LIQUID METAL MHD RESEARCH AND DEVELOPMENT IN ISRAEL

H. BRANOVER

Center for MHD Studies, Ben-Gurion University of the Negev, Beer-Sheva

ABSTRACT. The study of liquid metal MHD in Israel commenced in 1973. Initially it was concentrated mainly on laminar and turbulent flows influenced by external magnetic fields. In 1978 a liquid metal MHD energy conversion program was started. This program was developed at the Center for MHD Studies at Ben-Gurion University in Beer-Sheva, with the participation of specialists from the Technion, the Hebrew University of Jerusalem, Israel Atomic Energy Commission, and others. The program was sponsored initially by the Israel Ministry of Energy and Infrastructure, and later by the Ministry of Industry and Trade. Since 1980, Solmecs, a private commercial company has become a major factor in the development of liquid metal MHD in Israel. From the very beginning the program was based on broad international cooperation. A number of overseas institutions and individuals became participants in the program, particularly Argonne National Laboratory, Purdue University at Calumet, Indiana, the Energy Technology Engineering Center of Rockwell International at Canoga Park, California, Westinghouse R&D Center at Pittsburgh, Pennsylvania, Colorado School of Mines at Denver, Colorado, Nottingham University in England, the Institute de Mecanique at Grenoble, France, and more recently, the Institute for High Temperatures of the Soviet Academy of Science (IVTAN) and some other Soviet research institutes. Through extensive research and evaluation of a number of concepts of liquid metal MHD power generation systems, it was established that the most promising concept, demanding a relatively short period of development, is the gravitational system using heavy metals (lead, lead alloys) as the magneto-hydrodynamic fluid and steam or gases as the thermodynamic fluids. This concept was chosen for further development and industrial application, and the program related to such systems was named the Etgar Program. The main directions of research and development activities have been defined as follows: • investigation of physical phenomena • development of a universal numerical code for parametric studies, optimization and design of the system • material studies • development of engineering components • building and testing of integrated small-scale Etgar type systems • economic evaluation of the system and comparison with convertional technologies • development of a moderate scale industrial demonstration plant. At this time 6 items have been fully implemented and activities on the last item were started.

INTRODUCTION

Israel became involved in systematic magneto-hydrodynamic (MHD) studies in 1973 when the first small research facilities were put into operation at Ben-Gurion University. From the very beginning the Israeli program was confined to liquid metal (LM) MHD studies. The first investigations dealt mainly with LMMHD flow phenomena, but later an energy conversion program was started. Specialists from the Technion in Haifa, the Hebrew University in Jerusalem, Israel Atomic Energy Commission and other institutes participated in this program. However, most of the work was done at the Center for MHD Studies of Ben-Gurion University. The program was sponsored initially by the Israel Ministry of Energy, and later by the Ministry of Industry and Trade. Since 1980, Solmecs, a private commercial company, has become a major factor in elaborating the liquid metal MHD of Israel. A number of institutions and individuals in the USA, England, France and other countries became participants in the program. Recently the Institute for High Temperatures of the Soviet Academy of Sciences (IVTAN) and some other Soviet research institutes also have become involved in this collaboration.

As a result of an extensive research and evaluation of a number of concepts of LMMHD power generation systems, a most promising concept demanding a relatively short period of development was established. This is the gravitational system using heavy metals (lead, lead alloys and others) as the magneto-hydrodynamic fluid, and steam or gases as the thermodynamic fluids [1,2]. This system is now the basis of the Israeli LMMHD research and development program named the "Etgar" program ("Etgar" means "challenge" in Hebrew).

The Etgar program has now reached the stage of upscaling and commercialization. References [3-8] describe much of our work, such as studies of two-phase flows as well as phenomena in Faraday type DC liquid metal MHD generators, the development of a universal computer code (which incorporates a great number of empirical results), material studies, development of engineering components (including DC to AC invertors) and test results of the Etgar-3 integrated pilot plant. This paper concentrates on the results of economic evaluations of the Etgar type cogeneration Liquid Metal MHD power systems in comparison with conventional steam-turbine systems. It is shown that the system has well-established superiority over conventional steam turbine systems, especially in the cogeneration mode and in the power range of up to 20 MW power systems. The advantages stem not only from better performance characteristics, but also from substantial lower capital cost. The results of the economic analysis permit to establish the market potential for the Etgar liquid metal MHD power system.

