Solar photovoltaic energy products: from semiconductor physics to advanced energy technology

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Physics to industry

There is a long road to be traversed between the original enunciation of a fundamental physical principle and the final realization of an application of that physical principle in the form of an industrial product useful to society. The bridging of this gap between physics and industry consists of a series of innovative steps ranging from perfecting laboratory scale processes to converting those processes and associated techniques through upscaled, standardized production methods in a pilot plant, to large volume, cost-effective production on a commercially viable basis. This also includes the development of appropriate production equipment as needed. It is the collection of such knowledge, skills and equipment which constitutes the development of a complete technology package by which the physical principle is converted into an industrial technology to make a commercial product.

This paper presents such a case of 'Bridging the Gap' between semiconductor physics and the solar photovoltaic (SPV) industry. The case takes the form of the actual history of development and commercialization of SPV technology by our public sector company, Central Electronics Limited (CEL). CEL is today not only the nation's pioneer and largest manufacturer by far in the developing countries but the 5th largest manufacturer of single crystal silicon solar cells in the world.

Historical evolution of photovoltaics (PV)

The Photovoltaic (PV) Effect is the appearance of a voltage across a p–n junction or a rectifying contact as a result of its exposure to light. The light produces electron hole pairs. These pairs are separated by the inherent electric field across such junctions which causes a current to flow in the external circuit through the leads attached to the two sides of the junction.

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The Photovoltaic Effect was first discovered in an electrochemical cell by Becquerel[1] in 1839. The first solid state photovoltaic cell of selenium was made in 1877 by Adams and Day[2]. Although silicon solar cells based on natural (non-doped) junctions were made in 1941 (refs. 3, 4), it was only in 1954, that the first diffused p–n junction silicon solar cell was made by Pearson[5] and his group at Bell Telephone Laboratories, USA. It is that Pearson Cell which forms the basic building block of present-day solar photovoltaic energy generating systems.

SPV systems were first used commercially in 1957 as 'solar batteries' to power man-made earth satellites and this was the main application of solar cells till the mid-70's. However, it was the so-called 'oil crisis' of 1973 which spurred the development of technology for making solar cells, modules and complete SPV systems for *terrestrial applications*.

Solar PV systems are widely used to power various systems – both rural and industrial. Solar photovoltaic energy sources produce DC electricity directly from solar energy; they are modular in nature and their maintenance requirements are minimal; they are also absolutely non-polluting. Unlike other sources of electricity, the cost per unit of electrical energy generated does not depend drastically on the capacity of the photovoltaic energy generating unit installed. Therefore, small stand-alone SPV sources are just as viable economically as large and centralized ones, even at the present level of technology. All these advantages make solar photovoltaic energy sources eminently suitable for use in places where electricity is not available from conventional sources such as hydro, thermal or nuclear power generators and where diesel generators or electrochemical cells are not economical or feasible to use.

Single crystalline silicon technology is well understood and is mature due to its preponderant use in microelectronics. Hence, it is the principal raw material for making terrestrial solar cells as compared to other photoconductive semiconducting materials such as gallium arsenide.

The silicon PV chain

The silicon PV chain starting from the initial raw material polysilicon to the final SPV system is depicted in

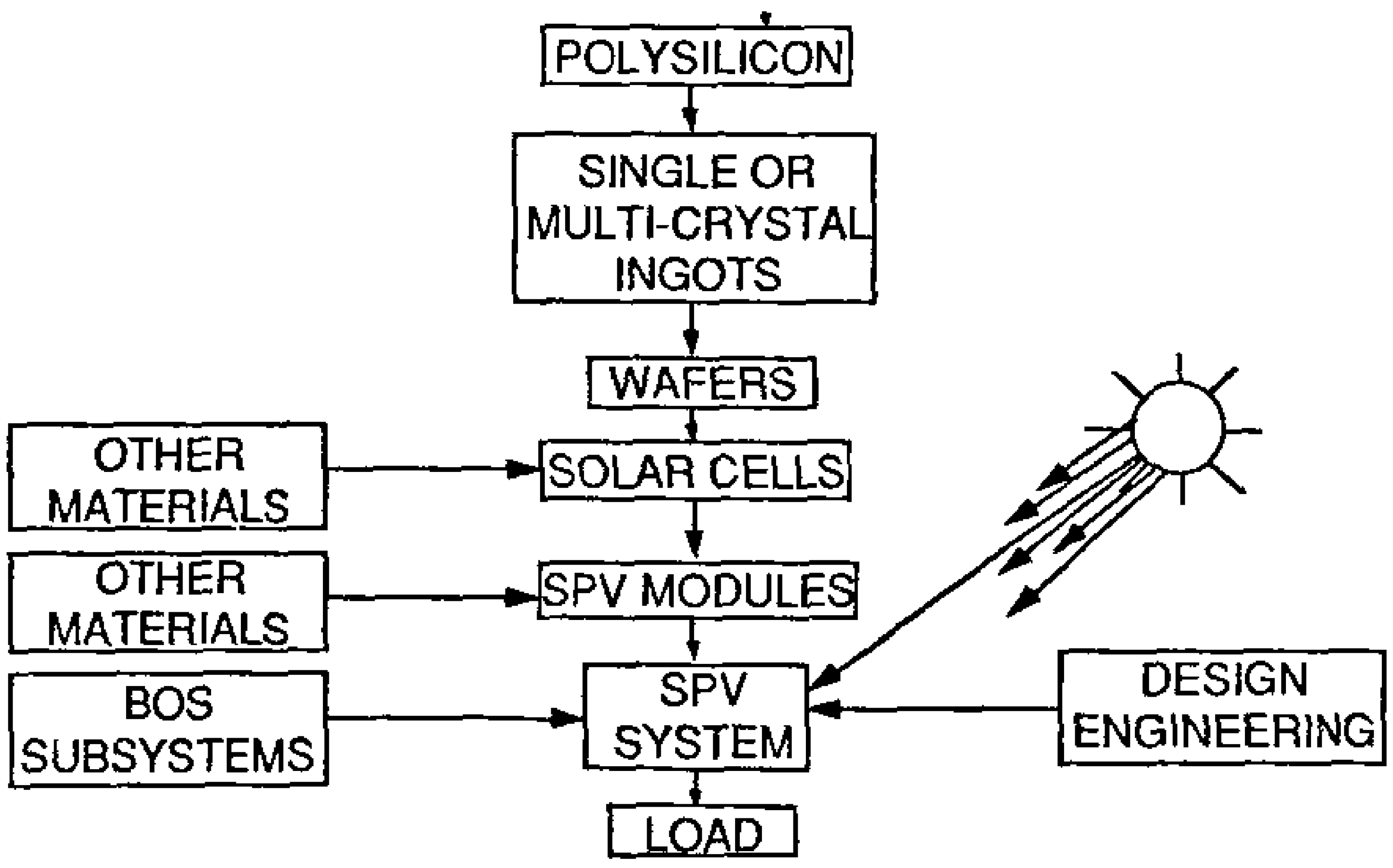


Figure 1. Schematic of silicon PV chain.

Figure 1. Polycrystalline silicon nuggets are the starting point in the PV chain. These are melted in a furnace and grown into single crystalline ingots. Such ingots are commercially grown by the standard Czochralski method upto a diameter of 100–150 mm. Then silicon wafers (thickness 200 to 400 microns) are sliced out of the ingots either by diamond impregnated internal diameter (ID) cutters or through multiple wire saws. The wafers are converted into solar cells through appropriate process technology using materials such as special chemicals, dopant elements e.g. phosphorus and boron and special conducting pastes of silver and aluminium compositions. These processes are drawn from the now well-known semiconductor device fabrication process, since the silicon solar cell is nothing but a large area semiconductor diode. A number of these cells are then interconnected and made into modules by means of basically a lamination process. This process involves the use (apart from the solar cells themselves) of other specialized materials such as tough tempered glass, soft polyester materials, metal frames and a junction box for extracting the electrical power. These SPV modules are the starting point for configuring a complete SPV system appropriate to a specific application. The final engineering of an SPV energy system is based on site and load-specific design including use of special computer software developed for that purpose. All the sub-systems other than the modules and the load (e.g. batteries, charge controllers/inverters) are termed the '*Balance of* the total Solar Photovoltaic *System*' (BOS).

