A BEAM-DOWN CENTRAL RECEIVER FOR SOLAR THERMOCHEMICAL HYDROGEN PRODUCTION

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ABSTRACT

We present the design and performance estimation of a 3 MWth beam down central receiver capable of providing concentrated solar energy to a particle-based thermochemical reactor operating at a thermal reduction (maximum) temperature of 1500°C. The configuration of this beam down optical system is unique in several ways including the positioning of the reactor near the top of the tower, the use of a flat tower reflector, and the absence of a terminal concentrator that is usually needed to increase the solar concentration ratio at the aperture for high temperature applications. Our baseline design for the beam down central receiver includes a 75 m tall tower with a North field of individually focused, ~1 m^2 heliostats that is capable of achieving an average concentration ratio in excess of 1,600 kW/m^2 (suns) over an aperture that is 2 m in diameter with a peak flux in excess of 6,000 kW/m^2.

1. THERMOCHEMICAL FUEL PRODUCTION

The thermochemical production of hydrogen from solar energy and water has been demonstrated with many processes. These range in complexity from the single step thermolysis [1] of water to multi-step processes involving low temperature reactions in solution [2-4] Currently, the most actively investigated approach is based on a two-step cycle involving the thermal reduction and re-oxidation of a metal oxide material [5-8]. The general form of the reaction sequence is

$$RED: \ {}^{1}/_{\delta} MO_x \rightarrow {}^{1}/_{\delta} MO_{x-\delta} + {}^{1}/_{2} O_2 \quad (1)$$

$$OX: \ {}^{1}/_{\delta} MO_{x-\delta} + H_2O \rightarrow {}^{1}/_{\delta} MO_x + H_2 \quad (2)$$

$$H_2O \rightarrow H_2 + {}^{1}/_{2} O_2 \quad (3)$$

where δ is the reaction extent, or the degree to which oxygen is removed from the oxide reactive material during thermal reduction. Reaction (1) is the thermal reduction of the reactive oxide, reaction (2) is the re-oxidation in the presence of steam, and reaction (3) is the sum of the first showing that all reactive solids are recycled. The conversion of solar energy to fuel product, hydrogen in this case, is a strong function of the temperature of the thermal reduction (T_{TR}) and re-oxidation reactions (T_{OX}) [9]. In general, for reactants based on iron oxide or cerium oxide the temperature required for thermal reduction is greater than 1400°C, with 1500°C commonly used for cerium oxide materials. The re-oxidation reaction is generally operated between 800°C-1200°C in order to achieve favorable reaction kinetics, although this is done at the expense of thermodynamic efficiency. In a continuous flow reactor the time required for the reactive material to complete one cycle may be as little as 30 s [10, 11], resulting in a heating/cooling rate as high as 1400°C/min. A rate change of temperature of this magnitude can induce thermal stresses in the reactive materials that, over time, result in mechanical failure. The durability of reactive materials with respect to thermal cycling can be improved by reducing the heat conduction length of the material, which may be accomplished by forming the reactive materials into powders or particles.

One practical consequence of using a particulate reactive material is that the design of the solar interface, the mechanism for providing concentrated sunlight to the reactor, becomes more challenging. In a conventional central receiver application, solar energy is converted to heat and absorbed by a heat transfer fluid (e.g. molten salt) flowing through pipes that are directly illuminated by concentrated sunlight and operate at a temperature near 600°C. In a solar fuels reactor the high operating temperature precludes the use of an indirect heating strategy, and the particles must be heated directly by concentrated sunlight. A reactor that utilizes either a fluidized [12] or moving packed bed [11] of particles must be oriented such that the concentrated sunlight enters the reactor vertically. This requires the use of a beam down optical configuration wherein concentrated light from the heliostat field is redirected into the reactor with a second mirror, called a tower reflector, positioned on top of the tower itself.

