ARL-TR-10196 • SEP 2025

Evaluation of Thermophotovoltaic (TPV) Devices in Different Irradiation Environments

by Naresh Das, Harry Hier, William Allmon, and Sunny Karnani

NOTICES

Disclaimers

ARL-TR-10196 ● Sep 2025

Evaluation of Thermophotovoltaic (TPV) Devices in Different Irradiation Environments

Naresh Das, Harry Hier, William Allmon, and Sunny Karnani
DEVCOM Army Research Laboratory

REPORT DOCUMENTATION PAGE

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED START DATE	3. DATES COVERED END DATE
September 2025	Technical Report	5 February 2024	15 August 2025

4. TITLE AND SUBTITLE
Evaluation of Thermophotovoltaic (TPV) Devices in Different Irradiation Environments

5a. CONTRACT NUMBER	5b. GRANT NUMBER	5c. PROGRAM ELEMENT NUMBER
5d. PROJECT NUMBER	**5e. TASK NUMBER**	**5f. WORK UNIT NUMBER**

6. AUTHOR(S)
Naresh Das, Harry Hier, William Allmon, and Sunny Karnani

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	8. PERFORMING ORGANIZATION REPORT NUMBER
DEVCOM Army Research Laboratory ATTN: FCDD-RLA-GC Adelphi, MD 20783-1138	ARL-TR-10196

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
DISTRIBUTION STATEMENT A. Approved for public release: distribution unlimited.

13. SUPPLEMENTARY NOTES
ORCID: Naresh Das, 0000-0002-2649-0209

14. ABSTRACT
Thermophotovoltaic (TPV) devices are the heart of portable solid-state power generation systems. We report here on the key performance metrics of thin-film indium gallium arsenide (InGaAs)-based (0.74-eV bandgap) TPV devices in both simulated solar and thermal irradiation environments. From our experiments of varying TPV device temperature, we determine the power degradation versus the device temperature for use in system design tradeoff studies with cooling power. Also, we provide power degradation for simulated solar irradiation and 1000, 1100, and 1200 °C thermal irradiation spectra. Notably, the increase in short-circuit current is higher for thermal irradiation than photovoltaic irradiation, reducing the impact of device temperatures for TPV uses and demonstrating the importance of using relevant irradiation environments to assess the TPV device performance.

15. SUBJECT TERMS
Energy Sciences, thermophotovoltaic, irradiation environment, portable power generation, indium gallium arsenide, InGaAs, short-circuit current, open-circuit voltage

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	C. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UU	18

19a. NAME OF RESPONSIBLE PERSON	19b. PHONE NUMBER *(Include area code)*
Naresh Das	(520) 691-5231

STANDARD FORM 298 (REV. 5/2020)
Prescribed by ANSI Std. Z39.18

Contents

List of Figures

1. Introduction

There exists a great need for multifuel and compact power sources for Soldier and small-unit applications. Thermophotovoltaic (TPV) devices are the heart of compact power generator systems.[1–4] Though various material systems for TPV devices have been tried, like germanium (Ge), gallium antimonide (GaSb), indium gallium arsenide phosphide (InGaAsP) among others, indium gallium arsenide (InGaAs)-based TPV devices have superior conversion efficiency and a broad range of spectral absorption characteristics compared to other materials.[5] Record-high TPV efficiency of greater than 35% is reported recently.[6] At the U.S. Army Combat Capabilities Development Command (DEVCOM) Army Research Laboratory (ARL), our compact power generator program goal is to assess the feasibility of a generator that uses TPV devices for energy conversion. We need to characterize the TPV conversion efficiency to predict the compact power generator performance. In the laboratory setup, typical TPV testing occurs using solar irradiation with high concentrated power and then TPV performance is predicted in thermal irradiation by extending the results from solar irradiation. However, we have done extensive evaluation of InGaAs TPV devices in both solar and thermal irradiation using a silicon nitride (SiN) thermal emitter element. It is generally understood that with an increase in device temperature, TPV performance degrades. It is understood that the power degradation with increasing device temperature is dependent on the spectral nature of the irradiation due to bandgap narrowing,[7] when the bandgap of the material decreases from room temperature value. We observed higher degradation due to solar irradiation than SiN thermal irradiation for similar generated power at higher device operating temperatures. By comparing the power degradation at different thermal emitter temperatures in the range of 1000–1200 °C, we found that the rate of degradation is higher for higher emitter temperatures.

