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PORTABLE LINEAR ACCELERATORS FOR COMMERCIAL APPLICATIONS

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ABSTRACT

This paper discusses microwave portable linear accelerators for electron beam curing of composites, non-destructive testing, and other commercial applications designed and build at SRC or with SRC participance. Comparatively light weight electron beam sources allow curing of graphite composites with thickness up to 3 cm when irradiated from one side and 7 cm when irradiated from two sides in time periods from several minutes to several hours, depending on generated electron beam power. Same systems with lower electron beam power are used for non-destructive testing of thick and dense objects using radiation flux, produced by electron beam stopped in a heavy metal target. It is possible to mount any of the portable linac heads described in the article on a robotic or C- arm and use it for radiation processing purposes. Some of the systems could be moved in a truck. Along with the standard systems, we are developing a number of new products and broadening the range of parameters. New products will make it possible to build comparatively inexpensive electron beam sources with average beam power from 10 to 100 kW and energy from 1 to 10 MeV. The development is focused on the portable systems with beam power in 1 to 35 kW range, which can be mounted on a crane or a robot.

INTRODUCTION

Electron beam cross-linking or "curing" of composites is a rapidly developing field of electron accelerator application, which is becoming a substantial addition to conventional thermal curing, especially when the parts are large and have a complex shape. The advantage of using an electron beam is that it can be scanned by means of electrical or magnetic scanning devices. In addition, if an electron source is compact enough, it could be mounted on a robotic or C-arm and moved to the sites using a truck. Electron beam treatment does not require big autoclaves and is not an inertial process, like thermal curing. In addition, recent studies made by leading experts in electron composite chemistry have shown that the properties of electron beam cured composites are even better than those of thermally cured composites [1,2,3].

Electron accelerators of various types can be used to generate the required beam characteristics. We believe that linear accelerators powered by a microwave or RF (radiofrequency) source is the most appropriate solution for a portable high energy machine. These accelerators is the core product of SRC. Most of the linear accelerators or, as they called, "linacs" referenced in Table 1 were originally developed for non-destructive applications, when the accelerated beam interacts with a heavy metal target installed at the output of a beam transporting channel and generates an intensive flux of X-rays. When the same system is used for e-beam treatment, the target is removed and an electron window is installed to extract the beam into air. Electron windows can be different in size to provide extraction of beams with various power values.

Time of e-beam treatment is heavily dependent on the accelerated beam power and penetration depth.
Using E-beam dose, provided in the Table, one can calculate necessary time of a material treatment. For example, using the number 12 kGy kg/min for MINAC-4, one can find that 1 kg of composite with thickness of 0.8 cm (effective e-beam penetration shown in the same column) can receive dose of 120 kGy in 10 minutes if the beam is evenly distributed over the sample surface.

The following Tables 1 and 2 summarize the parameters of systems manufactured or being developed by SRC .

TABLE 1 PRESENTLY DEVELOPED SYSTEMS

Number	1	2	3	4	5	6	7
Brand Name	Minac-1.5	Minac-4	Minac-6	Minilac	Minatron	Minatron	Minatron
Designer	SRC	SRC	SRC	SRC/RPC	SRC	SRC	SRC
Energy, MeV	1.5	4	6	2	2.5	6	9
Beam Power, kW	0.05	0.2	0.5	15	0.8	1	1
Penetration, g/cm^2	0.71	2.12	3.26	0.99	1.27	3.26	4.95
Eff. Penetration, cm**	0.27	0.80	1.22	0.37	0.48	1.22	1.86
X-Ray Dose, Rad/min@1m	3	100	300	6000	250	1000	3000
E-beam Dose:							
kGy kg/min	3.00	12.00	30.00	900.00	48.00	60.00	60.00
kGy m^2/min***	0.25	0.34	0.55	54.49	2.26	1.11	0.73
Window area, cm^2	0.33	0.50	0.83	75.00	3.20	1.67	1.11
Wall Plug, kVA	11	11	11	30	10	10	10
Wall Plug Efficiency, %	0.5	1.8	4.5	50.0	8.0	10.0	10.0
Irradiator length, m****	0.5	0.5	0.6	2	0.3	0.5	1.2
Irradiator mass, kg	150	180	180	364	364	409	455
RF source	magnetron	magnetron	magnetron	klystron	magnetron	magnetron	magnetron
Frequency Band	X-BAND	X-BAND	X-BAND	S-BAND	S-BAND	S-BAND	S-BAND

Usually, a dose of 150 kGy or of that order of magnitude is required to cure a graphite composite. The accelerators that are listed in Table 1 are considered comparatively low-power in electron beam curing industry. However, they can be used for so-called "local" curing in order to do patch repair in the field due to excellent portability. We provided our standard portable accelerators MINAC for test curing of composite structures manufactured by United Defense. A 0.75" (1.9 cm) thick composite was successfully cured by 4 MeV e-beam applied from two opposite sides of a composite structure.