Besides the development of liquid metal MHD power systems, Israel's program deals with a number of other applications of liquid metal MHD which, however, are beyond the scope of the present paper.

THE ETGAR PROGRAM — CONCEPT, MILESTONES, TIME-TABLE

The principles of operation of an Etgar Liquid Metal MHD energy conversion system are very simple and can be understood from Figure 1. The basic system consists of two vertical pipes (an upcomer and a downcomer) connected at the bottom with a crossover pipe and with a separator joining them at the top. A liquid-gas mixer is located at the bottom of the upcomer and a single phase MHD generator, from which electrical power is extracted, is located in the downcomer or lower crossover pipe. Operation of the system is as follows. A thermodynamic fluid — vapor, steam, gas (or volatile liquid boiled in direct contact with the hot liquid metal) is introduced into the mixer at the bottom of the upcomer at an appropriate temperature and pressure. A two-phase fluid with density lower than that of the liquid metal is created. As the two-phase fluid flows to the separator, the gaseous phase undergoes an expansion from the high pressure in the mixer to the low pressure in the separator, lifting liquid metal. The gaseous phase (thermodynamic working fluid) is removed in the separator (gravitational or cyclone type) and single-phase flow of the liquid metal (LM) returns into the downcomer. The separator has to be designed in such a way that a high portion of the LM kinetic energy is preserved.

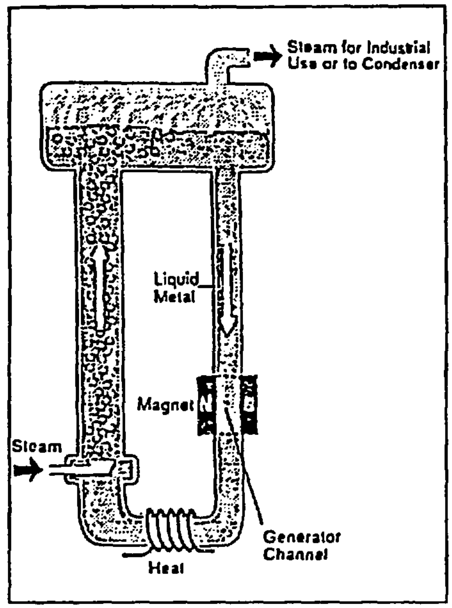

Fig. 1. *Schematic diagram of the Etgar type liquid metal MHD energy conversion system*

The pressure differential that exists between the upcomer and the downcomer due to the density difference causes the LM to circulate in the system; as the single-phase LM downflow crosses the magnetic field in the MHD generator, an electrical potential is generated and power is extracted. The flow rate in the loop self-adjusts to balance the density differential between the upcomer and downcomer with the frictional and acceleration flow losses and the electromagnetic forces acting in the MHD generator. Heavy LM, such as lead, is used for the electrodynamic fluid to maximize the pressure differential (or the expansion ratio of the thermodynamic working fluid) for a given loop height.

Several advantages of the described system stem from the simplicity of its design and ease of control. As will be shown below the installation cost is much lower than that of conventional turbine systems.

Moreover the LMMHD system components can be manufactured by any modern machine shop.

However, the major advantage of the Etgar concept is related to the fact that the LMMHD energy conversion system (ECS) performs a very special type of thermodynamic cycle. The LMMHD cycles differ from the conventional turbine cycle mainly by the expansion process: in the LMMHD system the expansion of the thermodynamic working fluid is nearly isothermal. This unique feature of LMMHD power conversion is due to the intimate contact between the thermodynamic working fluid (e.g., steam) and the LM, leading to a continuous heat transfer from the LM (which has a very high heat capacity relative to the heat capacity of the vapor) to the vapor or gas throughout the expansion process. The direct contact heat transfer in the MHD expansion process leads to two important results:

- it increases the average temperature of energy delivery from the heat source to the cycle, thus increasing the cycle efficiency;
- the isothermal expansion can be considered to be a process with an infinite number of reheat stages, while the additional heat delivery occurs without the need for extra reheaters. This results in substantially higher efficiency of the thermodynamic cycle.

Figure 2 compares the T-S diagrams of superheated Rankine cycles performed by the LMMHD ECS with that of a conventional steam turbine.

