Tandem Concentrator Photovoltaic Array Applied to Space Station Freedom Evolutionary Power Requirements

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Abstract

Additional power is required to support Space Station Freedom evolution. Boeing Defense and Space Group, NASA Lewis Research Center and Entech Corporation have participated in the development of a High-Efficiency Tandem Concentrator Solar Array. Boeing's high efficiency Gallium Arsenide and Gallium Antimonide solar cells make up the solar array tandem cell stacks. Entech's Mini-Dome Fresnel lens concentrators focus solar energy onto the active area of the solar cells at fifty (50) times one sun solar energy flux. Development testing for a flight array, to be launched in November 1992, is under way with support from NASA Lewis. The tandem cells, interconnect wiring, concentrator lenses and structure have been integrated into arrays and subjected to environmental testing. A tandem concentrator array can provide high mass and area specific power and can provide equal power with significantly less array area and weight than the baseline array design. Alternatively, for Station growth, an array of twice the baseline power can be designed which still has a smaller drag area than the baseline.

Tandem Concentrator Photovoltaic Arrays

- **Background of Tandem Concentrator Technology**
- APEX Mission Flight Qualification Modules
- Large Array Design for SSF Evolution

Boeing Tandem Concentrator Concept

- Boeing 30%+ efficient tandem solar cells

- 4 year NASA/Entech mini-dome concentrator effort

- Technology combination promises exceptional power to weight and power to area performance

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Boeing Tandem Concentrator Concept

BOEING

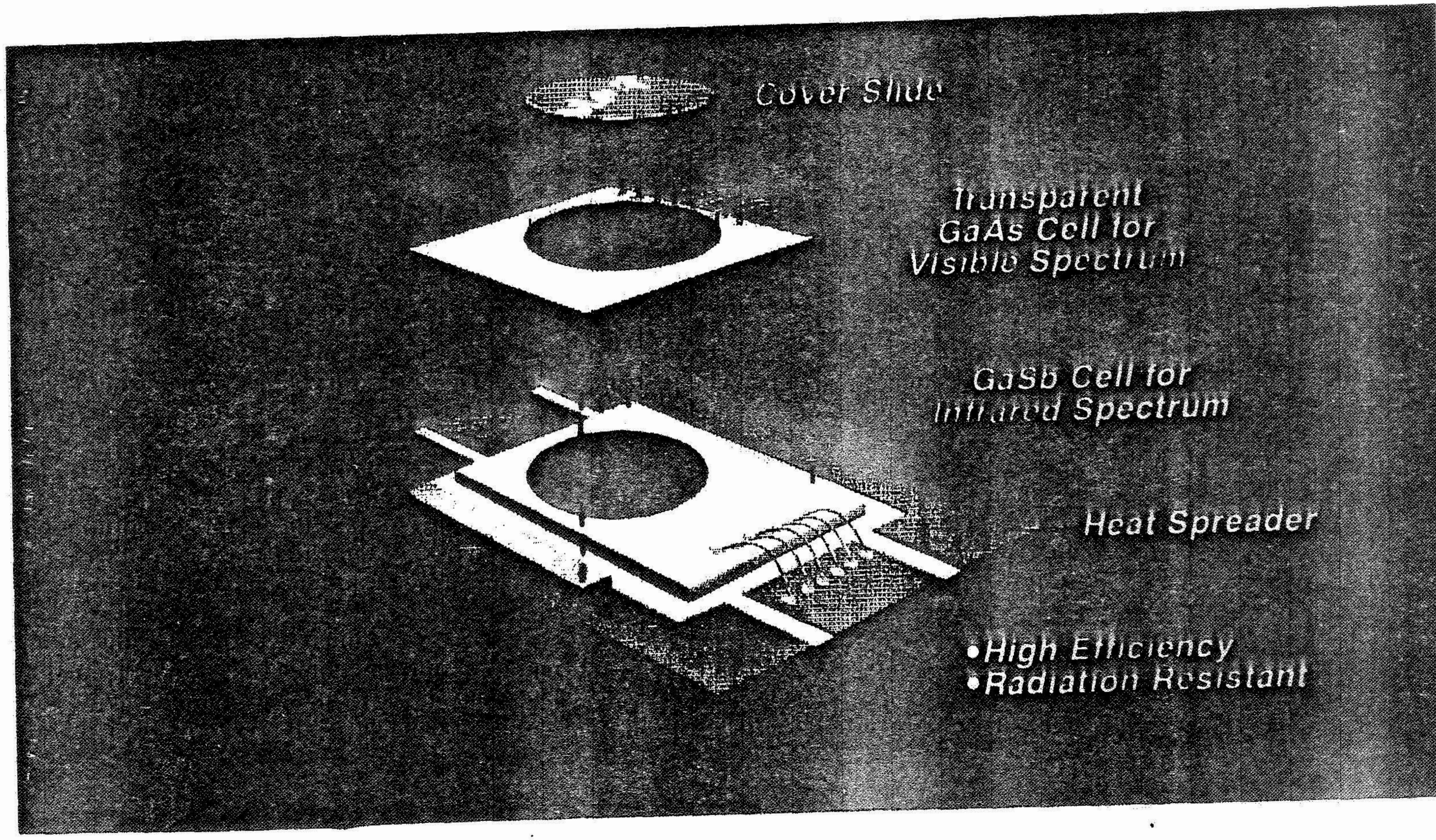
In 1990 Boeing announced a mechanically stacked tandem solar cell design capable of conversion efficiencies of more than 30% (AMO). The stack consist of an IR-transparent GaAs cell stacked on top of a GaSb cell. In an actual array the stacks are connected in triplets with the GaAs cells wired in parallel and the GaSb cells wired in series for voltage matching reasons.

