An EGS/HSA concept for Singapore

Grahame J.H. Oliver
Department of Civil Engineering, National University of Singapore. cvegjho@nus.edu.sg

Abstract

Hot springs are a good indicator for geothermal resources in Singapore. An Engineered Geothermal System (EGS) for commercial power generation would require 3 km deep directional wells in hot sedimentary aquifers (HSA) or in hot, wet, fractured granite and the generation of electricity from +150 ^{o} C hot water through binary cycle turbines with the 'waste' water being recycled down injection wells. Proof of concept for a 50 MW power station might cost US$ 19 million. Development costs (US$ 200 million) could be written off in 6.4 years after production started. Large corporations and the military could benefit from autonomous geothermal power sources (e.g. electricity, heat processing, district cooling). Several neighbourhood 50 MW geothermal power stations could provide part of the national base load with 'renewable', clean, green power generation of strategic importance for a country that is viewed as having no natural resources.

Keywords: Concept, EGS, Singapore.

Introduction

Sixty million people living on plate boundaries around the world already obtain their electricity from hydrothermal sources in young magmatic rocks. Many commentators see the return of the US$100-plus barrel of crude oil with future gas prices tracking that rise. Eighty percent of Singapore's electricity is generated from imported natural gas. Geothermal exploration of buried hot granite terrains in continental interiors is now attractive: in Australia and Alaska, EGS exploration has now passed into the development phase. Australian State Governments have committed US$ 90 million for research and demonstration and another US$ 750 million has been allocated to works programs for the period 2002 and 2013(1). In May 2009, the US Government announced a US$ 350 million stimulus boost for US geothermal energy(2).

The main heat releasing isotopes in rocks are ^{235}U, ^{238}U, ^{232}Th and ^{40}K. Granites usually have more of these elements than most other rocks. Granites with more than 10 ppm U can be classified as "hot" and provided the granite has been allowed to heat itself up under a thermal blanket of overlying rocks, significantly high temperatures can build up over millions of years. New technology means that boiling geothermal water or steam is not required. The commercial binary cycle Chena Power Station in Alaska boils R-134a refrigerant with 74^{o}C geothermal water extracted from Mesozoic hot granite, and produces 2-300 kWh at US 5 cents/kWh(3). This is in contrast to the US 30 cents/kWh cost of diesel generators previously used at Chena(3). The Geysers region in California generates electricity at 5 cents/kWh(4). US 5 cents/kWh is competitive against all forms of power generation except for coal.

Geology and hot springs of Singapore

Singapore lies inside the stable Asian continental plate called Sundaland. The island is composed mainly of Middle Triassic I-Type granite and minor gabbro, intruded into a km thick blanket of contemporary acid volcanics and partly covered by Upper Triassic and Lower Jurassic sediments (Fig. 1). There are three confirmed hot springs situated at or near the coasts (although the precise locality of the one on the SW side of Pulau Tekong is uncertain because of land reclamation). Seeping "steam" (*sic*) has been reported to me but not confirmed from another location on Sembawang Singapore Air Force base (Fig. 1). The best known hot spring at Sembawang has been drilled down to 100m into a 50 m wide fault zone in granite: temperatures of 70.2 ^{o} C were measured (Zhao et al. 2002). Chemical analyses classify it as a potable neutral chloride spring with total dissolved solids (TDS) measured at 914 mg/l and a Cl content of 431 mg/l (Zhao et al. 2002). I have applied various geochemical thermometers (listed in Bowen 1986) using Si, Na, K, Ca concentrations listed

