further testing of initial MAPS-40 thyratron design assumptions.

Some major design features, common to both MAPS-40 developmental samples, were:

1) A single "box type" of gradient grid, giving two hold-off spaces at 20 kV each.

2) Wall shields for both high voltage spaces, attached to the gradient grid, giving a symmetric high voltage structure.

3) Molybdenum plates of various thicknesses used for the anode, gradient grid, grid, grid baffle, and cathode baffle. Moly bars were used to join the gradient grid halves together and to join the grid baffles to the grid. Extensive use of molybdenum gave both high thermal conductivity and dimensional stability under conditions of high transient power input.

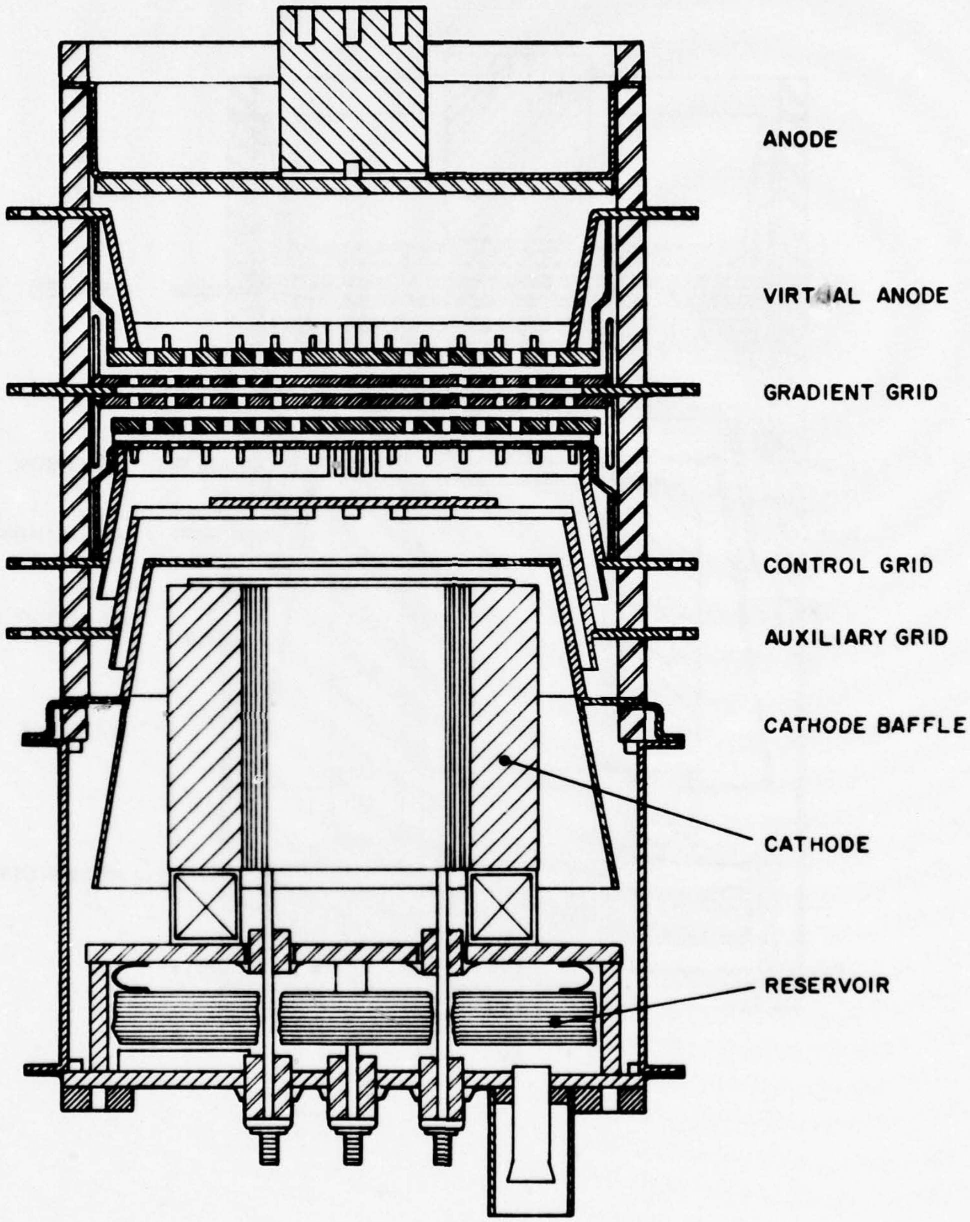


Figure 9. First 8-inch diameter developmental sample.