The LMMHD energy conversion (EC) technology appears to be especially attractive for cogeneration applications (production of electricity and heat simultaneously) and in particular for industrial cogeneration applications associated with heat sources which can deliver a large fraction of their energy at or above the cycle high temperature (constant temperature heat sources, e.g., solar collectors, fluidized bed combustors, boiling water, nuclear fission reactors, etc.). The LMMHD EC technology can offer a higher electricity-to-thermal (steam and/or heat) energy ratio than conventional cogeneration plants, while using a relatively simple system (without reheaters). The higher electricity generation ability of LMMHD cogeneration plants for a given rate of thermal energy supplied can be a significant economic advance of the plant if the utility is committed to purchase the supplied electricity at a reasonable price.

By bypassing the regenerator fully or partially (recovering the high temperature heat back to the boiler feed water) the electric to thermal ratio can be improved by up to 33% (depending on the cycle pressure difference) for a given power system and capacity; this is not possible in a steam turbine. This advantage is very important, since the industry needs a process with heat changes during the seasons and even during the day. The present conventional technologies can offer a solution to this basic requirement to change the load by designing systems with maximum capacity of process steam. Load reduction can be achieved by reduced electricity production. However, a turbine which works on partial load has a significantly reduced cycle efficiency. This is not the case in the LMMHD technology where the electricity production capacity remains constant while changing the electric to thermal ratio. Moreover, the possibility of reducing simultaneously power capacity and process heat generation exists also in the LMMHD technology. At this partial load, the cycle efficiency increases due to the reduction of both the slip ratio in the two-phase flow and hydraulic friction losses, at lower two-phase and single phase flow rates.

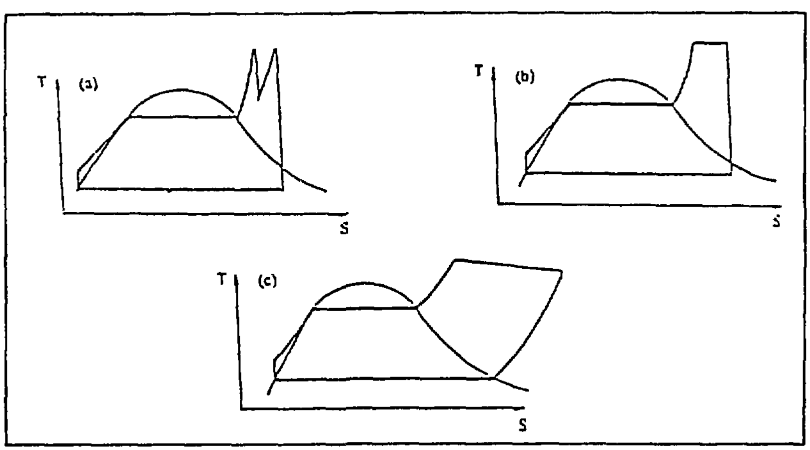

Fig. 2. *T-S diagrams for 3 versions of a Rankine type thermodynamic cycle:*
(a) A Conventional Turbine Cycle with One Reheating Stage;
(b) A Combined LMMHD/Steam Turbine Cycle;
(c) All LMMHD Cycle

Figure 3 presents a scheme of an Etgar system in which the volatile liquid is boiled in direct contact with the hot liquid metal and no separate boiler is needed.

Extensive experimental studies produced an empirical data base which together with data on thermodynamic properties of liquid metals and working fluids enabled the

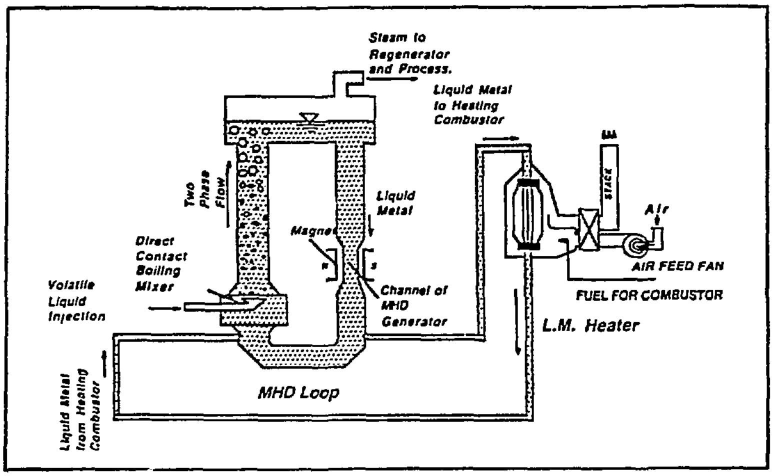

Fig. 3. Etgar facility with direct contact boiling mixer

development of a universal computer code for the design and optimization of Etgar-type LMMHD systems (as well as of LMMHD systems based on concepts different than the Etgar concept).