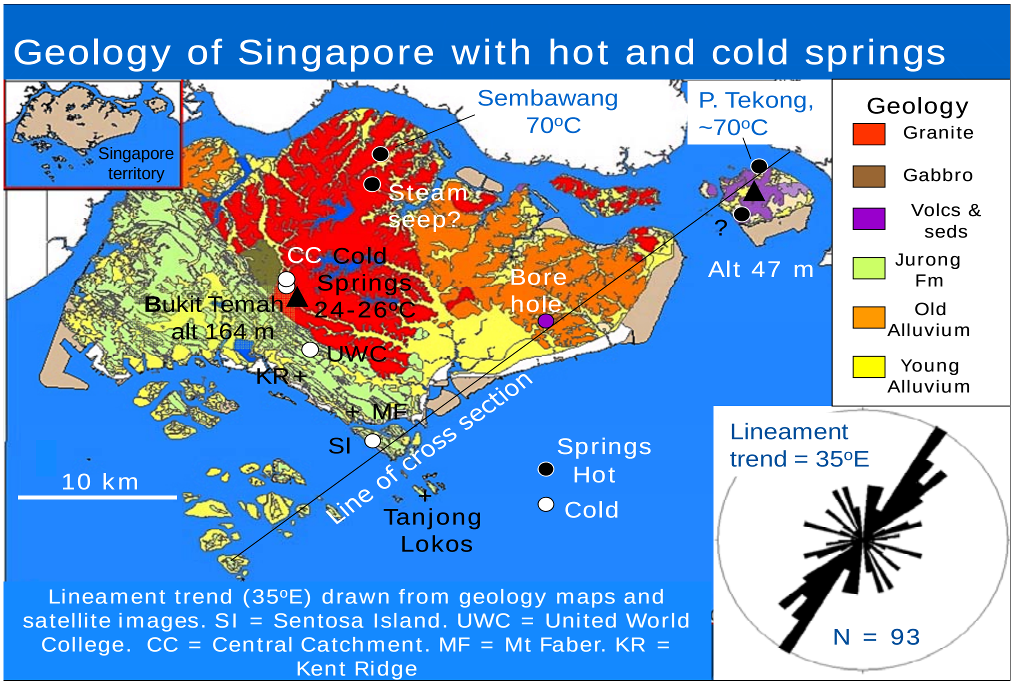

Figure. 1: Geology map of Singapore (after Lee and Zhou 2009)

in Zhao et al. (2002) which indicate underground reservoir temperatures between 122 and 209 ^{o} C: Na/K thermometers give temperatures of ~160 ^{o} C.

Granite bedrock is not normally considered to be permeable unless it is well fractured, jointed and faulted. I have investigated the granite quarries around Bukit Temah and Pulau Ubin and close spaced jointing is common. Cold springs occur around Bukit Tema, United World College and Sentosa Island (Fig. 2).

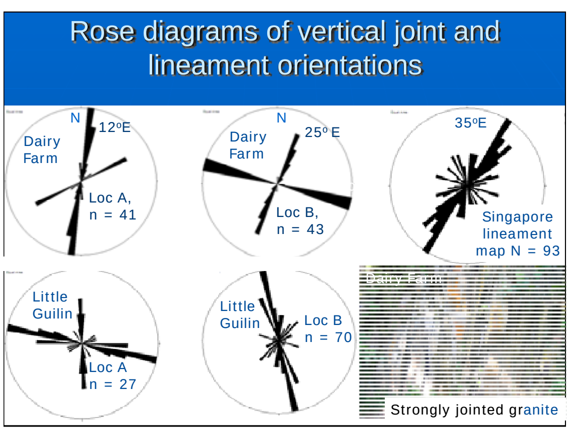

Figure 2: Structural data from quarries

The average maximum horizontal stress (sigma 1) in ~100 m boreholes in central Singapore has a 13^{o}E orientation (Zhou 2001). My analysis of the stress vectors in the Sumatra section of the Australian Plate collision in the Sumatra-Java trench and subduction zone to the SW of Singapore, suggests that the maximum horizontal stress in the hangingwall of the subduction zone is oriented 40^{o}E. The present day stress map of SE Asia[5], based on earthquake fault solutions and borehole breakouts and fractures, shows that the maximum horizontal stress is orientated 40^{o}E in neighbouring Sumatra. Furthermore, my lineament map of Singapore, based on topography, geological map and satellite data shows a very strong NE/SW trend (35^{o}E, see Figs. 1 and 2).The important implication is that any joints (of whatever age) that are orientated NE/SW could be open in this stress regime and would be the first to open at depth during an HF-acid fracture stimulation.

I have measured joints and fault orientations in various Singaporian granite and gabbro quarries and there is a NE/SW correlation with the lineament map (see Fig. 2). The prediction is that granite with a strong NE/SW orientation of open joint sets will preferentially channel ground water in a NE/SW direction away from the watersheds. Figure 1 shows that the confirmed hot springs in Singapore are indeed

NE of their associated watershed maxima.