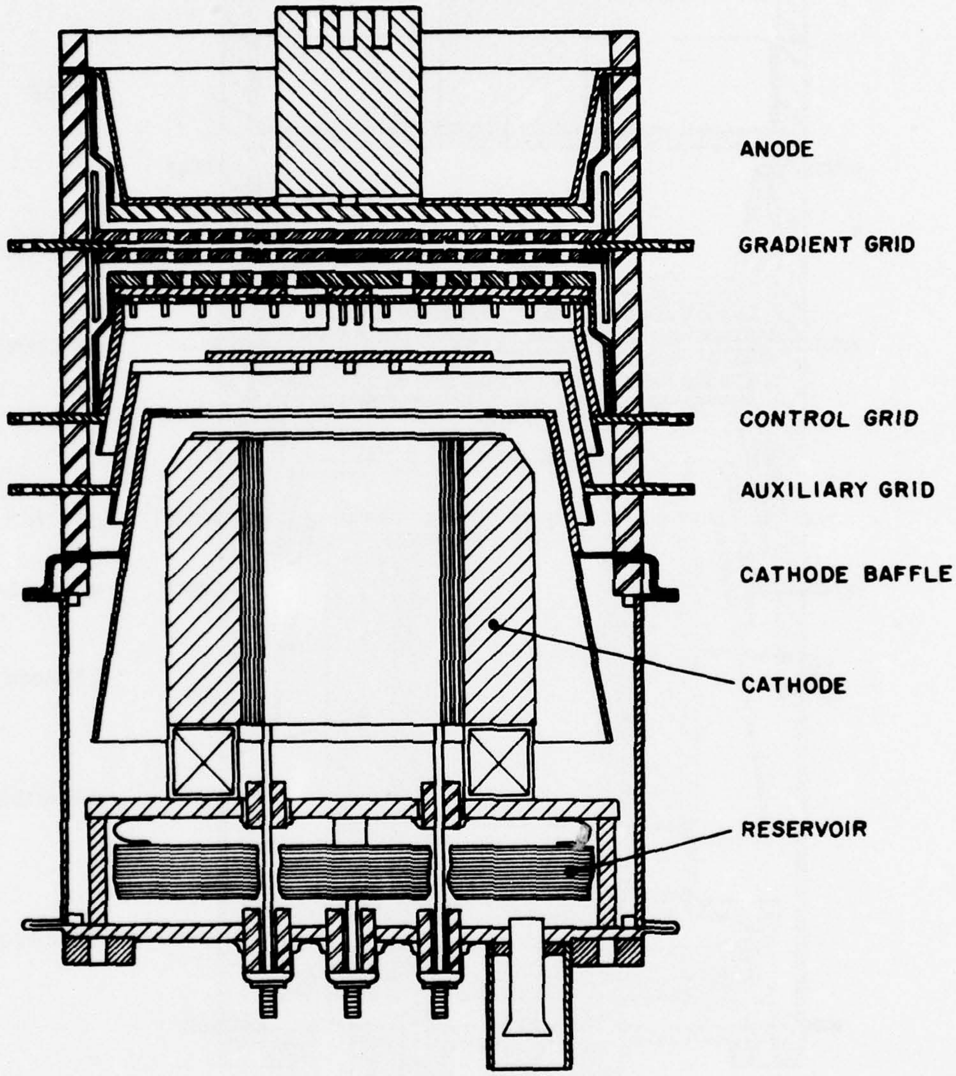


Figure 10. MAPS-40 developmental sample No. 002.

4) Various elements of the tube were supported by a nesting set of conical sections, made of copper for maximum thermal conductivity.

5) Ceramic seals were butt seals, with nickel-iron alloys at the cathode and extreme anode ends, and with 1/16 inch copper at the grid and baffle element seals. This method was used to provide minimum height and high thermal conductivity.

6) The cathode was mounted on a massive copper sole plate, thermally connected to the mounting ring by copper bars. This structure was introduced to provide thermal isolation for the reservoirs against surge heating by the cathode during "on" cycles.

7) A large cathode, nearly 5,000 cm^2 surface area, originally designed for the MAPS-70 thyratron, was inserted after minor structural modifications within the 8-inch diameter envelope.

8) A high capacity reservoir consisting of four quadrant sections, developed for earlier MAPS tube use.

Tubes constructed beyond this point were labeled as follows:

Developmental Samples:	MAPS-40
Prototype Thyratrons:	HY-7

Prototype thyratrons consisted of a regular anode design, a 5000 cm^2 cathode, and the standard MAPS reservoir, and incorporated only minor design refinements, plus processing improvements. Developmental samples contained major design departures in addition to processing improvements.

<u>HY-7, No. 001</u>

Design Parameters:	The first, 8-inch diameter, prototype thyratron, was essentially a refined version of the MAPS-40, No. 002, tube, incorporating numerous minor design improvements and a greater degree of dimensional control.

Purpose:	To rectify design weaknesses on the strength of evidence extracted from the testing and subsequent dissection of MAPS-40 thyratrons Nos. 001 and 002.

<u>HY-7, No. 002</u>

Design Parameters:	A replica of HY-7, No. 001.
Purpose:	Back-up to HY-7, No. 001. (This tube was lost due to a cracked gradient grid-to-anode ceramic. Improper ceramic inspection after grinding and/or non-uniform temperature distribution during the final body braze were believed to be the probable cause.)

<u>MAPS-40, No. 003</u>

Design Parameters:	This developmental sample incorporated a unipotential virtual anode structure considered superior to the standard virtual anode configuration of MAPS-40, No. 001.
Purpose:	Further assessment of the capabilities of a virtual anode in an 8-inch diameter thyratron structure.

<u>HY-7, No. 003</u>

Design Parameters:	A replica of HY-7, No. 001, of improved anode braze design, incorporating greater thermal impedance of the auxiliary grid connector ring; and changes in tube processing.
Purpose:	To provide improved anode braze design, assess benefits of modified processing of the tube, and bring some operating temperature relief to the auxiliary grid region.

<u>HY-7, No. 004</u>

Design Parameters:	A replica of HY-7, No. 001, of improved anode braze design, and revised anchoring of the MAPS reservoir heater connectors.

Purpose: Back-up to HY-7, No. 003. (This tube was lost due to oven temperature run-away, resulting in severe overheating and porosity of all body brazes.)

