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NASA Programs in Space Photovoltaics

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NASA PROGRAMS IN SPACE PHOTOVOLTAICS

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ABSTRACT

This paper highlights some of the current programs in advanced space solar cell and array development conducted by NASA in support of its future mission requirements. Recent developments are presented for a variety of solar cell types, including both single crystal and thin film cells. A brief description of an advanced concentrator array capable of AM0 efficiencies approaching 25 percent is also provided.

1. SPACE POWER SYSTEM DESCRIPTION

1.1 Space Photovoltaic Power System Description

Figure 1 contains a block diagram of a complete photovoltaic power system. As can be seen, it is comprised of a number of subsystem elements, one of which is the solar array. As shown in figure 2, the array itself is a set of subsystems, with the result that designing and building even the solar array, let alone the entire satellite power system, requires an interdisciplinary, well coordinated effort. We shall touch briefly on some of the important aspects of advanced array technology in section 4. The primary focus of the rest of the paper will be on advanced space solar cell research and development.

There are two figures of merit that are used to measure the performance of a space solar array, as well as the entire power system: power per unit mass in watts/kilogram (W/kg), and power per unit area in watts/square meter (W/m^2). These are referred to simply as specific power and area power density, respectively. The inverses of these quantities are also often used, and are known as specific mass (kg/kW), and specific area (m^2/kW). Typical values for state-of-the-art (SOA) space solar arrays, using silicon solar cells mounted on rigid panels, are 30 to 40 W/kg and 90 to 110 W/m^2 at the start of the mission, or beginning-of-life (BOL). The end-of-life (EOL) values for any given array are dependent on mission time and location. Chief among the factors affecting the ratio of EOL to BOL are radiation damage to the solar cells, followed by mechanical and electrical degradation of the cells, interconnections and array components from other environmental effects, such as plasma interactions and thermal cycling. Elimination, or at least substantial mitigation, of such effects is at the heart of all space photovoltaic device and system research and development efforts.

1.2 Space Solar Cell and Array Technology Drivers

The most important specific technology drivers for advanced space solar cells which derive from the general attributes described above are high efficiency and lifetime, with mass and cost of secondary importance. The principle reason is that the solar cells are a relatively smaller fraction of the total mass and cost of a system, while their efficiency and usable lifetime are major determinants of the balance-of-system (BOS) mass and cost. Array lifetime is mission specific, and is loosely defined to be the length of time the array operates before its output power has fallen to a level below that needed for reliable satellite or surface system operation. The chief cause of electrical degradation is radiation damage caused by the trapped charged particles in earth orbit, and solar flare protons. The extent to which a solar cell can resist radiation damage depends on many factors: the material from which it is made (i.e., silicon, gallium arsenide, indium phosphide, etc.), the structure of the device, and its annealability. We shall discuss the radiation resistance of several solar cell types in the next section.

2. ADVANCED SPACE SOLAR CELLS

Silicon solar cell arrays are still the primary sources of power for most satellites. Although specialized improvements continue to be made in silicon solar cells for space applications, they will not be discussed in this paper. The space silicon solar cell is considered a "mature technology," in which improvements are routinely accomplished by commercial vendors by implementing advanced fabrication techniques and cell designs in the manufacturing process. Our understanding of the fundamentals of high efficiency operation and radiation resistance in silicon solar cells is essentially complete (ref. 1). The same cannot be said for the advanced cell types and materials of current interest, however. Table I lists several advanced solar cell types that are of interest for use on planar arrays in high natural charged particle radiation environments, along with the data for commercial silicon cells. The laboratory efficiencies quoted for all cell types in the table are for 2 by 2 cm cells except where noted. The expected date of availability in each case is a subjective estimate of the time required to move the technology from the laboratory R&D phase through a successful demonstration on a pilot production line, given adequate funding to do so.

