DESIGN AND FABRICATION OF A TANDEM, FIVE MEGAMPERE INITIATE SWITCH FOR THE BATTERY UPGRADED SUPPLY

Prepared by

T. A. Aanstoos, R. C. Zowarka, Jr., and J. L. Upshaw

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Center for Electromechanics
The University of Texas at Austin
Balcones Research Center
Bldg. 133, EME 1.100
Austin, TX 78758-4497
(512) 471-4496

Design and Fabrication of a Tandem, Five Megampere Initiate Switch For the Battery Upgraded Supply

T. A. Aanstoos, R.C. Zowarka, and J. L. Upshaw

Center for Electromechanics
The University of Texas at Austin
Balcones Research Center, Mail Code 77000
Austin, TX 78712

Abstract - The battery upgraded supply (BUS) initiate switch is characterized by a cylindrical, linear motion, copper armature that slides between two sets of independently loaded copper contacts. One set of contacts always rides on the armature, while the other is isolated from the leading edge of the armature by an insulator; current is made at the armature/contacts leading edge. The switching contacts come to rest on fresh copper surfaces of the armature, well away from the leading edge. Such switches operate without major maintenance as long as two important parameters are maintained: the proper radial load applied to the contact and the speed of engagement at the leading edge. Contacts must be loaded sufficiently to overcome constriction forces - the conventional requirement is 1 g-f/A (9.8×10^{-3} N/A). Speed at make must be high enough to limit the instantaneous specific action in the contact so that the leading edge temperature does not cause damage. This speed is generally from 1 to 5 m/s. Similar switches with armature diameters of 10 cm have been used as making switches in various laboratory pulsed-power circuits with peak currents of as high as 560 kA and rise times as short as 50 ms.

The BUS is a 5 MA battery power supply charging a pair of inductors to 560 MJ. Details of BUS and energy management in the pulsed power circuit are presented in companion papers. This paper reports on the design, fabrication, and component testing for the tandem initiate switch system for BUS, in which each armature is rated for a 3 s rise to 2.5 MA peak current (2.8-MA fault), followed by a 5-s dwell before end-of-test interruption. The two switches are ganged on a common (but insulated) shaft, which contains an adjustable coupling for jitter control, and is actuated by a fast axial hydraulic actuator.

Special design features of this switch system include an externally adjustable radial spring, linear shaft bearings, safety interlocks, and temperature instrumentation. Full-scale component tests were designed and are being conducted to verify radial contact force, temperature distribution under full action, mechanical stability under full force, proper velocity profile for the full switch assembly, and elimination of jitter.

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Introduction

Switches with rings of independently loaded copper contacts surrounding a cylindrical, linear motion, copper armature have been used successfully in pulsed power circuits for many years. Fig. 1 shows the general configuration of such switches, which differ from butt contact devices in two important aspects; spring-mass dynamics do not create bounce off tendencies and the bulk of coulomb transfer is through freshly scrubbed copper surfaces

