

SPACECRAFT POWER SYSTEM TECHNOLOGIES

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Introduction

Space platforms are configured based on three basic systems. The first of these is the ground segment, in which the ground station, command and control center and operating units are located, and the other is the launch center and launch vehicle, and finally the space segment in which the space platform or satellite is located.

The most important and decisive factor in a space platform is the payload and its configuration. Payloads differ, sometimes according to the mission of examining the physical elements of space or observing space objects, sometimes according to the mission of communication to transmit information. The function of a communications satellite is to receive signals, amplify and retransmit the received signal. All of these processes are carried out by the satellite's subsystems.

Although there may be differences in the subsystems it has depending on factors such as mission type, mission region, mission duration, structure, in the most general sense, the subsystems of a space platform; It can be counted as communication, propulsion, telemetry, tracking, control, and monitoring (TTC&M), power, attitude control, structure, thermal control, and command and data handling subsystems, especially payload.

Given the vital role that satellites play in contemporary society, it is crucial to maximize their technological efficiency and, consequently, the rate of return for investors. The power system, which produces the energy required for the satellite to operate, determines the satellite dimensions, operating life, mission efficiency and cost depending on the useful payload of the satellite. In this process, reducing weight and ensuring sustainability are considered very important in improving the performance of power systems for the satellite (Keser, et al., 2017; Idare, B., 2018).

When the Sputnik-1 satellite, which is considered to be the beginning of the space age, was sent into space on October 4, 1957, the silver-zinc battery on it was the only energy source. The battery provided a total of 1 W of power to the two signal transmitters on the satellite. At the end of 3 weeks, signal reception from the transmitters ended with the depletion of the battery (Hyder et al., 2003). Today, the International Space Station, with 32800 solar cells and a total power generation capacity of 248 kW, continues its activities in the space environment as a science center where scientists from many nations conduct

space studies. While the amount of power needed in the first satellite in 1957 was 1 watt, the power requirement of the space platforms designed today has increased to hundreds of kW, enabling the design of different power systems in solar, thermal, nuclear and chemical structures that can meet the energy needs of these amounts.

While the power systems are being designed, besides the energy needed by the space platform, the power system through which this energy will be provided is equally important, and the main factor determining this is the mission area of the space platform. Because the primary power source for a spacecraft designed for deep space missions will be a nuclear power-based power system, while the primary power source for a space platform in earth orbits is likely to be photovoltaic systems.

The system that manages the process from the production of the energy determined for the payload and carrier system of the satellite to the distribution in a controlled manner is the satellite power system.

Spacecraft Power Subsystem

A spacecraft power subsystem usually consists of 3 basic components; primary and secondary power sources and a power control/distribution unit. These items are shown schematically in Figure 1.

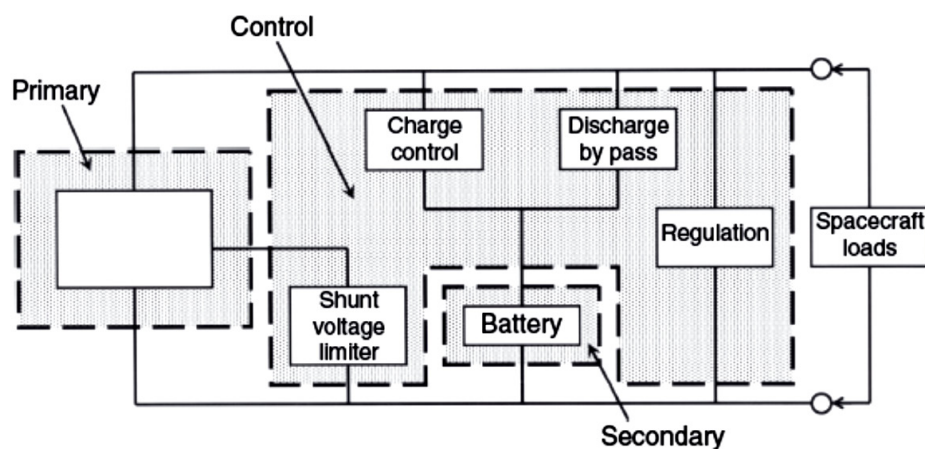


Figure 1. Schematic representation of the power system elements of a spacecraft (Fortescue et al., 2011)

The primary power system converts a fuel into electrical energy. In the first spacecrafts, the electrical energy was provided by batteries. Batteries doesn't convert a fuel into electrical energy, only use stored energy. In today's spacecrafts, solar cells are often used as the primary power system. While fuel cells are used as the primary power source in short-term manned space missions, fuel cell-solar cell hybrid systems are used if the mission period is longer. Hydrogen and oxygen molecules are combined to produce heat and water as the outcome of the reaction in the fuel cells. While the heat can be used to generate electricity, the water can be used for the needs of astronauts in spacecraft during the space mission. Nuclear powered systems use either a radioactive decay process (for RTGs) or a nuclear fusion process as their energy source. While RTGs benefit from the

thermoelectric effect, fusion reactors operate in a similar way to nuclear power plants on the world (Bennett, 1995). Figure 2 shows the cycle of the energy produced by the primary power systems and its transmission to the related units with the power control/distribution network.