1.1 SOLAR COLLECTION SYSTEM

A beam down central receiver has three main components: the primary field of heliostats that reflect incident sunlight, the tower reflector (TR) that redirects focused light from the field, and the receiver/reactor that converts focused light from the TR to heat that can be used for power or fuel production. An illustration of a beam down central receiver is shown in Figure 1. In operation, energy from the primary collectors (heliostats) is reflected toward an aimpoint, AP, located above the tower reflector. The concentrated light is intercepted by the tower reflector and beamed down into the reactor, which in the case of traditional beam down systems is located near ground level.

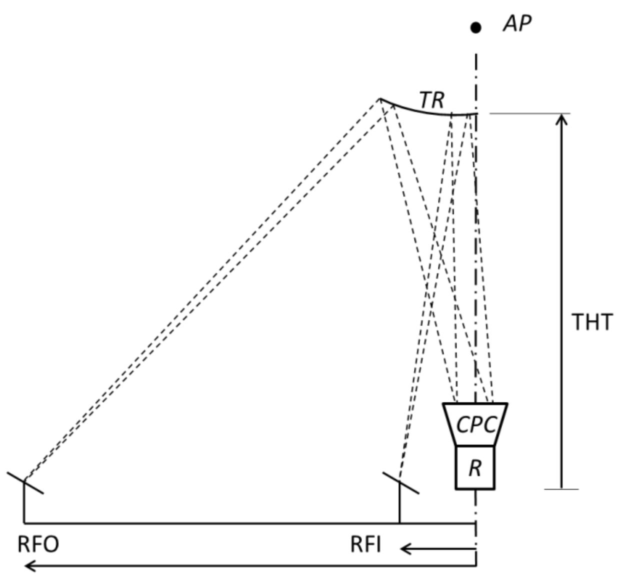


Fig. 1: The traditional optical configuration for the beam down central receiver. A curved tower reflector, TR, is used to direct energy from the field to a reactor located near the ground. Energy reaching the reactor is further concentrated with a CPC to achieve a greater concentration ratio. The field is defined by an outer radius, RFO, and inner radius, RFI.

The beam down optical system was invented by Rabl [13] and further developed by several other researchers over the last several decades [14-16]. All preceding development focused on using 1) curved optics for the tower reflector (either hyperbolic or elliptical) and 2) focusing the energy from the TR to a reactor placed at or near ground level. The combination of beam divergence upon reflection from the TR, due to the use of a curved optic, and the relatively large distance between the TR and reactor lead to a magnification of the image produced at the receiver aperture [15]. The resulting low concentration ratio must be increased with the use of a terminal concentrator, such as a compound parabolic concentrator (CPC), in order to improve receiver efficiency for high-temperature processes such as solar fuel production.

With our thermochemical reactor concept there is no requirement for the reactor to be positioned at ground level, only that the energy enter the reactor vertically. As such, we've modified the traditional beam down optical configuration, moving the reactor vertically to a position closer to the TR. As a result, the curved optic normally required in traditional beam down systems becomes a flat optic in our configuration. This combination of reactor proximity to the TR and having a flat TR reduces image magnification and allows a relatively high concentration ratio to be achieved at the reactor aperture without the need for a terminal concentrator. A schematic of the modified beam down collection system is shown in Fig. 2.

