NRL Report 6418

A 5-KJ Vacuum Clamp Switch for the Pharos 2-MJ Capacitor Bank

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August 30, 1966

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Washington, D.C.

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ABSTRACT

A five-kilojoule vacuum clamp switch has been developed at the Naval Research Laboratory for the Pharos magnetic-compression experiment. Four hundred and twenty of these switches will operate in parallel (at full two megajoules) as a passive clamp system for the main capacitor bank.

The clamp switch is a variation of the Pharos air trigatron starting switch, except that it is housed in a commercial Pyrex tee so that it can be evacuated to one millitorr. The tungsten-copper electrodes with a ten-millimeter gap will hold off the 20-kilovolt bank voltage at this pressure and yet trigger reliably at the low voltage as required. The electrodes, housing, and expansion chamber are assembled with O-ring vacuum seals, allowing rapid interchange or replacement of switch components. The trigger-pin assemblies are identical to those used for the atmospheric-gap starting switches.

The clamp-switch terminals, which are an integral part of the electrodes, allow direct mounting across the capacitor high-voltage stud and ground plate. No modification to the existing capacitor bank was required for installation, so the experimental program was not disrupted.

Life tests on seven prototype switches showed a reliable life of more than 4000 discharges at five kilojoules per switch. All failures were due to breakage of the Pyrex tee housings. The expected life of all other switch components is many times this.

PROBLEM STATUS

This is a final report on one phase of the problem; work on other phases is continuing.

AUTHORIZATION

NRL Problem H02-24
ONR Problem RR 002-10-45-5054

Manuscript submitted April 4, 1966.

A 5-KJ VACUUM CLAMP SWITCH FOR THE PHAROS 2-MJ CAPACITOR BANK

INTRODUCTION

The NRL Pharos facility (1), a large magnetic-compression experiment for high-density plasma research, was made operative in April 1961. Its two-megajoule main energy-storage capacitor bank, when switched into the six-nanohenry load coil surrounding the plasma, produces a 15-kilocycle damped oscillatory current waveform with a maximum of 16 megamps and a 75-percent voltage reversal. The required large initial di/dt dictates circuit parameters which result in an oscillatory discharge current and thus limits the time of the effective unidirectional magnetic field to the first half cycle.

The technique of electrically clamping a ringing LRC circuit at its first current maximum to effect an exponentially decaying current with a time constant long compared to a half-period, thus increasing the effective time of the magnetic field, had been used on low-energy banks. Any logical design of a clamp system for the high energy of the Pharos main bank requires a large number of clamp switches operating in parallel. These switches must hold off the capacitor-bank voltage during its charging cycle and then trigger as their electrode voltage passes through zero. These rigid requirements indicated that a major effort was worthwhile in securing a proper clamp switch. This effort included:

1. Investigation of available commercial switches

2. Evaluation tests for consideration of manufacture of switch designs described by other laboratories

3. The development at NRL and the manufacture of a new switch.

No satisfactory commercial switch was found. The unattractive cost, the large space necessary, the bank modification required for installation, and the lack of operational reliability precluded use of these switches.

Switches fabricated from some designs of other laboratories were tested and found unreliable for this application. In addition, the fabrication complexities of these switches would have made manufacture of a large number infeasible.

The design of the NRL clamp switch is very similar to that of the well-proved Pharos atmospheric trigatron starting switch (2), with its magnetic-blowout characteristic, except that it is mounted in a simple housing evacuated to a pressure which will give good triggering characteristics at low voltages. A switch that could be simply mounted on each of the 420 existing capacitor-bank modules and be capable of switching the five kilojoules of energy associated with it was a logical choice for a practical clamp-system design.

By fall of 1964, the effects which gave rise to plasma instabilities in the early experiments were corrected, so that the duration of the confined plasma was limited to the first half period of the damped oscillatory magnetic field (3). Five hundred clamp switches, of the type developed at NRL, had been manufactured. The clamp system was installed on the Pharos main bank in December 1964, and plasma instabilities are now being studied with effective magnetic fields lasting for more than five times that of the oscillating mode.