HY-7, No. 005

Design Parameters: Similar to HY-7, No. 004, with anode to gradient grid gap spacing reduced by 18%.

Purpose: Continuing assessment of the impact of tolerance tightening and revisions in the processing schedule of the tube.

HY-7, No. 006

Design Parameters: A replica of HY-7, No. 004, in all respects. Processed in similar fashion to HY-7, No. 005.

Purpose: To verify performance gains obtained in prototypes HY-7, Nos. 004 and 005.

MAPS-40, No. 004

Design Parameters: This tube was a replica of HY-7, No. 006, but incorporated a newly developed cathode and heater designed especially for the MAPS-40 thyratron.

Purpose: To determine the performance of the tube in the presence of an all-new, radically redesigned cathode and heater structure.

The above listed thyratrons constitute the total tube hardware constructed in the course of the MAPS-40 program.

A typical HY-7 thyratron is shown in Figure 11, flanked by compatible EG&G driver and heater transformer units.

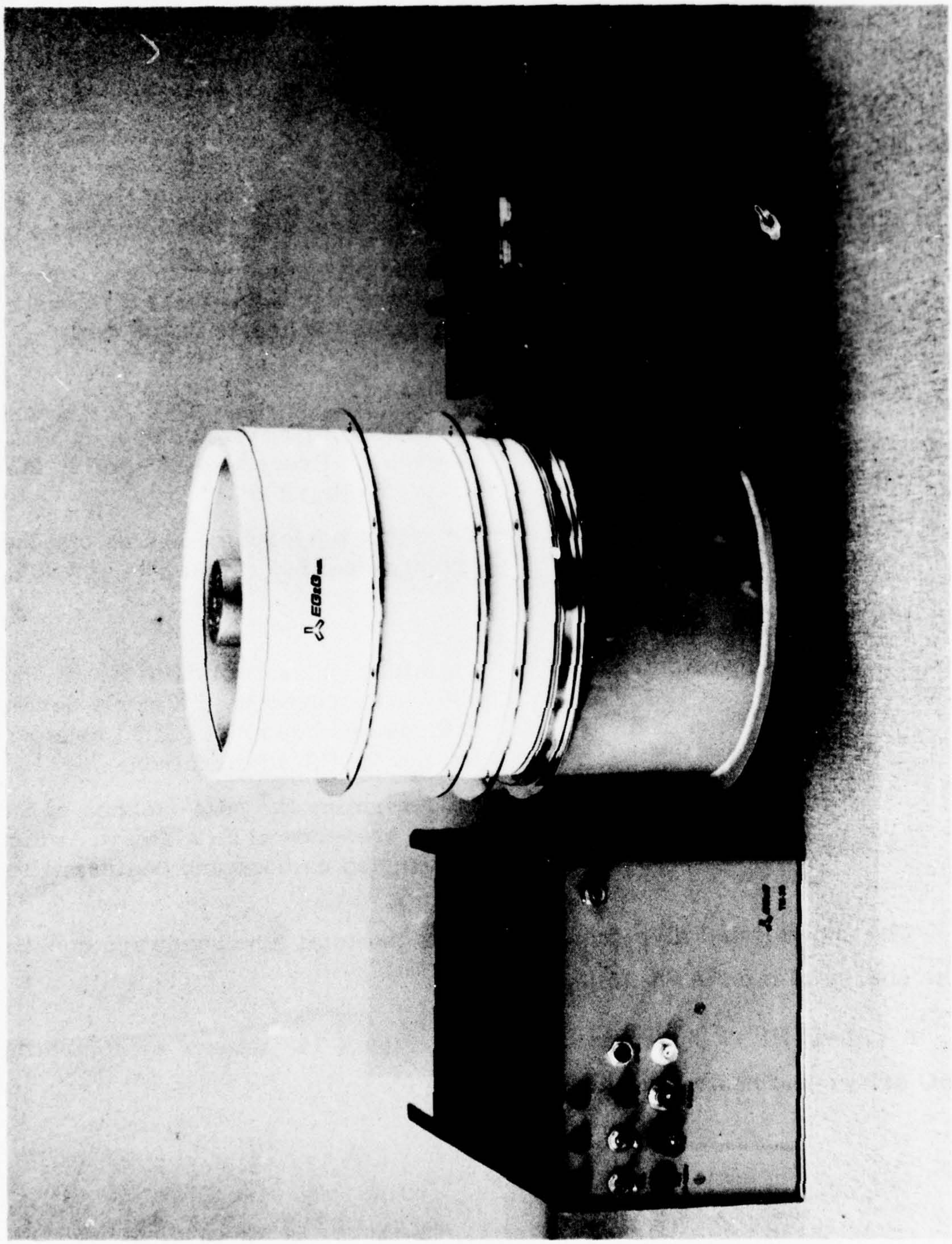


Figure 11. HY-7 Thyratron shown with EG&G driver and heater transformer units.

5. DEVELOPMENTAL SAMPLE/PROTOTYPE EVALUATION

Thyratron samples built during this period were partially or totally evaluated with the following results:

Q-001

The tube was tested at ECOM in a portion of the MAPS-40 experimental set-up at a pulse width of 20 microseconds. It exhibited current quenching at 3 kA peak, which translates into 9 kA per square inch, and is in reasonable agreement with extrapolations derived from smaller hydrogen thyratrons and from large cylindrical discharge studies.