For larger volumes of material or for mass production higher beam power machines shall be used. The following Table 2 represents the parameters of new higher power systems which are presently under development.

TABLE 2 SYSTEMS UNDER DEVELOPMENT

Brand Name	MINAC-8	CWAC-1	MAGBEAM-10	MAGBEAM-30
Designer	SRC	SRC	SRC/TIC	SRC/TIC
Energy, MeV	8	1	10	10
Beam Power, kW	0.8	10	10	30
Penetration, g/cm^2	4.39	0.43	5.52	5.52
Eff. Penetration, cm**	1.65	0.16	2.07	2.07
Total Dose, kGy kg/min	48.00	600.00	600.00	1,800.00
Dose, kGy sq.m./min***	0.66	84.71	6.52	19.57
Window area, cm^2	1.00	100.00	10.00	30.00
Wall Plug, kVA	11	50	30	70
Wall Plug Efficiency, %	7.3	12.5	33.3	42.9
Irradiator length, m****	1.2	2	2	2
Irradiator mass, kg	360	455	455	455
Suggested RF source	magnetron	magnetron	magnetron	magnetron
Frequency Band	X-BAND	S-BAND	S-BAND	S-BAND

* - for graphite composite, 1.6 g/cc
** - assuming 20% dose uniformity, it is approximately 60% of the maximum penetration
*** - for 60% effective penetration
**** - Including scanner, if applicable

1. "MINAC" PORTABLE ACCELERATORS

MINAC systems were initially built for radiographic applications. They are available in three standard models: MINAC-1.5, MINAC-4 and MINAC-6 [4]. Each system can be delivered either as an X-Ray or electron beam source and includes a control console, modulator unit, RF head, X-Ray (E-beam) head, water circulating unit, remote interlock unit and power transformer unit, which are interconnected by a set of power and signal cables, hoses and flexible RF waveguide.

Fig.1 4 MeV and 6 MeV linac (left) and RF head (right)

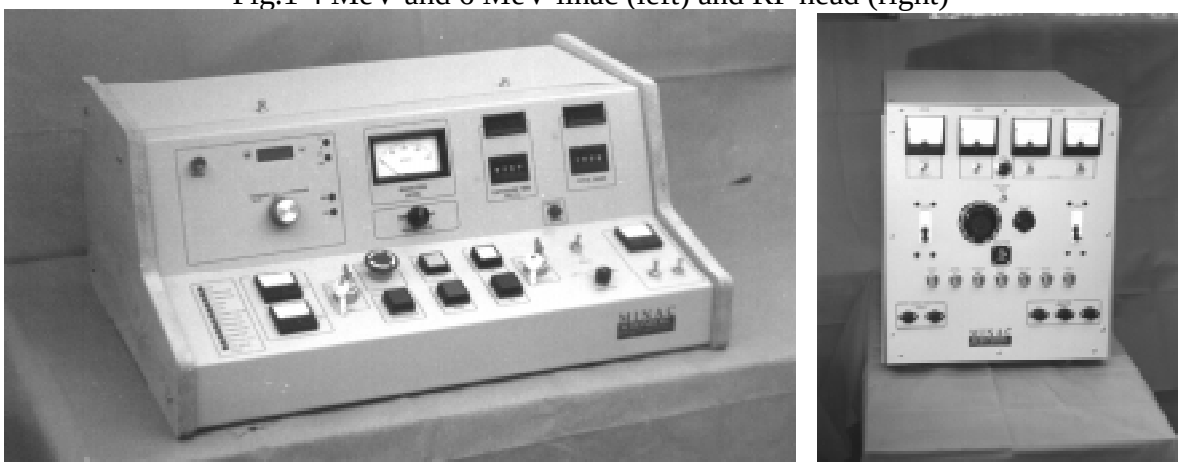

Fig.2. Control console (left) and modulator (right)

The RF Head contains a mechanically tunable magnetron, a pulse transformer, magnetron pulse modulator, electron gun filament isolation transformer, RF circulators, and other RF components. The pulse transformer steps the pulse voltage up to 36 kV. A voltage divider network is used to provide 18 kV to pulse the electron gun injector. An isolation transformer supplies power to the electron gun filament. Beam current can be regulated by varying electron gun grid voltage.

