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Stages of development, improvement and application of equipment for welding in space, created with the participation of Ukrainian scientists

Abstract

The article is devoted to the historical analysis of development and improvement of electrotechnical equipment that was developed and applied in the USSR to conduct works on welding and related technologies in space in the period from the 60s to the 90s of the last century and to assess the contribution of Ukrainian scientists in this field.

Keywords: *space, welding, electrotechnical equipment, Ukrainian scientists*

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Etapy rozwoju, ulepszania i stosowania sprzętu do spawania w kosmosie, tworzonego z udziałem ukraińskich naukowców

Abstrakt

Artykuł poświęcono analizie historycznej rozwoju i doskonalenia sprzętu elektrotechnicznego, który tworzono i stosowano w ZSRR do prowadzenia prac nad spawaniem i pokrewnymi technologiami w kosmosie w okresie od lat 60. do 90. ubiegłego wieku oraz ocenie wkładu ukraińskich naukowców w tej dziedzinie.

Słowa kluczowe: *kosmos, spawalnictwo, sprzęt elektrotechniczny, ukraińscy naukowcy*

1. Introduction

On October 16, 1969 V.N. Kubasov and G.S. Shonin conducted a welding experiment in space, which formed the basis of a new scientific and technological direction of space technology (Paton, Kubasov 1970). In fact, the scientists and specialists from different research and industrial organizations of the USSR, who prepared this complex and risky experiment – planned in the early 1960s by the academicians S.P. Korolev and B.E. Paton (Taglina 2010, p. 68) – became pioneers in the research and technological exploration of space. In the past nearly 50 years, several hundred similar experiments of fundamental and practical purpose have been carried out in space (Paton, Lapchinskii 1997; Paton et al. 2017; Strelko et al. 2019; Naden, Prater 2020). Naturally, the rapid development of space technology in the USSR affected the subject area and volume of scientific publications (Paton (eds.) 2000).

However, most of them were devoted to describing the conducted technological experiments and analyzing their results, history of preparation and conducting the experiments themselves (Paton 1972; Paton, Kubasov 1979; Paton, Dzhanibekov, Savitskaya 1986; Shulym et al. 1991, pp. 12–24.). By an order magnitude fewer research works were devoted to the development of electrotechnical equipment applied for carrying out these experimental studies, its design and functional features.

The aim of this paper is to review and analyze the stages of development, improvement and application of equipment for welding in space, created with the participation of Ukrainian scientists in the period from the 60s to the 90s of the last century.

2. Methods of investigations

The author used historical method (Garraghan, Delanglez, Appel 1946; Grigg 1991; Porra, Hirschheim, Parks 2014) to consider and analyze the stages of development, improvement and application of equipment for welding in space, created with the participation of Ukrainian scientists in the period from the 60s to the 90s of the last century.

3. Sources analysis

By the early 1960s, the USSR and the USA in their competition with each other were far ahead of other countries in the development of practical cosmonautics. Already at that time, the development of the first projects of long-term operating space orbital stations was started. Naturally, it was the time when the idea emerged that to create, maintain and repair them, welding in space would be required. Unfortunately, those years were characterized by the rivalry between the two countries, which not only led to a rapid development of cosmonautics, but also forced the respective governments to immediately classify all the new investigations aimed at the exploration of outer space as secret. Therefore, even now little is known about the practical realization of research works on welding in space in the USA in those years. The first publications about welding in space were of a purely popularizing nature (Paton 1964; 1969; 1975). However, already in those works, electron-beam welding was mentioned as the most challenging for space conditions. Of course, today the interest is given to more detailed information on the development of welding in space in the USSR in that period and the contribution of Ukrainian scientists.

