Developments in the manufacture of vacuum switches

by G.J. Rushton, B.Sc., M.Sc., Ph.D., C.Eng., M.I.E.E., M.Inst.P.
Chief Engineer, Vacuum Products
GEC Alsthom Vacuum Equipment Limited

A. Turnbull, B.Sc.,
Product Manager - Vacuum Equipment
GEC Alsthom Vacuum Equipment Limited

Introduction

On the 4th November 1965, GEC Alsthom Vacuum Equipment Limited announced the availability of the world's first 3.3kV, 300A vacuum contactor, incorporating glass enveloped vacuum switches.

In 1980, to maintain its world lead in vacuum switch technology, GEC Alsthom Vacuum Equipment Limited began a new development programme, leading to the manufacture of the first of a new range of ceramic enveloped vacuum switches in 1983. Considerable innovation has been exercised in the design of this new range of switches, which feature metallized ceramic envelopes and new style contacts. A major part of the development programme involved devising and perfecting a revolutionary new manufacturing technique, whereby the complete brazing, evacuating and sealing of each switch is performed in one operation in a specially designed vacuum furnace.

History of vacuum switching

The advantages of switching current in a vacuum, as opposed to air or oil, have been appreciated since the turn of the century. When the contacts of a vacuum switch open, the arc is formed mainly from vapourized contact metal, and continues to burn only until the first current zero appears in the a.c. waveform. At this instant, the arc ceases, the metal vapour deionizes, cools and condenses, and the contact gap quickly reverts to an area of high dielectric strength able to withstand the recovery voltage. As the arcing period does not exceed one half-cycle and the arc voltage is very low, the energy of the vacuum arc is therefore much less than that of arcs in air or oil and the contacts suffer far less wear than those in air or oil control gear. The resulting long life, combined with the additional advantages of small size, maintenance free operation, and low operating power requirements give an ideal switching device for motor control gear.

Records indicate that prototype vacuum switches were manufactured in the USA as early as 1923, however, successful development of a commercially viable vacuum switch had to await advances in several fields. Despite their initial promise, the early vacuum switches suffered from extremely short lives because of a lack of equipment to provide a sufficiently high vacuum and the inability of producing effective vacuum tight seals. In addition, the relatively impure materials of the time soon gave off enough gas to degrade otherwise good switches.

Research work carried out by the Electrical Research Association into contact materials in the 1950s was carried on by GEC and, combined with the company's extensive experience of glass-to-metal sealing of large thermionic devices, enabled prototype switches to be built in the early 1960s (Fig. 1). Successful solutions to all the problems associated with manufacturing a high reliability switch led to successful field trials of prototype units and culminated in the official launch of the 3,3kV vacuum contactor in 1965.

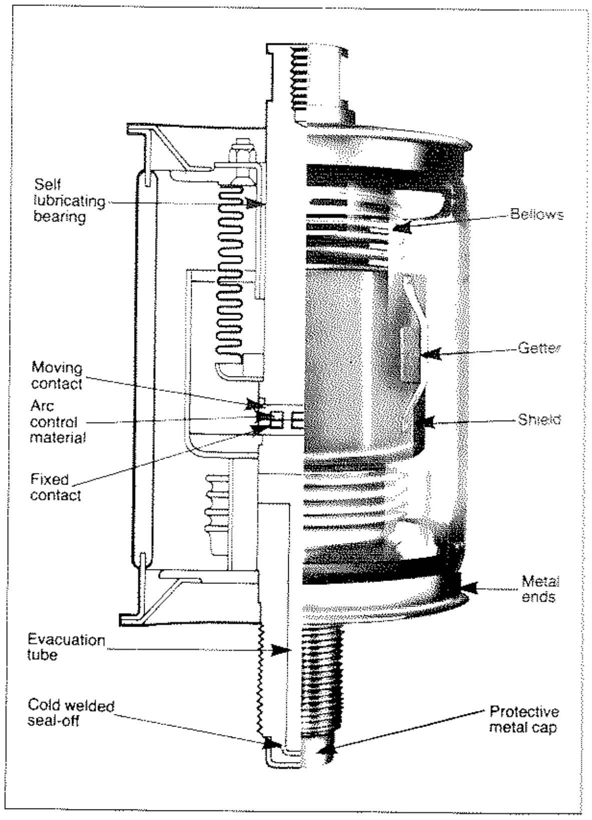

Fig. 1 Part section through a typical glass envelope vacuum switch.