The Boeing tandem cells have been flight tested at altitude in NASA's Lear-jet. The NASA data reported a conversion efficiency of 30.8% at 100 suns AMO.

For four years previous to this announcement NASA LeRC and Entech had been developing the mini-dome concentrator concept. By concentrating the sunlight on a relatively small chip with a domed fresnel lens one may substantially reduce costs by trading expensive cell material for cheaper lens and structure. Boeing contributed to this effort in the area of structural design of the panel and donated a 6 by 6 cell structure in 1991 which was used by Entech to assemble a prototype.

The marriage of these two technologies has been actively pursued since then in a joint effort to prove the concept can result in advanced photovoltaic arrays of much higher mass and area specific power than exhibited by present planar arrays while at the same time reducing cost per installed watt.

Boeing Tandem Solar Cell Design



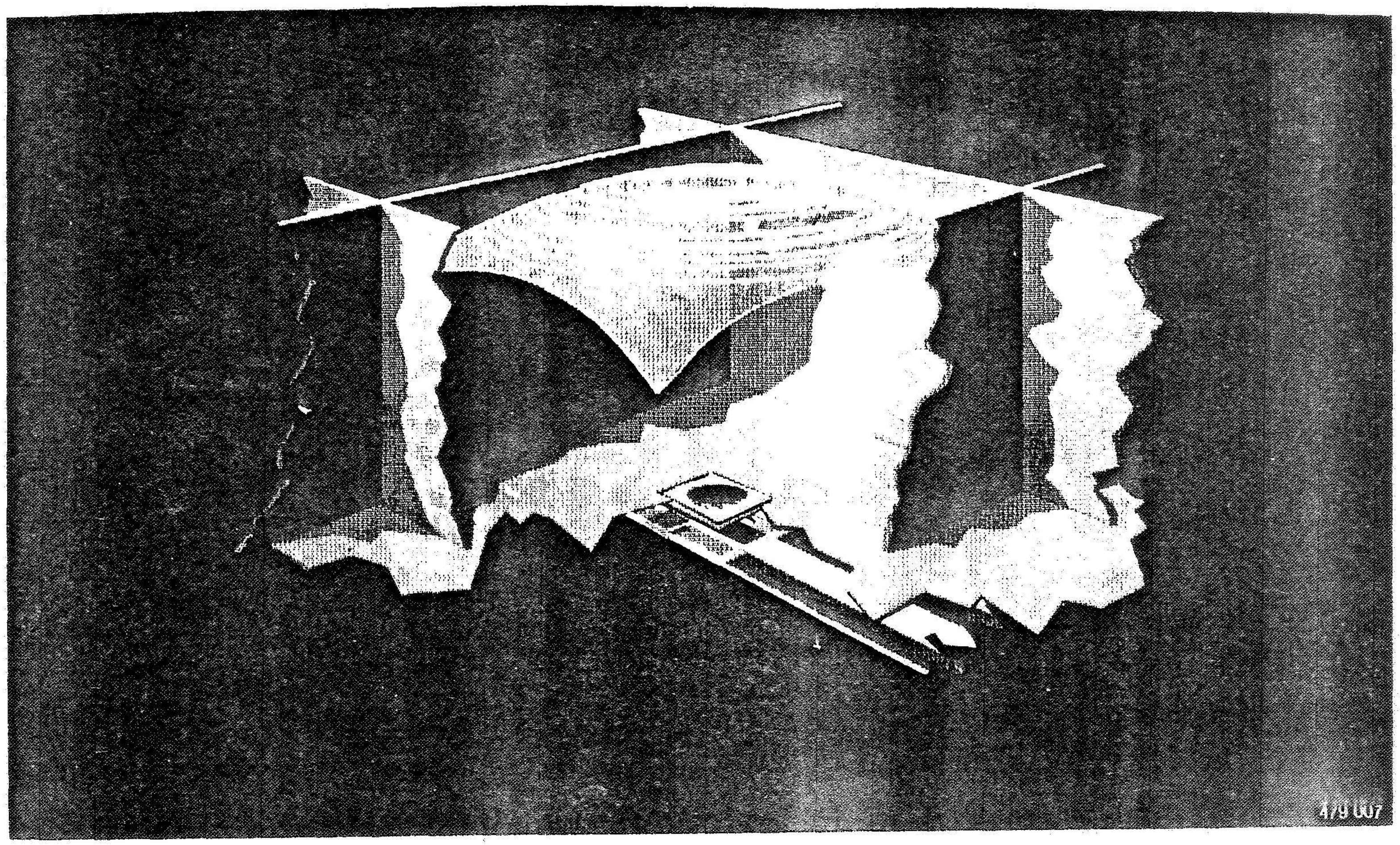
Boeing Tandem Solar Cell Design

The Boeing tandem solar cell design consists of two cells mechanically stack on top of each other. The top cell is a gallium arsenide (GaAs) chip which converts visible spectrum energy. It has been specially made to be transparent to the infrared solar spectrum which is absorbed by the bottom cell, a gallium antimonide (GaSb) chip.

The cells are mounted on a ceramic heat spreader which has had conductive areas plated to it to facilitate electrically connecting the cells to other stacks. In actual application, the stacks are wired together in triplets with the top cells of each triplet connected in parallel and the bottom cells connected in series for voltage matching reasons. The voltage matching scheme contributes several significant advantages in real-world applications.

A cover slide can be mounted on the top cell if required for radiation or plasma protection reasons. In addition, Entech has developed prismatic cover slides which, if adapted to the Boeing cell, can contribute a several percent performance increase.

Tandem Concentrator Arrangement



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Tandem Concentrator Arrangement

BOEING

A typical tandem concentrator arrangement consists of the domed fresnel lens, the cell stack and wiring, and the structure. The lens is actually a lamination of a glass dome and a molded silicone lens. It is cut square and bonded to the upper surfaces of an aluminum structure developed by Boeing. The cell stack is bonded to a ceramic insulator and heat spreader which is in turn bonded to the base surface of the structure. The interconnecting wiring is run inside the cavity where it is protected from atomic oxygen.