Heat flow and geothermal gradient

There are no direct measurements of heat flow, thermal conductivity of rocks or geothermal gradient from Singapore territory. Hall & Morely (2003) estimate that based on an extrapolation of oil and gas well data from central Sumatra, the Malaysian Peninsular and the Malay Basin, the heat flow values for Singapore are between 110 mW/m^2 in the east and 130 mW/m^2 in the west of the island (Fig. 3).

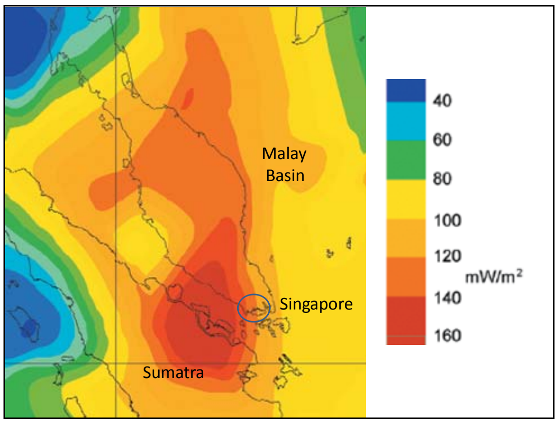

Figure 3: Contoured heat flow map of part of SE Asia. After Hall and Morley (2003).

Applying the Fourier Law of thermal conduction and assuming an average heat flow value of 120 mW/m^2 and an average thermal conductivity for granite of 3.48 W/mK gives a geothermal gradient of 34.5 ^{o} C/km. This assumes that the earth's crust below Singapore is made from granite.
There is a permanent spring at an altitude of 120 m at Jungle Falls on the N side Bukit Temah, the highest hill in Singapore (164m) in the Central Catchment Area, indicating a high water table (Fig. 1). The temperature of this spring is 24.0 ^{o} C (D. Higgitt pers. comm.). At 60 m asl on the NE side of Bukit Temah, another spring issues out of the granite along the Wallace Trail. The temperature is 26.0 ^{o} C, an increase of 2.0 ^{o} C over a 60 m drop in altitude from Jungle Falls, which could be interpreted as being caused by a geothermal gradient of 3.3 ^{o} C per 100 m (or 33 ^{o} C / km).

Ground water model for Singapore

The USGS groundwater model[6] for islands with an unconfined aquifer surrounded by seawater can be applied to Singapore (Barlow 2005). Assuming seawater has a density (*Ps*) of 1.025 g/cc compared with fresh water (*Pf*) of 1.0 g/cc, then according to the Gyben-Herzberg relation:

$$z = \frac{P_f}{P_s - P_f} \cdot h$$

a head (*h*) of 120m above sea level in the centre of the island will drive cold fresh water down 4.8 km below sea level (*z*). The permanent (24 ^{o} C) spring at an altitude of 120 m on Bukit Temah, (164m), indicates that such a high water table is present. Assuming that the average geothermal gradient for the Singapore region is 35 ^{o} C/km (Mazlan et al. 1999, and see discussion above), ground water at 4.8 km depth will reach 168 + 24 = 192 ^{o} C. Because of the high rainfall (2.4 m/year) and the 120 m head, the hot ground water will be driven along the fresh water/seawater transition and up to the surface at the coast (Fig. 4). As described before, this hot water is likely to be preferentially channeled along NE/SW orientated joints and fractures.

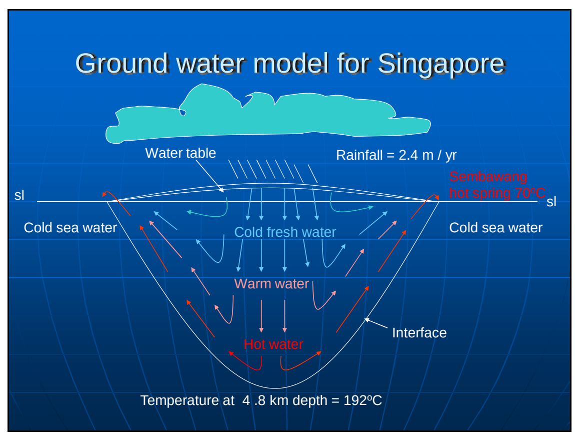

Figure 4: Ground water model predicts 192 ^{o} C water at 4.8 km depth.

