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Brayton System Hardware Summary

Introduction

Our design goal for the power conversion system of a CSP plant was to take an approach that was water-free, modular, and less expensive than steam-based CSP. This led us to examine the Brayton power cycle as a possible solution.

This document summarizes the design of the solar receiver and Brayton engine that were the core focus of Google's Brayton CSP project. For more information on the system performance, the Brayton System Performance Summary describes the performance modeling of our Brayton CSP system.

Google's Brayton CSP Engine Goals

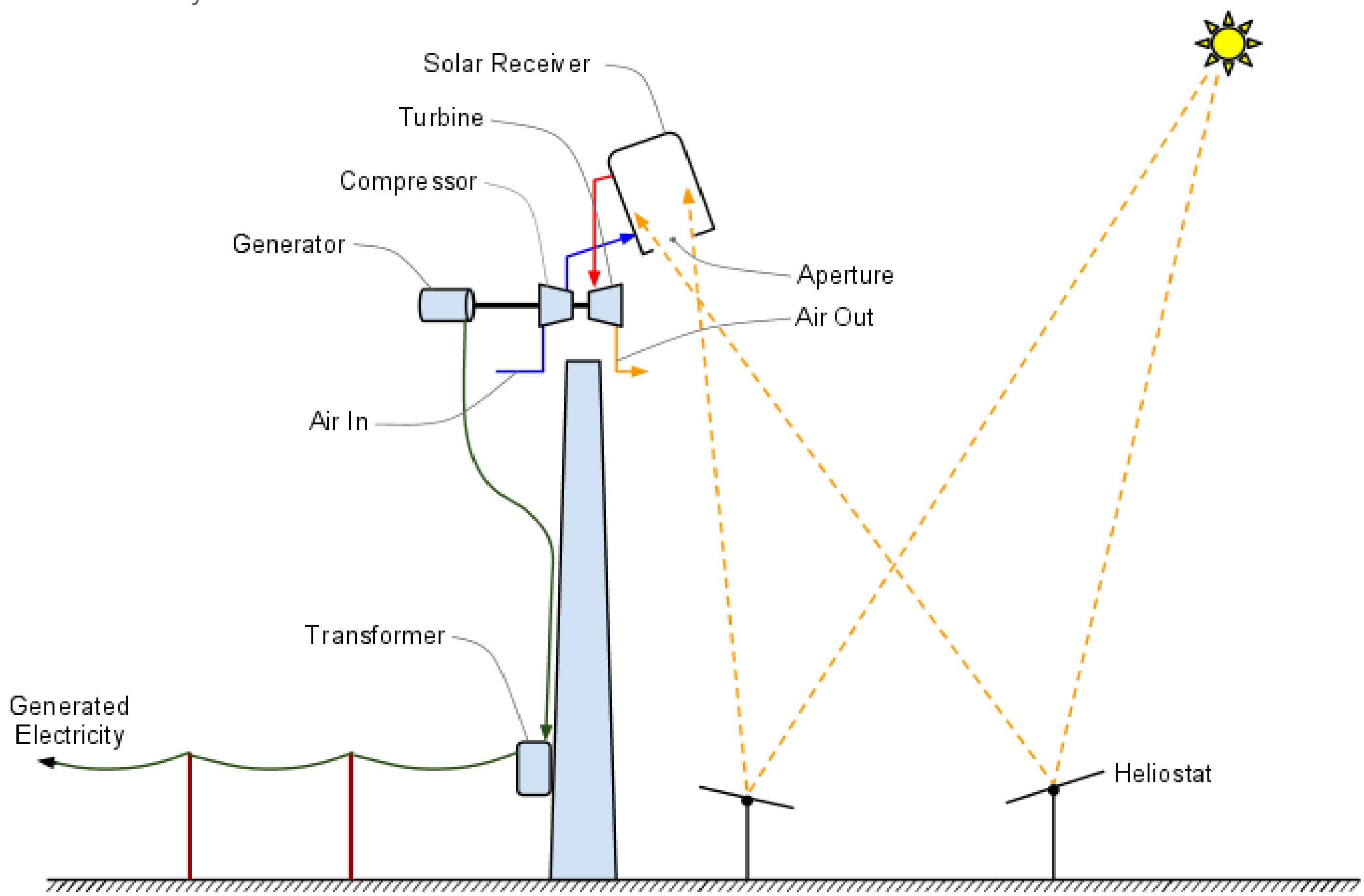
We began our engine design assuming an engine power rating of 1 megawatt (MW). 1 MW is large enough to build large power plants composed of multiple engines and heliostat fields, but still small enough to develop a prototype with a reasonable amount of time and investment.

Our design goals for this engine were:

- **High efficiency over a wide range of solar input:** The amount of solar energy collected by the field varies substantially depending on the time of day and season.
- **Robust and controllable enough to operate through rapid changes in solar input:** The engine and receiver must to be able to operate through the inevitable rapid changes in solar input that occur when clouds pass overhead, shading the field of mirrors.
- **Low cost when produced in volume:** The cost of a complete Brayton CSP power

plant needs to be much lower than a more conventional solar photovoltaic (PV) power plant in order to be a viable choice. The cost goals proved to be a moving target during the course of our project as the cost of solar photovoltaic panels continues to drop.

Our design configuration concept was to place a Brayton engine at the top of a tower. Electricity and data cables would be connected to the tower.