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Concentrator Advantages for Large Arrays

BOEING

- Significant reduction in cell material
- Smaller cells increase wafer yield
- Cost-effective to use high-efficiency cells
- Amenable to producibility increases via automation
- Structure and lens provide radiation protection

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Concentrator Advantages for Large Arrays

BOEING

A significant cost reduction is possible due to the much decreased amount of cell material required to produce an equivalent power output. The lenses and the structure required to support them costs considerably less than the large expanse of cell material which they replace.

Smaller chip sizes produce another advantage in that for a given size of Gallium wafer, and for a given number of surface defects, greater production yields are realized. This is due to better packing efficiency on the surface of the wafer for a larger number of small chips versus a smaller number of larger chips.

Another major advantage of the concentrator array concept is that it lends itself to high-rate production of large panels via automated methods similar to those in use in the microchip industry. At Boeing we are investigating methods for completely automated assembly of the back sheet which carries the cells and interconnecting wiring. The back sheet would later be joined to the rest of the panel structure.

Because the cell stack is completely contained within a closed structure, the degradation over time due to radiation may be lessened. This reduces the amount of overcapacity necessary to design into the system to achieve the end-of-life performance requirement. The degree of radiation protection has not yet been quantified or included in our array sizing calculations.

Tandem Concentrator Photovoltaic Arrays

- Background of Tandem Concentrator Technology
- **APEX Mission Flight Qualification Modules**
- Large Array Design for SSF Evolution

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Flight Qualification Program

BOEING

- Aggressive program to qualify modules for APEX
- Two 12-cell development units built & tested
  - Random Vibration and Shock (8.5 grms)
  - Thermal Vacuum (-73 to 90C)
  - Thermal Shock (-70 to 90C)
- Protoflight unit delivered to NASA LeRC in July
- Plasma test starting today at LeRC
- Two flight units to be delivered in October

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Flight Qualification Program