In 1964, at the Paton Electric Welding Institute (PWI) together with the Experimental Design Bureau OKB-1 (today S.P. Korolev Rocket and Space Corporation Energia, Korolev, Moscow region), a comprehensive program of scientific researches was developed, the aim of which was to create the equipment and technologies for joining materials in space by welding them together (NN_3, p. 107). Those works were headed by the academician B.E. Paton and led by him for over 50 years. At the E.O. Paton Electric Welding Institute (PWI) a group of specialists was created to carry out the works. It should be noted that starting from the first developments and experiments on welding in space, the PWI worked with many organizations and institutes (Paton et al. 2003c). The main such entities were the S.P. Korolev Rocket & Space Corp. Energia, Yu. A. Gagarin Research & Test Cosmonaut Training Center, the Ionosphere and Radio Wave Propagation of the Academy of Sciences of the USSR, the Space Research Institute of the Academy of Sciences of the USSR, enterprise Zvezda, the Institute of Terrestrial Magnetism, the Mission Control Center (Russia), and also the Institute of Electrodynamics of the Academy of Sciences of the UkrSSR (IED), and the Institute for Low Temperature Physics and Engineering of the Academy of Sciences of the UkrSSR.

The investigations began in the same 1964 (Paton 2009). The program envisaged several stages (Strelko, Pylypchuk, Berdnychenko 2019). At the first stage, the experimental welding equipment was developed for a number of welding methods which were the most promising for space conditions. It was significant that the applied equipment was designed to operate on the power supply from autonomous batteries, which simulated the on-board mains of a spacecraft. At the same time, the research vacuum stands were developed, which had to simulate the conditions of space to the maximum extent. At the second stage, several methods of welding were investigated in ground-based laboratories using the experimental equipment and research vacuum stands. This allowed simulating the space vacuum and temperature intervals characteristic of space to some extent. At the same stage, the possibility of using different protective and plasma-forming gases in space was studied to determine the optimal modes of welding, cutting and other technological processes. At the third stage, investigations were carried out already with the means accepted during the tests of the spacecraft and the training of the cosmonauts. A flying laboratory allowed a repeated short-time reproduction of zero-gravity conditions and large pressure chambers that provided a possibility to simulate the work in open space much more fully. They were equipped with welding equipment and testing stands. Finally, the fourth stage envisaged testing welding equipment and technologies already directly in space. The research program developed in the USSR, actively continued, had developed and improved up to 1991.

During that period a huge number of experiments was performed, many models of space welding equipment and different technological processes were tested. And all that time the stages of research mentioned above remained unchanged, as it allowed for the preparation of works in space in the best way.

This led to considerations over the results of using the developments of the electrotechnical equipment in conditions simulating space or in space. These were produced in the USSR from 60s to 90s of the last century. For the first time, the investigations simulating space were performed in the USSR in 1965 in a flying laboratory of the aircraft TU-104, providing a short-term (up to 25–30 s) reproduction of zero-gravity conditions (Shulym et al. 1991, pp. 12–24). To conduct investigations, the equipment complex A-1084 was created, consisting of a series of vacuum chambers, mechanical forevacuum and getter high-vacuum pumps, recording devices (ordinary and high-speed video cameras, oscilloscopes) and control equipment. The whole complex of equipment was located in the salon of the flying laboratory. For welding methods such as an electron beam, a consumable electrode arc, and a low-pressure constricted arc, special automatic devices could be installed on the lids of each of the chambers. As in the structures of space objects, metal of high thickness is not usually used, and the power of those welding devices did not exceed 1.5 kW. The conducted investigations revealed the most characteristic features of welding in the conditions of zero-gravity and vacuum.

On the basis of the investigations carried out by the specialists of the PWI and the IED, a special welding unit "Vulkan" (Fig. 1) was developed and manufactured. "Vulkan" was intended for experimental research in space of the previously mentioned welding methods (Paton, Kubasov 1970; Dzhanibekov et al. 1991, pp. 49–58).

"Vulkan" represented an integrated, completely autonomous device, which allowed performing electron beam welding in an automatic mode, welding by a constricted low pressure arc and arc welding with consumable and non-consumable electrodes (Paton, Kubasov 1970). The unit consisted of two main compartments. In one compartment, which was not sealed, welding devices and joined specimens were located; in the other one, which was sealed, the power supply units,

Fig. 1. Welding unit "Vulkan" in the Museum of the PWI
(photo by the author).

control devices, measuring and converting devices, automation means were located. The power source and the electron gun represented a single unit based on epoxy compounds, which served simultaneously as an insulating and construction material. Paton et al. (2003a) describes the advantages of