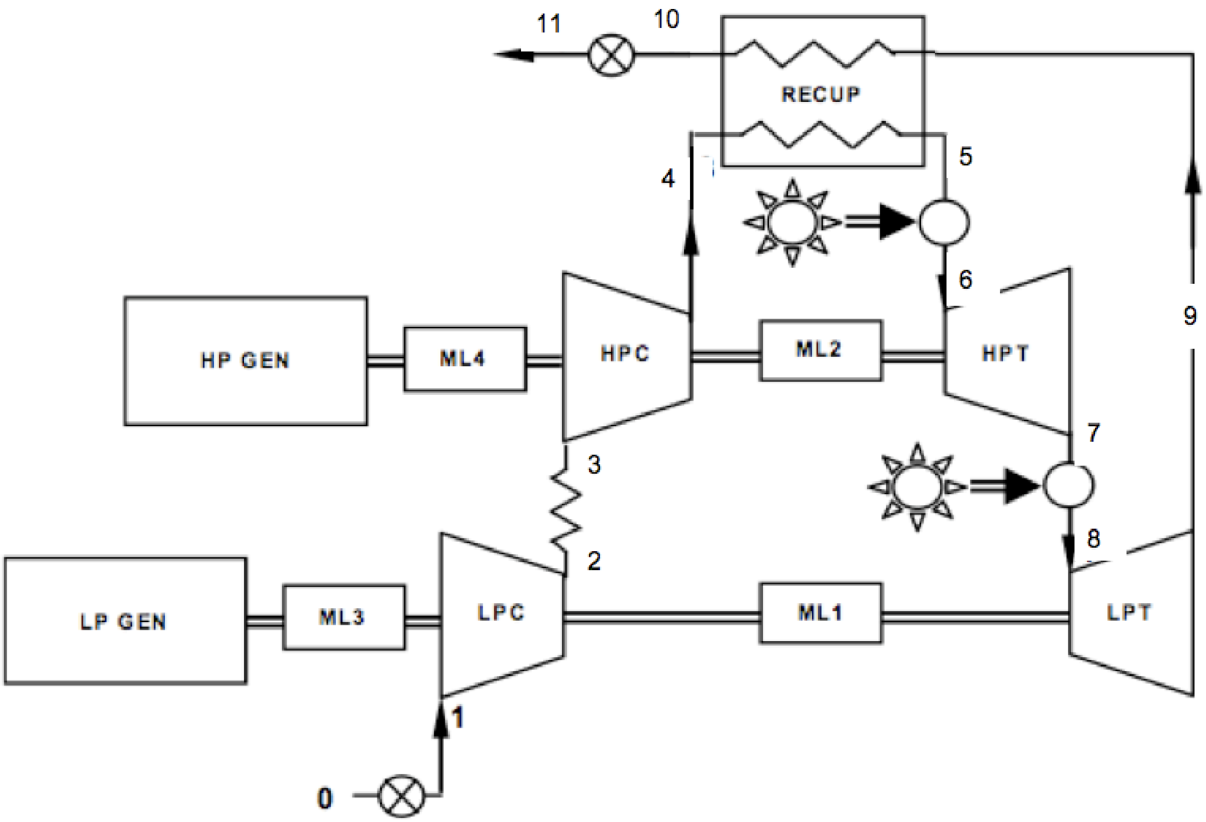


Brayton CSP system major components (The engine configuration shown is a simplified Brayton cycle).

Engine Configuration

We decided to utilize radial-flow turbomachinery, which is what is used in devices like turbochargers and microturbines. Radial-flow compressors and turbines can achieve pressure ratios of four to five in a single stage, compared to the axial-flow turbomachinery found in aircraft engines that requires multiple compression stages. To achieve an acceptable efficiency over a wide range of input power and to increase the power per amount of air mass flow (specific power), we decided to use two stages of compression and expansion, which would allow an overall pressure ratio of between 10 and 20.

The first engine configuration that we evaluated was an intercooled recuperated reheat cycle, or ICRR, shown below.



Initial engine configuration, an ICRR cycle (intercooled, recuperated, reheat)

This engine has two separate rotating shafts, each with a compressor and a turbine. The assembly of a shaft with a compressor and a turbine is called a spool. The two spools are denoted by their relative pressure: there is a low pressure spool, denoted 'LP,' and a high pressure spool, denoted 'HP.' A compressor is abbreviated as 'C' and a turbine is abbreviated as 'T.' A specific compressor or turbine on one of the two spools is denoted by 'LP' or 'HP,' for example 'LPC' means low pressure compressor.

The engine cycle has the following steps:

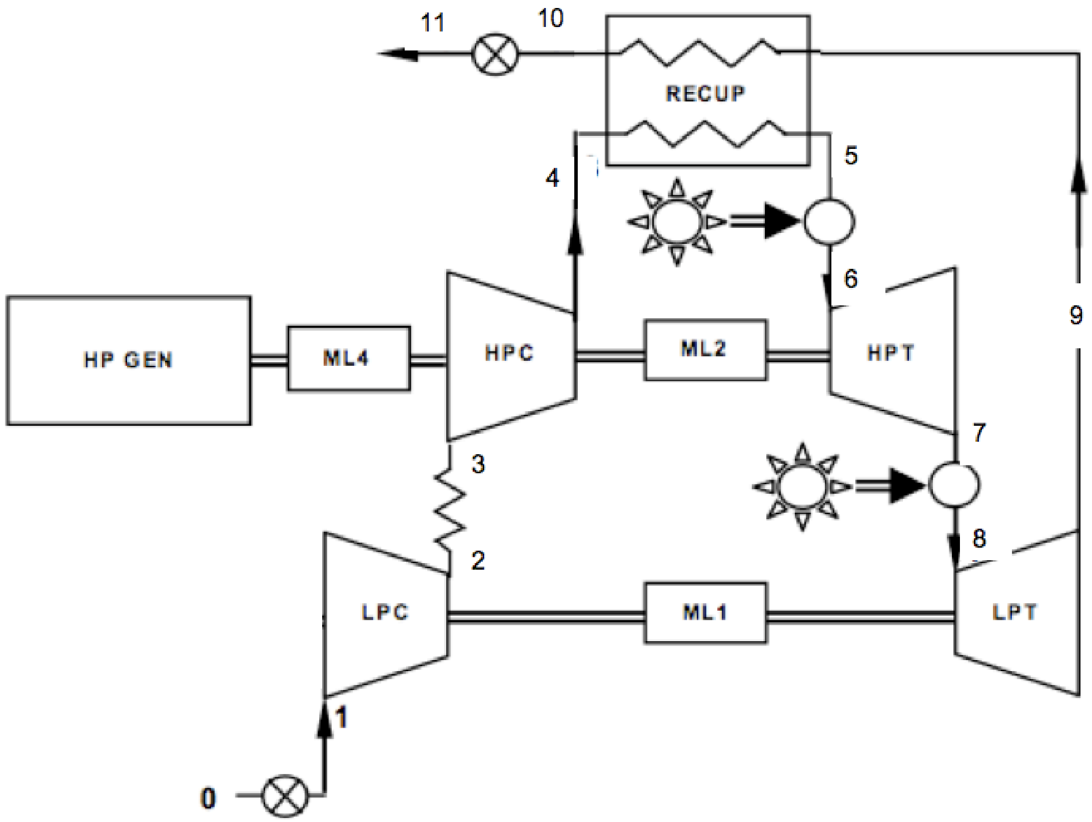
- Ambient air enters the engine at point 0, passes through an air filter and into the low pressure compressor (LPC) at point 1.
- The LPC compresses the air, which heats up as a result.
- The compressed, heated air exists the LPC at point 2 and passes through the intercooler (situated between points 2 and 3), which cools the air to nearly ambient temperature.
- The air is compressed further by the HPC and exits the HPC at point 4. This is the highest pressure point in the cycle.
- The air passes through the high pressure side of the recuperator. The recuperator is a heat exchanger that recovers much of the heat from the exhaust air back into the cycle.
- After exiting the recuperator, the air enters the solar receiver and absorbs concentrated solar heat between points 5 and 6. The air at point 6 is at the highest temperature in the cycle.