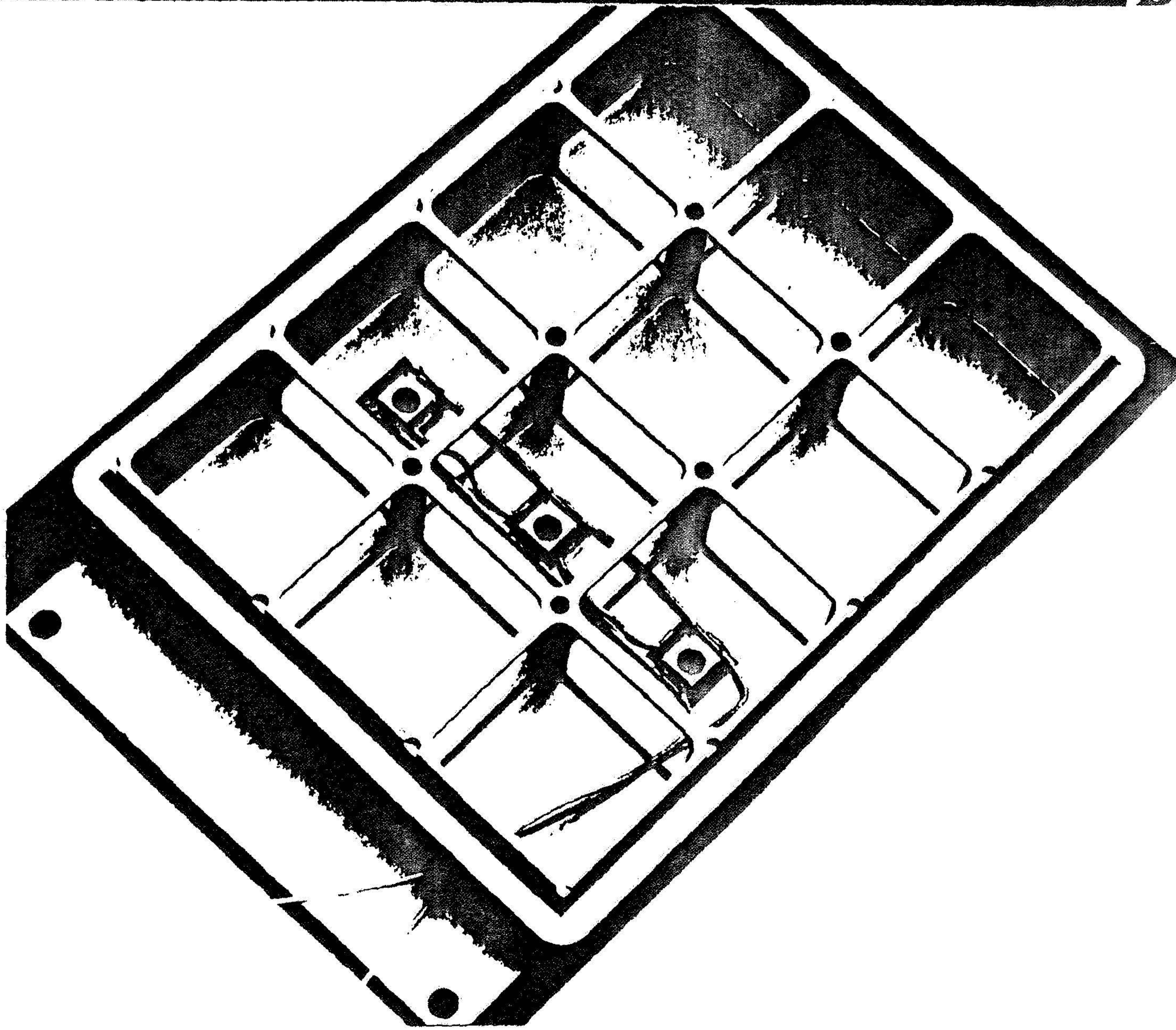
BOEING.

Since the beginning of this year an aggressive development program has resulted in the flight qualification of 12-cell tandem concentrator modules. Two development units were built and subjected to random vibration and shock tests, thermal vacuum and thermal balance tests and thermal shock tests. A protoflight unit was then assembled, subjected to full qualification testing and delivered to Lewis Research Center in July.

A plasma test article has also been delivered to Lewis Research Center and is schedule to begin plasma testing on August 8th.

Two more fully flight qualified units will be delivered in October, one of which will fly on the Pega-Star satellite and the other will take the place of the previously delivered protoflight unit. These units will have solar cells with even greater performance which is the result of on-going cell research and development.

Protoflight Unit Partial Assembly



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Protoflight Unit Partial Assembly