This report describes the NRL-developed clamp switch now in use on the Pharos main capacitor bank. A brief summary of the tests, evaluations, and conclusions made on commercially available clamp-switch designs is also included. A brief summary is also given of variations of the NRL-type switch, which was tested and used for other applications.

INVESTIGATION OF OTHER CLAMP SWITCHES

Commercially available ignitrons were investigated for the Pharos application, with the following results. Most consideration was given to the General Electric GL-7703, which is rated at 20 kilovolts and 35 kiloamps; the type Z5385, which is used in the one-megajoule section of the Zeus capacitor bank at Los Alamos for the starting switches (4); and the AEI types BK 178 and BK 194, used on the Zeta capacitor bank in England. These are rated at 25 kilovolts, 40 kiloamps, and 25 kilovolts, 80 kiloamps. In all cases, a clamp system using any of these ignitrons as the switch component would have had an excessive cost, undesirable complexity, and doubtful reliability.

Serious consideration was given to the use of a type of vacuum-clamp switch (5,6,7) developed at the Los Alamos Scientific Laboratory and the Lawrence Radiation Laboratory, and a number of tests on various models of this switch type were made at NRL. These switch models consisted essentially of a multiple-layer sandwich of insulator and electrode disks in a coaxial cylinder forming a series of gaps. The solid end electrodes compressed the disks to form vacuum-tight assemblies. Operation of these switches was possible only after the parts were precision machined and delicately assembled. The mechanical complication and cost of manufacturing large numbers of this type switch, plus their operational difficulties in a large clamp system, ruled them out for the Pharos application.

Variations of a type of switch proposed by K. Schmitter, et al., from the Institute of Plasma Physics, Munich, were also built and tested at NRL. These switches are vacuum coaxial trigatrons, with the insulator walls between electrodes being protected from the direct arc and deposits associated with it by overlapping baffles attached to the electrodes. The use of these switches was discontinued because of breakdown between the baffles and subsequent prefires.

During the development of the NRL five-kilojoule Pyrex tee switch, other models were tested with tees of different sizes, both larger and smaller. Some of these have been used at NRL in other applications requiring fewer switches. Of note among these is a 3-in.-diameter Pyrex tee clamp switch (8) operated in the 36-kilovolt push-pull circuit of the Pharos 130-kilojoule pulsed hexapole field (9). Additional features of this switch include a replaceable liner at the neck of the Pyrex tee, which has a service time of about 2000 shots before the liner is replaced, and tungsten rails extending from the electrodes into the neck of the tee to carry the arc away from the trigger pin. The Pharos main-bank clamp system, which has one clamp switch per energy-storage module, does not however require a switch of this size and complexity.

PRINCIPLE OF OPERATION

The clamp switch (Fig. 1) is a trigatron spark gap operating at a nominal pressure of one millitorr. A commercial Pyrex tee serves both as the vacuum chamber and as a mounting body for the electrodes and the expansion chamber. The electrode-gap dimension and the switch pressure place the operating point far enough up the negative slope of the Pachen pressure-distance vs voltage curve to give holdoff voltages greater than the 20-kilovolt capacitor bank voltage. A trigger pulse is applied near the time the electrode voltage from the ringing capacitor bank is passing through zero. This pulse rises to the seven kilovolts necessary to spark over the trigger-pin insulator in approximately ten nanoseconds. The trigger discharge acts as an electron source in the gap for the ionizing