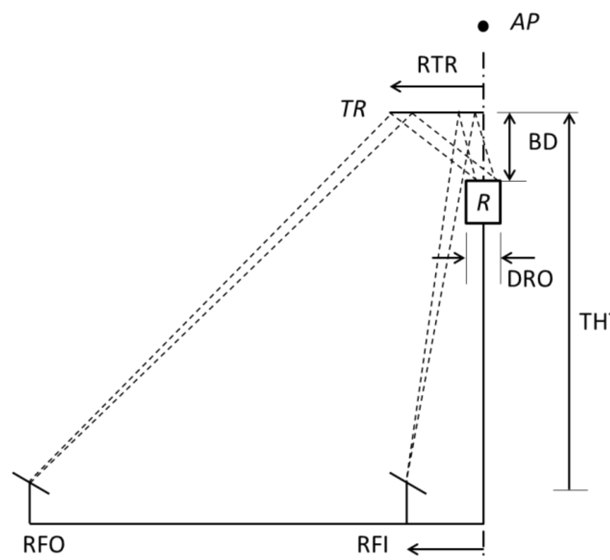


Fig. 2: A modified beam down collection system for thermochemical processes. The thermochemical reactor, R, is located a short distance, BD, from the tower reflector, TR, located a height THT. The heliostats are aimed at a common point, AP. All energy from the field is intercepted by the TR and reflected to the reactor. The divergence of the solar energy reflected from the field is a function of the

size of the sun and the optical errors in the collection system.

All of the parameters shown in Fig. 2 are related geometrically. The specification of component size and position is dependent on these geometric relationships as well as on two additional constraints: the innermost heliostats must not be blocked by the reactor, and the radius of the tower reflector (RTR from the centerline) is determined by the intersection location of the edge of the beam reflected from the outermost heliostat. The design of the collection system geometry begins with the definition of the reactor height, HR, the outer field radius, RFO, the inner field radius, RFI, and the half angle of aggregated optical error for a degraded sun image [17], σ_{tot}, expressed as

$$\sigma_{tot} = \sqrt{\sigma_{sun}^2 + 4(\sigma_{slope}^2 + \sigma_{track}^2)} \qquad (4)$$

where $\sigma_{sun}, \sigma_{slope}, and\ \sigma_{track}$ are the standard deviations of the sun size, and the error distributions associated with slope and tracking inaccuracy. The beam down length, BD is

$$BD = \frac{HR}{\frac{RFO}{RTR_i} - 1} \qquad (5)$$

where RTR_i is the ideal radius of the tower reflector measured from the tower centerline and assuming no optical error in the field. The actual size of the tower reflector, RTR_a, is determined such that all energy from the outermost heliostat is reflected to the reactor. The angle of the center ray of reflected light from the outermost heliostat relative to the horizontal is

$$\theta_1 = ATAN\left(\frac{HR}{RFO - RTR_i}\right) \qquad (6)$$

which is then further modified to include the optical errors resulting in an expression for the angle of the outermost ray reflected from the field

$$\theta_2 = \theta_1 + \sigma_{tot} \qquad (7)$$

The actual radius of the tower reflector, RTR can now be expressed as:

$$RTR_a = RFO - \frac{HR}{TAN(\theta_2)} \qquad (8)$$

The energy from the ourtermost heliostat that is reflected by the TR and will have the largest angular spread is used to determine the size of the reactor aperture, DRO.

$$DRO = 2\left(RTR - \frac{BD}{TAN(\theta_2)}\right) \qquad (9)$$

The reflected energy from all heliostats between RFO and RFI is assumed to be fully intercepted by the receiver aperture given that it is sized to intercept all of the energy from the heliostat having the larges image no the aperture plane. The angle of the central reflected ray from the innermost heliostat and relative to the horizontal is

$$\theta_i = ATAN\left(\frac{HR - BD}{RFI - \frac{DRO}{2}}\right) \qquad (10)$$

One of the design constraints is that none of the energy from the innermost heliostat is blocked by the receiver. In order to impose this constraint the position of the receiver (beam down distance, BD) is calculated iteratively, accounting for the angular spread of the beam from the innermost heliostat about the angle θ_i. The iterative solution is accomplished by changing RTR_i, which results in a change in the vertical position of the receiver, until the edge of the receiver coincides with the edge of the innermost reflected ray from the field. Once this final location has been identified the size of the reflected image at the plane of the reactor aperture may be calculated along with the average geometric concentration ratio.

