

# Cassini Power Subsystem

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**Abstract.** The electrical output of Cassini's power system has been decaying consistently as predicted during its 20-year mission between October 1997 and September 2017. The power telemetry data is presented for the entire Cassini mission, including launch, cruise, and Saturn tour, up to the most recent available data. The spacecraft has been powered by three independent Radioisotope Thermoelectric Generators (RTGs) connected in parallel, which were able to generate 882 W at the beginning of the mission shortly after launch. The decrease in power energy output has mainly been driven by the heat reduction of the hot side of the RTGs due to the natural radioactive decay of its heat source plutonium (mostly plutonium-238 [ $^{238}\text{Pu}$ ]), degradation of thermoelectric material performance, and interface degradation.

**Keywords:** Cassini, Power Subsystem, RTG.

## INTRODUCTION

The Cassini Power and Pyrotechnic Subsystem (PPS) includes three radioisotope thermoelectric generators (RTGs).[1] The RTG is a thermoelectric conversion power generating system composed of a heat source, which includes  $^{238}\text{Pu}$ , and a cool side, that converts thermal energy to electrical energy with a thermoelectric generator (TEG) system using the Seebeck effect. [2] During the entire Cassini mission, power output data has been communicated to Earth and recorded through telemetry data. The exponential decay of its heat source plutonium and material/interface degradation caused a total 30.5% power degradation over 19 years, which was expected per current lifetime performance prediction models (LPPMs). The comparison of LPPM predictions to actual-power-data was redefined in April 2013 and show good agreement, within about 0.3%. This paper will discuss the comparisons and reasons for the small prediction/data deviations. Other external environmental effects due to spacecraft control events can have an impact on the power output of the spacecraft. Environmental temperature variations and different solar exposures can increase the temperature of the cool side of the thermoelectric device and therefore decrease the power output. These spacecraft control events will be discussed and correlated to various power variations seen in the Cassini power telemetry data. This paper will then discuss the Cassini Plasma Spectrometer (CAPS) instrument and finally look at the mission power requirements and compare them with other deep space missions.

## CASSINI RTGS

Cassini's three RTGs contain a total of 32.7 kg of plutonium dioxide, which is comprised of 82.2% of  $^{238}\text{Pu}$  by weight. The half-life of  $^{238}\text{Pu}$  is 87.75 years. It produces uranium-234 ( $^{234}\text{U}$ ) by  $\alpha$  decay, which provides the main source of heat energy for the RTGs. Table 1 shows the detailed composition and characteristics of each of Cassini's RTGs.[3] The total heat output of all three RTGs corresponds to 13.2 kWt at beginning of life (BOL). In comparison to the RTG electrical output of 882.1 W, the calculated BOL efficiency is 6.69%.

