Thermo-Acoustic Generators for space missions

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Abstract

Airbus Defence & Space - Space Systems, Airbus Group Innovations and Hekyom have analyzed in a self-funded joint study the possible use of Thermo-Acoustic generators for space applications. To make the analysis more pragmatic, two different cases have been considered:

1) A telecommunications satellite, in geostationary orbit, with an electrical power demand of 40kW
2) A deep space exploration mission, with an electrical power demand of 100W.

1 Thermo Acoustic Power Generation – the principles

A ThermoAcoustic engine is a heat engine which converts heat into acoustic power and ultimately into electricity if appropriate conversion devices (e.g. alternator) are used. The working fluid is a gas, usually helium, maintained at high pressure (generally around 25 bars) inside a pressure vessel. The acoustic conditions are provided to get a resonant system.

1.1 The TAG unit

The ThermoAcoustic engine architecture proposed here and patented by Hekyom allows a Stirling-type TA engine without the usual drawbacks of a conventional Travelling-wave TA engine which are usually bulky and heavy loop-type machines.
In this concept, a linear motor generates an acoustic wave which is amplified through a TA amplification cell composed of a cold and a hot heat exchanger with a regenerator in between. The acoustic wave is then delivered to the resonator and converted into electricity via a second linear alternator at the end of the pressure vessel. Some of the energy produced is sent back to the linear motor. The resulting power is the net power.
Figure below describes a 2-stage TAG architecture and shows the efficiency against hot and cold heat exchanger temperature. At 1000°C, this concept should achieve about 40% efficiency. *Note that using a 3-stage TAG architecture will improve the global efficiency and reduce the weight and power of the wave generator*

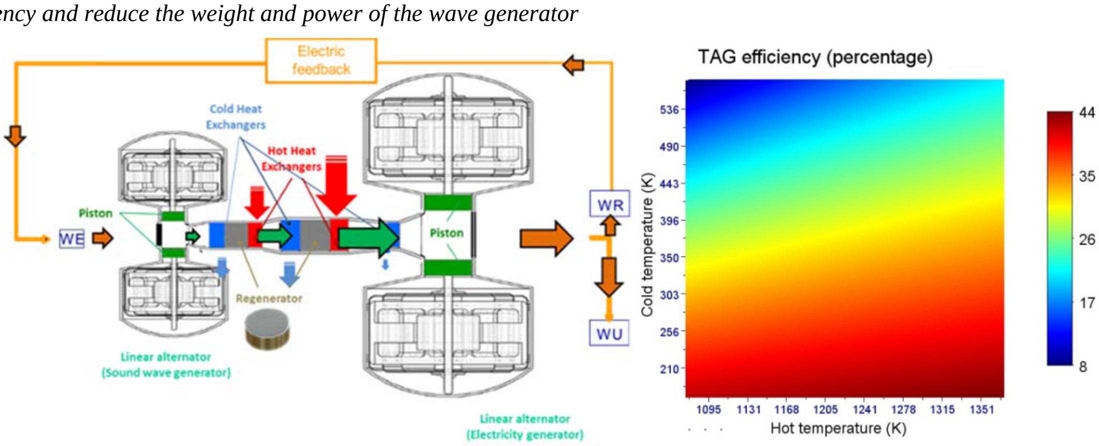


Figure 1 - TAG architecture and TAG efficiency as a function of hot and cold heat exchanger temperatures

1.2 TAG demonstrator

Airbus Group Innovations and Hekyom have jointly developed a Thermoacoustic engine aiming at demonstrating the high efficiency of the above TA engine architecture for high temperature applications. For the purpose of the demonstration, a single stage architecture has been designed and tested as the amplification of a 2-stage thermoacoustic engine is well known and easily predicted. A complex measurement set-up on the prototype has allowed correlating measured engine efficiency against predicted efficiency derived from in-house software (called "Crista"), as shown in Figure 2 below.

