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Flux Sensor Measurement and Calibration Requirements for High-Intensity Heat Flux Applications

A Trade Study

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Abstract. Stakeholders of CSP and non-CSP high-intensity broadband flux measurements were surveyed and interviewed to obtain flux sensor design and calibration requirements. Existing sensor technologies and existing calibration facilities were then compared against this standard. Stakeholders require a flux sensor designed for >5,000 kW/m^2 flux measurements, >1,000 life cycles, <500 ms response time, >60-minute exposure at maximum flux, and <5% measurement uncertainty. Stakeholders also require a sensor with minimal cost, short procurement lead time, and a high-intensity broadband flux calibration. Commercial CSP stakeholders primarily rely on infrared (IR) temperature measurements of receiver equipment to control CSP plant process operation, whereas CSP research and development (R&D) and non-CSP stakeholders rely on accurate flux gauge measurements for a variety of applications. It was determined that existing flux sensor technologies and calibration facilities do not comprehensively meet stakeholder needs. This study suggests a more robust circular foil gauge with a high-intensity solar flux calibration comprehensively meets stakeholder flux measurement needs. Improved circular foil gauge designs and an improved flux sensor calibration facility are discussed.

Keywords: Flux Sensor, Calibration, Trade Study, Stakeholder Requirements

1. Introduction

Concentrating solar power (CSP) is a renewable energy technology capable of meeting alternating current (AC) baseload requirements. CSP utilizes thermal energy storage (TES) systems for long (>5 hrs.) duration power dispatch, despite intermittency of the sun [1, 2]. There are four main types of CSP technology, including tower, parabolic trough, linear Fresnel, and parabolic dish [3]. These technologies require accurate and long duration measurement of high-intensity solar flux, >1,000 kW/m^2, particularly as CSP technologies are progressing to higher temperatures as part of the Department of Energy (DOE) Solar Energy Technologies Office (SETO) Gen 3 program [4]. Accurate high-intensity flux measurements are difficult to achieve over long durations due to sensor robustness, but such a measurement would improve CSP plant efficiency, power prediction, and automation.

High-intensity flux measurements are also required for non-CSP applications, such as industrial process heat (IPH), pulsed-power research, aerospace R&D, and defense R&D. IPH applications, such as those in manufacturing, plastic, textile, food, paper, chemistry, and surface treatment industries, require heat flux measurements to understand system thermal losses and minimize total energy consumption [5-7]. Pulsed-power research requires high heat flux measurements, >2,900 kW/m^2, to quantify the radiative energy transferred from arc flashes and inform worker safety standards [8]. Aerospace and defense R&D applications require flux measurement at extreme levels, >10,000 kW/m^2, particularly in propulsion and space vehicle re-entry research where significant heat flux is generated [9-11].

Few reliable flux measurement technologies exist for these high-flux levels, of which include cavity-type radiometers (also referred to as Kendall radiometers) and Gardon gauges [12, 13]. These technologies are rated for high-intensity flux that is typical for point focus CSP systems and non-CSP applications, and they are either used directly for point-focused measurements or indirectly in 2D flux mapping/imaging systems [14-16]. Cavity-type radiometers, however, are expensive and have long lead times whereas Gardon gauges quickly degrade in high-flux environments, resulting in measurement error [13].

Flux sensor calibration errors are recognized to contribute the largest source of measurement uncertainty in high-intensity broadband flux applications [15]. Flux sensors are commonly calibrated by accredited facilities using an infrared radiation source [17]. This calibration approach can introduce significant measurement error, up to 100%, when the incident flux is broadband [18]. This error poses a significant safety hazard, can result in damage to equipment, and can negatively impact system performance. Cavity-type radiometers, however, can be self-calibrating and do not require external calibration.

In this work, a trade study was conducted to determine which existing flux sensor technologies and calibration facilities meet high-intensity flux measurement requirements for CSP and non-CSP stakeholders. It was determined that existing flux sensor technologies and calibration facilities do not comprehensively meet stakeholder needs. The results of this work suggest a more robust circular foil gauge flux sensor and a high-intensity broadband calibration facility are needed. Initial design considerations for a more robust circular foil gauge are discussed, and an improved high-intensity solar calibration facility is proposed.