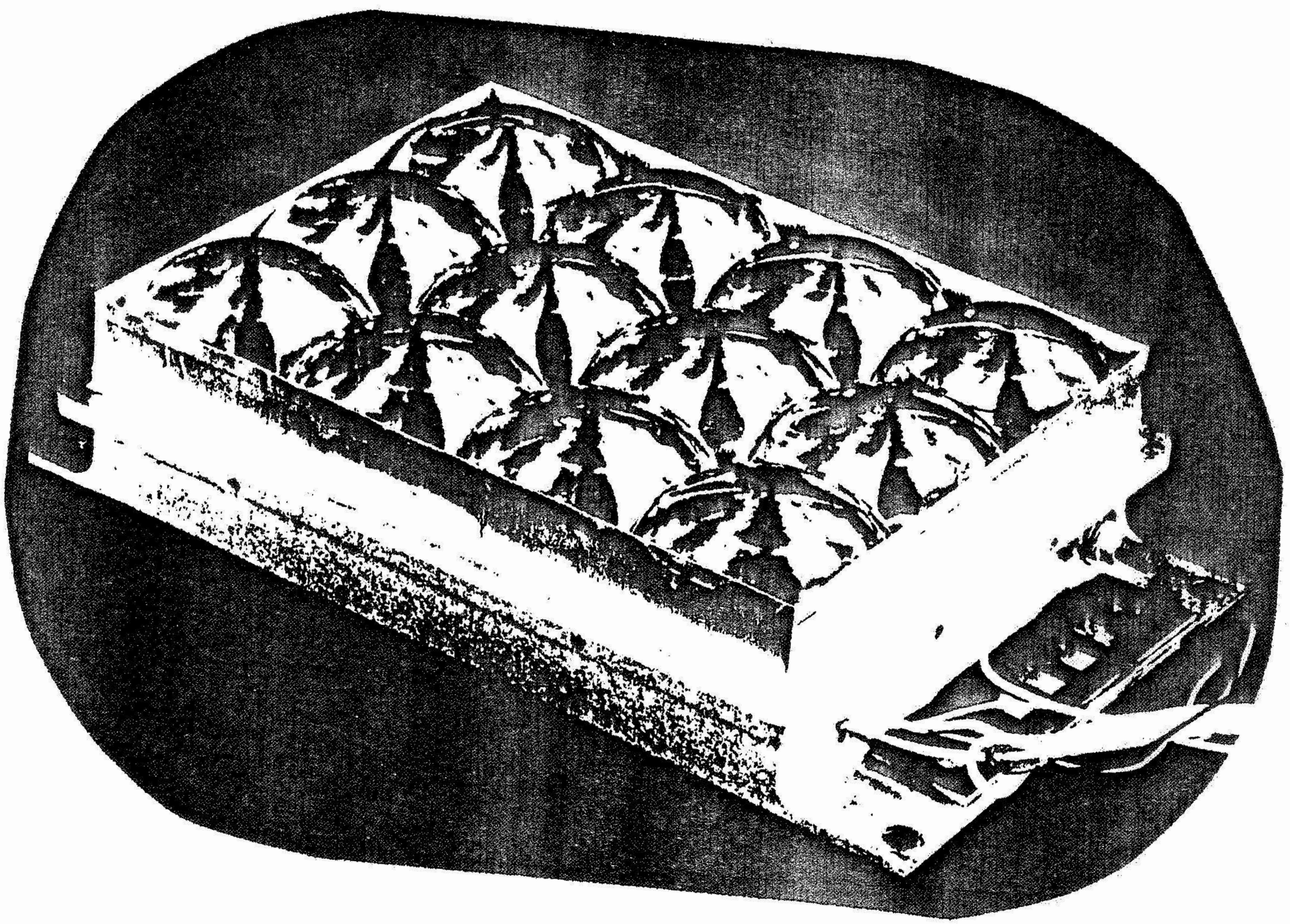
BOEING

This slide shows a Boeing 12-cell protoflight unit when partially assembled. The mostly-open very light-weight aluminum structure can be seen with three cell stacks mounted on the bottom surface.

At the present time we are connecting the stacks with round wire because of the limited time available for development before the APEX mission. The preferred method is to use thick-film flat conductor and we are continuing to develop designs along those lines.

The flange which runs around the periphery at the top of the structure is specific to this design and is only for mounting a protective cover which is removed before flight.

