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CONCEPTUAL DESIGN OF AN ADVANCED TROUGH UTILIZING A MOLTEN SALT WORKING FLUID

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Abstract

Recent studies in the United States suggest that parabolic trough levelized energy costs (LEC) can be reduced 10-to-15% through integration of a large salt energy storage system coupled with the direct heating of molten salt in the solar field. While noteworthy, this relatively small predicted improvement may not justify the increased technical risks. Examples of potential issues include increased design complexity, higher maintenance costs, and salt freezing in the solar field. To make a compelling argument for development of this new system, we believe that additional technical advances beyond that previously reported will be required to achieve significant LEC reduction -- greater than 25%.

The new technical advances described include the development of a high-concentration trough that has double the aperture and optical concentration of current technology. This trough is predicted to be more cost-effective than current technology because it's cost ($\$/m^2$) and thermal losses ($W/m^2$) are significantly lower. Recent trough optical performance improvements, such as more accurate facets and better alignment techniques, suggest a 2X trough is possible. Combining this new trough with a new low-melting point salt now under development suggests that an LEC cost reduction of ~25% is possible for a 50 MW, 2X salt plant relative to a conventional (1X) 50 MW oil plant. However, the 2X trough will also benefit plants that use synthetic oil in the field. An LEC comparison of 2X plants at sizes ≥200 MW shows only a 6% advantage of salt over oil.

Keywords: parabolic trough, molten salt, optics, economics

1 Introduction

There is currently a significant world-wide effort to reduce the LEC from parabolic trough plants. The R&D is aimed at the replacing the synthetic oil working fluid with lower-cost and higher-temperature fluids such as water/steam and molten salt [1, 2]. Switching to the new fluids will allow higher trough-field-outlet temperatures (increasing from 390 ^oC to > 500 ^oC) and a subsequent increase in the Rankine power block efficiency. In addition, higher temperatures will allow the integration of a low-cost energy storage system. This occurs because storage cost is inversely proportional to the temperature difference between inlet (290 ^oC) and outlet of the trough field. Thus, increasing this ΔT by a factor of 2, reduces the cost of storage by ~1/2 and makes it practical to build trough plants with up to 16 hours of thermal storage. These plants will have a much higher solar multiple (2.8 future vs. todays 1.3) and corresponding capacity factor (60% future vs. todays 25%) that will result in a reduction in LEC. This relationship between operating temperature, storage cost, capacity factor, and LEC has been known since the 1980's and was the reason that the molten-salt power tower was developed and demonstrated at Solar Two [3] in the late 1990's. To be economically competitive with future power towers, several USA organizations [2] believe that future troughs must emulate Solar Two and use salt as the receiver working fluid and storage media.

Kelly recently published a paper [2] that compared the LEC of current trough technology with future plants that use molten-salt in the solar field. The main results are presented in Figure 1. The first blue column is similar to the technology installed at Nevada Solar One in 2007; there is no thermal storage and therminol synthetic oil is used in the solar field. The second blue column is representative of the Andasol project now under construction in Spain; there is a nitrate salt thermal storage system that is charged by a solar field using therminol. The LECs for these plants are predicted to be the same. Addition of storage did not reduce LEC, even though capacity factor was increased from 27 to 38%, because the storage is expensive. The ΔT between hot and cold tanks is ~ 90 C and a costly heat exchanger is needed to transfer the heat from the oil in the field to the salt in the tanks. The 3rd blue column represents a scaleup of Andasol-type technology to its maximum practical solar-field size of ~1.3E6 m^2. Some LEC reduction for this 150 MW plant is seen relative to the 50 MW plant due to an improved economy of scale. The 4th blue column uses HiTec (nitrate/nitrite mix) salt in the field and in storage. This eliminates the costly heat exchanger but the LEC is still predicted to be the same as the other 50 MW plants. The LEC was not reduced because the operating temperature is not at the maximum possible for HiTec and an anomaly exists in the analysis, i.e. the design solar multiple and capacity factor were significantly lower which makes it difficult to compare results. The final blue column represents what could be achieved by a HiTec plant scaled up to its maximum size and temperature. However, the LEC for this 250 MW plant is only 9% lower than the 150 MW therminol plant.

