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The NASA Photovoltaic Technology Program

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In the last 30 years, photovoltaic technology has made impressive strides and has been the backbone of the space program. Solar cells have filled the skies from Earth to Moon, from Mars to Mercury, and in most imaginable orbits about Earth. Performance has steadily improved, durability and reliability refined and costs held stable. For the past 5 years, the OAST program has aimed at laying the foundation for high capacity, low earth orbit photovoltaic power systems. With the expected approval of the Space Station program, this work will transition into advanced development and flight. What forces are now shaping the program?

With a TRW artist's concept of the Space Station as background, figure 1 shows four major shaping forces. First, the long expected, eagerly anticipated eruption of a demand for additional energy in space seems to be happening. Both NASA, Air Force and commercial planners are forecasting a continuation of high capacity space systems. Supporting that need, but separate from it, is the opportunity to significantly reduce the mass of the power system portion of the geosynchronous orbiting spacecraft. With power system mass equalling payload mass, obvious opportunities exist to provide more power at less weight for commercial benefit. Corollary to geosynchronous orbit operation is the need to boost the radiation tolerance of solar cells. Such increased tolerance not only raises end-of-life power, which reduces the size and mass of the array, it also flattens the change of power with time which can lead to power system simplification. Increased radiation resistance will also open the door to the radiation intensive mid-orbits, providing additional benefit and flexibility to mission planners. Additionally, planetary needs continue to beckon. Expansion of the useful regime for solar arrays to beyond 5 AU and as close to the Sun as 0.1 AU appear achievable at costs and weights superior to competing radiosotope generators.

To become more specific, figure 2 lists some National Landmark Missions encompassing the civil, commercial and military sectors. All those missions require a variety of technology advances to come to fruition, and power is first and foremost on the list -- at least from our perspective here. Inspection of these opportunities suggests the thrusts of high efficiency, low mass, increased radiation tolerance and low cost continue as prime directions for the photovoltaic program. Of course, some of these missions may require nuclear-powered systems, so photovoltaics will again be confronted by technical challenge and competition. Such competition is healthy and is in the best national interests, for it will ensure that the best performing, most cost effective technologies emerge.

The current set of milestones for the photovoltaic program is shown in figure 3. Primary emphases cover cell research and technology, advanced devices and blankets and arrays. Major targets are increased efficiency, radiation tolerance, and concentrator and planar arrays with reduced mass and increased performance.

Five year plans are necessary for the near term program focus, but vision beyond that time frame is needed. Without the dreams of the future, say 25 years hence, then present opportunities can be missed, only to be painfully recovered in the future. The proper role of OAST technology program is to address the future, and such an outlook is shown in figure 4. While this is necessarily a comprehensive view of the entire Space Energy Systems Office program, it does show a long range view of photovoltaic technology. Capacity, performance, cost and increasing the operational envelope of photovoltaics are the guidelines. These projections are made on the advice and guidance of a broad range of experts from universities, government, and industry. Such projections are annually reviewed and updated and as such represent a living document that should accurately reflect the community view of the future.

Let's now review accomplishments of specific technology elements of the program. 1984 will see the flight of OAST-1, a 102 ft long demonstration solar array. Although the majority of the array is covered by mass simulators, there are two active panels. One panel is covered with 2x4 cm conventional cells while the other contains 5.9x5.9 cm large area silicon cells. A third panel contains a smaller array of 50 μm thick silicon cells. The 5.9 cm square cells with wraparound contacts have also been selected as baseline for the Milstar satellite, thus completing an arduous process of technology transfer. The technology of welded interconnects has also made strides. Current programs have demonstrated the durability of welded interconnects to the low earth orbit environment for accelerated cycle times beyond five years. Clearly, new capability is being introduced that provides a new measure of flexibility and durability to silicon arrays.

Concentrators have emerged as a cost-effective, viable alternative to silicon planar arrays as shown in figure 6. Miniature gallium arsenide solar cells with 19 percent efficiency at 100 times concentration and 80° C temperature have been demonstrated. The miniature 5x5 mm size is the key to the low operating temperatures in space. Complementing this cell is a cost effective miniature Cassegrainian concentrator panel using a carbon composite tri-hex isogrid design which permits effective packing of the circular electroformed nickel optics. This produces a lightweight, yet rigid, design capable of specific powers in excess of 30 W/kg. Alternate concentrator concepts are also being pursued. Prime example of this is the SLATS concentrator. This development program jointly sponsored by NASA, AFWAL and NRL provides an alternative concept of great promise. With a goal 200 W/m^2, miniature concentrator concepts offer technological transparency, permitting the use of increased performance cells such as the cascade cell.

