Technical White Paper: Solid Oxide Fuel Cell ("SOFC") Generators versus Thermoelectric Generators ("TEGs"); a Technical Comparison

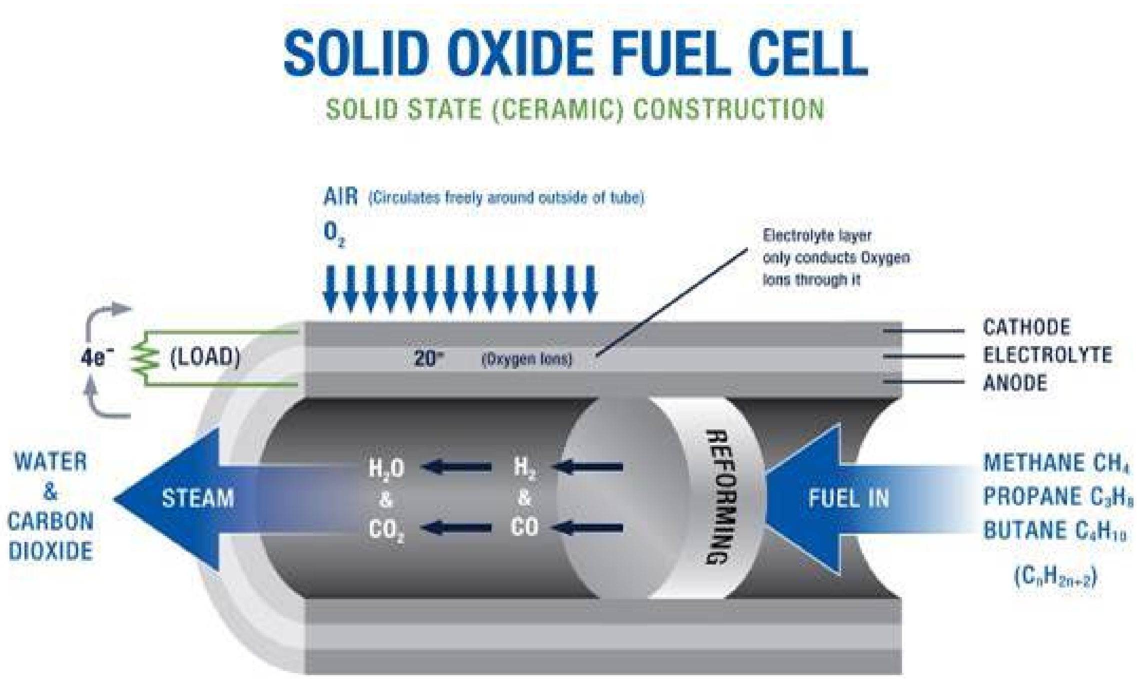
This Technical White Paper presents a comparison between Solid Oxide Fuel Cells ("SOFCs") and Thermoelectric Generators ("TEGs"). SOFCs are manufactured by Acumentrics, a Massachusetts based company while TEGs are manufactured by Global Thermoelectric based in Calgary, Alberta.

TEGs are based upon technology commercialized in the 1970s while SOFCs are truly 21st century technology. Nevertheless, both have earned reputations for being reliable pieces of power generation equipment.

While this paper is written by Acumentrics and therefore could be viewed as being 'biased towards SOFCs', Acumentrics has attempted to base our comparison on valid technical data and real world experience and believes it to be a fair, impartial and accurate comparison.

Solid Oxide Fuel Cells

Fuel cells convert the chemical energy in fuels to electric power through an electrochemical process similar to a battery.



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Like a battery, fuel cells convert chemical energy stored in the fuel to electrical energy.