To obtain a greater LEC reduction, the analysis was redone assuming use of an advanced receiver currently under development by industry which has a much lower heat loss (emissivity of 0.07 vs. 0.14). The results are the red columns. This new heat-collection element (HCE) is especially helpful in reducing the LEC of the 250 MW HiTec plant, now 14% lower than the advanced 150 MW therminol plant. While noteworthy, these relatively small predicted reductions in LEC do not appear to justify the increased technical risks. Examples of potential issues include increased design complexity, higher maintenance costs, and salt freezing in the solar field. To make a compelling argument for development of this new system, we believe that additional technical advances beyond those shown in Figure 1 will be necessary.

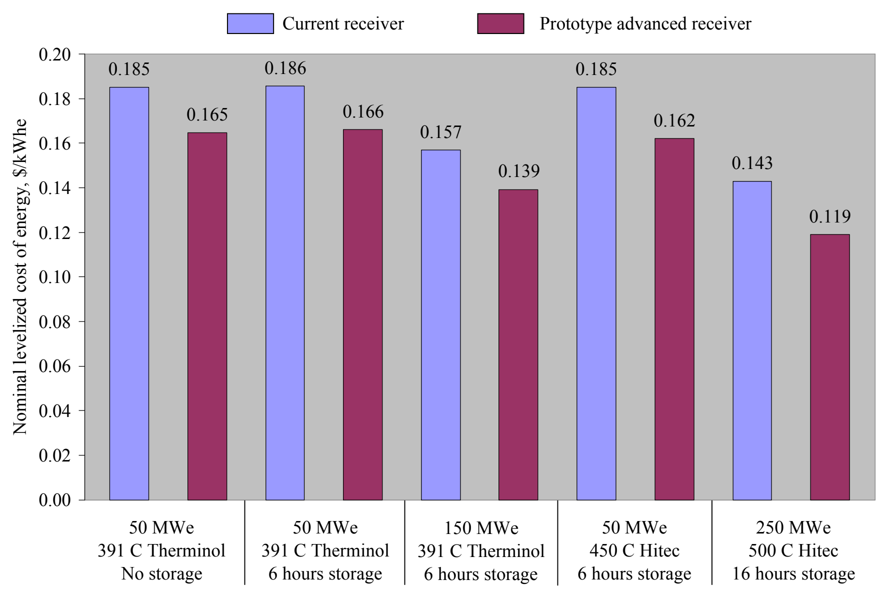

Figure 1. LEC comparison of current and future trough technology [2]

2 Proposed 2X Trough

All the cases presented in Figure 1 are based on a conventional trough with a 5 m aperture, an 80 degree rim angle, and a 0.07 m diameter HCE. Although the geometric concentration is 71, the peak flux is only about 40 suns (see Figure 2). These dimensions have remained virtually the same for the last 20 years. In this section we propose doubling the concentration by keeping the HCE diameter the same and increasing the aperture to 10 m. Such a trough, in theory, would enjoy ~½ the heat loss (W/m^2 basis) and a significant reduction in capital cost ($\$/m^2$ basis). As described below, recent R&D advancements suggest that it should be possible to build a 2X trough that also maintains a similar level of optical performance as a conventional trough. This has certainly been the case for parabolic dish systems in which the trend has been towards the development of high accuracy optical systems such as the Schlaich Bergermann und Partner EURODISH, the Sandia 10-kWe Advance Dish Development Systems (ADDS) and the Stirling Energy Systems (SES) 25 kWe dish/Stirling concentrators [4]. For example, the total error budget for the ADDS and SES collectors is less than 1.5 mrad.

The flux calculations in Figure 2 for todays 5 m trough are based on a 5.4 mrad system-level optical error. This 1-sigma error was calculated using the standard method of convolving errors of circular-normal distributions

$$\sigma_{sys} = \mathrm{SQRT}(\sigma^2_{slope} + \sigma^2_{align} + \sigma^2_{track} + \sigma^2_{wind}) = \mathrm{SQRT}(2^2 + 2.24^2 + 2^2 + 4^2) = 5.4 \text{ mrad.}$$

Wendelin measured a 3 mrad error for the Solargenix facet assemblies installed at Nevada Solar One [5]. This error includes slope and alignment errors. Since the slumped-glass mirrors have a slope error of ~2 mrad [6] this implies the alignment errors were ~2.24 mrad ($3^2 = 2^2 + 2.24^2$). The Eurotrough consortium estimated that tracking error using todays shadow-band technology is ~ 2 mrad and that wind-induced tracking error is ~ 4 mrad, given a 5 m/s average wind [7]. Combining terms yields a 5.4 mrad system error and results in acceptable levels of beam spillage, calculated by Trough-Helios [8] to be 3.5% at summer solstice in Barstow.