Q-002

The virtual anode introduced into this sample was intended to provide hydrogen storage in the grid-anode space and thereby improve current quenching behavior. It was also felt that, because of ionization in the virtual anode cavity during the main pulse, the tube might perform as its own inverse clipper.

In actual fact, the tube proved generally much less stable than Q-001, with the onset of quenching appearing as low as 1.3 kA at pulse widths of 20 microseconds, increasing to 1.8 kA at 10 microseconds. In addition, it displayed sustained poor forward voltage hold-off and, while it provided some inverse clipping, it would not operate into a high inverse condition.

Q-003

This tube was equipped with a virtual anode to further explore the concept. It also incorporated a 3/4-inch thick gradient grid, of the box type, needed to provide high thermal capacity and conductivity in the MAPS-40 thyratron.

The triggering properties of the tube were found to be good, with only a small increase in delay time over that of a corresponding triode. Jitter and delay drift were unaffected. Use of a thick gradient grid was found to be non-restrictive insofar as these electrical parameters are concerned.

Forward and inverse voltage hold-off behavior, however, was very poor. This may be attributable to the use of a virtual anode structure. More extensive testing of the switch was precluded by severe degradation of unknown origin.

Q-004

This tube was constructed to assess the effects of a 3/4-inch-thick gradient grid in the presence of a regular anode.

Results indicate that the influence of the thick grid on anode delay time, delay time drift, and jitter was minor. Also the forward hold-off voltage was far superior to that of tube Q-003, although still not quite up to expectations.

Further testing of this tube did not disclose any additional useful information.

Special HY-5

This tube was built with narrower grid slots (but unchanged total grid slot area) and shorter grid-anode spacing, considered to be of some advantage to recovery time.

Following considerable aging, the switch was operated up to 50 kV and at an average current in excess of 5 amperes. This was well above average performance for a HY-5 thyratron. Initially, it was not clear whether any substantial gain had been made with regard to recovery time.

Quantitative tests on both this developmental sample and another HY-5 thyratron comprising similar modifications, performed at a much later date, pointed unequivocally to a recovery time improvement factor of approximately 3 to 1. Regular HY-5 tubes exhibit a recovery time of about 30 microseconds, whereas in the closer-spaced tubes, recovery time is reduced to 8 - 10 microseconds.

This result was instrumental in establishing a valuable new design parameter for high-power hydrogen thyratrons.

MAPS-40, No. 001

At Fort Monmouth, the tube was operated at heater and reservoir voltages of 24 and 10.5 volts, respectively. The auxiliary grid was tied to the cathode through a 660-ohm resistor, while the virtual anode incorporated in this tube was strapped directly to the anode section. The gradient grid was tied down by means of 20-megohm dividing resistors. The test circuit contained no inverse clipper and no thyrites were used in either the auxiliary or control grid leads.

Initially, the tube was operated into a 1-ohm line and, following gradual aging, it reached low duty operation at 40 kV. It was subsequently connected to a one-half ohm line and gradually brought up in voltage. The tube exhibited signs of stress in this condition. There were numerous kick-outs, arising from instances of self-firing following burst mode operation, and a considerable amount of inverse arcing. The tube reached a high point of Ebb = 15 kV, and an average current of 25 A at 82 pps where, after another kick-out, it showed great reluctance to run at high epy. Subsequent cold hold-off voltage tests confirmed the fact that the tube had developed an air leak. At this juncture, it was returned to the Salem laboratory for further examination.

The tube was dissected and a complete examination of its internal electrode structure was carried out. The cathode was found to be generally in good condition and its vane tips showed no sign of abnormal heating. The cathode shield bore marks of repetitive arcing. Except for some minor ion bombardment marks on the gradient grid, the grids and anode were in excellent condition. Some electrode eccentricity was noted for correction in future tubes.

The only destructive evidence appeared on the stainless auxiliary and control grid shield extensions. Here, severe arcing caused extensive meltdown around the edge of the stainless steel rings.

MAPS-40, No. 002

At ECOM, the tube was operated at heater and reservoir voltages of 24 and 10.5 volts, respectively. The auxiliary grid was again tied down to the cathode through a 660-ohm resistor and the gradient grid by means of 20-megohm dividing resistors. Thyrites were used in the auxiliary and control grid circuits.

The tube aged up to 40 kV with a 1-ohm line without undue difficulty. However, upon turning over to a one-half ohm line, problems began to appear at 22 kV. A severe kick-out situation developed and the tube exhibited heavy clipping. After considerable aging and trimming of the cathode and reservoir heater voltages, the tube was able to reach a peak operating level of 35 kV, 35 kA, with corresponding average current and power levels of 40 A and 0.7 MW.

Its performance deteriorated beyond this point until it became inoperable, due to high electrical leakage which developed between the control and auxiliary grids as well as between the auxiliary grid and the cathode. Attempts to clean up the contamination responsible for this low resistance proved ineffective and ultimately led to opening up the tube to air.

The tube was then dissected and analyzed in great detail. Just as in serial No. 001, the grids and anode were in good condition. Except for the hastelloy cover, which was somewhat warped and bore arcing pot marks, the emissive surface of the cathode was in excellent condition and the vane tips exhibited only normal signs of minor overheating. The molybdenum gradient grid shield showed signs of arcing over a one-inch portion of its circumference. Again, the auxiliary and control grid shield extensions were the only areas where severe arcing and meltdown occurred; in this case, over most of the circumference of each stainless steel ring.