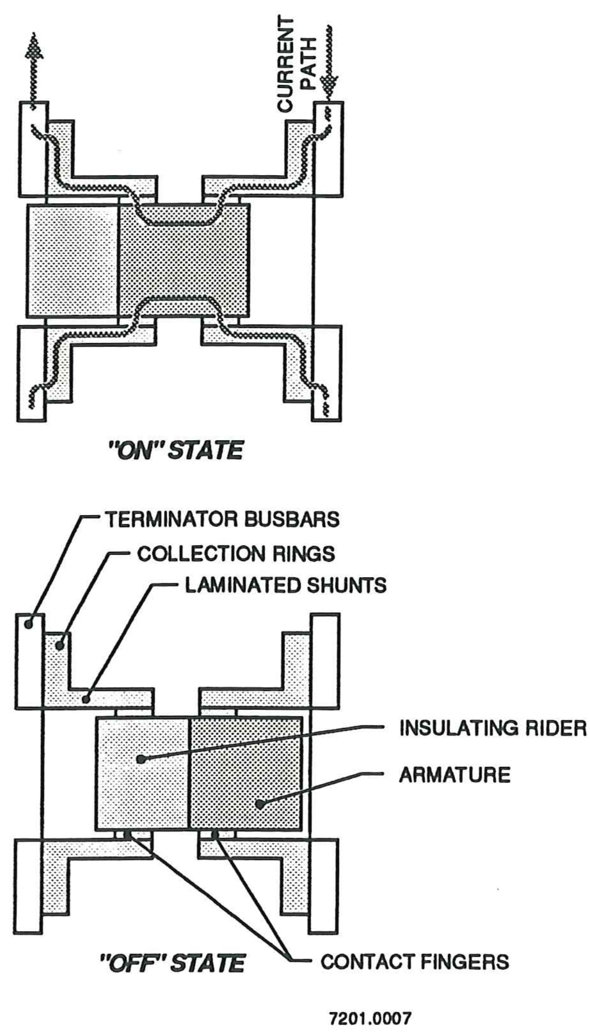

Fig. 1. General configuration of a Wildi-type switch

that have not been exposed to energy dissipation during contact closure. In 1976, Dr. Paul A. Wildi designed and demonstrated a pneumatically actuated, mechanically triggered switch with a 10 cm diameter armature (Fig. 2) [1]. Designed for closing duty with a peak current of 150 kA, this switch was tested by Dr. Wildi as a closing switch for a 5 MJ homopolar generator (HPG) at a peak of 560 kA and a rise time of approximately 60 ms [2]. Two similar switches (Fig. 3) are in service as parallel making switches for the 10-MJ disk HPG at the Center for Electromechanics, The University of Texas at Austin (CEM-UT), and have undergone many thousands of switching operations without failure [3]. In 1976, Benjamin M. Rech designed and built a staged, double commutation switch based on Wildi's designs that operated in the 15 to 500 kA range [4]. Among several other Wildi switches still in service is the 15 cm, 130 kA reversal switch for the poloidal circuit of the Doublet III Tokamak at GA Technologies, Inc. [5].

The Battery Upgraded Supply (BUS) is being built to replace the Battery Power Supply (BPS) at Eglin Air Force Base [6]. BUS is a 5.8-MA, 560-MJ system in which two banks of approximately 24,000, 12 V, lead-acid batteries each, form parallel battery/inductor/opening switch circuits for testing railguns (Fig. 4). This figure indicates how current is initiated simultaneously by mechanically ganged, electrically independent, Wildi-type switches in the low voltage leg of each bank circuit, as part of the high current switching (HCS) subsystem. Companion papers describe the overall BUS power supply, energy dissipation by the HCS subsystem, and BUS modeling [7,8,9].

Design Requirements

The general design of the initiate switches, and other BUS systems and componentry, was adopted because of the need for a safe, low maintenance, reliable, daily use device with the philosophy that the experimental cycle should not be limited by turnaround time of the power supply. Electrical requirements are; each switch must close with sufficient speed and negligible jitter to carry a rising current to 2.8 MA in 3.0 s, maintain full current for 5.0 s, followed by a falling current for approximately 0.125 s until final interruption by an external explosive switch [8]. Total action associated with this duty, which is required once per week, is approximately 18.98×10^{13} A^2s — a design requirement was adopted that, except for contact hot spots, switch components should not exceed a 90°C temperature change due to this action. To enable ganging of the two initiate switches on a common but insulated shaft, the two banks of BUS were situated in a fore-and-aft manner in the HCS assembly, making the initiate switches colinear (Fig. 5).