Lightweight array technology continues to advance and is nearing flight readiness as shown in figure 7. Under JPL leadership, multiple lightweight welded blanket designs have been developed. All these lightweight designs, with nominal 50 μm cells, have successfully passed 4000 geosynchronous thermal cycles from +65° to -175° C. Thus, confidence in >20 year durability is high. Lightweight blankets require lightweight deployment mechanisms. Toward that end, an 8-bay STACBEAM meeting goals for mass and frequency response has been demonstrated. Made from lightweight composites, this innovative approach will be integral to achieving a 300 W/kg, 300 V array in the future. Achieving this goal could lead to a 30 percent saving in mass for geosynchronous satellites. Success will require continuing advances in blanket and deployment mechanism technology. Cells, coverglasses and interconnects are targets of improvement.

Supporting this geosynchronous orbit thrust is research into improving the radiation tolerance of cells. Figure 8 demonstrates achievements made when the n-type dopant lithium was added to a conventional boron-doped n/p silicon cell. The lithium counterdoped the p-type boron and raised cell base resistivity from about 1 to 3 ohm-cm. Most importantly, it also raised the radiation resistance of this cell compared to an identical cell that contained no lithium. These cells had no antireflection coating. Additional research showed that the lithium preferentially combined with residual oxygen to prevent formation of the devasting boron-oxygen complex. None of the recombination centers formed by radiation resembled any defect formed in lithium-free material. Furthermore, significant annealing of the damage occurred at only 100° C. Such exciting results seem to offer great hope for the future and for the possibility of radiation durable arrays.

In the realm of high performance cells, two directions are being pursued as shown in figure 9. These future options include two options for cascade cells and ultralightweight CLEFT technology. All these approaches are based on III-V cell technology. In the three-junction electrically-stacked cascade cell, 17.6 percent AMO efficiency has been demonstrated for the bottom 1.15eV cell in the stack made from GaInAs. This performance was at 100x and 25° C. Furthermore, greater than 90 percent quantum efficiency has been demonstrated in the 1.55 eV bandgap mid-cell made from both GaAsP and GaAlAs. While interconnection of these cells by tunnel junction has not yet been achieved, a major step forward was made by development of a stable Mg p-type dopant for OMCVD. Development of Mg is important because it remains stable at high concentrations as additional layers are deposited. The three junction approach was selected because it is the approach most likely to achieve the 30 percent goal.

CLEFT technology has produced a 14.1 percent AMO, 6 μm thick GaAs cell with 5 kW/kg specific power. This is the highest specific power achieved for any cell to date. Additionally, CLEFT layers of AlGaAs have been demonstrated and device fabrication is proceeding. If high performance AlGaAs cells can be created, the option exists for a mechanically stacked two junction cascade cell. This device would have aligned metallic grid interconnects between the two cells and offers potential for efficiencies beyond 25 percent.

The payoff in the area of high efficiency silicon cell research is shown in figure 10. In the early 1970s, a goal of 680 mV for open circuit voltage in 0.1 ohm-cm silicon cells was established. This voltage level was a prerequisite for 18 percent AMO efficiency. In the past year, this goal was achieved using advanced processing technology in the MINP cell. Using 0.2 ohm-cm silicon, an efficiency of 16.5 percent was also demonstrated - almost 95 percent of the goal set a decade ago! Based on the research results to date, reexamination of the ultimate silicon cell efficiency was warranted. As a result, it is now believed that efficiencies beyond 20 percent AMO are achievable with more extensive use of MINP-type technology and with prudent alterations in the bulk silicon itself. It is believed possible to independently control certain voltage-critical materials parameters to achieve this goal.

Additional progress has been made in research into the plasmon converter, also shown in figure 10. Three critical areas of device performance - broadband coupling, transport and conversion - have been identified. Broadband coupling better than 90 percent over one-fourth the solar spectrum has been demonstrated by several techniques. Efficient transport of surface plasmons over near-millimeter ranges has been achieved. Metal-oxide-metal type conversion diodes have been eliminated from consideration and other semiconductor based diodes are under development. In summary, progress is being made in this new concept, critical barriers are being identified and hopefully surmounted. It remains too early to project ultimate performance potential or even feasibility of this alternative approach, but no insurmountable barriers have been identified to date.