HY-7, No. 001

This tube was operated at ECOM at heater and reservoir voltages of 15 and 11 volts respectively. The auxiliary grid was tied down to the cathode through a 660-ohm resistor and the gradient grid by means of 20-megohm dividing resistors. Thyrites were used in the auxiliary and control grid circuits.

The tube was able to operate into a 1/2 ohm line successfully to 45 kV. Its performance was satisfactory up to half the specified average current level, when the anode support overheated, developed a crack, and caused the tube to go down to air. The source of the crack was identified as silver penetration of the Driver Harris No. 146 alloy anode support, at the elevated temperature sustained by this part. The anode support was redesigned to avert similar accumulation of silver, in this region, in future tubes.

However, following close monitoring of the anode area during high average power operation of the next tube, the prime source of overheating was ascribed to asymmetric feeding of current in the anode region of the thyratron.

MAPS-40, No. 003

Following normal processing, this developmental sample was transported to Fort Monmouth for electrical testing.

Alerted by circumstances surrounding the loss of the previous tube, special vigilance was exercised, particularly in the early stages of progressive evaluation of this tube. Furthermore, ample time was allowed between each successively higher level of testing for the tube to adapt to and settle in in its increasingly demanding operating environment.

These precautionary measures proved quite rewarding and the tube eventually operated successfully in the 5/10 seconds on, 35/30 seconds off burst mode, into load impedances of 3/4 and 1/2 ohm respectively. The initial behavior of the tube was stable in relation to its predecessors with fewer kick-outs and some incidence of inverse clipping.

Of the numerous precautions exercised during the above tests, two seem worthy of special mention. First was the monitoring of anode temperature which permitted proper setting of reservoir voltage to meet the special gas pressure needs of the tube and provide non-marginal anode operating temperatures. The second consisted of observing the tube operate in a darkened environment, in a meticulous search of glow spots. This night-time viewing disclosed a discharge in one quadrant of the upper section of the tube commencing at 25 kV. Prompted by painful earlier experience, the tube was rotated 180 mechanical degrees and the glow reappeared in the same location relative to the PFN, underscoring the more-often-than-not ruinous influence of an asymmetric current feed.

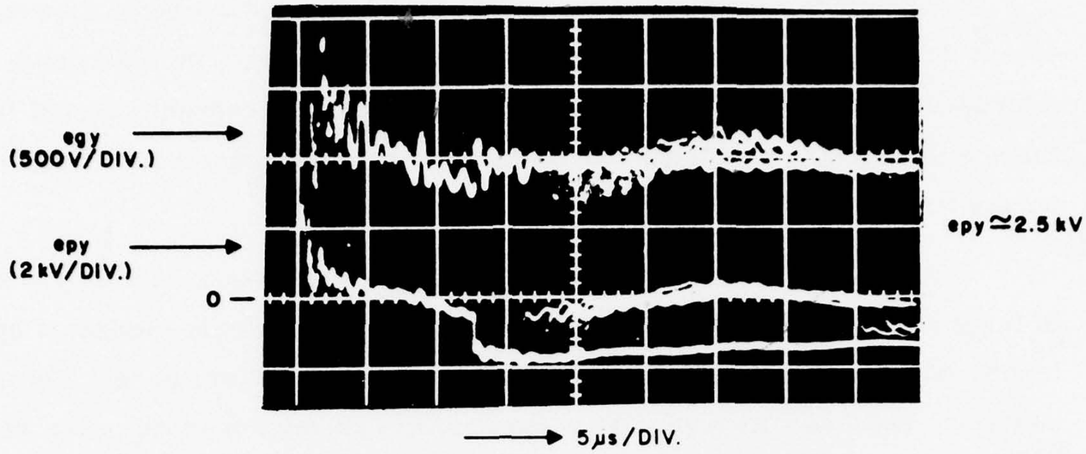
A circular copper hoop was improvised to clear the tube by about 3 inches and mounted at the level of the control grid. This hoop was fed from the PFN and coupled to the anode by four, 90°-spaced straps. Initial strap current measurement indicated an imbalance of 50%. This imbalance was subsequently reduced to 15% by trial and error. No glow was observed in the tube up to the highest level of subsequent operation.

The absolute necessity for symmetric current feed was thus unambiguously established for this high power thyratron and was diligently observed during the testing of all subsequent HY-7 and MAPS-40 tubes.

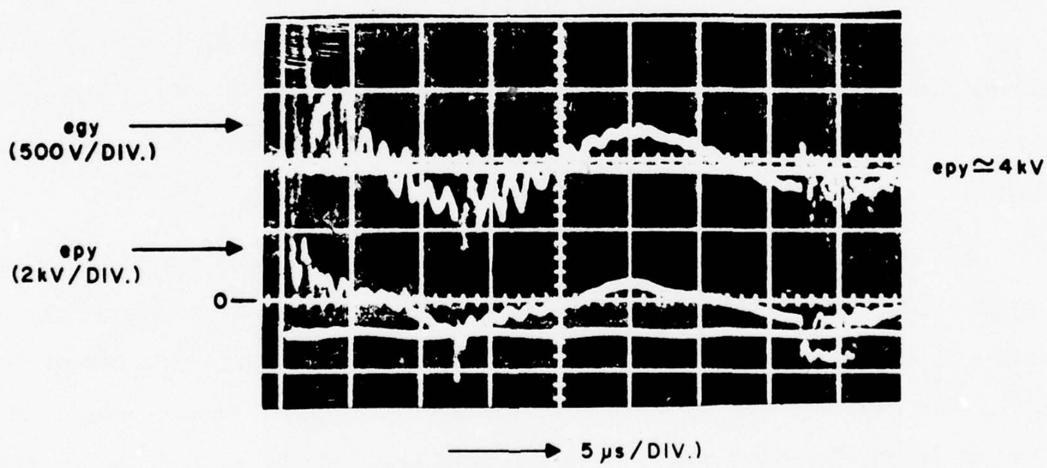
Further extensive and methodical testing of MAPS-40, No. 003, over a three-week period led to the attainment of some key performance milestones. The tube was operated satisfactorily up to the megawatt average power level at the end of this period.