For conservatism, each switch was sized so that no critical performance parameters would be required that have not already been demonstrated by Wildi-type switches in normal duty. Analyzing the resistive mismatch between angular positions around the armature that necessarily results from the side-feed geometry of the switch indicated that the top and bottom contacts will carry approximately 30% higher than average contact current; these positions then dominated the armature diameter and number of brushes, while the armature wall thickness was chosen based on temperature

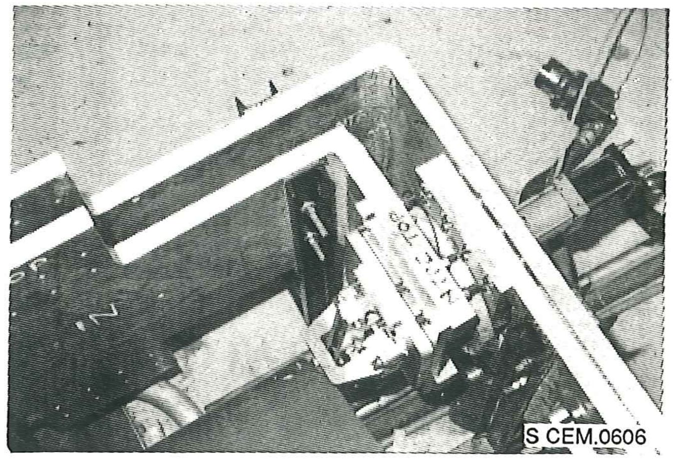

Fig. 3. One of two, 10 cm Wildi switches on the CEM-UT 10 MJ disk HPG

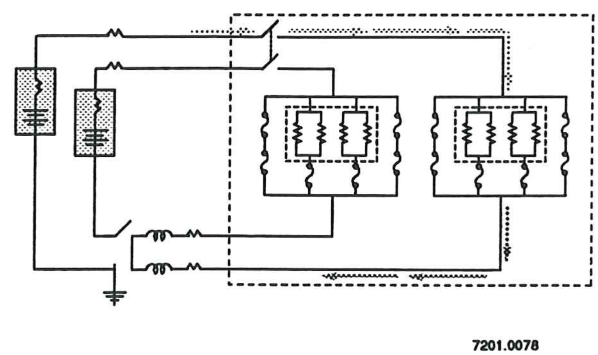

Fig. 4. BUS circuit schematic

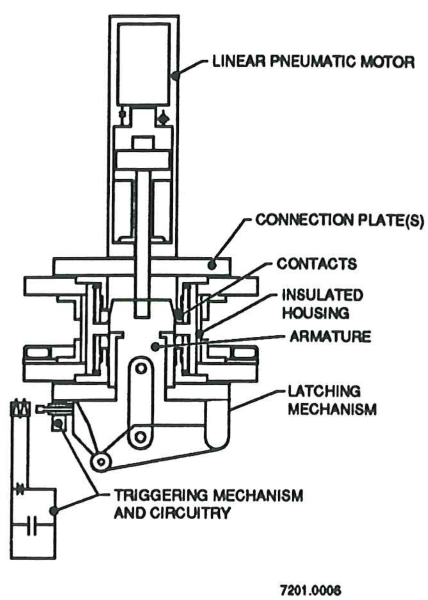

Fig. 2. Schematic of the 10 cm, 560 kA Wildi switch

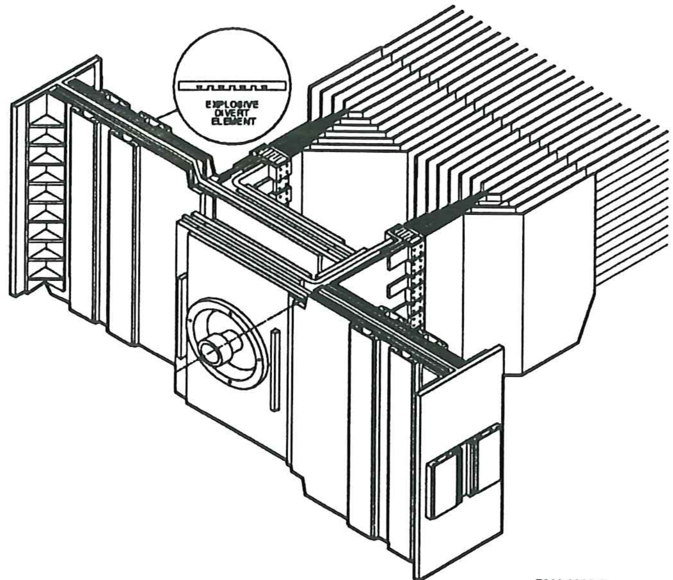

Fig. 5. HCS subsystem configuration

limits. All these considerations resulted in a BUS initiate switch design that is summarized in Table 1, which also notes the corresponding characteristics of the 10-cm, 560-kA Wildi switch at CEM-UT (Fig. 3).