In the first two years, 400 vacuum contactors were supplied to customers in a wide variety of industries, and vacuum contactors were steadily established as the main switching device for high voltage motors in the UK. The introduction of 660V, 1100V and 6600V vacuum contactors in 1967 saw the potential market for vacuum contactors increase, and sales steadily spread to more and more countries throughout the world.

Obviously, many customers were initially cautious about the use of such a revolutionary switching device, however, acceptance grew with experience and the sale of vacuum switches rose steadily from a total of 1200 in the first two years to over 1200 per month in 1980. By this time, it had become obvious that the production capacity of the vacuum switch plant in Rugby needed to be increased to cope with future demand, and various options were investigated.

The first possibility was to increase the capacity of the existing production line. The advantages of this course of action were quick implementation, no development

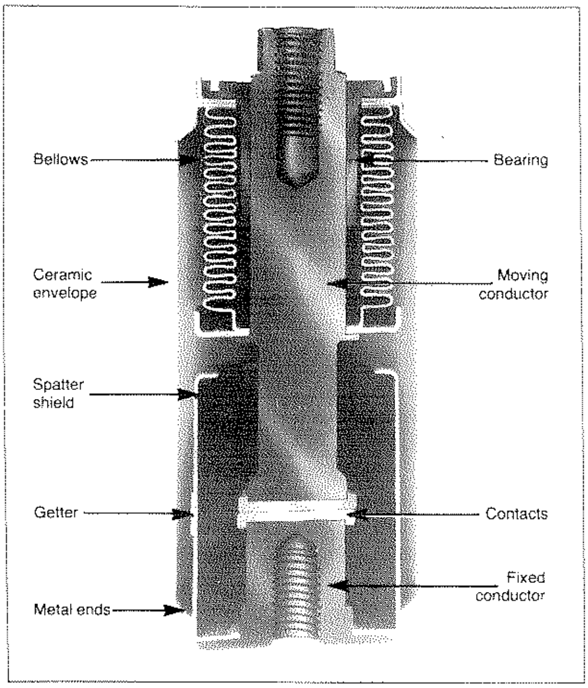

Fig. 2 Sectional view of typical ceramic envelope vacuum switch.

costs, and the use of proven technology and established methods. However, weighed against these advantages were the disadvantages of high labour and production costs, a very long manufacturing cycle time, and large space requirement.

The second alternative was to develop a completely new manufacturing technique, taking advantage of the many advances in material and vacuum technology which had occurred since 1965. An exhaustive review of new materials and techniques resulted in the decision to develop a completely new range of vacuum switches using metallized ceramic rather than glass envelopes (Fig. 2) and using a revolutionary single-stage manufacturing process.

Manufacture

To appreciate fully the advance in the manufacturing technique, it is necessary to compare the manufacture of the glass envelope vacuum switches with that of the new ceramic envelope vacuum switches.

Glass envelope switches

Although there have been design changes in the glass envelope vacuum switches to improve their performance, the manufacturing techniques have changed little since the switches were first introduced in 1965. The vacuum switches in this range all have glass envelopes and are similar to each other in design principle, the main differences being in the overall size of the switches and a choice of either a 'soft' low chopping current contact (0,3A average) made from molybdenum filled with antimony/bismuth alloy, or a 'hard' higher dielectric strength contact of sintered tungsten/copper. The manufacture involves a large number of labour intensive operations, resulting in long manufacturing times and a high level of work in progress on the factory floor.