> (…) the absence of high-voltage cable, connectors and terminals provided a significant increase in the reliability and maneuverability of the equipment, reduction in its weight. It almost eliminated the probability of the operator's injury with high voltage. The use of a solid insulation

instead of liquid insulating materials allowed reducing the dimensions of the equipment, reducing the thermal load due to the better thermal conductivity of the epoxy compounds, and increasing the manufacturability of the production of the power source. In order to increase the reliability of the operation of the welding unit "Vulkan", the elemental duplication and deep replacement redundancy were implemented, guaranteeing the preservation of the nominal parameters of the equipment of up to 35% of the circuit elements during failure. A fairly high operating frequency of inverters (1000 Hz) was chosen based on the desire to reduce the weight of the power source and its dimensions at the acceptable losses in steel. With increasing frequency, dielectric losses in the source isolation relatively little increased. The duration of the continuous operation of the welding unit "Vulkan" was short (up to 3 minutes) and was limited by the capacity of the battery. The power of welding devices for different methods ranged from 0.6 to 1.0 kW. Let us consider the features of the power source of the electron beam unit "Vulkan" in more detail. The power was supplied from rechargeable batteries. The constant voltage of 26...28 V was converted into the alternating of rectangular shape using the anode and incandescent transistor inverters (with the efficiency of 94%). The high-voltage transformer and the rectifier, assembled from semiconductor valves, formed a rectified accelerating voltage. With the aim of replacement redundancy of the cathode, a dual, automatically switchable electron optical system was used. A beam of electrons for welding and cutting was formed by an electron-optical system with a single-stage electrostatic focusing, to which accelerating electrode was introduced being under the potential of workpiece. Such a gun was different from the guns with additional magnetic focusing, extreme simplicity of design, small weight and sizes. As far as at a constant cathode temperature the focal length of a single-stage gun does not depend on accelerating voltage, it could be powered from metastable and even alternating voltage.

Based on the results of probe measurements, it was found that they showed that the specific power at the focus of the electron beam was about 1 kW/mm^2.The current of the electron beam was 60 mA, the accelerating voltage was 10 kV (Paton et al. 1975). The maximum duration of the continuous operation of the welding unit "Vulkan" was 3 minutes. The weight of the electron beam gun was 450 g. The weight of the gun with a power source unit was 6.5 kg.

The "Vulkan" automation unit, which provided the required welding modes, included the following components: a regulator that maintained the voltage in the anode circuit with an accuracy of ± 1%; a device that provided a delay for a given time in starting the anode inverter; a device that ensured its shutdown if a short circuit occurred; a device that provided automatic switching after eliminating the cause of the short circuit (Paton et al. 2003a).

At first there were no publications about these works. The scientific and technical articles devoted to the problem of welding in space began to be printed in the Soviet journals only after the first welding experiments in space conducted in 1969.

On October 11–16, 1969, the Soviet spacecraft Soyuz-6 successfully completed its flight. On October 16, 1969, during this flight, the cosmonauts Georgy Shonin (spacecraft commander) and Valery Kubasov (spacecraft flight engineer), did something no-one had done before, i.e. they conducted experiments on automatic welding and cutting metal onboard a spacecraft in space (Paton, Kubasov 1970; Strelko, Pylypchuk, Berdnychenko 2019). It was conducted with the help of the "Vulkan" unit. The "Vulkan" itself was installed in the living quarters of the spacecraft "Soyuz-6", and the control panel was in the descendant apparatus. Paton and Kubasov describe this experiment in their article (Paton, Kubasov 1970):

> (…) After depressurization of the living quarters, the cosmonaut-operator V.N. Kubasov, who was in the descent apparatus, switched automatic welding by a constricted arc of low pressure. Subsequently, he activated the automatic devices for welding with electron beam and consumable electrode. During each experience, the cosmonaut watched the operation of the unit following the signal board on the control panel. All the experiments were carried out in space

> in an automatic mode. The data on the mode of welding and conditions of the experiment were transmitted to Earth and recorded by self-recording devices (…).