TABLE I

INITIATE SWITCH DESIGN PARAMETER SUMMARY

Parameter	Unit	Demonstrated	BUS Initiate Switch
Peak Current	MA	0.56	2.8
Armature Diameter	cm	10	63.5
Contacts per Pole	—	24	160
Current per Contact	kA	23.3	17.5
Force per Contact	N	111	171
Lineal Current Density	kA/cm	17.5	14.0
Contact Current Density	kA/cm 2	9.64	6.03
Rise Time	s	0.05	3.0
Pole Gap	cm	2.5	3.8
Closure Speed	m/s	5.0	1.0

Based on these design requirements and parameters, a final design of the initiate switch assembly was performed. These switches vary from the 1976 Wildi design in three functionally important aspects. First, axial actuation is by a hydraulic cylinder fed by a gas charged accumulator and controlled by fast, positive response hydraulic flow control valves, thus eliminating a sensitive mechanical latch and trigger mechanism that was needed to operate the pneumatically actuated switch. Second, a set of three linear bearings and their support structure is incorporated to support the common shaft. This is necessary because far fields from the energy storage inductors create assymetrical forces on the current carrying members of the HCS subsystem. Third, an externally accessible mechanism is used to adjust the radial contact force; the 10-cm switch was adjusted by setting the neutral bend angle of a spring steel strap that was part of each contact's connecting laminated shunt.

Fig. 6 shows a side sectional view of the initiate switch assembly. The contacts and armature are CDA 11000 copper, with the contacts fabricated from plate and the armatures from a single ring forging. Each contact's laminated shunt is comprised of 75, 0.25-mm CDA 11000 shims, connecting the contacts to the copper collecting rings. Each armature is mounted to the 15.2-cm bronze shaft by a welded, 6061-T6 aluminum hub and spoke assembly. These spokes are chevron shaped to improve the axial stiffness of the spoke/armature assembly and to prevent extension of moving parts past the plane of the outer HCS structure for improved personnel safety. The shaft halves are joined by a dual pitch aluminum bronze coupling that adjusts jitter when rotated from outside by a tool inserted through the hollow shaft. The hydraulic actuator is a 15.24-cm stroke, 15.24-cm bore, position sensing, hydraulic cylinder rated at 20.7 MPa.

THERMAL ANALYSIS

A transient, two dimensional finite difference code was used to predict the temperature history of the armature in the region of a contact. The armature was chosen for this analysis rather than the contact because it is reasoned that the contact, having more free surfaces for convection heat transfer, will run cooler than the armature. Heat input for the model was solved from the expression:

$$kby\frac{d^2\phi}{dx^2} - 2hb\phi + \frac{\rho}{by}I^2 = 0 \qquad (1)$$

where the first two terms address the conductive and convective effects, and the third describes the heat input due to joule heating. Also, a time-varying heat input term due to the contact voltage drop (I x V=17.5 kA x 0.5 V = 8.8 kW peak) was assumed to be uniformly distributed on the area of apparent contact on the armature. This code was run for various cases, the most conservative using the assumption that 75% of the contact drop energy is absorbed by the armature. In this case, final temperature in the armature, slightly below the interface, can reach as high as 750 K (Fig. 7). This is a very local and short-lived temperature excursion that apparently does not adversely affect switch performance, and further analysis shows that forced convective cooling of the armature with standard condition air can reduce this temperature significantly, to approximately 55% of the absolute melt temperature of copper.