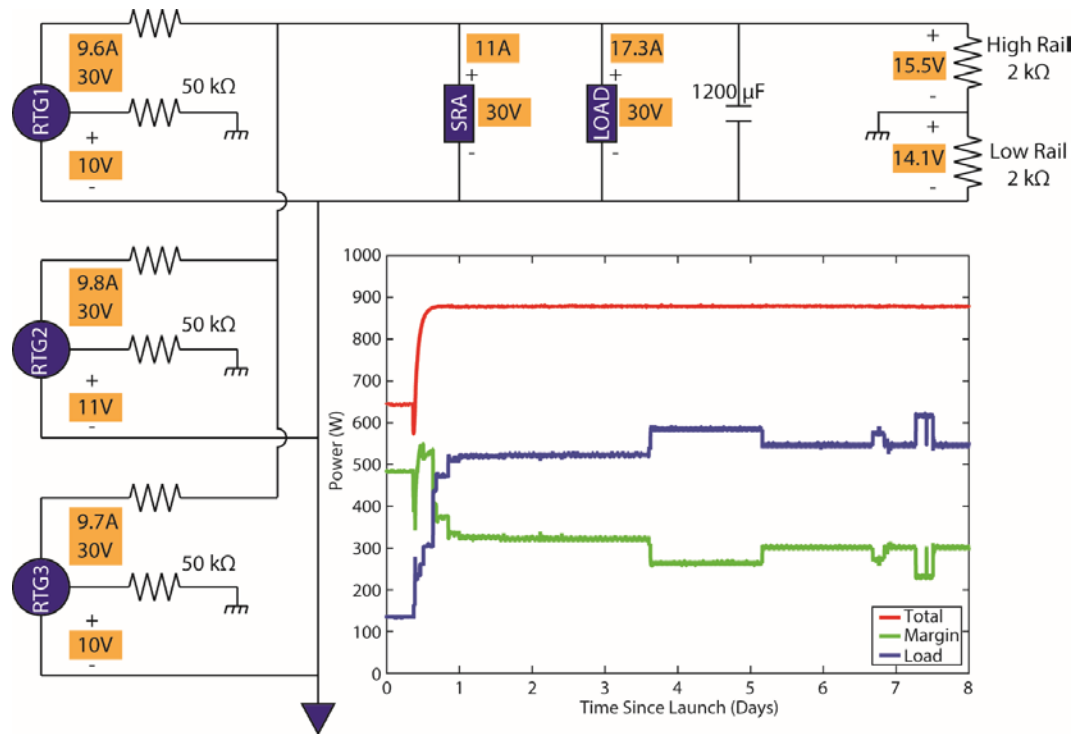
## CASSINI PPS ARCHITECTURE

Cassini PPS relies on the three RTGs and very limited energy storage. It is based on the continuous power production capability of the RTGs and does not include any battery for energy storage. The power bus is regulated at

30 V with a linear-sequential shunt regulator and contains about 1200  $\mu$ F for bus stability. The Cassini functional block diagram is depicted in Fig. 1.

**TABLE 1.** RTGs fuel composition at beginning of life [3]

	RTG 1	RTG 2	RTG 3	Total
<sup>238</sup> Pu Weight (g)	7693.70	7774.06	7756.40	23224.15
<sup>239</sup> Pu Weight (g)	1426.55	1447.79	1441.78	4316.11
<sup>240</sup> Pu Weight (g)	199.87	212.38	202.62	614.88
<sup>241</sup> Pu Weight (g)	20.24	20.75	20.54	61.53
<sup>242</sup> Pu Weight (g)	11.84	14.13	12.53	38.50
<sup>236</sup> Pu Weight (g)	1.07E-04	1.14E-04	1.13E-04	3.34E-04
Total Pu Weight (g)	9352.19	9469.12	9433.87	28255.17
Other Actinides (g)	235.07	166.96	184.74	586.77
Impurities (g)	14.46	15.54	14.26	44.26
Oxygen (g)	1275.94	1243.13	1263.33	3782.40
Total Fuel (g)	10877.65	10894.75	10896.20	32668.60
Pu-238/Total Pu (%)	82.27	82.10	82.22	82.19
Avg. Pellet Weight (g)	151.08	151.32	151.34	151.25
Heat Output (Wt)	4368.06	4413.78	4403.68	13185.52
Avg. Pellet Heat (Wt)	60.67	61.30	61.16	61.04
Avg. Pellet Density (g/cc)	9.83	9.94	9.90	9.89
Activity (Curies)	133934	135368	135040	404342

