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Sincerely,

for Charles C. Marye

Stephanie L. Carr
Chief

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A RAND NOTE

INDICATIONS OF A SOVIET PARTICLE-BEAM WEAPON PROGRAM II. PULSED-POWER CLOSING SWITCHES (U)

Simon Kassel

August 1981

N-1738-ARPA

Prepared For The Defense Advanced Research Projects Agency

DD254 form dated 10/23/80 for Contract MDA903-78-C-0189 and
Classified by multiple sources.
Downgrade to N/A on
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[illegible]

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER R-1738-ARPA	2. GOVT ACCESSION NO. AD-A026	3. RECIPIENT'S CATALOG NUMBER 253
4. TITLE (and Subtitle) Indications of a Soviet Particle-Beam Weapon Program, II. Pulsed-Power Closing Switches (U)		5. TYPE OF REPORT & PERIOD COVERED Interim rept.
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Simon Kassel		8. CONTRACT OR GRANT NUMBER(s) MDA903-78-C-0189, ARPA Order-3520
9. PERFORMING ORGANIZATION NAME AND ADDRESS The Rand Corporation 1700 Main Street Santa Monica, CA 90406		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 12 94
11. CONTROLLING OFFICE NAME AND ADDRESS Defense Advanced Research Projects Agency Department of Defense Arlington, VA 22209		12. REPORT DATE August 1981
		13. NUMBER OF PAGES 87
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office) (14) RAND/N-1738-ARPA		15. SECURITY CLASS. (of this report) ~~SECRET~~
		15a. DECLASSIFICATION DOWNGRADING SCHEDULE Review 8/31/2001

16. DISTRIBUTION STATEMENT (of this Report)

Security Restrictions Only

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

No restrictions

18. SUPPLEMENTARY NOTES

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

Particle Beams	Switches
Russia or USSR	Pulse Generators
Weapons Systems	

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

see reverse side

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

(U) The likelihood of a Soviet military program to develop charged-particle-beam weapons and the probable history of such a program are investigated on the basis of evidence in Soviet open-source technical publications. Individual notes examine three aspects of pulsed-power development: atmospheric propagation of high-current electron beams; repetitive pulsed-power switch technology; and probable history of Soviet accelerator developments. (EFP)

(U) PREFACE

(U) This Rand note was prepared in the course of a continuing study, sponsored by the Defense Advanced Research Projects Agency, of Soviet research and development of high-current high-energy charged-particle beams and their scientific and technological applications.

U~~(S)~~ The note is the second in a series investigating, on the basis of evidence in Soviet open-source technical publications, the possible existence of a Soviet military program to develop charged-particle beam weapons and the probable history of such a program. The note examines Soviet pulsed-power switch technology as an indicator of such a program. Other notes in the series examine Soviet work on the propagation of high-current electron beams in air* and indications of a new generation of charged-particle accelerators.**

(U) The note, prepared for the Director's Office, DARPA, may also be of interest to pulsed-power specialists engaged in the development of switch technology.

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*(U) Simon Kassel, *Indications of a Soviet Particle-Beam Weapon Program: I. High-Current Electron-Beam Propagation in Air* (U) The Rand Corporation, N-1737-ARPA, August 1981 (~~Secret~~).

**(U) Simon Kassel, *Indications of a Soviet Particle-Beam Weapon Program: III. The Timing of Pavlovskii's Accelerator Development* (U), The Rand Corporation, N-1739-ARPA, August 1981 (~~Secret~~).

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(U) SUMMARY

(U) ~~(S)~~ The evidence of Soviet open-source literature indicates a significant probability that at some time between 1973 and 1975 the USSR initiated an advanced phase of a charged-particle beam-weapon program. This conclusion is suggested by the findings of a study examining three aspects of Soviet pulsed-power development: electron-beam propagation through the atmosphere; repetitive pulsed-power switch technology; and indications of a third-generation of pulsed-power accelerators.

(U) ~~(S)~~ In contrast to a rapidly rising volume of publications concerning Soviet pulsed power in general and Soviet switch developments not directly related to beam-weapon requirements, open-source coverage of the pulse frequency and power characteristics of repetitive switches, the category considered most pertinent to beam-weapon development, declined. This publication pattern is assumed to have resulted from more stringent censorship of selected aspects of Soviet pulsed-power R&D during the period in question.

(U) The findings of the present note are based on the examination of 91 Soviet high-current, high-voltage switches developed during the past 15 years.

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(U) I. INTRODUCTION

U ~~(S)~~ Soviet open-source literature, representing the basic input to this study, reflects the relatively early stages of the research-development-test-evaluation cycle and provides practically no information on weapon prototypes. Within this limitation, however, the literature is large and comprehensive. The attempt to infer weapon applications from the published R&D reports must rely on methods of correlating this large quantity of available technical data.

U ~~(S)~~ The research area directly pertinent to the development of charged-particle beam (CPB) weapons is that of pulsed power. A previous study by this author suggested that the intense pulsed-power effort mounted by the Soviets has proceeded on a broad front, including military applications.* Another study indicated that in the early 1970s Soviet high-current relativistic electron-beam research was configured particularly well to CPB weapon development.** While these studies indicated capabilities and tendencies of the Soviet R&D efforts relevant to CPB weapons, they did not confirm the existence of specific programs to develop the necessary technologies.

U ~~(S)~~ The area of pulsed power is characterized by a broad range of technological applications and by an extensive commonality of research issues and equipment among these applications. Individual research issues that are unique to a particular application, such as the particle-beam weapon, are quite rare. In the development of indicators of existing weapon programs, such issues must be sought and identified, or at least approximated as closely as possible.

U ~~(S)~~ For the first note of this series,*** electron-beam propagation in air was selected as the indicator, since it is pertinent to

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*(U) Simon Kassel, *Pulsed-Power Research and Development in the USSR*, The Rand Corporation, R-2212-ARPA, May 1978, p. 118.

**(U) Simon Kassel and Charles D. Hendricks, *High-Current Particle Beams. II. The Siberian USSR Research Groups* (U), The Rand Corporation, R-1885-ARPA, April 1976 ~~(Confidential)~~.

***(U) Simon Kassel, *Indications of a Soviet Particle-Beam Weapon Program: I. High-Current Electron-Beam Propagation in Air* (U), The Rand Corporation, N-1737-ARPA, August 1981 ~~(Secret)~~.

few applications other than particle-beam weapons. For this report, closing switches become the indicator. While high-current, high-energy closing switches are a key element in many pulsed-power systems, special operating parameters, and particularly the repetition-rate specification, narrow the range of applications of the switch to the point where it is possible to draw some conclusions about weapon applications of the visible Soviet R&D efforts.

(U) The survey of Soviet high-current, high-energy closing switches presented in this report is based on three key considerations:

- o The type, or operating characteristics, of the switch.
- o The availability or absence of explicit indications of a dedicated application of the switch.
- o The time of appearance of the switch within the past 15 years.

U ~~(S)~~ These considerations, taken together, provide a means of identifying a set of switch developments with the highest probability of a weapon application. Another consideration, playing a supporting role in such an identification process, concerns the institutions, teams, and personalities responsible for the development of each switch type. or the analysis of these f.ctors, the survey covers 91 switch types developed and used in the Soviet pulsed-power R&D effort.

U ~~(S)~~ T· literature on these switches treats both repetitive and single-sh witches. Since the weapon application of closing switches turns largely on their capability for repetitive operation, the literature dealing with repetitive switches contains most of the material used in projecting a possible Soviet particle-beam weapon program. The material on single-shot switches serves mainly as an indicator of the level of Soviet switch technology, the source of repetitive switch versions. The Soviet development of single-shot switches also serves as a control in relation to the paradigm operating on the set of repetitive switches: since the applications of the repetitive and the single-shot sets differ, the differences in the evolution of and relationships between the two sets are significant to an assessment of a weapon program.

(U) Section II of this note describes the method developed for manipulating the repetitive switch data obtained in the survey. Section III presents the conclusions of the survey.

(U) The listing and technical description of the Soviet pulsed-power switches that form the basis of this survey, as well as R&D organizations responsible for them, are given in appendixes to this note. Appendix A presents the technical details of repetitive switches; Appendix B tabulates and describes single-shot switches; Appendix C lists the institutes, research teams, and organizations responsible for Soviet switch development; Appendix D lists the institutes in alphabetical order by acronym.

(U) II. SURVEY METHOD AND DATA ON REPETITIVE SWITCHES

U ~~(S)~~ In evaluating the possibility of an association, if any, between the Soviet development of repetitive switches and a particle-beam weapon program, the first step is to identify all Soviet repetitive switch projects associated with nonweapon applications. Available explicit statements in Soviet research reports established such an association by stating that a given switch was being developed for one, or several, applications ranging from the pumping of electroionization lasers and microwave generators to high-energy physics research involving spark chambers and particle accelerators. In the absence of such statements, this study examined each switch research project in context. If the research team responsible for the project was known to be working on the above applications, the nonweapon association of the given switch was considered established. Two categories of switches were thus identified: those dedicated to nonweapon applications and those with unspecified applications. It was assumed that switches associated in some way with a particle-beam weapon program would fall into the second category.

(U) The repetitive switches were further classified by period to determine the development of Soviet switch technology over time. In view of the uncertainty of fixing the first appearance of each switch type, the total time span under consideration was divided into two periods only: before 1974 and after 1973. The end of 1973 was chosen because it represents the median in the development of repetitive switches, as reflected in the open-source literature; that is, roughly one-half of the total were "old" switches, reported before 1974, and one-half were "new" switches, reported after 1973.

(U) The material on repetitive switches is thus grouped into four categories according to the four possible combinations of old and new switches and unspecified and specified applications. Table 1 displays the four categories of Soviet repetitive closing switches and their basic technical specifications and institutional affiliations.

Appendix A provides a more detailed description of each repetitive switch type, preceded by notes on Soviet research on the general problems of repetitive switching. Table 2 summarizes the breakdown of repetitive closing switches detailed in Table 1. Table 3 separates the repetitive from the single-shot closing switches reported before 1974 and after 1973.

Table 1

SOVIET REPETITIVE CLOSING SWITCHES BY PERIOD, APPLICATION, INSTITUTE, AND TYPE

No.	Year Reported	Institute[a]	Switch Type	Frequency (Hz)	Power	Ref.
			Old, Unspecified Applications			
1	1968	IYaFEA	Triggered gas gap	50	0.5 GW	[1]
2	1970	IYaFEA	$BaTiO_3$ air gap	30 k	0.5 MW	[2]
3	1971	FTI	Vacuum gap	0.1	15 GW	[3]
4	1973	IOA	Triggered gas gap	50	0.5 GW	[4]
5	1972	LEIS	Mercury thyratron	250	0.4 MW	[5]
6	1972	IYaFSO	Mercury thyratron	0.5		[6]
7	1965	IYaFSO	Ignitron	5	30 MW	[6]
8	1967	IYaFSO	Hydrogen thyratron	25	80 MW	[7]
9	1970	LPI	Cascade spark gap	50	2 GW	[8]
10	1970	FTI	Triggered arc	1	1 GW	[9]
11	1973	KPI	Triotron	x100	4.5 MW	[10]
12	1972	KPI	Trioplasmatron	1500	3 MW	[11]
13	1972	SKBRA	Untriggered gas gap	50	250 MW	[12]
14	1964	OIYaI	Triggered gas gap	0.2	9 GW	[13]
15	1967	Unident.	Autron	1 k	2 MW	[14]
16	1972	IAE	Vacitron	100 k	1 MW	[15]
			Old, Dedicated to Nonweapon Applications			
17	1972	FTI	Laser-triggered water gap	20	30 kW	[3]

Table 1 (cont'd)

No.	Year Reported	Institute	Switch Type	Frequency (Hz)	Power	Ref.
			New, Unspecified Applications			
18	1976	IYaFSO	Triggered gas gap	25	2 GW	[16]
19	1975	GIKF	Trigatron	10	2 GW	[17]
20	1975	Unident.	Mechanical	2		[18]
21	1974	Unident.	Triggered vacuum gap	0.1	10 GW	[19]
22	1977	Unident.	Ignitron	2	10 GW	[20]
			New, Dedicated to Nonweapon Applications			
23	1975	IOA	Untriggered gas gap	100	3 GW	[21]
24	1978	ISE	Untriggered gas gap	50	6 GW	[22]
25	1976	KIR	Triggered [illegible] gap	100	60 MW	[23]
26	1974	OIYaI	Triggered vacuum gap	20	0.6 MW	[25]
27	1977	OIYaI	Triggered gas gap	x100	13 MW	[25]
28	1975	IYaFMGU	Triggered gas gap	30		[26]
29	1976	IYaFSO	Cascade gap	1	25 GW	[27]
30	1976	IOA	Triggered arc	0.1	100 MW	[28]
31	1977	TVN	Rotating electrodes	20	1 GW	[29]
32	1978	TPI	Thyristor	1 k	30 MW	[30]

[a] Institutes are listed in alphabetical order by acronym in Appendix D, p. 78.

Table 2

SOVIET REPETITIVE CLOSING SWITCHES--SUMMARY

Period	Affiliation	Application: Nonweapon	Application: Unspecified
Before 1974	Known	1	15
	Unknown	0	1
After 1973	Known	10	2
	Unknown	0	3
Total		11	21

Table 3

REPETITIVE VS. SINGLE-SHOT CLOSING SWITCHES
BEFORE 1974 AND AFTER 1973

	Reported before 1974	Reported after 1973	Total
Single-shot	26	33	59
Repetitive	17	15	32
Total	43	48	91

(U) III. CONCLUSIONS

(U) Among the several categories of closing switches considered here, repetitive switches with unspecified applications are singled out as the least ambiguous indicator of a Soviet beam-weapon program. Repetitive switches are therefore the main subject of this section.

(U) Soviet switch technology has been developing during the past decade in an environment of a sharply accelerating pulsed-power technology. This is illustrated by the fact that the number of Soviet reports on pulsed power submitted for publication after 1973 was double that submitted between 1968 and 1974.

(U) Figure 1 compares the growth of Soviet pulsed power as a whole (based on the total number of papers published on pulsed-power R&D) with that of various categories of Soviet switches (total number of switch types). The growth of single-shot switches, as shown in Fig. 1, parallels that of pulsed-power, although at a lower rate. Repetitive switches with unspecified applications--the category of closing switches most likely to relate to beam-weapon development--show the opposite trend, decreasing sharply from sixteen types before 1974 to five after 1973. At the same time, repetitive switches explicitly dedicated to nonweapon applications increased from one type before 1974 to ten types after 1973.

(U) There are at least three possible explanations for the trends in Soviet repetitive switches apparent in Soviet open-source literature:

- The end of 1973 marked a logical shift in the development of repetitive switches from an early, generic, multipurpose approach to a later phase dedicated to nonweapon applications.
- Soviet researchers met little success and curtailed further development of repetitive switches, except for a few types dedicated to nonweapon applications.
- After 1973, increased censorship barred most repetitive switches with unspecified applications from open-source publications.

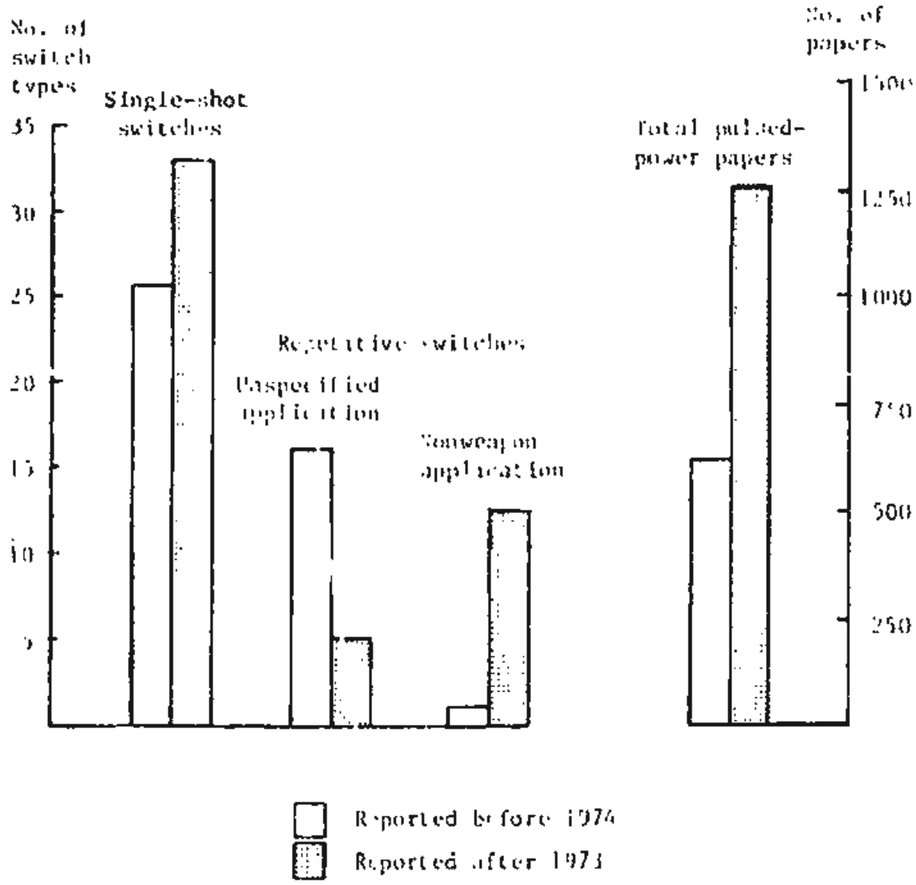

Fig. 1--Development of various categories of Soviet closing switches compared with each other and with growth of pulsed power as indicated by the number of pulsed-power papers published

(U) The first explanation is suggested by the relatively large number of repetitive switches dedicated to nonweapon applications that were reported after 1973. These switches would appear to be a direct outcome of early research on switches of unspecified application. However, this explanation has two serious flaws. First, while it provides a rationale for the rise in nonweapon switches after 1973, it fails to explain the drop in repetitive switches of unspecified application. Second, a shift from generic to specialized R&D implies a continuity in the research-development-test-evaluation cycle. There is no such continuity apparent in the Soviet work in this area. The R&D teams engaged in the development of repetitive switches dedicated to nonweapon applications are in almost all cases different from those identified with the switches of unspecified application.