- The hot air enters the high pressure turbine (HPT) at point 6 and is expanded in the HPT to a lower pressure and temperature, exiting at point 7. Because of the higher temperature entering the HPT vs. entering the HPC and because the turbine has a higher pressure ratio than the compressor, the turbine produces more power than the compressor consumes. The excess power on the HP shaft is converted to electricity by the generator (HP GEN).
- The air exiting the HPT at point 7 takes a second pass through the solar receiver (between points 7 and 8) and absorbs more solar power, increasing its temperature. This is the 'reheat' process.
- The reheated air enters the low pressure turbine (LPT) at point 8 and is expanded again, reducing its pressure and temperature, and producing shaft power. Excess power on the shaft drives the LP generator (LP GEN).
- The air exiting the LPT at point 9 passes through the low pressure side of the recuperator, transferring much of its remaining heat to the air on the high pressure side of the recuperator. The air exiting the recuperator is exhausted to the ambient atmosphere.

This initial engine configuration employs two variable-speed generators - one on each of the turbine spools. In order to provide variable speed, the generators must be connected to the grid through a power electronics system that is similar to an inverter used in solar photovoltaic systems to convert the DC power from solar cells into AC power suitable for the electric grid.

Although this candidate engine configuration provides a large degree of operational flexibility and two "knobs to turn" in order to tune the operating point, we had concerns about whether an engine approach that relied on power electronics could ever be cost-competitive with solar photovoltaic.

This cost hurdle provided the motivation to seek out engine configurations that would operate over a wide range of power output with a simple (and inexpensive) constant-speed generator tied directly to the grid without the cost of an inverter. The resulting modified engine design, which we called 'A1,' can operate over a wide range of input power levels with variable speed on the low pressure "free" spool, and constant speed on the high pressure spool.



Modified engine configuration (A1) with a single constant-speed generator

In both our initial and modified A1 engine configurations, the solar heat is added from the solar receiver to the airflow in two places: once before the high pressure turbine, and again before the low pressure turbine. This is called a "reheat" cycle. The reheat allows the engine to produce more power and operate at a higher efficiency.

With a reheat engine cycle, the solar receiver must be configured to add solar heat to two different passes of the air. This adds complication and difficulty in the design and fabrication of the receiver. Each pass through the receiver also incurs a small pressure drop (typically around 3%), which has a detrimental effect on engine efficiency - pressure drop across a turbine produces power, whereas pressure drop across a flow restriction does not.

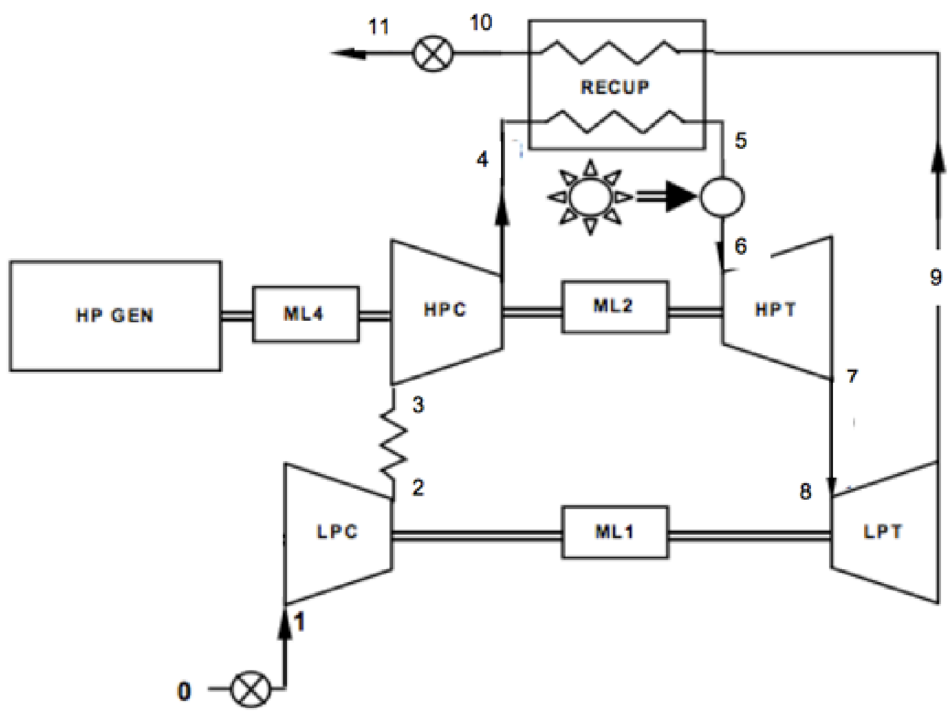
These considerations led to the question of how much the reheat pass through the receiver actually benefits the A1 engine configuration. Could the A1 configuration work equally as well with only a single pass receiver? If so, it would make the receiver fabrication much easier and cheaper.

A new design was developed to explore this simpler configuration. This ICR cycle (for intercooled, recuperated) cycle was denoted as 'A2' and is shown in the figure below.

Engine	
TIT HP (K)	1175
TIT LP (K)	883
Tamb (K)	298.2
Pamb (kPa)	93.8
PRL x PRH	10.95
massflow (kg/s)	4.828
LP power (shaft)	0.00
HP power (shaft)	949.8
Elec power (kW)	890.0

engine efficiency	33.96%

State Points	P (kPa)	T (K)
0	93.8	298.2
1	93.3	298.2
2	362.1	468.5
3	352.7	311.8
4	995.4	443.8
5	975.5	693.9
6	921.8	1175.0
7	234.6	882.7
8	234.6	882.7
9	96.9	721.7
10	94.3	473.1
11	93.8	473.1



Final engine configuration (A2), along with design point parameters

Simulations of the A1 and A2 configurations suggested that there is no efficiency advantage to A1's reheat receiver. This is due largely to the elimination of the pressure drop through the second receiver pass. The A2 configuration does, however, require about 15% more air mass flow than A1 to generate the same amount of electric power.

The final A2 design point parameters for the engine are also shown in the diagram above. The power rating of 890 kW was chosen in order to allow the use of a large off-the-shelf turbocharger for the low pressure spool.

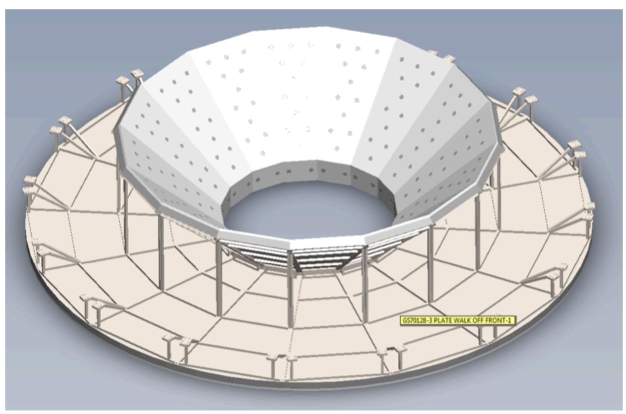
Solar Receiver Design

The solar receiver proved to be the biggest design challenge in the entire project. The receiver's job is to absorb concentrated solar energy and transfer as much of that energy as possible into the compressed air passing through the receiver at the required temperature - in our case, 1175K.