The Sembawang hot spring is 3.7 m above sea level which was at sea level during the warm interglacial periods at ~80 ka and ~125 ka (Kopp 2009). The Pulau Tekong hot spring is at 0.5 m above sea level, and from photographs, it looks to be in the mangrove transition, which explains the high Cl and Mg contents (Lee and Zhou 2009).

Exploration of geothermal prospects

Figure 5 illustrates the three prospects in the Singapore geothermal play: Pump testing of 100 m deep wells into a fault zone in the Bukit Temah granite at the Sembawang hot spring prospect produced up to 400 l/min at a constant 70 ^{o} C for many days (Zhao et al. 2002). However, this rate is not high enough to support a commercial power plant. Deeper production wells are required to intercept hotter water and these need to be coupled with injection wells to supplement the artesian flow.

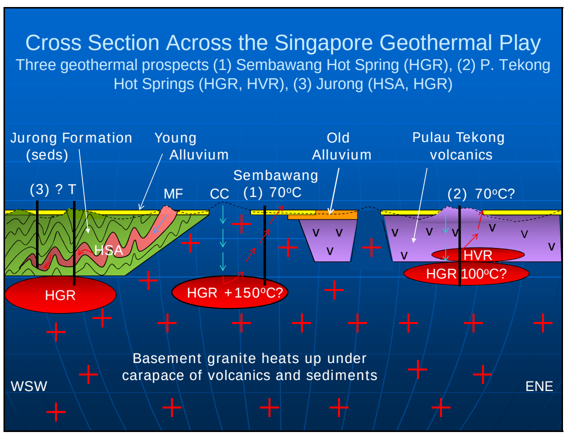

Figure 5: Geothermal prospects in Singapore. Arrows indicate a model for groundwater flow. CC = Central Catchment Area, MF = Mount Faber recharge area, HGR = hot granite rock, HVR = hot volcanic rock, HAS =hot sedimentary aquifer.

The Pulau Tekong prospect has two hot springs, one of which is estimated to be 70 ^{o} C, the other which has been lost due to land reclamation. The heat source is unlikely to be in the Triassic volcanic/sedimentary carapace but rather in the fractured granite underneath. The Jurong Formation prospect is composed of conglomerates, sandstones, mudstones, limestones and minor coal measures, unconformable lying or thrust on top of the granite basement (Lee and Zhou 2009). If the Jurong is thick enough (3 – 4 km?) then it could have acted as a thermal insulator to the 'hot' granite basement. If the Jurong is permeable enough, then any aquifers in contact with the 'hot' granite basement could have been heated to form a hot sedimentary aquifer. Cold springs on Santosa Island and from near United World College might be recharged from the high ground of Mt Faber and Kent Ridge. Strong jointing in open folded conglomerates at

Tanjong Lokos (Fig. 1) indicates good permeability.
Geophysical surveys: e.g. gravity, MT, TEM, 3D seismics, and heat flow surveys (i.e. a grid of 10 km spaced 300 m deep bore holes) are required to locate 2 - 3 km deep exploration wells that will test for high heat flow, geothermal gradients and stress orientation. These deep wells might intercept significantly hot artesian water (HSA) or hot dry rock suitable for EGS. Age dating of spring waters would be useful to model artesian flow rates: i.e. $^{3}H/^{3}He$, SF_6 and CFC's.

Proof of Concept

For the purpose of this study, it is assumed that 150^{o}C geothermal water will be used in a binary generation system. Obviously, viability will be increased with a hotter source but that would require drilling deeper, more expensive wells.
Proof of concept for an EGS 50 MW power station, providing power for 50,000 homes by tapping +150^{o}C water at 2 km depth might cost US$ 19 million: i.e. two 3 km long L-shaped wells at US$ 3 million/km, plus US$ 1 million for a 1 km HF acid-fracture job. The horizontal part of the wells should be 1 km long and orientated NW/SE so as to maximize intersections of NE/SW trending vertical joint and fracture sets (Fig.6).