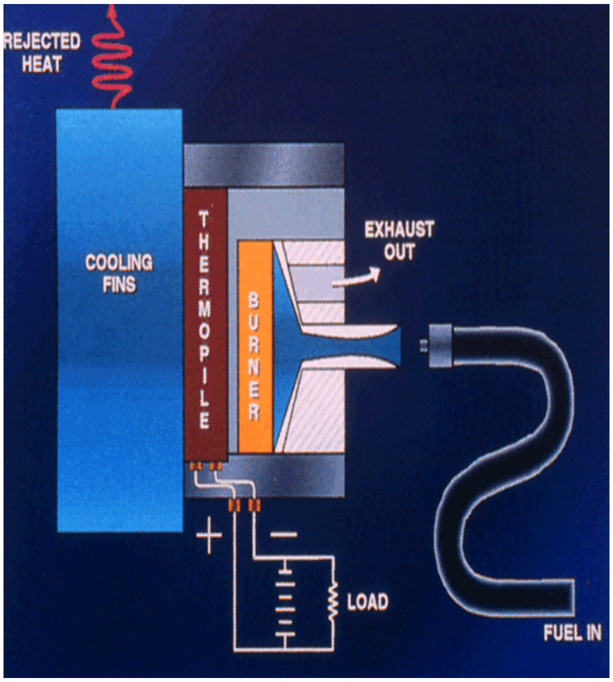
In the drawing shown above, a “chemical pump” moves electrons and ions from one side of a barrier (which becomes positively charged) to the other side (which then becomes negatively charged). In this way the fuel cell behaves like a battery that operates continuously until the fuel supply is exhausted.

The resulting product generates electrical power at about twice the efficiency of burning fuel in a reciprocating engine and at about 10 times higher than TEGs.

There are several types of fuel cells. Acumentrics SOFC fuel cells are constructed with ceramics, which are both durable and reliable. Operating these fuel cells at high temperatures enables internal processing of conventional fuels like natural gas or propane. Common, inexpensive materials such as nickel, manganese, and zirconium are utilized rather than the expensive precious metals that other fuel cells require to catalyze the electrochemical reactions. These materials are in the form of oxides, therefore the name: solid oxide fuel cell.

These ceramic oxides form cells in a tubular construction. The cells provide excellent strength as well as a geometry that is effective at separating the fuel from air. The ceramic tubes are highly resistant to thermal gradients caused by load changes and easy to cycle up and down as power requirements vary.

Thermoelectric Generators



TEGs operate based upon the Seebeck effect where the heat differential across a ‘thermoelectric material’ (aka a ‘thermopile’; basically a lead-tin telluride alloy) produces a small direct current.

To generate the heat, the TEG burns gaseous fuels such as natural gas.

For a more detailed description of TEG technology, it is suggested that the reader visit Global’s website.

The drawing at left shows the basics of a TEG operation.

Any TEG technical information cited in this TWP was obtained directly off Global’s website.

Similarities between SOFC and TEGs

To begin with, while totally different technologies are involved, there are three fundamental similarities between SOFCs and TEGs.

1. Both use gas, either natural gas or propane, to generate electricity.

2. Unlike the most common piece of power generation equipment, a reciprocating engine genset, the power generation unit of each (Fuel Cell Stack for SOFCs and Thermopile for TEGs) have no moving parts and are, consequently, inherently reliable.

3. SOFCs and TEGs both produce direct current power (VDC).

SOFC Load Ranges served

Acumentrics offers 4 standard products as follows:

Model	Typical load range Serviced in Watts	Voltage Output
• 250-Watt	100-250 Watts	5-60VDC
• 500-Watt	200-500 Watts	5-60VDC
• 1000-Watt	500-1000 Watts	5-60VDC
• 1500-Watt	900-1500 Watts	5-60VDC

As output is VDC, SOFCs can be paralleled together to achieve higher load regimes.

For example: a load of 2200 watts could be obtained by paralleling a 1500-watt and a 1000-watt SOFC together.

While SOFCs could be paralleled together for connected loads as large as 10kW continuous, Acumentrics believes the 'sweet spot' for our fuel cells is where the loads are no greater than 5kW.

TEG Load Ranges served

Global TEGs are offered in 5 basic models (Global offers 2 other models designated for explosive environments) with output power ranging from 21 watts up to 550 watts. With the sole exception of their largest model that comes with a rated output of 550 watts, all other TEGs have outputs less than 220 watts.