(U) The second explanation--that the work was stopped because of poor results--is also unlikely. The Soviets rarely abandon programs in pulsed power. Most important, however, the accelerating momentum evident in Soviet pulsed-power development clearly requires repetitive switch development for a range of applications. Among nonweapon applications, an outstanding example of the future need for advanced repetitive switches is inertial confinement fusion, which plays a major role in Soviet energy R&D.

(U) The third explanation of the switch publications trends, based on the censorship hypothesis, provides the least contradictory account of the relationships among the several categories of switches. According to this explanation, the drop in publications on repetitive switches of unspecified application is apparent rather than real and does not reflect the actual growth rate of the R&D process.

(U) This kind of discontinuity in the expected rate of progress also appears in the analysis of the performance specifications of the repetitive switches. The development of Soviet repetitive switches before and after the end of 1973 indicates significant technical progress. Figure 2 shows these switches distributed according to their repetition frequency and instantaneous power characteristics. The lines in the figure represent the state of the art at a given time. Thus, some of

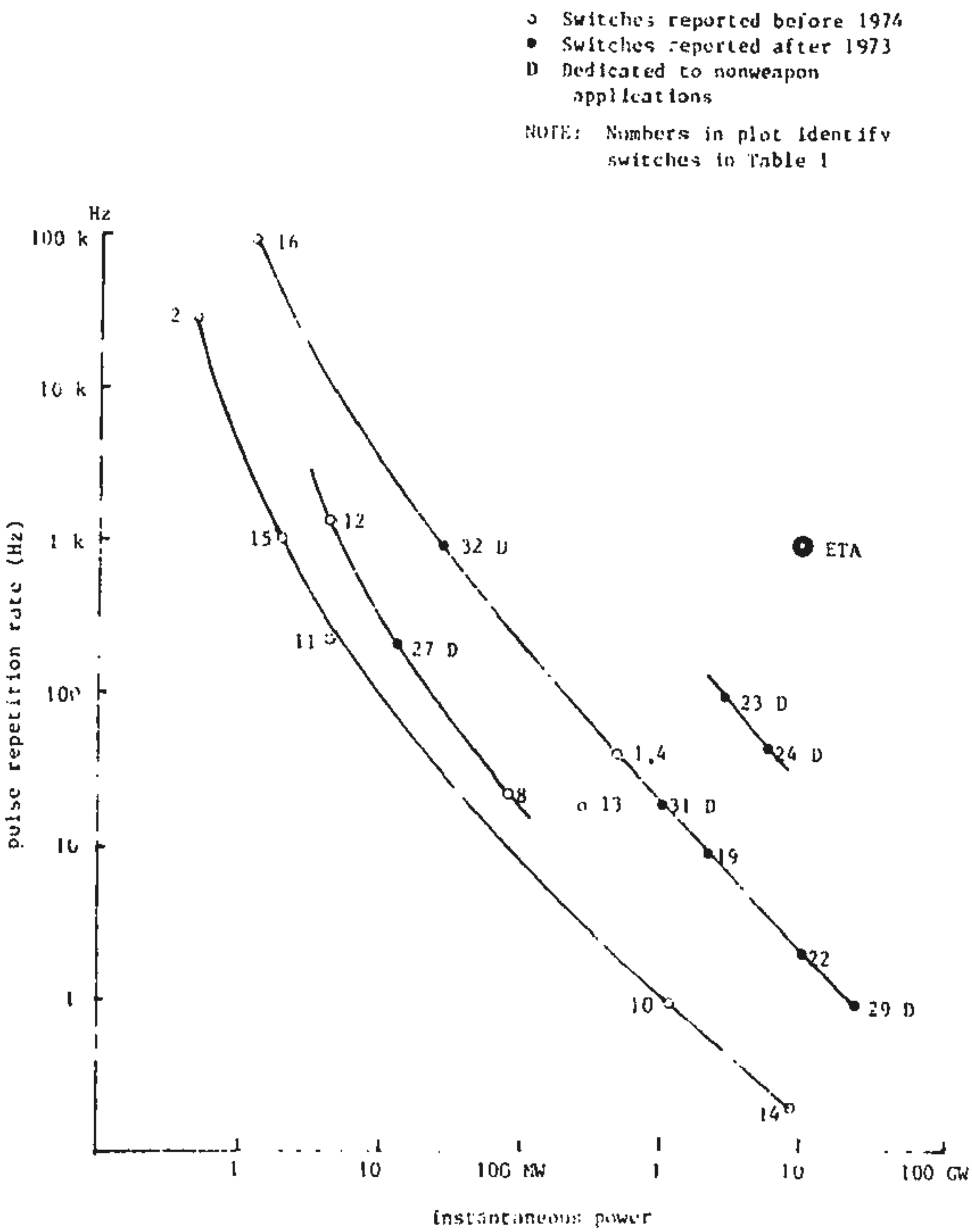

Fig. 2--Soviet repetitive closing switches frequency vs power distribution

the older Soviet switches fall on the line which at one extreme indicates 30 kH and 500 kW and at the other, 0.2 Hz and 9 GW. Some of the newer switches range from 1 kHz and 30 MW to 1 Hz and 25 GW. Still better are the switches for 100 Hz and 3 GW and for 50 Hz and 6 GW. However, this progress from the old to the new period is apparent only at the relatively low frequencies of 1 to 100 Hz. There are no Soviet switches in the GW range above 100 Hz.

(U) As in the case of the publications drop, the absence of such switches is difficult to explain in view of the systematic Soviet pulsed-power R&D. In particular, one would expect to find Soviet switches with capabilities approaching those of the ETA switch, which is already operational in the U.S. Chair-Heritage program. Although Fig. 2 indicates obvious progress in switch technology, in terms of frequency versus power, directed diagonally upward to the right, it also shows a clear break in such progress in areas significant to the weapon application.

(U) Two patterns are now evident in the Soviet open sources: a sharp decrease in unspecified-application repetitive switch types after 1973 and a break in switch development above 100 Hz and 1 GW. Each pattern, taken separately, may be considered inconclusive. Taken together, however, these patterns suggest the following hypothesis:

U Before 1974, the development of repetitive switches for beam-weapon purposes was relatively open and a part of the generic, multipurpose development of pulsed-power switches. At the same time, the demand for repetitive switches for nonweapon applications was relatively low. Since 1973, the censorship of beam-weapon-oriented research has become more stringent, some of that research has been transferred to closed institutes, and the demand for repetitive switches in nonweapon areas has increased. This hypothesis, implying an uninterrupted growth in repetitive switch development, is the only one that is consonant with the increasing pace of Soviet pulsed power.

(U) One way of testing this hypothesis is by examining more closely the category of five repetitive switches with unspecified applications reported after 1973. If, as hypothesized, the censorship of switch research became more stringent in 1973-1974, the publication of the five switches is open to question.

(U) Three of these switches were reported by authors for whom no institutional affiliation could be found. This represents the highest concentration of unidentified facilities in all the switch categories considered in this report. The absence of institutional identification can be another indication of stepped-up censorship, which may range from withholding affiliation data to prohibiting publication.

U~~(S)~~ The above hypothesis essentially specifies that a change in the nature of Soviet R&D relevant to a particle-beam weapon development occurred in 1973-1974. This change and its timing are consistent with the finding of the first report of this series, dealing with Soviet research on air propagation of charged-particle beams. Based on premises unrelated to the considerations presented here, the earlier report postulated a phased progression of a hypothetical Soviet weapon program as follows:

> The first stage, originating perhaps before the 1960s and lasting until nearly the end of that decade, consisted of preliminary theoretical work and the buildup of pulsed-power equipment. . . . The second stage, extending from the late 1960s to the mid-1970s, was ushered in by the advent of high-current diode accelerators. . . . Both stages generated a relatively abundant literature on the research results. The third stage, which began in the mid-1970s, was marked by a severely restricted publication policy.* The third stage . . . may have ushered in a new, higher level of more realistic experimentation and new accelerator equipment . . . warranting the imposition of secrecy.**

U ~~(S)~~ The third stage of the air propagation R&D coincides within one or two years with the advanced stage of pulsed-power-switch R&D postulated in the present report. While each of the two reports is based on indirect, and therefore speculative, evidence, their conclusions corroborate one another.

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*(U) Simon Kassel, *Indications of a Soviet Particle-Beam Weapon Program: I. High-Current Electron-Beam Propagation in Air* (U), R-2496-ARPA ~~(Secret)~~, forthcoming, pp. 8-9.

**(U) Ibid., p. vi.

U (S) The topics of air propagation and switch technology were selected as the least ambiguous indicators of Soviet beam-weapon development. These indicators are a part of the broad spectrum of pulsed-power research and development. It is significant that both indicators were found to display a time behavior that differed markedly from the trend of Soviet pulsed-power R&D: a drop in publication in the face of accelerating overall publication rate. It is clear that Soviet authorities place a high premium on pulsed power as a generic technology capable of many applications. It is likely that the Soviet pulsed-power development program includes active particle-beam weapon development. According to the finding of this study, such development may have commenced a new phase, militarily significant enough to warrant augmented publication censorship, in the mid-1970s. The pace and quality of the Soviet effort, as evidenced in the switch technology, make such a conclusion probable.

Appendix A
SOVIET REPETITIVE SWITCHES

1. THEORY AND EXPERIMENT

The requirement for a high repetition rate imposed on high-power switches entails considerable problems of switch design. While the Soviets have done extensive work on developing repetitive switches, they have published relatively little on the general problems of repetitive switching, cooling, gap purging, and electrode erosion. A brief account of Soviet reports on these topics follows.

The most comprehensive approach to switch development must be credited to G. A. Mesyats, who was associated with the Institute of Atmospherics (IOA) until 1978 and then with the Institute of High-Current Electronics (ISE), both in Tomsk. Working on switching high currents with short rise times, Mesyats postulated two basic switching principles [31]:

1. Avalanche switching, consisting of the generation of many electrons in the gap by the application of the electric field. In a sufficiently high field, each electron generates an electron avalanche. This eliminates the spark channel and stimulates fast processes that shorten current rise times to tenths of a nanosecond. According to experiments, current rise rates under such conditions can reach 10^{14} A/s. Avalanche switching is capable of achieving pulse repetition rates of over 10^4 Hz. Based on this principle, Mesyats reported the highest repetition rate published in the USSR--30 kHz--using a $BaTiO_3$ ceramic switch [2].

2. Injection of electrons directly into gas. Mesyats proposed this method in the course of developing the theory of avalanche switching. If the injected current is high enough, short switching time and high rise rate can be achieved without an avalanche, by means of the nonself-sustaining volume discharge. Mesyats called the switch based on this principle the injection thyratron. Instead of generating electrons by cathode heating, as in a conventional thyratron, the injection thyratron receives electrons through the cathode from an outside

source. This enables total control of the switching action: the switch can be closed and opened rapidly.

Both methods have a problem: as the effective field in gas drops, the electron drift rate decreases, resulting in a high residual resistance. The solution of this problem requires a gas that has a high electron drift rate at low fields. Mesyats proposed methane, because of its anomalous dependence of the drift rate on E/p. Methane may also be useful in the injection thyratron operating as an opening switch for an inductive storage system. In such a switch, methane may prevent instabilities due to the rapid rise of the electric field in the volume discharge plasma [31].

An important contribution to the theory of repetitive switching was made by Ye. P. Bel'kov of the Leningrad Polytechnic Institute (LPI). In his attempt to formulate a theory of channel gas cooling, Bel'kov referred to the work of A. B. Parker and D. E. Poole (*Brit. J. Appl. Phys.* v. 15, 1964, p. 1011) who considered the cooling process in the channel from the viewpoint of heat conductivity theory, but failed to obtain useful results, since the gas in the gap cooled much faster than predicted by the theory. Parker and Poole assumed an intensive motion of gas in the interelectrode space. As a result, the gas temperature was assumed homogeneous throughout the volume, except for thin layers next to the cold electrode surface, which should have a high thermal gradient. To reconcile the experimental results with theory, Parker and Poole postulated a transsonic velocity within the hot gas region. To verify these assumptions, Bel'kov used a Schlieren photography method and 20-kA current pulses (short pulses of 3 to 10 μs and long of 1500 μs) in a gap of 2 to 10 mm. The experiments showed a significant difference in the cooling dynamics of the long and short pulses. After the end of each pulse, as the discharge channel cooled, the gas moved from the periphery to the center of the region being cooled. After long pulses, this motion is laminar; after short pulses, the centripetal motion is more intensive. Bel'kov explained that at the end of a short pulse, the gas, limited to the discharge channel, is hot and cools rapidly because of high heat conductivity. The process of cooling and rising gas density occurs so fast as to make the gas motion turbulent. The cooling rate is sharply increased by mass transfer, which, in turn, further enhances the motion of gas [32].

An unidentified facility reported on experiments performed to determine electrode erosion and service life of vacuum spark gaps as functions of repetition rate. Pulse parameters were constant at 0.6 J, 200 A, ~1 kV, 0.2 MW, 3-μs pulse length, and 4-mm gap length. The repetition rate varied from 50 to 1000 Hz. The measurements included weighing cathodes of Mg, Cu, Fe, Ti, and Ta, taking anode temperatures, and spectroscopic analysis of the discharge.

It was found that the higher the repetition rate, the less the material transferred from the cathode to the anode per shot. The anode temperature increased with repetition rate. As the latter increased, the electrodes heated up, inhibiting the condensation of the metal vapor which remained in the gap between pulses and served as the discharge medium. This process decreased electrode erosion. The following mechanism was postulated:

The increasing average electrode temperature increases the metal-vapor pressure in the gap. The elevated vapor pressure, together with the ionizing energy of electrons, determined by voltage drop in the gap and the electron mean free path (exceeding the gap length), enhance the rate of collisions, producing singly-charged and multicharged ions. It is assumed that at high repetition rates, the positive space charge is established mainly by the multicharged ions, rather than by continuing vaporization of the cathode material.

In operation at 1 kHz, cathode erosion was negligible and there was no discernible deposition of cathode metal on the anode and trigger, even when Mg was used as the cathode metal. Under these conditions, the switch remained operational after 5×10^6 shots. Thus, for the same switched energy, increasing the repetition rate was found to decrease erosion [33].

2. OLD SWITCHES, UNSPECIFIED APPLICATIONS

The Tomsk complex led by G. A. Mesyats has been developing high-current multielectrode triggered gas gaps for repetitive operation since the early or mid-1960s. In 1967, the Tomsk Polytechnic Institute (TPI), the parent organization of several of Tomsk research institutes, submitted a report on an atmospheric-pressure air gap suitable for parallel operation in large capacitor banks. For single shots, the air gap was rated for 8 to 50 kV and 100 kA. At 8 kV, the delay time was 60 ns with a jitter of 5 ns. At 50 kV, the corresponding figures were 15 ns and 1 ns, with a lifetime of over 1000 shots [34]. A year later, the Institute of Nuclear Physics, Electronics, and Automation (IYaFEA) in Tomsk submitted the results of adapting this gap for 50-Hz repetition rate in the range from 3 to 30 kV and 15 kA [1].

In 1970, Mesyats was ready to publish a report on the development of subnanosecond triggered air switches, based on the avalanche discharge principle and made of $BaTiO_3$ ceramic. Under the IYaFEA byline, he described a 1-kV repetitive switch with a 0.6-ns pulse length. The repetition rate of the switch was 30 kHz for a current of 0.5 kA, and 1 kHz for 1 kA [2].* In a 1978 article, Mesyats added that the service life of this switch exceeded 500 hours. The results of tests in which the switch was driven by two thyratrons indicated that it was possible to form pulse pairs with a separation of up to 1 μs [35]. In 1973, IOA announced a 35-kV, 14-kA multielectrode gas gap, delivering 80-ns pulses and having a rise time of 2 ns and a repetition rate of 50 Hz. The switch, filled with nitrogen at 10 to 12 atm, had a service life of 2×10^6 shots at 50 Hz [4].

The same team of researchers working under Mesyats at IYaFEA and IOA produced the gap switches described above. The team included B. M. Koval'chuk, D. I. Proskurovskiy, Ye. B. Yankelevich, Ye. A. Litvinov, S. P. Bugayev, and G. P. Bazhenov. The team has been active since the mid-1960s in a systematic theoretical and experimental investigation of explosive emission from cathode whiskers, electric discharge in vacuum and gas, and the design of field-emission diodes. The team also designs and builds pulsed-power components to support its research. The subject

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*Both the 1967 and 1970 IYaFEA switches were described in Simon Kassel and Charles D. Hendricks, *Soviet Research and Development of High-Power Gap Switches*, The Rand Corporation, R-1333-ARPA, January 1974, pp. 24, 28.

of this research has a potential application in every significant area of high-current particle-beam technology.