1.2 DESIGN AND PERFORMANCE ASSESSMENT

In our baseline configuration, the field provides ~ 3 MW_{th} to the reactor at the design point of solar noon on the Spring Equinox (Day 81) assuming a system location in Daggett, CA. Our optical design goals include achieving an average flux at the reactor aperture of 3,000 kW/m^2 while avoiding the use of a terminal concentrator, and operating at a collection efficiency (power captured by the receiver aperture relative to power incident on the field) near 60 % on an annual basis[1]. To accomplish this, our field must be a relatively small North field, and have accurate, possibly individually focused heliostats. The design process begins with the calculation of the general specifications of the collection system, including the location and size of the tower reflector and reactor, as the outer radius of the heliostat field and tower height are varied parametrically. The analysis is constrained by a tower height range from 50-100 m, fixed position of the innermost heliostats at 0.1 tower heights (0.1 THT) from the base of the tower, outer heliostat radius from 0.8-2.0 THT. The intent of this analysis is to determine the geometric concentration ratio (CR) at the reactor aperture, and to identify the required field and tower size needed to exceed the 3,000 kW/m^2 target. The results of the calculation are shown in Figure 3 for tower heights of 50, 75, and 100 m.

[1] The flux target for the aperture is that needed for the receiver efficiency to exceed 80% when thermal losses are from radiation only, with the temperature of thermal emission equal to 1500°C (1773K).

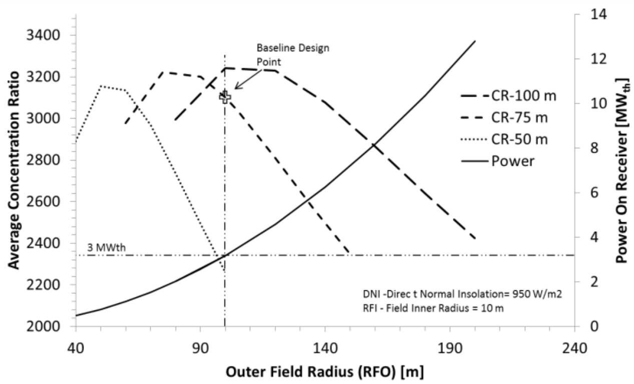


Fig. 3: The geometric concentration ratio achievable for several tower heights as a function of the outer field radius.

Figure 3 shows that a tower 75 m in height with an outer field radius of 100 m (1.33xTHT) has a total thermal power input of ~3 MW_{th} with an average geometric concentration ratio of 3100. The reactor aperture in this case, defined solely by the size of the concentrated beam, is 1.78 m in diameter while the TR is a 180^{o} semicircle of radius 5 m positioned 4.6 m above the reactor.

The next step in the design process is a performance simulation to calculate the thermal flux on both the TR and the reactor aperture along with an assessment of the collection system performance both at the design point and on an annual average basis. The performance evaluation was done using DELSOL, a computer program used in the design and optimization of central receiver systems [18]. A summary of the parameters used in the performance simulation of the baseline system is shown in Table 1.

TABLE 1: A SUMMARY OF RELEVANT SYSTEM DESIGN AND ANALYSIS PARAMETERS

Parameter	Value
Tower (North Field)	
Tower Height (THT)	75 m
Tower Diameter (DRO)	2 m
System Geographic Location	Daggett, CA
System Geographic Altitude	0.59 km
Collection Field	
Heliostat Size	1.07 m x 1.07 m
Number of Heliostats	6,606
Inner Field Radius (RFI)	10 m from tower base
Outer Field Radius (RFO)	100 m from tower base
Field Packing Density	49%
Reflectivity	94%
Slope and Tracking Error (comb.)	1.3 mrad
Mirror Cleanliness	95%
Sunshape	$S(r)=S_o(1.0-0.5138(r/4.65mrad)^4)$
Tower Reflector	
Reflector Location (TR)	79.6 m
Tower Reflector Radius (RTR)	5 m
Beam Down Distance (BD)	4.6 m
Receiver/Reactor	
Receiver Design Power Level	3 MW_{th}
Operating Temperature	1500^{o}C
Operating Pressure	1000 Pa
Receiver Aperture Radius	1 m
Thermochemical receiver aperture radius	0.7 m
Aperture Window Reflectivity	5%

DELSOL is not a raytracing program and cannot explicitly simulate the multiple reflections of a beam down power tower. However, since our tower reflector is flat we were able to define our geometry in such a way as to allow the use of DELSOL to analyze collection efficiency and to generate flux maps on both the tower reflector and the receiver aperture. The model geometry is shown in Figure 4.