Most TEGs come with output voltages of 12, 24 and 48VDC. Unlike SOFCs, however, where the rated power output in watts is the same regardless of the voltage, each TEG's specified power output is voltage dependent. For example, Global's Model 5220 is rated for 220 watts at 12VDC. That same model however, only puts out 176 watts when configured at 24VDC.

As with SOFCs, TEGs can be paralleled together to obtain higher load outputs.

Although TEGs have been paralleled together to service loads that were up to 5kW, those are really the exception rather than the rule. Most folks in the industry would consider the 'sweet spot' for TEGs to be where the connected loads are 1.5kW or less.

What are the main advantages and/or disadvantages of one versus the other?

1. Acumentrics believes an objective analysis would conclude a Reliability comparison between SOFCs and TEGs would come out as essentially awash.

Global TEGs have been around for almost 40 years and have developed a solid reputation for reliability. Global has *theoretical* reliability calculations that show a single TEG has a 99.3 predicted level of availability.

Unfortunately, Global TEGs, designed with 1970s, early 1980s electronics have never been equipped with data recording capabilities. Consequently, other than anecdotal stories of TEG reliability, there is no hard data available to prove or disprove exactly how reliability TEGs actually are.

On the other hand, SOFCs are almost exactly the opposite. Acumentrics has only been commercially selling SOFCs since early 2011 as opposed to almost 40 years for TEGs.

Acumentrics does not currently have theoretical calculated reliability values that it can provide its customers.

What Acumentrics does have however, is real data. *Each and every SOFC comes fully equipped with a remote monitoring and data collection system using state-of-the art electronics.*

Consequently, on a daily basis, Acumentrics receives real-time data as to how its fuel cells are operating.

With an installed base of SOFCs approaching 100, Acumentrics can report, based upon hard factual data, its SOFCs are achieving an availability of over 97.5%.

Having the data also allows Acumentrics to understand the root causes for any SOFC downtime. Acumentrics is systematically and continuously reviewing the data obtained and implementing well-planned out product enhancements to ‘harden up’ those areas that will result in higher levels of reliability.

Point of Interest: It turns out the single biggest factor in SOFC down time is not the fuel cell itself, but the fuel supply. Obviously a fuel cell (or a TEG or any other piece of power generation equipment that runs off gas) cannot operate if there is not fuel.

As incredible as it may seem, there have been more times than once when an O&M person shut off the supply of fuel only to not remember to turn it back on.

2. Acumentrics believes SOFCs offer distinct advantages over TEGS in the following areas:

- Larger Power Output Ranges

This was discussed above and will not be repeated other than to say that SOFCs are better suited to handle larger load regimes.

On the other hand, smaller load regimes (<150 watts) are better handled by TEGs.

- Maximum Power Output

Besides having a higher power output rating, SOFCs actually produce more power. The only models that can be considered as 'equivalent' are the TEG Model 8850 and the SOFC RP-500.

The 8550 puts out 550 Watts at 24VDC and 480 Watts at either 12 or 48VDC.

The RP-500 is rated for 500 watts at any voltage.

Furthermore, although Acumentrics conservatively rates the output at 500-watts, the RP-500 can put out up as much as 700 watts.

The reason for the 500-watt rating is that higher power outputs shorten the life of the Fuel Cell (more on that below under annual O&M).

Why this is considered an advantage is that the SOFC can handle short surge loads above 500 watts.

- TEG Temperature Derate

TEGs are rated for 20° C while SOFCs are not temperature dependent. Therefore at site locations where temperatures go above 20° C, TEG outputs must be derated. The same does not apply for a SOFC.

- Remote Monitoring and Control

Once again, discussed above. SOFC come equipped with state-of-the-art electronics that allows for complete monitoring, data recording and remote control.

One huge benefit of this function is the ability to fully diagnosed and potentially resolve any problems that may occur before having to dispatch a corrective maintenance repair team.