The X-Ray or electron beam head, which contains the accelerator unit, is separate from the RF head. It is interconnected by means of flexible RF waveguide, power cables and cooling system hoses. The flexible RF waveguide must be pressurized with sulfur hexafluoride (SF_6) gas to 38 PSIG before use.

The same control, power supply, RF generator, heat exchanger, dosimeters and interconnect cables are used both for MINAC 4 and MINAC 6 X-Ray heads.

2. MINATRON SYSTEM X-RAY AND ELECTRON BEAM CHARACTERISTICS

Using an S-band power source and a corresponding accelerator structure permits accelerating higher currents compared to the beam current achieved for X-band linacs, as presented in a Table 3 below [4]. However, the accelerating gradients reduce proportionally to the square root of operating frequency and the dimensions grow linearly with wavelength.

TABLE 3. PARAMETERS OF MINATRON SYSTEMS

X-RAY ENERGY/OUTPUT/PENETRATION

Energy	Radiation Output (max. intensity)	Radiation Leakage	Maximum Penetration 2R exposures, 1 hour, in steel @ 3 meters	Beam spot size	Half Value Layer
2.5 MeV	250 R/min. @ 1 m.	0.1%	8.5 inches steel (Fe)	2 mm	0.91"
6.0 MeV	1000 R/min. @ 1 m.	0.1%	14.0 inches steel (Fe)	2 mm	1.17"
9.0 MeV	3000 R/min. @ 1 m.	0.1%	16.0 inches steel (Fe)	2 mm	1.29"

ELECTRON BEAM CURRENT AND POWER CHARACTERISTICS

X-Ray Dose with installed target	250 R/min.	1000 R/min.	3000 R/min.
Beam Energy Level (MeV)	2.5	6.0	9.0
Operating Frequency (MHz)	2998	2998	2998
Accelerated Peak Current (mA)	350	130	100
Accelerated Avg. Current (mA)	300	130	100
E-Beam Peak Power (kW)	875	780	900
E-Beam Avg. Power (W)	750	780	900
Magnetron Peak RF Power (MW)	2.5	2.5	2.5
Magnetron Avg. Power (kW)	2.0	2.5	2.5
Pulse Voltage (kV)	40	40	40
P.R.F. (pulses/second, nom.)	250	250	250
Pulse Width (μsec)	3.5	3.5	3.5
Duty Cycle	0.0009	0.001	0.001
Injection Voltage (kV)	17	17	17
Gun Fil. Voltage (V)	6	6	6
Gun Fil. Current (A)	1.6	1.6	1.6
Voltage Requirements (VAC)	208/220 3 phase	208/220 3 phase	208/220 3 phase
Power Requirements (kVA)	11	11	11

Average electron beam power for the 9 MeV linac can be upgraded from 0.9 kW to 3 kW. This will reduce required time for irradiation more than three times.

3. MINILAC E-BEAM SYSTEM

We recently completed work on a portable traveling wave linear accelerator designed for 2 MeV at 1 A of accelerated current. This linac was later incorporated into MINILAC™ electron beam system with an average beam power of 10 kW, jointly developed by RPC and SRC [5]. This system is presently installed at the customer site and reliably operating 24 hours a day.

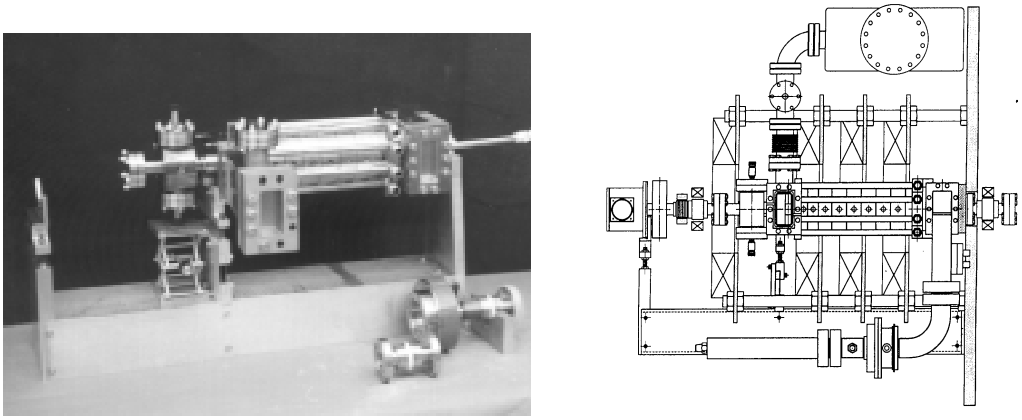

Fig.9 MINILAC™ beam centerline designed for the possibility of both vertical and horizontal operation.