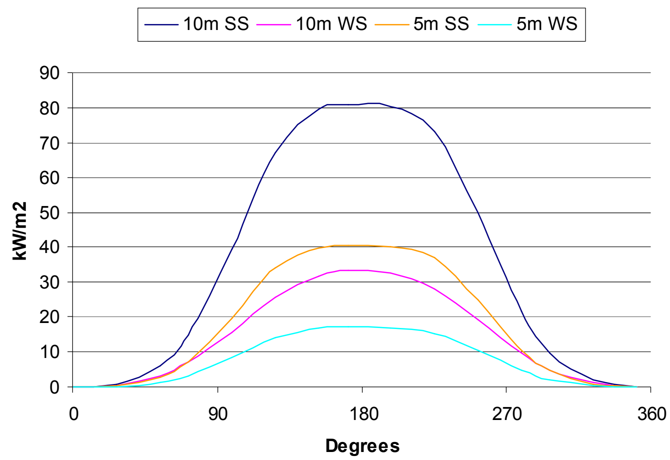

Figure 2. Trough Helios prediction of incident flux upon a 0.07 m diameter HCE for todays 5m aperture trough and a future 10m trough. System error is 5.4 mrad for the 5m trough and 2.5 mrad for the 10m trough. The King sunshape [9] and 1000 W/m² insolation were assumed.

If the 5.4 mrad system error is applied to the 2X trough, beam spillage would be unacceptably high at nearly 30%. Thus, the system error must be significantly reduced in order for the 2X trough to be practical. Trough-Helios investigations suggest that a 2.5 mrad error budget is a reasonable goal to achieve acceptable levels of spillage similar to todays 5 m trough. This is shown in Table 1. The winter solstice spillage is significantly greater for the 10 m trough; however, the extreme solar incidence angles (~60°) leading to this high spillage only occur a few hours per year.

System Error	Summer Solstice Noon Spillage	Equinox Noon Spillage	Winter Solstice Noon Spillage
2.0 mrad	1.7%	2.3%	6.8%
2.5 mrad	3.7%	4.5%	9.2%
3.0 mrad	7.2%	8.3%	14%
3.5 mrad	11%	12%	17%

Table 1. Trough Helios prediction of beam spillage for a 10 m trough with a 0.07 m HCE. For reference, the 5 m trough is 3.5% (SS), 3.8% (EQ), and 5.4% (WS).

As discussed in the subsections that follow, initial R&D evidence suggests the following subsystem error budget for the 2X trough.

- Mirror slope error reduced from 2 mrad to ~1 mrad
- Alignment error reduced from 2.2 mrad to 0.5 mrad
- Tracking error reduced from 2 mrad to less than 1 mrad
- Wind-twist error reduced from 4 mrad to less than 2
- and thus, $2.5 = \mathrm{SQRT}(1^2 + 0.5^2 + 1^2 + 2^2)$

2.1 Reduction in Slope Error

The key to reducing the overall optical errors of concentrating solar power systems is achieving a low mirror slope error. In the case of parabolic dishes, slope error typically dominates the overall error budget, representing more than half of the total.

Results from NREL VSHOT optical characterizations suggest that current slumped-glass trough mirrors have a latent slope error of ~2 mrad. However, it is important to note that the reported slope error measurements include the influence of mirror mount distortions. Figure 3 shows the influence of the mirror mount moment joints on an LS-2 mirrors. The latent slope error may, therefore, be somewhat less than 2 mrad. Efforts to better quantify the impact of mirror mounts, development of approaches that minimize mount distortions, and/or manufacturing development to improve the slope error of slumped glass mirrors could enable the use of traditional slumped-glass mirror options that achieve the accuracies needed for a high-concentration trough concentrator, ~1.5 mrad or better.