Fig.3 shows the manufacturing routine for these vacuum switches. The main stages of manufacture are as follows:-

Stages 1 – 3

Switch assembly commences with the procurement and manufacture of the detail parts. All components must use high purity materials manufactured to a high degree of quality and tolerance and must be thoroughly cleaned before assembly. Nickel-plating of many of the components is also necessary to ensure satisfactory joints are

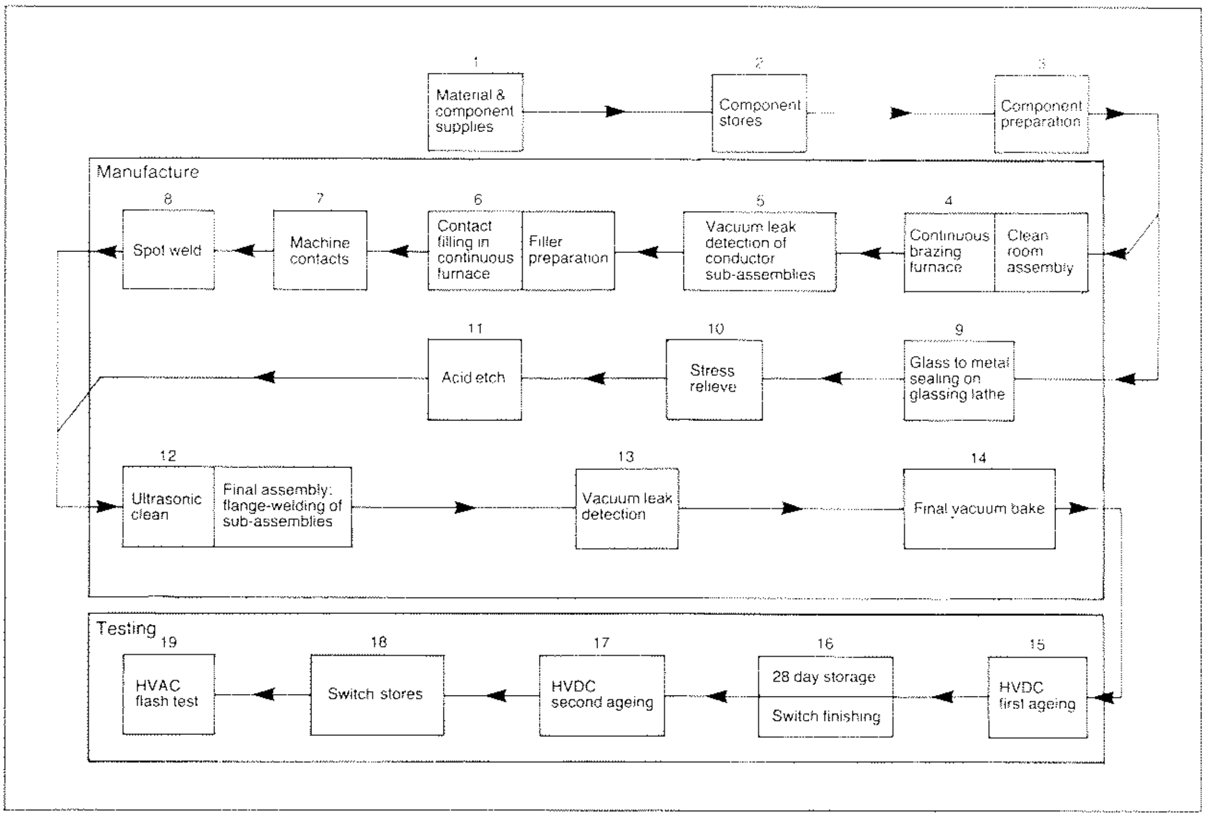

Fig. 3 Flow chart for the manufacture of glass envelope vacuum switches.

obtained with the hydrogen brazing operation.