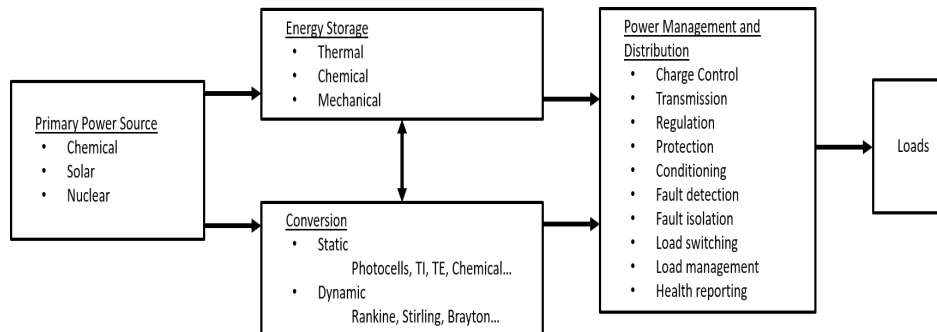


Figure 2.. Power generation-distribution cycle (Hyder et al., 2003).

The secondary energy source is used to store the converted electrical energy and distribute the energy to the spacecraft subsystems and its payloads in the absence of a primary energy source. For instance, secondary batteries are used when a solar powered spacecraft/satellite stays in the dark side of its period and primary power systems are not functional. Table 1. shows the specifications of some battery types used as secondary power systems. The power control and distribution system regulates the load-voltage values and distribute electrical energy to all spacecraft subsystems.

Table1. Secondary Batteries And Their Specifications (Hyder et al., 2003)

	Silver Zinc	Nickel Cadmium	Nickel Hydrogen
Energy Density (W.h/kg)	90	35	75
Energy Density (W.h/dm ³)	245	90	60
Oper Temp (°C)	0 – 20	0 – 20	0 - 40
Storage Temp (°C)	0 – 30	0 – 30	0 – 30
Dry Storage Life	5 years	5 years	5 years
Wet Storage Life	30 – 90 days	2 years	2 years
Max cycle life	200	20.000	20.000
Open circuit (V/cell)	1,9	1,35	1,55
Discharge (V/cell)	1,8-1,5	1,25	1,25
Charge (V/cell)	2,0	1,45	1,50
Manufacturers	Eagle-Pitcher, Yardney Technical Prod	Eagle-Pitcher, Gates Aerospace Batteries	Eagle-Pitcher, Yardney, Gates, Hughes

Primary Power Systems

The primary energy system converts a fuel into electrical energy. In the first spacecrafts, only batteries were used as the power source and thus there were no conversion process. Batteries doesn't convert any energy source to electrical energy, only use the stored energy inside. Later, with the developing technology, the use of fuel cells, photovoltaic and nuclear power systems in space missions had become widespread. Different primary power systems are shown in Figure 3. As clearly seen on the figure, photovoltaic and nuclear power systems are the most suitable power systems for spacecraft and satellites.

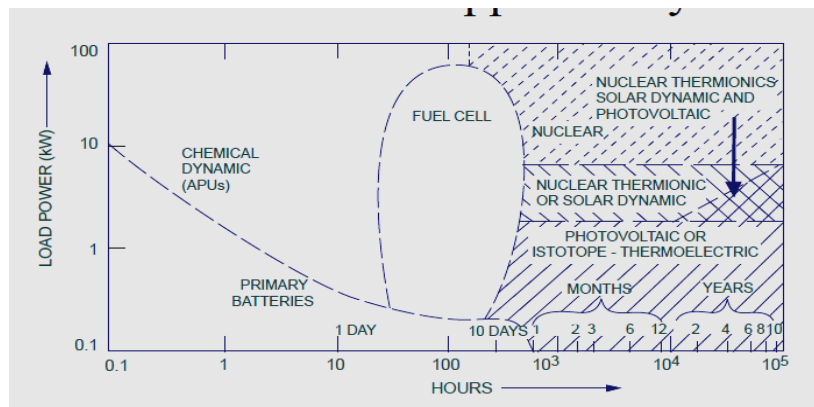


Figure 3. Primary power systems and their lifetime (Miller et al.)