2. Methods

2.1. Stakeholder Outreach

High-intensity flux measurement stakeholders in CSP and non-CSP industries for commercial and R&D applications were interviewed and surveyed to obtain flux sensor design and calibration requirements. Existing flux sensor technologies and calibration facilities were then assessed against this standard. A technical survey was provided to stakeholders and utilized during interviews to obtain technical input and to understand current measurement techniques and their limitations. Fifty-five entities were contacted, and sixteen responses were obtained. Ten responses were received from CSP R&D, and four responses were received from non-CSP R&D. Two responses were obtained from commercial CSP entities, and no responses were obtained from commercial non-CSP entities. Due to a limited number of commercial responses, R&D feedback is highlighted in this study and commercial feedback is generally described.

2.2. Flux Sensor Technologies

Per stakeholder feedback, one-dimensional (1D) planar sensors, circular foil gauges, and cavity-type radiometers were considered for high-intensity broadband flux sensor technologies in this study.

2.2.1. One-Dimensional Planar Sensors

One-dimensional (1D) planar sensors, such as Schmidt-Boelter gauges, relate a linear temperature gradient across an axial sensor thermopile to a voltage which is directly proportional to the incident heat flux [17]. Planar sensors respond to both convective and radiative heat transfer (i.e. total heat flux sensor), where convective heat transfer generally does not influence sensor measurements unless radiative flux levels are below approximately 50 kW/m^2 or convective heat transfer is relatively large. Schmidt-Boelter gauges are affordable heat flux sensors that provide high sensitivity with short response times. These types of gauges, however, are limited to moderate flux levels and temperatures.

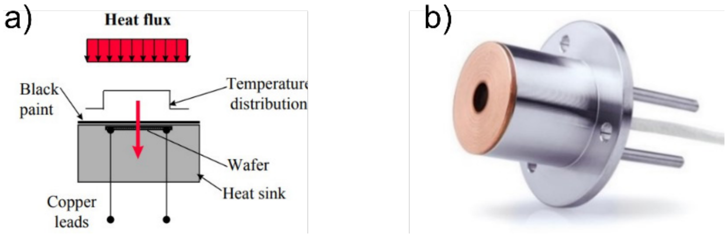

Figure 1. a) Schematic representation of a Schmidt-Boelter gauge [17] and b) a Gardon gauge as manufactured and sold by Hukseflux Thermal Sensors [19].

2.2.2. Circular Foil Gauges

Circular foil gauges, commonly referred to as Gardon gauges, utilize a radial temperature gradient between a hot and cold junction to relate voltage to heat flux. This is achieved using a copper body, a constantan (copper-nickel alloy) circular foil, and a copper signal wire in the center of the foil. The hot junction corresponds to the center of the foil while the cold junction is located at the weld point between the foil and the gauge body. Circular foil gauges are total heat flux sensors. Gardon gauges have similar response times to Schmidt-Boelter gauges but can measure larger fluxes due to the utilization of the radial foil technology compared to the axial thermopile technology. Despite their ability to measure large fluxes, Gardon gauges are known to fail or degrade quickly when exposed to large fluxes for long durations.

2.2.3. Cavity-Type Radiometer

Cavity-type radiometers, or electrical substitution radiometers (ESR), determine heat flux by relating electrical heating required to maintain the radiometer cavity at a uniform temperature to the difference between radiation in and out of the cavity aperture [20]. Cavity-type radiometer technologies can be self-calibrating, and their heat flux measurements are traceable to SI electrical units through calibrated measurements of electrical power. Cavity-type radiometers are recognized as absolute measurement devices and serve as a primary reference standard for the calibration of other heat flux sensors [17]. This type of heat flux sensor is commonly represented by the Kendall radiometer. These radiometers are reliable instruments that can operate at large flux levels and for longer durations than circular foil gauges. Cavity radiometers, however, have slow response times compared to circular foil gauges and planar sensors. Furthermore, cavity-type radiometers, such as the Kendall radiometer, are expensive and have extremely long procurement lead times (12+ months).

2.3. Flux Sensor Calibration Facilities

Three accredited flux sensor calibration facilities, including the National Institute of Standards and Technology (NIST), RISE Research Institute of Sweden, and ISO-CAL North America, were considered for high-intensity broadband flux sensor calibration. Solar furnace (SF) and high flux solar simulator (HFSS) facilities at the National Solar Thermal Test Facility (NSTTF) at Sandia National Laboratory (SNL) were also considered. NSTTF SF and HFSS facilities were included in this study due to familiarity by the authors. It is recognized that other similar facilities can be assessed accordingly.