The Institute of Nuclear Physics (IYaFSO) in Novosibirsk, which has also been working in this area, did not publish its own repetitive switch designs, if any, but merely reported on modifications of available Soviet industrial thyratrons and ignitrons. Since 1965, IYaFSO has shown interest in triggered 100-kA switches in the ms range, with some repetitive capability. The stimulus for this interest was the need for power supply systems to drive air-core accelerators. According to IYaFSO, as late as 1972 Soviet industry was not producing kA switches for ms pulses. The available hydrogen thyratrons were limited to the ns range, while mercury thyratrons had low repetition rates. Thyratrons and ignitrons are limited by prebreakdown oscillations causing overvoltages in inductive loads [5,6]. The following examples of industrial switches were available in 1969-1972:

TR-1-85/15 mercury thyratron

Current limit in prolonged operation	2 kA
Current limit for single pulses with a repetition rate of 0.5 Hz (subject to thermal breakdown above 0.5 Hz)	4.5 kA [6]

TGI-1-700/25 mercury thyratron

Current	20 A
Voltage	20 kV
Pulse length (continuously variable)	50 to 250 μs
Repetition rate (continuously variable)	0 to 250 Hz [5]

IVS-200/15 ignitron

Standoff voltage	25 kV
Current range	3.5 to 4.5 kA
Repetition rate	5 Hz [6]

IVS-200/SM ignitron

Current limit in prolonged operation	5 to 6 kA [6]

The above performance parameters are comparable to those of U.S. ignitrons available in the early 1960s:* voltage--20 kV; current--7 kA; repetition rate--100 Hz [36].

IYaFSO tested water-cooled ignitrons for operational suitability at repetition rates of 5 to 10 Hz. The IVS-200/15 ignitron met most of the requirements for use as the main switch of a 30-MW modulator in a power supply of a hard-tube current generator that drove a MV electron accelerator. The modulator, built by IYaFSO in 1965, was designed for 30 kV, 1 kA, 1.2-ms pulse length, and 5-Hz repetition rate. The performance of the ignitron revealed a weakness in the igniter, a semiconductor rod partly submerged in the mercury cathode; in prolonged operation the rod tended to pulverize and contaminate the mercury. In 1972, IYaFSO installed 3 igniters in each unit, good for 10^7 shots and a service life of 9 to 12 months [6].

In 1967, IYaFSO submitted a current switch for tesla transformers, based on hydrogen thyratrons, capable of enhancing the efficiency of the ELIT-1 1-MV electron industrial accelerator. Two TGI-1-2500/35 thyratrons connected in antiparallel constituted the switch, which operated at 33 kV, 2.5 kA, and pulse repetition frequency of 25 Hz [7].

The above work was performed by a small team dedicated to the design and construction of switches and pulsed-power components. The team probably provided hardware support for a wide range of development work at IYaFSO. The key members of the team were A. A. Yegorov, B. I. Grishanov, and Ye. N. Kharitonov.

The same IVS-200 ignitron that was tested by IYaFSO in 1965 for the relatively low repetition-rate capability of 5 to 10 Hz was used in 1976 by the Joint Institute of Nuclear Research (OIYaI) in Dubna at an operating frequency of 1 kHz. It seems unlikely that the IVS-200 had been upgraded for that application, because significant modifications would force a change in the designation of the ignitron. In the OIYaI switch system for a current generator of high magnetic fields, three IVS-200 ignitrons were connected in series, operating together with 26 B-500

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*T. R. Burkes, *A Critical Analysis and Assessment of High Power Switches*, Naval Surface Weapons Center, Dahlgren, Va., pp. 49ff.

silicon diode rectifiers. The current generator specifications required a 30-kA peak current, 160-μH load inductance, 500-μs pulse length, 160-μF capacitive storage, and a half-sine pulse shape. To meet these requirements, the switch parameters were as follows:

Voltage	30 kV	
Current	30 kA	
Energy	72 kJ	
Operating frequency	1 kHz	[37]

During the same period, Ye. P. Bel'kov engaged in significant development work on repetitive switching at LPI. Bel'kov's reports, published between 1970 and 1972, dealt with the feasibility of switching μs, 20- to 100-kA current pulses at the repetition rate of 50 Hz. He found the restoration rate of the electric strength of the spark gap--an important factor in repetitive operation--to be independent of the repetition rate if the energy deposited in the gap did not increase the temperature of the electrodes and of the gas to a significant extent. He also found, however, that hot spots could form on the electrode surfaces, because at high repetition rates there is a high probability that the spark channels of a series of pulses will all terminate at a single point. In the experiments reported in 1970, high-power current pulses were switched at 50 Hz by a ring-type cascade spark gap with a surface area of 50 cm^2. In repetitive operation the channel could move over the electrode area, ensuring a uniform wear. The following were the specifications of the switching system:

	Variant 1	Variant 2
Capacitor bank	0.12 μF	0.5 μF
Voltage	50 kV	50 kV
Repetition rate	50 Hz	25 Hz
Pulse length	25 μs	25 μs
Peak current	44 kA	65 kA
Average current	7.4 A	8 A

No hot spots were observed at the electrodes and spontaneous discharges did not exceed 0.03 percent [8].

The period of Bel'kov's publications coincides with that of other LPI authors on magnetic flux compression and electric discharges across long gaps. The research on magnetic flux compression was distinguished by a nonexplosive approach, in which the liner compression was effected by electromagnetic forces. The LPI Laboratory of High Voltage Technology, together with the Laboratory of Gas Discharge and Lightning Protection of the Moscow Power Institute, worked on electric discharges across long gaps. The results of these efforts were submitted for publication between 1968 and 1973. Following this period, LPI submitted a series of reports on the effect of a highly ionized laser channel in air on electric discharge in a long gap, and on sliding discharges.

A repetitive triggered arc switch operating in atmospheric air was developed by the Physico-Technical Institute (FTI) in Khar'kov and submitted for publication in 1970. The switch consisted of two air gaps, a pulse transformer, and a voltage divider. The air gaps were designed to allow for mutual UV illumination coupling. Because of the opposed transformer windings, the transformer inductance did not depend on the switched current. The electrode design allowed for a continuous shifting of the arc and prevented arc ejection from the gaps. The switch had the following specifications:

Voltage range	0 to 25 kV	
Peak current	50 kA	
Trigger energy	1.3 J	
Inductance	0.3 μH	
Delay time	0.6 μs	
Pulse repetition frequency	1 Hz	
Service life	3×10^4 shots	[9]

The work of the FTI team responsible for this development was limited to closing and opening switches, with the exception of one author, A. A. Aksenov, who published in 1979 a paper on ion beams [38].

In 1971, FTI reported on a small, durable, low-inductance spark gap capable of switching currents of 10^5 kA. The electrodes were arranged concentrically to decrease electrode erosion and to increase service life and peak current. Metal screens were used to reduce metal sputtering. The following specifications were obtained:

Gas pressure	10^{-4} to 10^{-5} Torr
Capacitor energy	1.5 kJ
Capacitor voltage	50 kV
Peak current	300 kA
Discharge period	1.3 μs
Pulse repetition frequency	0.1 Hz
Switch inductance	26 nH
Delay time	2 to 7 μs
Trigger voltage	5 to 15 kV
Main insulator height	8.4 cm
Main insulator internal diameter	16 cm [3]

The author of this report wrote only on closing-switch design.

In 1973, the Kiev Polytechnic Institute (KPI) demonstrated the feasibility of on-off control of triotron and trioplasmatron crossed-field switches. These switches were turned on by a positive pulse at the trigger electrode and turned off by reducing the magnetic field to zero or to a low value.

The triotron was stable at 15 kV with a load current of 300 A and provided continuously adjustable pulse length from 10 to 150 μs. The pulse repetition frequency ranged from a few to hundreds of Hz. The jitter did not exceed 10 ns, and delay time ranged from 0.6 to 0.9 μs. The pulse generator employing this switch was made to operate in the pulse burst made by having the repetition rate of the trigger pulses much higher than that of the magnetic field and by using a pulse-forming line. Under these conditions, for 15 kV, 200 A, and 7-μs pulse length, the burst repetition rate was 100 Hz and pulse repetition rate in a burst was 800 Hz [10].

The trioplasmatron was stable in the long- and short-pulse modes. In the long-pulse mode, the switch operated at 10 to 15 kV, 300 to 500 A, 1-μs pulse length, and pulse repetition frequency of 250 Hz. Jitter was 6 ns, and delay time was 0.65 μs. In the short-pulse mode, the pulse length was 100 ns, with 10 kV, 300 A, and pulse repetition rate of 1500 Hz [11]. The KPI team worked exclusively on crossed-field closing switches and has not published since 1973.

The Special Design Bureau for X-ray Equipment (SKBRA) in Leningrad submitted a report in 1972 on the development of small-size spark gaps suitable for parameter ranges of 10^3 to 10^6 A, 10^3 to 10^6 V, and 10^{-9} to 10^{-10} sec. The gaps were designed for a broad range of applications with a high breakdown voltage stability. The voltage was stabilized by increasing the number of free electrons in the gap at the time of breakdown, using for this purpose shaped electrode surfaces with projections amounting to 15 percent of the gap length. SKBRA developed a two-electrode gas spark gap for operation at high pressure and pulse voltages of 100, 150, and 250 kV. When tested with two successive pulses (separated by 50 to 10^4 ns), the electric strength of the spark gaps was restored in 6 ms in N_2 and in 2 ms in H_2. The following are some of the operating parameters of the switches:

Gas pressure	30 to 40 atm	
Switched energy	0.5 J	
Switching time	1 ns	
RMS scatter of breakdown voltage	1.5 %	
Pulse repetition frequency	50 Hz	
Service life	10^6 shots	[12]

The team performing the above work has been engaged also in the development of flash X-ray accelerators.

In 1964, OIYaI developed a triggered air spark gap rated at 40 to 150 kV and 1 to 60 kA. The main purpose of the switch was the achievement of the lowest possible jitter, low trigger voltage, simplicity of construction, and reliability of operation. Its operating parameters were as follows:

Jitter	5 ns	
Delay time	135 ns at 100 kV	
Trigger voltage	5 kV	
Pulse repetition frequency	0.2 Hz	
Standoff voltage	102 kV	[13]

The OIYaI team responsible for the above switch is not associated with any known project.

In 1967, a team of unknown affiliation reported a new type of a metal-ceramic, low-pressure hydrogen gap, called the autron. The switch had a plasma cathode, considered superior to heated or cold cathodes in operation requiring high currents and a wide range of switched voltages. The prototype autron switch was rated at 4 kA and 0.2 to 20 kV. A pulse repetition rate of 1 kHz was achieved with a current of a few hundred A. The power consumption of the plasma cathode did not exceed 40 W for a switched current of 1.5 kA and average current of 1 A. The delay time was 50 ns and jitter 25 ns [14].

The development of the autron switch had been initiated by A. M. Andrianov, who later (1970-1971) headed a research effort on the generation of pulsed MG magnetic fields [39,40]. Andrianov's institutional affiliation is also unknown.

The Kurchatov Institute of Atomic Energy (IAE) in Moscow reported in 1972 on the modification of thyratron-type switches for repetitive operation. According to Soviet researchers, hydrogen thyratrons in the GW power range have a delay time of 80 to 300 ns and jitter of 1 to 10 ns. Their repetition rate is limited to 20 kHz. Some types of thyratron can be boosted above 50 kHz by decreasing the operating voltage. Burkes (p. 31) reports better delay times for U.S. thyratrons (20 to 30 ns) although he gives only a few hundred Hz as typical for high-power tubes [36].

The Kurchatov researchers worked with the tacitron (E. O. Johnson, J. Olmsted, and W. M. Malter, Proc. J.R.E., 1954, Sept., p. 1350. A. Hux, Czechoslovak patent, class 21, d. 12/01, No. 90968, 15-7, 1959), a hydrogen switch with a hot cathode, control grid, and anode. A heated titanium generator serves as the hydrogen source, as in the thyratron.

The tacitron grid controls not only the ignition, but also the quenching of the discharge at rated anode voltage, because the hydrogen pressure is lower than that of the thyratron (0.05 to 0.3 Torr) and the grid is denser. The geometry of the grid is such that for a negative grid voltage of a few tens of V, the grid aperture is no larger than the thickness of the ion cloud formed at the grid surface. The grid is also a good heat sink. To increase the rate of plasma dissipation in the tacitron, the negative grid voltage must be restored quickly at the discharge quenching point. Therefore, the grid impedance does not exceed 100 ohms. Because of these features, current can be turned off by a negative grid voltage of 150 to 200 V. The anode current does not cut off directly at the end of the grid pulse. The discharge quenching process depends on various circuit parameters and other factors. Increased current or hydrogen pressure shift the switch into the thyratron mode of operation. However, the electric strength of the tacitron is restored faster than that of the thyratron, because of the more intense charge dissipation due to the grid. The grid control capability of the tacitron makes it not only useful as a modulator with partial discharge of capacitive storage having a controlled pulse length, but also makes it possible to increase significantly the repetition rate over that of thyratrons in full storage discharge systems, because tacitrons, as well as thyratrons, have a relatively low anode voltage in the conducting state.

The Kurchatov team tested the Soviet-produced TGU-1-5/12 tacitron. A production model of the tacitron was rated at 12 kV, with an average power of 12 kW from a water-cooled anode. The team also tested 20-kV laboratory tacitrons. Of particular interest was the use of tacitrons to form ns pulses. The team found that the 12-kV production tacitron could be used in high-power ns pulse-forming lines, where they delivered currents above 100 A, with pulse rise time not exceeding 30 ns, delay time from 25 to 70 ns, and repetition rate not less than 100 kHz. The experimental 20-kV tacitrons yielded 500-A currents at 50 kHz and 300-A at 100 kHz, with other parameters equal to those of the production tacitrons.

The analysis included the operation of tacitrons in the burst mode, with a burst repetition frequency of 50 Hz. A burst consisted of 20 pulses emitted at a repetition frequency of 10 to 150 kHz. The current was 300 A for 12 kV and 500 A for 20 kV. There was evidence that tacitrons in the burst mode could deliver higher current and repetition rate.

The cathode of the tacitron was strongly heated by ion collisions at rated current and high repetition frequency (tens of kHz). Simple methods of stabilizing cathode heater and grid voltage brought down the jitter to 1 ns [15].

None of the authors of the Kurchatov Institute team reporting on tacitron development has been found to have published anything else in the pulsed-power area.

3. OLD SWITCHES, DEDICATED APPLICATIONS

Among the repetitive switches developed before 1974, only one appears to fit the dedicated category, since it was produced in the context of work on laser pumping and microwave generation by means of high-current electron beams. The report on this switch was submitted in 1972 by the Physico-Technical Institute in Khar'kov. An air spark gap was triggered by a nitrogen gas laser operating at 3371 Å. The power output of the laser reached 30 kW with a pulse length of 10 ns. The breakdown was initiated by distorting the space-charge field with photoelectrons generated by quantum energy near the photoionization threshold. Coherent radiation permits the use of fewer electrons because of the high density of photons. The report offered no data on gap voltage and current. Electrode metals such as Cu, Zn, and Mo were tested in gap widths of 1.3 to 4.8 mm. The gap switch was intended for use in Blumlein lines that produce short rise-time pulses and require accurate synchronization of several high-voltage gaps often spaced long distances from one another. Synchronization tests of two gap switches 2 m apart showed a maximum jitter of 1 ns. The gap switches were triggered with a repetition frequency of 15 to 20 Hz. In this connection, gas lasers were considered superior to solid-state lasers in achieving high switching rates. The UV lasers were considered particularly promising for switches immersed in water because of the weak absorption of their output frequency [41].

The FTI team performing this work, led by Yu. V. Tkach, was engaged during that period in experimental research on collective effects of plasma-beam interactions as a basis of gas lasers and microwave generators [42,43]. It is possible that the Blumlein line with the repetitive laser-triggered switch was developed by the team in support of its work on these applications.

4. NEW SWITCHES, UNSPECIFIED APPLICATIONS

After 1973, published materials were found on five closing switch types, the application of which was not specified and the development of which proceeded without a clear context of dedicated research. Three of these were reported by aut' rs whose organizational affiliation was not known.

Of the two switches reported by known research institutes, one was de, loped by IYaFSO, which in 1976 submitted a report on a 300-kV pulse generator with a continuously variable voltage and pulse length to be used as an injector in a high-current linear accelerator. The repetition rate varied from single shots to 25 Hz. The pulse length limit was 50 ns, with a 3-ns rise time. The delay time was 2 to . ns. The switch, filled with nitrogen at 20 atm, had an automatic powered gap adjustment and a service life of 10^6 shots [16]. The IYaFSO team responsible for this switch has been working exclusively on pulsed-power components.

The second report on a switch by a known research institute was submitted for publication in 1975 by the Mining Institute of the Kola Affiliate of the Academy of Sciences, USSR (GIKF). The Mining Institute has been developing the concept of parallel or sequential delivery of multiple pulses to a load. The pulses may be delivered from a single generator to several loads or a sequence of pulses may be delivered from a single generator to a single load. The problem here is that the trigatron in the on-state affects the trigatron in the off-state, and the trigatrons affect one another through the trigger circuit. The sequential discharge of two capacitors with opposite polarity across the same load causes the voltage at the off-state switch to approach a double working voltage. Under this condition, the spontaneous firing of a trigatron can be prevented by using a switch whose working voltage is low in relation to its static breakdown voltage and by providing an isolation circuit to eliminate the mutual switch effects.