The experiment carried out in space confirmed the basic assumptions made earlier and the results of investigations obtained on the flying laboratory of "TU-104".These experiments made it possible to prove the fundamental possibility of cutting and welding in space. The analysis of the results of these experiments showed that the processes proceed most stably when using an electron beam for welding and cutting metals. It was during electron beam welding that welded joints of optimal geometry and properties were obtained. Electron beam welding proved to be excellent, while welding by a constricted arc of low pressure did not provide the required quality, and during welding with consumable electrode, a weld turned out to be non-uniform and lacked penetration.

Analysis of the equipment operation in space conditions showed that all small-sized welding devices included in the "Vulkan" installation complex worked reliably. The technical solutions used by Ukrainian scientists in the development and creation of these devices made it possible to successfully complete the planned set of experiments on welding in space. In the further development of small-sized devices for welding in space, these technical solutions were used.

Nikitsky et al. (2003):

> (…) by the early 1970s the problem of the fundamental possibility of performing automatic welding in space was solved positively. At the same time, there was a large category of works, including almost all types of repairs that could hardly be carried out using automatic welding. Therefore, the task of studying the possibility of performing manual welding in space was very relevant. Moreover, there were good reasons to be concerned about the cosmonaut-operator, who – equipped with a spacesuit under considerable excessive pressure – would not be able to perform such a professionally complicated process as welding due to the extremely limited mobility. The problem was complicated by the necessity of providing a complete safety to the operator.

All the mentioned facts forced astronauts to refuse to work in a spacesuit directly in vacuum at the initial stages. A compromise solution was found (Paton et al. 2003b):

> (…) for conducting investigations on manual welding in conditions which are as close as possible to space, in 1972 the E. O. Paton Electric Welding Institute designed a special testing stand "OB-1469". The stand represented a sealed working chamber with a volume of about 0.8 m^3, on the front wall of which a special fragment of a space suit was mounted. Between the fragment and the chamber, a desired pressure drop could be created, which reproduced the real conditions of the work of the cosmonaut most fully. Inside the working chamber the tools and manual welding devices were placed. The glazing of a pressure helmet of a spacesuit was equipped with a set of replaceable light filters, which allowed working with sources of heating of different brightness. The most important constructive advantage of the stand was a reliable provision of operator's safety in case of accidental depressurization, which provided a favorable psychological situation during work with high-temperature objects. The possibility of free medical and biological control over the condition of the operator and the convenience of carrying out different ergonomic investigations were also of great importance. Simultaneously with the stand in E. O. Paton Electric Welding Institute developed a set of special space tools "A-1500", which allowed performing welding in different methods (…).

Initially, the experiments were conducted in ground-based laboratories. In such cases, a working chamber was usually filled with inert gas or carbon dioxide. At later stages of the investigation, they were transferred to a flying laboratory and into vacuum. The experiments did not confirm the above-mentioned concerns. On the contrary, it turned out that after a certain short training the operators (not even professional welders) could perform high-quality manual welding of different welded joints – butt, fillet, overlapped joints – on stainless steels, aluminum and titanium alloys. It was also discovered that during arc welding in inert gas with consumable electrode under zero-gravity, the danger of burns is much lower than on Earth.

This was explained by the specific conditions for the existence of a weld pool in the absence of gravity. Such encouraging results allowed for an attempt to perform also manual electron beam welding, a process characterized by a very high concentration of thermal energy in the heat spot. For this purpose, a special manual electron gun was developed, which allowed using the stand "OB-1469" to successfully conduct a number of experiments on manual electron beam welding. The experiments showed that this method had great potential for application in space conditions.