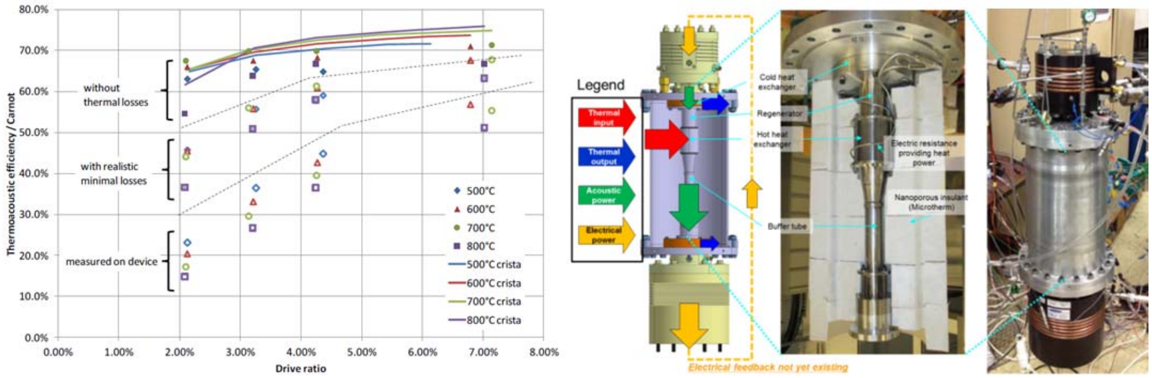


Figure 2 - Measured non-ideal efficiency (fraction of Carnot) and demonstrator set-up

This prototype has demonstrated the potential of the TAG to achieve a thermal efficiency of 40% at 1000°C for the hot temperature. Improvement on the design shall reduce the thermal losses that were measured during testing.

1.3 TAG in space – 2 test cases

Following the work performed between Airbus Group Innovations and Hekyom, a self-funded joint study on the possible use of Thermo-Acoustic generators for space applications have been engaged late 2012. In order to make the analysis more pragmatic, two different cases have been considered :
1) A telecommunications satellite, in geostationary orbit, with an electrical power demand of 40kW.
2) A deep space exploration mission, far from our sun, with an electrical power demand of 100W.

2 The telecom satellite case

Amongst all the spacecraft manufactured in the last 50 years, telecommunication satellites and space station are the two items that exhibit the biggest power demand. In this group, telecommunication satellites are setting the bench mark in terms of mass and power efficiency.
The market of the space solar array generators is completely driven by these missions which are good candidates to test the TAG technology.