Flight testing of technology remains a critical element in the program. In addition to the array flight of OAST-1, a JPL solar cell calibration facility will be flown, and two experiments flew aboard the Long Duration Exposure Facility launched April 6, 1984. These experiments (fig. 11) are the Advanced Photovoltaic Experiment (APEX) and Solar Array Materials Passive LDEF Experiment (SAMPLE). In APEX, 136 cells from around the world are being actively measured. Sixteen have full I-V curves while the remainder record short circuit current. In addition to assessing cell performance with time in orbit, absolute calibrations of these cells will be obtained. Cells include Si, GaAs, thick and thin, planar and concentrator. The APEX experiment also measures the solar constant with an absolute cavity radiometer and the solar spectral distribution through 16 narrow bandpass filters. A beam splitter is used to divide the solar spectrum into two regions above and below about 0.5 μm so total energy in these bands can be measured to aid solar simulator calibration.

The SAMPLE experiment is passive and contains a broad range of solar array materials, cells, mirror samples for concentrator applications and a variety of structural materials. Typical films include Kapton F, Black Kapton, White Tedlar, FEP Teflon, and Kevlar. Structural materials include graphite/epoxy, Halar, RTV elastomers, thermoplastics, polyimides and paints. A variety of solar cells and modules with different interconnect technology and exposure to the environment as well as metal and mirror samples of selected concentrator concepts complete SAMPLE. After flight, the optical and mechanical properties of these materials will be measured and used to guide low earth orbit array design.

In summary, the OAST Photovoltaic Technology Program continues to be broadly based, seeking to cover the widest range of technology options within the resource constraints. With expected rollover of those technologies applicable to Space Station, new thrusts are expected to be initiated which should lead to future civil, military, and commercial benefit.

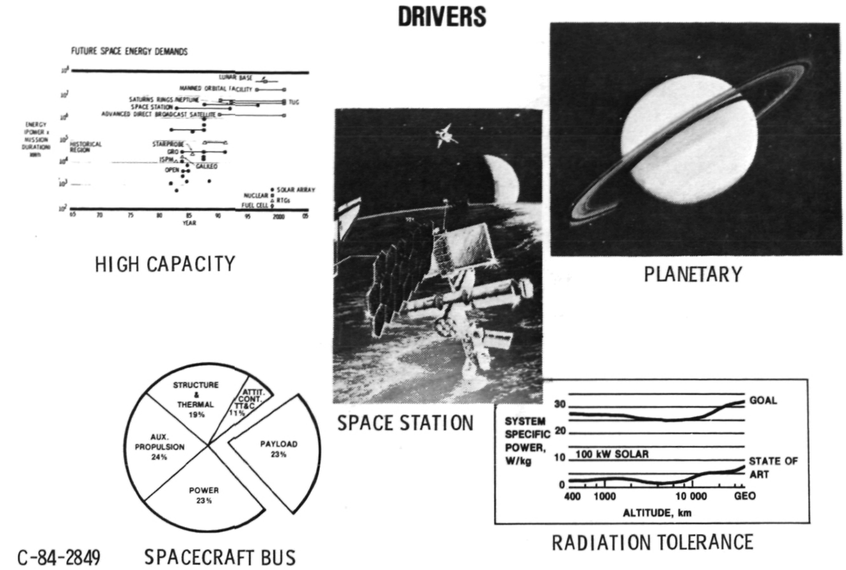


Figure 1. - Photovoltaic technology program.

CIVIL
- ★ UNMANNED OUTER PLANET
- ★ UNMANNED INNER PLANET
- ★ MANNED PLANETARY
- ★ LUNAR BASE
- ★ ADVANCED SPACE STATION
- ★ STARPROBE

COMMERCIAL
- ★ DIRECT BROADCAST SATELLITE
- ★ SPACE MANUFACTURING
- ★ GLOBAL RESOURCE MONITORING

MILITARY
- ★ SPACE BASED RADAR
- ★ SPACE DEFENSE
- ★ ADVANCED NAVIGATION SYSTEM
- ★ COMMUNICATION COMMAND & CONTROL
- ★ SURVEILLANCE & WARNING

TECHNOLOGY REQUIREMENTS
- ★ POWER
- ★ PROPULSION
- ★ ELECTRONICS
- ★ GUIDANCE & CONTROL
- ★ COMMUNICATION
- ★ MATERIALS & STRUCTURES
- ★ LAUNCH CAPABILITIES

C-84-2850

Figure 2. - National landmark missions.