In June of 1974, at the Yu. A. Gagarin Research & Test Cosmonaut Training Center, the prototype tests of the first model of a manual electron-beam gun (MEBG) were conducted, the main purpose of which was the evaluation of a possibility of performing manual electron beam welding and cutting by an operator in a spacesuit. Paton et al. (2003c):

> (…) As to its design, the electron beam installation used in these experiments included MEBG itself; high-voltage power source, electrically connected to MEBG by a high-voltage cable; unit-converter of voltage of 27...32 V of direct current into voltage of 15 kV of alternating current of high frequency; unit for control and telemetry; on-board control panel; on-board (ground) control panel; low-voltage power source; control and recording equipment. MEBG represented a diode electron beam gun with indirect incandescence. MEBG optical system provided a long-focus electromagnetic focusing of the beam at a distance from several tens to several hundred millimeters from the end of its anode. The current of the electron beam was up to 100 mA. The high-voltage power source was made in the form of a monolithic epoxy unit, similar to that of the welding unit "Vulcan". The power consumption of the equipment was up to 2 kW. For the prototype tests of MEBG a vacuum stand was created – a horizontally located chamber with a volume of 2 m^3. At one end of the vacuum chamber a high-vacuum unit was mounted consisting of two sorption-getter pumps

> (the development of the Institute for Low Temperature Physics and Engineering of the Academy of Sciences of the UkrSSR) and providing a vacuum of up to 10^{-4} Torr in a chamber of this volume. At the other end of the camera a fragment (the upper front part) of the space suit "Orlan" (development of the OJSC "Zvezda") was installed. Inside the chamber MEBG, a high-voltage power source and tablets with treated specimens were located. The whole testing cycle consisted of 7 experiments (pressure chamber ascents) with the total stay of testers "at altitude", i.e. in the pressure chamber for about 30 hours. At the same time, the cycle of direct work with MEBG for all 7 lifts was only 70 minutes, which once again proves the enormous labor intensiveness of such tests. Following the tests in the pressure chamber, a large cycle of flights was performed at the flying laboratory of "TU-104", where in the conditions of short-term zero-gravity in the vacuum chambers the arc, plasma and electron beam methods of manual welding were tested. The equipment developers convinced once again that the choice of the electron beam method was correct, since in those conditions it was difficult to maintain a stable arc and plasma. The conducted tests of MEBG solved the key technological and design problems and allowed specialists to start creating the first flight model of the universal manual onboard tool (…).

In such cases, a direct participation of a cosmonaut operator is required, who can evaluate the scope of the necessary works on the spot and make a decision as to the methods to be used. Nikitsky et al. (2003) wrote:

> (…) these were exactly the concepts that underlay the development, of an all-purpose manual welding tool for the cosmonaut, later on named simply 'versatile hand tool' (VHT) (...).

For such works, at the E. O. Paton Electric Welding Institute a versatile hand electron beam tool VHT (Nikitsky et al. 2003; Paton 2009) was created (see Fig. 2).

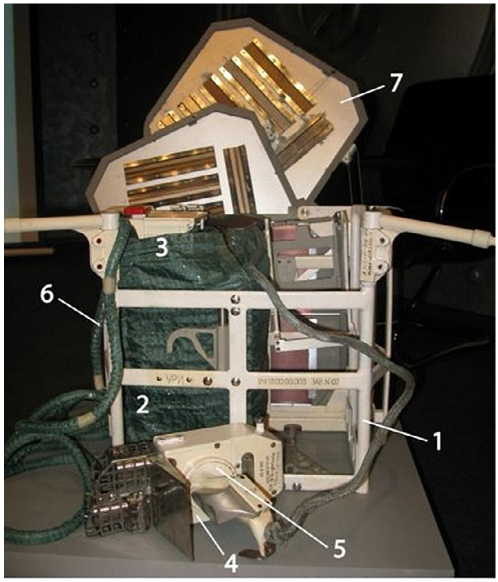

Fig. 2. Versatile hand tool (Assotsiatsiia «Al'fa ARS» 2015, fig. 8): 1 – container; 2 – high-voltage power source; 3 – remote control; 4 – working tool; 5 – handle with trigger; 6 – cable; 7 – tablet with six specimens.

As to its design, it was significantly different from the first model of a manual electron beam tool (Paton et al. 2017). It consisted of two diode electron beam guns of direct incandescence, which were connected to a high-voltage power source, to which a handle with a low-voltage cable from a secondary power source (inverter) and a control system were attached. For ease of transportation, all the units it comprised of were arranged in a single lattice container (Fig. 2, position – 1) with a working tool of a pistol type (Fig. 2, position – 4), a remote control (Fig. 2, position – 3) a high-voltage power source (Fig. 2, position – 2) and cable communications (Fig. 2, position – 6).