Stage 4
Assembly of the fixed and moving contact sub-assemblies takes place in a clean rooom. The sub-assemblies are brazed in a continuous moving belt hydrogen atmosphere furnace, taking 3 to 4 hours to pass through the furnace.

Stages 5 and 6
The brazed sub-assemblies are vacuum leak tested to ensure brazed joints are airtight. The parts are then passed through a second furnace where an antimony/bismuth filler alloy is melted into reservoirs machined in to the main molybdenum contact blanks. This filling operation is again carried out in a continuous moving belt hydrogen atmosphere furnace which operates at a temperature approximately 130°C below that of the brazing furnace.

Stages 7 and 8
The contact faces are machined to remove the surplus antimony/bismuth alloy. After cleaning of the sub-assemblies, spatter shield and getter are attached using conventional spot-welding techniques.

Stages 9 – 11
The fixed and moving contacts will be held in position and separated by a glass envelope assembly, which consists of nickel steel end-rings and boro-silicate glass. The end-rings are fused into the ends of a glass tube on a standard glassing lathe. The glass envelope assembly is then stress relieved and the end-rings acid cleaned to remove oxidation before the next operation.

Stage 12
The three sub-assemblies are ultrasonically cleaned and the complete switch is then formed by welding together the sub-assemblies in a plasma arc seam welding process. At this stage, the vacuum switch is still open to air via its hollow copper pumping stalk.

Stage 13
Prior to final evacuation, a further leak detector check is performed on the complete switch. A temporary high vacuum is created inside the switch through its pumping stalk, helium is sprayed around the various joints and any helium drawn into the switch due to a leak is detected by a mass spectrometer tuned specifically to helium gas.

Stage 14
The switches are placed on a vacuum rig to be pumped and baked using a separate pumping manifold and oven for each switch. The combination of a roughing pump and a baffled oil-diffusion pump produces a final vacuum pressure of approximately 10^{-6} torr in the vacuum switches. The glass envelope sets an upper temperature limit during bake-out of approximately 425°C. All of the vacuum switches contain getters which are activated separately by heating them to red heat using an induction coil immediately prior to the sealing-off of the vacuum switch from the pumping manifold. (The getter is a material which absorbs gas and is used as a safeguard to ensure the vacuum quality inside the switch is maintained during extended periods in storage.)

Finally, the switch is sealed-off and removed from the pumping system by pinching-off the pumping stalk to form an airtight seal.