2. Experimental Results

We used vendor-supplied thin-film 0.74-eV bandgap InGaAs TPV devices like those in Narayan et al.[6] with an active area of 0.6 cm^2 for performance evaluation using an ARL in-house solar simulator and an electrically heated SiN thermal emitter as irradiation sources. We used a Fresnel lens to concentrate the solar simulator irradiation for a total incident power equivalent to 67 suns. To measure TPV device operating temperatures, a thermocouple is sandwiched between an Alumina substrate and the TPV device using epoxy. For all TPV device tests, we used a cryo-cooled chiller and waited for temperature to stabilize before taking any irradiation measurements (Figure 1). We used a Keysight high-current curve tracer model 1501A for current–voltage (I–V) measurements up to 1 A. For the measurement greater than 1 A, we used a Keithly 2460 model source meter. For the thermal irradiation source, we used an electrically heated SiN thermal heater (Figure 2) of 1- × 2-inch rectangular size from Induceramic.* We used heating elements with heating Zone 45×17. Variable AC power supply is used to power the SiN heater. Temperature of the SiN heater was measured by the pyrometer.

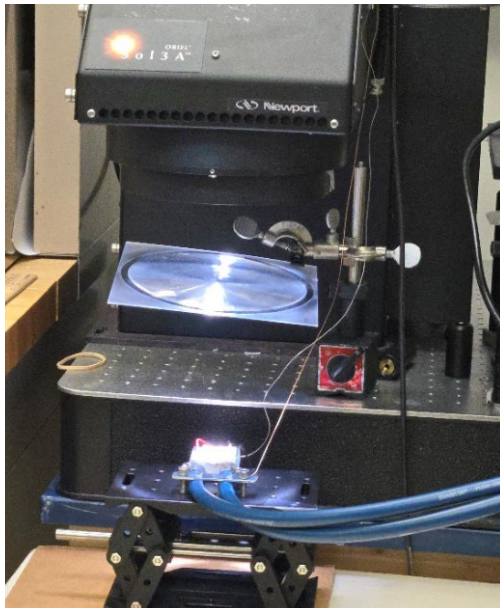

Figure 1. Solar simulator with Fresnel lens for concentrated incident power.

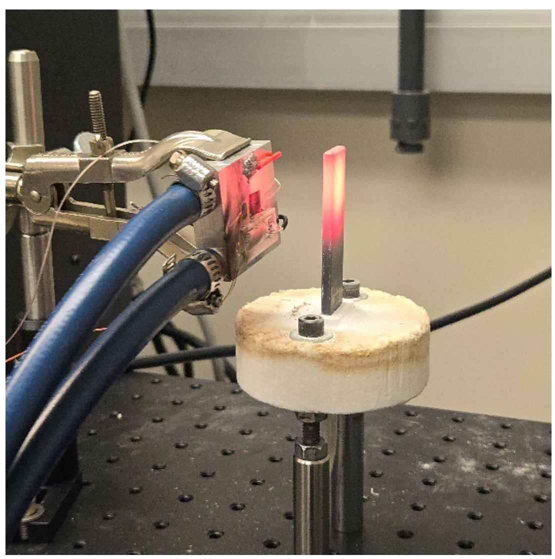

Figure 2. SiN heater setup for TPV performance evaluation.

*https://www.induceramic.com/industrial-ceramic-product/silicon-nitride-ceramic-heating-element-si3n4/silicon-nitride-ceramic-air-heating-element-si3n4

Figure 3 shows the spectral emission of a SiN thermal emitter in the temperature range between 1048 and 1191 °C. The temperature is measured at the center of the emitter where the emission uniformity is good, as seen in Figure 2. The light was collected using a Spectral Products CM110 Compact 1/8 Meter Monochromator.[†] The measurement range is 800–5500 nm. The monochromator detector was calibrated using a 1000 °C blackbody. As seen in Figure 3, for higher emitter temperature peak emission, the spectrum shifts to a lower wavelength. For 1048 °C emitter temperature peak emission occurs at 2100 nm whereas for 1191 °C emitter temperature peak emission occurs at 1800 nm. With the increase of emitter temperature, the peak energy of the emitted photon becomes higher. The peak spectral emission of the 1191 °C SiN emitter matches the peak absorption of the InGaAs TPV devices (1800 nm). The spectral emission from a solar simulator is well known and has peak emission in the visible spectral range of 400–600 nm. We used Newport Solar Simulator Model Sol 3A with IR heating element model 6575.

