Full Parabolic Trough Qualification from Prototype to Demonstration Loop

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Abstract. On the example of the HelioTrough® collector development the full accompanying and supporting qualification program for large-scale parabolic trough collectors for solar thermal power plants is described from prototype to demonstration loop scale. In the evaluation process the actual state and the optimization potential are assessed. This includes the optical and geometrical performance determined by concentrator shape, deformation, assembly quality and local intercept factor values. Furthermore, its mechanical performance in terms of tracking accuracy and torsional stiffness and its thermal system performance on the basis of the overall thermal output and heat loss are evaluated. Demonstration loop tests deliver results of collector modules statistical slope deviation of 1.9 to 2.6 mrad, intercept factor above 98%, peak optical performance of 81.6% and heat loss coefficients from field tests. The benefit of such a closely monitored development lies in prompt feedback on strengths, weaknesses and potential improvements on the new product at any development stage from first module tests until demonstration loop evaluation. The product developer takes advantage of the achieved technical maturity, already before the implementation in a commercial power plant. The well-understood performance characteristics allow the reduction of safety margins making the new HelioTrough collector competitive from the start.

INTRODUCTION TO THE HELIOTROUGH COLLECTOR DESIGN

The HelioTrough® collector was developed in co-operation of Flagsol with Schlaich Bergermann and Partner (sbp), Fraunhofer Institute for Material Flow and Logistics (FhG IML) and the German Aerospace Center (DLR), with CSP Services (CSPS) as subcontracted quality verification company. The collector is marketed by TSK Flagsol. The patented design and assembly procedures of the HelioTrough differ significantly from previous collector systems [1, 2]: The steel structure features a central continuous torque tube element supporting the cantilever arms. During collector assembly, mirror panels are precisely positioned face-down on a “mirror jig” before being adhesively bonded to the cantilever arms. This patented procedure saves one production step and permits a highly precise concentrator shape without requiring an expensively high accuracy of the structural elements. The implemented version of the HelioTrough® collector as shown in FIGURE 1 is 191 m long and provides a net collector aperture area of 1’263 m². Each of its ten modules is 19 m long and 6.8 m wide. Counterweights bring the center of gravity to the center of the torque tube as rotation axis. The collector rotates on the rims of special bearing flanges, which are inserted between the torque tubes flanges of two adjacent modules, as runways for roller bearings. With this design mirror gaps at the pylons are eliminated, and a significantly higher torsional stiffness is achieved, leading to a high average intercept value of the assembled collector. Significant cost reduction of the solar field is achieved with this collector design, compared to the SKAL-ET (EuroTrough) technology as stated in reference [3].

SolarPACES 2016
AIP Conf. Proc. 1850, 020010-1–020010-8; doi: 10.1063/1.4984334
Published by AIP Publishing. 978-0-7354-1522-5/$30.00

FIGURE 1. HelioTrough collector test loop in SEGS V, Kramer Junction, CA, USA

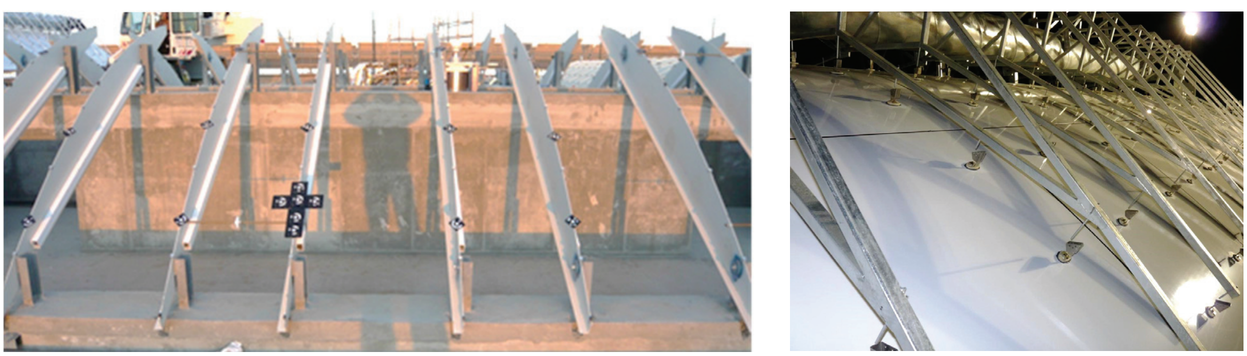
PARABOLIC TROUGH QUALITY CRITERIA AND THEIR ASSESSMENT

For the evaluation of the quality, thus performance of parabolic trough collector key components and systems, a number of criteria described in this section have been established in the past decade.