Stages 15 – 19
The switches are subjected to a series of mechanical and

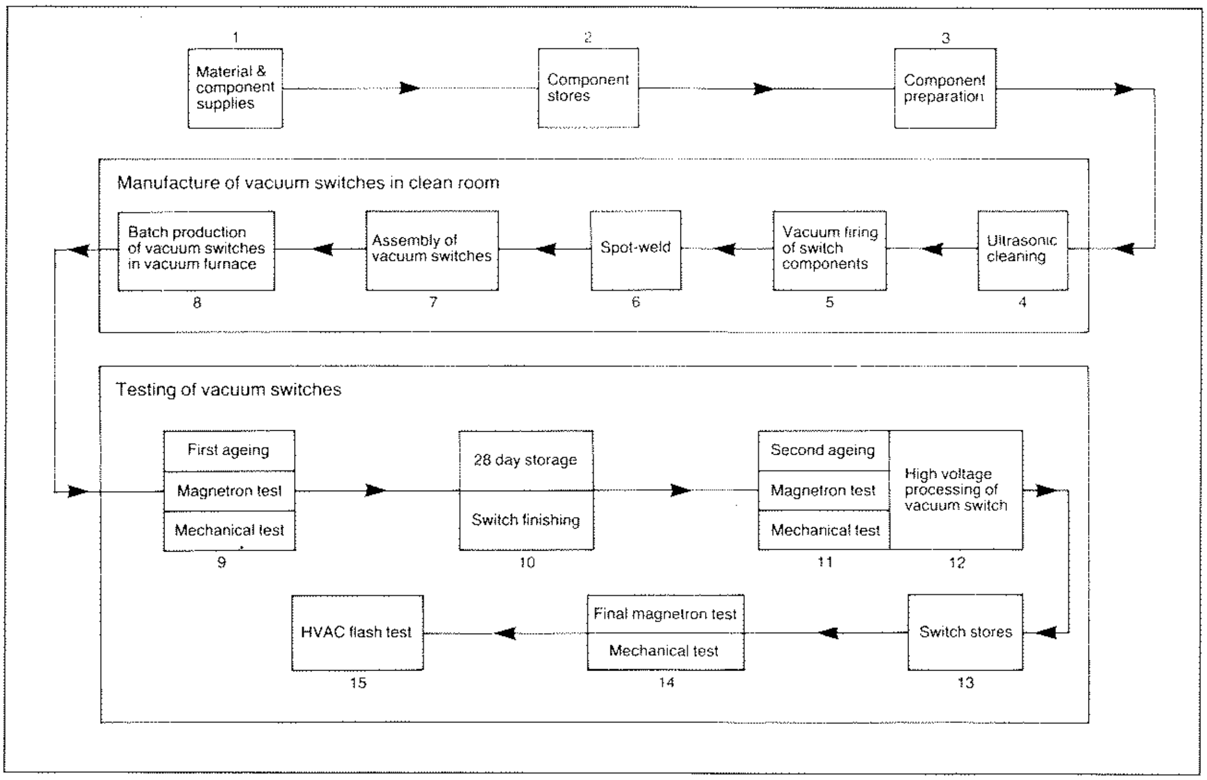

Fig. 4 Flow chart for the manufacture of ceramic envlope vacuum switches.

electrical tests immediately after manufacture, stored for a period of 28 days then subjected to further high voltage electrical tests. In this way, any deterioration in voltage withstand will be detected before the switches leave the factory.

Ceramic envelope switches

The new range of ceramic vacuum switches has been designed for manufacture in a 'one-shot' vacuum bake/ brazing operation following an initial vacuum out-gassing run for the individual vacuum switch components.

As the brazing is carried out in vacuum, the suitable choice of brazing alloys has eliminated the need to plate any of the vacuum switch components. The amount of spot welding has been kept to a minimum, and involves only attaching the getters to the spatter shield. Thus, there are effectively no sub-assemblies to manufacture, thereby considerably reducing the labour content and keeping the work in progress on the factory floor to a minimum. This simplified method of manufacture greatly assists quality control procedures and the scrap rate during manufacture has been reduced by an order of magnitude for the ceramic vacuum switches as compared to the glass envelope vacuum switches.

The most important criterion for the successful manufacture of vacuum switches is absolute cleanliness. With this new technique of manufacture, all manufacturing operations after the initial degreasing of the vacuum switch components are carried out in a self-contained, dust free clean room. The complete assembly of the vacuum switches is carried out in a laminar flow cabinet located within the clean room, with operatives wearing special protective clothing.

Fig. 4 illustrates the manufacture of ceramic envelope vacuum switches. The various stages are as follows:-

Stages 1 – 3

As with glass envelope vacuum switches, the quality of all materials and components used must be of the highest standard. All materials and components are subjected to a continuing quality control procedure to ensure that the required standards are maintained. Components required to manufacture a batch of switches are drawn out of the stores as required, chemically de-greased and hydrogen fired before going into the vacuum switch manufacturing clean room.

Stages 4 and 5

Within the clean room, the vacuum switch components are ultrasonically cleaned, and batch loaded into the vacuum furnace for an out-gassing run at temperatures up to 900°C (depending upon the melting point of the materials).

Stage 6

The only sub-assembly stage in the manufacture of the ceramic envelope vacuum switch consists of spot welding the getters onto the outside of the spatter shield.