2.1 Schematic of a solar based TAG power system

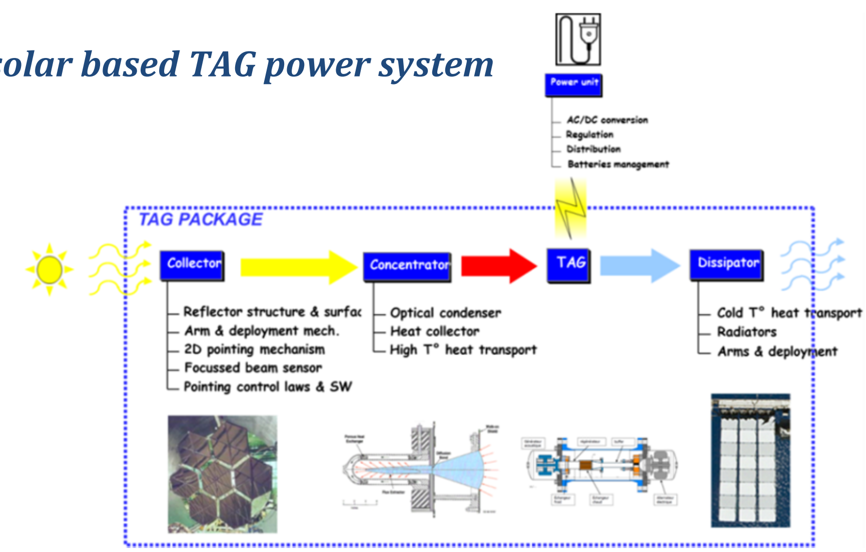


Figure 3 - Typical functional breakdown of a solar based TAG power subsystem

2.2 The study case requirements

We chose to direct the case on 2x20kWe maximum in order to focus the study on next generation satellites, but two other points of load have been selected at 2x5kWe and 2x10kWe, analyzed as de-scopings from the 40kW point.
The TAG implementation has to be compared to a standard solar array based system, with a mass of 2 x 210kg (including the drive mechanism) for a 2x20kWe end of life power capability.

2.3 Drivers first analysis

So as to minimize the overall surfaces of the light collector and the rejected heat dissipator to accommodable dimensions, high temperatures have to be selected for the hot point (1000 to 1200°C) and the cold point (150 to 200°C).

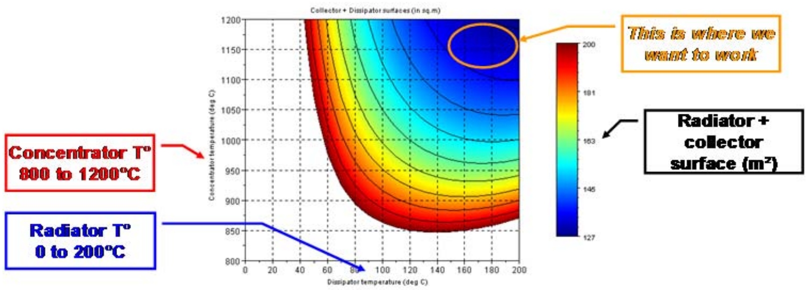


Figure 4 - Collector & dissipator surfaces as a function of hot & cold temperatures

As a consequence of this necessity, a high flux concentration (500 to 1000) is needed to achieve the required hot temperature, to minimize the infra red losses wrt the concentrated spot surface and to minimize the concentrator mass and complexity. This brings in turn the following constraints

- Stringent collector shape requirements (typ. 0.03° slope error for a 10m parabola) to achieve the concentration ratio
- Accurate 2 axis sun pointing of the collector (better than 0,05°) to keep the spot inside the concentrator. *Note that single axis pointing is used for PV solar arrays wrt the cosine law degradation - which does not apply for TAG case*
- Very high efficiency coatings (better than 95% to 90% after 15yrs) and cooling for secondary collecting surfaces
- Efficient & long life time hot temperature materials: for light to heat conversion (refractory metals or Ceramics – e.g. SiC), for hot heat transport (e.g. Li/Nb heat pipes), for insulation and adjacent units protection (very high temperature nanoporous foams and MLI)
- Efficient light transport technologies: Low weight optical fibers or light wave guides, with low absorption, high numerical aperture and able to sustain high temperatures on the light to heat conversion end

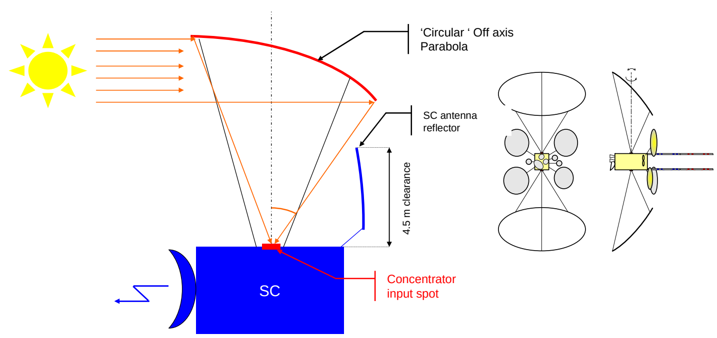
At system level, the first level criticalities are the following