Module/Concentrator Performance

Mirror and Collector Shape

The key quality criterion for the mirror *reference shape* is FDx, the statistical focus deviation value in transversal orientation, representing a root-mean-square deviation of the reflected ray from the ideal focal line of the individual mirror. The value is typically derived from deflectometric measurement [4] for example using a QDec system [5] in horizontal or vertical position of the mirror panel. This method can be applied to individual mirror panels to assess their production quality as well as to entire modules evaluating the interaction of mirror panels and supporting structure with reference to the collector design. In the latter case (larger units), the absorber reflectance method is more convenient for fast assessment [6]. The shape accuracy of the supporting structure itself can be determined by means of automatic photogrammetry [7] and be instructive in identifying systematic shape deviations, which have to be fed back into the assembly process and improvement of the assembly jigs. However, for collectors with structure and mirrors assembled in a single step like in the HelioTrough® assembly process, this is inapplicable. Thus, the assembly jig (shown in FIGURE 2) needs to be checked directly for geometric defects.



(a) (b)

FIGURE 2. (a) Part of mirror assembly jig with photogrammetric measurement targets, (b) assembled module on jig with mirrors glued to cantilever arms

Intercept factor values are derived from measured focus deviation results via ray-tracing. Required values are receiver diameter and alignment deviation, tracking accuracy and sun shape assumptions. Knowing the intercept factor helps quantifying the design limitations and potentials of particular mirror panels or the whole concentrator. The *shape deformation of mirrors and modules* as a function of the collector's tracking angle may be significant for the optical performance throughout an operating day. The shape deformation characteristics of a collector module are determined by photogrammetry in different collector angles [8] or by deflectometry [6] and expressed in terms of coordinate deformation or slope and focus deviation values. Measured for individual mirror panels or at module level, the method can reveal optimization potential or confirm achievements in terms of the *stiffness* of the mirror panels and their supporting structure. Also position and number of mounting elements (e.g. 4 or 6 mirror support brackets) can be optimized at demonstration scale level.

Collector Assembly Quality

The assembly quality of collectors in the solar field is mainly determined by the implementation of proper installation procedures to control the module alignment specifications. The absorber reflectance method (TARMES) [6] is used at the module interfaces to determine the alignment between individual modules of a collector and to the drive. Twist between neighboring modules would hinder proper tracking and may reduce the overall collector intercept factor. A typical measurement at the module interface is illustrated in FIGURE 3 using a green dummy absorber tube spanning from the second last receiver support of one module over its rear end to the first receiver support of the next module, thus covering six columns of mirror panels of the two modules.

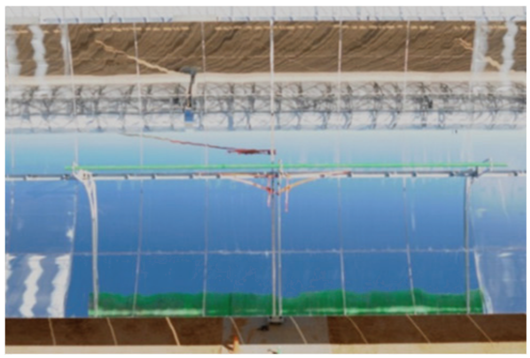


FIGURE 3. TARMES measurement image on two neighboring HelioTrough modules (three mirror rows on each module), green dummy absorber tube and its reflex at the bottom mirror row

Collector Quality in the Field

The overall quality of collectors in the solar field is tested and characterized in terms of their optical, mechanical and thermal performance. The overall *optical collector performance* depends on the average of local intercept values along the collector. These are directly measured around the receiver tube of the operating, focused collector, using the Camera Target Method [9], visualizing the path of reflected rays in the close vicinity of the receiver on a Lambertian target and quantitatively evaluating the intensity of the intercepted radiation. Exemplary HelioTrough results are shown in FIGURE 4.