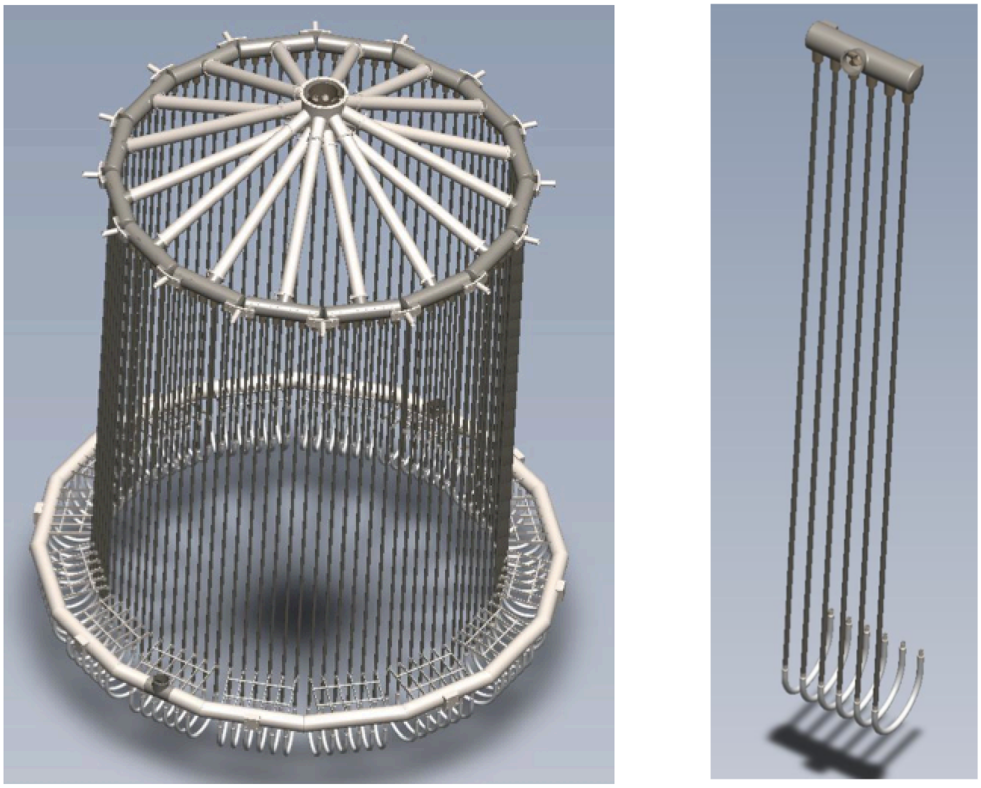
The receiver design we used is called a cavity receiver. With this design, each heliostat focuses at a circular opening in the receiver's outer surface called the aperture. The solar flux at the aperture can be very high - up to several thousand times that of sunlight. Flux at this intensity is too high to directly transfer into the compressed air, so the solar flux passes through the aperture and spreads out on an array of tubes positioned above the aperture.

The tubes are spaced apart from each other so that a portion of the incoming solar radiation hits the back wall of the receiver instead of directly on a tube. Part of the solar radiation hitting the back wall is is reflected, and the rest is absorbed, heating up the back wall. Together, the reflected radiation and the re-radiated thermal radiation from the hot back wall collects on the back side of the tubes, which serves to partially homogenize the energy flux across the circumference of the receiver tubes.

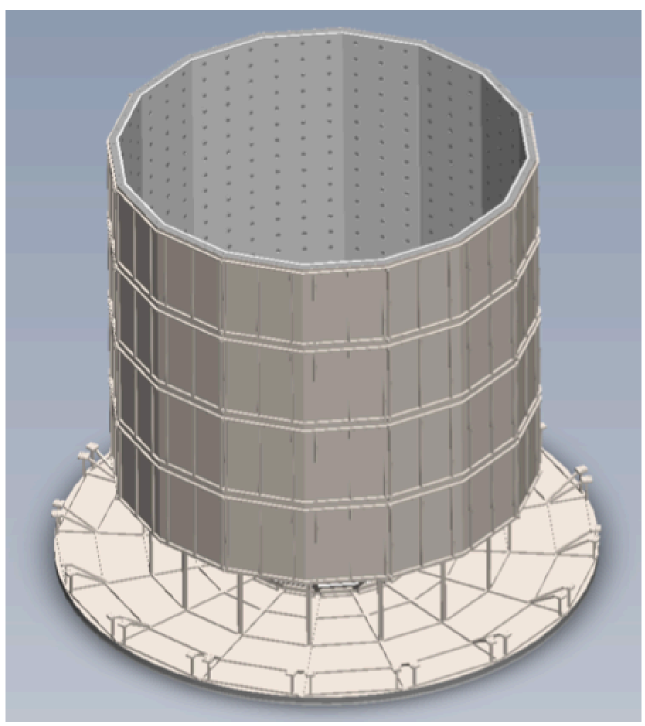
The following figures show the aperture, the tube assembly, and the back wall assembly.



Solar receiver aperture



Receiver tubes (each 4 meters long and with a 32mm OD); curves at bottom are to mitigate thermally induced stresses and strains



Solar receiver back wall assembly

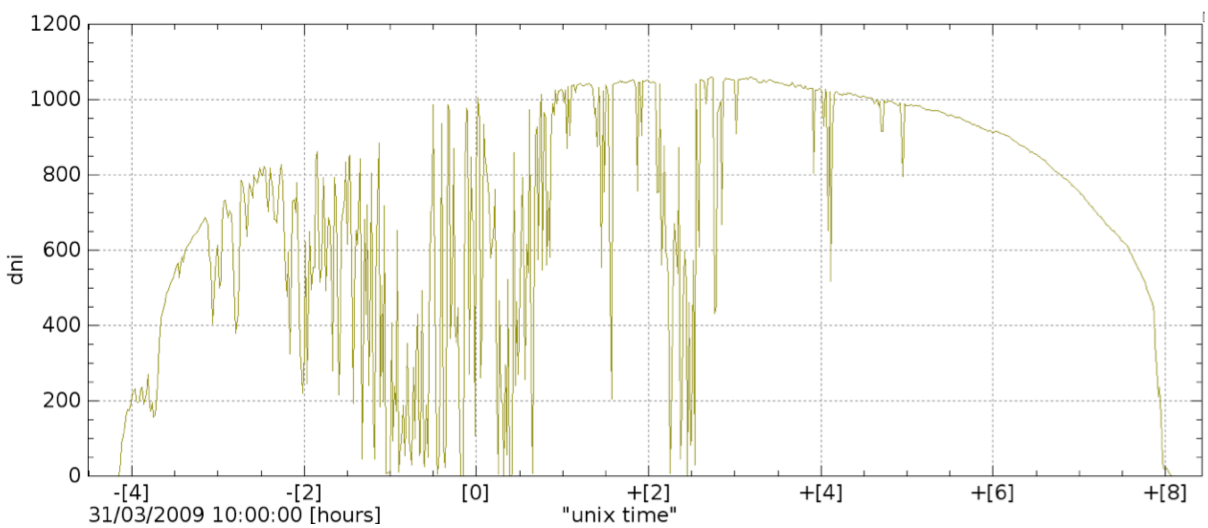
Receiver Analysis

Analyzing potential receiver designs proved to be extremely challenging due to the number of different physical processes involved. These processes included: pressure loads, gravity loads, thermal stresses and deflections, radiation absorption, re-radiation, complex material properties, convection, and conduction.