- Large collector & dissipator accommodation wrt masking or contamination constraints regarding the large RF antennas collimated beams, the RF repeater heat radiator walls field of views and the large plume of the electrical thrusters
- Power up after launch vehicle separation and transients handling during eclipse and/or power demand shedding. *Note that 2x200kg of Be for heat storage could provide the capability to sustain the longest eclipse duration but power up constraints impose to keep the standard electrochemical batteries*
- Early operations, including perigee raising and orbital inclination reduction, drive the required angular domain
- Safety & testability issues for on ground integration, and also for failure and safe mode concepts

2.4 Families of assessed concepts

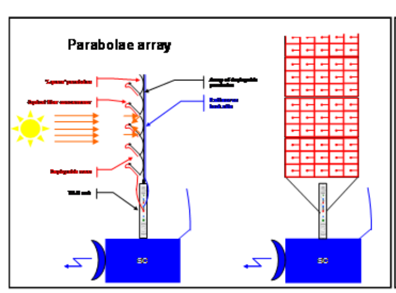
Family 1: Off axis collector – based on:

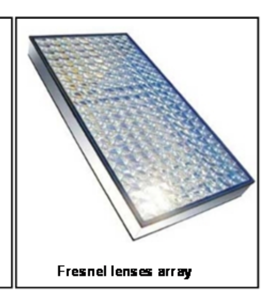
- Concentrator and TAG unit accommodated inside the satellite to minimize the rotating mass
- A large off axis collector (~70% surface efficiency), motorized with a gimbaled 2 axis annular mechanism. *Note that an additional protection device is needed vs non perfect pointing cases*
- Dedicated radiators, potentially behind the parabola (but non continuous rotation in that case for disentangling)



Family 2: Array collector – based on arrays of small collectors on deployable and rotating panels

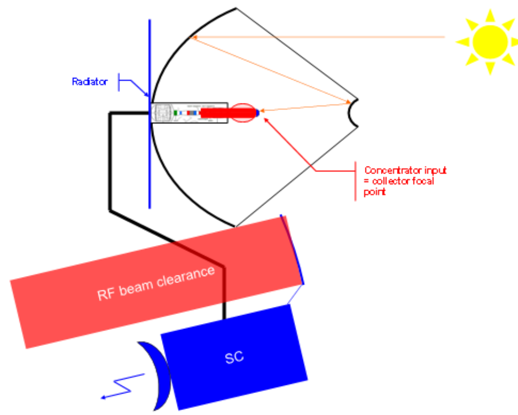
- Small collectors: square parabolas or square Fresnel lenses
- Optical fiber + light waveguide light transport from the collectors to the concentrator
- Concentrator and TAG unit accommodated in the TAG supporting mast, involving a rotating electrical power transmission device. Dissipator is located on each panel rear face





Family 3: Large collector fully external package – based on arrays of small collectors on deployable and rotating panels

- Preferably a Cassegrain collector amongst all the traded options (single Fresnel lens, single parabola, Gregorian, ..)
- Concentrator and TAG implemented between M1 and M2 reflectors – involves also a rotating electrical power transmission device
- Dissipator accommodated on the rear face of the M1 mirror



Several technological and conceptual trade-off have also been conducted at lower levels regarding:

- Collector concept (technology, deployment, focusing and pointing sensors)
- Mast concept (deployment, technology, mechanism)
- Concentrators & hot heat transport technologies
- Optical fiber + light waveguide candidate technologies
- Cold heat transport and dissipation

2.5 Synthetic results

The preferred concept is the Cassegrain solution (from family 3) which provides the highest overall efficiency (19%) and lowest mass (2 x 660 kg) of all the traded concepts, calling for a 10m M1 diameter per side.
Unfortunately, the TAG option is currently not competitive vs the current photo voltaic paradigm wrt the following issues:

- The mass issue: The specific power with TAG is ~30 We/kg whereas up to 85 We/kg can be considered with photovoltaic solutions over the same timeframe. Hence, with this mass penalty, the delta cost due to the TAG delta mass to launch in GEO is similar to the cost of the photovoltaic array itself
- The TRL issue, especially regarding low mass/high efficiency collectors, supporting mast and 2 axis accurate pointing mechanism, high temperature collectors, heat transport and nano porous insulation materials
- The system issues regarding accommodation, transients management, electrical propulsion compatibility, impacts on attitude control stability, failure modes and on ground testing.