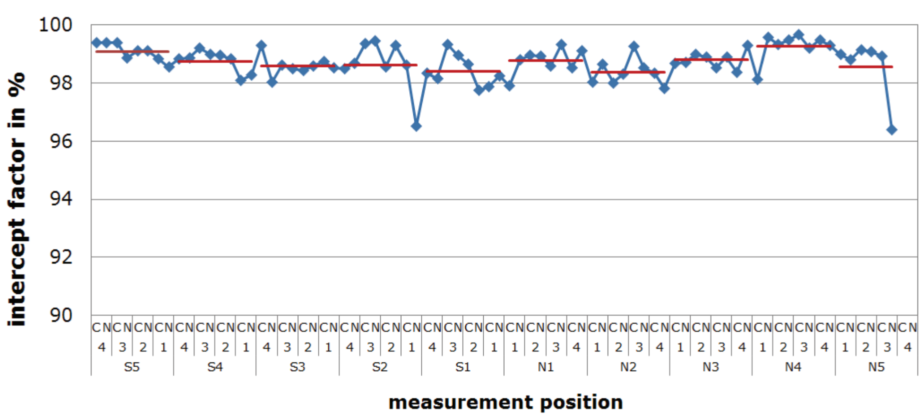
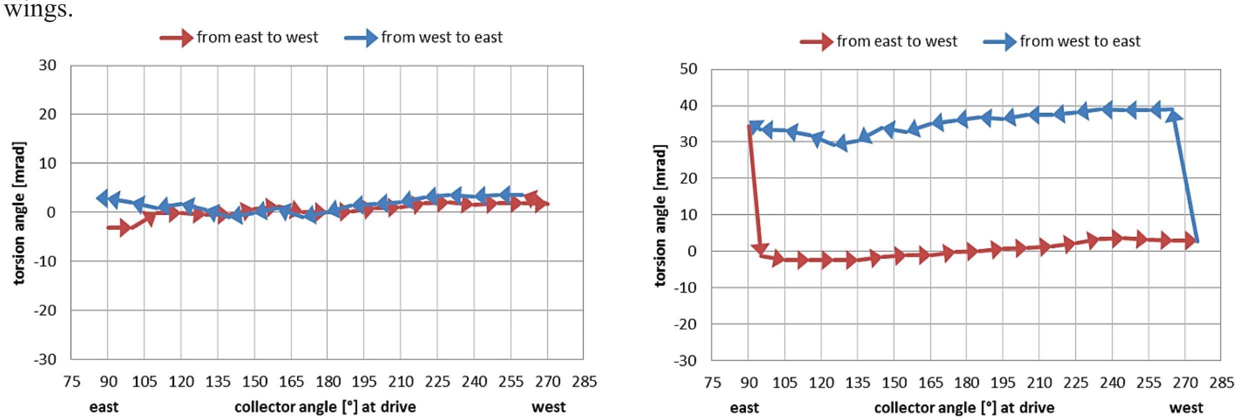


FIGURE 4. Local intercept values along collector 5I, tracking near east horizon

The main aspect of *mechanical performance* of a full size collector is its torsional tracking behavior determined by its torsional stiffness, imbalance of the modules with respect to the rotation axis, friction in bearings, forces from the flexible pipe joints (rotation and expansion performing assemblies REPA) and possible play [10]. Collector torsion may lead to reduced tracking precision as the distance to the drive increases. This can significantly affect the collector intercept and must be avoided by appropriate design and component selection. Collector torsion is measured with mirror panels and filled receiver tubes. High resolution inclinometers are installed at the front end of the module close to the drive and at the rear end of the last module of each collector wing. The measurement starts with the collector in one extreme collector angle (eastern or western horizon). It is then turned in steps of 10° towards the other extreme, and back, and at every step, measurement values are recorded. The torsion angle is defined as the angular difference measured between the rear end plate of the last module and the angle measured close to the drive pylon. FIGURE 5 illustrates the resulting hysteresis curves of two selected HelioTrough collector wings.



(a) (b)

FIGURE 5. Hysteresis curve of the southern wings of collector 5I (a) and collector 5J (b), featuring different bearings

Receiver Performance

Optical Performance: For the comparison of the optical performance of parabolic trough receivers sun simulator tests under repeatable conditions have become accepted. Such tests at DLR QUARZ Center provide values for optical performance of the receiver tube including the characteristics of glass envelope and receiver selective coating as well as its geometric (bellow) design [11]. *Thermal losses* of parabolic trough receiver tube measured as a function of absorber temperature in steady-state conditions in suitable laboratory test benches characterize the quality of the selectivity of the receiver coating and annulus vacuum.