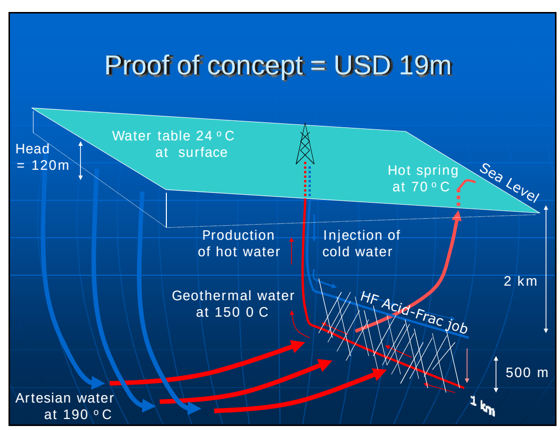

Figure 6: Proof of concept requires sufficient connectivity between injector and production wells.

If this was proved to be successful, then other pairs of L-shaped wells could be drilled from the same drilling pad until the requisite flow rates were acquired.

Development Costs

Development costs for a 1 MW demonstration power station can be estimated by comparison with the 400 kW binary generation system constructed at Chena, Alaska. This uses 74 ^{o} C hot spring water from shallow wells (~200 m deep) in granite and generates electricity using massed produced refrigeration components. Development costs were US$1300/kW[(3)], i.e. US$ 1.3 million/MW. Production costs at 5 US cents/kWh and selling at a domestic rate of 12 US cents/kWh would generate a profit of 7 cents/kWh, i.e. US$70/MWh. Based on these 2007 figures, and adding a notional US$ 1 million for deeper drilling than Alaska, in one year a proof of concept 1 MW power station (for 1000 homes) might make 70 x 1 x 365 x 24 = US$ 0.613 million "profit" before tax. The development costs could be written off in 2.3 / 0.613 = 3.75 years and save the equivalent of 10,000 barrels of oil/year (with crude oil at US$100 oil/barrel this is a saving of US$ 1 million/year in carbon credits).

The cost of actually drilling 3 km deep directional wells in granite in Singapore is unknown therefore it is difficult to estimate costs and times to break even for a commercial EGS 50 MW power station. According to the U.S. DoE (2006) the initial cost for larger field and power plants was around US$ 2.5 million per installed MW in the U.S. At 5% inflation per year, this is US$ 3.0 million per MW at 2010 prices. Sanyo et al. (2007) estimate that EGS would be US$ 4.0 million per MW at 2007 prices, i.e. US$ 4.6 million at 2010 prices. Estimates for Australia are equivalent to US$ 4.2 per MW at 2010 prices (see Appendix 1 in Cooper et al. 2010). An average of these estimates is US$ 3.93 million per MW.

A 50 MW EGS geothermal power station might therefore cost 50 x 3.93 = US$ 197 million. Assuming production costs at 5 cents/kWh and selling at a domestic rate of 12 cents/kWh generates a profit of 7 cents/kWh, i.e. US$70/MWh. In one year a 50 MW power station might make 70 x 50 x 365 x 24 = US$ 30.6m "profit" excluding taxes and interest payments. Write off would take 197/30.6 = 6.4 years: an EGS is assumed to last 30 years. 50 MW saves the equivalent of 0.25 million barrels of oil/year which at US$100/ bbl = US$25 million/year worth of carbon credits.

Markets

There is a domestic market of 5 million people and a sophisticated infrastructure of transport (electric Mass Rapid Transport system, airports), industrial (coal and biomass fired power stations, oil refineries, ship and oil rig construction), and military installations. Each of these could benefit from an autonomous supply of electricity. Alternatively, hot water could be used directly in process industries or to power district cooling projects using absorption chiller technology. Neighbourhood 50 MW geothermal power stations (costing US$ 200 million each) could be distributed around Singapore on reclaimed or Government land or concentrated on Pulau Tekong, to provide base load electricity. The generating costs would remain static whilst the cost of imported natural gas varies.

Environmental Impact

An environmental impact and risk assessment would be a high priority. Geothermal energy is viewed as renewable, clean and green with a small carbon footprint during the construction phase. No doubt, a rig capable of drilling 3 km long directional wells would be disruptive in Singapore's mainly urban environment. All the drilling for a power station could be conducted from one noise-proofed drilling pad.

The surface geology indicates that there is ample permeability in the strongly jointed granite and Jurong Formation and it might be that permeability stimulation at depth is not required. However, any HF acid-fracture job would create micro-seismicity. Singapore experiences micro-seismicity from the Java/Sumatra subduction zone and the population is seismically aware. Consequently, any frac-job would require monitoring with a seismic array.