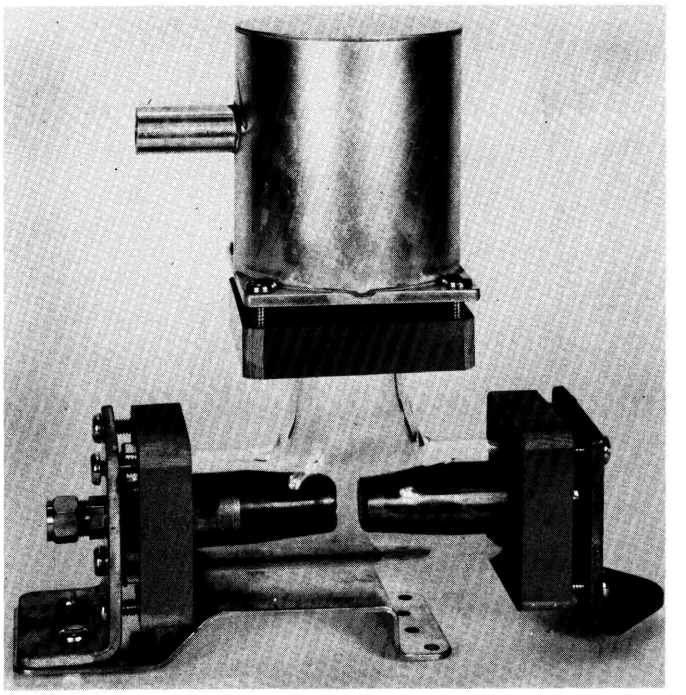

Fig. 1 - Clamp switch for the Pharos 2-MJ capacitor bank

of the gas molecules. The gas molecules, also generated by the trigger discharge, increase the gas pressure to the point where a rapid rate of ion formation takes place, and an unstable current growth occurs (10). The voltage, which tends to increase were the clamp switch not closed, causes the switch current to increase as determined by the external circuit.

The current passing from the cathode along the backstrap exerts a repulsive force on arc current. This feature moves the arc away from and reduces the erosion of the copper trigger pin. It also tends to increase the arc spot area, which decreases the electrode current density and cleans the insulator that bridges the electrode gap.

SWITCH DESCRIPTION

Electrodes

An unassembled switch is shown in Fig. 2. Except for epoxy potting of the trigger-pin assembly in the cathode, the switch can be completely assembled in less than five minutes. The anode and cathode of the clamp switch are designated by the way they are mounted on the positively charged Pharos main bank. This designation does not preclude their use in circuits with the opposite polarity.

Considerable reduction in the manufacturing cost has been realized by keeping the anode and cathode exactly alike for the main manufacturing process. The only differences are the mounting holes in the flanges and the addition of an axial hole in the cathode for the trigger assembly. The electrodes were manufactured by the Mallory Metallurgical Co., Indianapolis, Indiana, from NRL specifications. The mounting flange and tubular body of the electrodes are made from copper. Heavy metal caps are brazed to the copper body