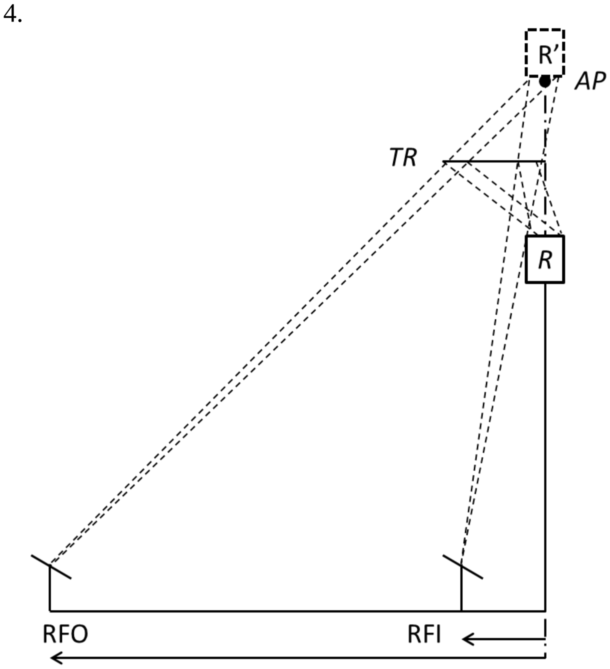
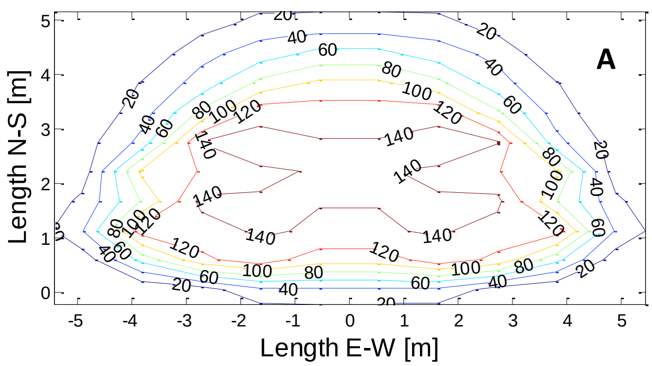
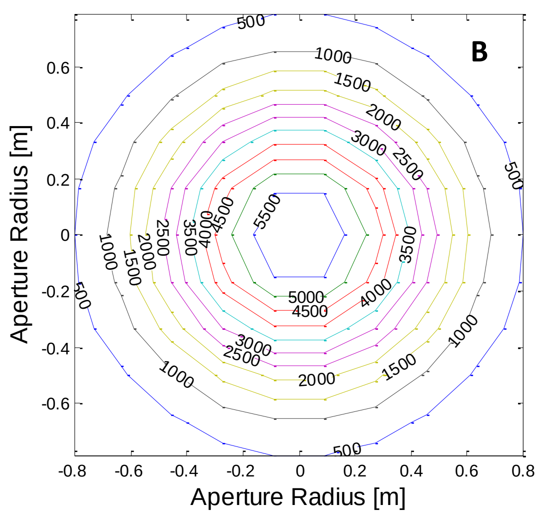


Fig. 4: The optical system configuration used in DELSOL to generate flux maps on the TR and at the reactor aperture.

The aimpoint, above the TR, is equal to the total distance traveled by light reflected from the field to the reactor, including the distance traveled on reflection from the TR. Since the TR is flat, a fluxmap at the aimpoint (AP at the aperture of image R') is essentially identical to one at the aperture of the reactor, R. In reality, there would be a slight difference in these two maps due to the optical errors of the TR. We assume that these are negligible in this analysis due to the fact that the mirror would likely have a slope error less than 1 mrad (not adding much to the total error and resulting beam divergence) and the distance of reflection (beam down distance) is relatively short. Flux maps at the receiver aperture and on the TR at the design point are shown in Figure 5 (A and B) while a plot of the flux distribution through the center of the aperture and the average flux as a function of radius is shown in Figure 5C.