The techno-economic performance of a solar cell or module is measured by its conversion efficiency (η). This is the percentage of the incident solar light energy which is converted by the cell/module into electrical energy. Today, n^+–p junction circular silicon solar cells of 100 mm diameter or square cross-section cells of 100 mm side have efficiencies in the range of 11%–14% in commercial volume production. The major factor presently preventing large-scale commercial exploitation of these power-generating devices is their high initial cost. Increase in the conversion efficiency has been recongnized as one of the key factors which would bring down the cost of photovoltaic power generation. To this end, researchers in laboratories and companies around the world are looking critically at the various loss mechanisms and attempting technological innovations to overcome the losses so as to approach the theoretical conversion efficiency limit of around 30% of n^+–p junction cells. In recent years, hand-made cells in the laboratory using hyperpure silicon wafers have shown efficiencies of 18%–19% for cells of 70 mm × 70 mm (45–50 cm^2)[6] and as high as 24% for small size cells (20 mm × 20 mm corresponding to 4 cm^2)[7]. The challenge is to achieve these higher efficiencies as *average* efficiencies of thousands of large area (100 mm × 100 mm) cells per day in commercial production in industrial plants and that too with commercial-grade CZ silicon wafers as the starting raw material.

SPV in India

Until 1975, activity in the field of SPV in India consisted only of R and D on solar cells in a few national laboratories. Development activity was directed only towards laboratory-scale solar cell fabrication, mainly oriented towards possible future space applications.

SPV in CEL

The activity at CEL in the area of solar photovoltaics extending over a decade and half, can be broadly broken up into the following macro-milestones:

1975–1980	:	R & D phase
1981–1985	:	Pilot plant operation
1986–1991	:	Industrial-scale technology proving and semi-commercial operations
1991 onwards	:	Commercial operation.

The development of solar cells for terrestrial applications was initiated at CEL following Government's decision, in 1975, to mount concerted efforts in this high-technology area. CEL has carried out extensive in-house R & D work spanning a decade for developing the complete technology for the manufacture of silicon solar cells and modules and designing, engineering and operating a pilot plant for production of such cells and modules based on the process technology and production engineering so developed. The activity also includes the development of a whole range of SPV systems and undertaking large-volume commercial production, supply, field installation and commissioning of such systems. Starting with processing of 38 mm diameter silicon wafers using vacuum metallization in 1978, CEL went through an evolu-

Table 1. Milestones of cell/module process technology development at CEL

Processing of 1" diameter solar cells	1977
First SPV module with aluminium substrate	1977
Liquid encapsulation of cells into modules	1977
Vacuum metallization of cells	1977
Processing of 2" diameter solar cells	1978
Processing of 3" diameter solar cells	1980
Introduction of expansion loop in cell interconnection	1981
Use of tempered glass in module instead of plate glass	1981
Introduction of glass substrate instead of aluminium for intrinsically safe modules	1982
Screen-printed metallization of cells instead of vacuum metallization	1983
Processing of 4" diameter solar cells	1984
First foldable module for expedition to Mount Everest	1984
Use of low-iron tempered glass for supertrate	1986
Tedlar–aluminium–tedlar substrate instead of aluminium	1986
Air-firing of cells after metallization	1988
Sirtl etch for edge isolation	1989
Processing of 4" pseudosquare solar cells	1989
Lead attachment to cells using automatic tabbing machine	1991
Automated chemical processing station	1993

tionary development process in terms of both different sizes of cells and the whole range of process technology for making them. The milestones of development of solar cells and modules showing the evolution of the process and production technology at CEL is given in Table 1.

Solar cell process technology

The solar cell production process flow chart is shown in Figure 2. The process flow chart corresponds to the Screen Printed Technology (SPT) of making silicon solar cells, which is the dominant technology currently in use the world over and also the technology developed and in commercial use at CEL. A perspective of CEL's modern solar cell process area is shown in Figure 3. The individual process steps in the SPT are as follows:

Surface preparation

The raw silicon wafers sometimes have oil or grease on their surface, due to adhesion of the cutting coolant used at the time the wafers are sliced out of the silicon ingots. Therefore, it is essential to prepare the silicon surface properly for subsequent polishing and texturization by cleaning its surface with suitable non-ionic detergents.

Chemical polishing and texturization

The raw silicon wafers also have saw marks which are likely to affect the performance of the solar cells made from such wafers. So, these saw marks need to be removed. This is done by alkaline polishing of the wafers. Further, in order to absorb more incident light, the polished wafers are subjected to texturization by preferential etching with low concentration alkaline solutions.

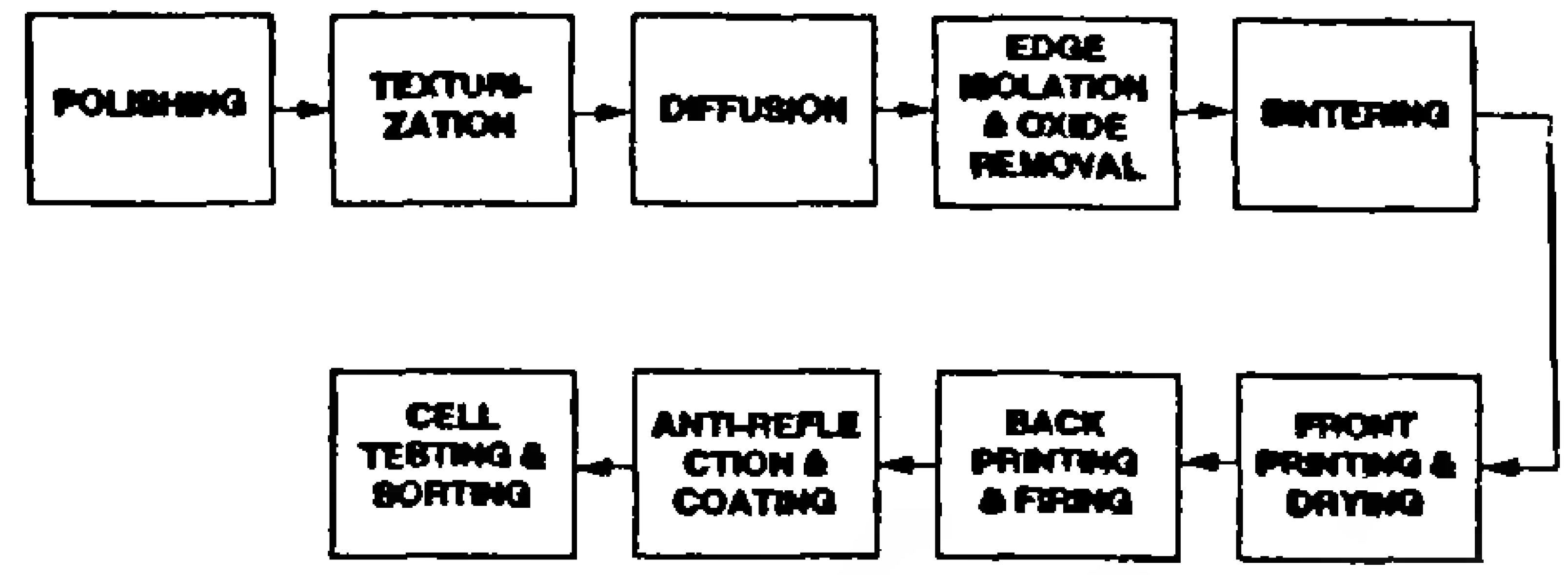


Figure 2. Solar cell process flow chart

Figure 3. A perspective view of CEL's modern solar cell process area

Figure 4. Indigenous automated chemical station

All these chemical process steps are now being carried out using an indigenously designed and fabricated automated chemical station. The chemical station has been designed and fabricated in association with the Bhabha Atomic Research Centre (BARC), Bombay (see Figure 4).

Diffusion

This is the process step in which the n–p junction is formed on the silicon substrate. This process is carried out using $POCl_3$ and N_2 and O_2 gases in a semi-automated diffusion furnace incorporating a microprocessor-based gas control and sequencing system.

Edge isolation

This process step is for the isolation of the junction at the periphery of the diffused silicon wafers. It is achieved either by chemical etching, plasma etching or laser scribing.

Back Surface Field

One of the limiting parameters of solar cell performance is the open circuit voltage which is limited due to the particular method of junction formation. This parameter (*i.e.* open circuit voltage) can be further enhanced by introducing another heavily doped p–type layer popularly known as back surface field. Screen-printed aluminium metallization is undertaken on the back of the wafer as the key step in this process. The introduction of the BSF enhances the overall efficiency of the solar cell.

Screen printing

For providing the contacts for carrier collection and interconnects both sides of the silicon, suitable conducting pastes are screen-printed and fired. This step is carried out by two semi-automatic integrated screen printers – one for screen printing the front surface of the cells and the second for printing the rear surface of the cells.