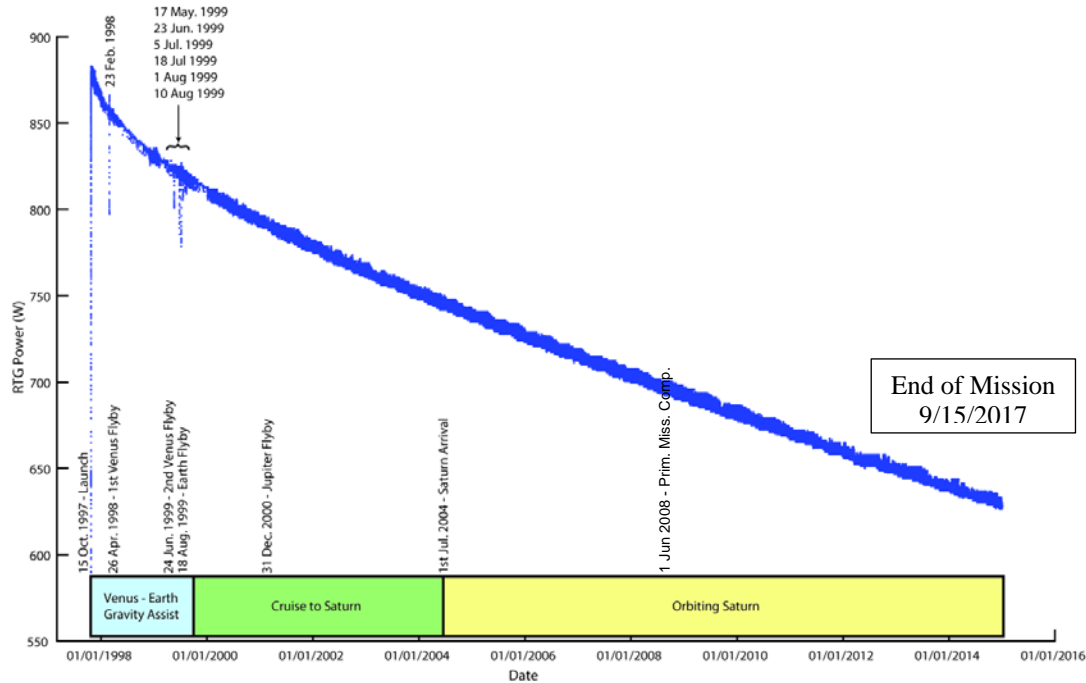


**FIGURE 1.** Cassini functional block diagram. The plot shows the total, margin and load power during the first eight days of the mission, including launch.

The three RTGs are connected in parallel. Therefore, the current generated by each RTG adds up to the total power output. At the beginning of the mission, the total power output of Cassini peaked at 882.1 W two days after launch. This was the highest recorded data point for the entire mission. Since very limited energy storage is available, Cassini power output needs to supply the overall spacecraft consumption at all times, in addition to a margin of 20 W to cover transient loads. The total spacecraft power consumption, or “LOAD,” averages to 469.18 W over the mission, well below the total power output capability. The excess in power, or “MARGIN,” is discarded from the spacecraft through heat radiation via the Shunt Regulator Assembly (SRA). For energy balance, at all times, the sum of the LOAD and MARGIN adds up to the total power output from the three RTGs. The graph shown in Fig. 1 gives the total power output, and the LOAD and MARGIN values during the first eight days of the mission. The measured current output, voltage, and case voltage arbitrarily chosen two days after launch is reported for each RTG. At the same time, SRA and load current and voltage are shown, as well as High-rail and Low-rail voltages.