TEGs simply do not have this functionality.

- Efficiencies

TEGs are the most inefficient of any source of power generation commercially available.

The result of this inefficiency, of course, is the amount of fuel burned.

If an indigenous source of natural gas is available, the prospect of having to send a refueling truck to the site is not an issue as it would be if the TEG were using propane.

Nevertheless, even burning natural gas, the cost associated with that gas is prohibitive.

SOFCs are over 10 times more efficient than TEGs. This means, for the same amount of power generation, SOFCs will consume significantly less fuel (natural gas or propane)

Global's model 8550 TEG, which has a rated output of 550 watts at 20° C, is widely deployed along pipelines.

Let's compare the fuel consumption of a single 8550 TEG with a 500-watt SOFC:

	Natural Gas	Propane
TEG	1695 Ft^3 per day	20.1 Gallons per Day
Dual SOFCs	137 Ft^3 per day	1.44 Gallons per Day

Note: The fuel consumption shown for the TEG is taken directly of the 8550 Technical Datasheet contained on Global's website.

If one placed a 'market value' of \$3.5 per 1,000 Ft^3, over the course of one year, a TEG would consume \$618 worth of natural gas while dual SOFCs would consume \$50, for a delta of \$568

Let's assume a pipeline project with 25 block valve sites. That delta becomes \$14,200 per year.

Let's now assume the pipeline is planned to operate for 20 years. That delta becomes \$284,000.

The comparison is even more dramatic if natural gas is not available such as would be the case for a crude oil pipeline.

Using a cost of propane delivered to the site of \$4.50 per gallon, the cost savings is startling.

Over the course of one year, a TEG would consume \$33,014 worth of propane while the SOFC would consume \$2,365 for a delta of \$30,649

Once again, a pipeline project with 25 MLBV sites. That delta becomes \$766,225 per year and a staggering \$15,324,500 over 20 years.

- Emissions

The Energy Industry is coming under ever-increasing pressure to become more 'green'.

A SOFC's fuel cell core enables the direct generation of DC power without emitting NOx and SOx pollutants with CO2 emissions being significantly lower than combustion based generators.

While Global does not publish TEG emission data, TEGs have a long-standing reputation throughout the industry as not being very 'environmentally friendly'.

On the other hand, fuel cell products, like the Acumentrics SOFCs, are defined as renewable energy sources by the US Government and are eligible for state and federal tax credits up to \$3,000 per system or more.

Let's drill down a bit deeper and try to put a cost onto this.

Two articles were published in December 2013 that discussed the energy industry associating a cost for carbon emissions. While every company in the industry has not yet done so, the 'writing is on the wall' and sooner or later (more than likely, sooner) every energy project will be mandated to account for carbon costs.

- http://www.bloomberg.com/news/2013-12-05/big-oil-braces-for-10-fold-surge-in-carbon-emission-costs.html
- http://www.nytimes.com/2013/12/05/business/energy-environment/large-companies-prepared-to-pay-price-on-carbon.html?_r=1&

These articles discuss companies putting a dollar figure on carbon emissions. The range is between $6 to $60 per ton. The articles state that ExxonMobil has assumed the highest cost of $60 per ton by the year 2030, while Xcel Energy, an USA-based utility, uses $20 per ton.

For discussion purposes, let's stay with same units compared above; a 500-watt SOFC versus Global's 550-watt TEG.

- Acumentrics' 500-Watt SOFC emits less than .5 lbs. per hour of CO2. That equates to 4,380 lbs. per year, 2.2 tons per year).

While not privy to specific emission data for TEGs, based upon anecdotal information obtained from different industry sources, Acumentrics' best estimate would be as follows:

- 550-Watt TEG emits about 10 lbs. per hour (87,600 lbs. per year, 43.8 tons per year)

Once again, using a pipeline project with 25 MLBV sites, the results would be as follows:

- SOFCs: 500-Watt with a total annual carbon footprint of 2.2 tons
- TEGs: 550-Watt with a total annual carbon footprint of 43.8 tons

Therefore for 25 such sites, the total annual carbon footprints would be:

- SOFCs: 55 tons
- TEGs: 1,095 tons

Let's put some cost numbers on top of all that.