RADIAL ACTUATION

The radial force required to overcome current constriction forces at the initiate switch contact is based on the Marshall rule of thumb of 1 g-f/A [9]. For ease of switch assembly and adjustment of this force, an externally adjustable contact force mechanism was designed. Shown in Fig. 8, this design uses an angled cantilevered spring, aluminum bronze CDA 95400, sliding in a grooved ring, and contacting an Al_2O_3 ceramic bar attached to a saddle that is bolted to the top of each contact. Rotating the threaded rod that swivels within each spring moves it in an axial direction in such a manner that both the location of, and deflection at, the point of contact between spring and ceramic bar change accordingly. This results in a "softening" spring characteristic, making the

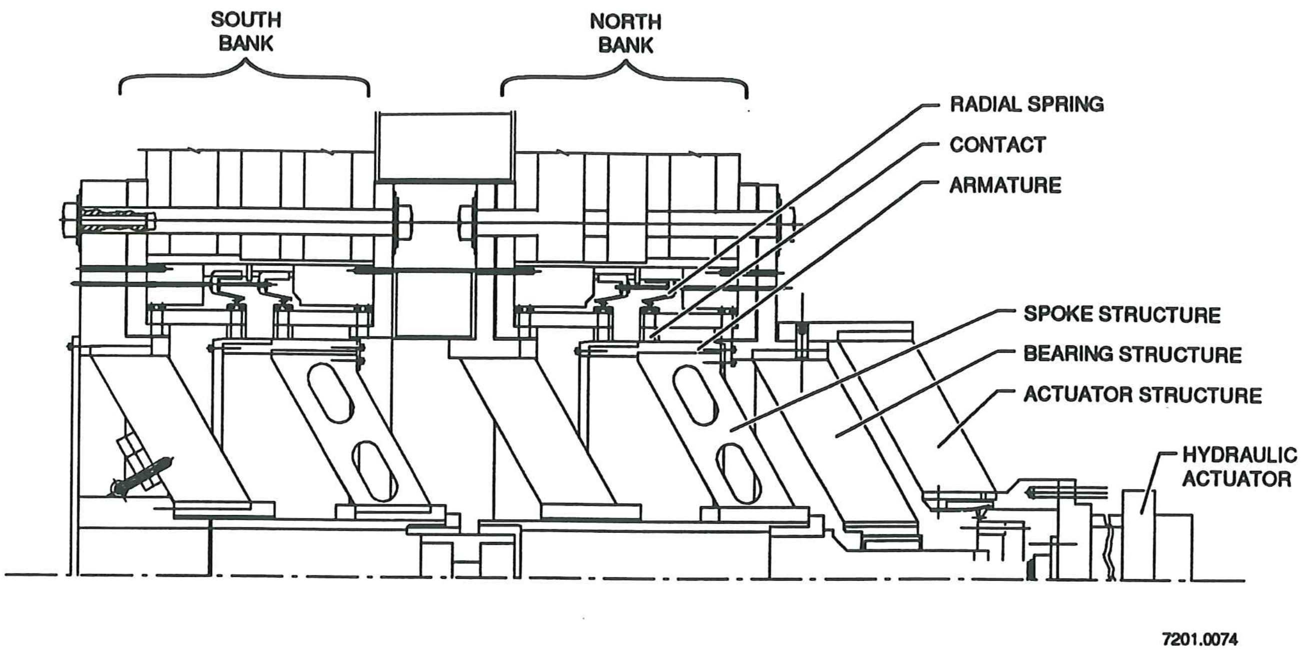

Fig. 6. Initiate switch subassembly

net radial force less sensitive to machining tolerance and varying friction. One simply counts the number of turns on the threaded rod with reference to a match mark to infer the resulting contact force. Fig. 9 shows the load/deflection characteristics of this spring, based on initial analysis.

The laminated shunt connecting the contact to the collector ring is limber in the radial bend mode, but bends in an ogee fashion because of the fact that the laminations are dip soldered at each end for improved joint conductivity. The resulting high radial compliance of the shunts minimizes their effect on net radial load on the contact and forces good parallel matchup between the contact and armature surfaces.

Axial Actuation

During closing, the instantaneous specific action at the contact to armature leading edges is a combined function of switch closing speed dx/dt and rate of current rise di/dt. A comparison was done showing the value of this peak action for the 10 cm Wildi switch closing at 5 m/s, and the initiate switch closing at 1 m/s. The results (Fig. 10) indicate that far less action is seen by the initiate switch at the slower closure speed, which is beneficial because the dynamic effects of the switch as a spring-mass system will be much milder at the slower closing speed. However, attempting to operate the switches at any slower speed could invite undesirable effects on the velocity profile due to stick-slip behaviour.