Although they are named differently in different references, in the most basic sense, primary power systems can be listed as in Figure 4.

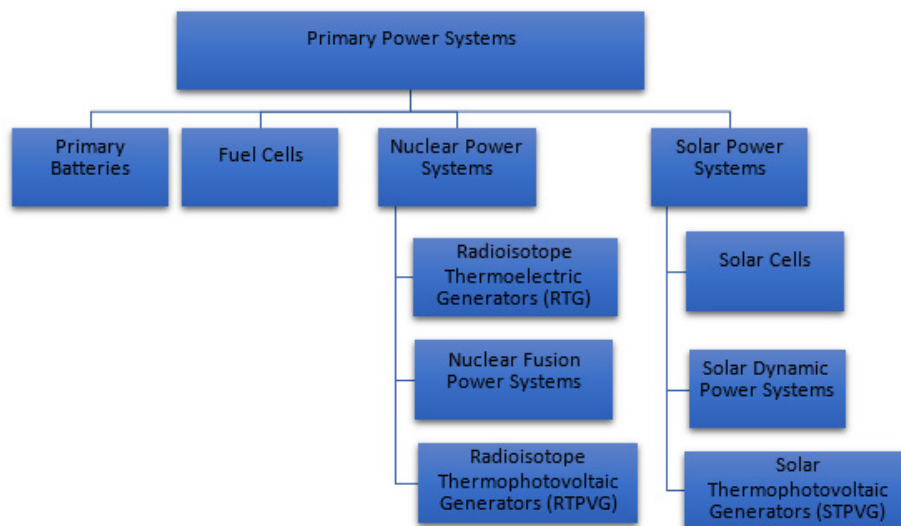


Figure 4. Primary power systems

Primary Batteries

Primary batteries convert chemically stored energy into electrical energy. The difference between primary and secondary batteries is that while the secondary batteries are used

to store the electrical energy produced in the primary power systems, primary batteries are the only power generation system in the spacecraft and the energy capacity of the spacecraft is limited with the energy stored in the primary battery. Battery types used as primary batteries and their properties are shown in Table 2.

Table 2. Primary Batteries (Miller et al.)

	Silver zinc	Lithium sulfur dioxide	Lithium carbon monofluoride	Lithium thionyl chloride
Energy Density (W.h/kg)	130	220	210	275
Energy Density (W.h/dm³)	360	300	320	340
Op Temp (°C)	0 – 40	-50 – 75	? - 82	-40 - 70
Storage Temp (°C)	0 – 30	0 – 50	0 – 10	0 - 30
Storage Life	30-90 days wet, 5 years dry	10 years	2 years	5 years
Open circuit voltage (V/cell)	1,6	3,0	3,0	3,6
Discharge voltage (V/cell)	1,5	2,7	2,5	3,2
Manufacturers	Eagle-Pitcher, Yardley	Honeywell, Power Conver	Eagle-Pitcher	Duracell, Altus, ITT

The first use of primary batteries dates back to Sputnik-1, which was sent into space by the Soviet Union in 1956. The functional life of Sputnik-1 ended with the discharge of the Silver-Zinc type primary batteries, since there was no other power system to support these batteries in the spacecraft. In the early stages of space studies, Silver-Zinc batteries were preferred, Nickel-Cadmium batteries were used for the next 20 years, and Nickel-Hydrogen and Lithium-Ion batteries have been used since the 1980s (Hyder et al., 2003).

Fuel Cells

The fuel cells shown in Figure 5 have been used as the primary power system, especially in space shuttles and manned space missions. Hydrogen and oxygen molecules are combined in electrochemicals in fuel cells resulting in water and electrical energy as the outcome of the reaction. It is especially designed for manned space missions, and hybrid power systems with photovoltaic-fuel cells are used in these missions. The water resulting from the electrochemical reaction can be used to meet the water needs of astronauts. Due to the necessity of carrying fuel, a fuel cell has limited duty time, heavy weight and needs a large storage area. Contrary to solar cells, a fuel cell is not affected by the external environment, since it is a closed system, It provides opportunity to produce

electrical energy both in the sun-exposed period and in the dark period of the orbit.