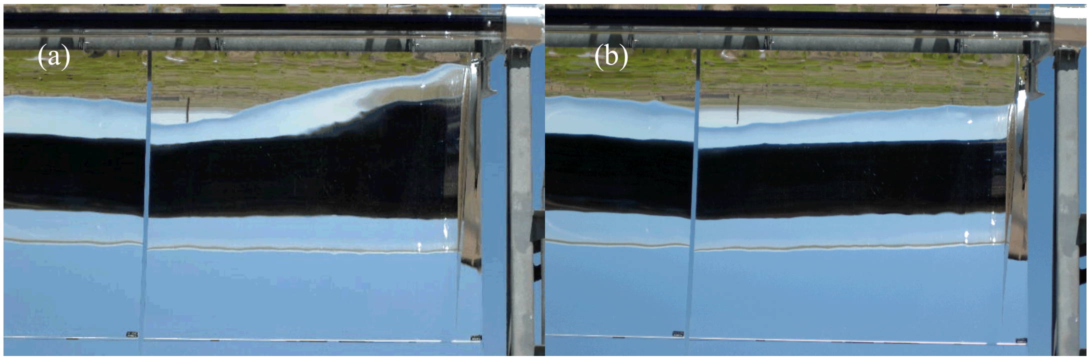

Figure 3. Photograph showing the impact of mirror mount distortion on curvature of a LS-2 mirror (3a). Figure 3b is the same mirror with the mirror mount loosened.

There are also other options such as structural sandwich construction supported mirrors such as the aluminum honeycomb mirrors used in the Sandia Advanced Dish Development Systems (ADDS), Figure 4, and SES systems. Compared to the large prototype honeycomb facets of the late 1970s which had slope errors of 3 to 4 mrad,[10] modern tooling and material technologies have enabled extremely accurate mandrels and mirror facets with slope error of less than 1 mrad. For example, the slope errors on the compound curvature parabolic gore facets used on the ADDS have slope errors of 0.8 to 1.4 mrad [11]. These and/or similar approaches used by McDonnell Douglas with stamped-back mirrors could certainly achieve the necessary accuracy. Although individual structural-sandwich mirrors are more expensive than individual slumped glass mirrors, because the sandwich is very strong there are opportunities to use it within the mirror trough structure. This could lead to a lower structural cost that compensates for the higher mirror costs. Structural facets also minimize O&M related to mirror breakage.

Figure 4. Sandia 10-kWe dish/String system dish system. The structural honeycomb facets have slope errors in the range of 0.8 - 1.4 mrad.

2.2 Reduction in Alignment Error

Sandia is addressing trough alignment with the Theoretical Overlay Photographic (TOP) alignment system [12]. The TOP technique has been validated on an LS-2 module at Sandia. To make the approach practical for commercial parabolic trough solar power plants, SNL is developing a field deployment system which is currently undergoing field testing and validation. The system (Figure 5) features a trailer-mounted fixture and image acquisition, processing, and analysis software. The overall goal is a practical system for accurate alignment of parabolic trough collectors. Based on similar approaches developed for parabolic dishes, achieving RMS mirror alignment errors of less than ½ the mirror slope error is a reasonable expectation.

Figure 5. The TOP alignment system can potentially reduce facet alignment errors to 0.5 mrad.

2.3 Reduction in Tracking Error

Early in the DOE trough development program, Sandia built and tested an innovative closed-loop tracking system. As depicted in Figure 6, the device consisted of 2 fine wires installed along each side of the absorber tube parallel to the axis. The wires changed resistance as a function of the solar flux arriving at the absorber from the reflectors. The resistance of the 2 wires was compared to produce a null signal when both wires were equally illuminated. This device was shown to be more accurate than a shadow-band tracker [13].

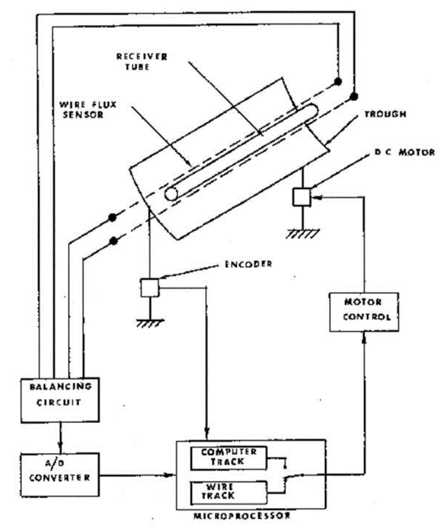

Figure 6. Solar Flux Tracker for Parabolic Trough Collectors

Some modern dish/Stirling systems also use a closed-loop tracking system. To meet the stringent demands of high-flux point-focus systems, Sandia has developed passively cooled flux sensors placed around the receiver aperture. These devices have proved to be extremely robust and should be inexpensive to manufacture. In addition, because this true closed-loop tracking approach inherently accounts for gravity deflection of the receiver relative to the concentrator and other indeterminate effects, it essentially eliminates tracking errors from the error budget. The development of similar approaches for parabolic trough closed-loop tracking should be an element of future trough research and development (R&D).