3 The deep space exploration mission

All space missions require a source of power which can be derived either from the sun, nuclear sources, or chemical reactions. Historically the processes include:

- Solar power, based on photovoltaic cells (η=28%, rising to ~35%) – used on the majority of Earth orbiting satellites
- Chemical conversion, based on fuel cell technology (η~50%)
- Radioisotope Thermal Generators (RTGs) based on Thermoelectric conversion (η~7%)
- Nuclear fission reactors using thermionic conversion, e.g. SNAP/TOPAZ (η~5%)

Many alternative energy conversion processes have also been investigated with the aim of increasing the efficiency, including:

- Thermo-mechanical conversion from Radioisotope Heather Unit (RHU), Stirling/Brayton/TAG (η~30%)
- Thermo-photovoltaic or TI conversion of RHU (η~30%)
- Thermal collectors (e.g. solar or geothermal)
- Electro-dynamic in planetary magnetic fields (i.e. conversion of s/c fuel)
- Bringing a source of fuel to consume in a (semi-) conventional engine (e.g. H2)
- Local fuel production/scavenging (e.g. H2)
- Conversion of local radiation flux (e.g. around Jupiter)

Away from Earth Orbit, there are two specific challenges which need to be addressed:

1. At orbits further away than Mars the solar flux is so weak that a huge solar PV array is required
2. At orbits closer than Venus the solar flux is so strong that heat rejection from a PV solar array becomes extremely difficult

For these reasons Nuclear Power Sources (NPS) are extremely attractive as mission enablers.

3.1 Existing Radio-isotopic Power Sources

Nuclear Power Systems has enormous heritage since the 1960's, including the most famous example "Voyager" which was launched in 1977 and continues to operate to this day beyond our solar system. Developed by NASA these units consist of pellets of Pu-238 which slowly decays releasing heat which is converted to DC electricity by a Thermo-Electric Generator (TEG). The most recent development of this technology is currently providing all the power needed for the Curiosity rover to explore the surface of Mars. This "Multi-Mission Radioisotope Thermal Generator" (MMRTG) was developed by Boeing and generates 290W of electricity at beginning of life with an overall system efficiency of 6.8% (the ratio of electrical output to thermal input,

including controller system). 8.1kg of Pu-238 is carried on-board and the total MMRTG mass is 57 kg, leading to a specific power of 5.1We/kg.
An alternative concept based on a Stirling convertor (the ASRG, Advanced Stirling Radioisotope Generator) has also been developed in the US, most recently by Lockheed. The major advantage of the ASRG is the higher conversion efficiency of the Stirling convertor leads to a system efficiency of 28% and therefore need for much less Pu-238 (0.88kg for 123We at BOL); critically important since the US recently had a shortage of Pu-238. However with the recent re-start of US Pu-238 production the ASRG programme has been scaled back. Nonetheless the performance is impressive, with a specific efficiency of 6.9We/kg.