In the design of VHT (see Fig. 3), the requirements for the equipment and the recommendations developed as a result of multi-year prototype tests were implemented. Especially for VHT, IED specialists developed a new inverter power supply on a modern element base to reduce the dimensions of the ready boards-assemblies (Drabovich, Yurchenko, Shevchenko 1985, pp. 65–67; Yurchenko et al. 2012). In the article (Paton et al. 2003c), the authors describe the composition, characteristics, and operation of the VHT:

(…) In VHT, the DC voltage of 23...34 V was converted to AC voltage of 5 kV of an output frequency of 20 kHz (for comparison, in the "Vulkan" the output frequency was 1 kHz). The power consumption of the source did not exceed 500 W. A beam of electrons (current of up to 70 mA) was formed by an electron-optical system with electrostatic focusing. For VHT the specialists of the PWI managed to create a small-sized high-voltage unit, which allowed to include it directly into the composition of the tool, at the same time getting rid of a high-voltage cable, a source of increased danger. The high-voltage power source consisted of high-voltage transformer common for both of the guns, anode rectifier and separate incandescence transformers. All these units were cast with epoxy compound into a single unit. The accelerating anode voltage of the high-voltage power source did not exceed 10 kV, which excluded generating hard X-ray radiation during operation of the electron gun. The total weight of the VHT installation was about 30 kg. VHT itself weighed 3.5 kg. VHT represented a monobloc, the basic element of which was a box body with a special handle, ergonomically designed under the spacesuit glove. On the front wall of the body, two electron beam guns were installed, covered with a special heat-shielding casing. Each of the guns could be equipped with either a focusing device or a crucible nozzle.

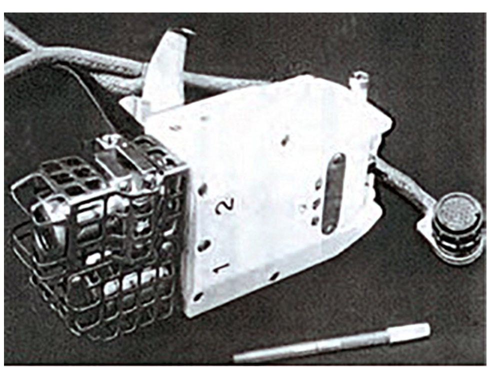

Fig. 3. Flight model of VHT (Paton et al. 2017, p. 28, fig. 2): 1 – high-voltage power source, 2 – lever, 3 – diode electron beam guns.

> In the first case, the gun was used for cutting, welding, brazing or heating with a concentrated heat source, and in the second, for evaporation with the aim of surfacing or heating by a distributed heat source. The toggle switch on the tool body provided a selective power source: either to one or the other gun (…).

At the end of July 1984, the "Soyuz T-12" spacecraft delivered the VHT aboard the "Salyut-7" space station (Paton et al. 2003c). On July 25, 1984, cosmonauts Vladimir Dzhanibekov and Svetlana Savitskaya carried out a spacewalk lasting more than 3 hours. The purpose was to experiment with welding, cutting, surfacing, and brazing of metals, using the VHT created by Ukrainian scientists (see Fig. 4).

Cosmonauts performed experiments on cutting metals on samples made of stainless steel and titanium alloy 0.5 mm thick. Specimens of the same materials with a thickness of 1.0 mm were subjected to welding and brazing. The silver coating was deposited on the aluminum plates with a thickness of 2 mm and an area of 0.06 m^2. In total 20 specimens were treated.

Fig. 4. Cosmonaut S. Savitskaya performs a deposition of coatings in space, overboard the orbital station "Salyut-7" (Paton et al. 2017, p. 28, fig. 3).

At the same time, each 6 specimens were subjected to welding, brazing and cutting and 2 specimens to spraying. All the treated specimens were dismounted from the tables and delivered to Earth for investigations, and the welding equipment remained at the station to carry out further works. The investigations fully confirmed the high quality of most of the specimens produced in space. For the first time in open space an experiment was conducted, which was unique as to its complexity in the preparation and organization and had an important scientific and applied value for further works.