Stage 7

Each ceramic envelope vacuum switch is assembled complete in a specially designed jig as shown in Fig. 5 within a laminar flow cabinet (Fig. 6). Specially shaped

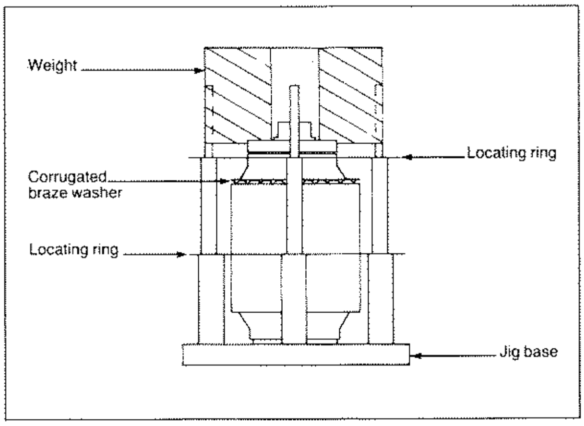

Fig. 5 Brazing jig with assembled ceramic envelope vacuum switch in position.

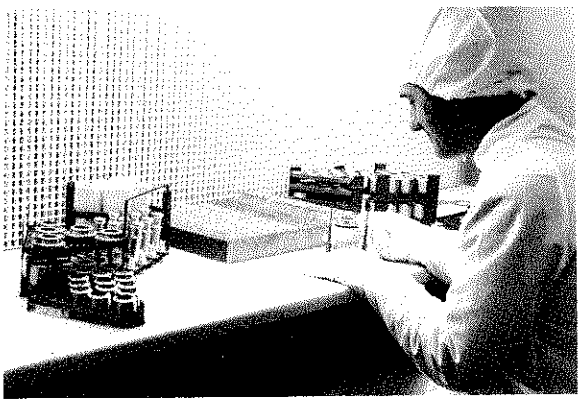

Fig. 6 Assembly of ceramic vacuum switches in a laminar flow cabinet.

silver alloy braze washers are sandwiched between each joint. The braze washer between the moving end metal pressing and the ceramic envelope is corrugated to ensure that air can be evacuated from the switch during the manufacturing cycle.

Stage 8

A batch of switches loose-assembled in their jigs is loaded into the vacuum furnace on a stand (Fig. 7). Fifty-two vacuum switches rated at 3,3kV, 400A can be loaded into the furnace in each batch. The vacuum furnace is sealed and pumped down to a pressure of approximately 10^{-6} torr. The switches are heated to a temperature of 600°C and held at that temperature for a sufficient period of time to achieve satisfactory out-gassing of the switch components. The temperature of the furnace is then raised briefly to 830°C when the braze alloy melts and the weight on the jig compresses the bellows sufficiently to close the gap where the corrugated braze washer was located. At this temperature the getters have automatically been activated. The temperature of the furnace is then lowered and the braze solidifies, sealing the vacuum into the switches. As the vacuum switches are cooled to room temperature, the getters absorb the small traces of residual gases, so further reducing the pressure inside the vacuum switches, resulting in a lower ultimate pressure than that obtained in the vacuum furnace itself. The vacuum furnace has a microprocessor programmed sequence to automatically control the furnace cycle. Fig. 8 shows the thermal cycle of the vacuum furnace during the switch manufacturing process.