The combined results for optical receiver performance and heat loss testing, in combination with durability tests, typically serve for selection of a particular receiver type and manufacturer for a collector design or installation from current market offers.

Thermal System Performance

The thermal system performance is evaluated from the system's thermal output or balance under particular operating conditions and commonly expressed as efficiency:

$$\eta_{\mathrm{sys}}\left(\theta, T_{\mathrm{m,HTF}}\right) = \frac{\dot{m}_{\mathrm{HTF}} \cdot c_{\mathrm{p,HTF}}(T_{\mathrm{m,HTF}}) \cdot [T_{\mathrm{out,\ HTF}} - T_{\mathrm{in,HTF}}]}{A_{\mathrm{Ap}} \cdot E_{\mathrm{b}} \cdot \cos(\theta) \cdot \chi^{3/2}} \tag{1}$$

The performance parameters of equations relating this output to prevailing operating conditions in terms of angle of incidence (θ), operating temperature ($T_{\mathrm{m,HTF}}$), direct normal irradiance (E_{b}), operating status (cleanliness χ) and other parameters are identified from test data by least square optimization honoring test conditions and data uncertainty [12, 13]. These are subsequently employed to predict yields.

HELIOTROUGH COLLECTOR TEST PROGRAM

The complete HelioTrough® development process was accompanied by qualifying measures as illustrated in FIGURE 6. At the early stages of HelioTrough® development durability testing monitoring the permanence of quality specifications under accelerated aging conditions had not been established and is thus not considered here.

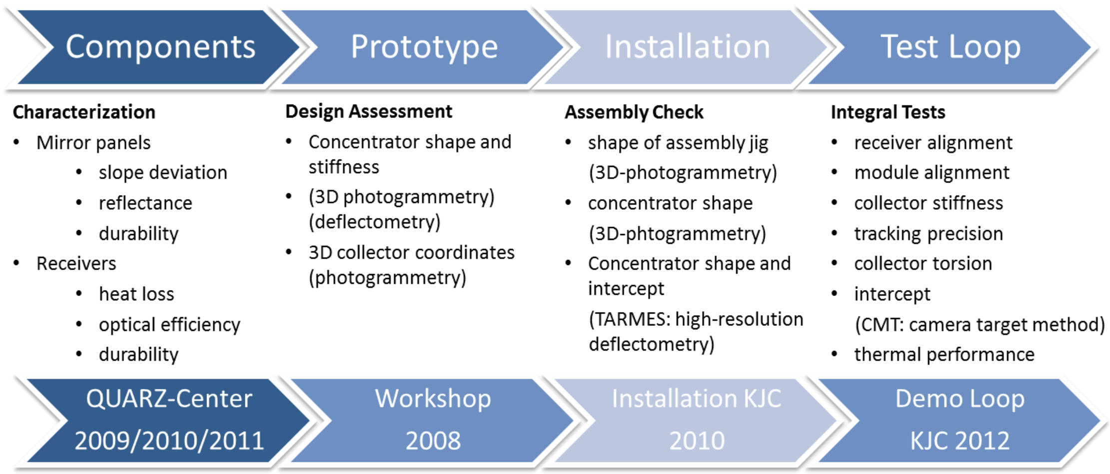


FIGURE 6. Typical stages of component and system qualification and methods applied during the HelioTrough collector development cycle (excluding endurance testing)

The selection of the most promising components was facilitated by mirror and receiver performance results obtained at DLR's QUARZ Test and Qualification Center for CSP Technologies. The first prototype installed indoors was assessed for concentrator shape and stiffness by deflectometry and photogrammetry. Later, the quality of the mirror jig and the on-site collector assembly were also checked by deflectometry and photogrammetry. Finally, two full size collectors and five shorter units of the demonstration loop were investigated for optical, mechanical and thermal performance. The modules/collectors of the demonstration loop chosen for assembly check and integral tests are identified in FIGURE 7. The entire installation was carefully monitored for more than two years in full operation.