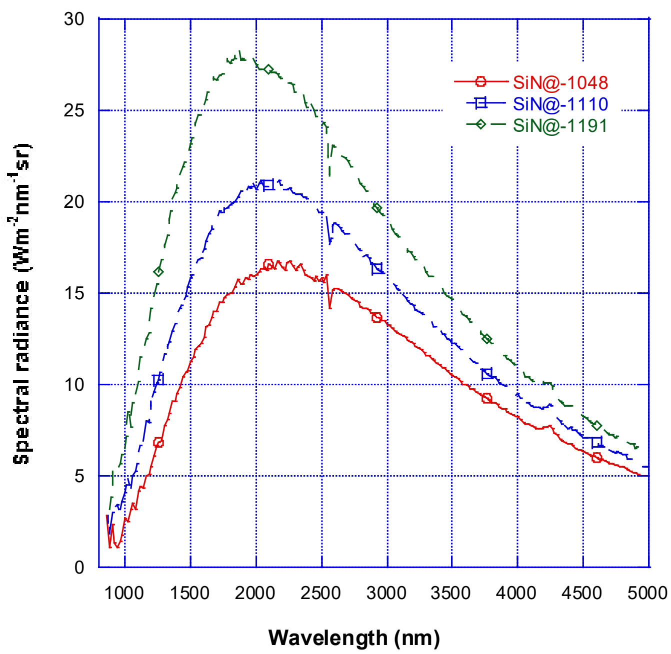

Figure 3. SiN emitter spectrum. Intensity increases with increase of SiN temperature.

In Figure 4, we show the external quantum efficiency (EQE) of the TPV cell for the temperature range between 20 and 50 °C. The EQE measurement system has a heated stage, and we adjusted the temperature before taking the measurement. With the increase of device temperature, the EQE has higher peak value in the spectral range of 1700–1800 nm. This is the range of peak absorption of InGaAs TPV devices. The EQE spectra shifts by 50 nm higher at the long wavelength end by

[†] https://www.spectralproducts.com/cm110.html

increasing device temperature from 20 to 50 °C. The interference pattern in EQE spectra may be due to thin InGaAs TPV cells, as cells are fabricated after removing the indium phosphide (InP) substrate layer.

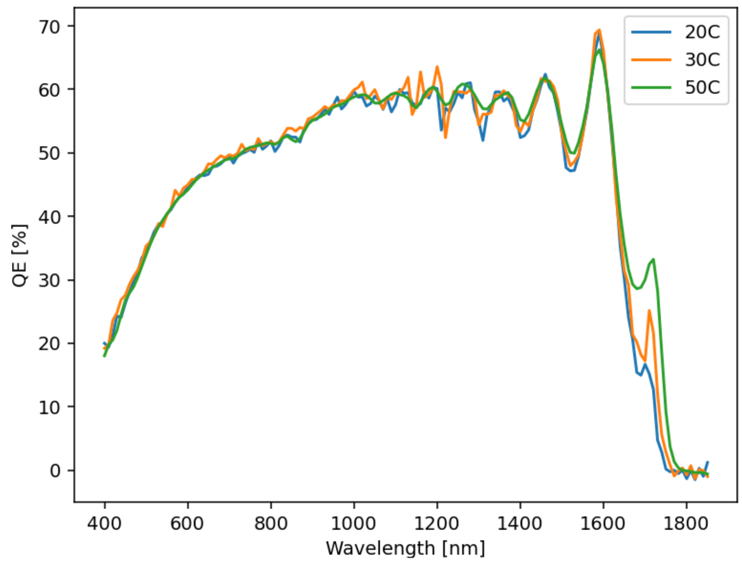

Figure 4. EQE of InGaAs TPV cell at different device temperatures.