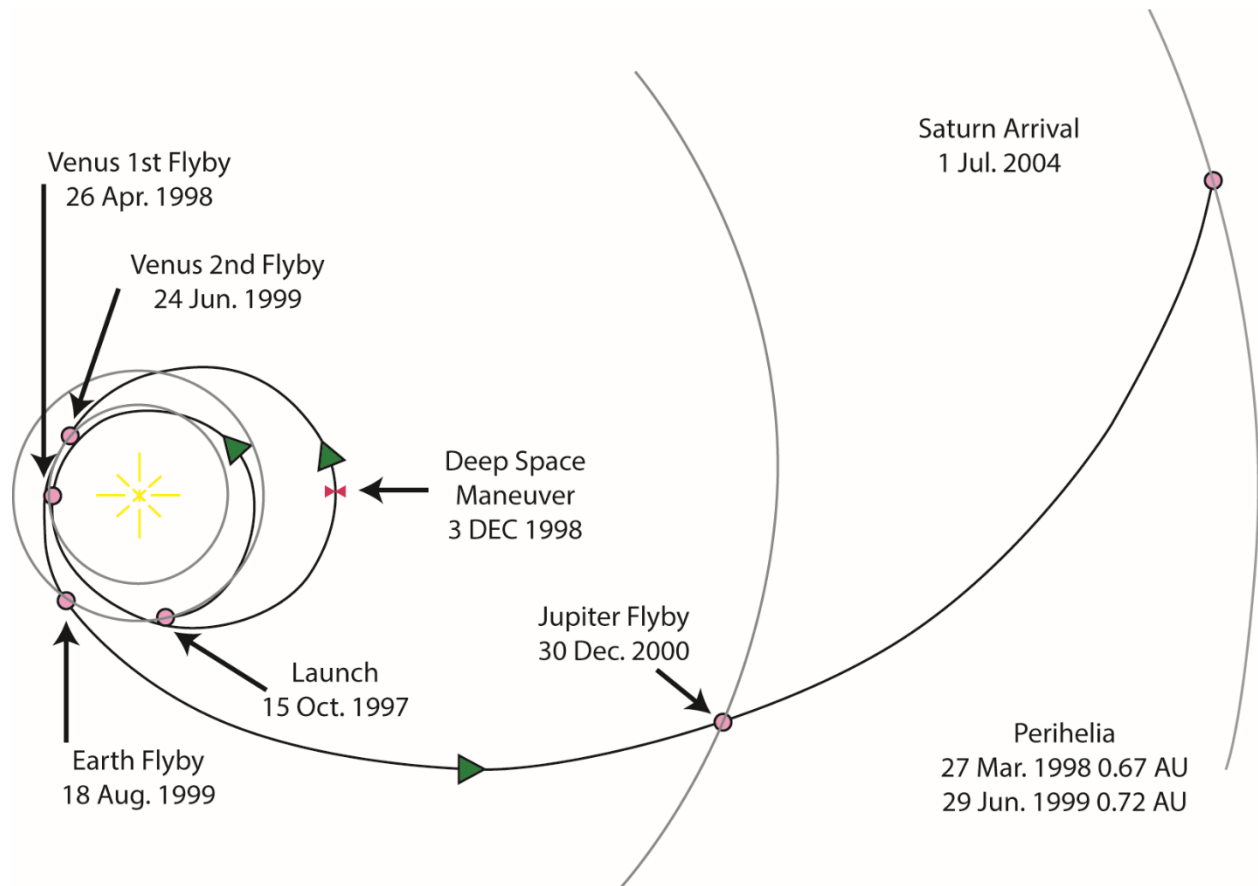
## CASSINI POWER OVER TIME

Cassini was launched on 15 October 1997 by a Titan 4B launch vehicle. [4] The mission is scheduled to end on September 17<sup>th</sup> 2017 and therefore, the entire mission is scheduled to last almost 20 years.



**FIGURE 2.** Cassini recorded power output telemetry data over the entire mission separated into three phases: The Venus-Earth gravity assist, the cruise to Saturn and Orbiting Saturn.

Fig. 2 shows the entire power history recorded on the spacecraft until 2015, communicated back to Earth through the Deep Space Network (DSN) and archived by Cassini telemetry. The overall decay shows an exponential behavior ranging from 882.1 W in the first days of the mission and predicted to degrade to about 600 W at the end of the mission, corresponding to a power decay of 32% over the 20-year mission. Figure 2 shows the three phases of the mission: (a) the Venus-Earth gravity assist, (b) the cruise to Saturn, and (c) the Saturn tour. The first phase lasted about two years, between October 1997 and October 1999. During this period, the power output decreased to ~820 W, corresponding to a decay of 7% compared to its BOL value. On 23 February 1998, a sharp power drop (i.e. within tens of minutes) was observed, which occurred around the time Cassini performed its first Venus flyby. This drop was 7.1% compared to the nominal power output and it recovered to its nominal value after a few minutes. The power drop was similar for all three RTGs with a power drop of 6.32% for RTG1, 7.66% for RTG2 and 7.31% for RTG3. This is attributed to the fact that during this time, solar exposure on the cool side of the RTGs (due to sun angle changes) created a reduction of the TEG temperature difference, resulting in a power output decrease in the TEG. The slight difference in power decrease between the RTGs is attributed to different solar exposure angles by the different RTGs. The same phenomenon occurred six times between 17 May 1999 and 10 August 1999, around the time of the second Venus flyby. During that second flyby period, the highest power drop observed was 5.32% with a power drop of 6.92% for RTG3. The power drops for RTG1 (3.53%) and RTG2 (5.95%) were less pronounced. For each of these six power drops, the nominal power value recovered after a few minutes. The second phase of the mission was the cruise to Saturn, which lasted about five years, between October 1999 and June 2004. During the cruise phase, the constant power decrease was about 70 W. The major event during this time, was the Jupiter flyby on 31<sup>st</sup> December 2000. The cruise trajectory is represented in Fig. 3. Major events such as Earth, Venus, and Jupiter flybys are shown.



**FIGURE 3.** Cassini’s seven-year Venus-Earth gravity assists and cruise to Saturn between launch on 15 October 1997 and Saturn arrival on 1 July 2004.

Finally, the third phase started on 1 July 2004 when Cassini achieved orbit insertion into the gravity field of Saturn. The Cassini power output was then 750 W, corresponding to a 15% decrease compared to the beginning of the mission.

The next section will focus on the Cassini Plasma Spectrometer (CAPS), which is one of 12 Cassini instruments, and its major impact on the power subsystem electrical network during the mission.