2.1 Gallium Arsenide Space Solar Cells

Although our theoretical understanding of gallium arsenide space solar cells is not as advanced as our understanding of silicon cells, cell development has progressed to the point that a GaAs cell with a simple p/n structure is now commercially available (ref. 2). What is lacking is the same depth of knowledge, as now exists for silicon at the microscopic level, of the effects on cell performance from unwanted material imperfections and impurities, particularly with regard to radiation damage degradation. Theoretical analysis predicts small but significant differences in the performance of p/n and n/p cells prior to and after radiation damage (refs. 3 and 4). Such differences have not always been observed in practice, in part because material quality and fabrication techniques are not fully under control, and in part because theoretical models still need better data on key electronic and material properties. Despite the present shortcomings in our understanding of state-of-the-art GaAs solar cells, the fact remains that they are more efficient than silicon cells. Laboratory efficiencies of 22.5 percent have been attained in GaAs cells to date (ref. 5).

2.2 Indium Phosphide Space Solar Cells

While the radiation resistance of GaAs is significantly better than that of standard (i.e., 200 μm thick) Si cells, the advantage disappears when GaAs is compared to thin silicon cells. The data are shown in figure 3, where the relative performances of both cell types are shown. The silicon cells in this case are 62 μm thick, and are designed for use on the newer, lightweight solar arrays that are currently under development by NASA (ref. 6). The primary difference is that the lightweight arrays do not have rigid panels made from aluminum honeycomb, but instead have panels made from a thin polyimide sheet, such as Kapton. The aluminum honeycomb panels provide a significant amount of protection from the charged particle radiation that is incident on the backside of the array, while the thin polyimide panels do not. The thin silicon cells provide a trade-off between absolute efficiency and radiation resistance by providing somewhat less power than standard Si cells at BOL, but degrading less (ref. 7). Hence the absolute EOL efficiencies of the two silicon cell types are comparable. Both are substantially lower than GaAs cells, but the impact is far different. Unlike the situation with rigid panels, the cells account for a larger fraction of the total lightweight array mass than they do on the former. Because of the similar radiation resistance behavior, the absolute EOL specific power of a flexible array is higher with thin silicon cells than with either standard silicon cells, any of the GaAs cell types, except the CLEFT 6 μm cell (ref. 8). Although the latter is still not yet a commercial device, its performance potential warrants further development.

Improvement of the EOL specific power of flexible arrays requires the development of cells with significantly better radiation resistance than either GaAs or thin silicon, provided they also have one of two other characteristics: extreme lightweight, or AM0 efficiencies comparable to GaAs (i.e., at least 20 percent AM0). Candidates in the former category are the thin film cells such as amorphous silicon and copper indium diselenide, which shall be discussed in a later section. In the latter category, only single crystal solar cells have exhibited the requisite high efficiencies. What is required is the demonstration of high radiation resistance. Figure 3 shows the relative efficiency degradation of InP solar cells as a function of 1 MeV electron irradiation. The normalized curves for GaAs and thin (62 μm) single crystal silicon are shown as well. Figure 4 contains the same sort of data for 10 MeV proton irradiations. The superior radiation resistance of InP is clearly evident. The room temperature band gap of InP is 1.35 eV, very near the band gap of GaAs cells. Hence, InP cells can be expected to have an AM0 efficiency comparable to that of GaAs cells. Efficiencies in excess of 19 percent AM0 have been demonstrated in laboratory devices (ref. 9).

Although InP is somewhat less dense than GaAs, and needs only a 4 μm thick active layer, the cells are still significantly heavier than the 62 μm Si cell. To compete effectively, InP cells need to be fabricated either on a silicon substrate, or as a stand-alone thin cell, similar to the CLEFT GaAs cell. A recent study (ref. 10) indicates, however, that the p/n cell may have a slightly higher efficiency than the n/p cell, because of a higher open circuit voltage. That possibility, coupled with interest in growing InP directly on silicon substrates, makes the p/n structure the one of choice for future development. The p/n structure is favored for heteroepitaxial growth because n-type autodoping by silicon from the substrate occurs in the adjacent InP layer during the OMCVD growth. If the first layer is p-type, a p/n diode is formed which seriously degrades the performance of the cell (ref. 11). If the first layer is n-type, the autodoping may actually enhance the output of the cell in much the same manner as doping density gradients have been found to work in silicon cells (ref. 1). More detail on the status of InP cell development can be found in the paper by Jain and Weinberg (ref. 12) found elsewhere in this volume.