2.4 Reduction in Wind Twist Error

The impact of wind on optical errors can be difficult to estimate and interpret. When measuring or calculating the optical impacts of wind, maximum deflections are typically determined. However, it is inappropriate to apply these errors directly to optical errors. Keeping in mind that error budget is expressed in terms of RMS, the correct wind twist optical error should represent one standard deviation of error and be weighted for area and time over an operational year. In addition, because twist is often cyclical, the rms value is further reduced as the trough twist back and forth. Although significant wind deflection errors are calculated for parabolic dish systems, it has been virtually impossible to measure any loss of performance due to wind. In fact, the difference in performance during windy and calm conditions is typically within measurement uncertainly despite the fact that wind also contributes the receiver heat loss.

Since wind twist is predicted by the Eurotrough consortium to be the most significant optical error source, future R&D should give significant attention to understanding and addressing this topic. The most straightforward method of minimizing wind twist is to simply reduce the number of modules on a solar collector array (SCA). Of course this is at the expense of higher drive costs. The sandwich construction honeycomb and other structural facets described above are much stronger than current slumped glass facets and should experience less flexure during windy conditions. In addition, large versions of these facets can become an integral part of the trough structure, rather than the current practice of attaching facets to a separate support structure. A trough based on a "structural facet" concept should be much stiffer and experience much less twist along the length of the solar collector during windy conditions. A reduction in twist error from 4 to less than 2 mrad is plausible, but careful structural analysis needs to be performed. R&D is needed to address all of these issues to enable industry to optimize designs.

3 LEC Calculations for 2X and Conventional Trough Power Plants

The EXCELERGY software [14] was used to perform the LEC analysis presented in Figure 1. We obtained the model and the input data from the authors of that work. We first reran the cases presented in their paper to more fully understand the analysis details[i]. We then compared annual performance predictions with SOLERGY [15] models of same-size trough plants. We found EXCELERGY and SOLERGY to be in close agreement so we also adopted EXCELERGY as our analysis tool. EXCELERGY also includes built-in cost and economic models that greatly facilitate LEC calculations.

The details of 3 cases presented in Figure 1 are reproduced as the grey columns in Table 2. The remaining columns are our new cases. Cases 3, 4, 6, and 9 are LEC predictions for 2X trough plants. The remaining cases assume use of a conventional (1X) trough. Cases 1 through 4 compare 50 MW plants. Cases 5 through 9 compare therminol and salt plants at their largest practical size[ii]. Most cases assume use of a future, low-emmissivity cermet (7% nominal) identified in Kelly to be "essentially a mandatory feature" for plants with 500 ^{o}C outlet temperature. This statement can be verified by comparing our high-emmissivity (14% nominal) cases 5 and 7; the LEC's of the maximum-sized salt and oil plants are virtually the same. According to Kelly, it is mandatory for salt because the advantage of a higher Rankine efficiency is counterbalanced by increased heat losses in the solar field and increased design complexity (i.e. higher costs.)

Examining the 50 MW case studies, EXCELERGY predicts a 12 to 15% lower LEC for a plant using salt in the field vs. one that use synthetic oil (compare case 1 with 2, and also compare case 3 with 4). The salt-in-field plants have 16 hours of storage, the amount leading to the lowest LEC. The oil plants have no storage; storage can be added but LEC stays the same as presented in Figure 1. Use of the 2X trough results in a 11 to 13% reduction in LEC relative to a 1X trough (compare case 1 with 3, and also compare case 2 with 4). Combining salt-in-the-field with a 2X trough results in an overall LEC reduction of ~25% (compare case 1 and 4). The 2X trough leads to lower LECs due to a significantly lower solar field cost and a higher annual efficiency. Lower field cost (\$206/m^2 vs. ~\$255/m^2) results from the improved economy of scale for the 2X trough; increasing the aperature from 5 to 10 m results in a 50% reduction in the number of HCEs, drives, controls, and piping interconnects[iii]. The higher annual efficiency is due to the lower specific HCE heat loss, W/m^2 of aperture basis.

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[i] A few errors were found in the paper: 1) all cases in Figure 1 were based on a 5 m aperture, not the stated values of 5.76 to 8 m, 2) the maximum plant size studied was 250 MW, not the stated value of 200 MW.

[ii] Kelly stated that the 150 MW oil plant in Figure 1 was near the maximum size. The field size was 1.3E6 m^2.

[iii] The total cost of the mirrors plus mirror-support structure is assumed to be the same (\$/m^2) for the conventional and 2X trough. As discussed in section 2.1, mirrors are expected to cost more for the 2X trough but this may be compensated by a lower cost mirror-support structure.