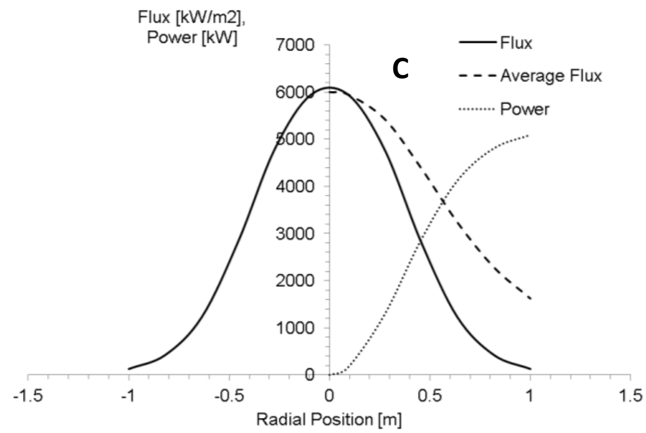


Fig. 5: The flux distribution on the (A) tower reflector, and (B) at the receiver aperture. The flux distribution along a line passing through the center of the receiver aperture (C) as well as the cumulative average flux as a function of aperture radius.

One of the consequences of a short beam down length is that flux on the TR is relatively high; the peak flux on the TR is 148 kW/m^2 (140 kW/m^2 shown in Figure 5). Segal and Epstein [16] show that In a traditional beam down configuration, with a curved TR and reactor near ground level, the flux on the TR might fall in the range of 20-50 kW/m^2. The maximum allowable flux on the TR is limited by several factors, principal among these being the working temperature limit of the mirror itself. In the case of the mirrors used by Segal and Epstein [*], the maximum service temperature was 120^{o}C-130^{o}C, corresponding to a flux limit of 30-35 kW/m^2 when cooling by free convection. We are currently developing both a model of heat transport in a mirror exposed to concentrated sunlight as well as an experimental capability to validate the model and evaluate commercially available high-flux mirrors such as those used in linear Fresnel systems. We note that mirrors made by Guardian for linear Fresnel concentrators can operate at a mirror temperature of 400^{o}C [19], and that an actively cooled mirror will be able operate at an input flux considerably larger than one cooled by free convection.

The flux at the receiver aperture has a peak value near 6,000 kW/m^2, and an average value over the entire aperture of 1,530 kW/m^2. The average flux is lower than the target of 3,000 kW/m^2 required for a receiver efficiency of 80% when operating at 1500^{o}C. However, the receiver may be split into two components: one windowed aperture with a radius of 0.7 m and having an average flux of 3,000 kW/m^2 (See Figure 5C), and a concentric tubular receiver operating at 800^{o}C and used to produce superheated steam needed for the hydrogen-producing thermochemical reaction. When divided in this manner, 86% (4135 kW) of the incident energy (4,809 kW) is supplied to the thermochemical reactor, while 14% (673 kW) strikes the concentric tubular receiver. The efficiency of the hybrid receiver is calculated with equation 11

$$\eta_{rec} = \frac{\sum_i (Q_{inc,i} - Q_{conv,i} - Q_{rad,i})}{Q_{total}} \quad (11)$$

where the amount of energy incident on the receiver is Q_{total} with a portion, Q_{inc}, applied to each of the two receiver sections. Energy is assumed to be lost by thermal radiation (Q_{rad}) from the high flux, windowed portion of the receiver and by both radiative and convective (Q_{conv}) losses on the lower flux, lower temperature concentric tubular receiver. Convective losses are calculated by assuming forced convection heat removal to flowing air at 9 m/s (20 mph). For the conditions outlined above, and assuming that the emissivity of all receiver surfaces is 100%, the receiver efficiency is 79%, close to the 80% target.