2.3 Thin Film Cells for Space Application

Although the thin film cells do not appear able to achieve efficiencies that compete with advanced, single crystal solar cells, they offer the potential for extremely high specific powers and low cost manufacturing techniques. The key technology issue is direct, monolithic fabrication of the cells and interconnects on space qualified, flexible substrates. There are at present three thin film cells of interest: amorphous silicon (a-Si), copper indium diselenide (CIS), and cadmium telluride (CdTe). Of these, only amorphous silicon has been fabricated in appreciable quantity on flexible substrates of any sort. Materials used with various degrees of success include thin stainless steel and polyester sheet (ref. 13), polyethylene terepthalate (ref. 14) and polyimide (Kapton) (refs. 15 and 16). Even though thin, the stainless steel substrate is still too heavy to yield high specific power arrays and is not of further interest in this discussion. Of the nonmetallic substrates, only the polyimide (Kapton) has been used in space solar arrays and has been shown to avoid degradation from the intense ultraviolet light in the AM0 spectrum.

There are a large number of possible structures for a-Si solar cells, and not all of them have been fabricated on each of the flexible substrates. In fact, because of the large number of different cell types based on amorphous silicon, care must be exercised when comparing their efficiency and radiation resistance. Many reports of high radiation resistance came from measurements made on early, low efficiency cells, primarily single gap, single junction structures. Table II illustrates the situation. There is as yet little or no data on the radiation resistance of the more advanced, higher efficiency a-Si solar cell structures.

CIS ($CuInSe_2$) cells on flexible, nonmetallic substrates have only recently begun to be investigated by NASA at the time of this writing, with the result that there is essentially no data to report. A related effort to deposit CIS cells on thin metal foils has been reported (ref. 17), but again, no efficiency or radiation damage data are available at this time. Radiation damage studies on CIS cells deposited on conventional glass substrates have shown superior resistance to 1 MeV electron radiation compared to the best single crystal cells of any type (ref. 18), and good resistance to proton radiation damage (ref. 19), as indicated in table II. There is no reported work on deposition on flexible substrates for any of the remaining cells listed in there. They are included here because they offer the potential for higher efficiency than CIS cells, with the possibility that they could be incorporated into monolithically integrated, flexible, thin film submodules.

2.4 Multiple Band Gap Space Solar Cells

No attempt will be made to summarize all the multiple band gap solar cell types that have potential for space application. Candidates range from two junction, mechanically stacked, two or four terminal devices to monolithically grown three junction structures with a variety of interconnect configurations. They can be combinations of thin film and single crystal devices, and can be designed for either planar or concentrator operation. The key point is that there have been rapid and significant advances in the technology for producing such cells (refs. 20 to 23).

The ability to accurately measure the performance of multiple band gap cells, however, has only recently begun to be addressed (ref. 24). Work recently performed at NASA Lewis Research Center has clearly shown the need for extreme care with MBG cell measurements. Results of experiments performed in the NASA high altitude aircraft to obtain the full I-V curve and the temperature dependence of MBG cells at low air mass show conclusively that conventional laboratory techniques will be misleading (ref. 25). The variation with temperature of the band gap of the upper cell has a major effect on overall device efficiency, as does the spectral content of the incident light used in the testing. Conventional laboratory simulators are often too rich in the red region of their output spectrum, and can give misleading (usually high) values for the MBG device efficiency. Measurement of the correct temperature dependence of such cells in the incorrect spectrum is virtually impossible. Until more advanced laboratory light sources are available, high altitude measurement of the full I-V characteristic and temperature dependence of the test device will be the only way to obtain correct results.

Although multiple band gap cells with up to three junctions are feasible, the gain in efficiency over two junction devices does not appear to justify the complexity in fabrication that appears necessary. For that reason, more attention has been paid to two junction devices. An issue not yet settled is which of two fundamentally different types of two junction cells is preferable for space application: monolithically grown cells or mechanically stacked cells. In the first case, the devices are most likely to have two terminals for interconnection to other cells on an array. Three, and even four terminal configurations are possible, with a great deal more complexity required in fabrication. In the second case, the devices are most likely to have four terminals. Again, two or three terminal configurations are possible, also with more difficulty in fabrication. From a practical standpoint, array designers have traditionally preferred two terminals; three or four terminals will increase the complexity of the interconnect design and wiring harness on the solar array. On the other hand, the monolithically grown cell will exhibit more radiation degradation than the four terminal device and has more stringent conditions on the selection of band gaps to maximize its efficiency. As we shall see in the next section, the use of two junction, four terminal, mechanically stacked cells may actually be an advantage in concentrator arrays.