We normalized the open-circuit voltage (V_{oc}) of the device at different temperatures to that measured at 20 °C. The normalized V_{oc} changes for different irradiation sources are shown in Figure 5. V_{oc} is the voltage value when short-circuit current (I_{sc}) is zero. In the case of solar simulator irradiation, the incident flux of 1.9 W and 3.9 W power is varied by the slit opening and using a Fresnel lens for increasing the irradiation intensity. Within the experimental error, the change in normalized V_{oc} is similar for all the different types of irradiations. There is a 7%–8% reduction in normalized V_{oc} by operating TPV devices at 50 °C compared to operating temperature of 20 °C. This decrease in V_{oc} is attributed to the narrowing of the bandgap and increased dark current. We observed no change in V_{oc} for the 1200 °C SiN emitter case, and it may be due to maintaining a stable device temperature at 30 °C at higher emitter temperature levels. In Figure 6, we show the normalized (to I_{sc} at 20 °C) change in I_{sc} for different irradiation types. Unlike V_{oc}, the change in I_{sc} is different for different types of irradiations. For solar irradiation, I_{sc} increase is less than 5%, whereas for SiN thermal irradiation, I_{sc} increase is more than 10%.

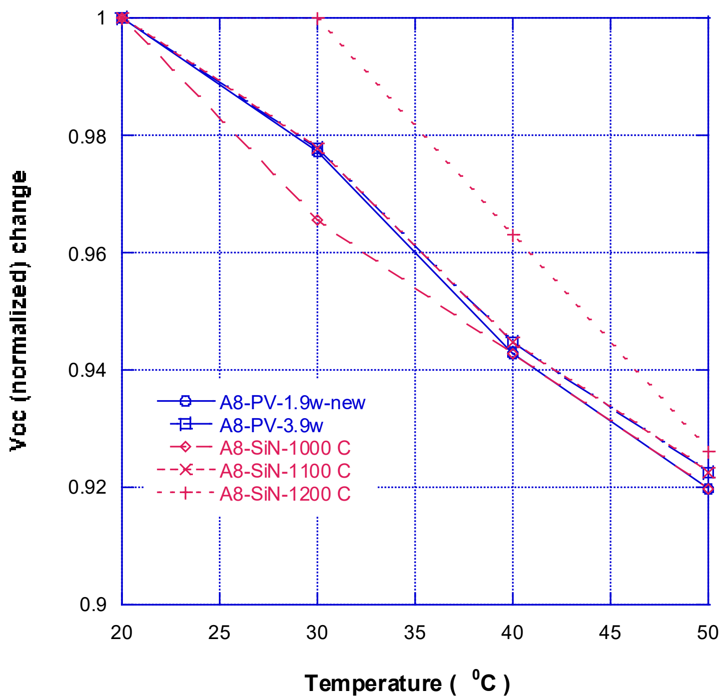

Figure 5. **Decrease of V_{oc} with increase of device temperature.**

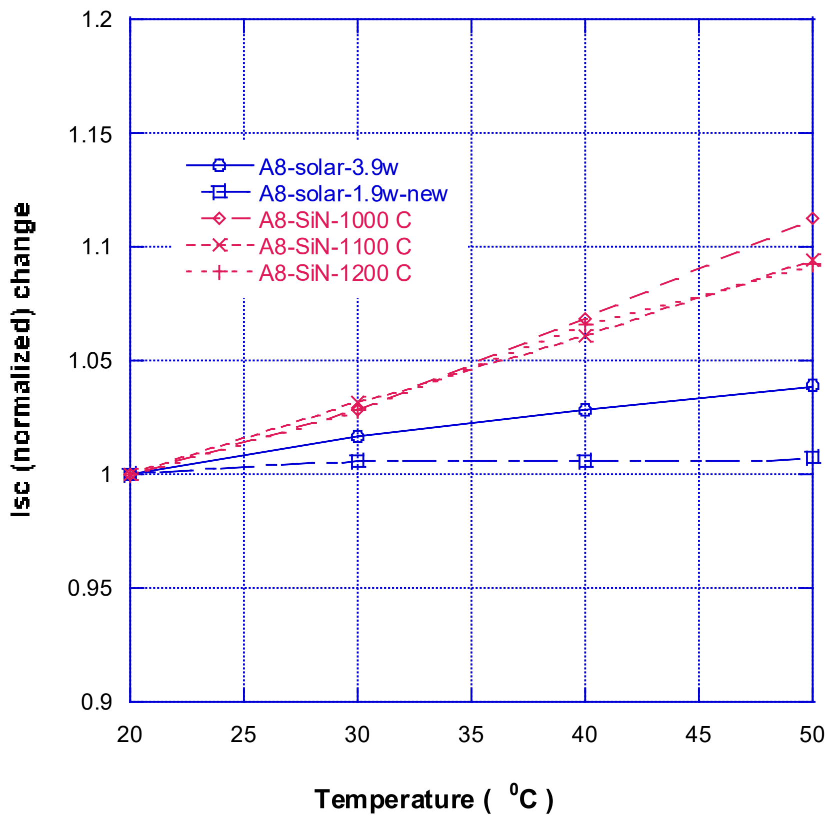

Figure 6. **I_{sc} increase is higher for SiN emitter than for solar irradiation with TPV device temperature.**