Anti Reflection Coating

To enhance the short circuit current of the solar cells, and hence their power output and efficiency, the reflection from the top surface should be reduced. This can be achieved by having a suitable Anti Reflection Coating (ARC) on the top surface. There are several techniques for applying such a thin ARC e.g. vacuum evaporation, plasma or spray pyrolysis. The most suitable technique for volume production is spray pyrolysis using suitable organo-metallic compounds.

Solar cell testing

The solar cells are then tested and sorted according to their current ranges, using a computer controlled automatic cell tester and sorter.

SPV module

Although solar cells are the basic building blocks of SPV power generating systems, it is the SPV modules and not the solar cell, with which system designers work. The current/power output of a single solar cell is too low to run most electrical appliances. So, several cells have to be interconnected to produce operationally useable power. In addition, the thin solar cells are fragile and so have to be protected from the environment. Thus a suitably interconnected combination of solar cells, when sealed hermetically with a transparent front glass cover, forms an SPV module. These modules can, in turn, again be suitably interconnected in series and/or parallel combinations and mounted on a metal frame structure to form an SPV panel. An aggregate of SPV panels in the field forms an SPV array. In respect of power levels, a typical standard module made of 36 nos. of 4" dia. circular cells will give a power output of 38–42 W whereas, a module made of 36 nos. of 4" pseudosquare cells will give around 45–50 W. The power and voltage levels of panels and array are dependent upon the specific system design and may, in practice, range from tens of watts to several hundred or thousands of watts of power and from a few volts to several hundreds of volts. Electricity generation from the SPV power source is totally modular in nature, and the SPV power capacity and system voltages can be tailored to meet the requirements of the user.

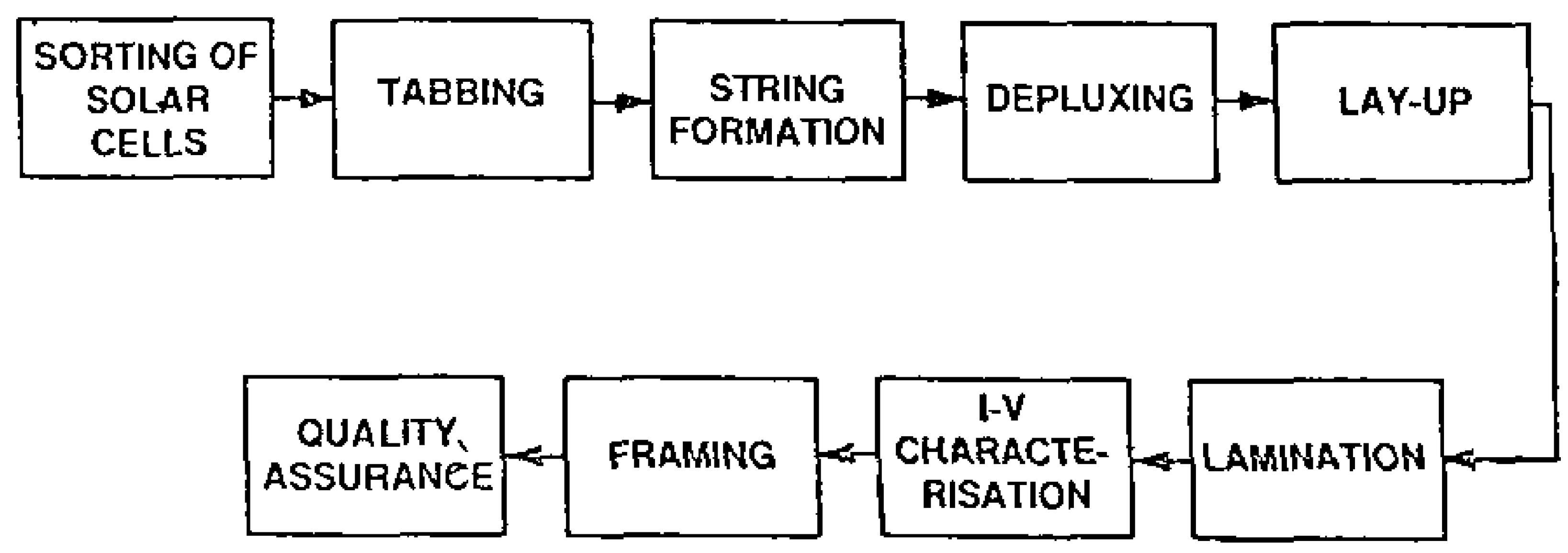


Figure 5. Moduling process flow chart.

Module manufacturing process

The solar cell moduling process flow chart is shown in Figure 5. The individual process steps are as follows:

Lead attachment and stringing

Leads are attached to each solar cell by a soldering process. The lead attachment is done either manually or through a semi-automatic tabbing machine. After lead attachment, a definite number of cells are interconnected in series to form a string of solar cells in a defined pattern to give a sizeable output power. The stringing or cell interconnecting operation is also performed by a simple soldering process. Automatic/semi-automatic equipment are also available for performing these operations. An automatic tabbing machine in CEL's moduling line is shown in Figure 6.

Figure 6. Tabbing machine for soldering leads to cells.

Lay up and encapsulation

The string of solar cells is then chemically cleaned and placed between a sheet of a special soft polymer called ethyl vinyl acetate (EVA) and a sheet of poly vinyl fluoride (PVF) which act as encapsulant substrate for the strings. A sheet of high transmission toughened glass is used as the substrate. The complete lay-up is then put in an encapsulating equipment called a laminator in which it is subjected to a specific time–temperature curing cycle to form the laminated module. While so far the lamination was being carried out using imported machines, indigenous laminators using state-of-the-art features including microprocessor control have now been got fabricated at a much lower price for carrying out this production step in CEL.

I. V. characterization

The laminated module is then tested in a sun simulator in which the module is exposed to a uniform illumination simulating the sun's insolation on a standard midday (i.e. normally designated as 'one sun' i.e. 100 mW/cm^2). Through electrodes attached to the module, the voltage across the module (*V*) and the current from it (*I*) are measured at different load conditions from 'open-circuit' (OC) condition to the 'short-circuit' (SC) condition and the complete I–V curve for each module is plotted automatically using a PC. Each such I–V curve is stored in the computer memory after suitably tagging it with the module number and other batch data. I–V characteristics of a typical module are shown in Figure 7.