Altogether, the following significant inputs were obtained:

1. The tube exhibited a negligible amount of inverse hold-off voltage (Figure 12), characteristic of hydrogen thyratrons operating at high peak current levels. It was therefore necessary to use an inverse thyratron clipper in the test circuit.



BREAKDOWN: t=3 TO 10 MICROSECONDS



BREAKDOWN: t< 0.5 MICROSECOND

Figure 12. MAPS-40 No. 003: Inverse Voltage Breakdown.

2. A small amount of "keep alive" auxiliary grid current, approximately 40 mA dc, sufficed to reduce TAD, normally exceeding 1 microsecond, to 0.2 microsecond or less. Higher levels of auxiliary grid current exerted little influence on TAD. The corresponding delay time drift during 15-second pulse bursts was 0.02 microsecond.

3. The short term adequacy of the reservoir was verified by a series of tests in which the length of the burst mode was gradually elongated up to the higher specification limit without adverse effect on performance. Earlier tests had disclosed no limitation with respect to the 10-microsecond pulse width.

It is evident that there is no occurrence of hydrogen gas starvation within the tube envelope. The available volume of gas in the active region of the tube and the reservoir response time seem to effectively counter the pumping action arising from the conducting intervals.

On the other hand, the tube appeared to perform best at two different settings of the reservoir voltage range for cold start-up and hot running conditions due to thermally induced volume/density phenomena in the grid-anode region.

4. Thermally, the control grid, gradient grid, and anode structures displayed exemplary behavior at full power. External surface temperatures in all three cases were near or below 300°C. However, a maximum temperature of 430°C was recorded in the region of the auxiliary grid. Steps were immediately taken to alleviate this condition on the next tube and to bring it under complete control in future prototypes.

<u>HY-7, No. 003</u>

The various safeguards and precautions accorded to the previous tube were exercised with minor refinements. For example, two mechanical surface thermometers were affixed to the anode section for continuous monitoring of its temperature. Temperature measurements of interelectrode spaces were also carried out routinely, at regular intervals, on the envelope of the tube between high power tests. More effective air-cooling was provided around the cathode enclosure of the tube. As a result of this improved cooling of the cathode enclosure and the provision of a heat choke in the connector ring of the auxiliary grid, the maximum temperature recorded in the auxiliary grid-to-cathode ceramic interspace was 335°C.

The tube reached full peak power operation in the 5-second burst mode after about ten hours of high voltage testing at Fort Monmouth, with a somewhat reduced number of intermediate kick-outs. At that point, this was the shortest aging time for a HY-7 thyratron consistent with a low-geared aging procedure.

In the course of high power testing, this thyratron was operated continuously at an average current of 20 A for a period of 30 minutes. This result constituted an unscheduled, but nonetheless significant, attainment.

HY-7, No. 005

Testing of this tube at Fort Monmouth adhered to the pattern of the two earlier samples, namely the institution of precautionary measures and methodical progression to the higher power levels. Basic electrical parameters were set as in the previous tubes.

Tube No. 005 went up to full voltage faster (about 2-1/2 hours) and with fewer prefires and kick-outs than any of its predecessors. Oscilloscope traces of peak voltage and current for this tube are presented in Figure 13. Similarly, it reached the 600 KW and 1 MW average power levels in the 10-second burst mode of operation after approximately 4 and 8 hours of operation respectively, with a behavior which appeared to be considerably more compliant than that observed in earlier 8-inch diameter tubes. As a result, it seemed to provide another positive milestone in the development of the MAPS-40 thyratron switch.

HY-7, No. 006

Testing of the tube followed the pattern of the last two prototypes in every respect.