APEX Mission Protoflight Unit



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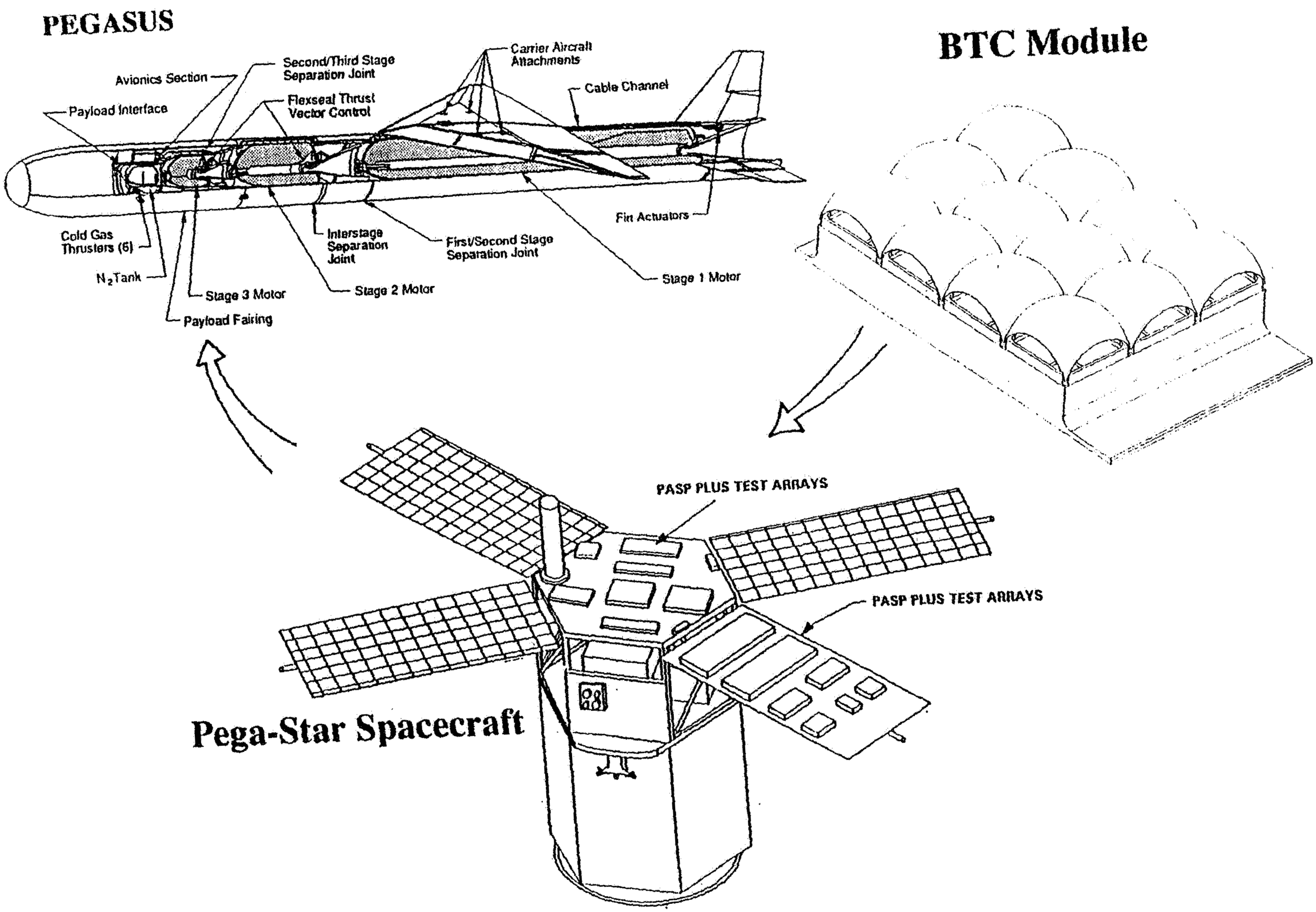
APEX Mission Protoflight Unit

BOEING.

This slide shows the completed protoflight unit. The lenses have been bonded to the top of the structure and a thin aluminum strip has been added as an atomic oxygen shield around the periphery. Also visible is a grounding screw and a phenolic connector strip where the interface to the spacecraft instrumentation is made.

APEX Mission Diagram



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APEX Mission Diagram

The Air Force's APEX (Advance Photovoltaic Experiment) mission will carry a total of three experiments with a minimum flight duration of one year. This flight is being conducted by the Air Force Geophysics Laboratory with experimental direction from the Air Force Wright Research Development Center's Aero Propulsion and Power Center.

One experiment is the PASP+ (Photovoltaic Array Space Power Plus Diagnostics) experiment which will test 13 different solar array designs in a high plasma and radiation environment.

The Boeing Tandem Concentrator module will be located on the sun-facing surface of the payload shelf of the Pega-Star satellite. The satellite is a 3-axis sun-stabilized platform. It will be injected into an orbit inclined at 70 degrees and fly a 350 km by 1850 km elliptical trajectory. This trajectory will repeatedly subject the experiments to high radiation levels while crossing the Van Allen belts, producing a 5 times greater exposure rate than the Space Station Freedom orbit. This is intentional to allow accelerated determination of radiation degradation rates. The orbit will also produce a highly charged plasma environment around the experimental solar arrays.

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Flight Experiment Characteristics

BOEING

- Direct space performance comparison of 13 arrays
- Voltage/current/temperature testing of each array
- High-bias voltage generation ($\pm$ 500v)
- Langmuir plasma probe
- Leakage current/arcing/radiation level sensors

Flight Experiment Characteristics

The PASP+ (Photovoltaic Array Space Power Plus Diagnostics) experiment will allow direct comparison of in-space performance of 11 different solar array types. During the flight voltage versus current curves will be generated to observe the power characteristics of each module under varying levels of illumination, bias voltage and plasma environments and at various operational temperatures.

A Langmuir probe will measure plasma characteristics while other instruments quantify arcing potential and leakage currents while the array is subject to various levels of bias voltage.

A dosimeter will be measuring ambient radiation levels to allow long-term correlation with degradation rates.