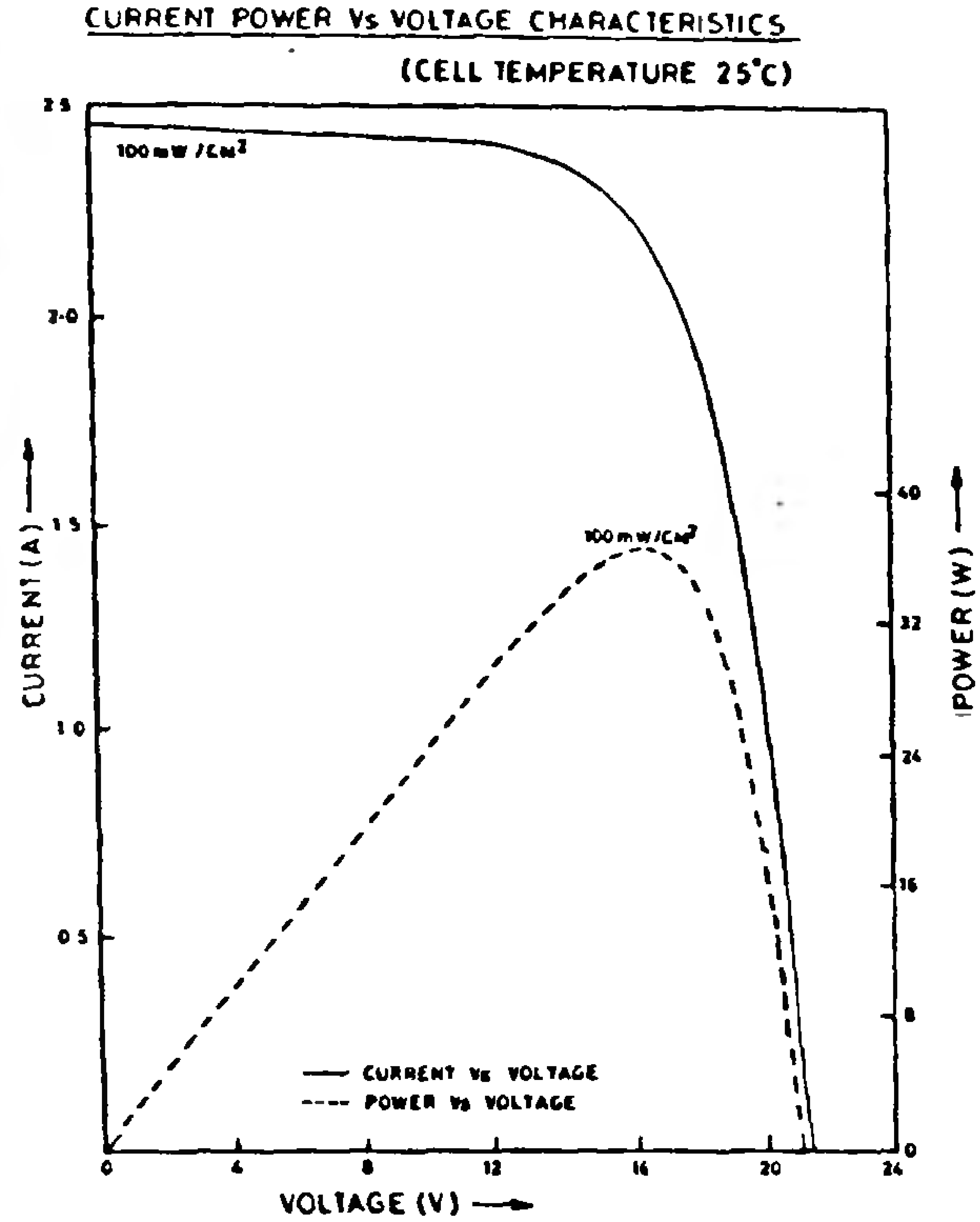
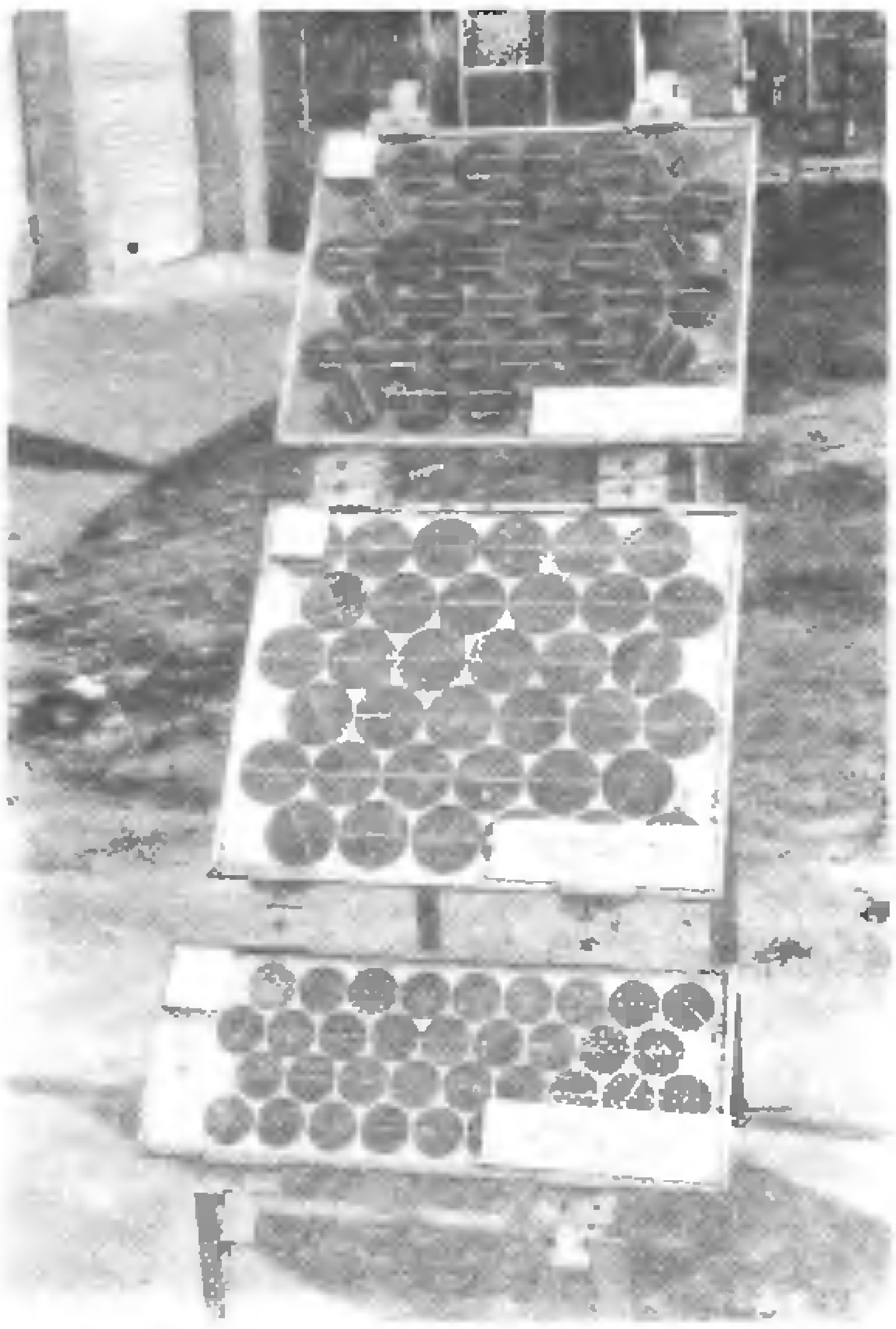


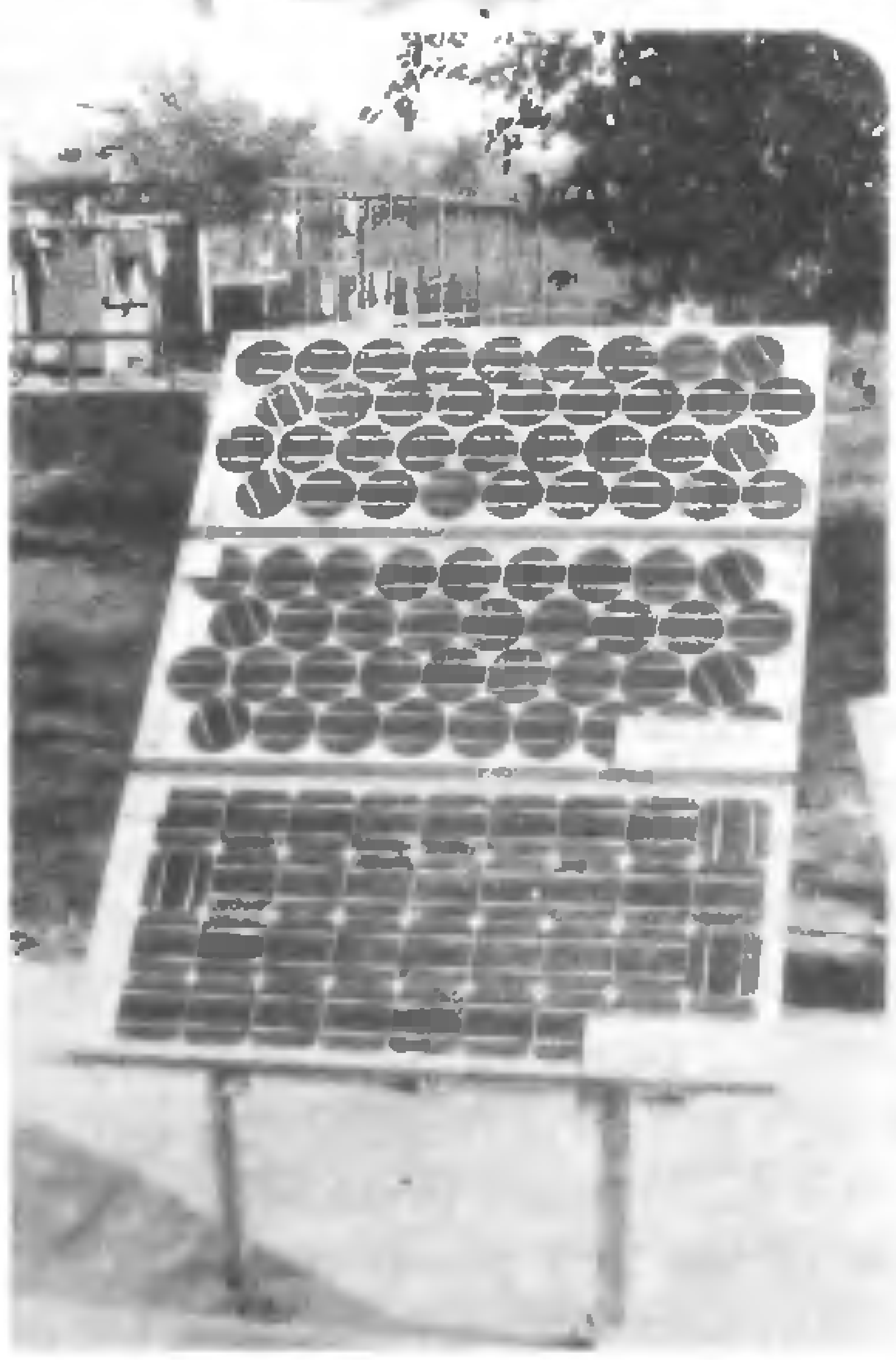
Figure 7. I–V characteristics of a typical module (36 No., 4" circular cells)

Figure 8. Hot water immersion test

Framing and termination

The encapsulated module is framed using aluminium channels of special design to protect the module from mechanical damage, and for mounting it on suitable structures to form a panel. A nylon terminal box is then fixed to provide electrical terminals to extract electrical current from the module.