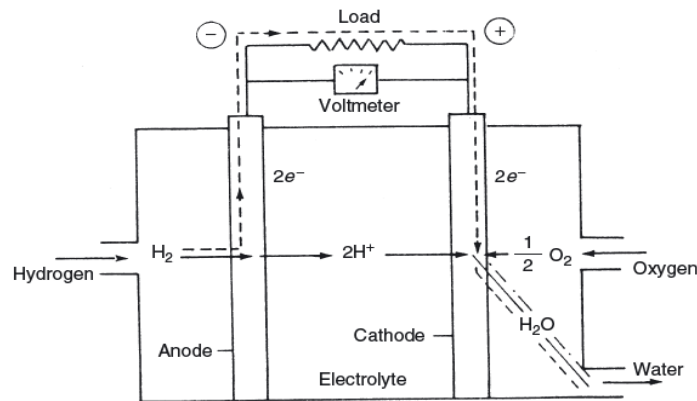


Figure 5. Schematic representation of a fuel cell (Fortescue et al., 2011)

Nuclear Power Systems

There are many nuclear power systems that have been used effectively in space studies for both power generation and heating since 1956. The basic principle of nuclear power systems is to generate electrical energy with different methods by making use of the heat emitted by the radioisotope material.

Radioisotope Thermoelectric Generators (RTG)

Space and terrestrial power applications using radioisotopes have been in use since 1956. RTGs are the most effective power generation devices, especially for deep space and planetary missions (Keser et al., 2019).

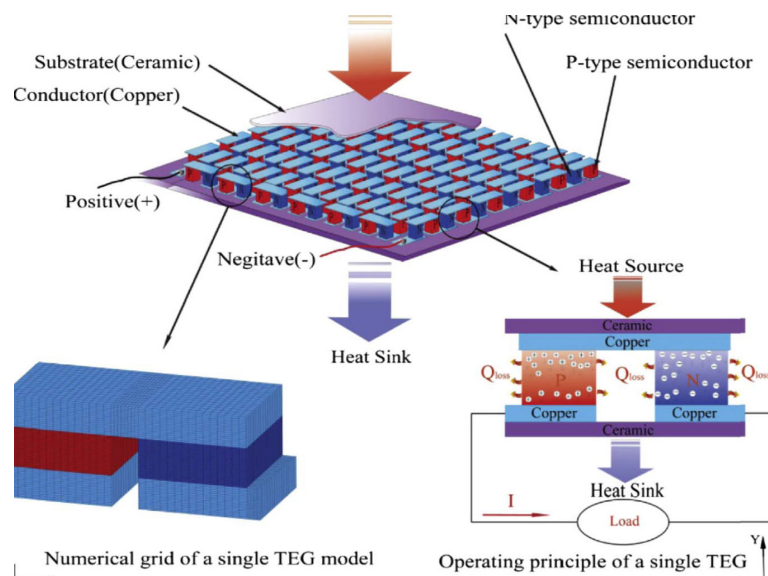


Figure 6. Working principle of a thermoelectric generator module (Twaha et al., 2016)

The Radioisotope Thermoelectric Generator is basically a device that produces electrical energy from the heat emitted by the radioactive material inside, based on the Seebeck effect method. Figure 6 shows the working principle of a thermoelectric generator

module. NASA uses Plutonium 238 as the radioactive heat source in most of the RTGs it produces. While the heat inside RTGs are around 1000°C , heat transfer elements are used for cooling and removing the heat. Silicon-Germanium (SiGe) is the most suitable material for use in RTGs, which operate at such high temperatures with a relatively low efficiency of 6.6% (Fagas et al., 2016). Figure 7. shows the structure of an RTG.

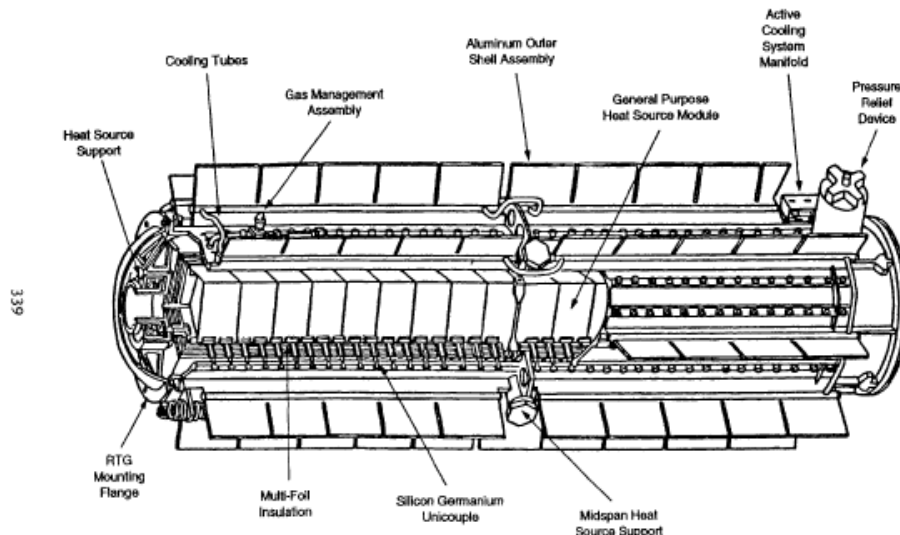


Figure 7. Schematic representation of a Radioisotope Thermoelectric Generator (RTG) (Pisacane, 2005)