We developed a set of coupled modeling tools to carry out these analyses. Some of our studies, such as the field optical performance, could be separated out from from detailed modelling of the receiver, but in the receiver there were many interdependencies that required simultaneous simulation of a number of physical processes. We developed optical simulation models, finite element structural and conductive heat transfer models, radiation models, and convective heat transfer models in an effort to understand and predict the effect of these physical processes on our receiver designs. Some of this code is available as open-source.

Receiver Feasibility

The operating conditions inside the solar receiver cavity are extremely challenging for any material. There are very high temperatures (~1000 deg C), large temperature gradients, internal pressures, and both temperature and pressure transients. The high-temperature cyclic conditions are particularly challenging for heat exchanger design. Sunrises and sunsets are small problems compared to intermittent cloud passages that can add significant and drastic illumination and temperature cycles.



Example of solar variation due to cloud passages.
DNI is "direct normal insolation," in units of W/m^2

Taken together, these conditions are extremely difficult for most metallic materials. Multiple issues are at play, including creep, fatigue, oxidation, and thermally-induced stresses and deflections. Initially, it appeared that ODS (Oxide Dispersion Strengthened) steel alloys might be feasible options. The ODS alloys we considered are a mechanically alloyed combination of iron, chromium, aluminum and molybdenum with a dispersion of yttria nanoparticles.

Unfortunately, ODS materials are very expensive (at minimum $75/kg, and potentially much higher), and they have a limited service history. Furthermore, as they are experimental materials, the creep and fatigue data sets necessary to do a proper lifetime analysis are unavailable. In particular, ODS creep strength falls rapidly above a threshold load that is not well characterized as a function of temperature, composition and process conditions. The practical considerations of cost, availability, and the lack of detailed mechanical performance data led us to rule out ODS alloys as potential Brayton CSP receiver material candidates.

Instead, we focused on two commercially available alloy candidates, APMT and Haynes 230 alloy. These materials are resistant to oxidation at our desired operating temperatures, and have reasonable strength and creep properties at those temperatures as well. However, the effects of diurnal and cloud-induced solar transients proved difficult to mitigate. After extensive analysis (to be submitted in a pending publication titled "*Service Life Estimation of Pressurized Air Solar Thermal Receiver Tubes*") and many design iterations, we were unable to reach a design approach that we believed would last for 20 years without significant tradeoffs in operating temperature and efficiency.

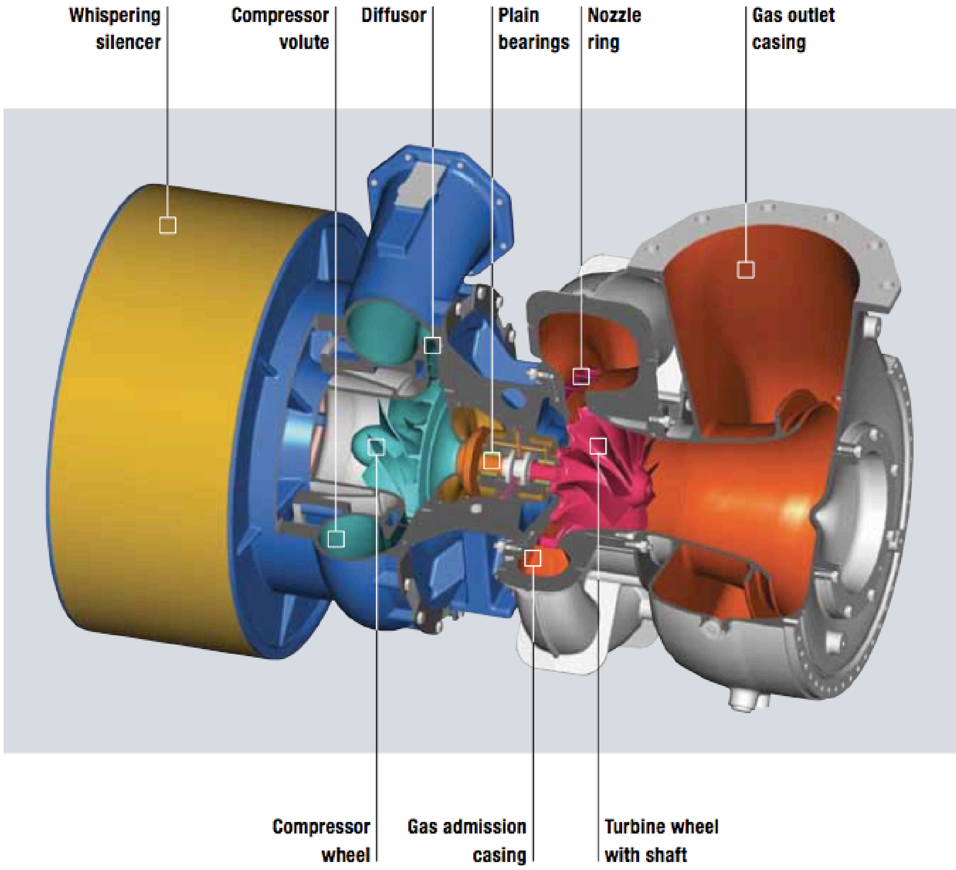
Initial evaluations of ceramic tube materials looked promising from a cost and properties standpoint, but the challenges of joining ceramic tubes to metal manifolds in the receiver appeared to be nontrivial. One of the benefits of ceramic materials is they don't creep very much in the temperature range we were considering. A corresponding disadvantage, however, is that the material tends to crack. Stress concentration can lead to fracture, and brittle fracture can launch projectile shards, which can induce cascading failures.

Engine Component Design

With the engine design point finalized, we began detailed design of the different engine subassemblies.

Low Pressure Stage

The low pressure stage acts as a turbocharger for the high pressure stage. It is very similar to a turbocharger on a large truck or marine engine: an intake silencer, followed by a compressor and turbine on the same shaft. In our design, an off-the-shelf turbocharger was used.