Quality assurance

A statistically selected number of modules from each production batch are then subjected to a number of quality assurance tests as also environmental tests such as hot water immersion test, hot/cold chamber tests, heat cycle tests, etc. Figure 8 shows the hot water immersion test equipment. The modules are now ready for use as a power generating source either individually or formed into a 'panel' or an 'array' depending upon the specific system design requirements.

The milestones of development of different types of modules keeping pace with the corresponding cell/module process technology milestones are given in Table 2.

Some of the typical modules from this product range are shown in Figures 9–11. The ONGC module is a pioneering instrinsically safe double glass module developed specifically for operation in explosion-prone environments such as on the off-shore, oil production platforms of the Oil and Natural Gas Commission (ONGC). These modules have also been certified to be intrinsically safe in Gr. I, Gr. IIA and Gr. IIB atmosphere hazardous area, by the Central Mining Research Station (CMRS), Dhanbad and accepted by the international insurers, Lloyds of UK. These are the first modules in the world with such certification.

As a result of all this technology development, CEL has presently the following types of modules in its regular production range:

	Type of module	Power output
a)	36 nos. of 4" circular cell module	38–42 W
b)	36 nos. of 4" pseudosquare cell module	45–50 W
c)	36 nos. of half circular cells of 4"dia.	10–14 W (8 V)
d)	36 nos. of half cells of 4" circular/ pseudosquare	10–20 W (16 V)
e)	Lantern modules – using 1/3, 1/2, 1/4 of 4" circular/pseudosquare cells	10 W (8 V/16 V)
f)	Lightweight foldable manpack module	24 W (16 V)
g)	Lightweight 'book case' type foldable module	14 W (14.5 V)
h)	Radio/tape-recorder module – 18 nos. of cut cells	3 W (8 V)

Solar photovoltaic (SPV) systems

The energy generated from the solar cell/module can be usefully harnessed to meet any specific load requirement through a properly configured SPV power system

Figures 9, 10 and 11 Different types of modules in the evolution of the technology

Table 2. Milestones of development of modules at CEL

First module of 1" diameter solar cells	1977
First module of 2" diameter solar cells	1978
First module of 3" diameter solar cells	1980
Intrinsically safe, double glass, stainless steel frame module for off-shore platforms of ONGC	1982
First module of 4" diameter solar cells	1984
First module using lamination technology	1986
First module of 4" pseudosquare solar cells	1989
High voltage module for solar PV power plants	1992
Foldable, light weight, polymer encapsulant defence modules to operate from − 30°C to + 55°C	1993
Lantern module	1993

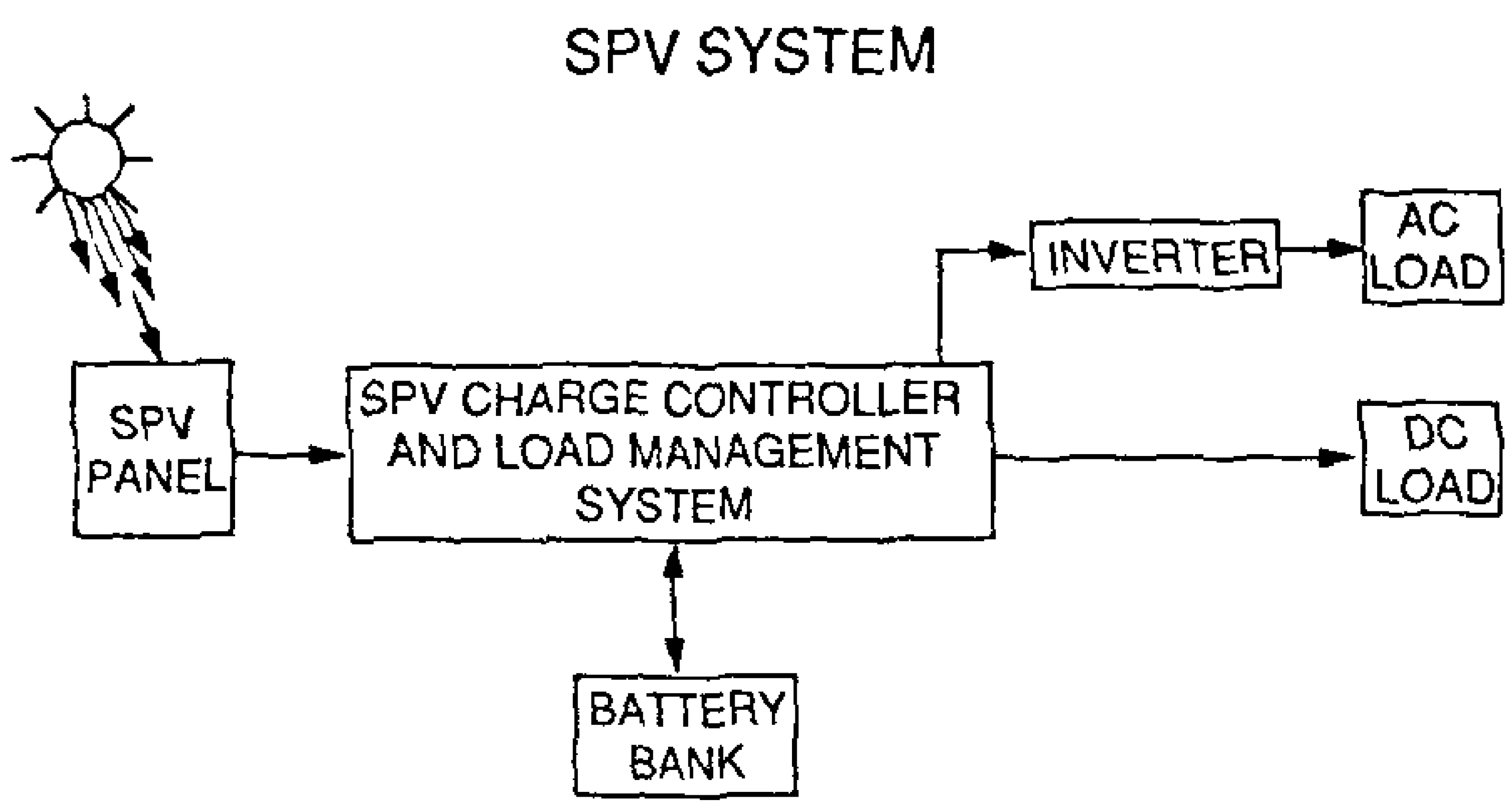


Figure 12. A simple schematic of an SPV system.

Table 3. Milestones of SPV systems development at CEL

SPV operated radio set in Jammu and Kashmir	1978
SPV irrigation water pumping system installed at Kalyani, West Bengal	1979
SPV pumping system for drinking water near Jaipur	1980
SPV community lighting systems installed at SOS children's village Leh, Ladakh, J and K	1980
SPV community television system installed at Kalyani, West Bengal	1980
Special SPV power pack for the first Indian scientific expedition to Antartica	1981
First SPV power system for unmanned offshore oil-well platform of ONGC	1982
SPV operated diesel dispensing pump	1982
Export of SPV water pumping and other systems	1983
First SPV powered stand-alone street lighting systems in Salojipalli, Andhra Pradesh	1983
SPV foldable modules for Everest-84 expedition	1984
SPV systems for direct reception community TV sets of Doordarshan	1985
SPV system for cathodic (anti-corrosion) protection of oil pipelines	1985
SPV system for vaccine refrigeration in village health centres	1985
Design and supply of first SPV system for very low power unmanned TV transmitters (VLPT) and TV Receive only (from Insat) (TVRO) terminals of Doordarshan	1986
Supply of SPV power system for weather monitoring, lighting and entertainment at an avalanche study station at Rohtang pass (alt: 3600 m/12000 ft.) in the Himalayas	1987
SPV powered lighting and television system for army camp at Siachin in the Himalayas (alt: 3600–5500 m/12000–18000 ft)	1987
Supply of first 2 kWP SPV village power pack	1987
SPV system for warning signals at unmanned railway level crossings	1988
SPV rural deepwell water pumping systems for national drinking water mission	1989
SPV power systems for rural telecommunication transmission and switching equipment	1989
Supply and installation of SPV systems in village Hitam-ulu, Sumatra, Indonesia	1990
SPV lighting systems for adult education under National Literacy Mission	1990
Supply and installation of 6 kWP power plant at Kariawali village in Uttar Pradesh	1990
Supply and installation of Asia's first 100 kW SPV power plant at Kalyanpur village near Aligarh, UP	1992
10 kW power generator for M. S. Swaminathan Foundation at Taramani, Madras	1993
Supply of foldable lightweight SPV modules for powering manpack communication equipment for the defence services to operate from − 30°C to + 55°C	1993