3. ADVANCED SPACE SOLAR ARRAY TECHNOLOGY

Figure 5 shows a 36 element submodule of an advanced space concentrator array concept now under development by NASA. A schematic of the basic conversion element is shown in figure 6. It consists of a unique, lightweight domed fresnel lens (ref. 26) mounted over a high efficiency concentrator cell. The cell can be a single junction, two terminal cell, or a multiple band gap cell with multiple terminals. This sort of technology transparency is one of the key features of the design; the second is the potential for low cost. The latter derives from the fact that concentrator arrays require a greatly reduced area to be covered by expensive semiconductor devices compared to planar arrays of the same output. An equivalent area must be covered by the lenses, but they are made inexpensively out of low cost materials.

The panel shown is designed for operation at a nominal 100X concentration ratio. Because the concentrator cell covers less than 5 percent of the panel area for the submodule shown, there is sufficient room on the panel to allow for innovative interconnection and wiring harness designs to be used without any impact on the area power density, as would be the case for a typical planar array. As a result, a mechanically stacked two junction cell can be interconnected in a variety of ways, such as a voltage-matched configuration rather than in a simple series (two terminal) or parallel (four terminal) manner. An immediate consequence is that the effects of higher operating temperature and radiation damage are not as severe as they would be for a two terminal device, and wiring design complexity is greatly reduced. This basic wiring scheme can be repeated until all the cells on the array are interconnected. The potential exists for significant gains in specific power and area power density with this technology compared to state-of-the-art rigid planar silicon solar arrays.

4. CONCLUSION

A wide variety of potential space solar cell technologies are beginning to emerge, ranging from ultralightweight, flexible thin film submodules to advanced, high efficiency concentrator arrays using multiple band gap solar cells. Blanket BOL specific powers exceeding 1000 W/kg are now feasible, with only modest advances in thin film efficiency. The radiation resistance of future space solar cells may be such that array lifetimes may be extended by at least a factor of three. Concentrator array BOL power densities exceeding 300 W/m^2 are also possible, with specific powers exceeding current rigid planar array technology.

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TABLE I. — ADVANCED PLANAR SPACE SOLAR CELL TECHNOLOGY STATUS

Cell type	Cell structure	Projected efficiency, percent	Laboratory efficiency, percent	Commercial efficiency, percent	P/P_o (1E15 cm^{-2} 1 Mev electrons)	P/P_o (E12 cm^{-2} 10 Mev protons)	Estimated date available
Thin silicon	62 μm substrate n/p diffused BSF, BSR	14.5	14.5	13.7	0.74	Damage equivalence to 1 MeV protons known	Now
GaAs	300 μm substrate n/p, p/n OMCVD, LPE	23	21.5	20	0.74	0.8	Now
GaAs/Ge	75 μm substrate 10 μm cell, p/n OMCVD	23	20.5	20	0.74	0.8	Now
CLEFT GaAs/Si	62 μm substrate 6 μm cell n/p, p/n OMCVD	23	20	----	0.74	0.8	1994
InP	300 μm substrate n/p OMCVD	22	19	----	0.975	0.9	1993
InP/Ge	75 μm substrate[a] 10 μm cell, n/p OMCVD	20.5	9	----	0.975	----	1995
InP/Si	62 μm substrate[a] 10 μm cell, n/p OMCVD	18.5	7	----	----	----	1997
CuInSe2	5 μm film, 50 μm glass substrate[a]	16	11	----	>0.98	0.9 (1 MeV)	1993

[a]Projected thickness. All radiation damage results without coverglasses.

TABLE II. — POTENTIAL THIN FILM SOLAR CELLS FOR SPACE APPLICATIONS

[All efficiencies estimated from AM1 and AM1.5 measurements.]