Space and terrestrial power applications using radioisotopes have been in use since 1956. SNAP-3, one of the first devices developed in this context, was first introduced in 1959. SNAP-3 was the size of a bunch of grapes, weighed 1.8 kg, had a power of 2.5 W and was capable of producing 11.6 kW/h of energy in a 280-day period. A Nickel-Cadmium battery that can provide the same amount of energy should weigh 315 kg. SNAP-3 used ^{210}Po Polonium alpha emitter isotope as its heat energy source (Raghep, 2012). A total of 45 RTGs in the USA have been used in 26 spacecraft designed for NASA's LEO orbit, missions on the Moon and Mars surface, and research-exploration missions on near-far planets for different missions of NASA.

RTGs are often used in deep space exploration and interplanetary missions. However, it is not cost-effective compared to solar cells and has many problems. RTGs operate at very high temperatures (about 1000°C) resulting in material problems, limiting the operational life of the spacecraft. Another important problem is that RTGs use radioactive materials as fuel, which is a very expensive, rare and dangerous material. These problems result in complex security restrictions and costly ground handling procedures. These factors make the costs of RTGs tens of times more expensive than solar cells, and this limits the use of RTGs to areas where solar cells cannot be used (Pisacane, 2005).

RTGs are not only used to generate energy, but also to protect the electronics, opto-electronics and other systems on the spacecraft from extremely low temperatures of deep space. By directing the waste heat emitted by the nuclear fuels in the RTGs to the related

devices, this problem can be solved with the waste heat energy of the RTGs without the need to use extra energy to heat these devices. RTGs are available in miniature size versions manufactured for heating purposes only. These miniature devices called LW-RHU (Low-Weight Radioisotope Heater Unit) have been used many times in spacecrafts designed especially for deep space missions by the USA (Summerer, 2006).

Nuclear Fusion Power Systems

It works on the same principle as the nuclear fusion systems used on earth. It has been used in spacecraft and deep space missions where high power requirements are required. Uranium-235 is used as a radioactive material. They were mostly used by Soviet Russia and are not used today.

Radioisotope Thermophotovoltaic Power Systems

Although RTGs have been used in many space missions by the USA and Russia, their efficiency is very low compared to photovoltaic and other primary power systems. The main reason for the low efficiency of RTGs is that the efficiency of the SiGe thermoelectric modules inside RTGs are between 5-10%. Today, studies are carried out on different designs to solve the low efficiency problem of RTGs. One of the most striking one of these studies is the Radioisotope Thermophotovoltaic Generator (RTPVG), which is seen in Figure 8. While the efficiency of thermoelectric modules that determine the efficiency of RTGs is between 5-10%, the efficiency of thermophotovoltaic (TPV) modules that determine the efficiency of RTPVGs is 20-25% (Wernsman et al., 2004) and has the potential to increase up to 40% (Datas, 2015). It has been seen as a potential primary power system to replace RTGs.

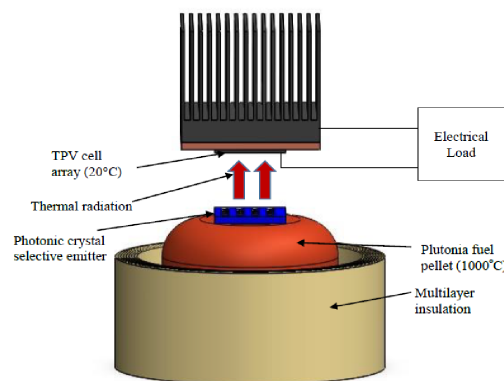


Figure 8. Radioisotope Thermo-Photovoltaic Generator (RTPVG) demonstration (Wang et al., 2015)

Radioisotope Thermophotovoltaic Generator (RTPVG) power systems were first introduced in the mid-1990s as an alternative system to RTGs and as a power system that could reach a power/mass ratio of 15 W/kg. This ratio means that it has a 3-5 times higher power/mass ratio than RTG and its derivatives (MMRTG(2.8 W/kg), GHPS-RTG(5.1 W/kg)). In line with this data, NASA started the first RTPVG project in 2003, 25 series-connected InGaAs TPV cells were used in the first prototype, and 50 watts of power was planned to be generated from a 250 watt heat source. In this context,

the targeted efficiency was around 18-20% and the power/mass ratio was 17 W/kg, but the data obtained were far from these values. With the developing technology and production techniques over time, InGaAs TPV cells which has 20% efficiency have been produced (Datas et al., 2017).