consisting of the SPV modules/panels/arrays and other Balance of System (BoS) components such as battery bank, charge controller, inverter and loads such as pumps, lamps, vaccine refrigerators, TV sets, radio communication equipment, Very Low Power TV transmitters etc. A simple schematic of a typical SPV power system is shown in Figure 12. The SPV panel generates DC electricity from the sunlight incident on it. Where the SPV system is to operate during the daytime e.g. a solar water pump, the electricity generated by the panels can be directly used to run the DC pump. On the other hand, where the application is at night, such as powering a light, the electricity generated during daylight hours is stored in a battery through appropriate charge regulating electronic equipment (charge controller) and the power is drawn off the battery at night. The DC power generated can directly be used to run DC load devices. If the load is an AC device, the DC power generated by the panels (or from the battery bank) is converted into AC power of the desired phases (single or three-phase) and frequency (normally 50 Hz), through an inverter and used to power the load/equipment.

SPV systems development at CEL

The design of SPV systems are load and location-specific. SPV power systems are custom-designed for a specific application at a particular geographical location, by taking into account both the intensity and diurnal/seasonal variation of solar insolation at that place. The total SPV panel/array capacity (in watts or kilowatts) and battery capacity (in ampere-hours) are accordingly chosen to meet the total load current, duration of daily use and the above mentioned solar insolation data. Automatic switching 'ON' and 'OFF' of the power from the SPV system to the load (say lights during night time) is also incorporated in the system design to restrict the usage of the SPV power to the exact duration of power requirement. This is to save the life of the system, particularly of the batteries and electronic BoS. Development of appropriate SPV systems to meet different applications and user needs is a primary requirement for wider promotion of the market for SPV power systems. Therefore, parallel to the development of the process technology to manufacture cells and modules, CEL has put in a major effort of development-cum-manufacture-cum-installation and commissioning of a range of SPV energy systems. CEL has continuously been developing a variety of SPV application systems, subjecting them to extensive field testing and then obtaining user acceptance. Thereafter, these systems are produced and supplied against user demands. Indeed the systems constitute the total technology because it is through such systems that solar electricity is actually applied to meet social and economic needs.

CEL has developed a computer software package for designing site and load-specific, stand-alone, SPV systems. The software enables the drawing up of a complete system specification based on site information such as the lattitude and longitude, solar insolation and load parameters including the duration of daily usage as also provision of battery storage for a specified number of 'successive sunless days'. The system design then includes the selection of an appropriate module type (using circular cells or pseudosquare cells for e.g.) for use in the total SPV panels/arrays for the system. For this reason, a close interconnection may be perceived between the system milestones and the module product development milestones.

The milestones of such SPV systems development and introduction into the SPV market by CEL is given in Table 3.

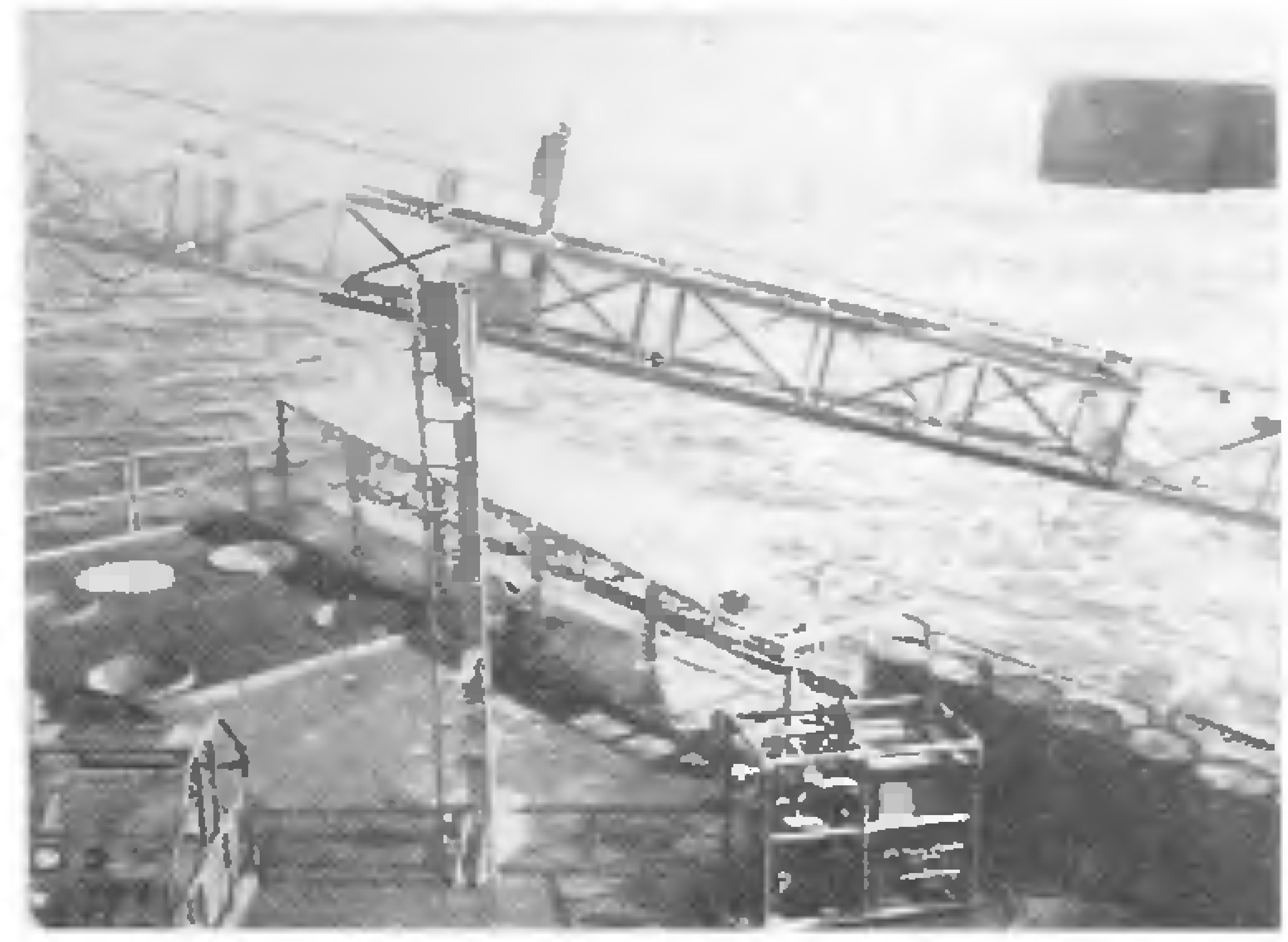


Figure 13. SPV panels on the off-shore oil well head platform of ONGC.

Figure 14. The panels of the SPV power source for the Very Low Power TV Transmitters (VLPT) of Doordarshan.

System for ONGC platforms and TV transmitters of Doordarshan

The cases of the SPV systems designed and developed for the off-shore oil production platforms (Figure 13) of the Oil and Natural Gas Commission (ONGC) and for the Very Low Power TV Transmitters (VLPT) of Doordarshan (Figure 14) which are among the unique SPV systems supplied to customers as 'world-firsts' had more than one distinctive feature. The first of those features was CEL's close interaction with the users – ONGC (through Engineers India Limited) and Doordarshan – and with the equipment manufacturers Gujarat Communications and Electronics Ltd. (GCEL), Baroda and Electronics Corporation of India Ltd. (ECIL), Hyderabad for the UHF radio communication equipment and the telemetry equipment respectively for the ONGC Oil Platforms and the GCEL again for the VLPTs for Doordarshan, to match the SPV power system with the electronic equipment concerned. Secondly, through such interactions, the power consumption of the concerned electronic equipment was reduced (in the case of the VLPT, to almost 50% of the original level) so as to make operation of the equipment with SPV power maximally cost-effective. More recently, a similar exercise is being done with the SPV lantern manufacturers so as to come out with an optimized least-cost product.