The system operates at the design level with a 71% RF to beam conversion. The operation was commenced within a year and final testing completed within a one month period. All aspects of the system from the modulator, water cooling, controls, monitor point, scanner, vacuum, etc. function in a suitable manner with few changes needed to obtain stable, full performance ratings.

We also developed a variety of linacs for a broad range of applications including systems for medical applications, synchrotron light sources, SLED - cavities and some L-band accelerator sections for sterilization, free electron lasers, etc. Two medical systems, Mobetron and Cyberknife, were developed by SRC together with the spin-off companies Intraop and Accuray, correspondingly.

Fig.3 Mobetron - system for Intraoperative therapy based on portable 12 MeV X-band linac

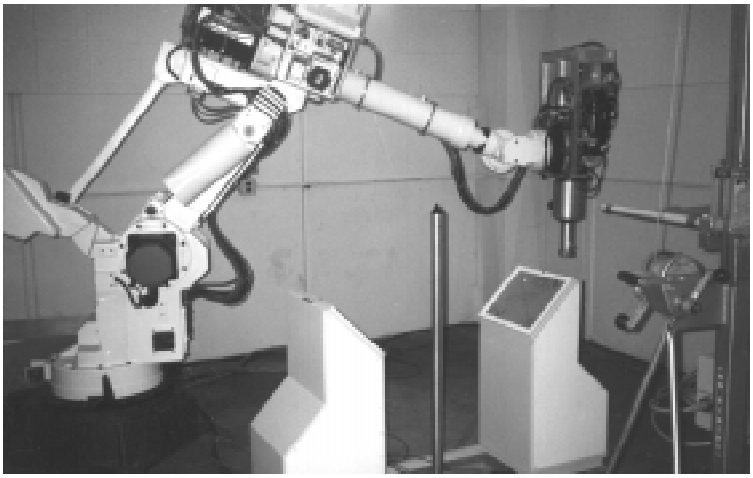

Fig.4 Cyberknife - system for stereotaxic radiosurgery based on portable 6 MeV X-band linac.

4. SYSTEMS UNDER DEVELOPMENT

4.1 Portable X-band systems.

Efficiency of X-band portable linacs for various applications has recently been improved. Advanced design and some improvements to the existing MINAC provided encouraging experimental results using a 1.5 MW magnetron [6].

MINAC-5 and MINAC-8 characteristics are summarized in the following Table 4.

TABLE 4. PARAMETERS OF NEW PORTABLE MINAC ACCELERATORS

PARAMETER	UNITS	MINAC5	MINAC8
Maximum Energy	MeV	6	9*
Maximum Current	mA	110	100
Nominal Energy	MeV	5	7.6
Nominal Current	mA	100	80
Linac RF Length	m	0.4	1
Max.DoseRate@1m	R/min	600	1000
AverageBeamPower	W	520	700
Approx.HeadWeight	kg	20	30

* - Smooth continuous regulation from 4 to 9 MeV

We developed an ultralight electron beam head prototype designed to deliver a 1.2 MeV electron beam at 1 A current in four beams in 12 cm long X-band structure [7]. The goal is to achieve 1 kW average power stored in four beams at 0.001 duty factor and 70 percent beam efficiency. The concept has an extensive list of potential applications, discussed in [7,8].

4.2 High Power Systems

Several system are under development. The parameters of a CW linac CWAC-1 designed for 1 MeV and 10 kW beam. It is the first-time development when a portable linac is to be powered by a CW magnetron. The technology used for this linac design (patent is pending) allows one to use a very low injection voltage (approximately 12 kV) and low gradients to achieve substantial capture and efficiency of the electron beam.

MAGBEAM 10 and MAGBEAM 30 - 10 MeV, 10 and 30 kW systems are under design and their parameters are presented in Table 2. These systems apply advance concepts which will allow us to create the comparatively inexpensive and compact sources with electron beam power adequate for a commercial electron beam curing and other radiation processing.

5. CONCLUSIONS

We have successfully used our 4 MeV linac for radiation processing of composites for armored vehicles. Polymer curing tests have been performed using a MINAC-4 electron beam unit. This highly portable linac delivers between 160 and 200 Watts of electron beam. The electron beam is passed through an aluminum scattering foil and applied to the composite materials up to 0.65 inch thick. Irradiation has been done using two side beam application. Doses between 25 and 200 kGy have been used to obtain cures of various resins. The approach of having an irradiator mounted on a robotic arm or C-arm used for medical linacs can be applied for radiation processing of composites. X-band linacs or the described

above lightweight S-band linacs are the appropriate electron beam sources to be used for electron beam curing of the systems with complex shape and developed surface.

6. REFERENCES

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