Solar Power Systems

Solar power systems generate electrical energy by utilizing the thermal or photovoltaic properties of solar energy. While photovoltaic energy conversion is available in solar cells, solar dynamic and solar thermal systems intensify solar energy and take advantage of its thermal properties.

Air Mass Coefficient (AM) and Solar Spectrum

The air mass coefficient is used to determine the solar radiation spectrum at the targeted point after the sun's rays move in and out of the atmosphere (in space). The most common use of the air mass coefficient is to provide standardizations in order to determine the efficiency of photovoltaic cells. It is usually symbolized by the abbreviation AM followed by numbering formats. While determining the efficiency of photovoltaic cells produced for use on earth, the value AM1.5 is the most used air mass coefficient. The AM0 value is always used when determining the efficiency of photovoltaic cells designed for use in artificial satellites and other space platforms. As shown in Figure 9., the determining factor in determining AM values is the incidence angle of the sun's rays to the earth. Accordingly, the AM value is determined as follows:

$$AM = 1 / \cos \theta \quad (1.1)$$

As shown in Figure 9, the angle θ is the angle between the point reached by the sun's rays and the surface normal (zenith). The AM value is calculated using the θ angle, and according to the AM value, the solar radiation intensity (W/m^2) and solar radiation spectrum can be reached in the region where the sun's rays fall, as shown in Table 3.

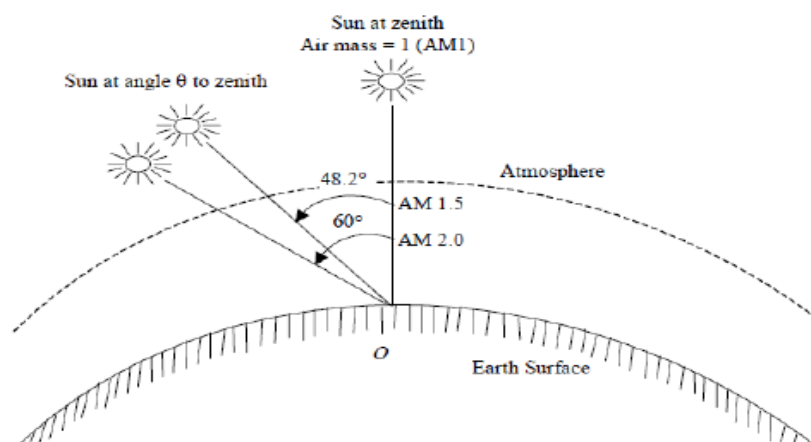


Figure 9. Relationship between AM values and incidence angle of sun rays

Outside the atmosphere, the solar radiation value in outer space is expressed by AM0 and is 1366 W/m^2 . AM values according to the angles of reaching the earth and radiation

values are shown in Table 3.

Table 3. AM values table

Incidence angle	AM	Standard	Solar radiation intensity (W/m ²)
-	0	ASTM E-490	1366,1
0°	1		1040
48.2°	1.5	ASTM G-173-03	1000,4
60°	2		840
75°	3.8		620
90°	38		20

As shown in Table 3, while the solar radiation intensity is 1000 W/m² in AM1.5, which is accepted as the common value for the sun rays reaching the earth, the intensity of sunlight emitted in space (AM0) is approximately 1.36 times of this value. Figure 10 shows the solar spectrum of solar radiation at different AM values. As seen in the solar spectrum, 5% of the sun's rays are in the ultraviolet (0-400 nm), 43% in the visible light region (400-700 nm), and 52% in the infrared region (700-2600nm) (Kruse et al., 2006).

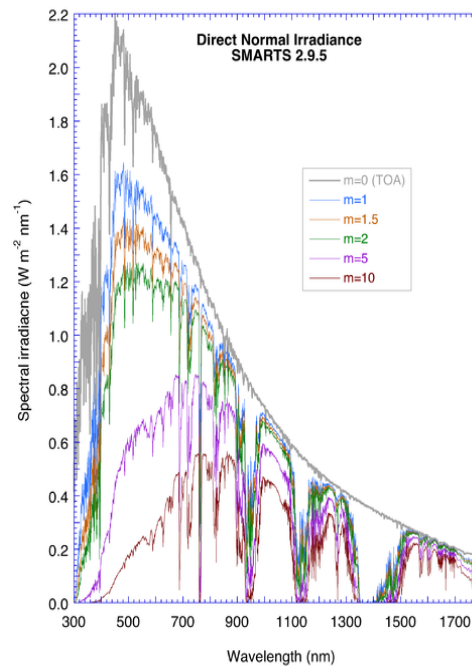


Figure 10. Solar spectrum of solar radiation values for different AM values (Gueymard, 2004)