1. Using Exxon's $60 per ton would equal:

   - SOFC: $ 132 per year or $3,300 for all 25 Sites
   - TEG: $ 2,628 per year or $65,700 for all 25 Sites

2. Using Xcel Energy's $20 per ton would equal:

   - SOFC: $ 1,100 for all 25 Sites
   - TEG: $ 21,900 for all 25 Sites

Those cost estimates however, are for only a single year.

Once again, in the example, the pipeline would be expected to operate for 20 years, if not longer.

Total Carbon costs for 20 years would be.

- Using Exxon's $60 per ton:
  - SOFC: $ 66,000
  - TEG: $ 1,642,500
- Using Xcel Energy's $20 per ton:
  - SOFC: $ 22,000
  - TEG: $ 547,500

Whether or not a specific project is taking carbon costs into account is the customer's decision. It can state with some level of certainty however, that carbon costs are becoming a huge factor in the G&O industry. SOFCs are clearly a 'green energy solution that works'.

- Power Out Footprint

SOFCs have a significantly smaller footprint per watt than TEGs.

For a 1000-Watt load, a TEG solution would require a minimum of two Model 8550s. The total 'real estate' footprint for dual TEGs would be over 54 square feet.

That same load could be serviced by a single RP-1000 SOFC with a footprint of only 7.5 square feet!

- Ambient Noise

Neither Global nor Acumentrics publishes actual noise levels in dB at 1 meter.

That said, SOFCs are virtually silent. The best way to describe noise from a SOFC is to equate it to one's laptop computer. There is some minor sounds coming from internal fans, but that is about it.

TEGs on the other hand, because of the 'venturi effect' of forcing the fuel air mixture into the TEGs burn chamber, make a very loud, very distinctive, continuous whining sound.

3. TEGs offer distinct advantages over SOFCs in the following areas:

- Low-end Operating Temperature

TEGs are rated by Global to operate at temperatures down to -40° C while Acumentrics currently rates its SOFCs down to only -30° C.

Note: A few SOFCs are deployed in some extreme cold weather locations (one site in northern Finland) that see wintertime temperatures well below the -30° C level.

Acumentrics expects it will be able to rate SOFCs down to -40° C at some point in the future when we have accumulated sufficient real world data to justify such.

- TEG Thermopile Lifetime

A clear advantage of a TEG is its expected lifetime.

The 'guts' of a TEG is called the thermopile. While TEG output must be derated to account for thermopile degradation, it has a 20-year life expectancy when run in a continuous mode. Cycling of TEGs (turning on and off) will result in more rapid degradation and a significant decrease in the expected thermopile lifetime..

The 'guts' of a SOFC is the 'tube assembly', more commonly referred to as the 'Fuel Cell Stack'. It has an operational life of approximately 1 ½ years (discussed in more detail directly below).

- Annual Preventive Maintenance

A distinct advantage TEGs have over SOFCs is the amount of required annual preventive O&M.

TEGs are easy to maintain. Global's recommended annual O&M for a TEG consists of a general inspection and the changing of a fuel orifice. Typically annual O&M takes a single field technician less than 1 hour.

SOFC annual preventive maintenance is a more complicated endeavor.

Like TEGs, annual O&M for a SOFC also consists of a general inspection and the changing of a fuel orifice

Two major elements of the SOFC also require replacement somewhere in the 1-2 year time window of operation.

- Fuel Cell Stack Bundle: This is the 'guts of the SOFC that actually produces the electricity. The fuel cell stack delivers steady power output for most of its life but starts to degrade at some point and subsequently will no longer be able to generate the unit's rated power. The degradation of the bundle is a function of many factors, the principle one being the amount of power out. In layman's terms, if a RP500 services an average load of 300 watts, its fuel cell stack can be expected to last longer than if that same bundle had operated at 500 watts.