2.3.1. National Institute of Standards and Technology (NIST)

The state-of-the-art accredited calibration facility for heat flux sensors in the U.S.A. is the National Institute of Standards and Technology (NIST). NIST is an ISO/IEC 17025 accredited calibration facility. NIST calibrates heat flux sensors using a calibration transfer technique, in which the calibration traces back through a secure chain to a high accuracy cryogenic radiometer (HACR) [17]. The NIST calibration is parallel with ISO/IEC 14934-2 method 3 and 14934-3 standards for the calibration of primary and secondary transfer standard sensors, respectively. During both primary and secondary calibrations, NIST utilizes a variable temperature black body heater to produce infrared radiation for calibration up to 50 kW/m^2. The calibration facility at NIST does not allow for calibration of the full spectrum or for calibration above to flux levels required by CSP and non-CSP stakeholders.

2.3.2. RISE – Research Institute of Sweden

The state-of-the-art accredited calibration facility for heat flux sensors in Europe is the RISE Research Institute of Sweden. RISE is an ISO/IEC 17025 accredited calibration facility. Heat flux sensors are calibrated following an “absolute” calibration technique, in which a circular black body furnace is used to determine the heat flux incident on the sensor to be calibrated up to 75 kW/m^2 via a radiative black body enclosure analysis [21]. The calibration follows ISO 14934-2 method 2 and ISO 14934-3 clause 6, and the heat flux calibration is traceable to the international thermal calibration standard ITS-90. Like NIST, the calibration facility at RISE does not allow for full spectrum calibration or calibration up to the high flux levels observed in CSP and non-CSP high-intensity flux applications.

2.3.3. ISO-CAL North America

ISO-CAL North America is an ISO/IEC 17025 accredited calibration facility that provides solar calibrations of pyranometers, pyrheliometers, UV radiometers, FIR pyrgeometers, net radiometers, quantum sensors, LUX sensors, and UV and VIS spectroradiometers [22]. ISO-CAL possesses both indoor and outdoor ISO 17025 accredited calibration facilities. For the calibration of all pyranometer, albedometer, and pyrheliometer makes and models, ISO-CAL meets several ASTM or ISO standards: ASTM G167, ASTM E824, ASTM G207, ISO 9846, and ISO 9847. Contrary to NIST or RISE, who provide a black body derived infrared calibration, ISO-CAL North America provides simulated solar calibration of flux sensors. The limiting factor of ISO-CAL North America’s service, however, is a maximum solar calibration flux level of 1 kW/m^2.

2.3.4. NSTTF Solar Furnace (SF)

The NSTTF at Sandia National Laboratories possesses an outdoor horizontal 16-kilowatt solar furnace that can concentrate solar energy to 6,000 kW/m^2 in a 5 cm diameter plane [23]. The NSTTF facility currently performs solar heat flux sensor calibrations for in-house applications and for a small number of outside customers. The procedure, which was published in 1988 [24], involves calibrating the flux gauge using a ground truth measurement provided by a self-calibrating Kendall radiometer. The sensor is calibrated at 12 discrete flux levels equally spaced between 20% and 110% of the rated capacity of the sensor. Calibrations for outside customers, however, are currently performed on a limited basis and the facility is not internationally recognized as a primary calibration provider.

2.3.5. NSTTF High Flux Solar Simulator (HFSS)

The NSTTF possesses a high flux solar simulator (HFSS) facility that is capable concentrating simulated solar light 1,100 kW/m^2. The facility simulates solar light with four metal halide lamps that are individually concentrated using ellipsoidal reflectors and focused to a target plane. A Kendall radiometer is used to determine the flux level in the target plane at various lamp intensities and with 1-4 lamps in operation. No flux gauge calibrations are currently performed at this facility.

2.4. Evaluation Criteria

Evaluation criteria were selected to assess sensor technologies and calibration facilities against stakeholder flux sensor design and calibration requirements for high-intensity broadband flux measurements. The flux sensor design criteria are as follows:

- Response time
- Robust design: Includes long duration high flux exposure capability
- Measurement reliability: Includes signal noise, measurement uncertainty, and measurement repeatability and sensitivity at and after maximum flux exposure
- Cost
- Procurement lead time

The flux sensor calibration criteria are as follows:

- Maximum calibration level
- Calibration radiation source
- Calibration certification level (accredited vs. traceable)
- Calibration accessibility

Each criterion is equally weighted and scored on a 1-3 scale for each technology and calibration facility. Scores of 1, 2, and 3 correspond to poor, moderate, and good agreement between stakeholder requirements and each technology or facility specification. The overall sensor technology or calibration facility score is determined by summing each criterion rank.