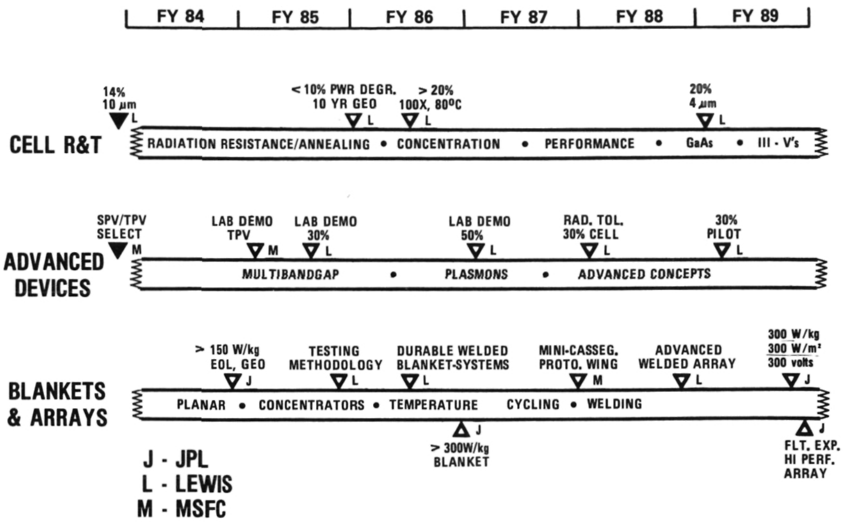


Figure 3. - Photovoltaic technology plan.

25 YEAR OUTLOOK

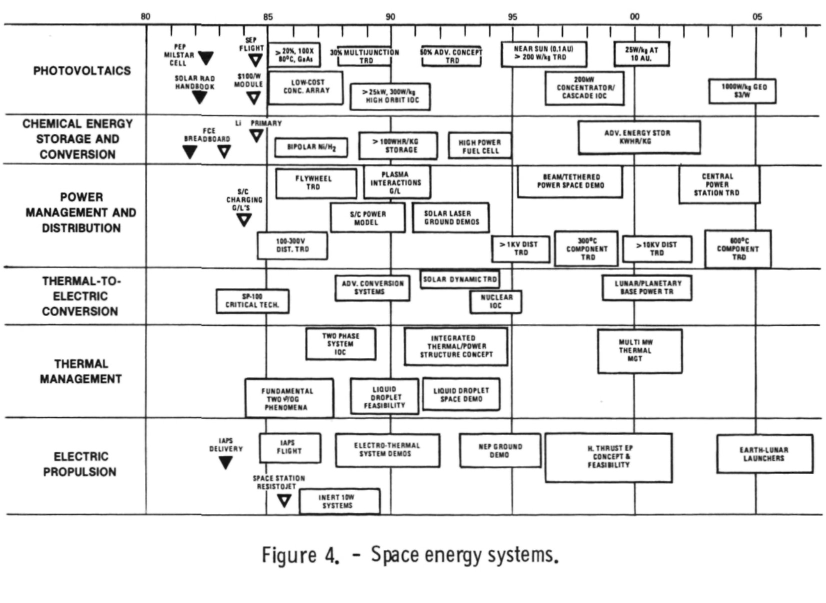


Figure 4. - Space energy systems.

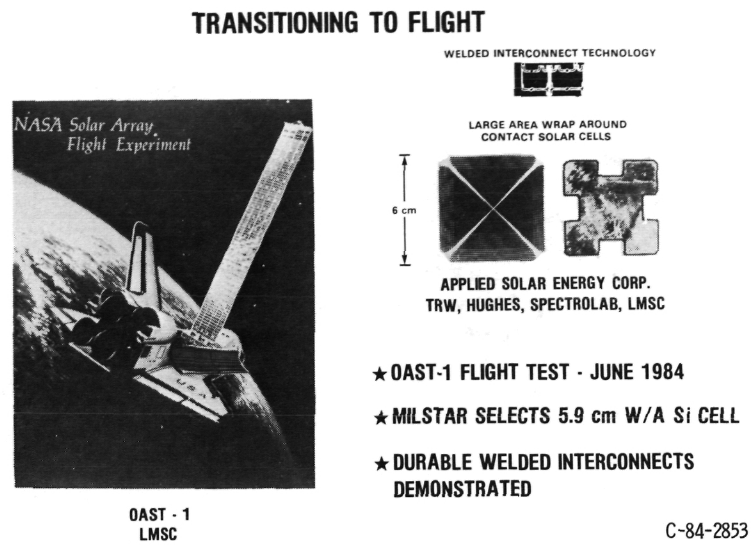


Figure 5. - Planar array technology.