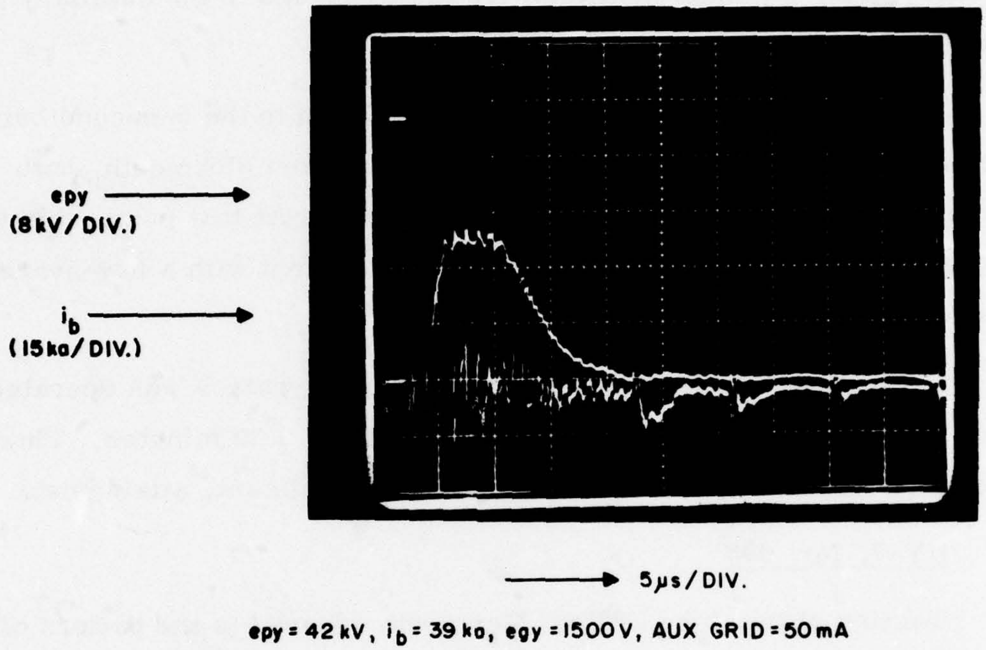


Figure 13. **Oscilloscope traces of peak voltage and peak current obtained on Thyratron HY-7 No. 005.**

The performance of this tube proved to be outstanding. It attained the megawatt average power level in the 10-second burst mode of operation after approximately 5 hours with very few prefires and only three kick-outs.

MAPS-40, No. 004

This tube was tested at ECOM on July 11 and 12. The tube's general performance paralleled that of the HY-7, No. 006, very closely.

Due to time restrictions, the tube was aged, in the 5-second burst mode, at an accelerated pace in relation to its predecessors, and reached the megawatt average power level in approximately 3-1/2 hours. The only discernible effect of the faster aging pace was the fact that nine kick-outs were sustained on the way to the megawatt power point.

The new MAPS-40 cathode thus gave a fine accounting of itself in the 5-second burst mode of operation.

Evaluation of tubes HY-7, Nos. 003, 005, and 006, as well as MAPS-40, Nos. 003 and 004, thus provided considerable evidence that, to the extent that it proved feasible to test them on available ECOM Test Laboratory equipment, these tubes were capable of performing in concert with the electrical specification requirements of the MAPS-40 program.

6. SIGNIFICANT ATTAINMENTS

Following the clean-up of certain vital trailing problems in the areas of electrical design, technology, processing, and testing, the development of the MAPS-40 thyratron entered a phase of gradual, steady, and cumulative progress which culminated in the manufacture of some developmental and prototype tubes of quite consistent and conforming performance. Table 3 provides a factual summary of significant attainments in chronological order, which is both succinct and self-explanatory.

Operation at 40 kV and 40 kA was achieved, as well as the megawatt average power level. A TAD figure of 0.2 microsecond was obtained by the use of a "keep alive" auxiliary grid current of 40 mA.

Certain design factors were subjected to minor modification, and some technological and processing techniques were revised and improved during the course of the program. The original design premises, however, proved to be well-founded, and, on the whole, somewhat conservative.

The attainments reported in Table 3 would not have been possible without the development of a disciplined and systematic approach toward the aging and testing of these switches. The establishment of precautionary measures and the fulfillment of conditions and needs specifically related to very high power switching were instrumental to the ultimate success of the project. The insights thus derived constitute a valuable, if intangible, achievement in terms of high power switching techniques.

Table 3. Significant Attainments.

Developmental Tube Number	Information Gained
Q-001	Level of quenching current verified. Need for 8-inch diameter tube confirmed.
Q-002 and Q-003	Introduction of a virtual anode, of the configuration envisioned at the outset, would be quite detrimental.
Q-004	Presence of a thick gradient grid exerts no adverse influence of any consequence on anode delay time, delay time drift, or jitter.
Special HY-5	Narrower grid slots and shorter grid-anode spacing may exert some beneficial influence on forward voltage hold-off and recovery time.
	Improvement in recovery time was confirmed.
MAPS-40 No. 001 and No. 002	Numerous critical assembly and exhaust problems associated with the massive tube structure were encountered and resolved.
	Partial specification performance was demonstrated. Inherent strengths and weaknesses of the electrode structure were revealed.
	No fundamental design restrictions were encountered. Modifications for future enhancement were suggested by experimental evidence. The need for controlled and methodical aging was underlined.
HY-7, No. 001	Modified ceramic-to-metal seals proved reliable, but further attention to dissimilar metal brazing was indicated.
	The need for closer monitoring of operating tube parameters was emphasized.
MAPS-40, No. 003	Milestone tube.
	Temperature monitoring procedures were established. Overheating of the auxiliary grid-to-cathode region was was determined.
	The critical need for symmetric current feed was ascertained.
	Benefits of methodical, stretched-out testing were underscored.

Table 3. Significant Attainments. (Cont.)