Two integrated power conversion systems have been built and tested in addition to laboratory scale experiments. The Etgar-3 plant, commissioned in 1985, is the most advanced integrated pilot plant built to date. It employs lead-bismuth alloy and steam and works at temperatures up to 170°C. The smaller ER-4 system works with mercury and steam at the same temperatures as Etgar-3. Several years of testing of the Etgar-3 facility verified a number of predictions regarding the performance of the Etgar type LMMHD energy conversion systems. There have not been any major failures or any material corrosion problems in the Etgar-3 facility which has operated for more than 3000 hours (cumulatively). Detail measurements of Etgar-3 performance characteristics (as well as the smaller system ER-4) demonstrated that the aforementioned universal computer code can be used with confidence for the optimization and design of LMMHD energy conversion systems. Analysis of results from all the aforementioned studies and engineering development of system components indicate that the database and practical experience necessary for entering the commercial stage of the LMMHD power system development has already been accumulated.

The first commercial scale demonstration plant to be built in the framework of the Etgar commercialization program will be the Etgar-5 plant. It will be working with lead as the electrodynamic fluid and steam as the thermodynamic fluid. Steam will be generated initially by a conventional boiler. For a later stage of operation it is envisaged that the steam may be supplied by a fluidized bed oil shale combustor. Provisions will also be made for injecting water directly into the hot lead and thus eliminating the separator boiler. Etgar-5 will operate in the cogeneration mode. Although the specific site on which the Etgar-5 plant will be erected has yet to be identified, it is a strategic decision to have Etgar-5 operating continuously in a real industrial environment. The main technical parameters of the Etgar-5 plant are presented in Table 1. A large team of experts from several countries as well as several engineering companies evaluated the current status of the project and concluded that the existing database and experience are sufficient to undertake the Etgar-5 stage. Figure 4 presents the general schematic diagram of the Etgar-5 plant with all the stated points of the energy conversion process. For illustration purposes it is supposed that the power plant is supplying low pressure steam to a phosphate drying facility.

Table 1. *Etgar-5 cogeneration system parameters*

Cycle high temperature	480°C
Steam temperature at boiler exit	390°C
Steam generator (boiler) mass flow rate	4.9 ton/hr
Cycle high pressure	28 bar
Cycle low pressure	5 bar
Total heat input	3.7 MWth
Electric plant efficiency	8.5%
Net electric power	315 kW

Steam delivery to process:

Saturated steam conditions	5 bar/163°C
Mass flow rate	5 ton/hr

Structure configuration:

Stage No.	Riser Diameter	Pipe Schedue	Riser Height
1	10"	40	17.74 m
2	8"	40S	17.72 m

An extensive R&D program will be implemented in parallel with the construction and testing of the Etgar-5 plant. This program will be related to further upscaling of the technology and development of the next plant Etgar-6 which will be designed for the 3-5 MW power range. The R&D program will consider next generations of Etgar plants as well as plants based on concepts different than Etgar. The time-table and the work plan is presented in Figure 5.