The next series of experiments with VHT was carried out during the implementation of the project "Mayak" in 1986, deploying and folding of a 13 m long hinged truss structure (Paton et al. 1999). The two-year hiatus allowed for a thorough analysis of the results obtained in 1984 and resulted in developing recommendations for improving the methods of land-based training of cosmonauts-operators. The training of cosmonauts J. Kizim and V. Solovyov, carried out using the same methods, made it possible to charge them with much more complex works in space, having a great practical orientation. The cosmonauts were charged with the task to weld and braze manually separate units of truss structures in open space, which were placed in special cassette manipulators. In the course of the works, after depressurization of the lock compartment, the cosmonauts brought VHT – equipped with new cassettes containing specimens of the truss structures – to the outer surface of the station and installed it on the bracing of the anchor platform. After completing the works on deployment and folding of the hinged-lever truss, the cosmonauts began welding its separate units. In total, 10 separate hinged units of the titanium alloy VT-4 were welded. Then the cosmonauts performed a complex operation of welding-brazing of the units of a tubular truss. Each unit represented a fragment of an open pipe made of steel 36NKhTYu, on which a ring of steel St3 was mounted, filled with brazing alloy. The joint was produced by 3–4 welded spots, and the gap between them was filled with molten brazing alloy. After completing the works overboard the station, the equipment and welded specimens were brought into hermetically sealed compartments, and then delivered to Earth. The investigations carried out on Earth showed a high quality of joints produced in space.

After conducting the experiment with VHT equipment and having generalized the accumulated experience, the works with the manual

EBG were continued. In the 1980s, a new generation of electron beam manual tool "Universal" was created (Paton et al. 2017; Naden, Prater 2020), designed for application as a part of large-sized long-term space orbital stations (see Fig. 5). During the development of this equipment, the task of unifying the main units was successfully accomplished.

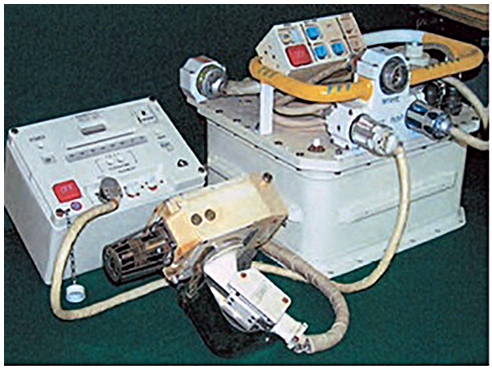

Fig. 5. General view of the manual electron beam tool "Universal" (Paton et al. 2017, p. 29, fig. 4).

"Universal" (Dzhanibekov et al. 1991, pp. 49–58) had a power 2.5 times higher than VHT, and almost twice higher accelerating voltage (8 kV). The higher power of this equipment allowed for – as shown by the experiments in a pressurized chamber – welding specimens with a maximum current up to 120 mA in the beam. Additionally, the "Universal" complex comprised of separate units, from which it was possible to compose specialized devices for automatic welding. The equipment "Universal" passed comprehensive tests at the PWI and at the J. Marshall and Johnson Space Centers (NASA, USA) and in 1997 was completely prepared for a space experiment on the board of one of the spacecrafts of the "Shuttle" series. Unfortunately, the experiment did not take place because of the accident of the "Columbia" spacecraft. This equipment was also certified in the Russian Federation for operation on the board of the orbital station "Mir". In the next years (2000–2020), the works on improving the manual electron beam tool for welding and related technologies in open space were continued. In particular, these years were devoted to creating more powerful power sources for the electron beam gun of a new generation, which allows the materials of almost all thicknesses used in the space equipment to be welded. The new design of the electron beam gun provided a significant increase in its service life and in the ability to work in manual and automatic modes.

4. Conclusions

The article analyzed the stages of development, improvement and application of equipment for welding in space, created with the participation of Ukrainian scientists in the period from the 60s to the 90s of the last century in the USSR. It has been determined that the greatest contribution among Ukrainian scientists to these developments was made by the representatives of Ye. Paton Electric Welding Institute and the Institute of Electrodynamics of the Academy of Sciences of the UkrSSR.

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