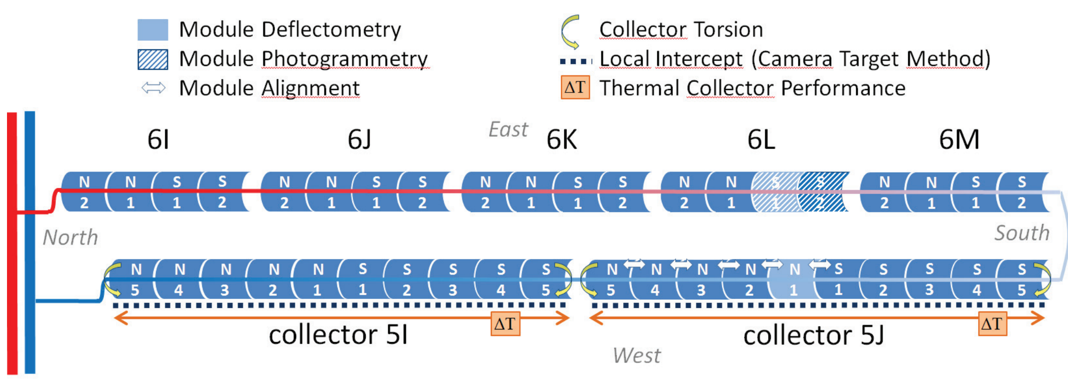


FIGURE 7. Set-up of the HelioTrough demonstration loop with indication of units tested for assembly and integral performance

TEST RESULTS, INTERPRETATION AND IMPACT ON THE HELIOTROUGH DEVELOPMENT

The results of individual tests of the HelioTrough® at different stages of development and for the design of component alternatives are summarized in TABLE 1. It shows which components were included in the final design and which were rejected for more promising alternatives.

Component Selection

Based on the difference of up to 1.7% in optical performance (derived from cold tests and the thermal expansion of the geometric design at an operating temperature of 350°C) between receiver designs A and B measured at DLR's ElliRec and the lower heat loss results, design B was selected as component for the final collector. Considering the increased surface area for the 88.9 mm diameter absorber tube this heat loss value of the larger receiver is even slightly better than expected (reference measurements for the current standard absorber tube diameter of 70 mm showing thermal losses of about 150 W/m).

In the course of the collector development mirror quality improved in FDx from 14.3 mm of first RP4 prototypes down to 4.2 mm for the latest commercially available panels. This corresponds to an increase from 97.2 to 99.2% being the maximum possible intercept value (ICsun) for this geometry and sun shape.

Collector Prototype

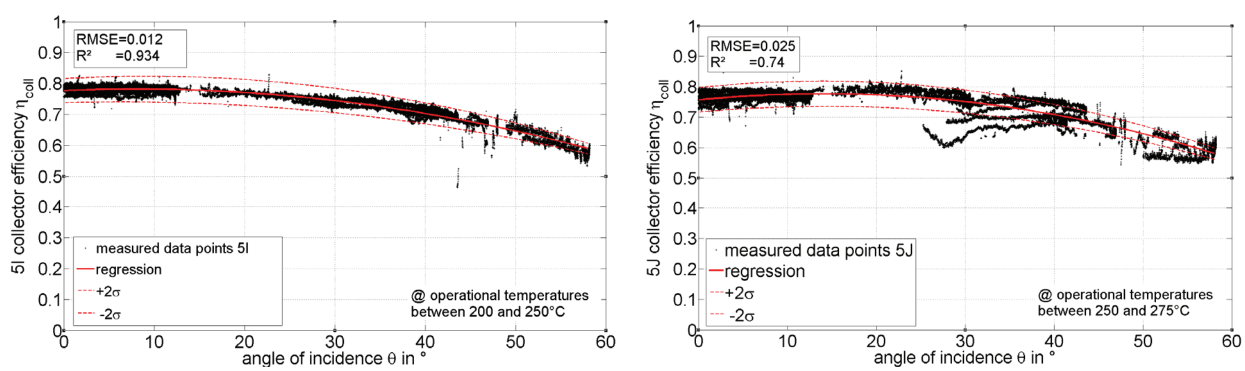
The photogrammetric and deflectometric measurements of the prototype in the workshop proved that the jig quality and the novel module assembly procedure are adequate and offer the required shape accuracy of the concentrator (in zenith position). They induced no significant additional deviations compared to the results for the panels themselves. As for the shape deformation however, considerable sagging of the panels due to gravity was observed in non-zenith position. This undesirable effect reducing the effective collector intercept was avoided later by a design revision of the interconnecting elements. Before the test loop installation, the number of support points per panel was increased from four to six and their positions on the panels were optimized.

Installation

TARMES and photogrammetric measurements carried out on sample modules and their interconnection during collector installation reconfirmed the quality of the assembly jig and procedures under field conditions. This also holds true for the used alignment procedure of the individual modules in a collector.