Categorization of SPV systems

SPV systems can be categorized on the basis of their application characteristics as rural, remote area and industrial systems. Such a categorized list of SPV systems developed and supplied by CEL is shown in Table 4.

A majority of the SPV systems meet the electricity needs for water pumping, village street and domestic lighting, vaccine refrigeration for immunization and other basic needs of rural areas not covered by conventional grid electricity. With the increasing use and

Table 4. Applications of SPV power systems

Rural applications
Village street lighting
Domestic and community lighting
Shallow well water pumping for irrigation and drinking water supply
Deep well water pumping for drinking water supply
Water purification systems
Village power plants
Vaccine refrigeration
Rural radio telephone sets and telephone exchanges
Very low power unmanned television transmitters
Direct reception television sets
Black and white and colour television receivers
Transistorized radio receivers
Solar lanterns
Remote Applications
Applications in Antarctica
Application in the Mount Everest expedition
Offshore telecommunication and telemetry
Hydro-meteorological stations
Satellite-based data collection platforms for meteorology and oceanography
Industrial applications
Cathodic protection of oil, gas, water and other pipelines
Powering of electronics on lighthouses
Obstruction warning lights at airports
Railway platform lighting and panel interlocking
Warning signal for unmanned railway level crossings
Petrol/diesel dispensing stations
Solar power generator
Defence applications
Manpack battery chargers
Applications by paramilitary forces

awareness of SPV power as an alternative source of energy, the battery manufacturers have come out with long life, maintenance-free batteries, specifically for use in SPV systems. This has rendered the SPV systems much more reliable and longer lasting for use in remote inaccessible areas.

SPV systems for the National Technology Missions

One of the major contributions of CEL's SPV power systems are to the National Technology Missions. Some 205 SPV-powered deep well water pumping systems using submersible pumps have been supplied for the drinking water mission through the Department of Rural Development. These pump systems are really complete village water supply systems and are capable of discharging 10,000 litres/day from depths as great as 120 m. Over 1,500 lighting systems using high luminosity Compact Fluorescent Lamps (CFL) have been supplied to as many Adult Education Centres in 14 states under the National Literacy Mission. Over 35,000 nos. of SPV power sources have been supplied for the Department of Telecommunication's Single Channel VHF Radio Links as part of the National Mission for Rural Communications. Solar-powered refrigerators are also being developed and supplied for the cold chain for storing vaccines and life-saving drugs in remote villages under the National Immunization Mission. Figure 15 shows CEL's SPV-operated lights in an Adult Education Centre at Salem District, T.N.

Figure 15. SPV operated lights in an Adult Education Centre at Salem District, Tamil Nadu.

Defence charger

The other pioneering development of CEL has been the 'Defence modules'. These are lightweight, foldable modules which can be carried 'manpack' by the soldier for charging the batteries of communication equipment (wireless radio sets) carried by him. These 'defence modules' have been type-approved by the Army, after exhaustive and extensive trials in actual field conditions ranging from the Rajasthan desert to the extreme cold weather conditions of the high Himalayas (3600–5500 m/12000–18000 ft.). Based on the feedback from such field trials by the customer, CEL has optimized the design, engineering and production technology of these modules. These foldable 'manpack' SPV battery charges have now been commercially manufactured and first supplies made to the Army. This defence-approved foldable module is the only one of its kind in the world. Figure 16 shows CEL's foldable modules in use at a base camp for charging batteries of communication equipment in the Indian Everest Expedition of 1984. The range and total number of SPV systems developed and supplied by CEL so far are shown in Table 5.

CEL has been responsible to a large extent for the creation of a national market for SPV products through its continuous and innovative development of new SPV application systems, even when no possible market for these systems existed.

Table 5. Solar PV systems supplied by CEL as on 31.3.95

1.	Stand alone street lights	11095
2.	Indoor lighting systems	251
3.	Lighting-cum-TV receiver systems	449
4.	Lighting systems for rural adult education centres	1558
5.	Solar PV lantern	1051
6.	Shallow well village water pumping systems	947
7.	Shallow well village water pumping systems (National Pump Programme)	92
8.	Deep well village water pumping systems	205
9.	Multi-use village power packs/micro power stations	21
10.	Vaccine refrigeration systems at rural health centres	30
11.	Terrestrial and direct-from-insat TV receivers	1253
12.	SPV power source for Very Low Power (unmanned) TV transmitters/transposers	211
13.	SPV power source for DOT's multi access rural radio communication systems	1831
14.	SPV power source for DOT's single channel VHF radio telephone equipments	31029
15.	Off-shore oil/gas platforms	27
16.	Cathodic protection systems for oil pipelines (to prevent corrosion)	12
17.	Obstruction warning lights systems for civil aviation	34
18.	Unmanned railway level crossing warning systems	20
19.	SPV systems for powering of compound lights/garden lights and water pumping system	1
20.	SPV system for diesel/petrol dispensing stations	15
21.	Defence systems	309
22.	Others	422
		11095

With the development and technology and technology-proving phase behind it, the SPV market could now be truly said to have come of age both in our country and world over with ever-increasing use of solar photovoltaic systems and power plants coming into vogue. Such a growing market is expected to lead to further cost-reduction of SPV power as a result of both economies of scale and technological advances.

100 *kW power plants*

CEL has pioneered during 1992–94 the design, engineering, construction and operationalization of two 100 kW SPV power plants, Asia's largest such plants. The plants are located at villages Kalyanpur and Ghosi in the state of Uttar Pradesh. Figure 17 shows the SPV array of the power plant at Kalyanpur. These power plants have been fully designed by CEL and installed on a turnkey basis against contracts from the Non-Conventional Energy Development Agency (NEDA) of the Uttar Pradesh government. The power plant at Kalyanpur powers 450 domestic lights, 50 street lights and 15 nos. of 5 HP water pumps. CEL has set up the plant on a turnkey basis including supply of the special high voltage SPV modules, the lights, pumps, and the Power Conditioning Units (PCU), building the control room to house the PCUs and batteries, and laying the cables and interconnecting the whole system etc. The plant is designed on a modular basis so as to consist of 4 nos. of 25 kW power units including the corresponding SPV sub-array, PCU and batteries. The PCU contains a charge controller for safeguarding the battery life and an inverter for converting the DC electricity from the SPV array/batteries into 3-phase, 440 V, 50 Hz AC. The PCUs also have a phase synchronization unit to enable their interconnection in parallel to meet the total load requirement in the stand-alone mode. One 25 kW sub-system has been interfaced with the national AC grid through a 2.5 KMs, 11 kV feeder line. All the PCUs including the one for the grid interfacing have been totally designed indigenously to cater to the type of voltage and frequency variations prevalent in the Indian grid. Power conditioning units available in the international market do not have the capacity of handling such variations. The 25 kW basic unit has now become a

Figure 16. Foldable modules in use at a base camp for charging batteries of communication equipment in the Indian Everest Expedition of 1984.

Figure 17. The SPV array of the 100 kW plant at village Kalyanpur, Aligarh District, UP.

standard module for such plants to be installed by CEL in future. The modular concept ensures built-in redundancy in the power plant operation so as to meet the load requirement (atleast partially) in the event of failure of any particular PCU. The undertaking of these two SPV power plants, the 1st of their kind in the developing countries, has provided a wealth of real field experience to CEL in this area, thus adding to its already wide range of capability in the SPV power systems.

National Pump Programme

This year, a National Programme for large-scale distribution of SPV water pumps to villages throughout the country has also been launched by the Ministry of Non-Conventional Energy Sources (MNES). This programme has been conceived to give concrete shape to the announcement of the Prime Minister, P. V. Narasimha Rao, of large-scale use of solar photovoltaic (SPV) power for the benefit of populations in unelectrified villages. The programme envisages the sale of these SPV pumps directly to the users under a suitable leasing/soft loan mechanism with instalment payments spread over 10–20 years. This is being attempted to offset the disadvantage of the initial high cost of the solar photovoltaic systems which is acting as a prime deterrent for the large-scale deployment of these systems inspite of its many other advantages. The success of this programme will see the emergence of a very large market for the solar photovoltaic systems in India.

Thrust areas for R&D

In order to progressively increase the share of SPV in meeting global energy demands, intensive research and development work is needed on a continuous basis both to refine and bring down the cost of existing manufacturing methods and to bring into manufacture cells using novel technologies.