The low-threshold trigatron developed for pulse-burst operation by the Mining Institute works in air and is designed for 0.3 of its static breakdown voltage. The principal feature of the design is the combination of grounded main and auxiliary electrodes. Producing sequential bipolar pulses, the switch showed a capability to switch current up to 30 kA, 10 μs long, from 10 to 70 kV with single or repetitive pulses with repetition frequency up to 10 Hz. The main gap was 65 mm long. The delay time varied from 25 to 100 μs. The service life of the switch was computed to be 500 to 1000 hours at 10 Hz [17]. The team of the Mining Institute has published no other material on pulsed-power components.

The following three switches were reported without identification of the producing organization. A report submitted for publication in 1975 described a solid-dielectric spark gap designed for repetitive operation up to 2 Hz. The switch included a dielectric tape-transport mechanism and a trigger system in the form of a needle puncturing the tape. The electrode dimensions were 200 x 100 x 5 mm; the tape was up to 2 mm thick; gap length, 1.5 mm; electrode inductance, less than 5 nH. The switch was tested at 20 kV, with a tape speed of 90 mm/s and puncture separation of 45 mm. At a pulse repetition rate of 2 Hz, a 100-m tape provided a series of 2200 shots. The maximum switched energy was 400 J [18].

A triggered vacuum spark gap was reported in 1975 with the following specifications:

Voltage range	1 to 20 kV	
Current	500 kA	
Pulse length (first half period)	5 to 100 μs	
Pulse repetition rate	0.1 Hz	
Service life	5000 shots	[19]

In 1978, the following specifications were published for the IRT-4 ignitron:

Voltage range	0.1 to 50 kV	
Switched current	200 kA	
Pulse length	~20 μs	
Delay time	1 μs	
Jitter	0.3 μs	
Pulse repetition frequency	2 Hz	
Service life	10^5 shots	
Switch diameter	190 mm	
Height	480 mm	
Weight	10 kg	[20]

5. NEW SWITCHES, DEDICATED APPLICATIONS

Of the eight repetitive switches considered here that were reported after 1973 and developed in the context of explicit applied-research goals, three are used in pulsed-power components for laser pumping, three are part of the equipment for high-energy particle physics research, one serves in an ondulator machine, and one in an electron beam-material interaction device. All eight were reported by known research institutes.

The laser-pump accelerator switches offer a rare example of successive switch development. In 1975, IOA of the Tomsk complex reported a high-pressure repetitive gas gap switch for an electron accelerator with a beam cross-section of 1000 x 100 mm^2.

The gas gap, filled with nitrogen at 3 to 8 atm, operated at 400 kV, 8 kA, 25-ns pulse length, delivering an average power of 5.5 kW. The pulse repetition rate was 100 Hz with forced blowing at 1.5 l/s. The gap switched a pulse-forming line (PFL) to the diode. To facilitate the operation of the gap, the PFL was a single coaxial line, reducing the current through the gap to half that of a Blumlein line. The gap operated during the first half of the charging voltage wave [21].

The further development of this switch was continued by IOA's successor in the pulsed-power area, the Institute of High-Current Electronics (ISE). In 1978, ISE submitted the results of attempts to improve the current stability of the switch by increasing the gas flow rate. The pressure range of the experiments was compressed to three points of 3, 5, and 7 atm of nitrogen. Closed-cycle blowing was accompanied by drying with KOH and cooling. The 3 cm gap, which had steel hemispherical electrodes 8 cm in radius, was installed in a 40-ohm PFL charged to 300 to 500 kV in 25 μs by a tesla transformer. For a pulse repetition rate of 50 Hz, the stability threshold of the gas flow rate was 2.5 m/s at all three gas pressures. ISE found that for a given pulse repetition rate, an optimum gas flow rate can be obtained to keep the parameter instability of the gap switch within 1 percent [22].

The parameters of the electron beam of this accelerator suggest the application to laser pumping. One of the authors of the above team, F. Ya. Zagulov, participated at the time in the development of a high-power N_2 + Ar laser [44].

A low-pressure triggered hydrogen gap switch was reported in 1976 by the Khar'kov Institute of Radioelectronics (KhIR). The metal-ceramic switch, operating at 0.2 to 0.3 Torr, was designed for a voltage range of 400 V to 30 kV. It was rated up to 30 kA for single shots and up to 2 kA for 100 Hz. The pulse length was 5 μs; delay time, 0.4 μs; and jitter, 10 ns. The switch was intended for an electron accelerator used as a laser pump [23]. The seal for the switch housing was made of a high-melting glass enamel patented by one of the authors in 1973 [45]. No other pulsed-power materials have been published by this institute.

Repetitive switches in support of high-energy particle physics research were developed by several institutes heavily engaged in such work. In 1974, OIYaI reported a three-gap vacuum gap for spark chambers operating at a pulse repetition rate of 20 Hz. The main specifications of the switch were as follows:

Operating voltage	8 kV
Peak current	80 A
Pulse rise time	10 ns
Delay time	30 to 60 ns
Jitter	7 to 15 ns
Service life	2.5×10^6 shots
Repetition rate	20 Hz

The switch was described as reliable and easy to manufacture [24].

In 1971, OIYaI developed a fast-acting, three-gap air switch for spark chamber power supply. Designed to operate at a pulse repetition rate of a few hundred Hz and MW pulsed power, the switch avoided the trigger gap problems of standard three-electrode gas gaps, but retained their advantages of being simple in design and maintenance and reliable in operation. The switch consists of the main, trigger, and shunt gaps. The principal departure from the standard three-electrode design is that the trigger gap contains a high-permittivity ceramic bushing which tightly surrounds the electrode rod and fills the trigger gap. The trigger electrode design follows the spark plug principle. A trigger pulse of negative polarity travels across an RC circuit to the trigger electrode, where it sets up a strong electric field gradient across the end surface of the ceramic bushing. The switch withstood 10^6 shots at 9 kV and 1.5 kA. The delay time was 60 ns; jitter, 5 ns; and pulse rise time, 10 ns [25].

In 1975, the Nuclear Physics Institute of Moscow State University (IYaFMGU) submitted a report on a Marx generator switch rated at 17 kV and 30 Hz without the need for forced gas blowing or spark adjustment. The Marx generator was part of a power supply to a spark chamber [26].

In 1976, IYaFMGU reported a three-electrode cascade switch for currents above 100 kA, featuring high electric strength, minimal inductance, and long service life. Designed for 50 kV and 500 kA, the switch operated with N_2 at 10 atm with automatic blow-through. A system of one cylindrical and two disc-type electrodes yielded an inductance of 15 nH and allowed for a prebreakdown overvoltage of both gaps, significantly decreasing the jitter. The switch had withstood 1200 shots at a 0.05 Hz repetition rate. With forced cooling, the repetition rate was brought up to 1 Hz. The switch was part of a high magnetic field generator for a high-energy particle accelerator [27].

IOA submitted a triggered arc switch design for publication in 1976. The distinguishing characteristic of the design was the forced motion of the arc by a magnetic field to protect the electrodes and thus to increase the maximum switched energy. The switch, designed as part of power supply to a magnet intended for ion sources and ondulators, had the following specifications:

Voltage range	0.4 to 3 kV	
Peak current	36 kA	
Switched energy	70 kJ	
Inductance	50 nH	
Delay time	14 μs	
Jitter	<1 μs	
Pulse repetition frequency	0.1 Hz	[28]

In 1977, the Institute of High Voltages (IVN) in Tomsk submitted a report on a pulsed-power system for shaping nonconducting materials, such as concrete. The system, which used forced air blowing and UV spark triggering, consisted of a resonance transformer and a pulse current generator. The switches in the transformer primary were multiple spark gaps with rotating cylindrical electrodes cooled with running water and operating in atmospheric air. The switches were rated for 50 kV, 20 kA pulses with a repetition frequency of up to 20 Hz [29].

The same switch, which had been developed by V. V. Khmyrov in the 1960s and reported in a book published in 1970, was used in the primary of a resonance transformer powered electron accelerator rated at 300 kV, 15 kA, 34-ns pulse length, with a repetition rate of 150 Hz. In this application, the rotating-electrode switch operated at 30 kV, 15 kA, 150 Hz for over 10^{9} shots. The forced-air was blown at the rate of 15 m/s. The accelerator was designed for flash X-ray and laser pumping [47].

In 1978, TPI developed a new method of increasing the power of magnetic pulse modulators up to 30 MW. The method, based on a parallel connection of coils wound on standard cores, facilitates core cooling and allows for a reasonable number of coil turns while maintaining a sufficiently low inductance. TChI-100 pulse thyristors are used as repetitive switches. The resulting magnetic modulator delivers pulses of 50 kV, 30 MW, 1.5-μs length, 0.4-μs rise time, and repetition frequency of 1 kHz. The modulator was developed for laser pumping [30].

Appendix B

SOVIET SINGLE-SHOT SWITCHES

Data on single-shot switches are summarized in Table B.1. The switches are then described by type in the same order as they are listed in Table B.1. The appendix closes with a short account of Soviet research on the problems of switch electrode erosion.

1. TRIGGERED GAS GAP SWITCHES

The repeated switching of high currents requires the parallel operation of multiple switch channels, since a single-channel operation entails severe penalties of electrode erosion and the destructive action of mechanical and thermal shock. Parallel operation, in turn, calls for high reliability and low jitter of the individual switch elements. In addition, many applications of the triggered gas gap switches, such as high-powered Marx generators, require a high voltage rise rate and short switching delay time.

a. Trigatrons

In developing the trigatron, the most widely used triggered gas gap switch, the Soviets have sought to optimize the above performance characteristics and to overcome the trigatron's limitations. The most important of these are the narrow range of operating voltages available without changing the gap length and gas pressure, the effect of trigger polarity and overvoltage on performance, and the need for isolation circuitry [48,58]. By the mid-1970s, Soviet researchers had accumulated a sizable body of design data for the trigatron, particularly relating to high-voltage (>1 MV) and high-current (from 0.1 to 1 MA) switches.

The Institute of Atmospheric Optics (IOA) in Tomsk focused on the use of a large number of parallel discharge channels to optimize the operation of these switches. The stable operation of such channels requires that $\sigma \leq t_f$, where σ is the jitter of the delay time and t_f is the transit time of an electromagnetic wave between neighboring channels.

Table B.1

TRIGATRONS

Year	Developer	Voltage (kV)	Current (kA)	Delay Time (ns)	Jitter (ns)	Gas — Composition	Gas — Pressure (atm)	Remarks	Ref.
					Old Switches				
1973	IOA	1200	30	5.1	0.5	$SF_6:N_2$	6	Two trigatrons in parallel	[47]
1973	IVN	1000			22	air	16	Distorted-field trigger, 5000 shots	[48]
					New Switches				
1974	IOA	380	130	5	0.5	$SF_6:N_2$	4-11	8 channels	[49]
1975	Pavlovskiy	500	250	8	1.2	SF_6	10	6 channels 1000 shots	[50]
1975	Pavlovskiy	100	22	50	10	SF_6	3-15	1500 shots	[51]
1976	IYaFEA	15	10	10^4	500	air	1	Plasma trigger 1000 shots	[52]
1977	IVN	75-100	500		10	air	1	7 trigatrons	[53]
1977	ISE	400		3.5	0.5	$SF_6:Ar:N_2$	10	8 channels	[54]

Table B.1 (cont'd)

MULTIELECTRODE GAS GAPS

Year	Developer	Voltage (kV)	Current (kA)	Delay Time (ns)	Jitter (ns)	Gas Composition	Gas Pressure (atm)	Remarks	Ref.
				Old Switches					
1967	TPI	50	200		1	Air	1		[34]
1969	TPI	30	40			Air	110 Torr	$BaTiO_3$	[55]
1969	TPI	4	4			Air	1		[55]
1973	IAE	150	100	8	4	Air	Blow-through		[56]
				New Switches					
1975	IYaFEA	1500		24	2.3			5000 shots	[57]
1975	IVN	100		15	1.5	N_2	2-7		[58]
1975	Pavlovskiy	15-75			3	N_2			[59]
1976	IYaFSO	50	1000			N_2	10-15	Frangible electrodes	[60]

LASER-TRIGGERED GAS GAPS

Year	Developer	Voltage (kV)	Gas Composition	Gas Pressure (atm)	Pulse Length (ns)	Rise Time (ns)	Jitter (ns)	Laser Power (kW)	Laser Pulse Length (ns)	Laser Wavelength (Å)	Ref.
1972	IOA	300	N_2	10-15	100	4	150	20	10	3371	[61]

Table B.1 (cont'd)

WATER SPARK GAPS

Year	Developer	Voltage (kV)	Current (kA)	PFL Data: Impedance (ohms)	PFL Data: Charging Time (ns)	Switch: Delay Time (ns)	Switch: Jitter (ns)	Remarks	Ref.
Old Switches									
1964	IYaFSO	200	200		1			Triggered 3-electrode	[62]
1970	IYaFSO	3000	120		0.7			Untriggered	[63]
1973	IYaFSO	1000	110	2.3			600	Untriggered	[64]
1973	IAE	250		50	1.3	30	3	Laser trigger 500 MW, 20 ns Laser beam	[65]
New Switches									
1975	IAE	270		1.1	0.05		10	Untriggered	[66]
1976	IVN	250		9.3	0.76		45	Untriggered	[67]
1976	IVN	1000		4.6	0.75	200	15	Triggered 3-electrode	[68]
1976	IVN	200		4.6	0.80	128	6	Trigatron 1 channel	[68]
1977	IVN	860		4.6	0.75	170	8	Trigatron 3 channels	[69]
1977	IVN	1000				200	15	Triggered 3 channels	[69]

Table B.1 (cont'd)

OIL-FILLED SWITCHES

Year	Developer	Voltage (kV)	Current (kA)	Delay Time (ns)	Jitter (ns)	Type	Ref.
			New Switches				
1978	IVN	350-450		<60	<10	Trigatron	[70]
1978	IVN	130		65	4	Triggered 3-electrode	[70]
1978	IVN		20		6	Untriggered	[70]

TRIGGERED VACUUM GAPS

Year	Developer	Voltage (kV)	Current (kA)	Inductance (nH)	Delay Time (μs)	Jitter (ns)	Remarks	Ref.
				Old Switch				
1970	Unident.	20	200			100		[40]
				New Switches				
1974	LPI	50	10-1200	6	0.2	20	5000 shots	[71]
1974	LPI			10	0.2			[72]
1975	LPI	1-100	1500	15	0.2	20		[73]
1977	KhPI	250						[74]

Table B.1 (cont'd)

SURFACE-FLASHOVER SPARK GAPS

Year	Developer	Voltage (kV)	Curren: (MA)	Inductance (nH)	Resistance (Mohm)	Rail Length (cm)	Delay Time (ns)	Jitter (ns)	Ref.
1976	LPI	40	2	5	7	45	40	10	[75]
1979	LPI	50	5	0.5	2	100	60	10	[76]

UNTRIGGERED GAS GAPS

Year	Developer	Voltage (kV)	Current (kA)	Gas: Composition	Gas: Pressure (atm)	Pulse Length (ns)	Rise Time (ns)	Remarks	Ref.
				Old Switch					
1971	IYaFSO	300	3	N_2	16	100	8	RIUS-1 accelerator	[77]
				New Switches					
1974	Unident.	350	26	SF_6	15	35	4		[78]
1974	ITEF	450	3	SF_6	9-16.5		1		[79]
1975	OIYaI	450	18	SF_6					[80]
1975	IYaFEA	100	20	N_2	2.7			Tonus-II 200 shots	[81]
1976	FIAN	700	100	SF_6	1.5-4	30-40		*Impul's*	[82]

UNCLASSIFIED

Table B.1 (cont'd)

THYRISTOR SWITCHES

Year	Developer	Voltage (kV)	Current (kA)	Pulse Length	Switch Area (cm^2)	Remarks	Ref.
Old Switches							
1972	IYaFSO		150	150 ms	227	220 units in series-parallel	[83]
1973	FTII				1	Laser activator	[84]
New Switch							
1977	FTII	2	1	50 ns switching time			[85]

ELECTRON-BEAM-TRIGGERED GAS GAPS

		Electron Beam			Switch		Gas				
Year	Developer	Voltage (kV)	Current (kA)	Pulse Length (ns)	Voltage (kV)	Current (kA)	Composition	Pressure (atm)	Delay Time (ns)	Jitter (ns)	Ref.
Old Switches											
1969	TPI	400	0.100	20		12	N_2	3-15			[55]
1970	IYaFSO	400	0.010	5	300		N_2	8	20	1	[86]
1971	IOA	350	2		700	40	N_2	7			[87]
1973	IOA	180	0.100	5					1		[88]
1973	IOA	330	0.130	30	1500		$N_2:SF_6$	4-11	15	0.8	[89]
New Switch											
1975	IOA	150			175	40					[90]

UNCLASSIFIED

Table 3.1 (cont'd)

SPECIAL SWITCHES

Year	Developer	Type	Voltage (kV)	Current (kA)	Delay Time (ns)	Jitter (ns)	Remarks	Ref.
				Old Switches				
1969	IYaFSO	Artatron	10	10			ms pulses	[91]
1970	Yefremov	Mechanical	14		36	3.5	Laser-punctured dielectric	[92]
1970	Unident.	Plasma jet	6-25	50-160		350		[93]
1972	IED	Plasma jet	150	200		<1000		[94]
1972	Yefremov	Mechanical	80	150	500	100		[95]
1973	KPI	Trioplasmatron	0.4-30	25	1000		50,000 shots	[96]
				New Switch				
1977	KGU	Ignitron	0.1-20	100		200	IRT-3	[97]

IOA found an optimum voltage of the trigger pulse which produces a minimum delay time. The institute also found that (1) increasing the number of channels from one to two cut the voltage fall time (switching time) in half, even when the current is not equally distributed between the two channels, and (2) for 10-kA currents, the rise in channel conductivity is possible without channel expansion, i.e., the initial cross-section of the channel is sufficient to carry 10-kA currents [47].