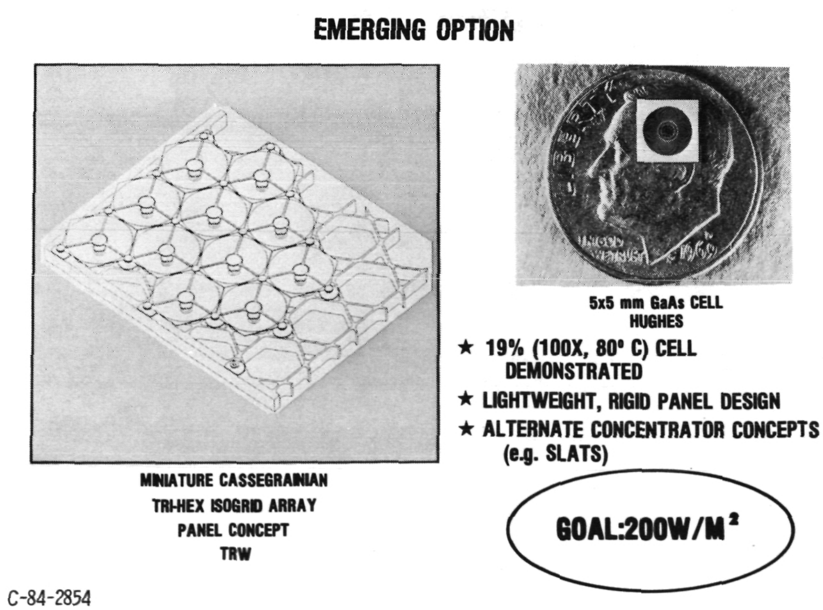
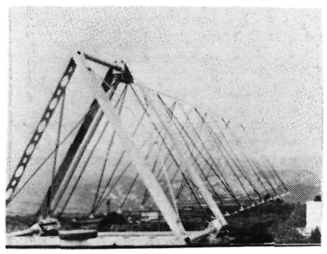
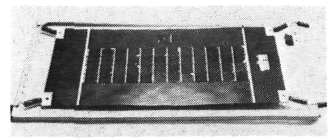


Figure 6. - Concentrator array technology.

APPROACHING FLIGHT READINESS



STACBEAM FULLY DEPLOYED
ASTRORESEARCH



50μm SILICON BLANKET
TRW

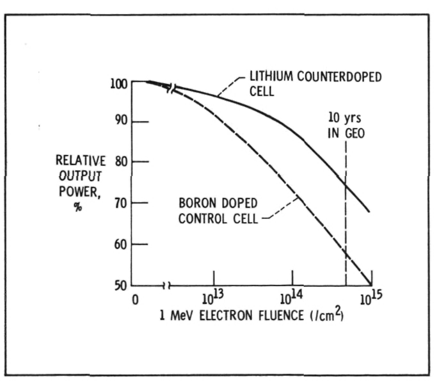
- ★ MULTIPLE LIGHTWEIGHT BLANKET DESIGNS
- ★ 4000 GEO THERMAL CYCLES PASSED
- ★ STACBEAM MET MASS & FREQUENCY GOALS

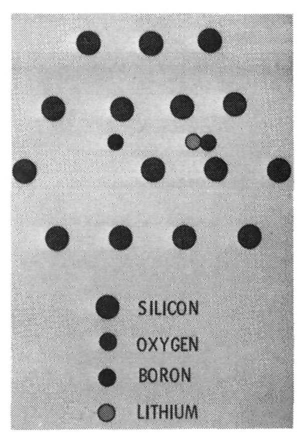
GOAL:
300 W/kg, 300 V

C-84-2855

Figure 7. - Lightweight array technology.

LITHIUM COUNTERDOPED n/p CELL

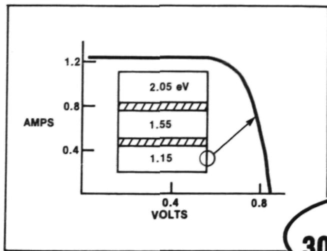




- ★ DECREASED RADIATION DAMAGE
- ★ ELIMINATION OF HARMFUL BORON-OXYGEN DEFECT
- ★ SIGNIFICANT ANNEALING AT 100° C

Figure 8. - Radiation tolerant cell research.