Developmental Tube Number	Information Gained
	40 mA of "keep alive" auxiliary grid current were found sufficient to reduce TAD to 0.2 microsecond.
	The short-term adequacy of the reservoir was verified.
	Megawatt average power operation was eventually achieved.
	The need for inverse clippers was unequivocally determined.
HY-7, No. 003	Confirmed lessons obtained on previous sample.
	Reached the megawatt average power level considerably faster and with reduced number of kick-outs.
	Improved performance probably was aided by (a) absence of unipotential virtual anode and (b) elimination of overheating of the auxiliary grid-to-cathode insulator.
	Thirty minutes of continuous operation at an average current of 20A.
HY-7, No. 005	Further confirmation of lessons learned on two earlier tubes.
	The tube reached the megawatt power level in 8 hours of aging with considerably fewer prefires and kick-outs than any of its predecessors.
	Improvements in controlled construction and processing were ascertained as beneficial.
HY-7, No. 006	Milestone tube.
	Tube reached the megawatt average power level in only 5 hours, with very few prefires and only 3 kick-outs.
MAPS-40, No. 004	Essentially confirmed the performance of tube HY-7, No. 006.
	To extent tested, the new MAPS-40 cathode performed very well.
	Provided early evidence of tube design consistency.

Table 4 provides direct comparison between major specification parameter objectives and representative developmental MAPS-40 thyratron performance.

Secondary achievements include a half hour of continuous operation at an average current of 20A and a cathode design which is not only capable of handling the requirement for high rms current, but, in addition, exhibits excellent mechanical endurance characteristics.

Table 4. Representative performance of developmental MAPS-40 thyratrons versus specification objectives.

Parameter (Units)	Rating	Operation (1)	Operation (2)	Representative Performance
epy (kV)	40	44	44	44
ib (kA)	40	44	11	44
egy (kV)	1.5 to 4.0	--	--	2
tp (μs)	--	10	20	10
prr (Hz)	500	125	250	125
Ib (A dc)	50	50	50	50
Ip (kA ac)	1.4	1.48	0.74	1.48
Pb (10^9 va/s)	400	242	121	242
dik/dt (kA/μs)	20	20	20	20/40
tad (μs)	--	0.2	0.2	<0.2
Δtad (μs)	--	0.1	0.1	<0.1
tj (μs)	0.02	--	--	0.02
Ef = Eres (V ac)	15 ± 1.5	--	--	*
If (A ac)	70	--	--	66
Ires (A ac)	40	--	--	40
tk (sec)	900	--	--	1200
Life (pulses)	--	5 x 10^6	5 x 10^6	--

*Ef = 15 (V ac)
Eres = 12 (V ac)

7. PROGRAM STATUS SUMMARY

After a faltering and somewhat inauspicious start, the development of the MAPS-40 thyratron settled down to what can best be described as a sequence of progressive achievement, culminating in the manufacture of four prototypes of consistent and adequate performance.

Whereas none of these tubes were tested to the full thirty-second burst mode of operation at 40 kV, the grace and ease with which they performed at 5, 10, and 15 second bursts augurs well for the longer burst mode train, when it becomes feasible to apply it, to the 40 kV level, at Fort Monmouth. On the other hand it is of interest to note that two of these prototype thyratrons were exercised to the 45 kV, 45 kA, peak current level, in 10-second bursts, without undue signs of stress. All of the tubes operated at an egy of 2,000 volts, well within the prescribed range. Also, the TAD goal of 0.2 microsecond was achieved with the aid of an auxiliary grid "keep alive" current of 50 mA or less.

Overall, it appears as if the objectives of this development program have been attained with room to spare, even though the presence of inverse clippers is necessary for the proper functioning of the tube. Whereas the specification of Table 1 calls for a current risetime rate of 20 kA/microsecond, some tube testing reported herein was carried out at twice that rate, or 40 kA/microsecond, without major difficulty. It will be instructive to explore such items as the upper limit of forward hold-off and the peak current capacity of the unique new MAPS-40 cathode in the near future and thereby establish ultimate limits of performance for the switch tube.

It must be observed, with some regret, that while the main thrust, during the second half of the project, was concentrated on the fabrication of working prototype tubes, some worthwhile R & D evaluations enumerated in the interim report escaped completion.

It must also be pointed out that the weight of the tube exceeded the original specification objective by 21 pounds. Foreseeable design refinements are expected to reduce this excess weight by 5 to 7 pounds. The volume of the tube is slightly in excess of the 0.5-cubic foot objective.

Life and reliability objectives must await later evaluation.

8. ACKNOWLEDGMENTS

The work performed in this development has borrowed heavily from electrical design improvements and technological advances registered in earlier high power thyratron switch programs and, more specifically, the MAPS-70 project (Contract No. DAAB07-74-C-0617).

While it is not possible to acknowledge every detail used, it is our pleasure to single out the following individuals for special mention, richly deserved, in view of their direct contributions to the program.

We are indebted to Messrs. J. Creedon and S. Schneider for unstinting support, encouragement, and numerous valuable suggestions, and to Mr. N. Reinhardt for the design of the original 5,000 cm^2 cathode and the MAPS reservoir, as well as the advanced design of the new MAPS-40 cathode.

Roger Plante carried out the early mechanical design work on this project, while Spencer Merz performed much of the early, rather difficult, testing of the original prototype models. He was also responsible for the design and construction of peripheral equipment such as heater and reservoir transformers and grid drivers.

Gerry Clark's efficient and competent handling of the numerous phases of assembly and processing of the developmental tubes was invaluable to the program, while the persevering assembly talents of W. Buttkus and K. Rogers contributed greatly to the ultimate success of the project.

9. RECOMMENDATIONS

It is respectfully requested that the following recommendations be carried out during any follow-on of this program:

- Secondary evaluations initiated in the course of the present work be carried on to realistic completion.
- A determined effort be made to establish ultimate performance parameters for the MAPS-40 thyratron, in terms of burst mode, as well as continuous operation.

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