## CASSINI PLASMA SPECTROMETER (CAPS): A SHORT HISTORY

CAPS is designed to measure the energy, charge, mass, and direction of particles in the Saturn magnetosphere, and in the solar wind at Saturn. Scientific goals included understanding the nature and sources of plasma, their transportation, and their “sinks.” In addition, CAPS contributes to multi-instrument observations of the Saturn system. The instrument is comprised of three sensors: an Ion Mass Spectrometer (IMS); an Ion Beam Spectrometer (IBS); and an Electron Spectrometer (ELS).[5, 6]

CAPS became operational just after launch and continued to operate until the instrument was turned off as the result of an onboard solid-state power switch (SSPS) trip on 2 June 2012.

During Saturn tour operations, CAPS experienced a series of short anomalies that affected the power subsystem, and those are summarized in this section. The first anomaly occurred on 28 June 2006, when Cassini experienced a Low Rail short (Low Rail to chassis), which cleared within 48 hours. The short was accompanied by shifts in the RTG case voltages, which were consistent with the shift seen on the Low Rail. At the time, the cause of the short was not

determined, but the robust rail design allowed the spacecraft team to continue to operate Cassini safely. There was no significant change in the state of the power subsystem for the next five years.

On 30 April 2011 a series of RTG case voltage shifts occurred, and the Low and High Rail voltages shifted to 0 volts and 30 volts, respectively. This condition continued for six weeks.

On 11 June 2011 a third shift in the power bus occurred. Analysis indicated that the High Rail shorted to the chassis, which led to a short-lived ( $< 1$  ms) connection between Low and High Rails. As a result of this short the Low and High Rails swapped voltage levels, to 30 and 0 volts respectively. RTG case voltage shifts were also observed. By this time, it was suspected that the CAPS instrument was involved, and four days later it was intentionally commanded off by the spacecraft team. Immediately, the Low and High Rail voltages changed to new magnitudes (7 V and 23 V), where they remained for the next nine months.

In response to the events of April and June 2011, reviews were conducted at JPL, and by the NASA Engineering and Safety Center (NESC). In early 2012, the NESC concluded that tin whiskers were the likely cause of the shorts, and that continued operation of CAPS was safe under that assumption.

The instrument was turned back on 18 March 2012. Two days later the bus levels changed for a fourth time. RTG output dropped by 2 W, and the Low and High Rails again swapped voltage levels (30 V and 0 V). The spacecraft remained in this condition for another 10 weeks.

On 1 June 2012, a series of four shorts occurred in quick succession, finally resulting in an onboard SSPS trip on June 2, which left CAPS powered off.

A second review over the next several months by the NESC found that the new trips differed significantly from previous events. Thermal data pointed to the IMS wax thermal actuator (WTA) as the likely cause of the most recent event, possibly due to anomalous activation of the WTA via an internal short. Ground testing and modeling produced results consistent with this scenario, and in its findings the review board recommended that the CAPS instrument remain powered off.

In the three years since CAPS tripped off, the Low and High Rail voltages have remained steady at 6 V and 24 V. RTG case voltages have also been steady over this duration. There is no plan to operate the instrument for the remainder of the mission.

## **POWER MISSION REQUIREMENT DISCUSSION AND COMPARISON WITH OTHER MISSIONS**

The Cassini power performance over the lifetime of the mission mimics the historical performance of RTGs for many deep space missions. RTGs have an excellent record of providing unparalleled success for extreme solar range and high radiation environments. The Pluto New Horizons mission recently joined the two Voyager missions as spacecraft traveling beyond the planets toward the Kuiper Belt, and ultimately into interstellar space. Galileo was an orbiter with an RTG power system, similar to Cassini, that lasted for many years in the severe radiation environment of the Jovian system. System architects and mission planners have employed the predictable and reliable performance of the RTGs independent of concerns about solar range and the radiation environment.

NASA chose to use RTG power for the Cassini mission based on a number of technical factors, including lower mass and improved attitude control compared to necessarily large solar arrays.