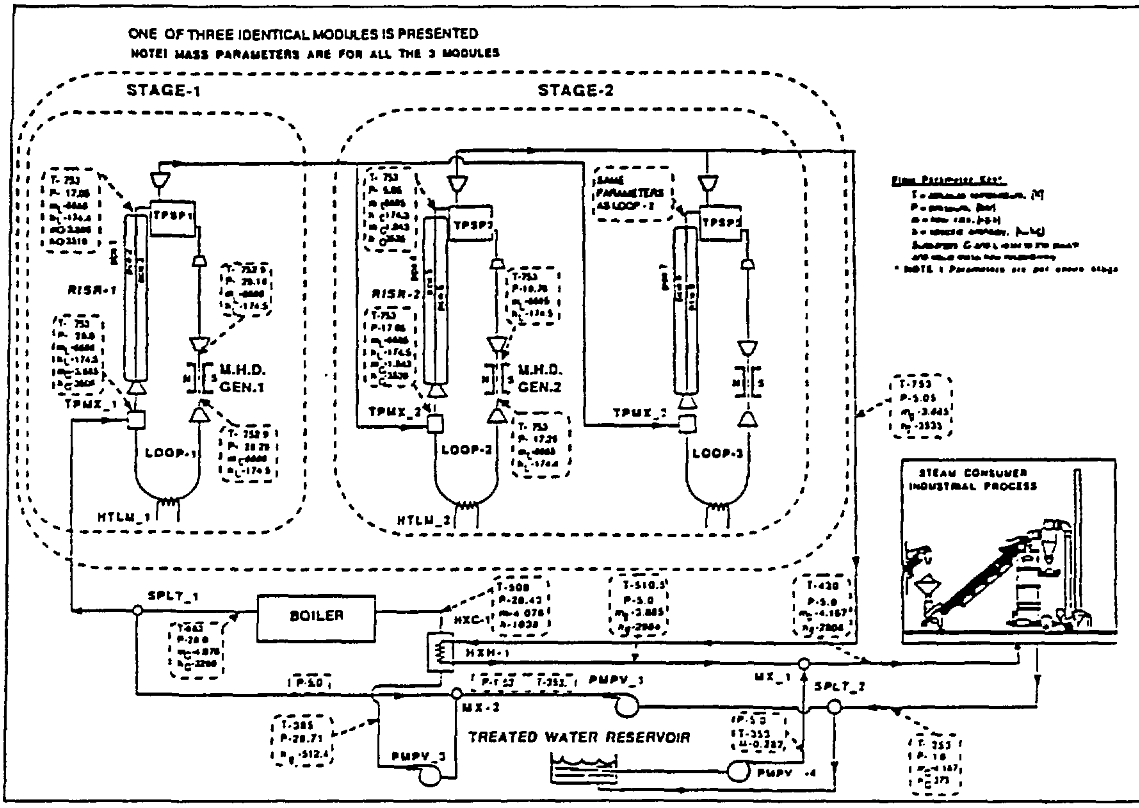

Fig. 4. *Schematic diagram of Etgar-5 demonstration plant*

The development beyond the Etgar-5 stage, namely the design and construction of Etgar-6 plant, will incorporate all the information obtained from operating Etgar-5 and the inputs from the supporting R&D program. This program, which will be conducted in parallel with the development of Etgar-5, will concentrate on further investigation of physical processes of liquid metal MHD power facilities (mainly involving the ability to control two-phase flow characteristics), further parametric studies, component optimization and material engineering. The Etgar-6 cogeneration integrated system (AC net electric power of 5 MW) will be the final development stage, operating under the same optimal parameters as that of the mature industrial Etgar-7 system.

The Etgar-7 mature plant will be designed to utilize different heat sources and will be able to operate in various applications at the 1-20 MW power range. The first mature commercial Etgar-7 plant is expected to be completed in five years from the commencement of development activities. An example of the main parameters of Etgar-7 plant stations for 3.68 MW gross electric output appears in Table 2 (which also contains data for competing turbines). One