The normalized power degradation for different types of irradiation is shown in Figure 7. As expected, the power degradation for solar irradiation is higher than SiN thermal irradiation. Also, we observed that power degradation for solar irradiation is higher for higher total incident power. For 3.9-W incident power, the degradation is 12% whereas for 1.9-W incident power, the degradation is 8%. Power degradation for SiN irradiation is minimal and varies between 2% and 4% (within the margin of experimental error) for irradiation temperatures between 1000 and 1200 °C. Since in an actual compact power generation system TPV cells will be operating at higher temperature ranges like 50–60 °C, the present cells will be suitable for thermal irradiation as their degradation is minimum.

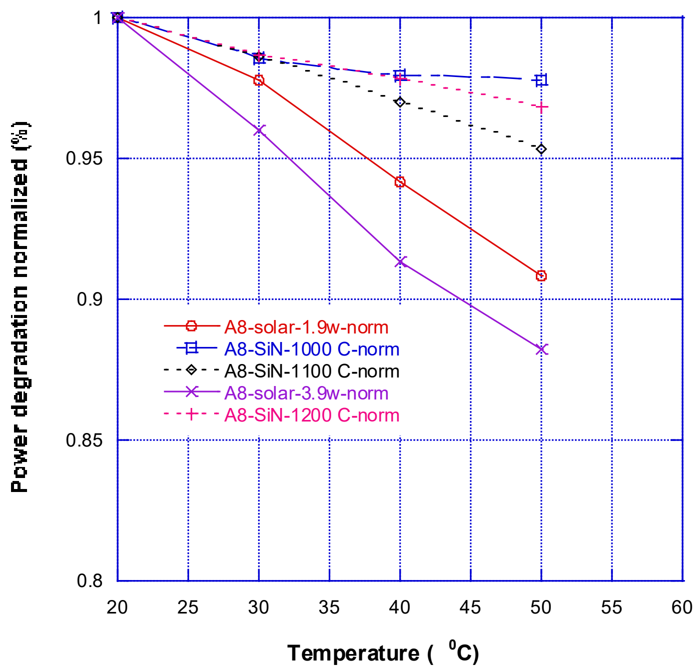

Figure 7. Power degradation for different irradiation conditions.

Alternatively, our results infer that the present InGaAs TPV cells are suitable for high-temperature operation (50–60 °C) where the requirement for cooling power will be minimal.

In Figure 8, we show normalized power degradation for different emitter temperatures but the same 7-mm gap between emitter and TPV devices. The degradation for three SiN emitter temperatures is quite different. The normalized power degradation with device operating temperature is the least for 1000 °C (2%) and highest for 1200 °C (5%) emitter temperature. At the same gap, the higher emitter temperature will result in higher fluxes/currents, thus series resistance becomes more of a factor. Resistance is dependent on temperature, and the current goes up with device temperature due to bandgap narrowing. Hence the case that has the highest fluxes will be impacted the greatest.