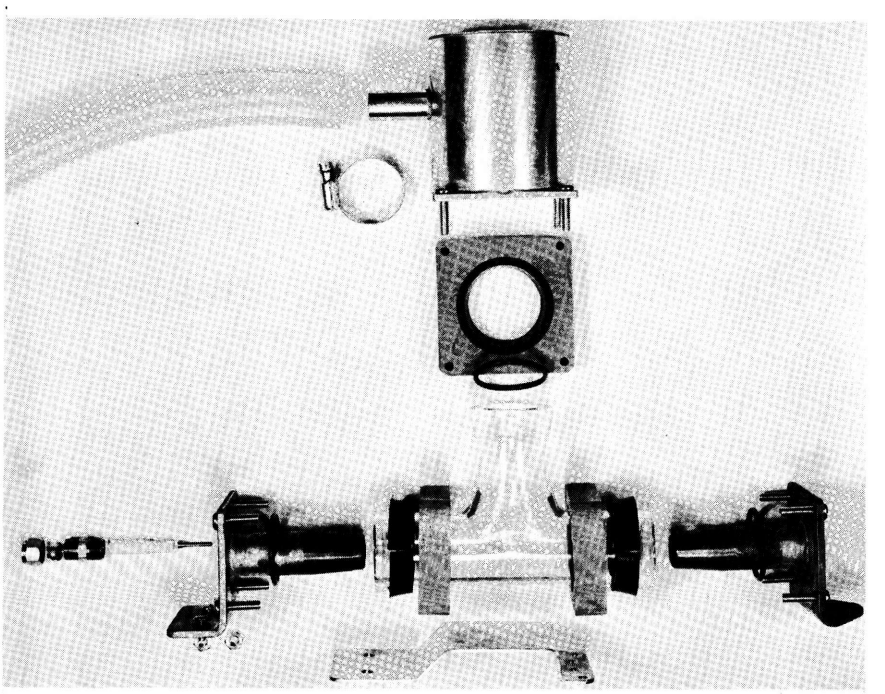

Fig. 2 - Unassembled clamp switch

in the area of the gap to prevent erosion resulting from an arc discharge of this energy. The caps are made from Elkonite 3W3, which is 68 percent tungsten and 32 percent copper by weight. The high copper percentage allows good brazing at the important joint between the cap and body. This joint must be vacuum tight and also pass the full module current. In the brass models of these electrodes, made at NRL, a major difficulty was experienced with this joint; however, no trouble has occurred with the 1000 electrodes of the Elkonite type made at the Mallory Co. The caps are extended 1-1/2 in. back from the gap to keep the joint out of the arc discharge. Evidence is seen of the arc extending back as far as 1 in. from the gap due to magnetic repulsion.

The end flanges are stamped from 3/16-in.-thick copper sheet, and the 90-degree offset is made in a press. In determining the thickness of the flanges, a compromise was made between a proper bend and desired mechanical strength. The flanges are brazed to the ends of the electrode bodies opposite the heavy metal caps. This joint must also be vacuum-tight and be able to carry the high currents. The anode flange has a 7/16-in.-diameter hole in the offset for direct attachment to the condenser high-voltage stud. The cathode flange has two 5/16-in.-diameter holes for attachment by 1/4-in. bolts to the backstrap.

Trigger Pin

The trigger pin is a 0.098-in.-diameter copper rod with a flared hole on the cable end. It is axially located in the cathode, with one end flush with the flat surface in the gap. The pin is epoxy potted in its aluminum oxide insulator bushing, which in turn is epoxy potted in the axial hole in the cathode. The trigger pin and insulator bushing are interchangeable with those of the Pharos starting switches; however they must be epoxy cast for a vacuum seal when used in the clamp switch. The trigger-cable ground connection to the cathode is made by a modified connector, Imperial Brass Co., type 62F-5/16 in., which is screwed in

the tapped hole at the end of the cathode body. The split ring of this fitting clamps the brass ferrule of the trigger-cable ground. The trigger-cable inner conductor extends to the trigger pin and connects with a push fit.

Housing

The body of the switch is a 1-1/2-in.-diameter commercial Pyrex tee. The major advantages of using a Pyrex tee for a switch housing are: (a) it maintains the proper surface insulation to hold off the bank voltage, both inside and outside the switch, (b) it withstands the electric arc without giving off carbon to contaminate the vacuum-pump oil (as do housings made of organic materials), (c) its simplicity and low cost greatly reduce the total cost of the switch, and (d) it allows visual inspection of the electrodes after assembly.

Attachment Flanges

The electrodes and expansion chamber are connected to the Pyrex tee housing with plastic attachment flanges, which use a wedging action on the outside diameter of the tee. The tapered inside diameter of the attachment flanges press against a gasket which fits against the tapered outside diameter of the tee. The electrodes and expansion chamber can be rotated for alignment purposes. The tapered gaskets are furnished with the tee and other Pyrex fittings. The attachment flanges are made in the NRL plastic shop by slicing one-inch sections from a single molding with outside dimensions of the flange and 1-1/2-in-diameter bore. The inside diameter of each slice is then tapered. A hole is tapped in each corner to attach the electrodes and expansion chamber. The two electrode flanges are identical, the flange for the expansion chamber being slightly larger.

Expansion Chamber

The expansion chamber body is a 3-1/2-in-diameter brass tube section with a flat bottom brazed on one end and a flange on the other. The flange has a one-half-depth O-ring groove which matches the one-half-depth O-ring groove in the neck of the Pyrex tee. Four holes in the end flange match those in the attachment flange on the neck of the tee. By putting the attachment screws in from this direction, the expansion chamber can be rotated after the switch is mounted on the capacitor bank to facilitate connection of the tube from the vacuum manifold. A 3/4-in. O.D. brass tube 1-1/2 in. long is brazed to the side of the chamber for a connection of the clamp switch to the vacuum manifold by a length of Tygon tubing.