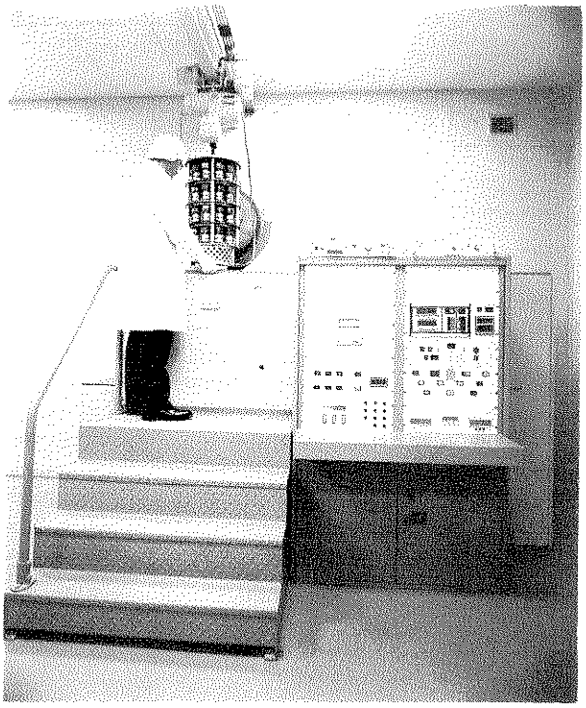

Fig. 7 Ceramic envelope vacuum switches being loaded into the vacuum furnace for the single-shot manufacturing process.

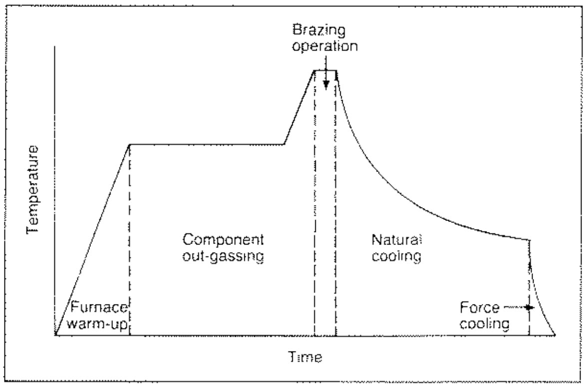

Fig. 8 Vacuum furnace temperature cycle for the vacuum baking and brazing of ceramic envelope vacuum switches.

Stages 9–15

The switches are subjected to an exhaustive series of mechanical and electrical tests immediately after manufacture, stored for a period of 28 days and then subjected to further tests. In this way any deterioration in vacuum quality will be detected before the switch leaves the factory. During the storage period, the switch finishing processes comprising painting, plating the conductors and fitting the bearing are performed.

To evaluate the vacuum quality in glass envelope switches, high voltage tests of the switch dielectric are carried out by experienced operators performing visual inspection for any electrical activity inside the switch during these tests.

Purely electrical methods have been employed for evaluating the vacuum quality in ceramic envelope switches as it is obviously impossible to perform any visual inspection of the interior of this type of switch. An apparatus has been specially developed for use on the factory floor, to automatically perform the required series of mechanical tests and to measure the gas pressure inside a ceramic vacuum switch by means of the well known 'magnetron discharge' technique. In this apparatus, the switch is located at the centre of a solenoid and 2kV d.c. is applied between the parted contacts of the vacuum switch. In this way, a magnetron discharge due to the crossed electric and magnetic fields can be obtained inside the switches for pressures down to less than 10^{-6} torr, the discharge current obtained being a measure of the gas pressure in the switch. In the case of switches whose pressure is too high or too low for this method to work, the apparatus automatically initiates a d.c. flash test in order to discriminate between these two extreme pressure regimes. Using this magnetron technique to measure any change in pressure over a set period of time allows the presence of any minute leak in the vacuum switch to be detected with ease (Fig. 9) thus ensuring that only switches of the highest quality are supplied to customer.