Noting that D. Markins in the United States had obtained a delay time of 25 ns and a jitter of 2 ns (IEEE Trans., 1971, NS-18, No. 4), the Soviet researchers claim to have developed trigatrons with a significantly shorter delay time, allowing for the parallel operation of two trigatrons with a 0.27-ns transit time between the two. The trigatrons were filled with 0.08 SF_6:0.92 N_2 at 6 atm. The Soviets quote a delay time of 14 ± 0.8 ns for a trigger voltage of 290 kV and trigger circuit resistance of 10 kohm. For 1 kohm, the delay time is quoted as 6.9 ± 0.13 ns. A minimum delay time of 5.1 ns with a jitter of 0.48 ns was obtained for 140 kV trigger voltage. The switching voltage was 1.18 MV. These trigatron characteristics were found to be practically the same with or without a protruding insulator [47].

IOA researchers compared switch operation in pure N_2 and in a mixture of 0.9 N_2 and 0.1 SF_6. They developed a 400-kV trigatron with eight parallel channels in a single gap switching a current of 130 kA. For 3?0 kV, the delay time in N_2 was 12 ns and jitter was 1 ns; in the mixture the delay time was 5 ns and jitter 0.5 ns. For 280 kV, the delay time in the mixture was 10 ns and jitter 1 ns. According to the report, over one-half of the stored energy is lost in a single-channel switching of 130 kA, while the loss observed when all eight channels operate does not exceed 10 percent of the stored energy [49].

The Institute of High Voltages (IVN) in Tomsk developed an air trigatron that operated on the distorted-field principle at atmospheric pressure. The field was distorted by an auxiliary trigger spark across an insulator bushing protruding into the gap. The spark was produced by a 50-kV, 0.5-μs pulse from a trigger generator. Field distortion was measured by the quantity h/s, where h is the distance the bushing protrudes into the gap and s is the gap width. The minimum operating voltage of the switch is a linear function of h/s up to h/s = 0.6. Above this value, the switch operates practically at any voltage up to self-breakdown. The switch also operated in a sharpening mode at 16 atm for 1-MV pulses with 50 μs rise time and jitter of 22 ns. The switch withstood 5000 shots without replacement of parts and without changes in its characteristics [48].

The more recently developed plasma trigatron, operating in atmospheric air, can switch 10 kA currents within a wide range of voltages. In this type of switch, the discharge is triggered by an ionized gas jet formed at high pressure. An insignificant wear of parts distinguishes the plasma trigatron. Only the insulation in the firing chamber is degraded during the triggering phase. The Institute of Nuclear Physics, Electronics, and Automation (IYaFFA) in Tomsk reported that the delay time varies with the operating voltage and can reach 30 μs for a breakdown voltage of 10 to 35 kV. The switch operates in the range of 0 to ± 15 kV and 10 to 10^4 A with a delay time of 10 μs and trigger pulse energy of 0.5 J. The jitter does not exceed ± 5 percent of the delay time. The current rise time is in all cases less than 2 percent of the delay time. No changes in the performance were observed in 1000 shots [52].

Trigatrons have also been developed for parallel operation without the isolation circuitry. The IVN designed a system of seven trigatrons that switch a total current of 500 kA at 100 kV with a 10-ns jitter. No gap adjustment was necessary within a voltage range of 75 to 100 kV, while the electric strength of the main gap was 120 kV [53].

A recent report emphasizes the importance of the multiple parallel spark discharge at high pressure as a means of increasing the rise rate of power i the load, enhancing the efficiency of the switch, and extending its service life. The Institute of High-Current Electronics (ISE) in Tomsk has been investigating an eight-channel trigatron for a coaxial, 400-kV PFL with a charging time of 1 μs. The switch with a ring geometry has a 1.-mm gap and eight trigatron pins. Each pin received a 20-kV pulse wit 7-ns rise time and a 120-ns tail. For a gas mixture of 0.8 N_2:0.1 Ar:0.1 SF_6, yielding a maximum voltage rise r te, the delay time was 3.5 ns with a jitter of 0.5 ns [54].

Multiple-channel trigatrons were also developed by the research group headed by A. I. Pavlovskiy. In 1975 the group reported a six-channel trigatron for a 2-ohm water pulse-forming line (PFL) charged to 500 kV in 1 μs. The switch, filled with SF_6 at 10 atm, delivered 0.25-MA current pulses of 20 ns, with a rise time of 5 ns, delay time of 8 ns, and jitter of 1.2 ns. The service life of the switch was 1000 shots [50]. At the same time, the group submitted a report on a 100-kV trigatron switch filled with SF_6 with pressure variable from 3 to 15 atm. The switch delivered current pulses of 22 kA and 1.25 kJ, with a delay time of 50 ns and jitter of 10 ns. The service life was 1500 shots [51].

b. Multielectrode Spark Gap Switches

The advantages of multielectrode spark gaps are high stability, or low jitter, and the capability for a broad range of operating voltages without adjustment of the electric strength of the gap. The disadvantage is complex design for compressed-gas operation, particularly in systems with distributed parameters [48].

In the mid-1970s, IVN developed three-electrode gas spark gaps for pulsed-power generators. The spark gaps, rated at 10 to 100 kV and triggered by the change of potential of the auxiliary electrode, used N_2 in a pressure range from 2 to 7 atm. Delay time was 15 ns, and jitter 1.5 ns. A voltage generator has been designed with the following characteristics:

Inductance	2.5×10^{-6} H	
Pulse front at 10 kohm load	10 ns	
Peak output voltage at 1 kohm load	450 kV	
Short-circuit current	55 kA	
Delay time	210 ns	
Jitter	10 ns	[58]

The Kurchatov Institute of Atomic Energy (IAE) in Moscow had at that time been pursuing the development of low-inductance spark gaps with a long service life, with provisions for gas flow and an external surge tank. Another feature to ensure durability of the switch was a removable plastic bushing inside the main insulator used to shockproof the structure. The continuous compressed air flow reduced the probability of thermal breakdown and removed the products of electrode erosion. The spark gaps operated at 4 to 5 atm, 150 kV, 100 kA and sustained 1000 shots without deterioration. Polishing the internal walls of the gap permitted sustained operation at 100 kV, 100 kA for 10^4 shots. Using the distorted field trigger, the delay time was 8 ns with a 4-ns jitter [56].

In 1975 A. I. Pavlovskiy's research group submitted the results of tests of a sharpening switch in N_2 and in SF_6. The switch operated at 15 to 75 kV with a 15-ns pulse length and 3-ns jitter. In N_2 the pulse rise time varied from 1.5 to 13 ns; in SF_6, from 2 to 16 ns [59].

Studying the problem of voltage stabilization with high-power spark gaps, IYaFEA found that with a three-electrode switch in SF_6, the voltage instability was less than 1 percent. However, the three-electrode switch can be used for voltage stabilization only with pulses having a flat plateau [98]. The institute also reported on the operation of these switches in the 1.5 MV-Tonus accelerator over a 3-year period. After 5000 shots without gas replacement and overhaul, the delay time was 24 ns and jitter 2.26 ns. An analysis of the field distribution across the insulator showed that the switch length could be reduced from 38 to 27 cm without degrading the electric strength; the shorter length significantly lowered the inductance [57].

The Institute of Nuclear Physics in Novosibirsk (IYaFSO) recently reported on an MA switch with frangible electrodes. The low-inductance (<8 nH) switch operates at 50 kV in 10 to 15 atm of N_2. One or both main electrodes are plates that disintegrate upon the passage of the current pulse, ensuring the effective removal of electrode erosion products from the gap and reducing the shock sustained by the switch structure [60].

A multielectrode air spark for 100-kA currents, operating at 8 to 50 kV without isolation circuitry was reported in 1967 by Tomsk Polytechnic Institute (TPI). At 50 kV and 200 kA, the switching time was 15 ns with a jitter of 1 ns. The service life of the switch was well over 1000 shots [34].

In 1969, TPI investigated avalanche discharges for switching ns and sub-ns current pulses. In one switch design, the 30-kV, 40-kA switch produced a pulse length of 5 ns at 110 Torr of air, using a $BaTiO_3$ ceramic. In another design, a 4-kV, 4-kA switch produced a pulse length of 0.15 ns at atmospheric pressure [55].

c. Laser-Triggered Gas Gaps

In 1972 IOA submitted a report on a gap switch for a 10-ohm glycerin PFL triggered by a 20-kW, 10-ns pulsed laser operating at 3371 Å. The switch was filled with N_2 at 10 to 15 atm. Designed for 80 to 300 kV and 100-ns pulse length, the laser trigger produced a pulse rise time of 4 ns and jitter of 150 ns [61].

2. WATER SPARK GAPS

Spark gaps for use directly in deionized water in conjunction with water PFLs were developed in the early 1960s at IYaFSO and in the 1970s at IVN in Tomsk and IAE in Moscow. In 1978, IYaFSO published a comprehensive historical account of the development of the water-insulated accelerator technology [62]. While the account goes beyond the immediate switching issues, it provides a useful context for water-switch development and is outlined below. The IYaFSO account is followed by an analysis of the basic types of water switches developed at IAE and IVN.

The development of water dielectric systems was stimulated by the need for magnetic field generators with a fast rise rate (>10^5 V, >10^5 A, <10^{-7}-s rise time) to produce collisionless shock waves that would heat plasma to fusion temperatures. According to the IYaFSO account, work proceeded in two stages.

In the first stage, at G. I. Budker's suggestion, in 1963 the laboratory directed by Yu. Ye. Nesterikhin at IYaFSO began research on the use of water as dielectric in low-impedance current generators. The method of purifying water with ion-exchange resins was borrowed from the I.2'u work with atomic reactors. Experimental data on the use of water in high-voltage storage systems were obtained from a paper by V. Sherrer of the U.S. Naval Research Laboratory (NRL).

In 1963–1964, IYaFSO, using a gap at 300 kV and pulse length of 1 to 3 μs, found the electric strength of water to be of the order of 300 kV/cm. Bubble formation was eliminated by outgassing and applying a 25-atm pressure. It was noted later that a fast flow of water through the system would also prevent bubble formation.

In 1964–1965, IYaFSO built a pulsed-current generator with a water line and a triggered water spark gap, called the *Vodyanoy*. Nesterikhin and others patented the system in 1966 (the patent was published in 1970). The generator operated with water under 25 atm of pressure. Gas-filled shock absorbers were used to weaken the hydraulic shock from the gap discharge. The triggered gap consisted of three electrodes at the end of the water line charged to 200 kV in 1 μs. The gap switched 200 kA in 30 ns. The current rise rate was 5×10^{12} A/s. These results, announced at the All-Union Conference on Nsec Pulsed-Power Technology in 1965, were received with skepticism, since the highest currents used at that time were 1 kA.

In 1967–1968, IYaFSO built a magnetic field generator with a rise time of 10^{-7} ns and a fall time of 3 to 4 μs, using water lines and switches. It was then found that the electric strength of a liquid dielectric decreases as electrode surface and charging time increase. The first results of the system's use to generate shock waves were announced in 1968 [62].

In 1970, IYaFSO described an untriggered water spark gap for the PFL of a flash X-ray machine. The PFL was charged to 3 MV in 0.7 μs. The spark gap current was 70 to 120 kA with a pulse length of 60 ns [63].

In 1973, IYaFSO submitted a report on the *Vodyanoy* accelerator, which featured an untriggered water switch operating at 110 kA, 1 MV, and pulse length of 45 ns. The switch had a gap length adjustable from 3 to 4 cm and a maximum inductance of 60 nH. Because of its large jitter of 600 ns, . ɔt-to-shot voltage varied from 800 to 1100 kV [64].

The second stage in the development of high-voltage water technology was represented by the high-current electron accelerators developed during the 1970s. The IYaFSO experience in the first stage served as a foundation for the expansion of this technology to the megavolt range at IYaFSO and other institutes. In 1970, IYaFSO began heating plasma with intense relativistic electron beams (IREB), which excited collective oscillations in plasma.

Generators with water insulation require fast primary storage, preferably with a charging time of 1 μs. However, MJ stores need a longer charging time. Budker suggested that 10-μs charging time could be tolerable in a water storage, if the electric strength of water were boosted by high pressure. IYaFSO found in 1969-1970 that 130 atm increased the electric strength of a 0.3-cm gap to 600 kV/cm for a 10-μs pulse length. Maxwell Laboratories performed analogous work in the United States a few years later (1974 publication). IYaFSO confirmed the dependence of the electric strength of water on pressure. It also determined that smooth, aged electrodes increased the electric strength of water.

In 1970-1971, IYaFSO built a megavolt storage with water at 100 atm. At 1.1 MV, the field intensity in the storage system reached 190 kV/cm.

In 1971, D. D. Ryutov proposed experiments to measure the electric strength of water under conditions that excluded electrode effects, by creating electrolyte layers at the electrodes. This method increased the electric strength of water to 1.3 MV/cm for a 5-μs pulse.

In 1972, the MV storage was used to build the *Vodyanoy* accelerator, which was used in experiments with electron beam transport and beam-plasma interaction in the fusion GOL-1 device. For further plasma interaction research, the *Vodyanoy* accelerator was recently improved by the installation of a triggered gas gap and a remotely controlled supply of anode foil.

The large difference in the dielectric constant of water and of solid dielectrics used in the accelerators necessitated research on the problems of field concentrations and remedial measures. In 1971-1972, IYaFSO studied the effects of monolithic and film dielectrics in water accelerators. Since 1973, it has been investigating MV-accelerator components, including switches, with water dielectric and designing new types of accelerators.

The *Voda 1-10* accelerator has a primary storage of 80 kJ. Two pulse transformers deliver 15 kJ to the intermediate storage. The water Blumlein, which is charged to 1 MV in 1.2 μs, has a field intensity of 135 kV/cm. The triggered water spark gap has a service life of 100 pulses. The anode has automatic transport of anode foil. The electron beam parameters are 1 MeV, 200 kA, 60 ns, and 10 kJ.

The *Malyutka* accelerator was designed to perfect a multichannel triggered gas gap. The design was published in 1976. The PFL was charged to 800 kV in 0.8 μs. The four-channel spark gap was filled with SF_6 at 3.8 atm. The jitter was 0.4 ns for 650 to 800 kV. The electron beam parameters are 400 kV, 150 kA, 30 ns, and 1 kJ.

The results of those tests were used to design the spark gap for the *Akvagen* accelerator (reported in 1976), claimed to be the most powerful accelerator of the series. The PFL is charged to 2.5 MV in 1.3 μs and stores 30 kJ. The primary storage consists of two identical capacitor banks for 100 kJ connected to two pulse transformers. The PFL switch consists of six parallel trigatron gas spark gaps with a 20-ns jitter. The main insulator of the machine is water of 5 atm. The *Akvagen* electron beam is rated as follows: 1.2 MeV, 400 kA, 60 ns, 15 kJ. In 1978, the beam energy was 5 kJ and work was under way to bring it up to the rated value of 15 kJ.

The development of the *Voda 1-10* and *Akvagen* utilized the experience of various Soviet laboratories, in particular, that of the Kurchatov Institute, which has been operating water accelerators since 1972. IYaFSO also used data on the *Gamble I*, *Gamble II*, *Hydra*, and other U.S. accelerators.

All of the IYaFSO high-current pulse accelerators use transformers instead of Marx generators because of the transformers' advantages at the 10-kJ energy level. Energy transfer efficiency (20 to 30 percent) is traded for simplicity by dispensing with the iron core. The transformer system is compact; the 100-kJ capacitor bank takes up an area of

3.5 m^2. The capacitors were developed jointly by IYaFSO and the Serpukhov capacitor industry institute (NIPKTI).

The computer center of the Siberian Department, Academy of Sciences, USSR, provided computer support for a study of the distribution of electric field in water and solid dielectric insulators. The KSI BESM computer program was limited to axially asymmetric systems. IYaFSO researchers concluded that the technology of water insulation in high-voltage pulse lines makes it possible to design compact IREB generators for 100 to 300 kA. These beams are used to heat dense plasma in mirror machines; they are also used in pellet fusion. The *Voda 1-10* and *Akvagen* are intended for experiments in heating dense plasma to a temperature of the order of 1 KeV in mirror machines [62].

Data on the water spark gap developed at IAE and IVN began to appear in 1973. The IVN stands out in its systematic approach to the problem of developing a workable theory and investigating the major variants of spark gaps suitable for water operation.

A basic disadvantage of water switches is firing instability, or high jitter. IVN has been working to solve this problem in both untriggered and triggered water spark gaps. According to IVN reports, untriggered gaps are suitable in fast-charging systems (less than 200-ns charging time) and triggered gaps in systems with a charging time over 1 μs. However, IVN used untriggered spark gaps in water PFLs with a longer charging time [68]. The following is an account of the theoretical considerations and experimental results obtained at IVN and the Kurchatov Institute.

a. Untriggered Spark Gaps

Untriggered spark gaps have been used in PFLs with charging time up to 0.75 μs. Experiments show that the switching time of water spark gaps depends weakly on field intensity in the gap and that field uniformity between the electrodes is not always desirable. The switching time can be shortened by increasing the rate of energy delivery to the channel formed in the discharge and by producing a shorter channel with reduced inductance and resistance. For the same switching time, jitter can be decreased by using electrodes with a spiked surface to make the field nonuniform [67].