  The normal expected life of a SOFC bundle is approximately 12,000 hours of operation or basically every 1 ½ years.

  This bundle is a 'line replaceable unit'. Replacement procedures, outlined in the unit's O&M Manual are relatively straightforward and should take 2 trained technicians approximately 2 hours start to finish.

- Desulfurization Filters: Much like the Fuel Cell Bundle, the SOFC's twin desulfurization canisters must be periodically replaced.

The normal expected life of these filters is every 3-4 years. Actual replacement, however, is direct function of the quality of the incoming gas. Natural gas containing little or no sulfides could easily last for years.

For propane SOFC models, it is anticipated these filters would last for 5 years.

For planning purposes, Annual O&M for a SOFC could reasonably be expected to take 2 men one full day.

SOFC versus TEG Comparison Matrix

The comparison matrix spreadsheet at this end of this TWP, while subjective in nature, provides a very accurate comparison between a SOFC and a TEG.

Acumentrics Technical White Papers

Acumentrics is a big believer in ‘speaking with data’ and has written a series of Technical White Papers (“TWPs”) that present objective and quantifiable attributes of the various technologies at the heart of today’s commercially available off grid power systems. By carefully examining the pros and cons of the different approaches the end user can make informed decisions and select the most appropriate power system for their specific project application.

Please feel free to contact Acumentrics and ask for what topics it has TWPs on.

Remote Power Comparison Matrix

Load Regimes Serviced	Load Ranges < 200 Watts	Load Ranges > 200 Watts < 500 Watts	Load Ranges > 500 Watts < 1000 Watts	Load Ranges > 1000 Watts < 1500 Watts	Load Ranges > 1500 Watts < 2500 Watts	Load Ranges > 2500 Watts	Load Ranges > 4000 Watts	Load Ranges > 5000 Watts
SOFC	2	1	1	1	2	2	3	3
TEG	1	2	2	2	3	3	3	3

While it might be 'technically feasible' to use the system, if it is considered as either 'financially marginal' or 'financially not feasible', it has been listed as a '2' or '3' respectively.

Reliability and Maintainability Issues	Actual System Availability Data	Ease of Maintainability	Special Tools Required	Special Skills Required	Ability to Diagnose Situation prior to O&M Crew dispatch
SOFC	1	2	1	1	1
TEG	3	1	1	1	3

Other Technical Parameters	Remote Monitoring and Control	Requires large, multi-day Battery Bank	Temperature Derating	Lifetime Degradation Derating
SOFC	1	1	1	1
TEG	3	1	2	2

Cost Related Issues	Cost to Extend Power Grid	Recurring Monthly Utility Bill	Initial System Cost	Cost of Foundation	Cost of Shipment	Cost to Install and Commission	Annual Preventive Maintenance Cost	Battery Bank Replacement Cost	Fuel Usage: Natural Gas	Fuel Usage: Propane or Diesel
SOFC	0	0	2	1	1	1	3	1	1	2
TEG	0	0	2	2	1	1	1	1	3	3

Total 10-Year Life Cycle Cost	Life Cycle Cost: Natural Gas	Life Cycle Cost: Propane
SOFC	1	1
TEG	3	3

Intangible Considerations	Susceptibility to Vandalism	Fouling due to Bird Excrement	Performance under extended periods of inclement weather	Requires large area of clearing to ensure 'unfettered access to the sun'	Ambient Noise	Energy Efficiency	Level of Emissions	Seismic Susceptibility	Size of Footprint	Expected Lifetime of Battery Bank	Expected Lifetime of Power Generation Equipment
SOFC	1	0	0	0	1	1	1	1	1	1	1
TEG	1	0	0	0	3	3	3	1	1	1	1

Relative Scale

3	Most Difficult or Most Expensive
2	
1	Least Difficult or Least Expensive
0	Not Applicable

Relative Rankings

SOFC	47
TEG	70

Like Golf, the lower the score the better

Worst Possible Score:	120
Best Possible Score:	40

Acumentrics