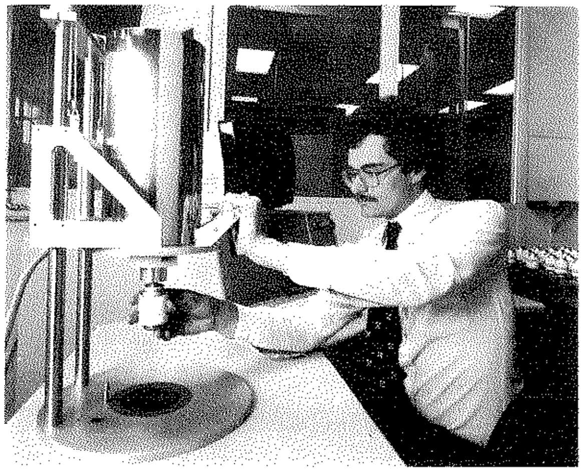

Fig. 9 Testing of ceramic envelope vacuum switches.

As a final test before leaving the factory, all vacuum switches, both glass and ceramic enveloped, are subjected to a standard high voltage a.c. flash test to check their voltage withstand.

Design considerations

The fact that all components in the vacuum switch are subjected to the maximum process temperature during manufacture necessitated many changes in the materials used. The most noteable changes are in the insulating medium, which is a metallized ceramic facilitating brazing, and in the composition of the contact materials.

The unrivalled experience of GEC Alsthom Vacuum Equipment Limited in the application of glass envelope vacuum switches to fuse-protected contactor switching applications led to the use of both hard and soft contact materials in order to successfully meet the many varied applications and requirements for vacuum contactors. The soft contact material is used in vacuum switches for general purpose applications such as direct-on-line starting of motors. The hard contact material is used in applications such as capacitor switching and reversing duties, where dielectric strength is of utmost importance.

This design philosophy has been carried forward to the ceramic envelope vacuum switches, which are also available with either soft or hard contacts. The existing hard contact material used in the glass envelope switches, in which the main constituents are copper and tungsten is now also used in the ceramic envelope switches. However, the existing soft antimony/bismuth filled contact material is not compatible with ceramic envelope vacuum manufacture due to its relatively low melting point. Therefore, an alternative soft contact material had to be identified which was compatible with the ceramic envelope vacuum switch manufacturing process. A contact material in which the main constituents are tungsten carbide and silver is used to provide the soft contact option in ceramic envelope vacuum switches. The melting point of silver is sufficiently high and its vapour pressure is sufficiently low for this material to be compatible with the new manufacturing technique of vacuum switches. In addition, the vapour pressure of silver is still sufficiently high so that, when combined with the thermionic characteristics of the tungsten carbide, an average chopping current of less than 0,5A is achieved.

Conclusion

Many thousands of vacuum contactors have now been supplied by GEC Alsthom Vacuum Equipment Limited to a wide range of industries throughout the world. Their reputation for reliable operation, long trouble free life, and low maintenance requirements has been proved in applications ranging from light infrequent use in process industries to very frequent arduous duty in steel works. This extensive experience has been used to design a comprehensive range of vacuum contactors to meet the requirements of most high voltage applications on systems up to 11kV.

The new simplified technique of manufacturing vacuum switches which has been developed is compatible with the large scale production required to meet the expanding vacuum contactor market. The use of ceramic rather than glass envelopes has allowed the processing temperature during manufacture of the vacuum switches to be increased prior to seal-off, which is beneficial to vacuum switch quality. The test procedures for the new ceramic vacuum switches are automated with improvement in both accuracy and efficiency of operation as is required for any large scale production method.

The greatly increased efficiency of the new manufacturing technique results in significant cost savings. The benefits of this are twofold. Vacuum contactors for use in the main traditional operating range of 3,3kV to 6,6kV will be able to compete more effectively in the increasingly competitive world markets. However, more important as far as continuing growth is concerned, is the possibility of manufacturing switches which can compete effectively in the large industrial market at voltages down to 600 volts, and also of producing switches specifically designed to meet the special requirements of new applications.

New ceramic envelope vacuum switches with ratings from 1,5kV to 7.2kV are now in manufacture. As developments and tests are completed, switches with both higher and lower ratings will be added to the available range, ensuring that GEC Alsthom Vacuum Equipment Limited continues to lead the world in vacuum switch technology.