Cutaway view of low-pressure spool - an [off-the-shelf turbocharger]() made by MAN Diesel & Turbo SE

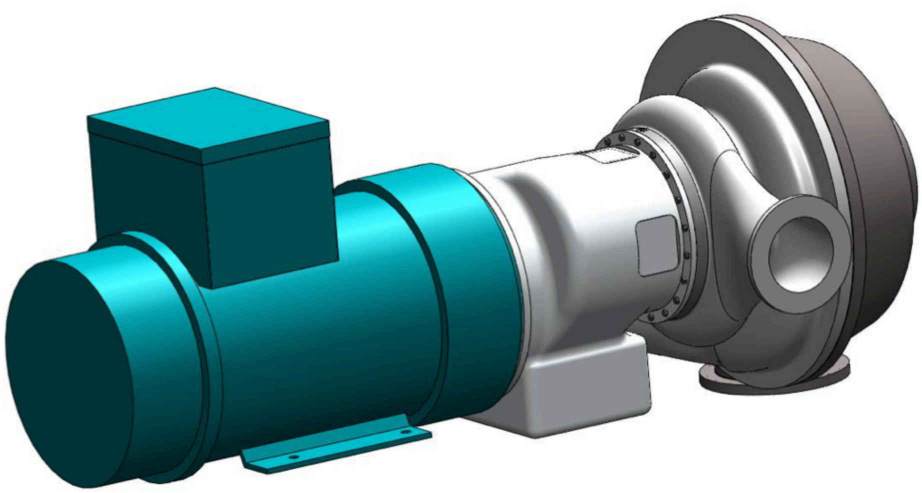
The low pressure spool is free-spinning, like a turbocharger. All the power generated by the LP turbine is used to compress air to be used by the high pressure stage. The more energy available in the exhaust from the high-pressure side, the faster the low pressure spool would spin.

Variable turbine nozzles in the MAN turbocharger

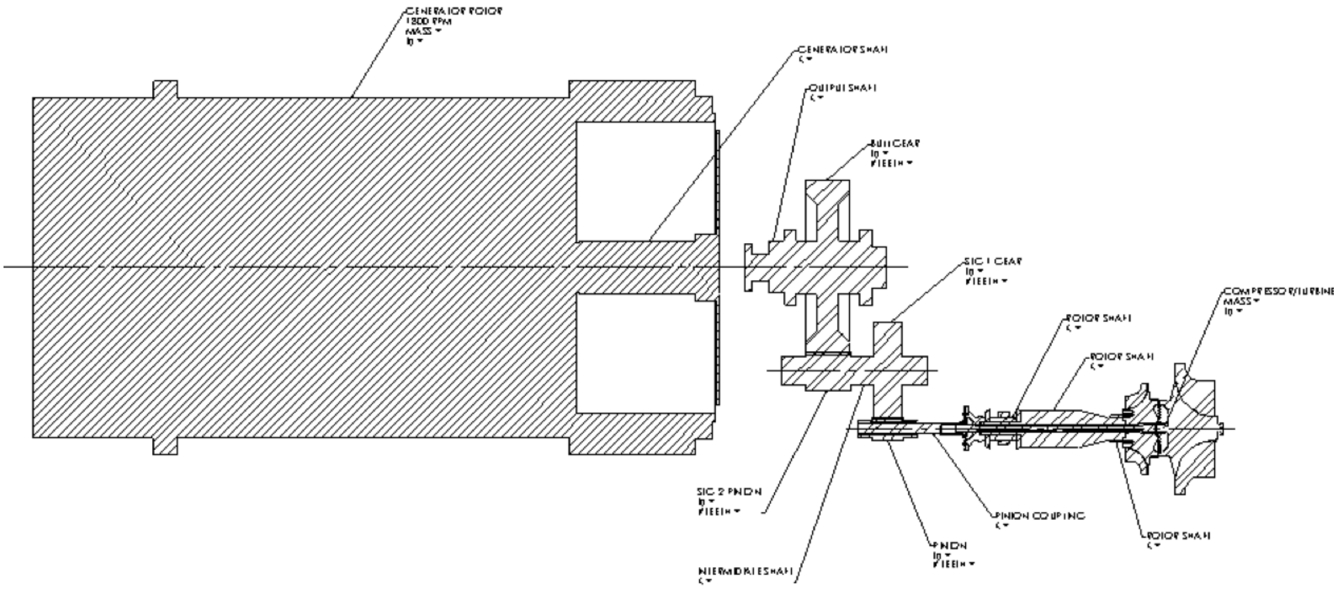
The turbine in the low pressure stage employs variable nozzles that allow control of the turbine pressure ratio, which dictates the overall operating point of the engine. This in turn provides necessary control over the temperature of the receiver and the HP turbine inlet temperature.

High Pressure Stage

The A2 configuration employs a high pressure spool that turns at constant speed. It is designed to drive a grid-connected generator.



High pressure stage assembly. From left: generator, gearbox, and HP spool



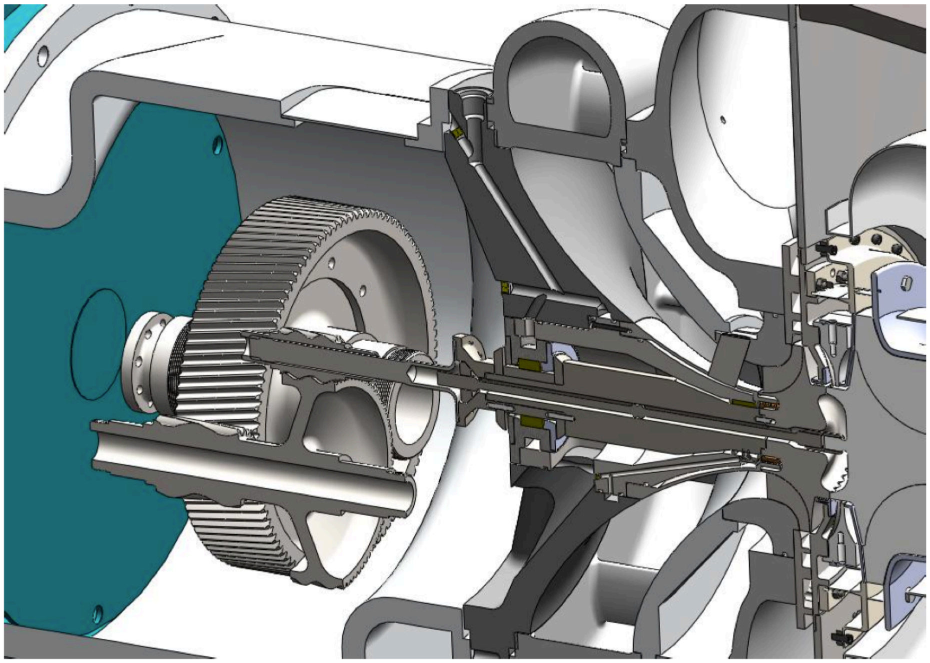
High pressure stage layout: generator rotor, gearing, and spool

Generator

The generator in the A2 engine configuration is a standard off-the-shelf 900kW synchronous machine. Cooling is accomplished through a built-in shaft mounted fan, and efficiency at rated power can exceed 96%. This is a low-cost type generator available from multiple manufacturers at a price point of approximately $18,000, or $20/kW.