Table 1. Criteria rank description.

Rank	Criteria
Poor (1)	Criteria metric below stakeholder requirement
Moderate (2)	Criteria metric meets stakeholder requirement
Good (3)	Criteria metric exceeds stakeholder requirement

3. Results

3.1. Flux Sensor Design Requirements

Table 2 summarizes R&D stakeholder flux sensor design requirements. Reported metric ranges correspond to the most frequently provided requirement feedback. R&D stakeholders generally require a flux gauge that has increased robustness, reduced signal noise, an affordable cost, and a reasonable procurement lead time. Although limited responses were obtained from commercial CSP stakeholders, it was expressed that flux gauges are difficult to implement into existing receiver designs. Thermal imaging of central receivers is typically used for process control and monitoring. Although this is an indirect measurement approach to managing flux at the receiver interface, a thermal image provides a continuous resolution compared to discrete point measurements achievable with flux sensors. Flux sensors are used in the commercial application on a calibration target for aim point calibration of heliostats.

Table 2. R&D stakeholder flux sensor design requirements. Results correspond to the most frequently provided requirement feedback.

Metric/Topic	**Predominant CSP Stakeholder Response**	**Predominant non-CSP Stakeholder Response**
Current Limitations	Cost, lead time, robustness, measurement uncertainty, signal noise	Lead time, robustness, measurement uncertainty, signal noise, response time, sensor size
Maximum Rated Flux [kW/m^2]	>5,000	2,500 – 5,000
Response Time [ms]	250 – 500	100 – 250
Angular Aperture [deg]	>90	60 – 90
Exposure Time at Max Flux [min]	>60	1 – 30
Sensor Lifetime at Max Flux [# cycles]	>1,000	500 – 1,000
Sensor Sensitivity After Max Exposure [%]	>97.5	>97.5
Repeatability at Max Exposure [%]	>97.5	>97.5
Expanded Measurement Uncertainty (k=2) [%]	<5	<5
Mounting Requirements	Standard flange	Smaller geometry
Spectral Requirements	Broadband	Broadband
Cooling Requirements	Water and/or glycol	Water and/or glycol
Sensor Coating Requirements	Robust to radiative and convective heat transfer	Robust to radiative and convective heat transfer
Sensor Cooling Line and Signal Cable Requirements	Robust cooling lines and cable sheaths. Minimal signal noise.	Robust cooling lines and cable sheaths. Minimal signal noise.

3.2. Flux Sensor Calibration Requirements

Table 3 summarizes R&D stakeholder flux sensor calibration requirements. Reported metric ranges correspond to the most frequently provided requirement feedback. R&D stakeholders generally require a traceable flux gauge calibration to high flux using a broadband or solar light source. Flux gauge calibration should be traceable to SI units, and the calibration procedure should be validated by other entities with similar calibration capabilities. Commercial CSP stakeholders do not require flux gauge calibration when they are not used due to receiver fabrication limitations.

Table 3. R&D stakeholder flux sensor design requirements. Results correspond to the most frequently provided requirement feedback.

Metric/Topic	**Predominant CSP Stakeholder Response**	**Predominant non-CSP Stakeholder Response**
Current Limitations	Calibration range and non-solar calibration	Calibration range and partial spectrum
Spectral Requirements	Broadband	Broadband
Calibration Ranges [kW/m^2]	>5,000	2,500 – 5,000
Calibration Traceability	Traceable measurement to SI units	Traceable measurement to SI units
Calibration Verification	Validated procedure	Validated procedure

3.3. Sensor Technology Assessment

Table 4 shows flux sensor technology specifications, an assessment of each specification according to the corresponding design criterion, and total technology scores for each flux sensor technology. The circular foil gauge received the highest overall sensor technology score whereas the 1D planar sensor scored the lowest overall technology score. The results suggest that the circular foil gauge technology is generally the most suitable for cost-effective high-intensity broadband flux measurements. The circular foil gage scored 15 out of 18 possible points and notably scored moderate or better for each criterion.