Cell type	Cell structure	Projected efficiency, percent	Laboratory efficiency, percent	Commercial efficiency, percent	Radiation resistance, P/Po	
					1×10^{15} 1 MeV, e−	1×10^{13} 1 MeV, p+
a-Si	Single junction, single gap on rigid substrate	10	<9.0	<5.0	0.80	0.65
a-Si	Tandem junction, single gap on rigid substrate	12	9.9	<5.0	----	0.75
a-Si	Tandem junction, single gap on flexible substrate	10	5.5	----	----	----
a-Si	Tandem junction, dual gap on rigid substrate	15	8.6	----	----	----
a-Si	Monolithic, multiple band gap on rigid substrate	18	10.9	----	----	----
$CuInSe_2$	3 μm cell, 1 μm window on glass substrate	>13	10.4	----	1.00	0.65
$CuIn_xGa_{1-x}Se$	3 μm cell, 1 μm window on glass substrate	>15	8.2	----	----	----
CdTe	Thin film on glass superstrate	>18	9.8	----	----	----
a-Si/$CuInSe_2$	Mechanically stacked tandem cell	>20	12.5	----	----	----

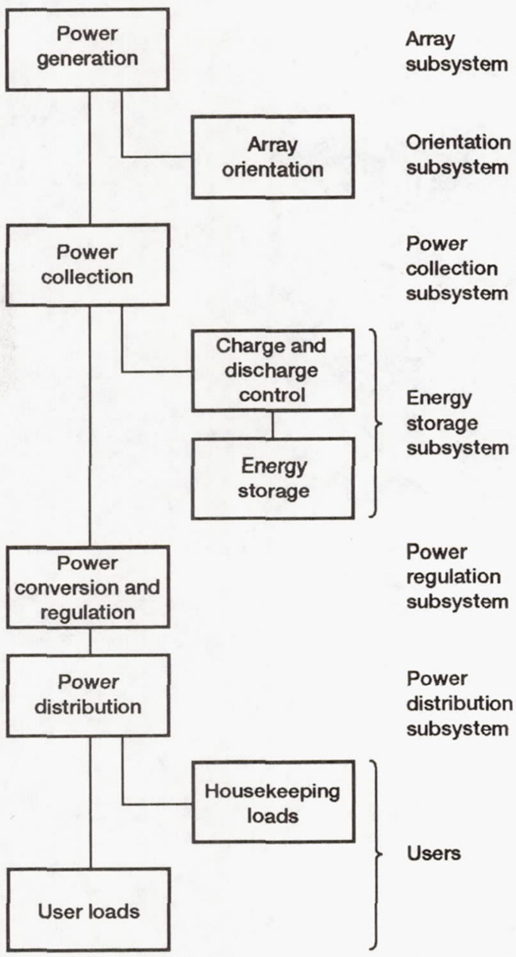

Figure 1.—Block diagram of a space photovoltaic power system.

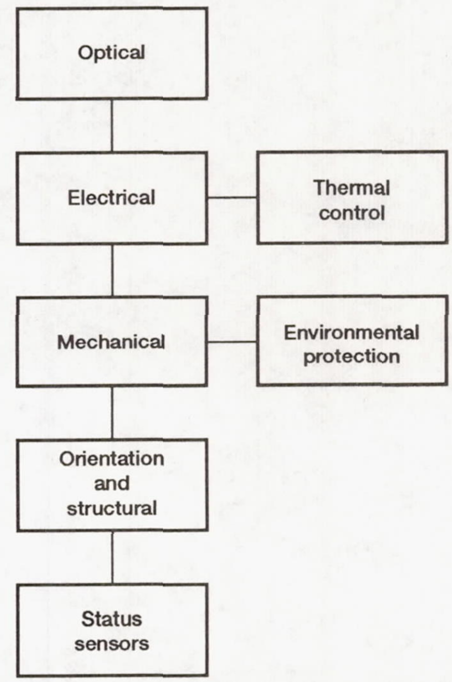

Figure 2.—Block diagram of a space photovoltaic power system.