Solar Cells (Photovoltaics)

Photovoltaic energy systems are energy conversion systems in which electromagnetic waves in the part of the visible light spectrum of solar spectrum are converted into DC current with semiconductor materials having photovoltaic effect. Photovoltaic energy conversion is explained and illustrated in Figure 11 (Apostoleris et al., 2018).

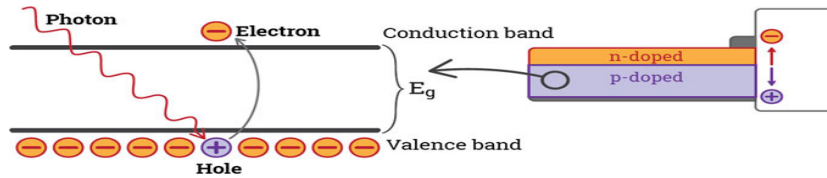


Figure 11.1. The operating principle of a photovoltaic cell: valence-band electrons in a semiconductor are excited to the conduction band by the energy of incident photons. Conduction band electrons and valence band holes are separated by a PN junction, causing current to flow through the external circuit (Apostoleris et al., 2018)

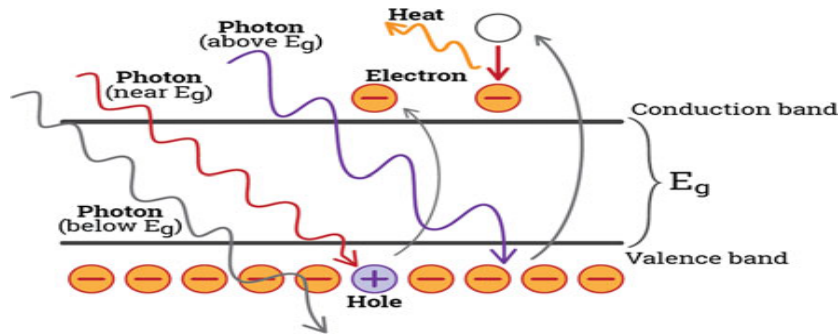


Figure 11.2. Interaction of photons of different energies with a PV cell: photons with energy below the band gap are transmitted; those with energy above the band gap create a carrier pair by promoting an electron, but the difference between the photon energy and the band gap becomes heat (Apostoleris et al., 2018)

In space studies, solar cells were first used in 1958 on the Vanguard and Sputnik-3 spacecrafts. The first solar cells used in space studies were of monocrystalline silicon structure and had an efficiency of approximately 10% (Kalogirou, 2017). Although the efficiency of these cells increased to 14% and above with the developments in silicon solar cell technology in the 1960s-1970s, Ga-As solar cells which were developed in the early 1960s and had lower efficiencies (11%) were mostly preferred in space studies due to their stability at high temperature and radiation.

Today, in parallel with the studies carried out in the field of photovoltaics and space, great developments have also been achieved in the field of space-qualified solar cells. Multilayer space-qualified solar cells with 28-32% efficiency have been used in many space platforms.

CPV (Concentrated PV) cells which have been produced within the scope of studies on multilayer solar cells also offer high efficiency energy conversion in lower PV cell areas compared to solar cells. As shown in Figure 12., solar energy concentrated up to 1000x by optical systems focuses on CPV cells, providing the opportunity to produce electrical energy at high power density. The efficiency values of CPV cells reached 44%. It is considered that they have a high potential for use in space platforms due to their low cost and high efficiency power generation in lower cell areas (Keser et al., 2019).

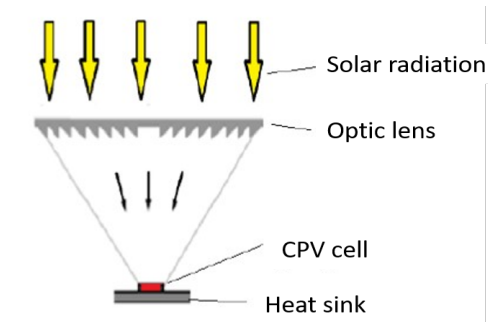


Figure 12. CPV cell power generation (Selimoğlu, 2013)

Solar Dynamic Power Systems

In these systems, high heat is obtained by concentrating sunlight on the receiver. Electric energy is obtained by circulating the gas/liquid heated by the heat obtained on the circuit. Studies have shown that it is 25% more efficient than photovoltaic solar cells. With such systems, it is possible to produce electrical energy up to 25 kW. Although studies on this subject have been carried out by NASA, it has not yet been used in a real space mission.