Backstrap

The backstrap is a simple piece of brass sheet which connects to the cathode on one end with two screws and to the capacitor ground plate on the other end with four screws. An offset of 5/8 in. is made in the backstrap to bring the return current closer to the arc. This arrangement lowers the inductance of the switch and makes the return current more effective for the magnetic expulsion of the arc. The clamp-switch backstrap is mounted to the capacitor ground plate during the energy-module assembly, and connection is made between the cathode flange and the backstrap during mounting of the clamp switch on the capacitor bank. However, the backstrap must be considered a part of the clamp switch, because its presence is necessary for the magnetic-repulsion feature of the switch.

ELECTRICAL PARAMETERS

The measured self-inductance of the clamp switch, including the terminals necessary for mounting on the capacitor bank, is 40 nanohenrys. The calculated minimum value is 35 nanohenrys, making the assumption that the arc diameter equals the electrode diameter, with no magnetic bending of the arc. The resistance, estimated from the decay in a clamped circuit, is in the order of 7×10^{-3} ohm at 60 kiloamperes.

The hold-off voltages of all clamp switches were measured before installation on the Pharos condenser bank. The switches were evacuated to approximately one millitorr and the measurements made with a 0.1-microfarad condenser connected across the switch to supply enough energy for a cleanup discharge in case of a switch sparkover. The voltage on the capacitor was raised until the switch sparked over or it reached 32 kilovolts. Voltage tests exceeding 32 kilovolts were considered irrelevant for switches to be operated on a 20-kilovolt condenser bank.

For a sample of 200 switches (the first 200 assembled), 130 switches (65 percent) held off the 32 kilovolts on the first application. The distribution of initial breakdown voltage of the other 32 percent is shown in Fig. 3. It must be emphasized that this was the voltage of initial breakdown. After one to ten discharges, which apparently serve as a cleanup mechanism, the hold-off voltages of all 200 switches was in excess of the 20 kilovolts required for operation.

Figure 4 illustrates the breakdown voltage versus pressure. The points on this curve are the highest voltages the switch will hold off for a number of minutes. The applied voltage for each point was exponentially increased, with a 15-second time constant. Extraneous points far from the curve are observed to depend on condition and life of switch, rate of charge and discharge, vacuum pumpdown history, etc. Changing the electrode polarity or grounding the trigger pin and expansion chamber have little effect on the breakdown voltage.