The infra-structure for a 1 MW 'proof of concept' power station would fit into 2 or 3 tennis courts. A 50 MW commercial power station could perhaps be located underground on an area the size of three or four football fields. Pipe work and high tension transmission lines would also be placed underground.

Water supply in Singapore is an issue and there would be an initial requirement to augment the working hydrothermal fracture system with fresh or storm water, but not sea water which could cause scaling. Once the system was pressured up and if the injector/production well connections were efficient, the requirement for augmented water would drop. Air rather than water cooling might be installed in tower blocks on top of the underground generating halls to condense turbine vapour for recycling. Sembawang hot spring has virtually no smell but Pulau Tekong hot spring is reported to be H_2S-rich (Lee and Zhou 2009); however, binary generating systems do not release fluids or gases to the atmosphere.

Summary

Hot springs in Singapore are good indicators for a geothermal power resource. A 1 MW demonstration geothermal power station in a hot spring area of Singapore could be commissioned for US$ 2.3 million. Construction of a commercial geothermal power generation would involve the drilling of 3 km deep directional boreholes and the generation of electricity from +150 ^{o} C hot water through binary cycle turbines with the cooled 'waste' water being recycled down injection wells. Proof of concept for an EGS 50 MW power station might cost US$ 19 million. Development costs (US$ 200 million) could be written off in 6.4 years after production started. Several neighbourhood EGS 50 MW geothermal power stations could supply base load electricity to the national grid. This is 'renewable', clean, green power generation of strategic importance for a country that is viewed as having no natural resources.

Acknowledgements

This research was funded by an internal NUS grant to Professor A. Palmer, Department of Civil Engineering, National University of Singapore, who is thanked for many insightful discussions.

References

Barlow P.M., 2005, Ground water in fresh water - salt water environments of the Atlantic coast, United States Geological Survey Circular, 1262, 26 pp.

Bowen, R., 1986, Groundwater, 2nd edition, Elsevier, 427 pp.

Cooper, G.T., Beardsmore, G.R., Waining, B.S., Pollington, N. and Driscoll, J.P., 2010, The Relative Costs of Engineered Geothermal System Exploration and Development in Australia. Proceedings of the World Geothermal Congress 2010, Bali Indonesia, 25-29 April 2010.

Hall, R. and Morley C.K., 2003. Sundaland basins. In: Clift, P. D., Wang, P., Kuhnt, W., Hall, R. and Tada R. (eds.) Continent-Ocean Interaction within East Asian Marginal Seas. Geophysical Monograph Series 1949, 55 – 85.

Kopp, R.E., Simons, F.J., Mitrovica, J.X., Maloof, A.C. and Oppenheimer, M., 2009, Probabalistic assessment of sea level during the last interglacial stage. Nature, 462, 863-867.

Lee, K.W. and Zhou, Y., 2009, Geology of Singapore, 2nd Edition, Defence Science and Technology Agency, Singapore, 90pp.

Mazlan, M., Abolins, P., Mohammad Jamaal and Mansar, A.,1999, In : PETRONAS. The Petroleum Geology and Resources of Malaysia. Kuala Lumpar 171-217.

Sanyal, S.K., Morrow, J.W., Butler, S.J., Robertson-Tait, A., 2007, Cost of electricity from enhanced geothermal systems. Proceedings Thirty-Second Workshop on Geothermal Reservoir Engineering, Stanford.

U.S. Department of Energy. (2006). http://www1.eere.energy.gov/geothermal/m/faqs.html

Zhao, J., Chen, C.N. and Cai, J.G., 2002, A hydrological study of the Sembawang hot spring. Bulletin Engineering Geology Environment, 61, 59-71.

Zhou, Y., 2001, Engineering Geology and Rock Mass Properties of the Bukit Timah Granite. Underground Singapore, 29-30 Proceedings, 308-314.

Web sources were accessed in May, 2010.

(1)http://www.searchanddiscovery.com/documents/2008/08181goldstein/index.html.

(2)http://useconomy.about.com/od/candidatesandtheeconomy/a/Obama_

(3)http://www.chenahotsprings.com/geothermal-power/.

(4)www.geyser.com.

(5)http://wwwwsm.physik.unikarlsruhe.de/pub/stress_data_frame.html

(6)http://pubs.usgs.gov/circ/2003/circ1262/#heading156057192.