The axial actuator hydraulic circuit is shown in Fig. 11. This circuit is designed to operate in two modes—slow speed for maintenance operations and fast speed for current initiation. When enabled, the fixed displacement hydraulic pump pressurizes the accumulator to the preset pressure required for the closing speed selected (the system is designed to close the initiate switches at up to 4-m/s if required.) At this point, force is equalized across the piston

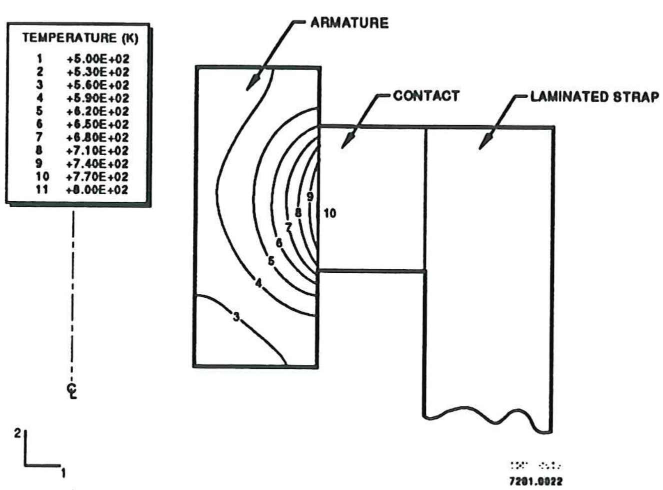

Fig. 7. Temperature distribution in armature

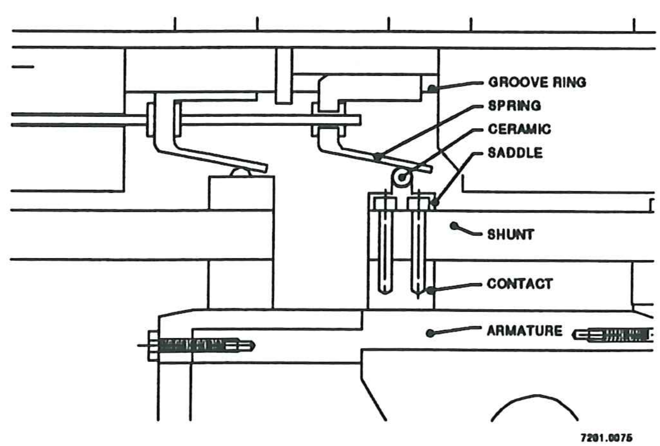

Fig. 8. Radial force actuator geometry

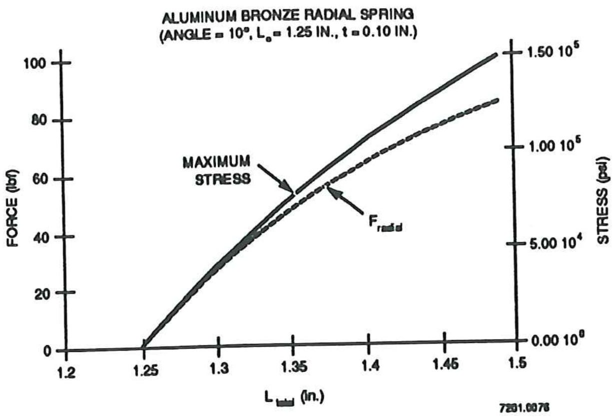

Fig. 9. Load vs. deflection for the radial actuator spring

in the cylinder because flow from port B is blocked by the positive seated dump valve. At the appropriate time, the BUS control system initiates current by opening the solenoid vent valve, which in turn allows the pilot operated, fast response dump valve to open, causing the switch assembly to be accelerated by the cylinder as a result of the stored pressure at port A. Appropriate control interlocks ensure that such high pressure, high speed operations are only allowed by remote automatic control, and only when the HCS area is evacuated [7].