Gearbox

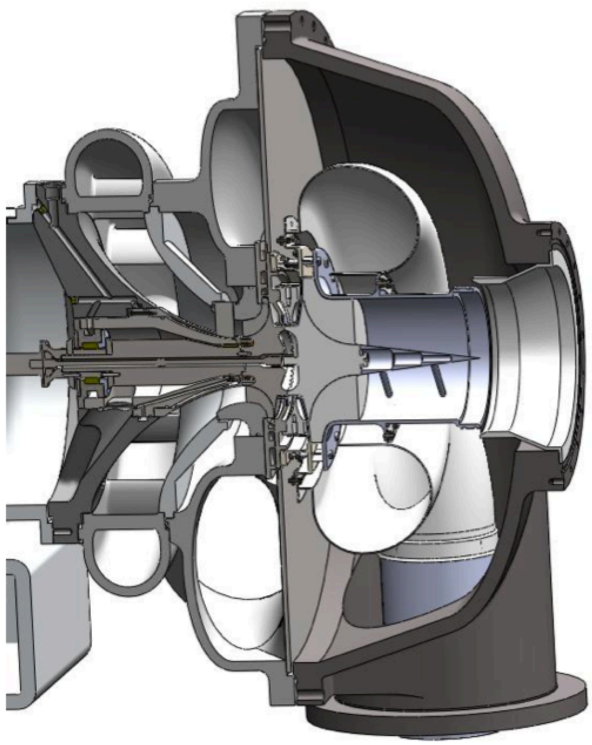
A gearbox is necessary to convert the 43,662 rpm of the high speed HP spool down to the 1800 rpm generator speed. The gearbox configuration is shown in the figure below. The gearbox design was carried out by Aero Gear, Inc., a specialist in aerospace gearboxes.



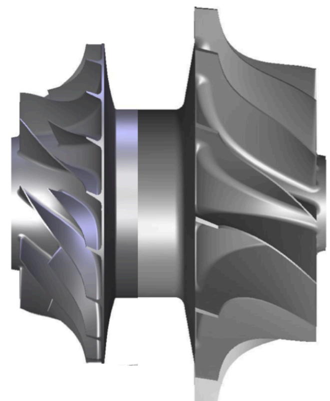
Gearbox configuration. Generator is on left, HP spool on right

HP Spool Compressor and Turbine

Cutaway views show the HP compressor and turbine, with a nominal speed of 43,662rpm.



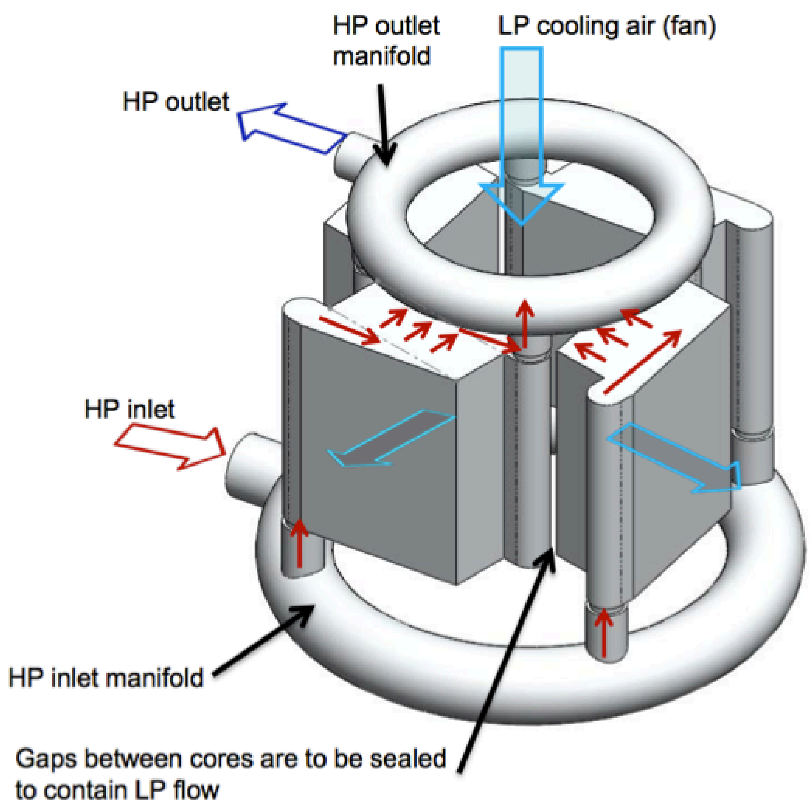
Cross section of the HP stage



Close-coupled HP compressor and turbine. The turbine diameter is 267 mm (10.5 in.) and nominal speed is 43,662 rpm

Intercooler

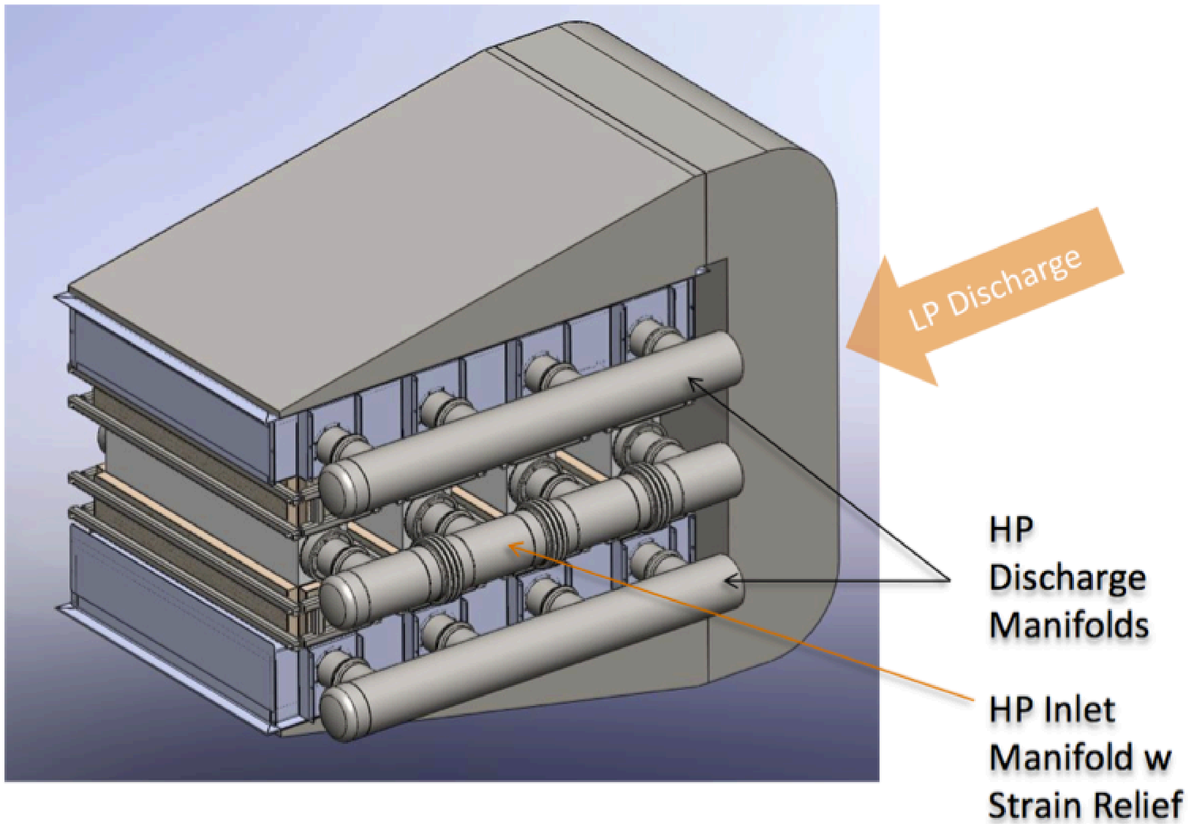
An intercooler cools the air exiting the LP compressor before it enters the HP compressor. By rejecting the heat, the HP compressor needs to do less work per unit mass flow.