Tandem Concentrator Photovoltaic Arrays

- Background of Tandem Concentrator Technology
- APEX Mission Flight Qualification Modules
- **Large Array Design for SSF Evolution**

BTC Large Array Design Requirements

- ORU compatible with baseline Beta gimbal and power control system
- Same end-of-life power as baseline wing
- 0.1 g max. on-orbit acceleration
- 0.5 hz minimum frequency
- Plume impingement loads
- 2 degree pointing accuracy tolerance goal

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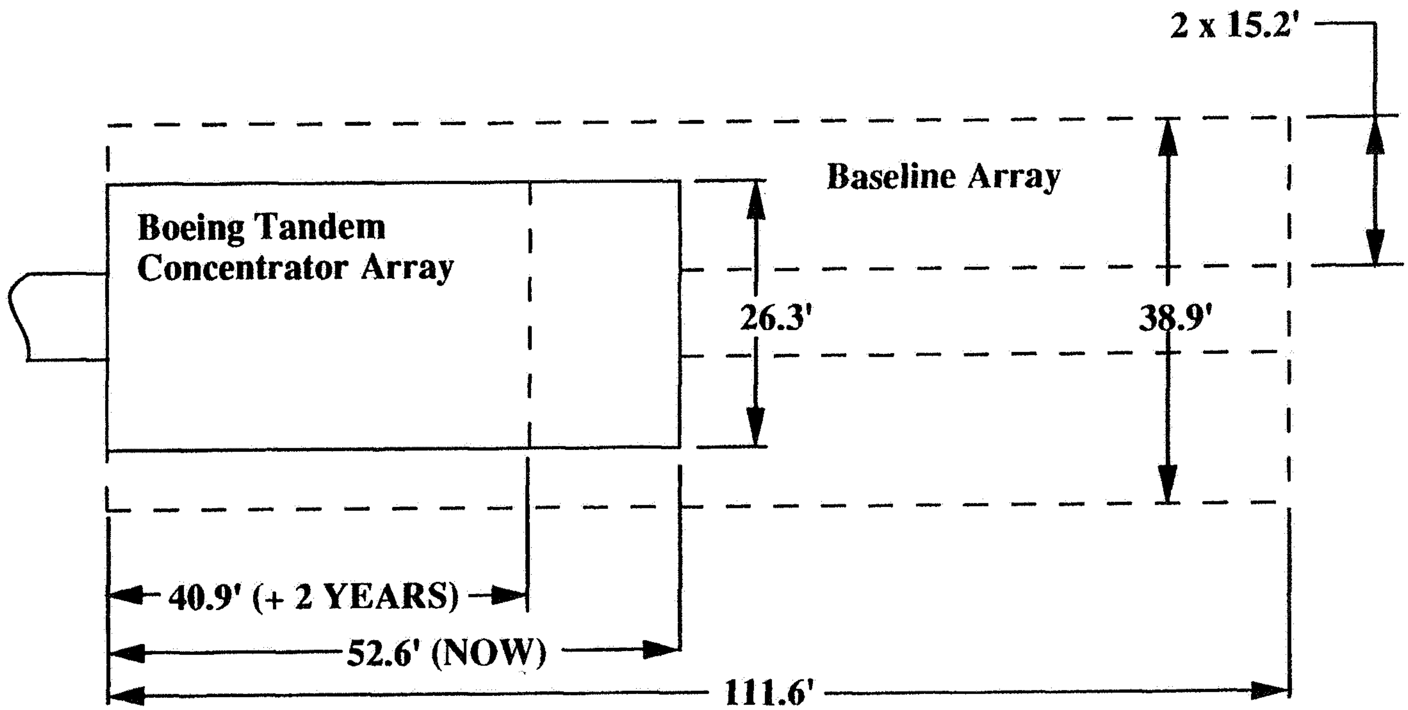
BTC Large Array Design Requirements

BOEING

Boeing is developing designs for large tandem concentrator arrays by using the application to growth versions of Space Station Freedom as a design focus. We have therefore adopted as a requirement for the array the necessity of being an orbital replacement unit which interfaces directly to the baseline Beta gimbal and electric power distribution system. We have chosen to meet the end-of-life power and voltage requirements of the baseline array to allow easy comparisons. The design could just as well be scaled to an equivalent area as the baseline array and therefore produce more power.

Additional requirements are a 0.1 g maximum on-orbit acceleration level (calculated from the On-Orbit Structural Design Loads Data Book, SSP 30800, dated April 15, 1990) and a 0.1 hz minimum structural first mode frequency . We have set a design requirement of 0.5 hz for ourselves, however. Power production degradation has been estimated to be 17.4% over 15 years, slightly less than the baseline array due to the higher radiation resistance of gallium-arsenide cells. We have not included the benefit of the better protection afforded by the structure and lenses as yet. Our goal is to provide a 2 degree allowance for pointing accuracy.

BTC Advanced Array Design



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BTC Advanced Array Design

BOEING

The Boeing SSF growth array design uses cells of 5.4 mm diameter. The spherical lens provides a focus spot of 3 mm diameter. The extra cell material will allow a 2 degree off-axis pointing error before the sunlight energy begins to move beyond the power producing area of the cell.