IVN developed an untriggered spark gap for a water PFL with variable impedance from 3.7 to 9.3 ohms, charged up to 1 MV in 0.6 to 0.75 μs. In the optimal case, the jitter was found to be 45 ns at 200 kV [67]. The Kurchatov Institute developed a multichannel water spark gap for a PFL designed for electron-beam-driven fusion experiments, where the power was expected to exceed 10^{15} W. Since the diameter of the PFL under these conditions cannot be less than 10 m, the main problem is the design of a multichannel switch capable of ensuring low jitter and short switching time. Early PFLs designed for 10^{12}-W, 100-ns pulses were equipped with untriggered, single-channel water switches. The switching time of such gaps, depending on PFL impedance, could drop below 10 ns for 5 to 15 ohms. However, as impedance decreases, switching time increases, and can be as long as 50 to 60 ns. Increasing the number of channels shortens the switching time of low-impedance PFLs. U.S. researchers studying multichannel switching in water (L. S. Levine and I. H. Vitkovitsky, IEEE Trans. NH-18, 1971, No. 4, p. 255) observed untriggered operation of three channels with a delay time of 200 ns for a breakdown voltage of 185 to 250 kV and effective charging time* of 200 to 850 ns. In 1975, the Kurchatov Institute obtained a switching time of 15 ns with an untriggered six-channel peripheral switch system of a fast-charged (50 ns effective), 1.3-ohm, 270-kV PFL. The electrode gaps of the switch system were 3.5 mm long. The breakdown of all six channels was observed with a jitter of less than 10 ns [66].

b. Triggered Gaps

Single-channel gaps. For trigatron switches, the jitter was found to depend on the following factors, given a constant PFL charging time: trigger voltage; trigger gap length; arrival time of the trigger pulse (measured from the start of PFL charging); trigger pulse rise time; and

*Effective charging time is defined as the time during which the voltage across the switch electrodes exceeds 0.63 of breakdown voltage.

the protrusion of the trigger electrode into the gap. In attempting to reduce jitter, however, IVN researchers found that only the first three of these factors could be adjusted, because (1) any further shortening of the currently available 10-ns rise time of the trigger pulse was hardly effective with 100-ns delay times and (2) electrode protrusion tended to distort the field at the anode, leading to a significant drop in breakdown voltage. IVN thus concluded that for optimal jitter the trigger gap length should be 0.1 to 0.2 of the main gap length; trigger voltage should be 0.1 to 0.3 of the gap breakdown voltage; the trigger pulse should be timed to arrive 100 to 150 ns before the end of the charging period (of the order of 1 μs) [68].

In their experimental work, IVN researchers used a 4.6 ohm coaxial PFL charged to 1 MV in 0.75 or 0.8 μs. According to results submitted for publication in 1976, they obtained a jitter of 6 ns with a delay time of 128 ns, using a trigger voltage of 200 kV and a trigger gap of 6 mm [68]. For a 5-cm main gap and 850-kV breakdown voltage, these results were well within the optimum range specified by the theory.

Multichannel gaps. IVN specified that the output pulse rise time depends on the number of channels; the length of the main gap; and the electric field intensity in the gap. For a constant PFL charging time, the length of the gap and the value of the field will also be constant. Therefore, the only way to shorten pulse rise time is to increase the number of effective channels across the gap. IVN experiments show that four to six channels in a multichannel trigatron shorten the output pulse rise time by 15 to 20 percent and increase peak current by 10 to 15 percent in comparison to single-channel operation [68]. They concluded that proper design of water trigatrons could ensure ns jitter, in turn, making it possible to achieve multichannel operation capable of shortening the switching time, decreasing electrode erosion, and increasing efficiency of the system [69].

IVN experimental work on multichannel triggered water switches (published in 1977 and 1978) focused on the three-electrode gap and the trigatron. The same water PFL was used as in the single-channel switch experiments. In the three-electrode gap switch, IVN achieved a jitter of about 15 ns in a delay time of 200 ns for a working voltage of 1 MV. It also found that a 15 percent drop in voltage doubled the jitter.

Several types of trigatrons were tested. In a three-channel trigatron, IVN found that the delay time depended strongly on the gap length. For a 5-cm gap, the delay time, which was 170 ns at 860 kV, increased 30 percent when the gap length increased 1 cm. The jitter was 8 ns in the 5-cm gap and 10-ns in the 6-cm gap. Three-channel switching was observed with a probability of only 92 percent within 80 percent of the breakdown voltage. The current pulse rise time was then 16 ns at a peak current of 160 kA.

IVN also tested the so-called ring trigatron, which was designed to provide a near homogeneous gap field. The ring trigatron with a 5-cm gap showed a weaker dependence of delay time on voltage than the three-channel type. The delay time of the ring trigatron was slightly below 220 ns [69].

A six-channel trigatron had been tested somewhat earlier to determine the output pulse rise time. It was found to be 15.5 ns for six channels, which was 15 to 20 percent shorter than the rise time in single-channel operation. The average current rise rate was 10^{13} A/s [68].

Laser-activated gaps. The Kurchatov Institute reported in 1974 on the use of a laser spark to initiate a high-voltage breakdown of distilled water. This work was inspired by Guenther's earlier experiments in the United States with laser-spark initiation in oil (A. H. Guenther and J. R. Bettis, Proc. IEEE, v. 59, No. 4, 1971, p. 689). The main advantage of the method was the possibility of reducing switch jitter. A 500-MW, 20-ns neodymium laser was used with a gap 7-mm long at 250 kV. In an untriggered mode without the laser, the delay time with respect to the start of PFL charging was 1550 ns with a jitter of 100 ns. The laser shortened the delay time to 30 ns with a jitter of a few ns [65].

3. OIL-FILLED SWITCHES

The category of oil-filled spark-gap switches is represented by a single report published in 1978 by IVN. The report reviews IVN work on trigatrons, three-electrode spark gaps, and untriggered switches designed for a 22-ohm oil Blumlein pulse-forming line charged by a Marx generator in a range of 200 to 600 kV and 200 to 920 ns. The experiments showed that when PFL charging time is shorter than 200 ns, the untriggered spark gaps with inhomogeneous field can have ns jitter. The following are the results of experiments:

Trigatrons		
PFL charging time	300 ns	
Breakdown voltage	350 to 450 kV	
Delay time	<60 ns	
Jitter	<10 ns	
Three-Electrode Spark Gaps		
Voltage	130 kV	
Delay time	65 ns	
Jitter	4 ns	
Untriggered Gaps		
Needle electrode current	20 kA	
Breakdown field intensity	270 kV/cm	
Jitter	6 ns	[70]

4. TRIGGERED VACUUM GAP SWITCHES

A systematic theoretical and experimental investigation of triggered megampere vacuum switches has been pursued at the Leningrad Polytechnic Institute (LPI) at least since the mid-1960s. The early results, submitted for publication in 1970, involved (1) material analysis of the main spark gap components (cathode, anode, trigger system, and insulator) and (2) the discharge mechanism and propagation of the plasma jet in the trigger region. The discharge was found to affect the materials of all electrodes and insulators. The investigation also focused on switches with relatively long gaps (40 mm) and kA pulses of 0.15 to 1.5 μs. These pulses were said to correspond to the initial stages of the discharge of high-powered MA vacuum switches [99]. The test results published a few years later included the following switch specifications:

Voltage	50 kV	
Current	10 kA to 1.2 MA	
Pulse length	1 ms to 10 μs	
Capacitor bank energy	50 kJ	
Delay time	0.2 μs	
Jitter	20 ns	
Switch inductance	6 nH	
Electric strength of internal insulation after prolonged operation	65 kV	
Service life	>5000 shots	[71]

LPI's work on the development of triggered vacuum switches produced steady improvements. A switch type developed in 1975 had double the voltage range and a better timing performance. Th disadvantage of low electric strength typical of vacuum spark gaps was overcome in this design, which had two triggered chambers in series, each with a wide range of operating voltages. The specifications of the switch were as follows:

Voltage	1 to 100 kV	
Current	1.5 MA	
Inductance	15 nH	
Delay time	1 to 0.2 μs	
Jitter	20 ns	
Electric strength of internal insulation after prolonged operation	125 to 145 kV	[73]

In another design, reported in 1974, switch inductance had been decreased to 10 nH and delay time to 0.2 to 0.15 ns [72].

Recent LPI work, submitted for publication in 1977, involved the time-dependent impedance of the discharge channel in a triggered vacuum spark gap, focusing on the trigger system. The optimal system had the trigger electrodes on the periphery, ensuring shorter delay times, more uniform current distribution, and lower initial inductance. The switch is said to be in production [100].

During the 1970s, the Khar'kov Polytechnic Institute (KhPI) analyzed and designed spark gaps for Marx generators. In 1973, KhPI reported on the role of UV illumination in triggering the switches and on the measurement of switching time in large Marx systems. The theoretical approach of this work emphasized jitter as the main criterion of synchronous operation of spark gaps, which may number more than 30 to 40 units. According to the institute, the literature stresses the need to ensure triggering illumination among the gaps, although it fails to supply quantitative data on the effect of illumination on the operation of the generator. The KhPI report said also that some Western authors (Heilbronner) concluded from their experiments that UV illumination has no perceivable effect on generator spark gaps. Finally, the report presented quantitative data on the effect of mutual illumination on switching time, based on tests of a seven-stage Marx generator [101].

The static discharge voltage of the gaps was 110 kV; the charging voltage per stage was 90 kV. An intermediate generator of trigger pulses was used to ensure the breakdown stability of the first controlled gap. It was concluded that illumination is significant only for the second and third stages, where overvoltages are comparatively low. The total switching time of the seven-stage generator, excluding the breakdown time of the first controlled gap, did not exceed 400 to 500 ns, with about one-half of this time representing the switching time of the second gap. The breakdown of each gap of the fourth to the seventh stages took only 20 to 30 ns; the breakdown time was determined mainly by the transit time of the electromagnetic wave [101].

In 1977, the Khar'kov Polytechnic Institute reported on the design of a fast-acting multiple-gap system using a chain of elongated spark gap electrodes. The voltage increment $\Delta V = (V_c - V_b)/Ve$ (where V_c is the charging voltage and V_b is the minimum breakdown voltage) was 0.8 at 250 kV for 12 gaps. The switching time of less than 100 ns was 2 to 3 times shorter than the switching time of spherical spark gaps [74].

A 1970 paper, submitted by an unidentified institute, described a 58-kJ capacitor bank delivering output pulsed power of 1.4×10^{11} W and short-circuit current of 3.5 MA. The bank was designed to approximate the performance of explosive flux compressors, but to eliminate their hazardous operation and poor reproducibility of results. The principal feature of the system was the low capacitor and spark-gap inductance, which allowed for an overall system inductance of 5 nH. The three-electrode vacuum switches had the following characteristics:

Voltage	20 kV	
Current	200 kA	
Pressure	3×10^{-3} Torr	
Service life	20,000 shots	
Jitter	0.1 μs	[40]

5. SURFACE-FLASHOVER SPARK GAPS

The Leningrad Polytechnic Institute has been working on surface-flashover high-current spark gaps for capacitive storage systems since at least the early 1960s.* Between 1976 and 1979, the institute published a fairly comprehensive series of reports on theoretical and experimental results.

The surface-flashover principle is said by LPI to find an ever increasing use in Soviet electrophysical equipment, such as high-current switches, intense-light sources, and high-energy lasers. In these applications, a sliding discharge develops along the interface between a gas and a thin (typically 2 mm) solid dielectric, the reverse side of which is coated with metal. In spark-gap switches of this type, the electrodes are metal rails up to 1 m long, with a gap of less than 2 cm and a central trigger electrode rail. The discharge formation is due to a fast-changing voltage across the electrodes.

According to LPI, surface-flashover spark gaps can be used in capacitive stores of medium and high energy, in which current reaches 10^8 A. These stores require switches with minimal inductance and internal gap resistance, a broad range of operating voltages, short

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*Earlier studies of dielectric surface discharges for triggering fast spark gaps, performed at the Institute of Atmospheric Optics, were reported in Simon Kassel and Charles D. Hendricks, *High-Current Particle Beams. II. The Siberian USSR Research Groups* (U), The Rand Corporation, R-1885-ARPA, 1976, pp. 22ff. ~~(Confidential)~~.

switching time, and a stable delay time (low jitter). The multichannel discharge in air over a dielectric surface is said to be capable of meeting these requirements, which call for a large number of parallel spark gaps. The objective is to develop surface-flashover switches with a 100-ns delay time and 10-ns jitter.

The purpose of recent LPI research has been to fill the gap in knowledge about the delay time of these switches and the mechanism of the discharge itself. The overall conclusion of this research is that surface-flashover switches demonstrate sufficiently low jitter within a wide range of voltages. The satisfactory control of these switches at relatively low voltages makes them suitable for work in the parallel as well as in the crowbar modes [76,102,103].

The delay time for specific gas or solid dielectric materials depends mainly on the voltage rise rate at the trigger electrode. The voltage rise rate may be increased to reduce the delay time. The switching time is a function of heating and gas-dynamic expansion of the channels formed by the sliding discharge [76].

Below the breakdown voltage, there is a so-called incomplete discharge stage when the channel does not span the entire gap. The circuit is closed through the capacitance formed by the channel and the second electrode. When LPI studied surface-flashover in 1962, it postulated the possible existence of a thermal equilibrium in the sliding-discharge plasma within 1 to 10 μs. Assuming that the postulate was correct and that the electric field in the channel during the incomplete stage (1 atm) was fairly high (150 to 300 V/cm), one could expect high gas temperatures. However, no systematic measurements of gas temperature in the surface-flashover channel were made at that time. The recent, spectroscopic measurements showed that gas temperature in an incomplete sliding discharge in air and in SF_6 did not exceed 2000 K. The concentration of electrons in air at 260 Torr was 2×10^{15} cm^{-3}. The plasma of the incomplete sliding discharge was not in equilibrium, and the 1962 assumption was considered incorrect [102].

The axial field gradient in the incomplete discharge channel amounts to 0.3 to 1 kV/cm, while the field intensity at the front of the channel has a constant high value because of the thin dielectric.

For pulsed voltages of 50 to 100 kV and the generally used 2-mm dielectric, the normal and tangential components of field intensity at the front of the channel can reach 10^6 V/cm. At the point completion of the discharge, the axial field gradient in the channel rises sharply to 10 kV/cm because all the power supply voltage appears at the spark and the subsequent drop is determined by heating and gas-kinetic expansion of the channel. The present studies of the discharge by X-ray spectroscopy provide the first experimental indication of high-energy electrons generated at the discharge front due to the high field intensity. In the experiment, a 20-cm gap in atmospheric air was used together with an organic glass ($\varepsilon = 7$) plate 2 mm thick. The voltage pulse had 150-kV, 3-ns front, 350-ns pulse length, and 70-ns tail [103].

LPI has in recent years published two designs of low-inductance MA surface-flashover spark gaps. The first, reported in 1976, had main electrodes 45 cm long, the trigger electrode 40 cm long, and repeatedly switched 0.5 MA currents. It was claimed to be capable of switching currents up to 2 MA in parallel and crowbar-mode operation. Its specifications were as follows:

Inductance	5 nH	
Internal resistance	7 mohm	
Interelectrode gap	160 mm	
Operating voltage range	0 to 40 kV	
Trigger pulse rise rate	10^{12} V/s	
Delay time	40 ns	
Jitter	10 ns	[75]

The second spark gap, reported in 1979, had main electrodes 1 m long generating up to 40 channels in the discharge. The current handling capability of this design was up to 5 MA per single gap. The following were the optimum characteristics of the spark gap:

Inductance	0.5 nH	
Internal resistance	2 mohm	
Interelectrode gap	150 mm	
Operating voltage range	20 to 50 kV	
Trigger pulse voltage	80 to 100 kV	
Delay time	60 ns	
Switching time	140 ns	
Jitter	10 ns	[76]

6. UNTRIGGERED GAS GAPS

A number of institutes have reported on PFL untriggered gas gaps with a broad range of parameters. In 1971, IYaFSO in Novosibirsk developed an early high-pressure nitrogen gap for the RIUS-1 electron accelerator intended for pellet fusion research. The PFL switch operated at 16 atm and delivered 100-ns pulses with 8-ns rise time at 300 kV an' ᴗ kA [77].

A series of SF_6 gaps were described in publications submitted in 1974-1976 by several institutes. The Theoretical and Experimental Physics Institute (ITEF) in Moscow described a switch for 9 to 16.5 atm, yielding a voltage rise time of 2 ns in an oil Blumlein and 1 ns in an SF_6 Blumlein. At 450 kV, the jitter was 3 to 6 ns [79]. An unidentified facility reported on a glycerin PFL switch filled with SF_6 at 15 atm. The standoff voltage of the switch was 350 kV. current was 26 kA, pulse length was 35 ns, and rise time was 4 ns [78].

The Joint Institute of Nuclear Research (OIYaI) in Dubna developed an SF_6 gap for a 25-ohm streamer-chamber PFL. The switch operated at 450 kV, had a 440-ns delay time and 12.3-ns jitter, and was good for 10^5 shots [80].