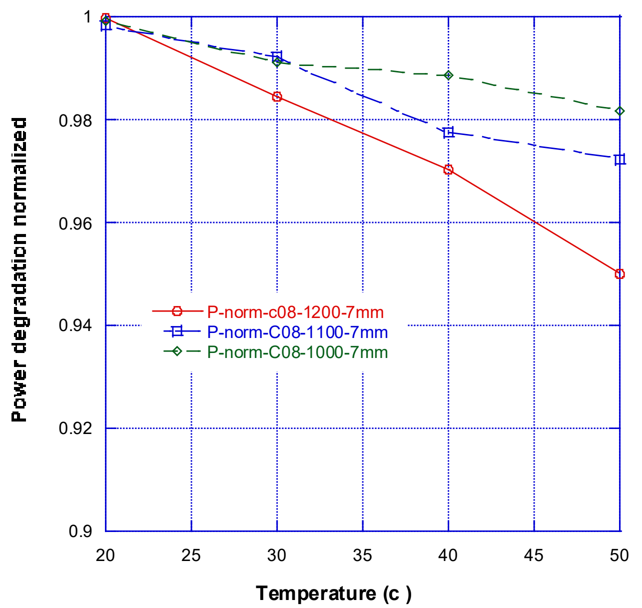

Figure 8. Normalized power degradation for different emitter temperatures with the same gap (7 mm) between emitter and TPV device.

3. Discussion

We report here the effect of 1) TPV device operating temperature, 2) SiN thermal emitter temperature, and 3) solar irradiation on performance of the TPV device. We made an extensive investigation of TPV device performance at different irradiation levels and different device operating temperatures. The I_{sc} increases with an increase of SiN emitter temperature simply by the higher irradiation.[8] The V_{oc} decreases with device operating temperature and is attributed to bandgap narrowing of InGaAs TPV materials. We also observed a small reduction (5%–6%) in normalized fill factor values (data not shown here) for devices operating in similar temperature ranges. Power generation, which is a product of V_{oc} and I_{sc}, decreases with an increase of operating temperature. V_{oc}, and generated power, decrease but I_{sc} increases with higher device operating temperature. Power degradation for solar irradiation cases in the measured device temperature range of 20–50 °C is around 10%, whereas for the SiN emitter case it is around 4%. In Figure 3, we showed the spectral irradiation of SiN emitters at three different temperatures. With the increase in emitter temperature, total irradiation power density increases, and the peak emission shifts to a lower wavelength. The peak spectral emission for 1200 °C SiN emitter (1800 nm) matches with the peak absorption wavelength of InGaAs TPV cells. Though the peak emission of SiN emitter at 1200 °C is close to InGaAs TPV cell band edge absorption, for high SiN emitter temperature there may be more electron-hole pair generation not contributing to power generation due to wider spectral emission (Figure 3). These noncontributing electron-hole pairs may increase the localized heating, which results in higher power degradation. We observed the degradation at higher emitter temperature is higher than that due to lower emitter temperature.

The EQE of the TPV cell shifts to higher wavelength with the increase of device temperature. This may be due to lowering bandgaps, which allows low energy or higher wavelength photons to be absorbed by the TPV materials. Though not shown here, V_{oc} increases with higher emitter temperature for irradiation between 1000 to 1200 °C temperature. Similarly, for solar irradiation V_{oc} also increases with higher incident power (1.9–3.9-W range). However, V_{oc} decreases for all the irradiation cases when TPV cell temperature increased from 20 to 50 °C. The normalized V_{oc} values decreased by 7% for the above TPV operating temperature range.

By comparing the device degradation due to solar irradiation and SiN thermal irradiation (Figure 7), we found that the degradation due to solar irradiation is higher than thermal irradiation for similar power generation levels. The difference is due to the spectral wavelength range of solar radiation 400–600 nm being far from the InGaAs band edge versus the SiN emitter wavelength region of 1500–2500 nm overlapping with the band edge. Thus, the SiN emitter spectrum is absorbed by the InGaAs cell as the bandgap narrows with increasing device temperature. Hence, we cannot simply extrapolate solar irradiation results to predict TPV device performance in thermal irradiation environments.