Robustness, measurement reliability, and procurement lead time could be improved for the circular foil gauge. The inhibiting limitations of the 1D planar flux sensor are the maximum flux range and sensor robustness. High-intensity fluxes experienced in CSP applications, as well as some non-CSP applications, exceed the maximum flux range of the sensor. The inhibiting factors of the cavity-type radiometer are the response time, cost, and procurement lead time. For CSP applications, the sensor response time could be overcome, however, the cost and severely long procurement lead time are inhibiting for all applications.

Table 4. Flux sensor technology specifications and assessment. Rankings shown in brackets correspond to ranks of poor (1), moderate (2), and good (3).

Sensor	1D Planar Sensor	Circular Foil Gauge	Cavity-Type Radiometer
Flux Range [kW/m^2]	2 – 1,100 (1)	25 – 50,000 (3)	200 – 20,000 (3)
Response Time [ms]	50 – 450 (2)	100 – 250 (3)	1,800 – 30,000 (1)
Robustness: Long duration high flux exposure	Low (1)	Moderate (2)	High (3)
Measurement Reliability	Moderate (2)	Moderate (2)	High (3)
Approximate Cost	$1,400 (3)	$1,600 (3)	$50,000 (1)
Approximate Procurement Lead Time	2-3 weeks (2)	2-3 weeks (2)	12+ months (1)
Total Evaluation Score	**11**	**15**	**12**

3.4. Calibration Facility Assessment

Table 5 shows calibration facility capabilities, the assessment of capabilities against corresponding criterion, and total facility scores. The solar furnace facility at the NSTTF scored the highest when compared to stakeholder calibration requirements. The accredited calibration facilities and the considered high flux solar simulator facility did not comprehensively meet stakeholder calibration requirements, primarily due to radiation source and flux range limitations. The NSTTF facility scored the maximum for calibration range and calibration radiation source, while scoring within an acceptable range for calibration certification level. It is noted that other solar furnace facilities with similar capabilities could be assessed similarly.

The NSTTF facility must make its calibration capabilities more available to outside customers and should pursue primary calibration provider status. The inhibiting limitations of NIST and RISE facilities are the maximum calibration flux level and the calibration radiation source. Stakeholders require calibration to flux levels far exceeding the range of NIST and RISE, and stakeholders require a broadband calibration radiation source. The inhibiting factor of ISO-CAL

North America is the maximum calibration flux level, and the NSTTF high flux solar simulator is inhibited by a lack of calibration procedures and maximum flux level.

Table 5. Calibration facility capabilities and assessment. Rankings shown in brackets correspond to ranks of poor (1), moderate (2), and good (3).

Facility	NIST	RISE	ISO-CAL North America	NSTTF SF	NSTTF HFSS
Maximum Calibration Flux Level [kW/m^2]	50 (1)	75 (1)	1 (1)	6,000 (3)	1,140 (1)
Calibration Radiation Source	Black Body (1)	Black Body (1)	Solar Simulator (2)	Solar (3)	Solar Simulator (2)
Calibration Certification Level	Accredited (3)	Accredited (3)	Accredited (3)	Traceable (2)	No calibration (1)
Calibration Accessibility	Open to public (3)	Open to public (3)	Open to public (3)	Internal (2)	No calibration (1)
Total Evaluation Score	**8**	**8**	**9**	**10**	**5**

4. Study Outcomes

4.1. Improved Circular Foil Gauge

To comprehensively meet stakeholder flux sensor needs, several improved circular foil gauge designs are being considered. The circular foil gauge is well described in literature [25,26,27]. Ignoring heat loss corrections, the steady state temperature distribution over the circular foil takes the form

$$T(r) = (\Phi R^2/4\lambda t)(1-(r/R)^2) + Tc \tag{1}$$

with T the temperature, Φ the heat flux, R the chamber diameter, λ the thermal conductivity of the foil, t the foil thickness and T_c the cold junction temperature, with the radial coordinate $r = 0$ the center of the foil, the position of the 'hot junction' and with $r = R$ the radius of the chamber, the position of the cold junction.

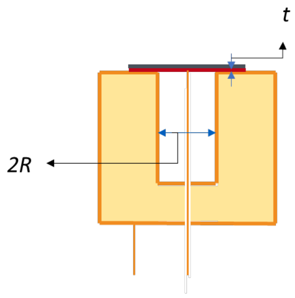

Figure 2. Gardon gauge construction, with parameters to be varied. Colors correspond to materials used, copper (orange), constantan (red) and coating (black).