These and other measures taken on the technology front along with appropriate policy support from the Government, is expected to steeply reduce the cost of solar cells and modules and hence of the corresponding SPV systems in the country, by the year 2000.

Assessment of CEL's experience in 'Bridging the gap'

When one undertakes an 'Operation Hindsight' of CEL's experience with developing and commercializing SPV technology, several interesting features of 'bridging the gap' between physics and industry come to light.

First, in cell-making, cell-interconnecting and module-making, there is a close interplay between process steps and the equipment with which those steps are implemented in industrial production. Almost every production equipment has to be extensively 'tuned' or optimized in terms of parameter settings and operating conditions, in order to get the best results. Second, selection of an appropriate mix of manual operation and (semi) automation, the choice being made so as to minimize the overall process cost for a plant of 2–3 MW of cells per year. Third, in respect of the choice of the source of supply of the process equipment, a judicious mix of indigenous and imported equipment is made to achieve a cost-effective mix without trading off quality and yield. Some equipment are bought in the world market. This is done where technological sophistication and performance with high throughputs are the dominant consideration. In other cases, indigenous equipment are selected without sacrificing the same technical and throughput factors, but at far lower cost. Fourth, even where equipment are imported, modifications need to be effected in the equipment after use in the plant so as to optimize the equipment into the process line, thereby increasing its effectiveness and performance. Notable examples of such modifications done by CEL are in the tabber and laminator. Considerable modifications were effected in the machine while using it in CEL's line by which its performance increased several-fold. The knowledge acquired by CEL's engineers in making these improvements also provides a sound base for such equipment to be designed and manufactured in our country with substantial cost savings. Fifth, as the process is an integrated one, there is considerable interaction and interactive feedback between one production step and atleast the immediately preceding and succeeding steps in the total process sequence. Continuous iteration is therefore needed, *along the whole process sequence*, to achieve the highest performance solar cells. Sixth, and very crucially, continuous in-process measurements and off-line specialized measurements are needed for both process optimization and control and for product quality control and assurance. The science-base is ever-

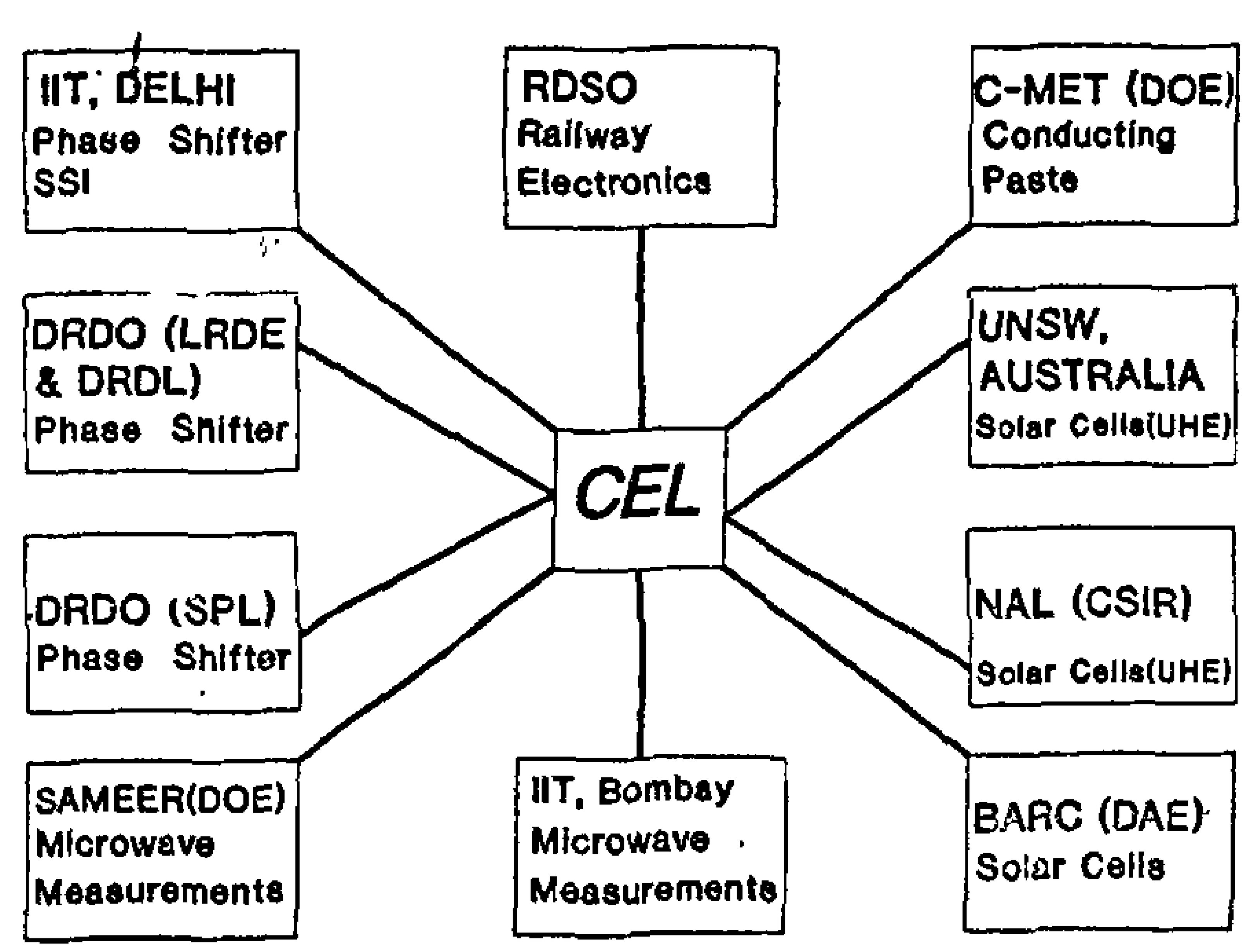


Figure 18. CEL's technology linkages.

present. Seventh, the whole process of technological advance is incremental and evolutionary in character i.e. relatively small improvements are being made all the time to improve process yield and product i.e. solar cell and module quality and performance. This has to be a continuous drive undertaken endlessly. Eighth, as the technology is continuously evolving in this way, the industrial work force operating the plant has to be extensively trained to do two things simultaneously: operate the plant on a disciplined basis with process and machine settings which have been specified as the 'optimum', at a particular point of time. However, to be open, at the same time to apply modified settings as the R & D effort (which is going on all the time) reveals the need for altered process parameters in order to achieve improved performance, whether of efficiency, yield or quality. This calls for flexibility of response and the collection, review of large amounts of data on a continuous basis.

External linkages

In the evolutionary development of technology described in the foregoing, the development process has been largely undertaken in-house by CEL's SPV group. However, there has also been close interaction and help from external agencies e.g. research laboratories, test houses and indigenous and foreign equipment manufacturers. This interaction is schematically shown in Figure 18.

Conclusion

The case of CEL's experience demonstrates the importânce of entering an area of advanced technology at an early stage in the evolution of the technology and of the building up of indigenous capacity to convert science into technology and further, technology into industrial production capacity.

It also clearly brings forth the importance of pilot and demonstration phases in proving the new technology and the capability to optimally mix process know-how, equipment engineering and plant engineering.

As a result of sustained work over the last 15 years (1977–92), CEL has built up considerable capability in the SPV area of integrating science, technology and industry, rather than generating the scientific knowledge and then trying to bridge the gap to industrial application.

1. Becquerel, A. E., *C.R. Acad. Sci.*, 1839, **9**, 145–149.
2. Adams, W. G. and Day, R. E., *Proc R. Soc.*, 1877, **A25**, 113.
3. Ohl, R. S., 'Light-sensitive Electric Device' US Patent no. 2, 402, 622; Light-sensitive Device Including Silicon, US Patent no. 2, 443, 552; both filed 27th May, 1941.
4. Kingsbury, E. F. and Ohl, R. S., *Bell System Tech. J.*, 1952, **31**, 802–815.
5. Chapin, D M., Fuller, C. S. and Pearson, G. L., *J Appl. Phys.*, 1954, **25**, 676–677.
6. Green, M. A., Wenham, S. R., Zhao, J., Zolper, J. and Blakers, A. W., Proceedings of the 21st IEEE Photovoltaic Specialists Conference, Kissimmee, Florida, USA May 21–25, 1990, p.207.
7. Green, M. A., Wenham, S. R. and Zhao, J., Proceedings of the 23rd IEEE Photovoltaic Specialists Conference, Louisville, Kentucky, USA. May 10–14, 1993, p.8.
8. Saitoh, T., Shimokawa, R. and Hayashi, Y., Proceedings of the 4th Photovoltaic Science and Engineering Conference, Sydney Australia, February 14–17, 1989.