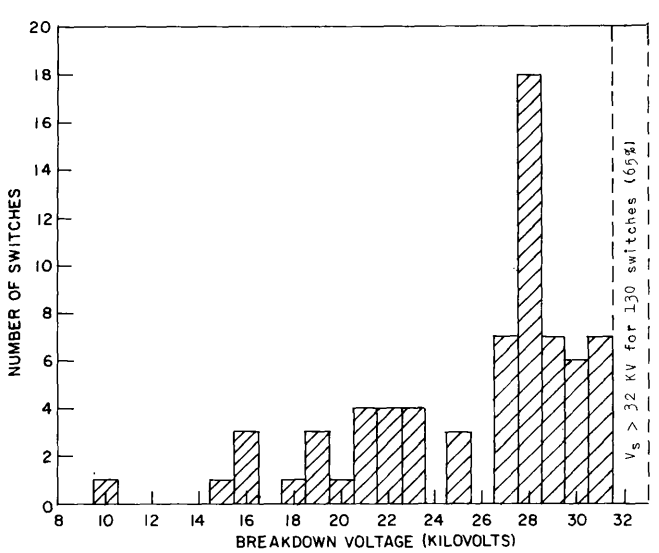

Fig. 3 - Initial breakdown voltages for 200 clamp-switch samples

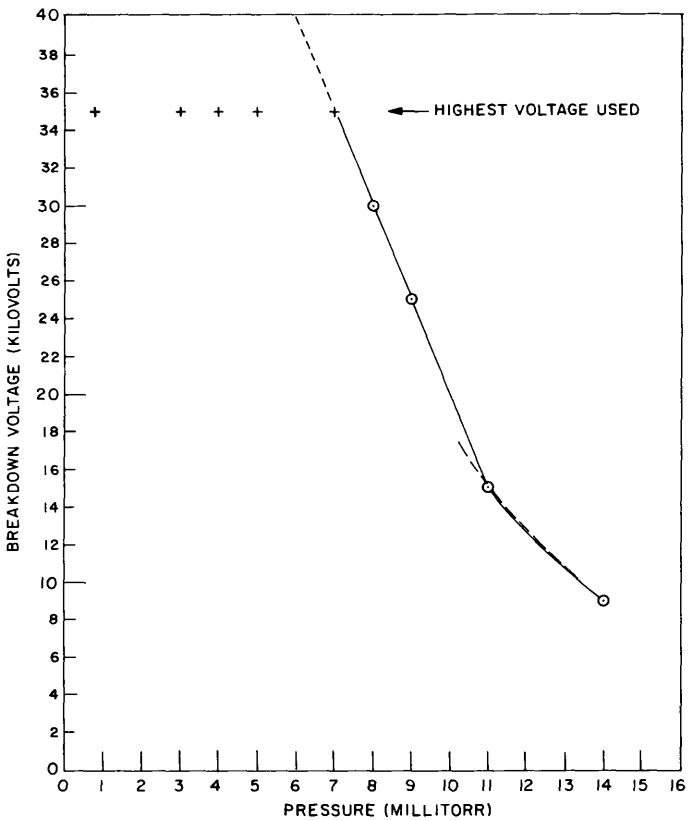

Fig. 4 - Clamp-switch voltage breakdown versus pressure, 1-1/2-in. Pyrex tee switch, ten-millimeter gap spacing

A switching and jitter time of less than one microsecond is not required for this application; therefore no large effort was made either to measure accurately or to influence it.

LIFE TESTS

Many thousands of discharges were made on various models and prototypes of this clamp switch during its development. These discharges are not included in the results described of the final life test on switches from the production run. These previous tests do, however, add life-test information—for example, (a) electrode erosion rates at higher energies, (b) trigger pin life under different conditions, and (d) O-ring deterioration.

The final life-test assembly consisted of seven energy modules identical to the five-kilojoule energy modules in the Pharos bank. These tests served the additional purposes of a mechanical mock-up and operational procedure check. The bank was charged to 20 kilovolts, the starting switches fired, and the clamp switches were triggered at the first current maximum. The total inductance of the test circuit for the seven switches in parallel was 1200 nanohenrys. This value gave a total load current of 350 kiloamperes, with a rise time of 11 microseconds and an L/R decay of 100 microseconds after clamping. The total circuit resistance was 0.2 milliohm, of which about 30 percent was estimated to be in the clamp switches. These electrical parameters in the test circuit simulated the clamp

service required on Pharos. A 425-liter-per-minute forepump with a liquid nitrogen cold trap supplied the one-micron manifold pressure.

No clamp-switch failures occurred in 4300 shots. Not wishing to extend the life test for months, the shot rate was increased toward the end of the test from the initial one shot in two minutes to two shots per minute. This rate is considerably higher than the duty cycle of Pharos. The temperature of the Pyrex tee housing increased to more than 100° C after approximately 50 shots at this accelerated rate, in spite of forced cooling. Three of the seven switch housings finally broke during cooling. It would have been a simple matter to replace the broken tees and continue with an expected additional 4000 shots, but further life tests of the switch at this point were considered irrelevant for the intended application on Pharos. Additional life testing will not be undertaken unless the usage on Pharos indicates a necessity for it. Only five minutes are needed to replace a tee, and its cost is $12.50.