We performed experiments by varying SiN thermal irradiation temperatures (1000–1200 °C) but kept the gap between emitter and TPV device at 7 mm (Figure 8). In this case, though the view factor will be the same, it is expected that 1200 °C emitters will have higher power generation than 1000 °C emitters. However, from the normalized power degradation plot it is seen that higher degradation occurs (5%) for emitter temperature of 1200 °C compared to 1000 °C emitter temperature (2%). We believe this important observation of higher degradation for higher emitter temperature with the same view factor is not reported earlier. This will help in optimizing emitter temperature when developing an efficient multifuel compact power generation system for U.S. Army applications. We believe experiments with lower emitter temperatures than 1000 °C may be more rewarding.

4. Conclusions

By comparing the results from solar and thermal irradiation experiments, we conclude that the power degradation from solar irradiation is higher than thermal emitters and hence results cannot be extrapolated to predict the performance of one irradiation from another. We also conclude that with similar input power generation, degradation is higher for high emitter temperatures. Since TPV devices will be operating at higher temperatures than room temperatures for thermal irradiation environments, InGaAs will be the preferred device material as its degradation is minimal at higher emitter temperatures. We also conclude that by using InGaAs-based TPV devices, cooling power requirements will be minimal as these TPV devices perform well at elevated device temperatures. Our results will be useful in designing an efficient compact power generation system for Army applications with optimized power input for specific operating conditions.

5. References

1. Chan W et al. Enabling efficient heat-to-electricity generation at the mesoscale. Energy Environ Sci. 2017;10:1367–1371. https://doi.org/10.1039/C7EE00366H

2. Fraas LM, Avery JE, Minkin L, She H, Ferguson L. Scale up designs for hand-held light-weight TPV DC power supply. 2017 IEEE PVSC-44. IEEE 44th Photovoltaic Specialists Conference; 2017 June 25–30; Washington, DC. p. 1863–1868. https://doi.org/10.1109/PVSC.2017.8366559

3. Qui K, Hayden ACS. Direct thermal to electrical energy conversion using very low bandgap TPV cells in a gas-fired furnace system. Energy Convers Manag. 2014;79:54–58. https://doi.org/10.1016/j.enconman.2013.12.017

4. Bitnar B, Durisch W, Holzner R. Thermophotovoltaics on the move to applications. Appl Energy. 2013;105;430–438. https://doi.org/10.1016/j.apenergy.2012.12.067

5. Das N, Hier H, Allmon W, Karnani S, Waits CM. Evaluation of InGaAs thermo-photovoltaic devices for compact power generation. DEVCOM Army Research Laboratory (US); 2023 Sep. Report No.: ARL-TR-9795.

6. Narayan TC et al. World record demonstration of >30% thermophotovoltaic conversion efficiency. Proceedings of the 2020 47th IEEE Photovoltaic Specialists Conference (PVSC); 2020; Calgary, AB, Canada. p. 1792–1795. https://doi.org/10.1109/PVSC45281.2020.9300768

7. Tuleya RS, Nicholas RJ. Band gap dependent thermophotovoltaic device performance using the InGaAs and InGaAsP material system. J Appl Phys. 2010;108(8):084516. https://doi.org/10.1063/1.3488903

8. Bierman DM et al. Enhanced photovoltaic energy conversion using thermally based spectral shaping. Nat Energy. 2016;1:16068. https://doi.org/10.1038/nenergy.2016.6

List of Symbols, Abbreviations, and Acronyms

AC	alternating current
ARL	Army Research Laboratory
DEVCOM	U.S. Army Combat Capabilities Development Command
EQE	external quantum efficiency
GaSb	gallium antimonide
Ge	germanium
InGaAs	indium gallium arsenide
InGaAsP	indium gallium arsenide phosphide
InP	indium phosphide
IR	infrared
I_{sc}	short-circuit current
I–V	current–voltage
SiN	silicon nitride
TPV	thermophotovoltaic
V_{oc}	open-circuit voltage

1 (PDF)	DEFENSE TECHNICAL INFORMATION CTR DTIC OCA
1 (PDF)	DEVCOM ARL FCDD RLB CI TECH LIB