The Lebedev Physics Institute (FIAN) in Moscow developed a new spark gap for the *Impul's* electron accelerator, a first-generation IREB accelerator. The *Impul's* was built by the Laboratory of Problems of New Accelerators at FIAN in 1969-1971. In 1973, a new module was added to the main accelerator to make the first Soviet machine with two independent electron beams. The Blumlein insulator was glycerin. The gas gap for the Blumlein was filled with SF_6 at 1.5 to 4 atm. The switch operated at 700 kV, 100 kA, 30 to 40-ns pulse length. The switching time was 10 ns for two or three channels, and the jitter was 10 ns [82].

In 1975, the Institute of Nuclear Physics, Electronics, and Automation in Tomsk published a simple design of a 100-kV, 20-kA switch for the *Tonus-II* accelerator. The switch operated at a pressure of 2.7 atm of nitrogen. After 200 shots at 30-second intervals, the voltage dropped 5 percent. Gas-blowing restored the initial voltage. The inductance of the switch was 5 nH [81].

7. THYRISTOR SWITCHES

Triggered semiconductor switches, or thyristors, have recently been gaining acceptance in Soviet industrial and laboratory practice. Researchers at IYaFSO in Novosibirsk claim the following advantages for thyristors: absence of heated cathodes; small size; and capability to handle hundreds of amperes at repetition frequencies of hundreds of herz, and thousands of amperes in single shots. IYaFSO's work with thyristors involved large, high-energy generators of long-current pulses operating at relatively low repetition frequencies.

In 1972, IYaFSO developed and put into operation a thyristor switch system for a synchrotron magnet. The system could handle 150-kA, 1.5-ms pulses with peak energy of 100 kJ. The switch system consisted of 220 type TL-150-8.0 thyristors connected in a series-parallel network. The thyristors were rated at 40-W power loss for an average current of 40 A without forced air cooling. The total power loss of the switch system was 1760 W, representing 2 percent of the generator power loss. The total area of the switches was 5 m^2. In three years of reliable operation, the system did not lose a single thyristor [83].

The Ioffe Physico-Technical Institute (FTII) in Leningrad engaged in the systematic development of thyristor switches during the 1970s, after first studying their turn-on characteristics, for purposes of high-power, fast-rise applications, in the late 1960s. The early stage of this research was devoted to the measurement of on-state propagation in the p-n-p-n structure, using a contact probe with a pneumatic damper to ensure high spatial and temporal resolution [104]. By 1971, a simple one-dimensional diffusion model of on-state propagation was proposed and the claim made that no satisfactory two-dimensional model was available. The current density considered in this study was of the order of 10 kA/cm^2, while the velocity of propagation varied from 1.6×10^4 to 3.4×10^4 cm/s for 3 kA/cm^2 [105].

In 1973, a neodymium laser was used to activate the thyristor switch. For a 1-cm^2 thyristor, the laser energy was 10^{-7} to 10^{-4} J and power was 10^{-1} to 10^3 W. The investigators found experimentally that the laser-activated thyristor turned on its entire volume when the laser-pulse energy exceeded the subcritical level by a factor of four [84]. The laser-activated, high-powered semiconductor switch was investigated during the years that followed, with emphasis on the behavior of the initial switching area and the effect of area size on the transient process [106]. Attempts have been made since 1975 to shorten the current rise time by increasing the incident laser power. An ionization shock wave passing from the collector to the emitter, also studied as an alternative to laser initiation, was found suitable only for very low voltages [107].

In 1977, the FTII investigators observed peak currents of the order of 1000 A at 2 kV with switching time of 50 ns. The experiments were similar to those of U.S. researchers (Zucker et al., *Appl. Phys. Lett.*, v. 29, no. 4, 1976, p. 261) published in 1976, except that Zucker observed peak currents of an order of magnitude higher. Unlike the U.S. experiments, the Soviet study included a reverse-biased diode as well as a thyristor [85]. In 1978, the investigators concluded that for practical switching applications, the diode was less desirable than the thyristor.

Soviet research experience in studying power and modulator silicon thyristors showed that the maximum current density for a kV semiconductor switch should not exceed 2×10^4 A/cm^2. Thus, for a working area of a few cm^2, the switch should handle up to 10^5 A. Research results also showed that if the total laser flux density per pulse has a limit of 0.1 J/cm^2, a silicon plate 40 mm in diameter can have resistance as low as 10^{-4} ohm. If the switch impedance is to be 1 percent of load impedance, the current can reach 10^6 A at 10 kV. According to Soviet researchers, these switches are limited primarily by the allowable peak current density [108].

The same research team worked exclusively on thyristor switches throughout the development period. Other teams of the Ioffe Physico-Technical Institute in the pulsed-power field studied field-emission cathode whisker formation, plasma heating by electron beams as part of fusion research, and electric discharge through a laser spark in air. The team developing switches appeared to have no connection with the others.

8. ELECTRON-BEAM TRIGGERED SWITCHES

Electron beams as triggers for gas gap switches have been studied since the late 1960s at TPI and IOA in Tomsk and IYaFSO in Novosibirsk. The first reports on the results were published in 1970. IOA investigated ways to achieve minimum pulse front length (shortest rise time) of the accelerating voltage and of the corresponding rise time of the electron current pulse. The spark gaps used to shape the pulse front have a high inductance and spark resistance, preventing pulse rise times as low as 1 to 10 ns. The initiation of a large number of parallel spark channels, however, by lowering the inductance and resistance of the switch, shortens the rise time. This operation requires ns stability of the spark initiation delay time necessary to satisfy the condition for parallel-spark switch: $\sigma < t$, where σ is the jitter (rms of delay time dispersion) and t is the transit time of the electromagnetic wave between two neighboring spark channels. Short delay time and switching time are also necessary. A short delay time requires a high concentration of charged particles in the gap; this concentration can be obtained by electron-beam ionization of the gas. Short switching time depends on a discharge without channels, or a large number of parallel spark channels, although the currents in the individual channels may vary [87,89].

In 1969, TPI noted an avalanche-discharge switch triggered by an electron beam. The beam parameters were 400 kV, 100 A, 4 A/cm^2, and 20-ns pulse length. The 0.8 cm gap was filled with N_2 at 3 to 15 atm. The switched current was 12 kA [55].

In 1970, IYaFSO submitted a report on the preliminary studies of a 150 to 400 kV, 10 A, 5-ns electron beam injected into a 4-cm gap at 360 kV filled with N_2 or SF_6 at 8 atm. In nitrogen, the delay time was 20 ns and jitter 1 ns. With SF_6, the gap voltage could be increased to 1 MV with the same delay time and jitter [86].

In 1971, IOA reported on experimental work with electron-beam triggering of spark gaps in N_2. A 100 to 350-kV beam was used with N_2 at up to 16 atm. A discharge without channels was obtained with switch voltages above 100 kV and currents of tens of kA. It was found that such a discharge is characterized by the absorption of 10^7 to 10^9 W/cm^2 in the gas in about 10 ns. In one of the experiments, a 350-kV, 2-kA electron beam produced a discharge without channels with peak current of 40 kA at 700 kV in a 7 atm nitrogen [87].

In another series of experiments reported on in 1973, IOA investigated an N_2:SF_6 switch in the MV range, comparing the switch stability when triggered by an electron beam and by trigatrons. The spark gap was 5.5 cm long, filled with the gas mixture at 4 to 11 atm. The electron beam trigger was 330 kV, 130 A, and 30 ns. For 1.5-MV switch voltage, the delay time was 15 ± 0.8 ns when triggered by the electron beam and 5.1 ± 0.5 ns with trigatron initiation. It was concluded that both methods can yield a subnanosecond jitter above 1 MV [89].

IOA continued to experiment with N_2 at 1 to 16 atm. A 180-kV, 100-A electron beam with 5-ns pulse length was used to control a switch for a 40-ohm PFL with a charging time of 0.5 μs. The delay time was 1 ns [88]. The concept of a volume discharge sustained by an electron beam evolved into a switching system, which IOA called the injection thyratron. The injection thyratron featured control of both the opening and closing actions of the switch, which consisted of two regions, gas and vacuum, separated by a thin metal foil. The cathode in the vacuum region emitted electrons which, accelerated by voltage, passed through the foil into the gas region. The fast electrons ionized the gas and thus caused current to flow in the switched circuit. The current was turned off by stopping the electron beam. Uniform ionization of the gas region required that the electron energy be sufficient to cross the foil and the entire interelectrode gap. For example, for a

10-cm gap, atmospheric pressure, and aeral foil density of 5×10^{-3} to 10^{-2} g/cm^2, the necessary electron energy is 100 to 150 keV. The advantage of the injection thyratron, according to its developers, is its ability to interrupt output current independently of the anode voltage.

The switch is suitable for high repetition rates, since the minimum distance between pulses (deionization time) equals the current fall time. The disadvantage of the switch is a fairly high power dissipation requiring gas blow-through at high repetition rates. The switched current is determined mainly by the electrode area. A discharge across a large area is not considered to be a problem. For example, according to experimental results for a peak voltage of 175 kV, in switching μs pulses at current density of 0.4 A/cm^2 and electrode area of 1000 cm^2, the total discharge current was 40 kA [90].

9. SPECIAL SWITCHES

The Yefremov Institute of Electrophysical Equipment (IEFA) in Leningrad has been developing spark gaps with a solid dielectric in which the triggering effect depends essentially on mechanical action. In 1971, IEFA reported on a spark gap triggered by a focused beam of a Q-switched ruby laser. The laser beam punctured a hole in a polymer film serving as the dielectric and caused an electrical breakdown of the gap. This method of initiation is claimed to yield short delay and switching times and, in conjunction with the low inductance of solid-dielectric gaps, to be suitable for the production of high-voltage nanosecond pulses. The experimental spark gap was used to switch a 50-ohm PFL. The 20-MW, 20-ns ruby laser output, when focused on polyethylene, lavsan, or teflon film 40 to 200 μm thick, made holes in film up to 100 μm thick. For an operating voltage of 14 kV, a 56-μm lavsan film yielded a delay time of 36 ns with a jitter of 3.5 ns [92].

In 1975, IEFA published a report (submitted for publication in 1972) on a solid-dielectric spark gap in which the polyethylene film was ruptured at two points by exploding aluminum foil. The gap consisted of two 500 x 500 x 25 mm brass plates forming the electrodes, one of which was hinged to facilitate the replacement of the ruptured film. A delay time of about 0.5 μs was obtained above 150 kA at 80 kV. The jitter did not exceed 100 ns [95].

The Kiev Polytechnic Institute (KPI) has been working on crossed-field switches, called triotrons and trioplasmatrons. The main objective of this work was the development of switching devices that meet the requirements of high current, short delay time, low jitter, light weight, and small size. The triotron is a triggered gas switch with a cold cathode and a constant magnetic field. In 1971, KPI reported on a triotron capable of extended operation in the range of 0.4 to 30 kV and 10 to 20 kA. The switch, with a diameter of 59 mm and height of 200 mm, was designed for 250 MW pulsed power and was filled with hydrogen at 10^{-2} Torr [109]. Two reports published in 1973 demonstrated the feasibility of on and off control and repetitive operation of this type of switch. A trioplasmatron filled with mercury switched 25-kA, 1-μs current pulses within the range of 0.4 to 30 kV and a delay time of less than 1 μs. The service life was 5×10^4 shots [96].

The Institute of Electrodynamics of the Ukrainian Academy of Sciences reported in 1973 on a high-current switch for plasma spectroscopy studies. The switch, designed for 150 kV and 200 kA, used a plasma jet as the trigger. The jitter was a fraction of μs. The plasma jet was generated in a capillary discharge [94].

The plasma jet principle in closing switches was described in a 1970 paper of an unidentified institute. The switch was closed by a plasma jet formed in air by the switched current itself. The switching time was 1.5 to 20 μs, with a jitter of 0.35 μs. The voltage ranged from 6 to 25 kV and current from 50 to 160 kA [93].

Between 1965 and 1967 IYaFSO worked on switching 10-kA, millisecond current pulses with reverse voltages of a few kV. The IYaFSO switches were designed to initiate the discharge by a special trigger and to quench it by passing the current through the null value. The gas in the switch, in contrast to that in thyratrons, mattered only during the initial phase of the discharge, with the remainder of the process occurring mainly in the vapor of the electrode metal. IYaFSO selected cold, solid cathodes operating in the arc discharge mode with a practically uniform field and the same trigger potential for either polarity.

Beginning in 1967, IYaFSO worked on the development of a reliable spark-type trigger for the arc discharge switch. A special cathode and trigger structure protected the trigger from the arc discharge. The resulting model withstood 10^7 shots. A theory developed in 1969 permitted IYaFSO to determine the structure of the switch for each specific application, given data on the velocity of the discharge, pulse length, and current. The performance of triggered switches with cold, solid cathodes is being improved mainly by designing large deionizing surfaces that allow for decreasing the arc discharge plasma density and increasing the pressure drop rate, for example, by means of an artatron-type magnetic trigger field. Systems with flat electrodes and a short arc for ms pulses proved capable of switching 40 to 50 kA with 4 to 5 kV reverse voltage, or 15 kA with 10 kV forward voltage [92].

The Kiev State University submitted a report in 1977 describing the use of industrial IRT-3 ignitrons in a pulse-current generator. These ignitrons (reported on in 1974) had the following specifications:

Inductance	40 nH	
Switched current	100 kA	
Voltage range	0.1 to 20 kV	
Pulse length	4 μs	
Jitter	0.2 μs	
Service life	10^5 shots	[98]

10. SWITCH ELECTRODE EROSION

An early study of electrode erosion in spark gap switches was conducted by the Physico-Technical Institute (FTI) in Khar'kov [110]. In a report submitted for publication in 1970, FTI described tests of electrodes at 100 kA, within a pulse length range of up to 3 ms, at atmospheric pressure, and in vacuum. The method of protecting the electrodes was based on electrode configuration. Concentric rings on the electrode surface produced electrodynamic interaction of the discharge currents in the rings, causing the electric charge on the electrodes to move radially and azimuthally. The resulting erosion was found to be comparatively slight and the trigger structure on the electrodes free of sputtered metal. The service life of the switch electrodes was 10^4 to 10^5 shots.

A systematic experimental investigation of the surface finish and erosion of spark gap electrodes and their effect on switch performance was conducted at the Moscow Power Institute (MEI). Early results of the experiments were submitted for publication in 1972. Electrodes with coarse finish were studied in air at 1 to 5 atm using 0.5-cm gaps at 270-kA currents and 20-μs pulse lengths. The study focused on the dependence of the electric strength of the gap and statistical distribution of breakdown voltage on the microstructure of the electrode surface [111]. A parallel study developed an approximate analytic method for calculating electrode erosion in spark gap switches. According to MEI, Western experimental literature of the 1960s did not contain adequate data for the selection of optimal erosion-proof conditions suitable for most practical applications of these switches. The Soviet work was an attempt to obtain such data experimentally [112,113]. A more recent paper, submitted for publication in 1976, analyzed switch electrode erosion from the viewpoint of the medium (gas or liquid) surrounding the electrodes and its effect on the erosion process. Since in the case of μs pulses erosion is similar to that observed with industrial-frequency currents, both types of current were investigated. According to experimental data, high-current pulses at gas pressure of 10 Pa produced a minimum erosion rate of 0.5 mg/C for copper electrodes. In vacuum (10^{-3}Pa), copper erosion rate is lower, approaching micrograms per coulomb. This is in agreement with U.S. findings of a minimum of 10 μg/C.* It was concluded that (1) the average current density on the electrode surface increases with the density of the medium; (2) increasing the density of the medium increases the ejection of molten electrode metal; and (3) for any discharge conditions, there is a regime for which

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***Advanced Power Systems Technology Survey and System Concept Applications*, prepared for Ballistic Missile Defense Advanced Technology Center (BMDATC), U.S. Army Corps of Engineers, Huntsville Division, *HNDTR*-77-32-ED-SR, 31 December 1977, p. 3-68.

specific electrode wear approaches a limiting value. Specifically, the limiting value of electrode wear is approached in dense media at a lower integrated electric charge passing through the switch than in rarefied media [114].

The IYaFSO recently reported on the development of frangible electrodes for MA spark gaps (report submitted for publication in 1976). The switch was designed to operate at 50 kV in 10 to 15 atm of nitrogen. The switch inductance was below One or both electrodes of the switch were plates that disintegra ed the passage of the current pulse, ensuring an effective removal of electrode erosion products from the gap and a reduced shock to the structural parts of the switch. With a single disintegrating electrode, the switch operated in strong magnetic fields with 1.5 MA, capacitor bank of 30 kJ, and discharge circuit frequency of 200 to 300 kHz [60].

Appendix C

SOVIET RESEARCH TEAMS

Members of the Soviet teams whose research and development of switches is discussed in Appendixes A and B are listed below by institutional affiliation, type of switch worked on, and year(s) in which the report(s) on that switch or related work was published. (These dates differ from those cited in Appendixes A and B, which represent the year the report was submitted for publication.)