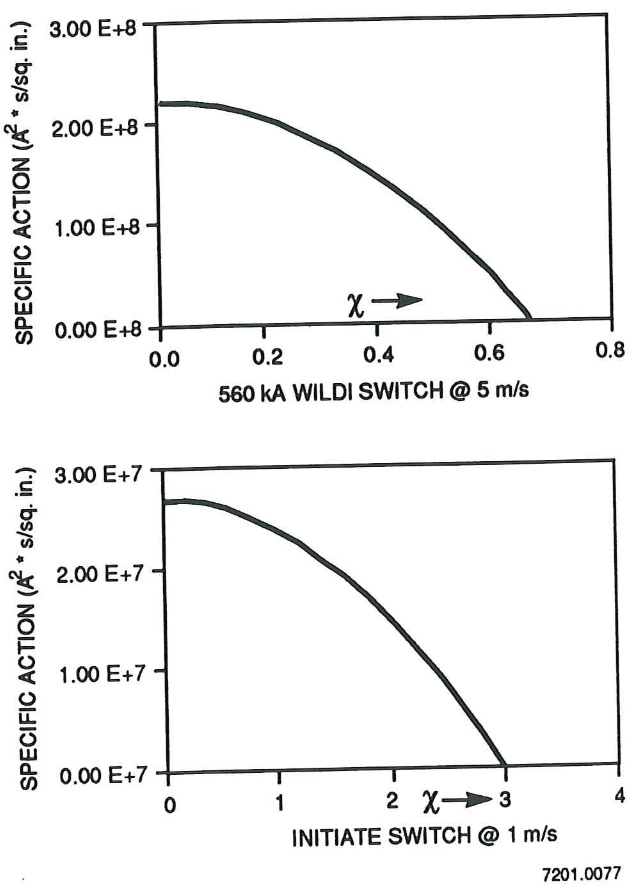

Fig. 10. Comparison of peak specific action for the 10 cm, 560-kA switch and the BUS initiate switch

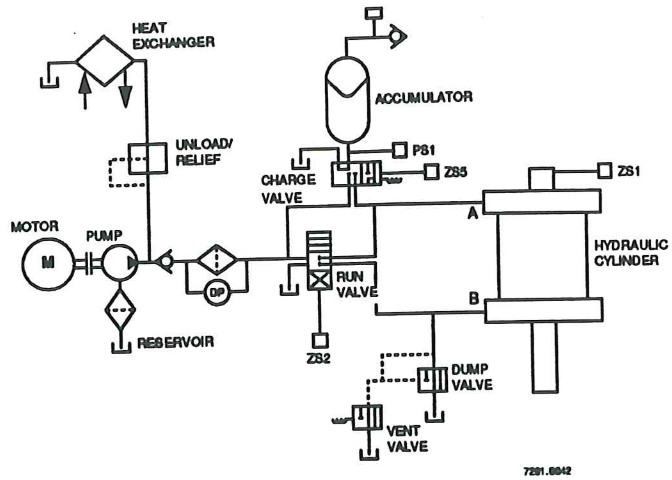

Fig. 11. Schematic of the axial actuator hydraulic system

Testing the Initiate Switch Subsystem

To completely test and verify the design of the initiate switches is to build and test BUS itself. However, four test plans will test the radial actuator design, the full current action capability of the switch, the full force capability of the switch, and the axial actuator design. Testing the radial force actuator and the full action capability are being conducted in a combined fixture containing a full size prototype laminated shunt and contact and angular segments of the armature and collector ring (Fig. 12). This fixture incorporates as much as possible the same materials, joint designs, and dimensions of the full switches. A staged battery test loop with a graded load resistor will be used to synthesize both a charging cycle and a railgun operation cycle to test the results on the temperatures at various locations in the switch components. These temperatures will be sensed and recorded by implanted thermocouples and by an infrared imaging system.