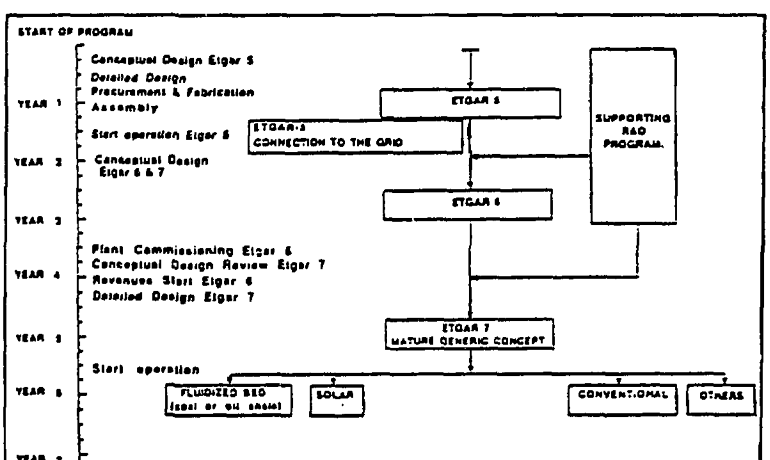

Fig. 5. *Etgar program time-table*

Table 2. *Etgar-7 main parameters as compared with steam turbines*

	Etgar-7		Steam Turbine Isentropic Efficiency 70%	74%	80%
Pressure	Bar	60	63	60	60
Temperature	°C	277	408	480	480
Gross electrical output	kW_e	3668	3315	2960	3200
Net electrical output	kW_e	3429	3000	2715	2950
Heat to industrial processes	kJ/h	56395			
	MWth	15.66	17.8	14.2	14.0
Heat from fuel	MWth	21.1	23.1	18.6	18.6
Steam flow	T/H	24.3	31.7	24.6	24.6
Steam to industrial processes					
@ 236°C	T/H	21.7			
@ 160°C	T/H	23.4	26.6	21.1	20.7
Heat to electrical power ratio	MW_{th}/MW_e	4.6	5.9	5.2	4.7
Fuel flow	kg/h	1912	2096	1688	1688
Fuel flow allocated to process heat	kg/h	1422			
Fuel flow allocated to electric power	kg/h	468	481	400	398
Fuel consumption	gr/kWh	134	145	135	131
Total efficiency	%	90.5	90	91.4	91.0
Electrical efficiency	%	17.4	14.3	15.9	17.2
Installation cost [$/kW]		1339	1793	1920	1905
Electricity cost [cents/kWh]		3.497	4.647	4.985	4.936

parameter not mentioned in the table is the magnetic field strength for the MHD generator. It should be stressed that one of the basic features of the Etgar type MHD facility is that it demands a moderate magnetic field — usually about 0.5 Tesla or even less.

COMPARATIVE ECONOMIC ANALYSIS OF THE ETGAR TECHNOLOGY

During the last two years several economic studies of the Etgar technology as well as surveys of its market potential have been performed. An overall evaluation of the technology from the scientific, engineering and economic points of view has also been performed by a group of international experts. A thorough study of the installed cost, performance characteristics and cost of electricity for a mature Etgar cogeneration system was performed by the United Project Services (UPS) — a leading Israeli engineering company[9]. This study also compared operation parameters of an Etgar type plant with those of steam turbines working in the cogeneration mode. The main results of this investigation performed for a 3.68MW_e plant are given in Tables 2 and 3. It should be stressed that the UPS analysis[9] is based on real price proposals from manufacturers for each component of the system (and not on the basis of some averaged data given in the literature). The numbers presented in Tables 2 and 3 show very convincingly the superiority of the Etgar system over turbines in terms of substantially lower installation and electricity costs. Annual economic projections for a 3.68 MW_e Etgar plant are given in Table 4. These results lead to the conclusion that the payback period for such a plant is about 4 years.

Table 3. *Etgar-7 versus steam turbo-generator. Economic comparison*

	Etgar-7	Steam Turbine Eff. 70%	Steam Turbine Eff. 74%	Steam Turbine Eff. 80%
Service life (year)	30	25	25	25
Availability (hr/year)	7884	7000	7000	7000
Gross electricity production (kW)	3668	3315	2960	3200
Net electricity production (kW)	3429	3000	2715	2950
Installed cost				
Total cost of system ($000)	4911	5944	5684	6096
Cost per kW ($/kW)	1339	1793	1920	1905
Energy cost:				
when fully allocated to electricity (cents/kWh);	8.046	10.368	10.067	9.548
partial allocation to electricity after cleaning steam cost (cents/kWh)	3.497	4.647	4.985	4.936

The following Table provides annual economic projection data for a 3.68 MW_e Etgar-7 plant.

Table 4. *Etgar-7 annual economic projections*

	US($000)
Steam income 23.4 ton/hr x 7880 hr x $8.2/ton	1513
Electricity income 3668 kWh x 7880 hr x $0.06/kW	1735
Expected income	3248
Operational expenses	(1849)
Operational profit	1399
Levelized capital cost (at 9% interest rate)	(478)
Expected profit	921

Using the economic data for Etgar cogeneration systems, a market study was performed by the Arthur D. Little Company, Inc., in Boston[10]. This study takes into consideration the substantially lower installation cost of an Etgar system with power up to 20 MW as compared to steam turbine systems. It also reflects the fact that the Etgar technology has a very flexible thermal to electrical power ratio and other unique features. The *Dunn and Bradstreet* study[11] states that about 80% of all cogeneration units installed in the USA are concentrated in plants producing below 20 MW_e.