Some of the switches were disassembled and examined at various stages of the life test. The electrodes showed a discoloration at the location of the arc discharge; however, there was negligible erosion at the completion of the test. The trigger pin and insulator bushing showed only a small amount of erosion. No discernible deterioration of the rubber O-ring from corona could be seen. The Pyrex tee housings were considerably crazed on the inside after only ten shots. After about 50 shots, parts of the inside showed black deposits. These deposits were concentrated at the flange of the electrodes and did not form a bridging path across the insulator from anode to cathode. Erosion of the Pyrex tee was concentrated in the area where the neck joins the cross piece. The wall thickness in this area decreased with the number of shots, becoming approximately two-thirds its original thickness at the end of the test. The erosion was further evidenced by the considerable quantity of residue trapped in the expansion chamber, which was analyzed and found to contain more than 98 percent elements from the Pyrex.

During this series of shots, which took place over a period of five weeks, there were a few prefires initially. After the first 50 shots, no prefires were experienced for the rest of the test.

SUMMATION

The five-kilojoule vacuum clamp switch, developed at NRL, has been used successfully as the switch component for the Pharos clamp system. The 40 nanohenrys self inductance and approximately seven milliohms resistance of each switch are suitable parameters for the 420 paralleled units required for the two-megajoule bank.

The clamp switches, which were tailored to fit mechanically the existing Pharos condenser bank, allowed the addition of the clamp feature with negligible interruption of experiments.

The initial cost of the clamp switch is $75.00, and becuase of the replaceable-parts feature a very long life with low maintenance cost is expected.

ACKNOWLEDGMENTS

The author gratefully acknowledges the many contributions of others in the development of this switch. A major factor in the successful conclusion of this project was the helpful discussions with Dr. A.C. Kolb, Dr. W.H. Lupton, and Dr. E. Hintz. Many of the design features are credited to Mr. L. Melhart. Particular appreciation is expressed to Mr. R.L. Borkey for his contributions to the switch development and for the many laborsome hours he spent in the test and evaluation program. Appreciation is expressed to Mr. C.B. McCool,

Mr. Max Hutton, and Mr. D.R. Drake of the Mallory Metallurgical Co. for their contributions to the electrode design and their efforts in the manufacturing of them in quantity.

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1. ORIGINATING ACTIVITY *(Corporate author)* Naval Research Laboratory Washington, D.C. 20390	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE

A 5-KJ VACUUM CLAMP SWITCH FOR THE PHAROS 2-MJ CAPACITOR BANK

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

An interim report on the problem.

5. AUTHOR(S) *(Last name, first name, initial)*

Young, Marvin P.

6. REPORT DATE August 30, 1966	7a. TOTAL NO. OF PAGES 14	7b. NO. OF REFS 10

8a. CONTRACT OR GRANT NO. NRL Problem H02-24 b. PROJECT NO. c. RR 002-10-45-5054 d.	9a. ORIGINATOR'S REPORT NUMBER(S) NRL Report 6418 9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*

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13. ABSTRACT

A five-kilojoule vacuum clamp switch has been developed at the Naval Research Laboratory for the Pharos magnetic-compression experiment. Four hundred and twenty of these switches will operate in parallel (at full two megajoules) as a passive clamp system for the main capacitor bank. The clamp switch is a variation of the Pharos air trigatron starting switch, except that it is housed in a commercial Pyrex tee so that it can be evacuated to one millitorr. The tungsten-copper electrodes with a ten-millimeter gap will hold off the 20-kilovolt bank voltage at this pressure and yet trigger reliably at the low voltage as required. The electrodes, housing, and expansion chamber are assembled with O-ring vacuum seals, allowing rapid interchange or replacement of switch components. The trigger-pin assemblies are identical to those used for the atmospheric-gap starting switches. The clamp-switch terminals, which are an integral part of the electrodes, allow direct mounting across the capacitor high-voltage stud and ground plate. No modification to the existing capacitor bank was required for installation, so the experimental program was not disrupted. Life tests on seven prototype switches showed a reliable life of more than 4000 discharges at five kilojoules per switch. All failures were due to breakage of the Pyrex tee housings. The expected life of all other switch components is many times this.

DD FORM 1 JAN 64 1473

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