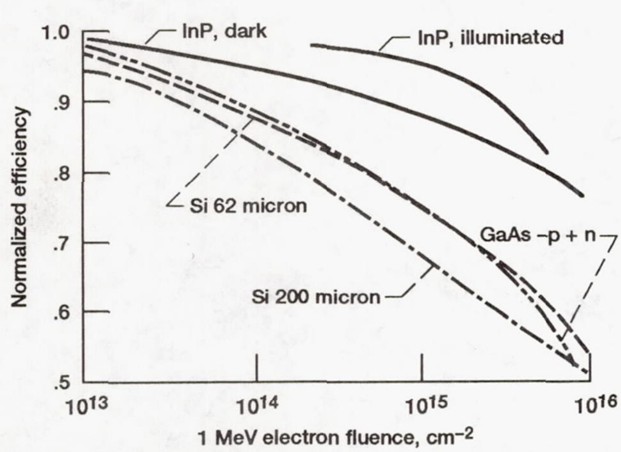

Figure 3.—Normalized cell efficiencies of Si, GaAs, and InP after 1 MeV electron fluence.

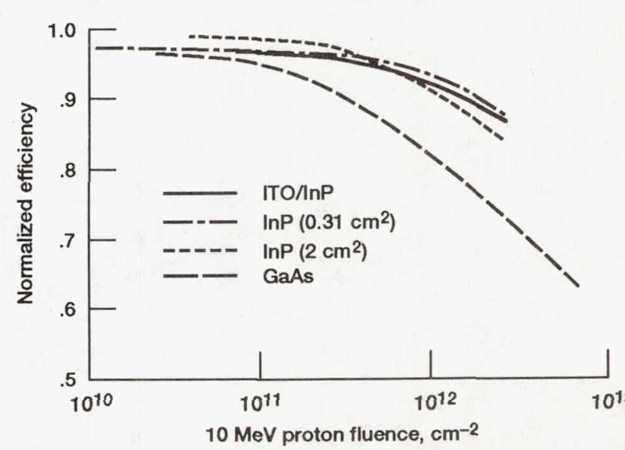

Figure 4.—Normalized cell efficiencies of InP and GaAs after 10 MeV proton fluence.

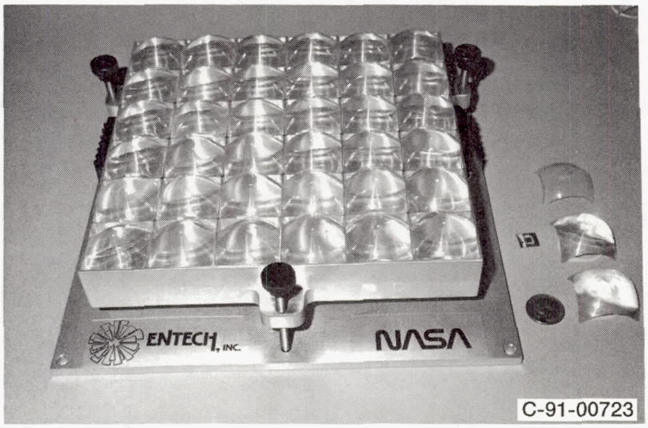

Figure 5.—High efficiency mini domed Fresnel lens concentrator submodule.

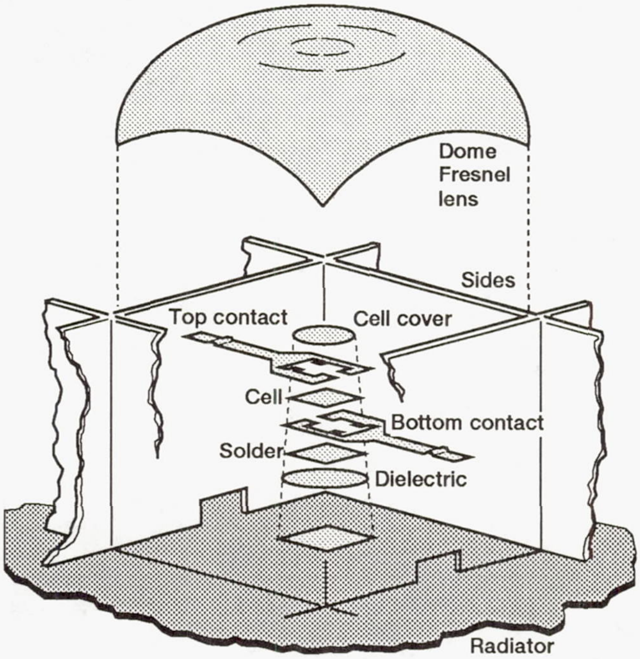

Figure 6.—Schematic representation of mini domed Fresnel lens/cell element.

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13. ABSTRACT *(Maximum 200 words)*

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