Intercooler layout

Recuperator

The recuperator transfers heat from the LP turbine exhaust back to the process air. This allows the same input of solar heat to yield a higher turbine inlet temperature, improving the power conversion efficiency of the engine.

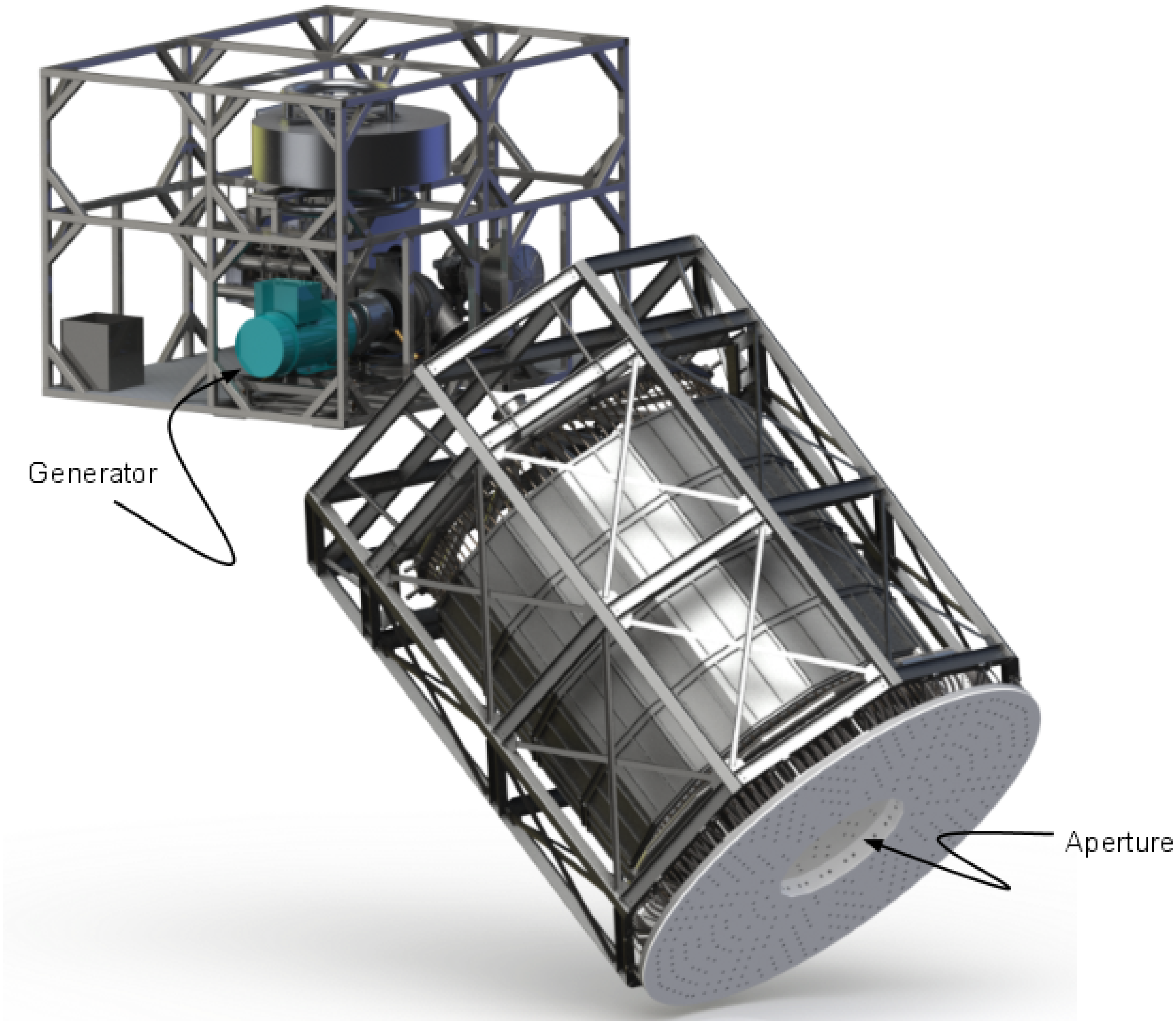


Recuperator layout

The materials limits for the recuperator constrain the operating regime of the engine. The LP discharge temperature can be very hot, and it needs to be maintained at a level below that of the material limits of the recuperator. This is discussed in the Brayton Performance Modeling document.

Engine/Receiver Assembly

A graphic rendition of the Brayton CSP 1 Megawatt power plant is shown below.



Fully assembled engine and receiver (aperture diameter is 1.5 meters, and overall receiver is roughly 6.5 meters long)

Conclusions

Although we did not ultimately carry out our design through to a prototype, we came away with a number of important results and perspectives.

Engine components

- The turbomachinery design is well within current experience levels. The low pressure spool can be an off-the-shelf large turbocharger, such as what is used in large marine diesel engines.

Solar Receiver

- The receiver design proved to be much more difficult than originally expected. A viable design is likely possible with ceramic materials, but much more development is needed.
- More advanced Brayton cycles (such as supercritical closed-cycle CO2) that can operate efficiently at lower temperatures may prove viable for this application, and will require further development. Additionally, volumetric particle receivers (as is being developed at San Diego State University partly through a Google research grant) and other unconventional receiver designs also show promise.