The full force test is designed to evaluate the mechanical stability of an initiation switch under conditions similar to rated performance. An assembled switch will be equipped

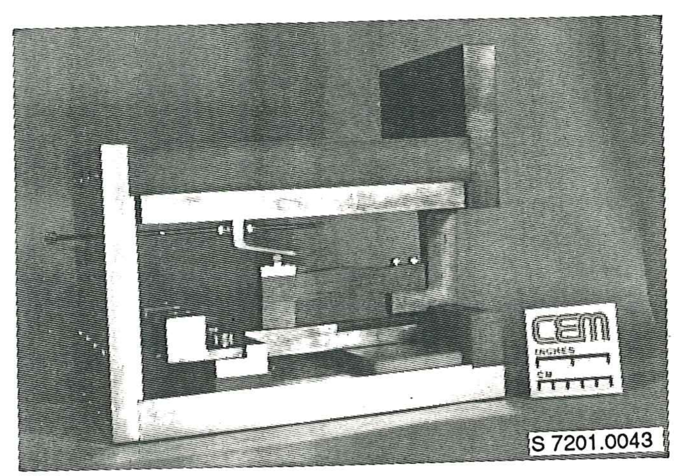

Fig. 12. Radial force and full action test fixture

with a reduced set of contacts evenly distributed around the armature such that each contact carries rated current and the current feed geometry is similar to that in the HCS subsystem. One of the six, 10 MJ, 1.5 MA HPGs that comprise the Balcones 60 MJ power supply will be used as a current source to pulse the test switch to 600 kA with a rise time of approximately 0.200 s in this test [11].

The axial actuator test will be performed in a final check assembly of the HCS subsystem. This test will determine the precision and controlability of the hydraulic actuator system and will also serve to seat the contacts.

Fabrication

Because the switch assembly is supported and registered by the HCS busbar plates, carefully planned co-machining procedures have been worked out for tolerance control in all parts that influence switch concentricity, cylindricity, parallelism, and other critical geometric features. Following rough fabrication (welding, bending, and brazing) of main busbar components, preliminary (Stage 1) machining will be done to achieve bar squareness, straightness, and flatness. Then both circuit HCS sets will be preassembled and subjected to Stage 2 machining. Following this, the bars will be disassembled, deburred, inspected, and Stage 3 machining will be performed. Another complete preassembly together with the initiate switch preassembly will take place, followed by Stage 4 machining. One final disassembly will be conducted for final inspection and electric joint inspection.

Stage 2 and 4 machining determine final axial and angular alignment between the two ganged initiation switches. Therefore, both these procedural steps are performed with the HCS busbars preassembled, clamped, and supported as they will be installed. Location pin patterns within and between each HCS circuit subassembly will be machined during Stage 1 machining in order to ensure repeatability of this setup.

While so arranged, Stage 2 will establish the final bore diameter in each HCS circuit, in which diameter the initiate switches are to be assembled. Also in this same setup, the counterbores in opposing busbar faces in each circuit will be turned. These counterbores serve to locate the current collector ring flanges, thus locating the initiate switch with respect to each HCS assembly.

After Stage 2, the HCS assemblies are disassembled and Stage 3 machining is performed. This stage establishes all bolt and pin hole patterns that join and clamp the initiate switches to the HCS busbars. When this stage is completed, the initiate switch bodies and bearing support pedestals, with undersized diameter bearing inserts, will be preassembled again as in Stage 2. This will be the Stage 4 machining setup, during which time the bearings will be line bored. This step will complete the major fabrication processes for both the initiate switches and the HCS busbars.

Conclusionsn

A ganged pair of 2.8 MA closing switches has been designed and is being fabricated as part of the high current switching system of the Air Force's Battery Upgraded Supply system at Eglin Air Force Base. These switches are used to initiate current in two parallel banks of batteries and must carry full current for a 5 s test duration after charging two, 280 MJ energy storage inductors. The initiate switches are based on the principles of operation of a family of sliding copper contact, cylindrical armature, fast acting closing switches designed and demonstrated by Paul A. Wildi. Four subsystem tests are in progress to verify switch designs including the radial and axial actuators, maximum temperature at full action, and mechanical stability under full forces.

Acknowledgments

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