3.2 State of the art in Europe

In Europe there is growing interest in the development of an RTG capability to enhance the capability of future European deep-space missions. ESA have initiated the development of RTG technology with 3streams:

- Thermo-electric generator (TEG) converters for low power (5 to 50We)
    - Leicester University & Airbus DS (supported by Fraunhofer IPM) have developed a TEG-RTG breadboard
- Stirling for higher powers (250We)
    - SEA & RAL (supported by University of Oxford) are leading this activity with a breadboard under development
- Radioisotope activities are on-going with a focus on Am-241 (Am_2O_3) instead of Pu-238 due to availability and cost
    - National Nuclear Laboratory (NNL) in UK will lead extraction of Am-241
    - SEA, Leicester and Lockheed Martin developing containment and encapsulation

A key aspect is the fuel production and the plan is that Am-241 fuel pellets will be produced at Sellafield by chemically separating Am-241 from aged Magnox-derived plutonium dioxide. Although Am-241 has better availability and lower cost than Pu-238, it still requires a full suite of handling & safety protection and has a lower thermal output per kg (105Wth/kg compared to 411Wth/kg for Pu-238).

3.3 The study case requirements

The purpose of the Radioisotope TAG (RTAG) study was to determine if the TAG technology could offer any advantages compared to the other on-going developments in Europe. The first step was to define the requirements and four types of mission classes for exploration and planetary missions were defined:

- 10kW : human exploration
- 1 kW : multi-mission orbiters such as Cassini, JIMO-Light
- 100W : ‘manoeuvrable’ field science such as Mars Rovers, Aerobots, sub-surface Europa probe
- 10W : complement to solar cells, miniature geophysical packages

All require :

- a technology which is scalable since total number of missions will always be small
- to minimize amount of radioactive material by high efficiency (cost & safety)
- >5 years operation highly desirable to account for spectrum of possible life-times
- ability to self-start
- management of thermal power during cruise phase
- possibility for redundancy
- low radiation flux + compatible with RHU with impact protection
- output voltage ~ 28V DC and compatible with power demand profile of mission (e.g. peak or continuous power)
- and low vibrations

An **exploration mission of 100W** electric was selected as the baseline, which enabled a direct comparison with other developments. In this case this meant that the total mass (including $^{241}Am_2O_3$ fuel) should be <60kg (including radiators) to be competitive, with the other required identified as (based on outputs from Airbus Defense and Space/Leicester/SEA NSTP study for UKSA & ESA studies)

- Voltage 28V DC
- Exported vibrations <0.1N
- Reliability >90% for 15 years
- SPF free (*note that the ASRG is not SPF free*)
- Volume <= $0.5m^3$
- Capable of being mounted on a rover or boom
- Stackable/modular for multi-mission approach

3.4 Assessed concepts

The RTAG principle is based on a Radioisotope Heather Unit (RHU) consisting of a 200Wth (end-of-life) Am-241 encapsulated in a graphite impact shell and outer aeroshell. This system prevents the scattering of nuclear material in the event of a launcher failure on the pad or in Earth's atmosphere. Each module weighs 5kg and contains 1.9kg of Am-241. This does not represent an module in current production but instead is expected to be similar to the final design.

In the basic RTAG the RHU is insulated from the environment (both radiatively and conductively since the unit could be operated in both vacuum and air). The RHU is then connected to a TAG which is mounted in a thermo-mechanical structure including radiators to carry away the waste heat from the unit. Integral to the unit are conditioning and control electronics which ensure correct phaing and safe operation of the TAG, whilst also converting the AC output of the TAG in to DC current for the spacecraft bus.