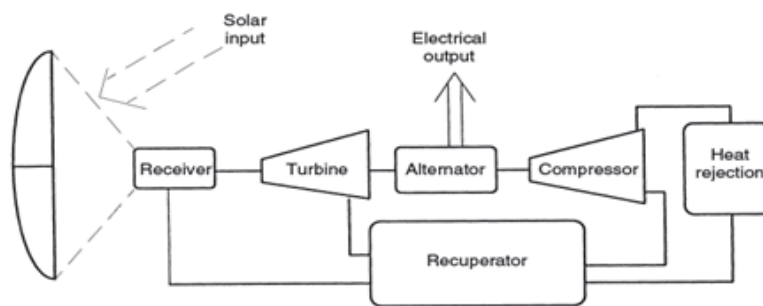


Figure 13. Solar dynamic Brayton cycle (Fortescue et al., 2011)

Figure 13 shows a solar dynamic Bryton cycle designed by NASA for use on the International Space Station. While the International Space Station was being built, it was designed to replace the 75 kW output solar cells currently in use with two 25 kW solar dynamic Bryton cycle power systems. Helium and Xenon gasses would be used in the cycle, and a temperature of 1042°K would be achieved there by focusing the sunlight on the receiver with the concentrators. However, the project could not be implemented due to high cost and budget constraints (Fortescue et al., 2011).

Solar Thermophotovoltaic Power Systems

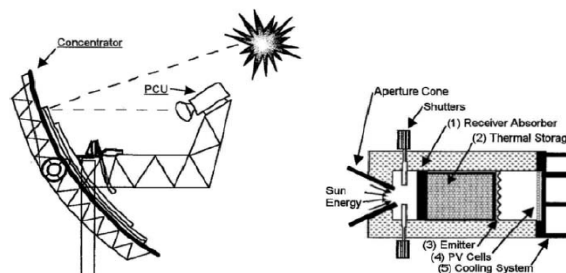


Figure 14. Solar thermophotovoltaic power system diagram (Hyder et al., 2003)

As shown in Figure 14, the sun rays are concentrated on the receiving system, resulting

in a temperature of over 1000°C in the thermal storage. With the temperature obtained, the emitter material emits infrared radiation, and the infrared rays emitted reach onto the photovoltaic cells selected in accordance with the emitted wavelength, and electrical energy is obtained from there.

Although solar thermophotovoltaic power systems (STPVG) have not been used in a real space mission, it has shown that it can be among the future space power systems with its high efficiency and low weight. A typical photovoltaic power system consists of solar cells and a battery pack. A satellite in LEO orbit spends approximately 30 minutes of each orbital period in the dark side. While in the dark part of the period, the satellite uses energy stored in secondary batteries. For this reason, instantaneous energy production at least one and a half times the instantaneous need is mandatory in power systems working with solar cells. The most striking feature of thermophotovoltaic power systems is that they continue to produce energy in the dark part of the orbit. In this way, they do not need extra energy production or a secondary battery group to store the energy produced, as in solar cells. Thanks to these advantages, it is possible to design power systems that are up to 20% more efficient than solar cells (Hyder et al., 2003).

While factors such as high efficiency, low cost and high production and supply network in market conditions can be shown as the main reason for the preference of solar cells in all space platforms designed for orbital missions, factors such as being affected by harsh space conditions, low operating temperature range, and high volume-mass ratio. There are also negative aspects. On the other hand, the only reason why RTGs are preferred in planetary and deep space missions despite their safety problems and very low efficiency values is that they are the only primary power system that can actively produce power in the harsh conditions of the region where they are operating. However, due to the high potential of TPVGs, which have not yet been used in a real space mission, to be the primary power system of the future, there are findings in the relevant literature that innovative power systems should be designed for application (Wernsman et al., 2004; Datas, 2015; Wang et al., 2015).

In this context, in a study carried out to investigate the designability of a TPVG-based power system for space applications that can eliminate the negative aspects of existing primary power systems, studies to develop the designs of TPVG power systems, which are considered to be the primary power system of the future for space platforms, and the availability of these power systems in space platforms has been researched.

As seen in the references, the information presented in this section was obtained from the previous studies by the authors and other literature, and with a general evaluation, the introduction part of a postgraduate study in this field (Bulat, B; 2021) was used.

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