Examining the ≥200 MW low-emmissivity case studies, the LEC reductions relative to the 50 MW cases are due an improved economy of scale. It should also be noted that the solar field size in our 200 MW oil plant without storage (case 6) is the same as Kelly's 150-MW oil plant, with 6 hours of storage, shown in Figure 1. EXCELERGY predicts a lower LEC for the 200 MW plant vs. the 150 MW plant so we believe the 200 MW oil plant is a better point of comparison with salt plants. Assuming use of a 2X collector in both oil and salt, EXCELERGY predicts a 6% lower LEC for the maximum-sized salt plant vs. the maximum-sized oil plant (compare case 6 with 9).

	50 MW LS2+ 391 C Oil Lo ε No stor	**50 MW LS2+ 500 C HiTec Lo ε 16 hr**	**50 MW 2X 391 C Oil Lo ε No stor**	**50 MW 2X 500 C Hi Tec Lo ε 16 hr**	**200 MW LS2+ 391 C Oil Hi ε No stor**	**200 MW 2X 391 C Oil Lo ε No stor**	**250 MW LS2+ 500 C HiTec Hi ε 16 hr**	**250 MW LS2+ 500 C HiTec Lo ε 16 hr**	**250 MW 2X 500 C Hi Tec Lo ε 16 hr**
Case	1	2	3	4	5	6	7	8	9
Mirror Area (km^2)	0.282	0.515	0.275	0.515	1.24	1.08	2.99	2.57	2.57
Solar Multiple	1.35	2.6	1.35	2.6	1.35	1.35	2.6	2.6	2.6
Aperture Width (m)	5	5	10	10	5	10	5	5	10
Peak HCE Flux (suns, SS)	41	41	82	82	41	82	41	41	82
Solar Field Direct Cost ($M)	72	128	58	106	301	216	704	607	499
Solar Field Direct Cost ($\$/m^2$)	255	249	211	206	242	200	235	236	194
Storage Direct Cost ($M)	0	45	0	45	0	0	226	221	221
Total Plant Direct Cost ($M)	118	220	104	195	419	334	1071	969	861
Total Plant Installed Cost ($M)	160	295	141	264	570	453	1437	1300	1148
Annual O&M Cost ($M)	3.7	4.9	3.7	4.9	7.8	7.2	15.6	14.2	14.3
Annual Effic (%)	16.2	17.2	16.9	18.3	13.6	17	13.7	17.2	18.3
Capacity Factor (%)	29	57	30	60	27	29	52	56	60
LEC ($/kWh)	0.165	0.144	0.147	0.125	0.141	0.107	0.143	0.119	0.101

Table 2. Characteristics of trough plants operating in the Mojave Desert. Shaded columns taken from analysis summarized in Reference 1.

The LEC predictions in Table 2 deserve an important caveat: *it is assumed that use of salt does not degrade equipment availability relative to the current therminol trough plants operating in California without storage.* Thus, for all cases the availabilities of the trough field and overall plant are assumed to be 99% and 94%, respectively. Based on our experience with the molten salt system at the Solar Two power tower, this assumption may be optimisitic unless great care is used in designing and maintaining the salt system. Equipment unavailability due to salt freezeup is a real issue and this will be especially true for a trough field with many miles of salt piping. We don't believe it is practical for troughs to use the high freezing point (220 ^oC) nitrate salt used at Solar Two. HiTec salt might be used (as we have assumed in Table 2), but its freeze point is still uncomfortably high at 142 °C. Consequently, Sandia is now developing an advanced salt mixture with a melting point of less than 100 °C that also does not degrade at a 500 °C operating temperature [16].

4 Summary

Our analysis suggests that an optically accurate 2X trough, combined with the advancements of other researchers (i.e. low-emissivity HCE, low-melting point salt, etc.), can result in a significant reduction in LEC of both oil-based and salt-based plants. A 2X trough with the proposed 10 m aperture and proposed 2.5 mrad system-wide optical error does not currently exist. However, there is significant evidence at a subcomponent level that such a device could be built. Recent dish-Stirling prototypes have demonstrated ~1.5 system-wide error, so why not troughs? The proof will be in the building.

Our EXCELRGY analysis predicts a marginal LEC advantage of salt plants vs. oil plants. At the 50 MW level, the advantage is 11 to 15% and at the maximum practical field size the advantage is only 6%. Based on the analysis presented here, it is unclear whether development of the more complex salt system is justified.

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