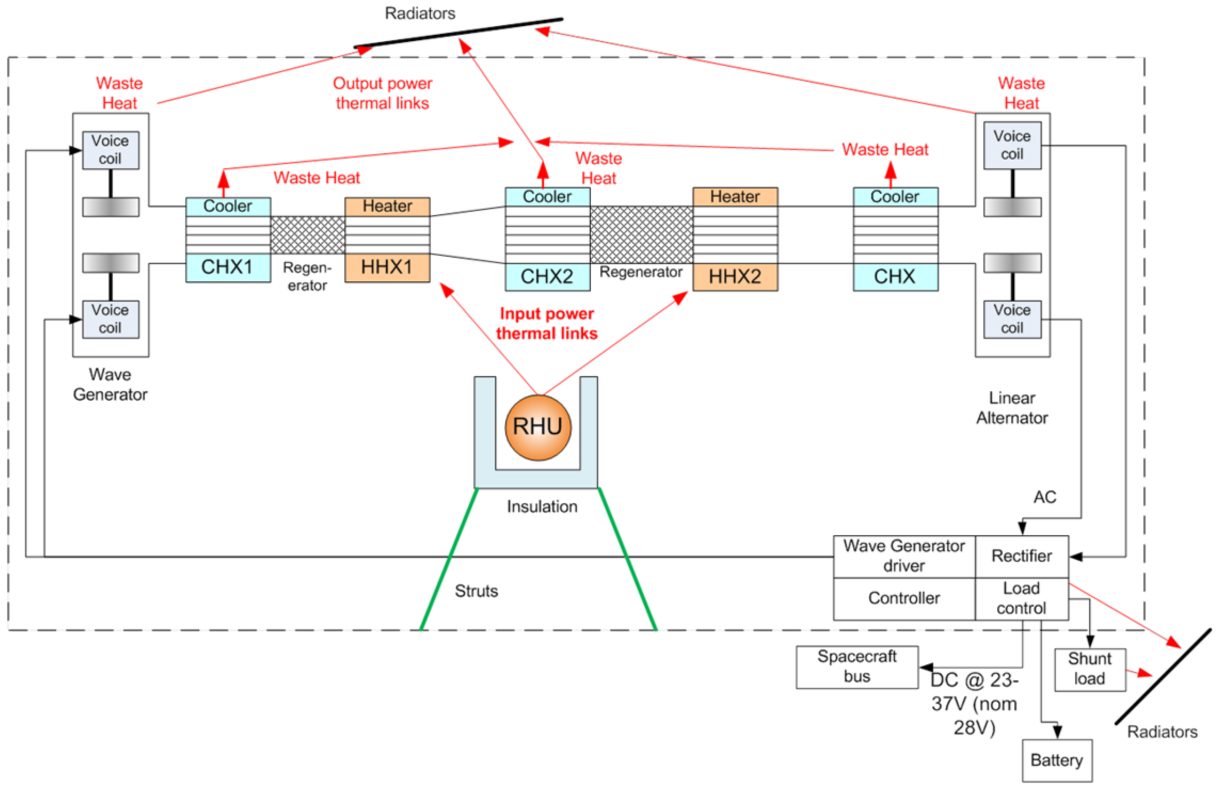


Figure 5 - The basic RTAG architecture

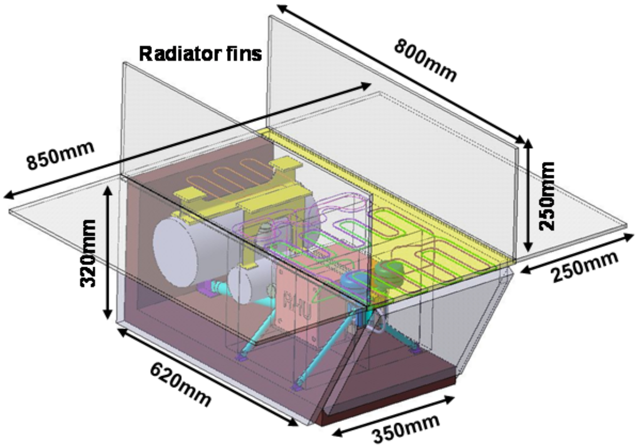
The first trade-off was on an overall concept for redundancy and modularity, with the aim to make the RTAG applicable to as wide a variety of exploration missions as possible (including both deep space and Mars surface). Because the rate of missions is likely to be very low (maybe one per 10 years) it was decided that the core architecture would remain the same but the external architecture would likely to be optimized for each mission. Hence the basic design was a single 100We output unit which, if necessary, could be used multiple times on the same spacecraft to provide more power.