The field efficiency (optical performance of the collection field) was calculated with DELSOL at the design point (solar noon on Day 81) as well as over several other days the aggregate of which represents an operating year using the following equation

$$\eta_{field} = \eta_{opt} * \eta_{cosine} * \eta_{B\&S} * \eta_{atm} * \eta_{int}$$

with the individual loss terms defined as

- η_{opt}: Fixed reflectivity of the heliostat (93%), secondary (95%), windowed receiver transmission(95%), soiling (90% - field and TR)
- η_{cosine}: Cosine loss (90% at design point, 89% annual)
- η_{atm}: Atmospheric attenuation (98% at design point, 98% annual)
- $\eta_{B\&S}$: Blocking and shading (92% at design point, 90% annual)
- η_{int}: Intercept (90% at design point, 90% annual)

The field efficiency of the baseline configuration was found to be roughly 54% at both the design point on an annual average basis. Overall, the field efficiency is relatively high due primarily to its small size, minimizing atmospheric losses, and compactness relative to the tower height, which minimizes cosine losses. It should be noted that the current field layout has not been optimized, and it is likely that even higher field efficiency could be achieved with a different layout. While DELSOL can perform field optimization, there are other strategies developed specifically for thermochemical systems that should be explored [20].

The collection efficiency (the product of field and receiver efficiencies) on an annual basis for the combination of a short beam-down tower and a thermochemical reactor operating at 1500°C with a net thermal power input of 3.29 MW_{th} to the reactor is 43%. By comparison, a collection efficiency of 59% was achieved in a prior analysis based on an 88 m^2 parabolic dish collector with a 15 cm aperture diameter [9]. The difference between the two cases is largely due to cosine, blocking and shading, and intercept losses present in the central receiver analysis that do not affect the parabolic dish configuration as greatly.

2. CONCLUSIONS

Particle based solar thermochemical reactors require a "vertically incident" concentrated solar energy input that can be supplied with a beam down optical configuration on a central receiver platform. We have shown that by placing the thermochemical reactor closer to the tower reflector it is possible to use a relatively small and flat tower reflector and avoid the necessity of a terminal concentrator while still achieving an average flux over the aperture of the thermochemical reactor of 3,000 kW/m^2 (peak of 6,000 kW/m^2). The annual average collection efficiency, the ratio of energy captured by the receiver/reactor to that incident on the collection field, can be 43% or more with this configuration. Reducing this concept to practice will require, at a minimum, further consideration of the thermal design of the tower reflector as it will be exposed to non-uniform incident flux ranging from a peak of 140 kW/m^2 to a minimum of 20 kW/m^2 and an accurate collection system.

Although this paper emphasizes the development of a novel collection system, it is instructive to consider the implication of the predicted collection efficiency on the viability of solar thermochemical fuel production. At a high level the conversion of solar energy to fuel, on an annual basis, is the product of the collection efficiency and the reactor conversion efficiency. Consider that a 15% efficiency (annual solar to electric) photovoltaic module could be combined with a 75% efficient water electrolyzer to produce hydrogen on a large scale at 11% annual solar to fuel efficiency. A more efficient dish-Stirling generator connected to the same electrolyzer could achieve an annual solar to hydrogen conversion efficiency of 18%. The combination of either PV or dish-Stirling and an electrolyzer is something that could be built today. In order for solar thermochemical fuel production to compete with this more conventional approach there must be a technical or economic incentive (probably both). Assuming that a 20% solar to fuel efficiency is the target a thermochemical reactor using a the beam-down central receiver platform discussed here would need to achieve a conversion efficiency of heat captured by the receiver/reactor to chemical energy in the fuel of roughly 50%. The theoretical potential of solar thermochemical fuel production exceeds this level of performance [10,11], but demonstrated performance is significantly less indicating substantial room for improvements [21].

3. ACKNOWLEDGEMENTS

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