The principal conclusions of Arthur D. Little's[10] study are:

- LMMHD EC is best matched (in scale and thermal/electric power ratio) to the industrial/commercial (I/C) cogeneration market. It substantially supersedes competing technologies both in performance and in economic characteristics;
- Because of lower installation costs, reliability and simplicity, the LMMHD technology is highly competitive and can expect market penetration in industrial cogeneration markets for plants of up to 20 MW_e. The forecasted penetration by the end of the decade is between 25%-33% of the market for plants of up to 20 MW_e. This forecast leads to annual installations of LMMHD plants below 20 MW_e in the range of $125 million to $165 million for the U.S. market alone. The worldwide market is estimated to be at least three times that of the United States, i.e., $375 million to $495 million, and it is anticipated that due to the simplicity of the technology, much higher penetration rates will be achieved in countries which are not producers of turbines.

CONCLUSIONS

The LMMHD technology reached the stage of commercialization and, according to a very thorough technical and economic evaluation, is highly advantageous and competitive. Its penetration into the market is feasible by the middle of the 90's. The first system to be commercialized will be the Etgar type cogeneration system. It is expected that the penetration process will be followed by modification of the technology to expand substantially the areas and scale of its application.

ACKNOWLEDGEMENT

This work was sponsored by Solmecs (Israel) Ltd. The author is thankful to all researchers of the Center for MHD Studies of Ben-Gurion University who participated in the studies presented in this paper.

REFERENCES

1. Branover, H: "MHD Power Generation Program of the State of Israel," In Proceedings of the 23rd Symposium on Engineering Aspects of Magnetohydrodynamics, Somerset, PA, pp. 44-60, 1986.
2. Branover, H and El-Boher, A: "The "Etgar" Program for the Development of Liquid Metal MHD Conversion Technology," In Proceedings of the 10th International Conference on Magnetohydrodynamic Electrical Power Generation, Vol. 1, Tiruchirapalli, India, pp. 1.19-1.26, 1989.
3. Branover, H: "Liquid Metal MHD Energy Conversion Technology," submitted to Perspectives in Energy, Moscow, International Energy Club.
4. Unger, Y, El-Boher, A, Lesin, S, Ritz, DJ and Branover, H: "Experimental Studies of Two-Phase Liquid Metal Gas Flow in Vertical Pipes," Proceedings of the 21st Intersociety Energy Conversion Engineering Conference, Vol. 1, San Diego, pp. 645-650, August 1986.
5. Unger, Y, El-Boher, A, Lesin, S, and Branover, H: "Two-Phase Liquid Metal-Gas Flows in Vertical Pipes," Proceedings of the 9th International Conference on Magnetohydrodynamic Electrical Power Generation, Vol. 2, Tsukuba, pp. 743-752, November 1986.
6. El-Boher, A: "Investigation of a Magnetohydrodynamic Generator at Different Two-Phase Flow Patterns," Ph.D. Thesis (in Hebrew), Ben-Gurion University, Mech. Eng. Dept., 1987.
7. "LMMHD Power Conversion Technology Status and Development Program" Solmecs (Israel) Ltd.—Center for MHD Studies, Ben-Gurion University, 1990.

8. Sukoriansky, S and Talmage, G: "A Computer Package for Analysis of Liquid Metal MHD Power Conversion Systems," Proc. of International Specialist Meeting on Mathematical Modeling of MHD Power Stations, Eindhoven University of Technology, Eindhoven, The Netherlands, April 28-29, 1986.

9. United Project Services, Ltd., "MHD Cogeneration Power Plant — Etgar-7", Techno-Economic Study Report, Beer Sheva, Israel, September 1990.

10. Arthur D. Little, Inc., "The United States Cogeneration Market Relative to Solmecs LMMHD Technology," prepared for Solmecs (Israel) Ltd. by EJ Cook and DE Kleinschmidt, 1989.