Assessment of Test Loop

The tests on the full-size HelioTrough® collectors in the demonstration loop constitute a final assessment of the design. Both collectors generally show good local intercept as exemplarily displayed in FIGURE 4 (theoretical geometrical maximum 99.2% for this configuration) with collector 5I slightly outperforming 5J. Being the first demonstrator of full design length, the impact of the different bearing alternatives is revealed at this stage for the first time. Supplementing results of the torsion measurement (FIGURE 5), the results for overall collector performance on the same days in FIGURE 8 show how torsion translates to underperformance of up 15% for an otherwise well performing collector [14]. These results motivate the change from bush to roller bearings in the final design.



(a) (b)

FIGURE 8. Quasi steady-state overall thermal collector efficiency for E_b > 700 W/m² of collector 5I with roller bearings (a) and collector 5J with bush bearings (b) [14]

TABLE 1. Test results of the HelioTrough® for key performance criteria at the different stages of development with indication of accepted and rejected design options

		Qualification Stage			
	Criterion **Valuation basis**	**Component** **Test-Laboratory**	**Module** **Test workshop**	**Demo-Loop** **Field**	**Accept √** **Reject x**
Receiver	**Receiver performance**				
	optical eff. *Design A* @T_{amb}=20°C	*DLR ElliRec* 0.99*	-	-	x
	optical eff. *Design B* @T_{amb}=20°C	*DLR ElliRec* 1.00*	-	-	✓
	Heat loss *Design A* @T_{rec}=350°C	*DLR ThermoRec* 223 W/m	-	-	x
	Heat loss *Design B* @T_{rec}=350°C	*DLR ThermoRec* 171 W/m	-	-	✓
Parabolic trough concentrator	**Reflectance**				
	$\rho_{\mathrm{dir,660nm}}$	*QUARZ Lab* 95.9%	-	-	✓
	Shape				
	Initial panel, 4 supporting points	*QDec* SDx=3.5 mrad *QDec* FDx=13.8 mm	*PG* SDx≈5 mrad *PG* FDx≈25 mm	-	x
	New panel, 6 supporting points	*QDec* SDx=1.3 mrad *QDec* FDx= 4.9 mm	→	*PG, TARMES* SDx=1.9–2.6 mrad FDx=8.9-11.8 mm	✓
	Module alignment in collector				
	Alignment deviation (rms)	-	-	*TARMES* 0.5 mrad	✓
	Overall optical quality (intercept)				
	New panel, 6 supporting points	*QDec* 99.2%**	-	*TARMES* 98.4–99.2% *CTM* 98.4–98.8%	✓
	Torsion (angle) between first and last module of collector wing				
	Sliding bearings (collector 5J)	-	-	18 mrad	x
	Roller bearing (collector 5I)	-	-	1-3 mrad	✓
System	**Thermal system performance [14]**			*Loop Perf.Test*	
	optical efficiency (5I)***	-	-	0.816	✓
	Heat loss c_1	-	-	0.0622 W/(m²K)	✓
	Heat loss c_2			0.00023 W/(m²K²)	✓
	Specific (collector) heat capacity			2653 J/kgK	✓

** measurement relative to DLR reference*

*** maximum possible intercept value for this geometry: 99.2%*

**** test for collector 5J evaluated but result rejected due to torsion*

CONCLUSIONS

As shown on the example of TSK Flagsol's HelioTrough® collector, the continuous accompanying qualification of a collector development throughout all stages from component selection to full-size demonstration proves very beneficial: By assuring that potential problems are identified and eliminated at the earliest possible stage, the development cycle is accelerated. Besides confirming the quality of the general design and implementation, tailored measurement and evaluation techniques helped further improving the collector performance by selecting high quality mirrors and receivers and reconsideration of the number of mirror supporting points as well as innovative bearings to reduce torsion. Furthermore, they enable a quantitative assessment of the effect of the corrective measures and provide a full qualification of the collector. Early optimistic performance predictions from optical measurements are finally confirmed at collector level by reliable intercept factor values and thermal performance measurements.

ACKNOWLEDGMENTS

The authors thank the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) and the German Federal Ministry for Economic Affairs and Energy for their support of the work presented by funding the HelioTrough collector development and qualification (methods) within the projects ANDA NT, ANDA NTpro and StaMeP and the US Department of Energy (DoE) for co-funding the installation of the demonstration loop at SEGS V, Kramer Junction, CA, USA.

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