The hot junction temperature at a given heat flux level is the limiting factor in Gardon Gauge design. Thus, to increase the rated flux level, while maintaining the sensor working principle, one can decrease chamber diameter *R*, or increase foil thickness *t*. Three variations of prototypes will be built based off the existing Hukseflux GG01-1000 model, rated for 1000 kW/m², with a smaller chamber diameter, with a larger foil thickness, and with both effects combined. To improve the understanding of the prototype behavior, all prototypes will be fitted with the extra functionality of a temperature measurement of the cold junction temperature, and of water-cooling inlet and outlet temperatures. This will also allow the validation of theoretical models at high heat flux levels.

Failure mode effect analysis and risk assessment identified the black coating as a critical part of the sensor design. In preparation of the prototype testing, an extensive test campaign is set up to evaluate four coating candidates for use on the novel high-intensity flux gauges. Coating candidates will be tested in solar furnace, solar simulator, high-flux wind tunnel, and tube furnace facilities. This test campaign is anticipated to be completed by the end of 2022.

4.2. Improved Calibration Facility

The findings of this study suggest a more accessible solar furnace facility, that is recognized as a primary calibration provider, is ideal for high-intensity broadband flux sensor calibrations. This has prompted the identification and implementation of a management system at the NSTTF solar furnace for performing a high volume of calibrations for outside customers. Additionally, the trade study has prompted upgrades of the NSTTF solar furnace calibration hardware and procedures in accordance with ISO/IEC 17025 to ensure the validity of results, enable participation in international proficiency testing, and make possible primary and traceable calibration provider status. These improvements will enable the NSTTF to comprehensively meet the calibration needs of high-intensity broadband flux measurement stakeholders.

Hardware upgrades to the facility are underway and include a cloud monitoring camera, improved DNI sensor, IR camera, pyranometers, and a spectrometer. The NSTTF 10,000 sun Kendall radiometer aperture is to be calibrated at an accredited entity and traceable multimeters will be upgraded to ensure traceability of Kendall cavity voltage and current measurements to SI units. Following the establishment of traceability to SI units, the NSTTF will validate the Kendall response against a NIST calibrated gauge up to 50 kW/m^2. Uncertainty in calibration extrapolation to higher fluxes will then be rigorously characterized through assessment of response linearity. The NSTTF will also participate in international proficiency testing to ensure the NSTTF primary transfer standard sensor meets international standards at high flux. Furthermore, existing calibration procedures at the NSTTF are under revision and a subsequent peer review of the updated procedures will ensure validity of calibration results. These actions together will enable the accomplishment of primary calibration provider status for high-intensity broadband flux applications.

5. Conclusions

Stakeholders of CSP and non-CSP high-intensity broadband flux measurements were surveyed and interviewed to obtain flux sensor design and calibration requirements, and existing sensor technologies and existing calibration facilities were compared against this standard. Stakeholders require a flux sensor designed for >5,000 kW/m^2 flux measurements, >1,000 life cycles, <500 ms response time, >60-minute exposure at maximum flux, and <5% measurement uncertainty. Stakeholders also require a sensor with minimal cost, short procurement lead time, and a high-intensity broadband flux calibration. Commercial CSP stakeholders primarily rely on infrared (IR) temperature measurements of receiver equipment to control CSP plant process operation, whereas CSP research and development (R&D) and non-CSP stakeholders rely on accurate flux gauge measurements for a variety of applications. The circular foil gauge technology was determined to meet a majority of stakeholder flux measurement requirements, however the existing technology exhibits degradation when exposed to high flux for long durations. Regarding calibration, it was determined that existing accredited calibration facilities do not meet calibration flux level and radiation source requirements. This work proposed three improved circular foil gauge designs to improve flux gauge robustness and comprehensively meet stakeholder flux measurement requirements. This work also proposed a high-intensity broadband flux sensor calibration facility at the NSTTF solar furnace to meet stakeholder flux sensor calibration requirements.

Author contributions

Luke McLaughlin wrote the original draft of this document. Hendrik Laubscher, Nathan Schroeder, Kenneth Armijo, Jörgen Konings, and Robert Dolce reviewed and edited this document. Kees van den Bos contributed to conceptualization.

Competing interests

The authors declare no competing interests.

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Data availability statement

The data reported in this work is available upon request. Please contact Dr. Luke McLaughlin (lpmclau@sandia.gov).

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