CANDIDATES FOR THE FUTURE



THREE JUNCTION CASCADE
VARIAN

**GOAL:
30% EFFICIENCY**

★ ACHIEVED 14.1% AMO 6µm THICK CLEFT GaAs CELL

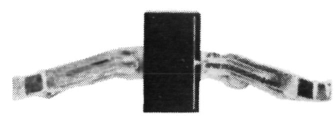
★ DEMONSTRATED CLEFT AlGaAs LAYERS

★ EXPLORING MECHANICALLY STACKED CASCADE

★ 17.6% AMO, 1.15eV, GaInAs DEMONSTRATED, 100X, 25^{o}C

★ > 90% QUANTUM EFFICIENCY 1.55eV, GaAsP, GaAlAs

★ STABLE Mg p-TYPE DOPANT DEVELOPED

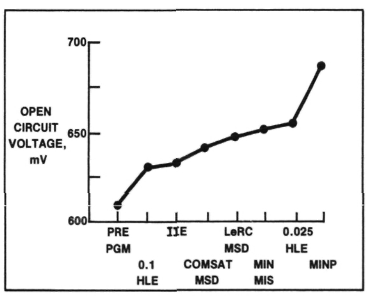


GaAs CLEFT CELL
MIT-LL

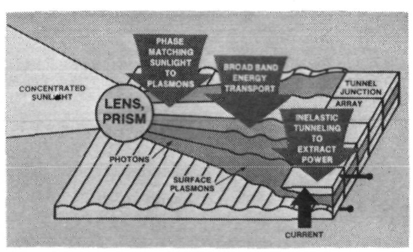
C-84-2857

Figure 9. - High performance cells.

PROGRESS



HIGH EFFICIENCY Si
LeRC, UNSW



PLASMON CONVERTER
LeRC, U Az, U CAL, U ROCHESTER

- **680 mV GOAL ACHIEVED**
- **20% AMO POTENTIAL**
- **MATERIALS MODIFICATION OPTIONS IDENTIFIED**

- **CONCEPT DEFINED**
- **KEY BARRIERS IDENTIFIED**
- **DEMONSTRATED BROADBAND COUPLING OF SUNLIGHT**

Figure 10. - Basic research.

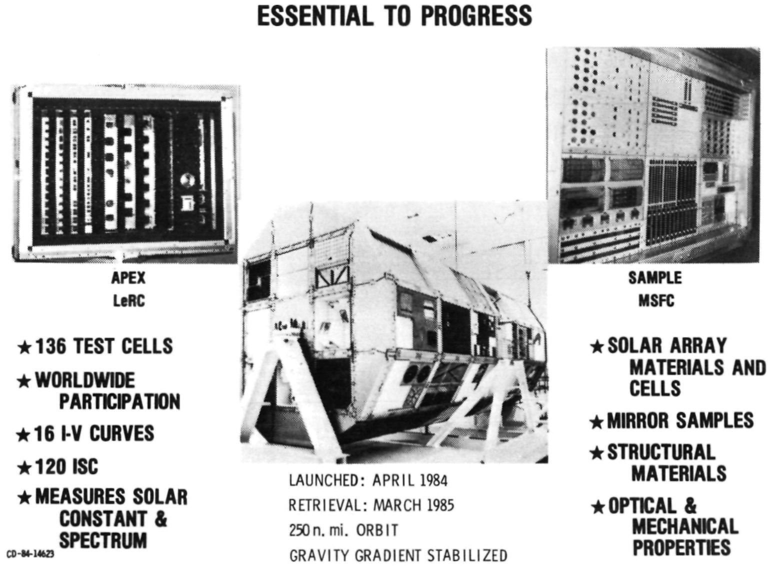


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Figure 11. - Long duration exposure facility experiments.

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16. Abstract
The NASA OAST Program in Space Photovoltaics is reviewed. From the perspective of national landmark mission requirements and 5-year and 25-year long range plans, the texture of the program is revealed. Planar silicon and concentrator GaAs array technology advances are discussed. Advances in lightweight (50 μm cell) arrays and radiation tolerance research are presented. Recent progress in cascade cells and ultralightweight GaAs planar cells is noted. Progress in raising silicon cell voltage to its theoretical maximum is detailed. Finally, advanced concepts such as plasmon converters and the LDEF flight experiments pertaining to solar cell and array technology are shown.

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