Different trade-offs were carried out on the TAG mounting scheme, insulation system, heat exchanger and transport design (including direct conduction and heat pipes). A key trade-off was the external radiator design since a key aspect of a TAG is that the overall efficiency is strongly related to the cold-end temperature. Since the radiators are strongly impacted by the presence of convection and the first application was likely to be a Mars rover, the radiators were designed to take advantage of convection and also to fit into the fairing a descent module compatible with an Ariane 5 launcher. The possible advantages of deployable radiators was not used because of the additional complexity and need to limit the moments-of-inertia for the rover dynamics.

3.5 Synthetic results

The final RTAG concept consists of the RHU, TAG, thermo-mechanical enclosure, radiators, loop heat pipes, and various internal mounting systems. The design was supported by TAG analysis, preliminary mechanical and thermal models, and electrical simulation. With 2 x 400Wth RHU assemblies the best performance in the Mars atmosphere was 126W electrical output, i.e. a total system efficiency of 32%. It may be possible that this could be increased to 34% if recently observed improvements to TAG efficiency are also realized. The overall mass was estimated at 50.0kg which leads to a specific power of 2.5We/kg. It should be noted that the cause of the difference to the alternative US concepts is the lower thermal output per kg of the European Am-241 fuel, compared to Pu-238 which is used by NASA. The TAG efficiency is seen to be comparable to that of a Stirling convertor although the TAG has no moving parts at the hot end and is therefore expected to be more reliable.

A possible development program was defined for the RTAG with the main focus on the RHU (including the fuel production). A period of 6 years was deemed adequate for the entire project, although this is highly dependent on the fuel production success and also the funding available.



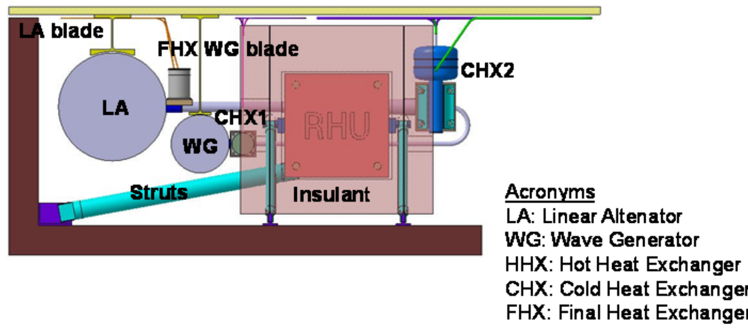


Figure 6 – The RTAG concept

Losses	Power [W]	% of input
TAG	176	44%
WG	3	1%
LA	27	7%
Controller	11	3%
Insulation	17	4%
RHU struts	8	2%
TAG conductive	30	8%
Sub-total	272	68%
Output DC	126	32%
Input Power	400	100%

Mass budget		
RHUs	10.0	20%
TAG core	1.1	2%
Controller	4.0	8%
Alternator	4.1	8%
Wave generator	0.5	1%
Insulant	6.1	12%
Box	14.1	28%
Top fins	3.4	7%
Side fins	3.4	7%
RHU supports	1.5	3%
Thermal HW	1.8	4%
Total mass	50.0	

Table 7 – RTAG power losses and mass budget

4 Conclusion

Thermo Acoustic Generator technology, while being not adequate compared to the photovoltaic conversion concepts for solar powered missions, is an attractive alternative for Radioisotope power based missions for which this technology can bring similar or slightly better specific power and efficiency figures (respectively 2.5 We/kg and 30%) than Stirling based conversion systems while augmenting the system reliability thanks to the reduction in moving parts.

So far, the thermo-acoustic generator is not yet part of the European roadmap for deep space electrical generator, but we have demonstrated it is a valid candidate. The ESA technological directorate ESTEC has been made aware of this new technology that should be considered in the panorama.