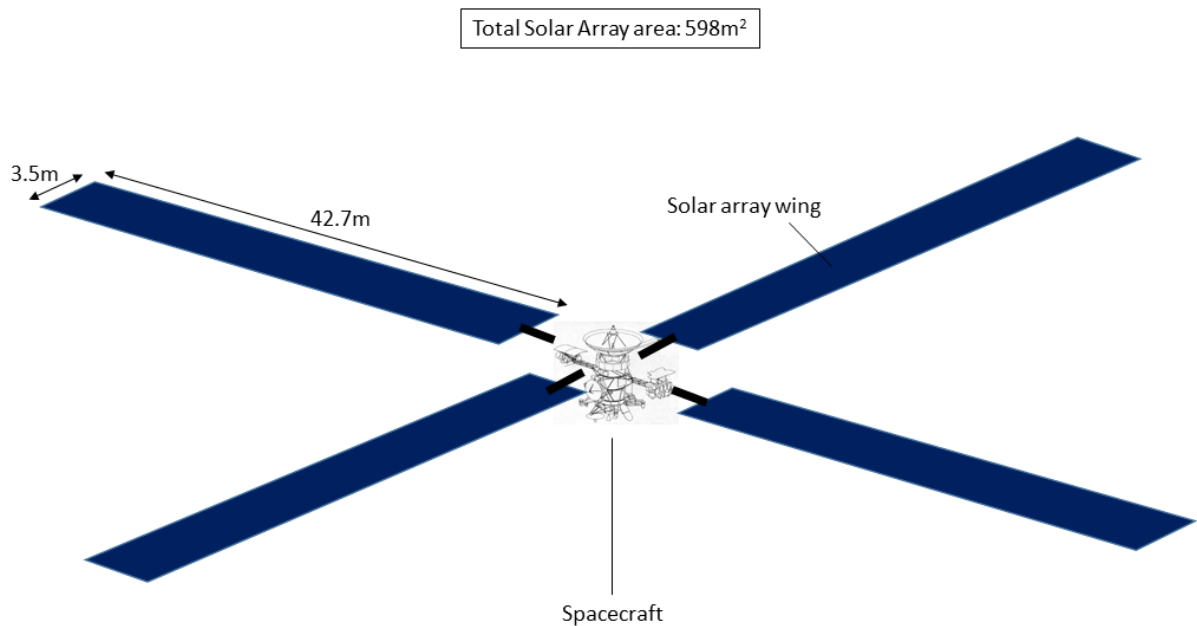
Solar cell efficiency has shown steady improvement over the years since Cassini was developed. NASA's on-going Juno mission is the first solar-powered mission to Jupiter, which was achieved by a combination of solar array design and mission planning. For Juno, solar cell characterization for limiting radiation degradation and optimizing Low Intensity and Low Temperature (LILT) performance resulted in the design of a solar array that can produce 416 W end of mission at 5.5 Astronomical Units (AU).[7] Mission planners designed a Juno tour that remains in

constant solar illumination and avoids the radiation belts around Jupiter to protect the three large solar arrays, in contrast to the RTG-powered Galileo mission, which targeted the icy moons directly in the Jovian radiation belt.

The Juno mission achieved two major milestones in 2016: in January, on its way to Jupiter, Juno surpassed Rosetta to become the most distant solar-powered spacecraft in history, and in July, it successfully completed Jupiter orbit insertion.

In another example, the planned Europa Mission is leveraging the lessons learned from Juno; its baseline design is a solar-powered spacecraft that specifically targets one of the icy moons, Europa.[8] Europa Mission planners are designing a Jovian orbital tour with numerous close flybys of the valuable science target while maintaining solar array power output degradation to less than 30% at the end of mission. The estimated end of mission power is on the order of 600 W, through the use of an approximately 90 m<sup>2</sup> array. Although the estimated mass of the solar array is a factor of three greater than an equivalent RTG-powered system, the cost could be an order of magnitude lower. Cost and timely availability of hardware are always key factors when designing a mission power system.

A solar-powered Saturn mission at about 10 AU would be more of a challenge, notionally requiring a 300 m<sup>2</sup> array for a Cassini-like mission with the current solar cell technology and a mass impact factor of nine over an equivalent RTG system. At the time of the Cassini development, a solar-powered Saturn mission would have required about 600 square meters (see Fig. 4).[9] Solar cell technology has improved by a factor of two since the development of Cassini, however even this amount of area (i.e., 300 m<sup>2</sup>) is challenging. Therefore, even given these advances in solar cell / array technology, a Cassini-type mission with a similar science instrument payload would most likely still require a RTG power system solution.



**FIGURE 4.** A conceptual all-solar dual junction GaAs/Ge configuration for the Cassini spacecraft. Reproduced from [9].

## CONCLUSION

A review of Cassini Power Subsystem performance was presented and anomalies associated with the CAPS instrument were discussed. A comparison with other deep space missions and power alternatives was then discussed.

## ACKNOWLEDGMENTS

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