Each panel in the array is composed of nine structural modules each containing 576 cell stacks (192 triplets). Each module structure is approximately 36" square and 1" deep. Based on current actual performance of assembled triplets and lenses a total of 18 panels are required to provide the needed end-of-life power and minimum voltage equal to a Space Station Freedom baseline wing. Our development program has produced rapid performance increases in the past year and we predict that within 2 years an additional 25% improvement in overall performance will be achieved. The expected performance increase will reduce the number of required panels to only 14 and bring us very close to our long-term performance goals.

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BTC vs. SSF Baseline Performance

BOEING

	BTC	Baseline
Power (kW, BOL)	29.4	30.8
Area (m^2)	128.8	315.4
Mass (kg)	421	849
Area specific power (W/m^2)	228.4	97.7
+ 2 year projection	293.5	
Design Goal	300	
Mass specific power (W/kg)	69.8	36.3
+ 2 year projection	87.8	
Design Goal	100	

BTC vs. SSF Baseline Performance

BTC array performance numbers are calculated using present power outputs from working triplets. These numbers therefore include all actual sources of loss such as lens scatter and reflection, interconnection losses, etc. Actual triplet performance has increased dramatically during this past year's development effort and increases are expected to continue in the future.

Two year projections for the BTC array are based on an assumption of a 25% total power increase believed achievable compared to the present actual performance. These increases are expected as the result of the addition of anti-reflective coatings on the lenses, better cell and lens efficiencies, and prismatic cell covers.

Weight calculations included the mast, blankets or panels, hinges or other locking mechanisms, and wire harnesses. Not included for either array are deployment mechanisms or actuators.

Baseline array performance numbers and area and weight calculations are taken from the WP-04 Preliminary Design Review package.

BTC Array Design For SSF Growth

- Double the baseline wing power
- Panel Area required = 258 m^2
- Wing mass = 900 kg; 0.4 hz minimum frequency
- Add 4 outboard wings for a 150 kw station

BTC Array Design For SSF Growth

Given the preceeding data we can speculate on what type of design might be required for the evolutionary Space Station. Assuming that the total station power level needs to be doubled, then an array which delivers twice the baseline power per wing would be desired. Using our 2 year projected values, such an array would have an area of 258 square meters and a mass of approximately 900 kg, assuming its minimum structural frequency would be 0.4 hz. Four such wings added outboard of the baseline array would increase the power available from 75 to 150 kw.

Additional Areas of On-Going IR&D

- Mechanisms and truss design for large arrays
  - Computer simulations of deployment dynamics
- Module design optimization and producibility
- Critical component detail design, fabrication and environmental testing
- Ready to support large-scale ground demonstration in 1992

Additional Areas of On-Going IR&D

At Boeing we have an on-going IR&D program which aims to develop every aspect of tandem concentrator technology. One such area are the mechanisms and truss structures needed to deploy large photovoltaic arrays in space. Once a design concept is identified, we use computer modeling techniques to simulate the static and dynamic behavior of such deployable trusses when weightless.

We are continuing to optimized our module structural design and are trading various materials against aluminum, notable GrEp and metal matrix materials. We are also investigating thepossibility of automating the stack assembly and interconnection tasks.

As the design studies identify critical components or processes needing development, we are fabricating prototypes and subjecting them to performance and environmental testing in our test chambers in Kent, Washington. This work is starting now and will be increasing in intensity through the remainder of this year and next.

As a result of these efforts we plan to be ready to support a large-scale ground demonstration, presently envisioned as a partial array with full-size components, in late 1992.

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Summary of Advanced Solar Power Program

BOEING

- High-efficiency cells and lenses developed and tested
- 12-cell modules have been flight qualified and will be spaceflight tested on APEX mission in 1992
  - This flight will achieve "Technology Readiness Level 7" for tandem concentrators
- Large-array design effort focussing on SSF evolution

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Summary of Advanced Solar Power Program

BOEING

Boeing has developed tandem solar cells with conversion efficiencies exceeding 30% when tested with standard methods at 100 suns and air mass zero. When combined with the mini-dome fresnel lens design underdevelopment at NASA and Entech photovoltaic arrays with significant performance gains compared to the present state of the art can be expected.

In the past year Boeing has developed and space qualified 12-cell modules using lenses from Entech and the Boeing tandem cells by combining them in lightweight aluminum structures and assembled the system using in-house micro-electronic processes. Such a module will be flight tested on the APEX mission and will elevate tandem concentrator design to NASA technology readiness level seven, which is "System Validation Model Tested In Space."

Boeing also has underway a program to develop tandem concentrator tehcnology further in every aspect from the individual cells to large array designs suitable for Space Station Freedom evolutionary requirements.