LEBEDEV PHYSICS INSTITUTE (FIAN), MOSCOW

Untriggered Gas Gap -- 1977

L. N. Kazanskiy	A. A. Kolomenskiy	G. O. Meskhi
	B. N. Yablokov	

PHYSICO-TECHNICAL INSTITUTE (FTI), KHAR'KOV

Laser-Activated Gap, Microwave Generation -- 1972-1973

V. U. Abramovich	Ya. Ya. Bessarab	L. I. Bolotin
Ya. B. Faynberg	N. P. Gadetskiy	Yu. V. Tkach
Ye. A. Lemberg	I. I. Magda	I. N. Mondrus
V. D. Shapiro	V. I. Shevchenko	A. V. Sidel'nikova
	A. I. Zykov	

Ion Beams -- 1979

A. I. Aksenov	V. M. Khoroshikh	V. G. Padalka

Triggered Arc, Triggered Vacuum Gap, Switch Electrode Erosion

1970-1973

I. I. Aksenov	N. G. Baranov	Yu. A. Mishutin
Yu. S. Pavlov	V. I. Slatin	S. A. Smirnov

IOFFE PHYSICO-TECHNICAL INSTITUTE (FTII), LENINGRAD

Thyristor -- 1970-1979

M. M. Akhmedova	I. G. Chashnikov	I. V. Grekhov
A. F. Kardo-Sysoyev	M. Ye. Levinshteyn	V. G. Sergeyev
V. B. Shuman	A. I. Uvarov	V. M. Volle
	I. N. Yassiyevich	

MINING INSTITUTE OF THE KOLA AFFILIATE, ACADEMY OF SCIENCES, USSR (GIKF)

Trigatron -- 1976

A. N. Danilin   A. Kh. Yerukhimov   I. M. Zarkhi

KURCHATOV ATOMIC ENERGY INSTITUTE .IAE), MOSCOW

Untriggered Spark Gap, Inertial Confinement Fusion, Magnetic Flux Compression -- 1975

S. I. 'nevskiy   V. I. Liksonov   S. L. Nedoseyev
Yu. L. Sidorov   V. P. Smirnov

Multielectrode Spark Gap, Magnetic Confinement Fusion, Laser Pumping -- 1974

M. V. Babykin   S. S. Sobolev   V. V. Starykh
A. I. Zhuzhunashvili

Inertial and Magnetic Confinement Fusion, Electron-Beam-Driven Chemical Reaction -- 1974

B. A. Demidov   S. D. Fanchenko   M. V. Ivkin
V. A. Petrov

Tacitron -- 1972

V. D. Dvornikov   V. A. Krestov   S. T. Latushkin
L. M. Tikhomirov   L. I. Yudin

INSTITUTE OF ELECTRODYNAMICS (IED), KIEV

Plasma Jet Switch -- 1973

N. I. Fal'kovskiy

YEFREMOV INSTITUTE OF ELECTROPHYSICAL EQUIPMENT (IEFA), LENINGRAD

Mechanical Switch -- 1975

A. B. Andrezen   V. A. Burtsev   A. B. Produvnov

Mechanical Switch -- 1971

A. I. Babalin   V. A. Rodichkin   G. Ya. Rus'kova
A. M. Timonin

INSTITUTE OF ATMOSPHERIC OPTICS (IOA), TOMSK

Triggered Gas Gap -- 1973

D. I. Proskurovskiy
Ye. B. Yankelevich

Triggered Arc Switch -- 1977

S. P. Bugayev	V. I. Koshelev	A. F. Medvedev
	M. M. Nikitin	

Laser Triggered Switch -- 1973

Yu. I. Bychkov	A. P. Khuzeyev	Yu. D. Korolev
Yu. A. Kurbatov	V. M. Orlovskiy	V. F. Tarasenko

Electron-Beam Triggered-Switch,
Untriggered Gas Gap, Trigatron

1971-1976

V. Ya. Borisov	B. M. Koval'chuk	V. V. Kremnev
V. A. Lavrinovich	V. V. Lopatin	A. A. Makushev
G. A. Mesyats	Yu. F. Potalitsyn	G. Ya. Vlasov
A. S. Yel'chaninov	V. G. Yemel'yanov	F. Ya. Zagulov

High-Power Laser -- 1976

Yu. I. Bychkov	N. V. Karlov	N. F. Kovsharov
V. F. Losev	G. A. Mesyats	A. M. Prokhorov
V. F. Tarasenko	F. Ya. Zagulov	

INSTITUTE OF HIGH-CURRENT ELECTRONICS (ISE), TOMSK

Injection Thyratron

1978-1979

G. A. Mesyats
V. G. Shpak

Untriggered Gas Gap, Trigatron -- 1979

S. D. Korovin	B. M. Koval'chuk	V. A. Lavrinovich
G. A. Mesyats	Yu. F. Potalitsyn	V. V. Toptygin
A. S. Yel'chaninov	F. Ya. Zagulov	

INSTITUTE OF THEORETICAL AND EXPERIMENTAL PHYSICS (ITEF), MOS

Untriggered Gas Gap -- 1975

V. A. Artem'yev	V. M. Knyazev	N. N. Luzhetskiy
V. P. Nikolayev	I. I. Pershin	I. V. Rechitskiy

HIGH-VOLTAGE INSTITUTE (IVN), TOMSK

Trigatron, Multielectrode Gas Gap

1974-1979

V. N. Churilov	I. I. Kalyatskiy	V. V. Khmyrov
G. S. Korshunov	Yu. A. Krasnyatov	M. T. Pichugina
V. V. Sedov	V. V. Ustyuzhin	V. F. Vazhov

Untriggered Spark Gap, Water Spark Gap, Multielectrode Gas Gap, Oil-Filled Switch

1977-1978

V. V. Balalayev	N. K. Kapishnikov	M. G. Korotkov
V. M. Muratov	V. Ya. Ushakov	

Multielectrode Spark Gap, Trigatron -- 1976

V. P. Chernenko	V. R. Kukhta	V. I. Logachev
V. V. Lopatin	G. Ye. Remnev	V. I. Tsvetkov

INSTITUTE OF NUCLEAR PHYSICS, ELECTRONICS, AND AUTOMATION (IYaFEA), TOMSK

Multielectrode Spark Gap, Untriggered Gas Gap

1975-1976

A. T. Matyushin	V. T. Matyushin	V. S. Pak
G. Ye. Remnev	N. S. Rudenko	A. A. Shatanov
V. I. Smetanin	V. I. Tsvetkov	Yu. P. Usov

Solid Dielectric Switch, Multielectrode Gas Gap

1969-1970

V. V. Khmyrov	B. M. Koval'chuk	G. A. Mesyats
	V. P. Osipov	

Trigatron -- 1977

V. V. Baraboshkin

INSTITUTE OF NUCLEAR PHYSICS, MOSCOW STATE UNIVERSITY (IYaFMGU)

Multielectrode Gas Gap -- 1976

I. Ya. Antipov	V. A. Khrushchev	Yu. V. Kuznetsov
Ye. V. Lazutin	I. M. Piskarev	A. V. Shumakov

INSTITUTE OF NUCLEAR PHYSICS (IYaFSO), NOVOSIBIRSK

Multielectrode Spark Gap, Switch Electrode Erosion

1977-1978

V. N. Karasyuk
G. I. Sil'vestrov
G. S. Villeval'd

Untriggered Gas Gap, Ignitron, Electron-Beam-Triggered Switch, Untriggered Water Spark Gap

1968-1978

Ye. A. Abramyan
E. L. Boyarintsev
V. M. Fedorov
L. P. Fominskiy
V. A. Kapitonov
Ye. N. Kharitonov
V. A. Kornilov
V. M. Lagunov
V. S. Panasyuk
O. P. Pecherskiy
A. G. Ponomarenko
S. M. Shirkin
A. M. Sidoruk
V. D. Tarasov
V. A. Tsukerman
V. V. Vorob'yev
A. A. Yegorov
V. A. Yelkin

Three-Electrode Gas Gap, Thyristor

1976-1977

A. A. Avdiyenko
A. F. Bulushev
B. I. Grishanov
Ye. N. Kharitonov
Yu. G. Matveyev
Ye. P. Mel'nikov
A. A. Mit'ko

Thyristor -- 1970

M. Yu. Gel'tsel'
A. A. Podminogin

KIEV STATE UNIVERSITY (KGU)

Ignitron -- 1978

Yu. N. Levchenko
V. A. Zhovtyanskiy

KHAR'KOV POLYTECHNIC INSTITUTE (KhPI)

Triggered Vacuum Gap

1974-1978

I. R. Pekar'

INSTITUTE OF RADIOELECTRONICS (KIR), KHAR'KOV

Triggered Gas Gap -- 1977

G. I. Nosov
S. A. Smirnov

KIEV POLYTECHNIC INSTITUTE (KPI)

Triotron, Trioplasmatron

1971-1973

Yu. D. Khromov	V. I. Krizhanovskiy	A. I. Kuz'michev
L. P. Pavlenko	A. I. Shendakov	L. N. Shmyreva
A. I. Soldatenko	A. I. Vishnevskiy	S. Sh. Zaydman

LENINGRAD ELECTRICAL ENGINEERING COMMUNICATIONS INSTITUTE (LEIS)

Mercury Thyratron -- 1972

L. Z. Gogolitsyn

LENINGRAD POLYTECHNIC INSTITUTE (LPI)

Triggered Vacuum Gap, Surface-Flashover Spark Gap, Discharge in Air

1971-1979

G. I. Belyayev	M. L. Chepkalenko	M. A. Chernov
P. N. Dashuk	A. V. Grigor'yev	V. B. Ikonnikov
G. S. Kichayeva	S. L. Kulakov	S. N. Markov
T. G. Merkulova	Ye. A. Sergeyenkova	P. I. Shkuropat
V. L. Shutov	M. D. Yarysheva	A. K. Zinchenko

Multielectrode Spark Gap, Magnetic Flux Compression

1971-1972

Ye. P. Bel'kov

MOSCOW POWER INSTITUTE (MEI)

Switch Electrode Erosion

1973-1978

V. A. Avrutskiy	G. S. Belkin	G. M. Goncharenko
V. Ya. Kiselev	Ye. N. Prokhorov	

MOSCOW ENGINEERING PHYSICS INSTITUTE (MIFI)

Triggered Gas Gap, Trigatron

1975-1976

B. A. Afanas'yev	A. S. Fedotkin	A. I. Gerasimov
A. P. Klement'yev	G. D. Kuleshov	D. N. Miloradov
A. I. Pavlovskiy	S. Ya. Slyusarenko	V. A. Tananakin
	V. P. Tsiberov	

JOINT INSTITUTE OF NUCLEAR RESEARCH (OiYaI), DUBNA

Multielectrode Spark Gap -- 1978

L. K. Lytkin   A. F. Pisarev   V. F. Pisarev
G. S. Revenko

Untriggered Gas Gap -- 1977
(with High Energy Physics Institute of GDR)

Ya. V. Grishkevich   G. Peter   D. Poze
Kh. Ryuger   A. Shrind   K. Tryuchler

Ignitron -- 1977

V. A. Bulanov   G. A. Ivanov   L. V. Svetov

Triggered Vacuum Gap -- 1975

G. D. Alekseyev
D. M. Khazins

Untriggered Gas Gap -- 1965

I. B. Issinskiy
K. P. Myznikov

SPECIAL DESIGN BUREAU FOR X-RAY EQUIPMENT (SKBRA), LENINGRAD

Untriggered Gas Gap, Laser Pumping -- 1973

E. A. Avilov   N. V. Belkin   A. V. Dudin
M. A. Kanunov   A. A. Razin   A. P. Zykov

TOMSK POLYTECHNIC INSTITUTE (TPI)

Multielectrode Gas Gap, Triggered Gas Gap

1968-1970

B. M. Koval'chuk   V. V. Kremnev   G. A. Mesyats
Yu. F. Potalitsyn

Thyristor -- 1978

N. P. Polyakov   P. P. Rumyantsev   V. V. Sinenko
Yu. P. Yarushkin

UNIDENTIFIED AFFILIATIONS

Triggered Gas Gap -- 1968

L. G. Ivleva
L. N. Vagin

Triggered Vacuum Gap -- 1975

O. G. Bespalov
P. A. Smirnov
A. S. Knyazyatov
A. N. Udovenko
A. I. Nastyukha

Mechanical Switch -- 1975

V. A. Alekseyev
B. V. Kalachev
I. V. Smirnov
G. I. Kromskiy

Ignitron -- 1978

V. P. Andronova
A. M. Serbinov
R. G. Antokhin
V. I. Sysun
Yu. D. Khromoy

Plasma Jet Switch -- 1970

V. S. Komel'kov
V. I. Modzolevskiy

Untriggered Gas Gap -- 1975

R. K. Bevov
V. S. Mezhevov
A. P. Strel'tsov
Yu. B. Smakovskiy

Triggered Vacuum Gap

1970-1971

A. M. Andrianov
A. Yu. Sokolov
V. F. Demichev
A. K. Terent'yev
P. A. Levit
G. A. Yeliseyev

Repetition-Rated Switch Erosion -- 1979

L. S. Eyg
E. N. Kosmarskiy
I. A. Voronezhskaya
L. G. Sinel'nikova

Appendix D

LIST OF SOVIET RESEARCH INSTITUTES

Soviet research institutes referred to in this report are listed below in alphabetical order by acronym.

FIAN	Physics Institute imeni P. N. Lebedev, Academy of Sciences, USSR; Moscow
FTI	Physico-Technical Institute, Academy of Sciences, Ukrainian SSR; Khar'kov
FTII	Physico-Technical Institute imeni A. F. Ioffe, Academy of Sciences, USSR; Leningrad
GIKF	Mining Institute, Kola Affiliate of the Academy of Sciences, USSR; Apatity
IAE	Institute of Atomic Energy imeni I. V. Kurchatov; Moscow
IED	Institute of Electrodynamics, Academy of Sciences, Ukrainian SSR; Kiev
IEFA	Scientific Research Institute of Electrophysical Equipment imeni D. B. Yefremov, State Committee for the Use of Atomic Energy; Leningrad
IFANU	Institute of Physics, Academy of Sciences, Ukrainian SSR; Kiev
IOA	Institute of Atmospheric Optics, Siberian Branch, Academy of Sciences, USSR; Tomsk
ISE	Institute of High-Current Electronics, Siberian Branch, Academy of Sciences, USSR; Tomsk
ITEF	Institute of Theoretical and Experimental Physics, State Committee for the Use of Atomic Energy; Moscow
IVN	Scientific Research Institute of High Voltages, Tomsk Polytechnic Institute imeni S. M. Kirov; Tomsk
IYaFEA	Scientific Research Institute of Nuclear Physics, Electronics, and Automation, Tomsk Polytechnic Institute imeni S. M. Kirov; Tomsk
IYaFMGU	Scientific Research Institute of Nuclear Physics, Moscow State University imeni M. V. Lomonosov; Moscow

IYaFSO	Institute of Nuclear Physics, Siberian Branch, Academy of Sciences, USSR; Novosibirsk
KGU	Kiev State University imeni T. G. Shevchenko; Kiev
KhIR	Khar'kov Institute of Radioelectronics; Khar'kov
KhPI	Khar'kov Polytechnic Institute; Khar'kov
KPI	Kiev Polytechnic Institute; Kiev
LEIS	Leningrad Electrical Engineering Communications Institute imeni M. A. Bonch-Bruyevich; Leningrad
LPI	Leningrad Polytechnic Institute imeni M. I. Kalinin; Leningrad
MEI	Moscow Power Institute; Moscow
MIFI	Moscow Engineering Physics Institute; Moscow
OIYaI	Joint Institute of Nuclear Research; Dubna
SKBRA	Special Design Bureau for X-Ray Equipment; Leningrad
TPI	Tomsk Polytechnic Institute imeni S. M. Kirov; Tomsk

[illegible]

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12. Avilov, E. A., N. V. Belkin, A. V. Dudin, A. P. Zykov, M. A. Kanunov, and A. A. Razin, *PTE*, No. 1, 1973, p. 137.

13. Isainskiy, I. B., and K. P. Myznikov, *PTE*, No. 3, 1965, p. 131.

14. Vagin, L. N., and L. G. Ivleva, *PTE*, No. 6, 1968, p. 157.

15. Dvornikov, V. D., S. T. Latushkin. V. A. Krestov, L. M. Tikhomirov, and L. I. Yudin, *PTE*, No. 4, 1972, p. 108.

16. Avdiyenko, A. A., A. F. Bulushev, B. I. Grishanov, and Yu. G. Matveyev, *PTE*, No. 2, 1977, p. 129.

17. Danilin, A. N., A. Kh. Yerukhimov, and I. M. Zarkhi, *PTE*, No. 1, 1976, p. 106.

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24. Alekseyev, G. D., and D. M. Khazins, *PTE*, No. 5, 1975, p. 105.

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32. Bel'kov, Ye. P., *ZhTF*, Vol. 41, No. 8, 1971, p. 1678.

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AE--*Atomnaya energiya*
DAN SSSR--*Doklady Akademii nauk SSSR*
FKOM--*Fizika i khimiya obrabotki materialov*
FP--*Fizika plazmy*
FTP--*Fizika i tekhnika poluprovodnikov*
IVUZ FIZ--*Izvestiya Vysshikh uchebnykh zavedeniy, Seriya fizika*
IVUZ RAD--*Izvestiya Vysshikh uchebnykh zavedeniy, Radioelektronika*
OIPOTZ--*Otkritiya, izobreteniya, promyshlenniye obraztsy, Tovarnyye Znaki. Ofitsial'nyy byulleten'*
PMTF--*Zhurnal prikladnoy mekhaniki i tekhnicheskoy fiziki*
PTE--*Pribory i tekhnika eksperimenta*
RE--*Radiotekhnika i elektronika*
VAN SSSR--*Vestnik Akademii nauk SSSR*
ZhETF--*Zhurnal eksperimental'noy i teoreticheskoy fiziki*
ZhETF, Pis'ma--*Pis'ma v Zhurnal eksperimental'noy i teoreticheskoy fiziki*
ZhTF--*Zhurnal tekhnicheskoy fiziki*
ZhTF, Pis'ma--*Pis'ma v Zhurnal tekhnicheskoy fiziki*